THE IMPACT OF SWIM TRAINING LOADS ON SHOULDER MUSCULOSKELETAL PHYSICAL QUALITIES

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Glossary of Terms

AC	Acromioclavicular
ACL	Anterior cruciate ligament
ACWR	Acute chronic workload ratio
AE	Athletes exposure
AU	Arbitrary units
CET	Combined elevation test
CG	Control group
CI	Confidence interval
CV	Coefficient of variation
EMG	Electromyography
ER	External rotation
ES	Effect size
ETL	External training loads
HGF	Handgrip force
HHD	Hand-held dynamometer
ICC	Intraclass correlation coefficient
IG	Intervention group
IOC	International Olympic Committee
IR	Internal rotation
ITL	Internal training loads
JPS	Joint position sense
LD	Latissimus dorsi
LOA	Limits of agreement
N	Newtons
Nm	Newtons meter
N/Kg	Newtons per kilogram
Nm/Kg	Newtons meter per kilogram
MCID	Minimal clinical important difference
MDC	Minimal detectable change
MET	Muscle energy techniques
PML	Pectoralis minor length

ROM	Range of motion
RCT	Randomized controlled trials
RPE	Rating of perceived exertion
SA	Serratus anterior
SD	Standard deviation
SEM	Standard error of measurement
SFP	Shoulder forward position
SIS	Shoulder impingement syndrome
sRPE	Session rating of perceived exertion
STT	Supraspinatus tendon thickness
VAS	Visual analogue scale

Abstract

Competitive swimmers are exposed to high amounts of training loads. With a prevalence reported as high as 91%, shoulder pain is the main cause for missed or modified training in swimmers. The aetiology of injuries in sports is multifactorial including the interaction between multiple risk factors. Within these factors, training loads are considered the major cause of injuries in athletes. Although there is consensus that shoulder pain in swimmers is mainly caused by excessive training loads, there is a lack of research in this area. This might reflect the inefficacy of injury prevention programs and that the prevalence of shoulder pain remains high.

Therefore, this thesis aimed to determine the effects of swim training loads on shoulder physical qualities associated with shoulder pain in swimmers. The results showed that the intensity of a swim-training session is an important factor leading to decreases in shoulder external rotation (ER) range of motion (ROM) and shoulder rotation isometric peak torque. Interestingly, we also found that these changes were more pronounced in swimmers of a lower level of competition. Furthermore, the accumulation of training loads over a week negatively impacted shoulder ER ROM and wellness factors (fatigue, sleep quality, and muscular soreness). These results provide information about the complex interaction between training loads and risk factors for shoulder pain in swimmers.

Clinically, this study might help coaches and practitioners working with swimmers to know which factors and when they need to be monitored. Monitoring can help to understand swimmers’ response to training to adequately prescribe and manage training loads, minimising the risk of injury and maximising performance. Finally, interventions addressing these factors might also help to reduce the risk of injury.

Publications

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Conferences

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Chapter 1

Introduction

Shoulder injuries are common in overhead athletes. Overhead sports can be categorised as throwing or striking, such as baseball, javelin, volleyball and tennis, and non-throwing or striking, such as swimming (Oberlander et al., 2000). Several studies have investigated how shoulder injuries occur in these athletes, what factors contribute, and how this risk might be reduced. This thesis focuses on competitive swimmers; in particular, it aims to understand the effects of training loads on the physical qualities of the shoulder, as the interaction of these two factors, that is load potentially bringing about changes in physical qualities could have significant implications for injury predisposition. This knowledge will help clinicians and coaches to understand a swimmer's response to training as a means to adequately prescribe and manage training loads, minimising the risk of injury and maximising performance. This introduction will provide an overview of the epidemiology, aetiology, and risk factors for shoulder pain in competitive swimmers.

1.1. General injuries and injury mechanisms in swimmers

Swimming is a popular overhead sport, and it is practised by millions of people each year from a recreational to a competitive level (Tate et al., 2012). Since it was introduced as an Olympic sport in 1896, swimming has evolved into a competitive activity exposing athletes to significant training loads (Wolf et al., 2009). Injuries are common in this population, with general injury rates ranging between 2.12 to 5.55 per 1000 athletes exposures (AE) during training seasons (Chase et al., 2013; McFarland & Wasik, 1992; Ristolainen et al., 2014; Wolf et al., 2009) and 28 to 61 per 1000 athletes during competitions (Mountjoy et al., 2010, 2015). As a consequence of the high amount of training hours and the repetitive nature of the sport, overuse injuries are the most commonly reported. Studies have found that between 44.4% and 63.7% of all the injuries sustained during training seasons (Chase et al., 2013; Kerr et al., 2015) and 37.5% sustained during competitions (e.g. Aquatic world championship) (Mountjoy et al., 2010) are classified as overuse. Considering the large number of injuries and the overuse mechanism, it is important to know which body part is the most commonly affected.

The shoulder is the most common body part to be injured, accounting for 31% to 44% of all the injuries, followed by the spine (16% to 21%) and the knee (5.5% to 14.9%) (Chase et al., 2013; De Almeida et al., 2015; Kerr et al., 2015; Wolf et al., 2009). The higher percentage of shoulder injuries reported might be explained by the 90% of the propulsive force that comes from the upper limbs during swimming (Pink & Tibone, 2000). Also, it can be attributed to the fact that elite swimmers swim up to 14,000 m/day, which is more than 2500 shoulder revolutions per day and 16,000 per week (Pink & Tibone, 2000; Wanivenhaus, Fox, Chaudhury, & Rodeo, 2012). Comparably, around 1000 shoulder revolutions per week have been reported for a professional tennis player and baseball pitcher, 300 for a javelin thrower, and 200 for a professional golfer (Scovazzo, Browne, Pink, Jobe, & Kerrigan, 1991). The propulsive forces generated by the upper limbs in combination with the high amount of training volume predispose athletes to a high number of overuse shoulder injuries.

Shoulder pain has been reported as the main factor for missed or modified training in competitive swimmers (Chase et al., 2013; Weldon & Richardson, 2001). As a result of this, shoulder pain might interfere with training and competition performance, developing chronic injuries and leading in some cases to the retirement from sports participation (Hibberd & Myers, 2013). The prevalence and incidence of shoulder pain in competitive swimmers is high (Chase et al., 2013; Feijen, Struyf, et al., 2020; Hibberd & Myers, 2013; Holt et al., 2017; McLaine et al., 2018; McMaster & Troup, 1993; Rupp et al., 1995; Sein et al., 2010; Tessaro et al., 2017; Walker et al., 2012). Importantly, the latest research has not shown a decline in prevalence or incidence. This demonstrates the importance of understanding the aetiology and the risk factors associated with the development of shoulder pain in this population in order to develop effective preventive programs.

1.2. Aetiology of shoulder injuries in swimmers

The aetiology of injuries in sports is dynamic and multifactorial including the complex interaction between multiple risk factors (e.g. training-related, biomechanical, psychological, and behavioural factors) (Bittencourt et al., 2016). Training-related factors (i.e. training loads) are considered a major factor for injuries as every athletic injury is sustained while athletes are exposed to training or competition workloads (Windt & Gabbett, 2017). Training loads are defined as “the cumulative amount of stress placed on an individual from a single to multiple training sessions (structured or unstructured) over a period of time,” (Soligard et al., 2016), which are applied to induce positive physiological changes and maximize performance (Windt & Gabbett, 2017). However, their inadequate management (balance between load and recovery) can increase the risk of overtraining (Meeusen et al., 2013) and injuries (Eckard et al., 2018).

The aetiology of shoulder pain in swimmers is not well understood. The definition of "swimmers' shoulder" has evolved from a clinical diagnosis to a condition characterised by shoulder pain and dysfunction (Struyf et al., 2017; Tate et al., 2015). There are several proposed mechanisms of shoulder pain in swimmers, including overuse and fatigue of the shoulder muscles, laxity and instability, and swimming stroke biomechanics (De Martino & Rodeo, 2018; Matzkin et al., 2016). Despite this, there is consensus that fatigue as a result of training loads (e.g. swim-volume or intensity) is the main factor for the development of shoulder pain in swimmers (De Martino & Rodeo, 2018; Gaunt & Maffulli, 2012; Matzkin et al., 2016; Struyf et al., 2017). The work-load aetiology injury model proposed by Windt and Gabbett (2017) suggests that the risk of injury is dynamically changing as a result of the training loads applied and their effects on modifiable risk factors (e.g., decrease in shoulder strength after a training session). Therefore, risk factors for shoulder pain in swimmers (particularly modifiable) need to be considered to reduce the risk of injury.

1.3. Risk factors for shoulder pain in swimmers

Several potential modifiable (e.g. training volume, shoulder rotation range of motion, rotation force, latissimus dorsi length, etc) and non-modifiable risk factors (e.g. age, level of competition, history of injury, etc) have been associated with shoulder pain in swimmers (Feijen, Tate, Kuppens, Claes, et al., 2020; Hill et al., 2015; Struyf et al., 2017). Although not directly associated to shoulder pain, impairments in well-being factors, such as perceived muscular soreness, fatigue, sleep quality, and stress, have been also found in overtrained swimmers (Hooper et al., 1995). Alterations of well-being factors could potentially increase the susceptibility of shoulder injury in swimmers as they have been reported as injury predictors in other sports (Cahalan et al., 2018; Galambos et al., 2005; Hamlin et al., 2019; Laux et al., 2015; Pensgaard et al., 2018; Watson et al., 2017). The complex system approach for sports injuries proposed by Bittencourt et al. (2016) emphasizes understanding the interactions between risk factors to identify injury risk profiles for an athlete or group of athletes. Considering the key role of training loads in the development of shoulder pain in swimmers, it is important to understand the interactions between training loads and these factors.

1.4. Interaction between training loads and risk factors for shoulder pain in swimmers

To date, the effects of swim-training loads on physical qualities of the shoulder in competitive swimmers have only been investigated in two studies (Higson et al., 2018; Matthews et al., 2017). These studies found that shoulder joint position sense, ER ROM, and pectoralis minor length were immediately affected after a single swim-training session. Although this is emerging evidence, the impact of different training intensities on these factors and if the changes are transient or long-lasting is still unknown. Also, the investigation of more musculoskeletal risk factors is needed. Regarding well-being factors, the peak swim-training volume during a season and acute increases in swim-training volume has been associated with decreases in mood and sleep quality and increases in muscular soreness (Morgan et al., 1987; O'Connor et al., 1989; Taylor et al., 1997). Despite this, it is still unknown how these factors are affected by specific amounts of swim volume. Understanding the specific responses of these factors to training loads might provide a broader understanding of the multifactorial nature of shoulder pain in swimmers.

Overall, shoulder pain is a common complaint among competitive swimmers. Shoulder pain interferes with training and competition performance, developing chronic injuries and leading in some cases to retirement from the sport. Considering the multifactorial nature of injuries in sports and the main role of training loads, it is important to understand how training loads interact with other factors associated to shoulder pain in swimmers. There is evidence of the acute effects of training loads on musculoskeletal and wellness factors associated with shoulder pain in competitive swimmers. Although this provides important information, there are gaps in the literature. First, training loads are not explicitly described in all the studies, which limits the ability to understand the magnitude (e.g., volume and intensity) at which these changes occur. Second, only a few factors have been studied, which affects the understanding of the multifactorial nature of shoulder pain in swimmers. Finally, it is unknown how long these risk factors take to recover after a training session.

The lack of knowledge in this area possibly explains why the prevalence of shoulder pain in this population remains high. Furthermore, it reflects the inefficacy of injury prevention programs for shoulder pain in swimmers. To date, only three studies have investigated the effects of an intervention program on shoulder pain with contrasting and inconclusive results (Lynch et al., 2010; Manske et al., 2015; Swanik et al., 2002). Understanding how training loads affect potential risk factors might help coaches and practitioners to identify which factors to observe and when they need to be monitored. Monitoring can help to understand a swimmer's response to training as a means to adequately prescribe and manage training loads, minimising the risk of injury and maximizing performance. Finally, interventions addressing these factors individually might also help to reduce the risk of injury.

1.5. Aims and hypothesis

The primary aim of this thesis is to determine the effects of swim-training loads on shoulder physical qualities associated to shoulder pain in swimmers.

Therefore, the objectives and hypothesis of this thesis are:

- To review the literature related to epidemiology, aetiology, risk factors and management of shoulder pain in competitive swimmers (Chapter 2).

- To review the literature regarding the reliability of several shoulder musculoskeletal physical qualities (Chapter 2).

- To examine the intrarater and test-retest reliability of tests that assess shoulder function in a non-swimmer population. To establish the definitive tests for the following studies. To assess the symmetry between the dominant and nondominant side (Chapter 3).

- To determine the acute effect of training intensity on shoulder musculoskeletal physical qualities namely shoulder range of motion, joint position sense, rotation isometric torque, latissimus dorsi length, handgrip force, and combined elevation test in competitive swimmers (Chapter 4).

  Null hypothesis- Physical qualities of the shoulder in competitive swimmers will be unaffected by a low and high-intensity swim-training session.

- To compare the baseline differences in shoulder ER ROM and rotation isometric peak torque between university and national level swimmers. To compare the post-swim changes of these physical qualities within and between groups (Chapter 5).

  Null hypothesis- There will be no significant difference between groups in baseline shoulder ER ROM and isometric peak torque. There will not be a significant difference in post-swim changes in these physical qualities between groups.

- To analyze the changes in physical qualities of the shoulder and wellness factors over a week of training in competitive swimmers (accumulation of training loads). To compare the changes in these variables between different swim-training volumes performed during the week (Chapter 6).

  Null hypothesis- Physical characteristics of the shoulder and wellness factors in competitive swimmers will be unaffected by the accumulation of training loads over a week. There will not be a significant difference between the effects of different training volumes on these factors in competitive swimmers.

- To investigate if shoulder ER ROM and rotation isometric peak torque recover after a high-intensity training session by the next training session in competitive swimmers who show a negative response to a high-intensity training session (Chapter 7).

  Null hypothesis- Shoulder ER ROM and rotation peak torque will have recovered by the evening training session on the same day.

Chapter 2

A narrative review of the literature

This literature review provides the rationale and background for this thesis, the following topics are discussed:

- Prevalence and incidence of shoulder pain in swimmers.
- Swimmer's behaviour and injury definitions.
- Swimming biomechanics and shoulder muscle activation during the freestyle stroke and common swimming errors.
- Aetiology-injury models in sports.
- Aetiology of the "swimmers' shoulder".
- Training loads classifications, monitoring, and relationship with injuries.
- Risk factors for shoulder pain in swimmers.
- Interactions between training loads and risk factors for shoulder pain in swimmers.
- Injury prediction and prevention in sports.
- Swimming performance and musculoskeletal risk factors.
- Intervention strategies for shoulder pain in swimmers.
- Reliability of outcome measures.

This literature review aims to critically appraise the existing literature regarding the epidemiology, biomechanics, aetiology, and risk factors for shoulder pain in competitive swimmers. This will help to understand the gaps in the literature and establish the directions of this research. Electronic databases were searched, using the following keywords: "swimming"; "shoulder pain"; "risk factors"; "training loads", "recovery"; "wellness"; "overuse injuries"; "prevention"; "reliability"; "range of motion"; "strength"; "combined elevation test"; "latissimus dorsi length"; "joint position sense"; "handgrip strength", "inclinometer"; "hand-held dynamometer". The following databases were searched: PubMed, Science Direct, Cochrane Library, Web of Science, and Google Scholar. Also, the Web of Science alerts was used to identify new research published in the area.

2.1. Epidemiology of shoulder pain in swimmers

2.1.1. Prevalence and incidence of shoulder pain

According to The International Olympic Committee (IOC) statement for injury surveillance in sports (Bahr et al., 2020), prevalence is defined as "the number of existing cases divided by the total population at risk at given time point". Prevalence can be divided into point prevalence (e.g., the proportion of athletes with a current injury) and period prevalence (e.g., the proportion of athletes injured in the last season or last year) (Bahr et al., 2020). Furthermore, the incidence is defined as "the number of new injuries in a population that develop during a defined period of time," (Bahr et al., 2020).

The prevalence of shoulder pain in competitive swimmers has been reported to be between 24% to 91%. The large variety of results may be due to the different factors (e.g., age, level of competition, injury definition) including the type of prevalence reported. Regarding the type of prevalence, studies investigating point prevalence have shown the lowest proportion of swimmers with shoulder pain. McMaster et al. (1993) found that 26% of the elite swimmers surveyed had current shoulder pain (McMaster & Troup, 1993). Similarly, Rupp et al. (1995) and Holt et al. (2017) reported that 23% and 24% of competitive swimmers presented current shoulder pain at the time of the survey, respectively. Conversely, studies reporting period prevalence have found a higher proportion of swimmers with shoulder pain. For instance, 85% (Hibberd & Myers, 2013) and 51% (Tessaro et al., 2017) of competitive swimmers that were surveyed had experienced shoulder pain during the last year. The highest prevalence has been reported by Sein et al. (2010), who found that 91% of elite swimmers have experienced an episode of shoulder pain during their careers (Sein et al., 2010). A previous study (McMaster & Troup, 1993) supported this reporting that 73% of swimmers surveyed have experienced shoulder pain during their life. This shows that the prevalence of shoulder pain in swimmers increases as the window of time increases. One limitation of the studies investigating period prevalence is that injury recording was based on questionnaires. It has been shown that an important number of injuries are not reported in retrospective questionnaires completed by athletes due to recall bias (i.e. forgotten injuries) (Fuller, 2006; Junge & Dvorak, 2000).

Alternatively, some studies have investigated the incidence of shoulder injuries in swimmers. A 1-year prospective study found that 38% of the swimmers reported shoulder pain that interfered with training or competition (Walker et al., 2012). This study also found a shoulder injury incidence rate of 0.3 per 1000 km of swimming, suggesting that within a squad of 20 swimmers, at least 5 of them will have a shoulder injury during a 16-week training period (average of 50 km per week) (Walker et al., 2012). Likewise, a later study found that 38% of competitive swimmers sustained a shoulder injury during one training season (Chase et al., 2013). Similarly, Kerr et al. (2015) reported that 34.7% of men and 36.8% of female swimmers developed a shoulder injury during two training seasons. More recent studies found that 47% (McLaine, Bird, et al., 2018) and 30% (Feijen, Struyf, et al., 2020) of swimmers reported an episode of shoulder pain during a follow-up period of two years. This shows that prospective studies reporting incidence have more consistent values of shoulder pain than cross-sectional studies reporting prevalence (possibly, to some extent, to the different types of prevalence reported).

Despite this, the literature demonstrates the relevance of shoulder pain in competitive swimmers. Moreover, the latest research has not shown a decline in prevalence (Holt et al., 2017; Tessaro et al., 2017) or incidence (Feijen, Struyf, et al., 2020; McLaine, Bird, et al., 2018). This demonstrates the importance of understanding the aetiology of shoulder pain in this population to develop preventative strategies.

2.1.2. Shoulder pain and time loss from training and competition

Shoulder pain is the main cause of missed or modified training in competitive swimmers (Chase et al., 2013; Weldon & Richardson, 2001). Despite the high incidence and prevalence of shoulder injuries, most of the swimmers do not stop training (Mountjoy et al., 2016). This is reflected in the low time-loss of training or competition due to shoulder concerns. Sein et al. (2010) found that 91% of the elite swimmers surveyed reported an episode of shoulder pain during the last month, but none of them discontinued training permanently due to pain. This is supported by a 2-season prospective study (Kerr et al., 2015) reporting that 12.5% to 15.8% of female swimmers and none of the male swimmers diagnosed with shoulder tendinopathy or shoulder impingement syndrome (SIS) stopped training for more than one day due to the shoulder complaints. Similarly, a cross-sectional study conducted by Tessaro et al. (2017) found that 31% of the swimmers that reported shoulder pain during the last year stopped training, whereas 69% continued training despite the pain.

The possible explanations for these findings are the swimmers' beliefs about shoulder pain (Hibberd & Myers, 2013) and the high number of overuse injuries (Mountjoy et al., 2016). Hibberd et al. (2013) investigated the habits and attitudes of competitive swimmers around shoulder pain. Interestingly, the authors found that 72% of the swimmers used pain medications to control their shoulder pain during training, with 47% reporting regular use. Moreover, only 14% of the swimmers who reported shoulder pain, visited a health professional to be diagnosed (Hibberd & Myers, 2013). These findings might reflect the cultural beliefs of competitive swimmers around training with shoulder pain to complete the practice volume. This is supported by a recent study (Tate et al., 2020) showing that 96.29% of swimmers experienced some level of shoulder pain (i.e. low pain ratings) during the end of a training season without discontinuing training. As a result of this, shoulder pain might sometimes interfere with training and competition performance, developing chronic injuries and leading in some cases to the retirement of sports participation (Hibberd & Myers, 2013).

2.1.3. Injury registration and definitions

There is a lack of consensus on shoulder injury definition across studies, which can also explain the varied results reported of prevalence and incidence. Some studies have used a time-loss definition: shoulder injury as a condition that restricts the athlete´s participation in training or competitions (Chase et al., 2013; Feijen, Struyf, et al., 2020; Kerr et al., 2015; McLaine, Bird, et al., 2018; Wolf et al., 2009). Considering the large number of swimmers that continue training despite shoulder pain, this pain definition might underestimate overuse shoulder injuries in this population (Bahr et al., 2020; Mountjoy et al., 2016). Conversely, other studies have incorporated a non-time-loss definition that includes modification rather than cessation of training. For instance, Walker et al. (2012) defined shoulder injury as the pain that interferes with training or competition causing cessation or modification of the activity (Walker et al., 2012), whereas McMaster et al. (1993) defined it as the pain that interferes with training or progress with training (McMaster & Troup, 1993). Furthermore, Hibberd et al. (2013) defined shoulder injury based on the intensity of the pain and the alteration of the swimming technique (Hibberd & Myers, 2013). The inclusion of training modification in the surveillance of injuries would increase the likelihood of reporting overuse injuries in swimmers considering a large number of swimmers that continue training with pain (Mountjoy et al., 2016).

Although IOC statements in injury surveillance in sports (Bahr et al., 2020; Mountjoy et al., 2016; Soligard et al., 2016) recommend the use of time-loss definitions for injury and severity, they are aware of its limitations (e.g., underestimate of overuse injuries). Therefore, they suggest that in sports where overuse injuries represent a substantial burden on health and performance (e.g., swimming), injury definitions that record sport participation, training modifications, performance reductions and symptoms should be implemented (e.g., Oslo Sports Trauma Research Centre Questionnaire on Health Problems [OSTRC-H]).

2.1.4. Summary epidemiology

Evidence shows a high prevalence and incidence of shoulder pain in swimmers. More importantly, recent studies have not reported a decrease in shoulder pain. The time-loss of training and competition due to shoulder pain is low, which is probably explained by swimmers' beliefs (training despite the pain) and the high number of overuse injuries. However, different populations and injury definitions across studies make comparisons more difficult. A recent systematic review investigating the epidemiology of injuries in swimming (Trinidad et al., 2021) found that only a few studies followed the IOC injury surveillance guidelines. The main methodological issues reported were the limited description of injuries (type and severity) and the population investigated (age and gender). The report of shoulder injuries following the IOC recommendations might be necessary to provide a better understanding of the epidemiology of specific swimming populations.

2.2. Swimming biomechanics

There are four types of swimming strokes: freestyle, butterfly, backstroke, and breaststroke. Although the demand on the shoulder can differ based on the stroke (Martens et al., 2015), the majority of practice is performed in freestyle (Beach et al., 1992; Hibberd & Myers, 2013; Sein et al., 2010). For instance, Beach et al. (1992) reported that 80% of practice is spent performing the freestyle stroke in competitive swimmers. Furthermore, 90% of elite swimmers spend more than 50% of their training time in the freestyle stroke regardless of their speciality (Sein et al., 2010). Considering this, many of the risk factors for the development of shoulder pain are common to all swimmers, regardless of stroke speciality (Hibberd & Myers, 2013). This is supported by two large studies (Kruger et al., 2012; Tate et al., 2012) showing no relationship between swimmers main stroke and shoulder pain (N = 518; age range = 17-90 years). The next section will present the normal kinematics and muscle activation patterns during the freestyle stroke and how this is affected by shoulder pain.

2.2.1. Freestyle stroke and shoulder biomechanics

Freestyle stroke can be divided into six phases: hand entry, forward reach, pull through, mid-pull through, hand exit, and mid-recovery (Matzkin et al., 2016). The shoulder position during the hand entry phase is characterised by shoulder forward flexion, abduction and internal rotation (IR) (King, 1995). During this phase, the supraspinatus and deltoid (anterior and middle portions) abduct and flex the shoulder, whereas the upper trapezius, rhomboids, and serratus anterior position the glenoid fossa of the humeral head (Pink, Perry, Browne, Scovazzo, & Kerrigan, 1991). Since this phase requires the shoulder to be in maximum forward flexion, the swimmers roll their body to achieve maximum forward reach to prepare for the pull-through phase (Matzkin et al., 2016). The pull-through phase is when more propulsion force is generated, with the pectoralis major and latissimus dorsi (LD) being the main muscles (Nuber et al., 1986; Pink et al., 1991). The pectoralis major is responsible for the initial pulling, with the teres minor resisting the internal rotation forces. Then, the LD continues extending the shoulder in the late stage of this phase (Pink et al., 1991). At the end of the pull-through phase, the posterior deltoid begins to lift the humerus out of the water (Pink et al., 1991). Importantly, the same muscles acting in the hand entry phase are activated in the hand exit to position the arm for the recovery phase (Pink et al., 1991).

During the recovery phase, the shoulder is abducted and externally rotated (Matzkin et al., 2016). In the mid-recovery phase, the maximum external rotation (ER) range of movement (ROM) is achieved, which is related to the infraspinatus peak activity to control the IR force produced by the subscapularis (Pink et al., 1991). Importantly, the subscapularis and serratus anterior (SA) are constantly active during all the stroke phases (Pink et al., 1991). The constant activity of subscapularis is a consequence of the predominant IR forces during the stroke and also as a result of its stabilization role, centring the humeral head and preventing its anterior-superior translation (Gaudet, Tremblay, & Begon, 2018; Pink et al., 1991). This stabilization function is supported by Gaudet et al. (2018) showing that the subscapularis is active during shoulder internal and external rotations movements. Concerning the SA, its constant activity helps to position the scapula during all the stroke phases (Pink et al., 1991). Particularly, before the pull-through phase, the SA´s role is to position the scapula in protraction and upward rotation to allow an effective propulsive motion (Scovazzo et al., 1991). It has also been shown that the SA is activated during both external and internal shoulder rotation, suggesting that it is an important stabilizer of the glenohumeral and scapula-thoracic joints (Gaudet et al., 2018). The subscapularis and serratus anterior are two important muscles in charge of the shoulder stabilization during swimming; however, their constant activity makes them susceptible to fatigue (Pink & Tibone, 2000).

2.2.2. Freestyle stroke and shoulder pain

Only one study (Scovazzo et al., 1991) has investigated muscle activation patterns in painful shoulders of swimmers during the freestyle stroke. Using electromyographic (EMG) analysis, Scovazzo et al. (1991) found that the SA activity was decreased during the middle pull phase with a resultant increase of the rhomboids´ function to stabilize the scapula. This diminished activity would lead to an ineffective propulsive phase (Scovazzo et al., 1991). Concerning the subscapularis, its activity is decreased during the mid-recovery phase with a subsequent increase in the infraspinatus activity (Scovazzo et al., 1991). A decrease of the upper trapezius, rhomboids, and anterior and middle deltoid activity during hand entry and exit in painful shoulders has also been shown (Scovazzo et al., 1991). The most important muscles providing stability to the shoulder during swimming are affected by pain and fatigue.

2.2.3. Freestyle stroke swimming errors and shoulder pain

It is hypothesized that the swimming technique plays an important role in the development of shoulder pain (Hibberd & Myers, 2013). The dropped elbow during the pull phase has been reported as the main error during freestyle swimming (Virag et al., 2014). This error places the shoulder in a more externally rotated and horizontal adduction position leading to the mechanical disadvantage of the propulsive muscles, probably predisposing swimmers to shoulder injuries (Virag et al., 2014; Yanai & Hay, 2000). Yanai et al. (2000) suggested that this could be a compensatory strategy to decrease the shoulder impingement by dropping the elbow and increasing the external rotation. This is supported by studies reporting that pull-through is the most frequently painful phase reported by swimmers (Pink & Tibone, 2000; Tessaro et al., 2017; Walker et al., 2012).

The elbow drop during the recovery phase has been reported as the second most frequent error in swimmers (Virag et al., 2014). It has been suggested that this error may be a consequence of pain rather than the cause (Pink & Tibone, 2000). This strategy is probably also used to decrease the internal rotation to avoid the pain produced by the impingement position (flexion and internal rotation) (Scovazzo et al., 1991). Furthermore, it has been associated with an increase of the infraspinatus activity with the same aim of decreasing the internal rotation ROM (Pink & Tibone, 2000). Consequently, a dropped elbow during the recovery phase results in the elbow entering before the hand into the water. This will cause an upward force on the humerus, leading to a superior translation of the humeral head and consequent impingement (Virag et al., 2014). Furthermore, this error is associated with other errors, such as an incorrect hand entry position (lateral or medial to the body axis) and hand entry angle (thumb-first) probably increasing the risk of a shoulder injury (Virag et al., 2014).

Despite some studies suggesting biomechanical errors during the freestyle stroke are potentially harmful for the shoulder, a recent study showed contrasting results. In a prospective study, Feijen et al. (2020) studied the association between swimming errors and the development of shoulder pain in competitive swimmers. The authors found that the odds of shoulder pain was lower (OR, 0.37; 95% CI, 0.16-0.91) in swimmers who had a hand entry error (lateral hand entry), suggesting that this error might be an adaptative mechanism to avoid extreme shoulder positions at the hand entry phase (flexion and IR).

2.3. Aetiology of injuries in sports

To effectively reduce the risk of injuries, it is essential to first understand their aetiology or cause. Before reviewing the aetiology of shoulder pain in swimmers, the injury-aetiology models in sports will be presented. Several injury-aetiology models in sports have been reported in the literature (Bittencourt et al., 2016; Gissane et al., 2001; Kalkhoven et al., 2020; Meeuwisse, 1994; Meeuwisse et al., 2007; Windt & Gabbett, 2017). In a mid-90s article, Meeuwisse et al. (1994) claimed that most of the research investigating causation of sports injuries was based on a single factor approach, which limited the ability to determine the true cause of injuries. Considering this, Meeuwisse et al. (1994) proposed the first multifactorial injury model in sports. The model postulated that intrinsic or athlete-related risk factors (e.g., flexibility, history of injury, and somatotype) may predispose athletes to injuries. Once the athlete is predisposed, extrinsic or environmental factors (e.g., equipment, weather condition, and playing surfaces) interact with the intrinsic factors making the athlete susceptible to injury. However, the sole presence of these factors was not sufficient for an injury to occur. From a biomechanical perspective, an inciting event (e.g., inversion in ankle sprain) was the final link in the chain causing the injury.

Despite introducing the first multifactorial approach for injuries, Meeuwisse et al.´s (1994) injury model was based on a linear paradigm: a starting point (exposure to risk) and an endpoint (injury). Unfortunately, this did not reflect the nature of injuries in sports; in most cases, athletes are not permanently removed from sports participation due to injury, and therefore, an injury may not always represent a definitive endpoint (Gissane et al., 2001). Considering the limitations of the linear model, Gissane et al. (2001) developed a cyclical model for contact injuries in sports. This model emphasized that after an injury, athletes may return to play with modified intrinsic risk factors changing their predisposition to injury. In a later study, Meeuwisse et al. (2007) complemented this model and introduced the ‘dynamic, recursive injury model’. This model added that the susceptibility to injury is also changing as a result of repetitive sports participation even without the presence of injury. If sport participation does not lead to injury, physiological adaptations may occur (i.e., change in intrinsic risk factors) with consequent decreases or increases in the risk of injury. Otherwise, if an injury occurs, the athlete could either recover and return to play with modified intrinsic risk factors (e.g. reduced ROM or strength) increasing the risk of injury, or be removed from sports participation due to no-recovery (Meeuwisse et al., 2007).

Almost a decade later, a non-linear complex model approach for sports injuries was proposed (Bittencourt et al., 2016). Bittencourt et al. (2016) stated that the recursive model proposed by Meeuwisse et al. (2007) was not sufficient to address the complex interaction among several factors. This approach suggested that an injury results from the interaction of multiple factors (web of determinants), which produce regularities (risk profile or sum of factors) and result in an emergent pattern (sports injury). Thus, understanding the multidirectional interactions between multilevel factors (i.e. biomechanical, physiological, psychological, and behavioural) may help to identify frequent patterns, creating a risk profile of an athlete or group of athletes (Bittencourt et al., 2016). To illustrate the complexity, Figure 2.1 shows the web of determinants for an anterior cruciate ligament (ACL) injury in basketball players. Unanticipated environmental events, dynamic knee valgus, and hip muscle weakness are the main elements of the web of determinants. These elements are the ones that mainly interact (unidirectional or bidirectional) and influence, or are influenced by, other factors. These interactions will influence the occurrence of an ACL injury. Importantly, this approach emphasises that a single risk factor (e.g., dynamic knee valgus) does not ensure the manifestation of an injury.

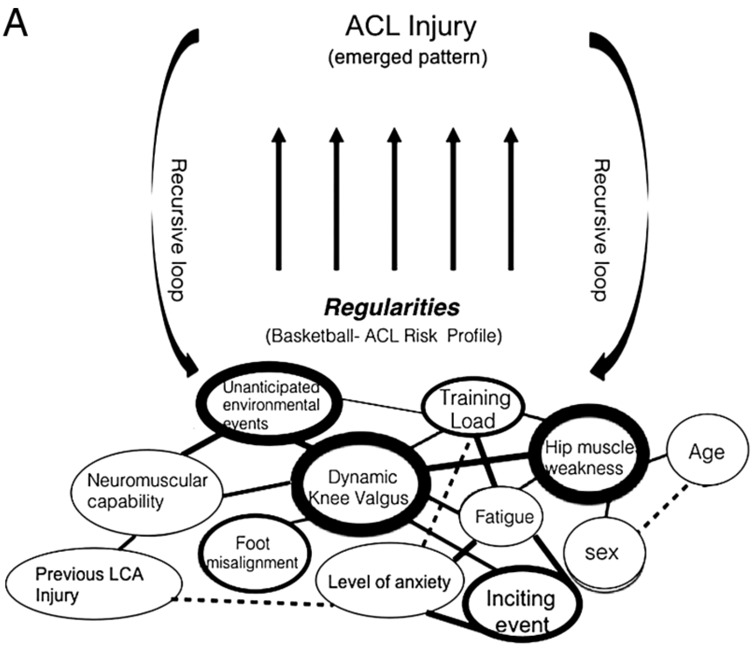

Figure 2.1 - Web of determinants for an ACL injury in basketball athletes (Bittencourt et al. 2016). Variables circled by darker lines have more interactions than variables circled by lighter lines and exert a greater influence on the outcome (injury). Dotted lines represent a weak interaction and thick lines represent a stronger interaction between variables. Arrows indicate the relationship between the observable regularities, which captures the risk/protective profile, and the emerging outcome.

More recently, Windt & Gabbett (2017) proposed the workload-injury model, emphasizing the relevance of workloads in the aetiology of sports injuries. Based on Meeuwisse et al.´s (2007) model, these researchers explicitly outlined that the athlete´s adaptations come as a result of each workload applied. This model proposes that workloads from training and competitions are a “vehicle” in which the athletes are exposed to injuries. Workloads can cause (positive or negative) physiological adaptations (e.g. fitness or fatigue), affecting intrinsic modifiable risk factors and, therefore, dynamically changing the risk of injury for the subsequent training (Windt & Gabbett, 2017). For example, a training session can lead to acute fatigue and consequently decrease force production (modifiable risk factor), predisposing an athlete to an increased risk of injury in the following training (if adequate recovery is not provided). Consensus statements (Bourdon et al., 2017; Soligard et al., 2016) and a systematic review (Eckard et al., 2018) in training loads have supported the importance of workloads in the aetiology of sports injuries (training loads are further discussed in Section 2.4). An important concept is load capacity, which represents the maximum workload that an athlete can tolerate safely without a resulting injury (Gabbett et al., 2019). Several factors might moderate the workload-capacity relationship, including age, physical qualities (e.g., strength, aerobic fitness, speed), life stress, biomechanical, and emotional factors (Esculier et al., 2020; Gabbett et al., 2019; Verhagen & Gabbett, 2019).

Recent reviews in sports injuries (Fonseca et al., 2020; Stern et al., 2019) further support that injuries emerge from a non-linear, dynamic, and complex interaction among multiple factors, including training loads. Another recent study (Kalkhoven et al., 2020) proposed an injury framework based on concepts of load tolerance and load application of specific body tissues. The authors stated that the framework of previous injury models was general and did not provide detailed explanations of causal relationships with injury. Based on Meeuwisse et al. (2007), this framework emphasized the importance of mechanical properties of body tissues; the amount of stress and strain that a given tissue can withstand is determined by the mechanical properties and resultant strength of that tissue. When the strength of a tissue within the body is exceeded, injury occurs. Importantly, the athlete physiology (intrinsic risk factors) will impact the loading and the loading tolerance of specific tissues. Overall, what all these injury-aetiology models have in common is the need to understand the interactions between factors, and especially, the relevance of load application in the development of injuries.

2.3.1. Aetiology of shoulder pain in swimmers

The term “Swimmer’s Shoulder” was first introduced by Kennedy and Hawkins in 1974 as a synonym of subacromial impingement (Kennedy et al., 1978). This definition refers to anterior shoulder pain as a result of repetitive impingement of the supraspinatus and bicipital tendons against the anterior third of the coracoacromial arch (primary impingement). Primary impingement is described as being mainly due to anatomical variations, such as bony osteophytes, narrowing the subacromial space (Sørensen & Jørgensen, 2000). However, currently, “swimmer’s shoulder” represents a condition characterized by pain and dysfunction of the shoulder, rather than a specific clinical diagnosis (Tate et al., 2015; Tessaro et al., 2017). Furthermore, there is a general agreement that shoulder pain in swimmers results mainly from the excessive amount of training loads swimmers are exposed to (Hibberd & Myers, 2013; Hill et al., 2015; Struyf et al., 2017). The amount of training load can lead to secondary shoulder impingement, supraspinatus tendinopathy, and errors in swimming technique (Figure 2.2).

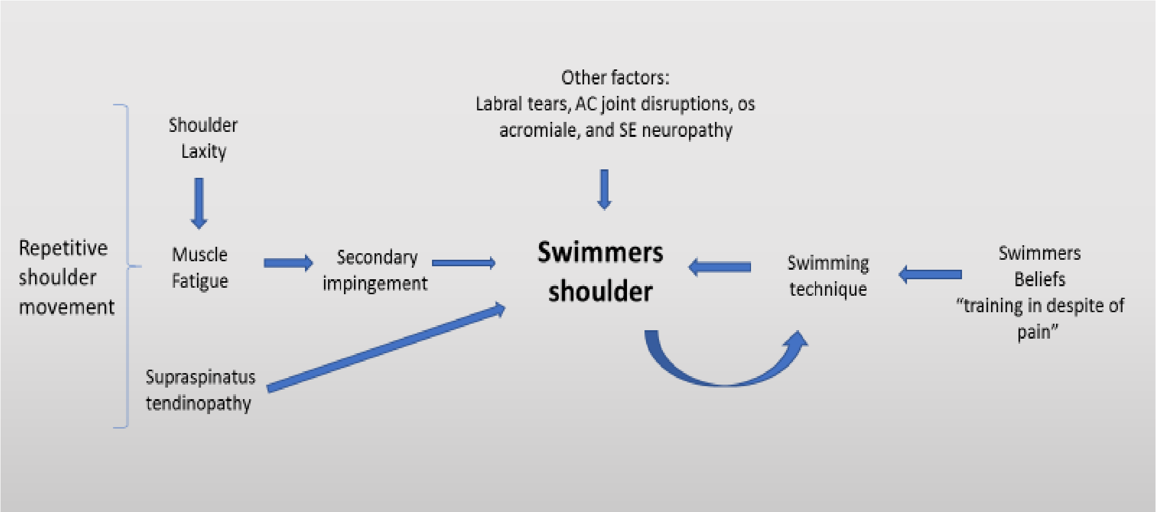

Figure 2.2 - Summary of causes of shoulder pain in swimmers.

Regarding shoulder impingement, secondary impingement is theorised to be the result of functional reductions in the subacromial space and is thought to better explain shoulder pain in the younger athletic populations than primary impingement (Delbridge et al., 2017). It is theorized that repetitive movement during swimming leads to muscle fatigue and joint laxity resulting in secondary impingement (De Martino & Rodeo, 2018). Repetitive movements may cause fatigue of the rotator cuff and scapular muscles to maintain the humeral head centred in the glenoid fossa leading to excessive humeral head translation and subsequent impingement (De Martino & Rodeo, 2018; Wanivenhaus et al., 2012). Also, repetitive movements can gradually stretch the shoulder capsule-ligamentous structures leading to subclinical laxity and instability (Rodeo, Nguyen, Cavanaugh, Patel, & Adler, 2016). The decreased passive stability provided by the ligaments needs a greater contribution of the muscles to stabilize the joint, leading to muscle fatigue and consequent secondary impingement (Weldon & Richardson, 2001). In addition to the laxity acquired by the repetitive movements, the inherent generalized laxity present in swimmers may also contribute to the shoulder instability (Rodeo et al., 2016).

Secondary impingement can be subacromial (external) or intraarticular (internal) and may occur in various positions during the stroke (De Martino & Rodeo, 2018; Wanivenhaus et al., 2012). In the subacromial impingement, the rotator cuff impinges against the acromion under the coracoacromial arch when the arm is positioned in flexion and internal rotation during the recovery phase. Whilst, the intraarticular (anterosuperior) impingement is produced during the hand entry phase (shoulder flexion and IR) impinging the biceps tendon and the rotator cuff against the anterosuperior margin of the glenoid and labrum (De Martino & Rodeo, 2018;

Wanivenhaus et al., 2012). Although secondary impingement seems to be better in explaining the mechanism of shoulder pain in swimmers, other hypotheses have been considered.

Studies have also suggested that supraspinatus tendinopathy is an important cause of shoulder pain in swimmers (Rodeo et al., 2016; Sein et al., 2010). It is hypothesized that repetitive overhead movements lead to the subacromial bursa and supraspinatus tendon thickening with consequent mechanical compression (Rodeo et al., 2016). It has also been suggested that shoulder pain might be related to intrinsic supraspinatus tendon mechanisms as a result of swimming training loads (Porter et al., 2020). Importantly, other factors, such as labral tears, os acromiale, AC joint disruption, and suprascapular neuropathy, can also cause shoulder pain; thus, they should be considered in the differential diagnosis (Matzkin et al., 2016).

Swimmers´ behaviour and stroke technique are also important factors. In a study investigating the attitudes and behaviours of competitive swimmers and shoulder pain, it was found that swimmers find it normal to train with pain (Hibberd & Myers, 2013). The authors concluded that as swimmers continue training despite the pain, the stress over the shoulder is maintained over time generating alterations in the swimming technique and leading to a continuous cycle of shoulder pain (Hibberd & Myers, 2013). This is supported by Struyf et al. (2017) who suggested that swimming errors associated with high swim-volumes may be an important contributory factor for shoulder dysfunctions.

2.3.2. Summary of aetiology

Overall, the aetiology of sports injuries has evolved from the study of a single to multiple factors. It has also progressed from a linear to a dynamic and recursive approach; the risk of injury is dynamically changing as a result of previous injuries and sport participation. The predisposed athlete (alterations in intrinsic risk factors) in combination with the exposure or extrinsic factors (e.g., training loads) may lead to a vulnerable athlete. Current approaches emphasize the importance of investigating the non-linear complex interactions between multilevel factors (i.e., biomechanical, physiological, psychological, and behavioural) to create a risk profile of the athlete, which might help to improve the prediction and prevention of injuries in sports. Furthermore, training loads have been proposed as a central factor for the aetiology of sports injuries.

Understanding of the ‘swimmers’ shoulder’ has evolved from a clinical diagnosis to a condition characterized by pain and dysfunction. Most studies agree that the excessive amount of training volume (i.e., a component of training loads) is the main factor leading to shoulder pain. It is theorized that training loads and their consequences (i.e., fatigue) play an important role in the aetiology of shoulder pain. The main theory suggests the repetitive movements performed by swimmers can result in muscle fatigue and consequently in secondary shoulder impingement. Also, swimmers' behaviours play an important role; training despite the pain results in continuous stress to the shoulder leading to errors in the swimming technique, thus leading to a cycle of shoulder pain.

Considering the relevance of training loads in the development of sports injuries and, especially, shoulder pain in swimmers, it is necessary to understand how training loads interact with other risk factors. This might help to inform which swimmers are predisposed or at higher risk of shoulder injury. Before discussing this, the next section will review the most important aspects of training loads. Then, the risk factors associated with shoulder pain in swimmers will be described followed by the evidence of the interactions between them.

2.4. Training loads

2.4.1. Training loads definition and measures

Training loads are defined as "the cumulative amount of stress placed on an individual from a single to multiple training sessions (structured or unstructured) over a period of time," (Soligard et al., 2016). Training loads can be categorized into external/internal, subjective/objective, and relative/absolute (Soligard et al., 2016).

External training loads (ETL) are defined as any stimulus applied to an athlete independent of their internal characteristics (Soligard et al., 2016) or the amount of work performed by the athlete (Windt & Gabbett, 2017). ETL can be applied over varied periods (seconds, minutes, hours, week, etc) and with varying magnitude (duration, frequency and intensity) (Soligard et al., 2016). Whilst, internal training load (ITL) involves quantifying the athlete's physiological and psychological response to the external load (Soligard et al., 2016). ITL can be further categorized into subjective (self-reported) and objective (not self-reported) measures (Saw et al., 2016). Examples of subjective measures include rating of perceived exertion (RPE), session RPE (sRPE), and well-being questionnaires; whereas examples of objective measures include heart rate and blood lactate levels (Eckard et al., 2018; Windt & Gabbett, 2017). Recent studies have also proposed quantifying the load on specific body tissues (e.g., forces on bones and loads on tendons) as a measure of objective ITL (Martin et al., 2018; Matijevich et al., 2020). Measures of ETL and ITL are shown in Table 2.1.

Table 2.1 - Measures of external and internal training loads. Table adapted from (Soligard et al., 2016; Windt & Gabbett, 2017).

External load	Internal load
Frequency (session per day, week, year) Time (seconds, minutes or hours) Distance covered (meters, kilometres) Time motion analysis (e.g., global position system analysis) Movement repetitions count (e.g., jumps, throws, and serves) Accelerometer loads	Subjective • Rating of perceived exertion • Session-rating of perceived exertion (RPE*minutes) • Well-being questionnaires (e.g., Recovery Stress Questionnaire for Athletes) Objective • Blood lactate • Heart rate • Biochemical/hormonal/immunological assessments • Physical qualities (ROM, force, etc) • Specific tissue load (wearable sensors to assess bone forces or shear wave tensiometer for tendon load)

Training loads can also be categorized into relative and absolute load. Absolute load is ‘the load applied, irrespective of the rate of load application or history of loading,’(Soligard et al., 2016). Absolute loads can be divided concerning the time the load has been applied; days (acute load) or weeks to months (chronic loads) (Soligard et al., 2016). It has been suggested that acute load is a marker of fatigue or what the athlete has performed, whereas chronic loads are analogous to the state of fitness or what the athlete has been prepared for (Hulin et al., 2014). On the other hand, relative loads “take into account the rate of load application, history of loading and fitness level,” (Soligard et al., 2016). Relative load often express variations in loads between two periods of time, such as the difference in loads between two successive weeks or the calculation of the acute chronic workload ratio (ACWR) (Eckard et al., 2018). The ACWR is commonly used in the sports literature to assess acute changes in load, and it is defined as the ratio between a week training load (i.e. acute load) and the mean of the previous four weeks (i.e. chronic load) (Hulin et al., 2014).

Considering the number of measures reported, the selection should be based on the sport context, goals of loads monitoring, financial constraints, and psychometric properties of the measures (Windt & Gabbett, 2017). It is important to mention that consensuses in training loads and injury (Bourdon et al., 2017; Soligard et al., 2016) recommend the combination of ITL and ETL to monitor an athlete´s response to training. Furthermore, subjective measures of ITL such as the RPE or sRPE (RPE x time in minutes), should be preferred, because they can be easily used in clinical practice (Soligard et al., 2016). Systematic reviews in training loads and injuries (Drew & Finch, 2016; Eckard et al., 2018; Jones et al., 2017) have found that sRPE is the most frequently used measure in the literature. The sRPE is a valid and reliable method to monitor training load in various sports and populations (Haddad et al., 2017), including swimmers (Wallace et al., 2008; Wallace et al., 2009).

Some studies in swimmers have incorporated the sRPE^{km} to measure ITL in swimmers (Collette et al., 2018; Nagle et al., 2015), which is calculated by multiplying the RPE by the swim-volume (km). Collette et al. (2018) found that this method was the strongest measure associated with the recovery-stress status of swimmers during a training season. A recent narrative review (Feijen, Tate, Kuppens, Barry, et al., 2020) summarized the most common monitoring strategies used in competitive swimmers. For ETL, training volume was the most commonly used, whereas for ITL, heart rate, blood lactate, the perceived effort of training, and mood profiling were the most common. This review provides important information; however, specific measures to monitor the shoulder joint (e.g., ROM, strength) were not included. Although subjective measures of ITL (e.g., heart rate and RPE) are useful to assess response to training, they provide a limited understanding of specific injury mechanisms and the loading of specific tissues (Kalkhoven et al., 2021).

2.4.2. Training loads and injuries

Although training loads are applied to induce positive physiological changes and maximize performance, their inadequate management (balance between load and recovery) can increase the risk of injuries (Windt & Gabbett, 2017). Three systematic reviews have assessed the relationship between training loads and injury (Drew & Finch, 2016; Eckard et al., 2018; Jones et al., 2017). The last systematic review included 57 articles (Eckard et al., 2018) and concluded that there was a moderate established relationship. This shows a large amount of new research in this area and reflects the importance and relevance of this topic. Most of the articles analysed by Eckard et al. (2018) included rugby, soccer, and Australian football players.

These systematic reviews reported three types of relationships between load and injury: direct, inverse, and U-shaped. The direct relationship was reported in studies assessing acute changes in loads using the ACWR. Specifically, when the acute load rises relative to the chronic load, the injury risk increases (Hulin et al., 2014). However, it is suggested that the ACWR only explain 47% of injury likelihood and has to be used in combination with other factors (Gabbett, 2020). Despite the increasing interest in the ACWR, some authors have exposed their limitations (Kalkhoven et al., 2021). Some of these include statistical flaws and the inability to estimate cumulative tissue damage, tissue strength and recovery, and mechanical loads (Kalkhoven et al., 2021). More in-depth discussion of the ACWR, particularly its controversies (Impellizzeri, McCall, et al., 2020; Impellizzeri, Menaspà, et al., 2020), is beyond the topic of this literature review. Regarding swimmers, a recent prospective study found a direct relationship between the ACWR and the development of shoulder injury (Feijen, Struyf, et al., 2020).

The inverse relationship between training loads and injuries was found in studies assessing chronic loads (Eckard et al., 2018). Although higher workloads have been associated with a higher risk of injury, they also contribute to well-developed physical qualities, and thus a reduced risk of injury (‘training load-injury paradox’) (Gabbett, 2016). The protective effect of training appears to come from two sources: (1) exposure to load allows the body to tolerate load, and (2) training develops physical qualities that are associated with reduced risk of injury (Gabbett, 2018). Several studies have reported that high chronic loads and well-developed physical qualities decrease injury risk in team sports (Gabbett et al., 2012; Gastin et al., 2015; Malone et al., 2019; Møller et al., 2017). A similar pattern has been reported in swimmers; although higher chronic loads have been associated with a greater prevalence of shoulder pain (Hill et al., 2015), they have also been associated with more developed physical qualities (Bae et al., 2016; Cheung et al., 2018). Furthermore, recent studies (Barry et al., 2021; Feijen, Struyf, et al., 2020) have reported that lower-level swimmers (i.e. lower chronic loads) have a greater risk of injury and illness than higher-level counterparts. A possible explanation for this is that fitter and stronger athletes can better tolerate the amount of and changes in workloads (Malone et al., 2019; Møller et al., 2017).

Finally, a U-shaped relationship has also been reported; over and undertrained athletes may also influence the risk of injury (Malone et al., 2017). For example, low loads might not be enough to elicit physiological adaptations, whereas high loads (without enough recovery) might result in the overloading of the tissues (Eckard et al., 2018). Overall, the literature shows the complex relationship between training loads and injuries.

2.4.3. Athlete monitoring: how and when?

The main aim of athlete monitoring is to maximize performance and minimize the negative effects of training (e.g. injury, illness, and overtraining) (Gabbett et al., 2017; Saw et al., 2017). Load monitoring is implemented to understand athlete response to training and readiness to train or compete, explain changes in performance, appropriately plan and modify training programs, and to reduce the risk of injury, overtraining, and illness (Halson, 2014; Soligard et al., 2016).

Gabbett et al. (2017) proposed the athlete monitoring cycle, which is based on a training-response model. This cycle provides a strategy to interpret the data of an athlete from a single training stimulus to the exposure of a subsequent training stimulus (Gabbett et al., 2017). The cycle consists of four steps: (1) the workload the athlete performs (ETL), (2) the athlete response to the workload (ITL), (3) if an athlete is tolerating the workload (i.e., perceptual well-being), and (4) whether the athlete is mentally and physically prepared for another training stimulus (readiness to train/compete). The aim is to provide an intervention (e.g., additional training or extra recovery) to maximize positive and minimize negative responses of training (Gabbett et al., 2017). Considering that Gabbett et al. (2017) did not implicitly include factors such as recovery or life stressors, Sawczuk et al. (2019) proposed the integrated athlete monitoring cycle (Figure 2.3). The authors suggested that the training response will be different if an athlete´s recovery is compromised (e.g., sleep) or if the underlying life stress (e.g., social, academic) is increased.

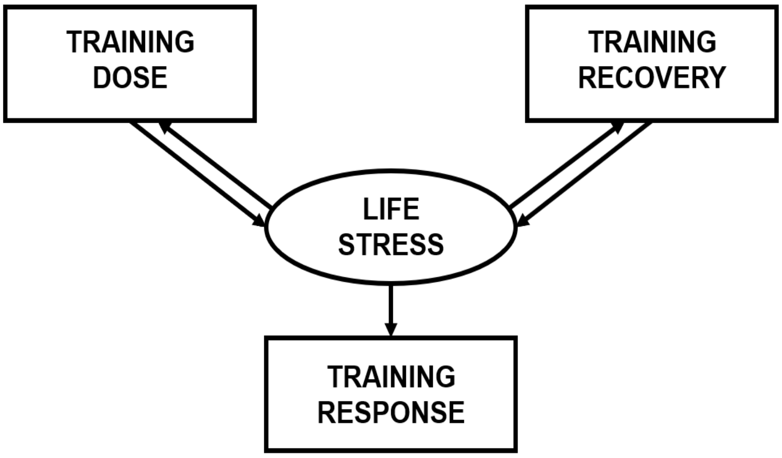

Figure 2.3 - Integrated athlete monitoring cycle (Sawczuk, 2019).

2.5 Risk factors for shoulder pain in swimmers

This section reviews the risk factors for shoulder pain in swimmers. To date, one systematic review (Hill et al., 2015) and one narrative review (Struyf et al., 2017) have investigated this relationship. Understanding which factors are associated with shoulder pain might help to determine the most relevant factors to monitor in the following studies. According to aetiology models in sports (Section 2.3), injuries are multifactorial, including intrinsic and extrinsic risk factors. Extrinsic factors will be briefly discussed in Section 2.5.1, while intrinsic factors will be discussed in detail in Section 2.5.2.

2.5.1. Extrinsic risk factors for shoulder pain in swimmers

Some examples of extrinsic or environmental factors include equipment, weather condition, and playing surfaces (Meeuwisse, 1994). Within these factors, training equipment might be the most relevant in swimmers. Despite this, a systematic review reported a low level of certainty between shoulder pain and training equipment (Hill et al., 2015). For instance, a cross-sectional study found that the use of hand paddles and kickboards aggravated shoulder pain in competitive swimmers (McMaster & Troup, 1993). The authors concluded that hand paddles increase water-resistance during propulsion, which might consequently increase loads on the shoulder. However, two cross-sectional studies found no association (Stocker et al., 1995; Tate et al., 2012).

2.5.2. Intrinsic risk factors for shoulder pain in swimmers

Intrinsic risk factors were divided into modifiable and non-modifiable (Table 2.2) to differentiate those that can be changed (i.e. through training loads or interventions) from those that are stable (Windt & Gabbett, 2017).

Table 2.2 - Summary of intrinsic risk factors for shoulder pain in swimmers.

Intrinsic risk factors	
Non-modifiable	History of shoulder pain, level of competition, age, gender, and arm dominance
Modifiable	Musculoskeletal • Shoulder range of motion and flexibility • Shoulder muscular performance • Functional tests • Others
	Well-being
	Training-related

2.5.2.1. Non-modifiable risk factors

Non-modifiable risk factors might help to identify groups at risk of injury (Rosen et al., 2017). Hill et al. (2015) investigated several non-modifiable risk factors for shoulder pain in swimmers including history of shoulder pain, level of competition, years of swim, age, and arm dominance. Within these factors, level of competition and history of shoulder pain were the only with a moderate level of certainty. Considering this, they will be discussed in more detail.

History of shoulder pain

Several studies have found a relationship between history of shoulder pain and the development of shoulder pain in swimmers. In a one-year prospective study, Walker et al. (2012) found that swimmers with significant shoulder pain in the last 12 months were 4.1 times more likely to develop shoulder pain that interfered with training or competition. Similarly, another one-year prospective study reported that swimmers with shoulder pain in the past year had 2.5 times higher risk of developing another injury in the same body location (Chase et al., 2013). Furthermore, two cross-sectional studies found that history of shoulder pain was related to shoulder pain and disability (Tate et al., 2012) and shoulder impingement syndrome (Bansal et al., 2007) in competitive swimmers. These results might be explained as residual deficits from previous injuries can affect the function and limit the range of motion predisposing to the development of new injuries (Tate et al., 2012). Importantly, history of shoulder injury in swimmers can also affect other body regions as a result of compensatory strategies (Chase et al., 2013).

Only one study has found no association. In a recent prospective study, Mclaine et al. (2018) found that history of shoulder pain (shoulder pain that prevented participating in training or competition for two or more sessions during their careers) did not influence the incidence of shoulder pain in swimmers during two seasons. It is important to consider that only 47% of the participants completed the follow-up questionnaire, which possibly affected the results. Despite the different definitions of pain, there is evidence supporting that previous shoulder injuries predispose to the development of new shoulder injuries. Importantly, a recent study found that history of shoulder pain also influences swimming performance (Matsuura et al., 2020). Considering this, it might be important to identify swimmers with history of shoulder pain and assess the possible deficits that may predispose them to reinjury.

Level of competition

Studies have found direct and inverse associations between level of competition and shoulder pain in swimmers. Regarding direct relationships, a cross-sectional study (McMaster & Troup, 1993) found that international level swimmers reported more history of shoulder pain (71%-75%) than national level counterparts (38%-55%). Likewise, a later cross-sectional study (Bansal et al., 2007) reported a higher prevalence of shoulder impingement syndrome in international level swimmers (35%) compared to national (20%) and state (12%) level swimmers. Some studies have also investigated this relationship between competitive and recreational swimmers. A cross-sectional study (Zemek & Magee, 1996) found that 67% of elite swimmers reported history of shoulder overuse dysfunction, compared to only 13% of recreational swimmers. These results might be explained, to some extent, because higher levels of competition are exposed to greater swim-volumes (Tate et al., 2012, 2015), which can increase the risk of shoulder pain (further discussed in Section 2.5.2.2.3). On the contrary, a recent two-year prospective study found an inverse relationship; Feijen et al. (2020) reported that regional-level swimmers had a lower risk of shoulder pain (OR, 0.19; CI, 0.058-0.629) than club-level counterparts. As a result of inconsistent training, this group was probably less prepared for even small variations in training load (Feijen, Struyf, et al., 2020).

Overall, studies reporting a direct relationship between level of competition and injury did not present consistent characteristics (e.g., age, gender, or sample size). The only factor in common was the cross-sectional design of most studies, which could have affected the reporting of injuries (i.e., recall bias, discussed in Section 2.1.1). Although a prospective study reported an inverse relationship, it is not enough alone to reach conclusions from. Overall, it is unclear to what extent the level of competition contributes to shoulder pain in swimmers.

Other non-modifiable factors

Studies have failed to find an association between shoulder pain and age (Kruger et al., 2012; Tate et al., 2012; Tessaro et al., 2017). In a cross-sectional study, Tate et al. (2012) included 236 female swimmers between 8 and 77 years of a similar competitive level. The authors divided the swimmers into four age groups and found that the prevalence of shoulder pain was not significantly different between them. Similarly, a three-year retrospective study found no association between shoulder pain and different age groups (25 to 94 years old) in 282 national level swimmers (Kruger et al., 2012). Furthermore, a recent cross-sectional study found no association between age group and shoulder pain in 197 competitive swimmers ranging from 12 to 20 years old (Tessaro et al., 2017). This shows that age, on its own, is not a factor that affects the development of shoulder pain in swimmers. However, the cross-sectional designs of the studies might be a limitation.

The evidence is contradictory for the relationship between sex and shoulder pain in competitive swimmers. Six prospective studies (Chase et al., 2013; Feijen, Struyf, et al., 2020; Kerr et al., 2015; Lanese et al., 1990; McLaine, Bird, et al., 2018; Walker et al., 2012), two retrospective (Kruger et al., 2012; Wolf et al., 2009) and one cross-sectional study (De Almeida et al., 2015) found no association. Whilst, two retrospective studies (Sallis et al., 2001; Tessaro et al., 2017) and one prospective study (Mountjoy et al., 2010) found an association. Studies reporting a positive relationship found that females had a higher risk of shoulder injury than males. It is suggested that, from a biomechanical perspective, females perform more shoulder revolutions per lap due to a shorter arm stroke, which may predispose them to a higher number of shoulder injuries (Wanivenhaus et al., 2012). However, these findings have to be interpreted with caution as results are based on two retrospective studies and one prospective study performed with a short follow-up (Aquatic World Championship). On the other hand, five prospective studies ranging from one to three training seasons and including a total of 757 swimmers reported no relationship. Although there is contradictory evidence, it seems that sex might not be a relevant factor for shoulder pain in swimmers.

Finally, no association has been found between arm dominance and shoulder pain in swimmers in two prospective studies (Cejudo et al., 2019; Walker et al., 2012), which might be explained by the bilateral demands of the sport.

2.5.2.2. Modifiable risk factors

As discussed in Section 2.3, modifiable risk factors are constantly changing as a result of sports participation and are important in injury prediction. The relationship between these factors and shoulder pain was investigated in both reviews (Hill et al., 2015; Struyf et al., 2017). Understanding how modifiable risk factors are associated to shoulder pain in swimmers might help to manage training loads and to target injury prevention programs. Modifiable risk factors were divided into (1) musculoskeletal, (2) well-being, and (3) training-related factors (Table 2.2).

2.5.2.2.1. Musculoskeletal risk factors

Musculoskeletal factors were further divided into a) shoulder ROM and flexibility, b) muscular performance, c) functional tests, and d) other factors.

a) Shoulder ROM and flexibility

An adequate shoulder ROM is necessary to perform competitive swimming at a high level (De Martino & Rodeo, 2018; Rupp et al., 1995). The main deficits of shoulder ROM reported in swimmers will be discussed.

Rotation range of movement

The measurement of shoulder rotation ROM in abducted position is a recommended component of the clinical examination of overhead athletes (Blanch, 2004; Reinold & Gill, 2010). No significant differences in rotation ROM between dominant and non-dominant sides have been found in swimmers, which can be explained by the bilateral demands of the sport (Harrington et al., 2014; Holt et al., 2017). On the contrary, clear side-to-side differences have been documented in throwing athletes, characterized by a shift of the total arc of motion with an increase in ER and a decrease in IR of the throwing arm compared to the non-throwing arm (Shanley et al., 2015; Wilk et al., 2011). The high levels of eccentric stress placed on external rotator muscles to decelerate the throwing motion may increase the posterior cuff stiffness and consequently decrease the IR ROM (Moore-Reed et al., 2016; Reinold et al., 2008).

Contradictory findings have been reported between shoulder rotation ROM and shoulder injury in swimmers. Four cross-sectional (Bak & Magnusson, 1997; Beach et al., 1992; Harrington et al., 2014; Holt et al., 2017) and two prospective studies (Cejudo et al., 2019; Feijen, Struyf, et al., 2020) found no association. Whilst, two cross-sectional (Bansal et al., 2007; Tate et al.,

2012) and two prospective studies (Tate et al., 2020; Walker et al., 2012) found an association. Regarding studies reporting a relationship, results vary according to the direction (ER or IR) and magnitude (increase or decrease) of the limitation. For instance, Bansal et al. (2007) found that competitive swimmers (17-35 years) with SIS had an increased passive ER range compared to swimmers without SIS (Bansal et al., 2007). Conversely, a later study reported that competitive female swimmers (8-11 years) with shoulder pain and disability had reduced passive shoulder IR compared to an asymptomatic age-matched group, suggesting that reduced posterior shoulder flexibility may lead to shoulder impingement during the stroke (Tate et al., 2012). Both studies are cross-sectional which limit their ability to determine whether the limitation of ROM is a cause or consequence of pain. Furthermore, none of the studies reported the stabilization method used to measure rotation ROM, which is a methodological limitation (will be discussed in Section 3.3 of Chapter 3).

Regarding the prospective studies, Walker et al. (2012) found that swimmers with either low ER (<93°) or high ER (>100°) active ROM measured at preseason, had a higher risk of developing shoulder pain at year one. The authors suggested that increases in ER may be associated with micro traumatic damage of the anterior shoulder joint affecting neuromuscular control and leading to secondary impingement, whereas limited ER may increase the probability of mechanical shoulder impingement during the recovery phase. Limitations of ER ROM might be important, as this movement is necessary during the mid-recovery phase when the arm is abducted at 90° (Pink & Tibone, 2000). Interestingly, a recent prospective study (Tate et al., 2020) found that IR ROM reductions over a season were associated with decreases in shoulder pain and disability in swimmers. The authors suggested that this loss of motion might be a positive adaptation, though failed to suggest why this might be the case.

Although studies reporting associations have some similarities (e.g., supine testing position), the different cohorts (age and sex), study designs, injury definitions, and measurement protocol limit the comparisons. Similarly, studies not reporting a relationship have no consistent pattern either. Overall, some studies have reported a potential association between rotation ROM (decreased IR, and increased or decreased ER) and shoulder pain. However, the evidence is inconclusive.

Shoulder flexion ROM (latissimus dorsi length)

Before the propulsive phase, sufficient shoulder flexion is necessary to provide the maximum available reach (Herrington & Horsley, 2014). Shoulder flexion requires an optimal LD length to allow the humerus to externally rotate and the scapula to upwardly rotate (Herrington & Horsley, 2014). LD is one of the main muscles that contribute to forward propulsive power during swimming by extending, adducting, and internally rotating the arm (Pink et al., 1991). The repetitive load over the LD during swimming can result in muscle hypertrophy but can also lead to increased muscular stiffness and resistance to elongation (Wilson et al., 1994). Importantly, LD stiffness has been associated with alterations in scapular kinematics, which can potentially affect stroke biomechanics and increase the risk of shoulder pain (Laudner & Williams, 2013). As a consequence of the demands of the sport, swimmers have reduced LD flexibility compared to non-athletic population and rugby players (Herrington & Horsley, 2014).

Despite the importance of LD length for swimmers, few studies have investigated its relationship with shoulder pain. Tate et al. (2012) found a reduced LD length in swimmers with shoulder pain compared to an asymptomatic group. The authors concluded that, theoretically, reduced flexion may decrease stroke length increasing the number of strokes needed and therefore leading to greater shoulder loads. On the contrary, two studies have not found a relationship. In a cross-sectional study Beach et al. (1992) reported that shoulder flexion ROM was not different between swimmers with and without shoulder pain. Similarly, Feijen et al. (2020) reported that LD length (measured every 6 months) was not associated with the development of shoulder pain over a two-year follow-up.

To sum up, all studies investigated different cohorts and used diverse injury definitions. Importantly, the measurement protocol also differed across studies (shoulder initial rotational position and the presence of abdominal contraction), affecting comparisons (this is discussed in Section 2.10.2). Overall, there is contradictory evidence for the relationship between LD length shoulder pain.

Shoulder horizontal abduction (pectoralis major length)

Only one study has investigated the relationship between shoulder horizontal abduction ROM and shoulder pain. A recent prospective study (Cejudo et al., 2019) found that decreases in shoulder horizontal abduction ROM (pectoralis major flexibility) measured at preseason was associated with the development of shoulder pain during a training season. This might be explained, as pectoralis major is an important propulsive muscle during swimming (Pink et al., 1991). However, more studies are needed to support these findings.

b) Shoulder muscular performance

Muscle strength and endurance are necessary for body propulsion during swimming (Pink et al., 1991). For practical purposes, muscle performance was divided into shoulder force (rotators, extensors, and handgrip force), and neuromuscular control (e.g., joint position sense).

Shoulder-rotation peak force and endurance

Shoulder rotation force in overhead athletes is an important aspect of clinical examination (Habechian et al., 2018). Theoretically, the fatigue of rotator cuff muscles has been proposed as the main mechanism of secondary shoulder impingement in swimmers (Section 2.3.1). No differences in rotation force have been reported between arms in this population (Batalha et al., 2013; Habechian et al., 2018; McLaine et al., 2018). This is in contrast to throwing athletes who show greater force in the dominant side (Noffal, 2003).

The relationship between shoulder rotation peak force and pain in swimmers has been reported with inconsistent findings. Three cross-sectional (Beach et al., 1992; Harrington et al., 2014; Rupp et al., 1995) and two prospective studies (Feijen, Struyf, et al., 2020; McLaine, Bird, et al., 2018) found no association. Whilst, two cross-sectional studies (Bak & Magnusson, 1997; Tate et al., 2012) found an association. Bak et al. (1997) reported reduced eccentric and concentric IR force of the injured shoulder compared to the uninjured side of 15 competitive swimmers (15-25 years old). Force was measured with isokinetic dynamometry in a seated position (Bak & Magnusson, 1997). Similarly, Tate et al. (2012) found that female competitive swimmers (12-14 years old) with pain and disability had reduced IR isometric force compared to asymptomatic age-matched swimmers. Force was measured with a hand-held dynamometer (HHD) in prone. Since the subscapularis muscle is constantly contracted during the stroke (Pink & Tibone, 2000), both studies concluded that IR force deficits may affect stroke dynamics. However, given the cross-sectional designs of the studies, whether the force deficits seen were due to pain inhibition or a compensatory strategy to remain pain-free is unknown. For studies not reporting a relationship, there is no consistent pattern; they differ in study design, testing position (prone or supine), measurement instrument (isokinetic dynamometry or HHD), and type of contraction (isometric, concentric or eccentric). One limitation of all studies is the different measurement units used (e.g., N, Nm, Nm/Kg), which limits the comparison (which will be discussed later in Section 3.3 of Chapter 3).

Regarding muscle endurance, few studies have been published in swimmers. In a cross-sectional study, Beach et al. (1992) found that swimmers with shoulder pain had decreased ER endurance measured with isokinetic dynamometry. More recently, two prospective studies showed a direct relationship between shoulder pain and decreased posterior shoulder endurance (Feijen, Struyf, et al., 2020; Tate et al., 2020). The different type of contraction (isometric, concentric, eccentric) and measurement unit (torque, seconds, number of repetitions) used in the studies limit the comparisons. Despite this, they provide important information about the relevance of posterior shoulder endurance in the development of shoulder pain in swimmers.

Overall, based on cross-sectional studies, reduced IR peak force and posterior shoulder endurance might be potential risk factors for shoulder pain in swimmers. Furthermore, the latest evidence supports the importance of posterior shoulder endurance in the development of shoulder pain. Despite this, results have to be interpreted with caution due to methodological differences.

Handgrip peak force

Handgrip Force (HGF) provides an objective indicator of the functional status of the upper limb (Massy-Westropp et al., 2011) and an indirect assessment of the rotator cuff function (Horsley et al., 2016). Horsley et al. (2016) reported a strong correlation (r= 0.75-0.91) between HGF and external rotator isometric peak force measured with HHD. Similarly, moderate to strong correlations (r= 0.40-0.71) between HGF and a concentric peak force of shoulder external rotators and abductors muscles have been reported with isokinetic dynamometry (Mandalidis & O'Brien, 2010). These findings are supported by several EMG studies showing that gripping tasks increase the activity of either the infraspinatus (Antony & Keir, 2010) or both the infraspinatus and supraspinatus muscles (Alizadehkhaiyat et al., 2011; Sporrong et al., 1995). This might be explained by the co-activation of distal and proximal arm muscles during gripping tasks (Hodder & Keir, 2012). Importantly, HGF has been positively correlated to swim performance (e.g. time in 100 m) in this population (Garrido et al., 2012; Geladas et al., 2005; Saavedra et al., 2010; Zampagni et al., 2008). Despite this, no studies have investigated the association between HGF and shoulder pain in swimmers.

Shoulder extension peak force

Although shoulder extension force is an important propulsive movement during swimming, only one study has investigated its relationship with shoulder pain. A 24-month prospective study (McLaine, Bird, et al., 2018) found that reductions of shoulder extension force measured at preseason predicted the development of shoulder pain in swimmers. More research is needed to support these findings.

Joint position sense

Proprioception is essential for the practice of sport-related activities, providing neuromuscular control and joint stability (Riemann & Lephart, 2002). Proprioception is defined as the afferent information provided by 3 submodalities: kinesthesia, force sensation, and joint position sense (JPS) (Myers & Lephart, 2000). Myers et al. (2000) defined JPS as the ability to consciously recognize the position of a joint in the space. During functional movements, the shoulder mainly relies on the dynamic stabilizers to provide stability and prevent unwanted movements of the humeral head (Higson et al., 2018). Dynamic stabilizers use a proprioceptive feedback loop provided by these 3 sub modalities (Riemann & Lephart, 2002). Importantly, it has been shown that fatigue negatively affects shoulder JPS in swimmers (Higson et al., 2018; Matthews et al., 2017), which may consequently increase the risk of secondary impingement.

Despite the importance of shoulder JPS, no studies have evaluated the association with shoulder pain in swimmers. Yet, this relationship has been widely studied in the non-athletic population and other sports. The findings are inconsistent; some studies have found JPS impairments in the injured shoulder when compared to the uninjured side (Anderson & Wee, 2011; Herrington et al., 2010; Sahin et al., 2017), while others have found no associations (Aydin et al., 2001; Green et al., 2013; Haik et al., 2013). The discrepancy of results might be as a result of different protocols and measurements instruments used such as inclinometers, motion analysis systems, isokinetic dynamometers, and digital cameras. The different pain definitions and populations studied may also explain the differences. Unfortunately, it is unknown whether impaired JPS is associated with a shoulder injury in swimmers due to the lack of research.

c) Functional tests

Common upper limb functional tests in swimmers include the upper quarter Y-balance test, the closed kinetic chain upper extremity stability test, and the combined elevation test (CET) (Blanch, 2004; Bullock et al., 2017; Butler et al., 2014; Butler et al., 2016). Unfortunately, no studies have investigated the relationship of these tests with shoulder pain. Since the CET is the most specific to assess upper limb function in swimmers, it will be discussed.

Combined elevation test

The CET is a screening tool that assesses the strength and mobility of the upper limb (Dennis, Finch, Elliott, & Farhart, 2008). A biomechanical study found that the CET specifically evaluate the combination of shoulder flexion, scapular retraction and thoracic extension (Allen et al., 2017). Reduced thoracic extension ROM may lead to an anterior tilt of the scapula (Culham & Peat, 1994), narrowing the subacromial space and causing impingement of the subacromial structures (Bullock et al., 2005). Furthermore, a reduction of thoracic extension can consequently decrease shoulder flexion ROM (Bullock et al., 2005) and lead to SIS (Hunter et al., 2020).

This test has been used in sports, such as swimming and cricket (Blanch, 2004; Dennis, Finch, McIntosh, & Elliott, 2008). Regarding swimming, the CET is related to the achievement of the streamline body position (Allen et al., 2017). The movement performed in the CET is essential for achieving a high elbow position during the stroke (Blanch, 2004). This is important because a drop elbow has been suggested as a sign of potential shoulder injury (Pink & Tibone, 2000). However, the association between the CET performance and shoulder injuries in swimmers cannot be determined due to the lack of studies.

d) Other musculoskeletal risk factors

Other potential musculoskeletal risk factors for shoulder pain in swimmers include pectoralis minor length (PML) and scapular dyskinesis (Hill et al., 2015; Struyf et al., 2017). Two cross-sectional studies found PML decreases in swimmers with shoulder pain (Harrington et al., 2014; Tate et al., 2012). Reductions of the PML can alter scapular position (e.g., increase anterior tilt and internal rotation) decreasing the subacromial space and possibly increasing the risk of shoulder pain (Lynch et al., 2010). However, as a result of the cross-sectional design, the causal relationship is unclear. Regarding scapular dyskinesis, one cross-sectional study (Tate et al., 2012) and one prospective study (Feijen, Struyf, et al., 2020) found no association with shoulder pain.

Recent studies have also investigated the role of thoracic rotation ROM. The rotational movement of the spine is important for swimming, especially during the recovery phase (Blanch, 2004) as it allows body roll and to breath at both sides (Cassella et al., 2014). Despite this, a cross-sectional (Welbeck et al., 2019) and a prospective study (Feijen, Struyf, et al., 2020) found no associations.

2.5.2.2.2. Well-being factors

Subjective measures of training loads (e.g. well-being questionnaires, sRPE) are more sensitive than objective measures to assess the athlete response to training loads (Saw et al., 2016). There is a large amount of evidence showing that impairments of athlete´s well-being are associated with injuries in several sports (Cahalan et al., 2018; Galambos et al., 2005; Hamlin et al., 2019; Laux et al., 2015; Pensgaard et al., 2018; Watson et al., 2017). Because of this, there is an increasing interest in well-being questionnaires for athlete monitoring as they provide a time-efficient and non-invasive method to assess athlete response and readiness to train or compete (Coutts et al., 2007; Saw et al., 2016). (Examples of these questionnaires are discussed in Section 6.2 of Chapter 6).

Although it has not been directly associated with shoulder pain in swimming, impairments in well-being factors have been found in overtrained swimmers (Hooper et al., 1995). Hooper et al. (1995) found that swimmers with overtraining symptoms (i.e., performance deterioration and prolonged high levels of fatigue) reported higher levels of muscular soreness, stress, sleep quality, and fatigue during a training season than non-overtrained swimmers. Also, in combination, these tests predicted overtraining before the deterioration in performance became apparent several weeks later in the season. Considering the multifactorial nature of injuries in sports, impairments of well-being factors might also increase the susceptibility of shoulder injury in swimmers. However, due to the lack of research in swimmers, this relationship is unknown.

2.5.2.2.3. Training-related risk factors

a) Training volume

Training volume (i.e., number of hours and weekly swim-distance) has been proposed as an important factor for the development of shoulder pain in swimmers (discussed in Section 2.3.1). Despite this, a systematic review (Hill et al., 2015) found a low level of evidence for this relationship. Four cross-sectional (Harrington et al., 2014; Hidalgo-Lozano et al., 2012; Hidalgo-Lozano et al., 2013; Sein et al., 2010) and two prospective studies (Chase et al., 2013; Walker et al., 2012) found no associations. Whilst, two cross-sectional (Sein et al., 2010; Tate et al., 2012) and two retrospective studies (Kruger et al., 2012; Ristolainen et al., 2014) found an association. From these studies, only Kruger et al. (2012) found a negative association between swim-volume and risk of shoulder pain.

Because of the inconsistent findings, a more recent systematic review (Feijen, Tate, Kuppens, Claes, et al., 2020) investigated this relationship in different age groups. Including two new studies (De Almeida et al., 2015; Tessaro et al., 2017), the researchers found moderate associations between swim-training volume and shoulder pain in adolescent swimmers (15 to

17 years) and low association in the other age groups. Although adult swimmers perform similar or greater swim-volume than adolescents, the results might be explained because adolescents are suddenly exposed to higher training-volume (Feijen, Tate, Kuppens, Claes, et al., 2020). Therefore, the risk of shoulder injury might not only arise from high chronic loads but more likely from the excessive and sudden increases in acute loads relative to what the athlete is prepared for; adolescents are not prepared for these loads, whereas adults have possibly adapted to the loads over time (Feijen, Tate, Kuppens, Claes, et al., 2020). A recent prospective study by Feijen et al. (2020) support this showing that swimmers who were exposed to a one-unit increase in the ACWR (a measure of the change in loads), the odds of shoulder pain increased by 4.3 times (OR, 4.31; 95% CI, 1.00-18.54).

Overall, the role of swim-volume in the development of shoulder pain is unclear. Importantly, the latest research suggests that changes in volume might be more important than the total amount. This is further supported by Tate et al. (2020) who reported no association between shoulder pain and swim-related disability with the amount of swim-volume during a training season.

b) Training type and injuries

Swimmers' training is divided into in-water (swimming volume and training techniques) and dry-land related activities: strength, flexibility and cross-training activities (other sports or activities) (Tate et al., 2015). Tate et al. (2015) reported that collegiate swimmers perform an average of 5.82 ± 0.53 swimming sessions and 3.82 ± 1.61 sessions of dry-land training per week. Studies have reported that between 10% and 44% of all injuries occur outside the pool (McFarland & Wasik, 1992; Walker et al., 2012; Wolf et al., 2009). Although most injuries occur during swimming practice, an important number take place in activities outside the pool. For this reason, the type of cross-training activities and the strengthening program are important to consider.

Some studies suggest that strength training is a protective factor for the development of shoulder pain in swimmers. In a retrospective study, Kruger et al. (2012) found that swimmers performing strength training had less risk of developing shoulder pain. One limitation of this study is that the strength programs were not described. In a recent retrospective study, Tessaro et al. (2017) found that swimmers performing a dry-land warm-up (e.g., three times a week for less than 10 minutes) had less probability of developing shoulder pain. The authors suggested that the warm-up should include moderate-intensity activities (cycling or light run) in combination with the strengthening of the core, lower limbs, and specific shoulder muscles involved in swimming. Additionally, stretching exercises should be performed only when muscular or capsular stiffness is present.

Regarding cross-training activities, Tate et al. (2012) found that swimmers participating in other sports such as soccer, walking, and running reported less pain compared to participants involved in upper extremity sports such as water polo. This might be explained as cross-training activities (not involving the upper limbs) provide relative rest for the shoulder and improve lower limbs and core strength (Tate et al., 2012). Furthermore, it has been shown that adolescent participating in various sports had less probability of injury compared to the ones participating in a single activity (Auvinen et al., 2008). To sum up, cross-training activities not involving the upper limbs in combination with a strengthening program of 3 times per week might be protective against shoulder pain in swimmers.

2.5.3. Summary risk factors

Several potential modifiable and non-modifiable risk factors for shoulder pain in competitive swimmers have been reported. For non-modifiable factors, history of a shoulder injury and level of competition (direct and inverse relationship) are considered the most relevant. These factors might help to subgroup swimmers according to the risk of injury.

Regarding modifiable risk factors, the evidence is contradictory. This might be explained by the different definitions of shoulder pain, heterogenicity of the samples (e.g., age, sex, level of competition), and the methodology used. For musculoskeletal factors, shoulder rotation ROM and strength are the most studied. Decreases in IR ROM, increases and decreases in ER ROM, and reductions of IR peak force and ER endurance have been proposed as potential risk factors for shoulder pain in swimmers. Since other factors such as shoulder extension force, LD length, JPS, PML, and CET have been less studied, this relationship is less known. Although wellness factors have not been directly associated with shoulder pain (due to lack of research in this area), impairments in these factors have been found in overtrained swimmers. Moreover, wellness factors have been extensively associated with injuries in other sports, and thus, might be important factors to consider. Finally, training-related factors such as training volume (e.g., amount of changes and mainly sudden changes) might play an important role in the development of shoulder pain. Also, an adequate dry-land program including strengthening exercises in combination with cross-training activities not involving the upper limbs might be protective for shoulder injuries in swimmers. The number of factors reported in the literature reflects the multifactorial and complex aetiology of shoulder pain in swimmers.

Although these studies provide important information, we need to be cautious with their interpretation. Most of them are cross-sectional in design, and thus unable to determine the causation of the condition. Although prospective studies are the most appropriate to determine the cause of a condition (Struyf et al., 2017), most of the prospective studies included in this review were based on a single testing (i.e. pre-season testing). Pre-season testing might not consider the dynamic nature of injuries; thus, a single measure may not provide sufficient information to predict an injury (Cook, 2016) (this will be discussed in Section 2.7). Importantly, the latest studies have measured modifiable risk factors more repeatedly: three measurements during a year (Tate et al., 2020) and four during two years (Feijen, Struyf, et al., 2020). However, this might not be enough to account for the dynamic changes of these factors as some of them can change after a single training session (explained in the next section).

Since modifiable risk factors can be changed through training and interventions, understanding the interaction between them (rather than a causal relationship of a single factor with injury) might be more relevant for the prediction and prevention of injuries (Bittencourt et al., 2016). More specifically, understanding how training loads interact with the athlete´s capacity (load tolerance given by intrinsic factors) might be crucial to decrease the risk of injuries (Owoeye, 2020).

2.6. Effects of training loads on potentially modifiable risk factors for shoulder pain in swimmers

This section will present studies investigating the effects of training loads on modifiable risk factors for shoulder pain in swimmers. To provide a broader understanding of this relationship, other overhead sports (e.g., throwing or striking) will be also discussed.

a) Shoulder physical qualities

Regarding throwing sports, Reinold et al. (2008) reported decreases in shoulder IR and total rotation ROM immediately after baseball pitching in the dominant side. The changes continued to exist 24-hours after pitching. Similarly, a more recent study (Newton & McCaig, 2018) reported a decrease of IR ROM in the throwing arm of cricket players after a training session. In striking sports, the findings are similar. Moore-Reed et al. (2016) found decreases in shoulder IR and total rotation ROM of the dominant arm in professional tennis players immediately and 24-hours after a match. Furthermore, Williams & Hebron et al. (2018) reported reductions in shoulder IR, ER ROM, and total ROM of the dominant arm following serving and groundstroke tasks in professional tennis players (Williams & Hebron, 2018). There are consistencies that throwing/striking sports mainly decrease IR and total ROM after a training session. As discussed in Section 2.5.2.2.1, this might be explained by the high levels of eccentric stress placed on the external rotators to decelerate the throwing or striking motion.

Regarding swimming, only two studies have investigated the effects of swim-training on risk factors for shoulder pain (Higson et al., 2018; Matthews et al., 2017). Matthews et al. (2017) found a bilateral decrease in ER ROM and an increase in JPS error in the dominant extremity after a swim-fatigue protocol in 17 national swimmers. However, no significant differences in shoulder rotation force and IR ROM were found. In a later study, Higson et al. (2018) found reduced ER ROM and PML and increased JPS errors after a two-hour training session in 16 elite swimmers. No differences were found in IR ROM. There are some consistencies showing decreases in shoulder ER ROM and JPS. These studies provide preliminary evidence of the acute shoulder adaptations that occur as a consequence of swimming training loads. Since some of these physical qualities have been reported as potential risk factors for shoulder pain in swimmers (Hill et al., 2015; Struyf et al., 2017), the researchers suggested that their acute maladaptation can potentially increase the predisposition to shoulder injury in the subsequent training.

As reviewed in Section 2.5, training loads need to be explicitly described to understand the response to training. For instance, Higson et al (2018) only defined ETL in terms of time (2-hours), without specifying neither the distance nor the intensity. Furthermore, ITL was not measured, thus, the swimmer’s response to the training is unknown. Regarding Matthews et al. (2017) study, ETL was defined by the volume (8 sets of 100 m swim), while ITL was defined by the levels of blood lactate. It is important to mention that these studies only assessed one type of training, and thus, one intensity and volume. This might limit the ability to understand the magnitude (e.g., volume and intensity) at which these changes occur. Finally, none of them investigated the recovery of shoulder physical qualities after a training session.

Overall, these studies reflect the current interest in understanding the acute effect of training loads on shoulder musculoskeletal risk factors in overhead sports. It also demonstrates the varied responses to training as a result of the different type of sports (throwing/striking or non-throwing/striking) and their demands (high levels of eccentric muscle activity or repetitive movement), making it difficult to compare between studies. Regarding swimmers, there are few studies assessing shoulder musculoskeletal responses to training and none investigating their recovery. Furthermore, the training loads at which these responses occur are not always described.

b) Well-being factors

The effects of training loads on athlete well-being have been studied in different sports such as basketball (Clemente et al., 2017), football (Clemente et al., 2019), rowing (Jürimäe et al., 2004), and university athletes (Hamlin et al., 2019). All these studies found that accumulation and acute increases in training loads negatively affected well-being factors. Regarding swimmers, the peak swim-training volume during a season has been associated with mood (Morgan et al., 1987; O'Connor et al., 1989; Raglin et al., 1996) and sleep disturbances (Taylor et al., 1997). It has been also shown that a 3-day (O'Connor et al., 1991) and 10-day (Morgan et al., 1988) acute increase in swim-training volume negatively affect subjective ratings of muscular soreness, mood, and perception of training loads in competitive swimmers. This is supported by a more recent study (Nagle et al., 2015) reporting that increases in swim-training volume during a season was associated with decreases in the recovery-stress status of swimmers. There is evidence that the peak swim-volume during a season and acute increases in swim-volume negatively affect wellness parameters. However, more studies are necessary to understand this relationship.

c) Supraspinatus tendon thickness

Recent studies have investigated the effects of training loads on specific shoulder tissues. Porter et al. (2020), found that swimmers with history of shoulder pain had increased supraspinatus tendon thickness (STT) immediately and 6-hours after a training session compared to the pain-free shoulder. In a subsequent study, the same authors investigated the effects of different training loads of the supraspinatus tendon of healthy swimmers. STT was immediately increased after a high-volume swim-session and recovered after 6-hours. Interestingly, after a high-intensity session, STT was immediately increased after the session but recovered after 24-hours. These results are important as they show how specific shoulder tissues respond to different training loads. Furthermore, it demonstrates that swimming intensity might be more relevant than the volume in shoulder response.

2.7. Injury prediction and prevention in sports

The prediction of injuries in athletes is an area of increasing research due to the impact of player availability on success in elite sports (Eckard et al., 2018). Prediction is a key component of injury prevention (Bittencourt et al., 2016) that is used to identify which athletes are more likely to sustain an injury than others, or in other words, to identify "who" is at risk of getting injured (Nielsen et al., 2020).

Researchers (Eckard et al., 2018; Windt & Gabbett, 2017) have emphasized the importance of modifiable risk factors in the prediction of injuries as they can change and be altered by previous injuries (Meeuwisse et al., 2007) or training loads (Windt & Gabbett, 2017), modifying the intrinsic factors and consequently the injury predisposition. Despite this, research has focused on a non-dynamic model ignoring that sports injuries occur in a dynamic environment (Cook, 2016). Most studies are based on a single assessment of baseline measures (e.g. strength and flexibility measured at preseason), without considering their internal changes and the influence of external factors over time (Cook, 2016). The resistance to injury is not a steady-state, which is an inherent assumption in any pre-season testing model (Fonseca et al., 2020; Stern et al., 2019). Although a single measure might have limited value for predicting and preventing injuries (Pozzi et al., 2020), they can help to determine which factors to monitor (Bahr, 2016; Van Dyk & Clarsen, 2017).

Current literature suggests that research should focus on how different risk factors vary and interact over time, preferably using prospective study designs and repeated measures (Baroni & Oliveira Pena Costa, 2021; Eckard et al., 2018; Fonseca et al., 2020; Stern et al., 2020; Van Dyk & Clarsen, 2017). An important concept is secondary injury prevention, which involves the early detection and interventions addressing clinical signs which may result in injury (e.g. decreases in strength after training or competition) (Van Dyk & Clarsen, 2017; Wollin et al., 2020). A randomized controlled trial (RCT) (Wollin et al., 2019) found that in-season monitoring of hamstring strength after football games during a season reduced the risk of injury. Although regular in-season monitoring seems to be the most appropriate approach for injury prediction, challenges of competitive athletes, such as training schedules, travel, competitions, among other issues, need to be considered (Baroni & Oliveira Pena Costa, 2021).

Another consideration for injury prediction is the statistical approach used. Researchers (Fonseca et al., 2020; Stern et al., 2020; Van Dyk & Clarsen, 2017) have suggested that screening and injury prediction is too complex for some statistical models used (e.g. linear regression models). Since injury prediction is seen as an analogy of the prediction of weather or hurricanes (Stern et al., 2020; Van Dyk & Clarsen, 2017), more complex non-linear approaches, such as agent-based and system dynamic modelling (Hulme, Mclean, et al., 2019; Hulme, Thompson, et al., 2019), machine learning approaches (López-Valenciano et al., 2018), and neural network techniques (Kakavas et al., 2020), have been proposed.

Despite the complexity of predicting an injury, we first need to know which factors to monitor. To achieve this, understanding the interactions between modifiable risk factors for shoulder pain in swimmers and training loads might be necessary. This can inform which athletes are more likely to be predisposed to injuries. Then, in-season monitoring of these factors may help to reduce the risk of injury.

2.8. Swimming performance and musculoskeletal risk factors

It has been reported that several factors affect swimming performance. These factors include anthropometric (e.g. height, hand length, and upper extremity length), physiological (e.g. aerobic and speed endurance), and physical variables (e.g. horizontal jump, shoulder strength, and HGF) (Garrido et al., 2012; Geladas et al., 2005; Gola et al., 2014; Matthews et al., 2017; Saavedra et al., 2010; Zampagni et al., 2008). Regarding physical variables, HGF has been widely studied and associated with performance in swimmers. Using regression analysis, Zampagni et al. (2008) found that HGF explained 52% of the variance in 50 meters time and 15% of the variation in 800 meters time during freestyle stroke in master swimmers (40 to 80 years old) (Zampagni et al., 2008). Another study found a moderate correlation between HGF and performance in male ($r = 0.51$) and female ($r = 0.54$) young swimmers (11.6 to 13.5 years old). The performance was measured by the best competition time achieved in any of the four strokes and at any swim distance (Saavedra et al., 2010). In a later study, Garrido et al. (2012) found that the relationship between HGF and swimming performance was affected by sex and stroke type. The highest correlations ($r = 0.53$-0.82) were reported in 100 meters freestyle in females. These results suggest that HGF is an important parameter to consider when assessing swimming performance, particularly for sprint performance (≤100m).

Other physical factors and their association to swimming performance have been also investigated. Gola et al. (2014) found a relationship between swimming velocity (25m and 50m distance) and upper limb strength (shoulder extensors and elbow flexors). In a more recent study, Matthews et al. (2017) used stroke length as a measure of performance and investigated the correlations with shoulder physical qualities, such as shoulder ROM, JPS and force.

However, the study found no significant correlations. In conclusion, there is evidence that HGF is associated with swimming performance; however, there is limited knowledge of other shoulder physical qualities. Furthermore, the different definitions of swimming performance affect the comparisons between studies.

2.9. Intervention studies for shoulder pain in swimmers

This subsection is presented as a scoping review. It aims to investigate the effects of exercise therapy interventions on shoulder pain and shoulder musculoskeletal risk factors for shoulder pain in swimmers.

The effect of exercise therapy interventions on shoulder pain and musculoskeletal risk factors for shoulder pain in competitive swimmers: a scoping review

Abstract

Objectives: To describe the evidence base relating to the effectiveness of exercise therapy interventions on shoulder pain and shoulder musculoskeletal risk factors for shoulder pain in swimmers.

Design: Scoping review.

Methods: Studies investigating the effect of exercise therapy on shoulder pain and musculoskeletal risk factors for shoulder pain in swimmers were identified from five databases (MEDLINE, PubMed, Scopus, Web of Science, and Cinahl). Critical appraisal of the literature was also performed.

Results: From 452 papers identified, 14 studies were included in this review. An exercise program of six to eight weeks including strengthening exercises (shoulder external rotator and scapula retractor muscles) and stretches (pectoral muscles) can decrease the incidence of shoulder pain in swimmers. Furthermore, a combination of exercises and stretches with manual therapy techniques can help to decrease shoulder pain in injured swimmers. Regarding risk factors, a strengthening program of more than 12 weeks increased shoulder external rotation force and endurance; however, this was not associated to decreases in pain. Finally, open kinetic chain exercises and a dry-land program are superior to close kinetic exercises and water training for improving shoulder external rotation strength and endurance.

Conclusions: Exercise therapy has positive effects on reducing the incidence of shoulder pain, the management of shoulder pain, and improving shoulder musculoskeletal risk factors in competitive swimmers. However, due to methodological limitations of the studies, caution must be used when applying these results in practice. Future research should focus on high-quality randomized controlled trials for prevention and management of shoulder pain in swimmers.

Keywords: Swimming, shoulder injury, rehabilitation, therapeutic exercises, injury prevention.

Highlights

- Strengthening and stretches reduce the incidence of shoulder pain in swimmers
- Strengthening and manual therapy decrease shoulder pain in injured swimmers
- Strengthening of more than 12 weeks increase shoulder ER strength in swimmers

2.9.1. Introduction

The shoulder is the most commonly injured joint in competitive swimmers and the main cause of missed or modified training (Chase et al., 2013; Weldon & Richardson, 2001). The prevalence and incidence of shoulder pain in swimmers are high ranging between 23% to 91% (K. Holt et al., 2017; McMaster & Troup, 1993; Sein et al., 2010; Tessaro et al., 2017) and 30% to 47% (Chase et al., 2013; Feijen, Struyf, et al., 2020; McLaine, Bird, et al., 2018; Walker et al., 2012), respectively. Importantly, the latest research has not shown a decline in prevalence (K. Holt et al., 2017; Tessaro et al., 2017) or incidence (Feijen, Struyf, et al., 2020; McLaine, Bird, et al., 2018).

Sports injuries are multifactorial, including the interaction between intrinsic (i.e., athlete related) and extrinsic (i.e., environmental) risk factor (Bittencourt et al., 2016; Meeuwisse et al., 2007). Regarding intrinsic factors, several modifiable (e.g., training-related, musculoskeletal physical qualities, etc) and nonmodifiable risk factors (level of competition, history of shoulder pain, etc) have been reported as potential contributors to shoulder pain in swimmers. (Hill et al., 2015; Struyf et al., 2017). Modifiable risk factors have received much interest in the athletic population as they might help to identify athletes at risk of injury (Windt & Gabbett, 2017). Importantly, they can also be changed through therapeutic interventions (Batalha et al., 2015; Manske et al., 2015). Within modifiable risk factors, shoulder musculoskeletal qualities have been extensively studied in swimmers. Studies have shown that alterations in shoulder range of motion (ROM) (Bansal et al., 2007; Cejudo et al., 2019; Tate et al., 2012; Walker et al., 2012), flexibility (Harrington et al., 2014; Tate et al., 2012), strength (Bak & Magnusson, 1997; McLaine, Bird, et al., 2018; Tate et al., 2012), and endurance (Beach et al., 1992; Feijen, Struyf, et al., 2020; Tate et al., 2020) are associated to shoulder pain.

Several reviews and clinical commentaries in swimmers suggest including some of these musculoskeletal factors in interventions to reduce the risk or manage shoulder pain (Blanch, 2004; Bradley et al., 2019; Dorssen et al., 2020; Gaunt & Maffulli, 2012; Matzkin et al., 2016; M. M. Pink & Tibone, 2000; Wanivenhaus et al., 2012; Weldon & Richardson, 2001). These studies recommend incorporating shoulder stretches and strengthening exercises (targeting scapular, rotator cuff, and core muscles) to the interventions. Despite the number of studies, no one has yet systematically analysed and summarized the evidence regarding the effects of exercise therapy in shoulder pain in swimmers. Furthermore, the effects of exercise therapy on musculoskeletal risk factors associated with shoulder pain has not been reviewed either.

This limited knowledge might explain why the incidence and prevalence remain high. Reviewing the literature with a systematic approach might help inform of the strengths and weaknesses of the studies, the quality of the evidence, and exercise therapy interventions performed (dosage, exercise progression, etc). This information can help practitioners working with swimmers to choose the most appropriate treatment to reduce the risk and manage shoulder pain. This review aimed to identify and describe the evidence base relating to the effectiveness of exercise therapy interventions on shoulder pain and shoulder musculoskeletal risk factors for shoulder pain in swimmers. The objectives were to identify gaps and provide recommendations for future research and practice. We agreed on the following review question: *What evidence is there on the benefits of exercise therapy interventions on shoulder pain and shoulder musculoskeletal risk factors for shoulder pain in competitive swimmers?*

2.9.2 Methods

Scoping reviews examine the extent, variety, and nature of a topic, summarize the findings of a heterogeneous body of knowledge, and identify gaps in the literature to help the planning of future research (Tricco et al., 2018). In contrast, systematic reviews focus on answering a particular question (Munn et al., 2018). Due to the broad research question, and diverse evidence, a scoping review methodology was selected. The five-stage scoping review process proposed by Arksey and O Malley (Arksey & O'Malley, 2005), with the subsequent adaptations by Levac et al. (Levac et al., 2010) were used. This includes (1) identifying the research question, (2) identifying relevant studies, (3) study selection, (4) charting the data, and (5) collating, summarizing and reporting the results. The extension for scoping reviews of the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA-ScR) checklist was followed (Appendix 1) to provide methodological transparency (Tricco et al., 2018).

Search and selection of the studies

Medline, PubMed, Scopus, Web of Science, and Cinahl databases were searched using a combination of the following terms: competitive swimmers (swimming [Mesh] OR water sports [Mesh] OR swim), AND shoulder pain (shoulder injuries [Mesh] OR shoulder function OR painful shoulder), AND exercise therapy (exercise [Mesh] OR rehabilitation [Mesh] OR motion therapy [Mesh] OR resistance training [Mesh] OR therapeutic exercise [Mesh] OR physical therapy modalities [Mesh] OR muscle stretching exercises [Mesh]). The search was performed through July 2021 and no limits were used for age and level of competition as a means to include a wider range of studies. The search of the literature was performed by one researcher (MY). Exercise therapy is defined as “a regimen or plan of physical activities designed and prescribed for specific therapeutic goals, with the purpose to restore normal musculoskeletal function or to reduce pain caused by diseases or injuries” (*Exercise Therapy - MeSH - NCBI*).

The eligibility criteria of the studies were based on the PICOS acronym (population, intervention, comparison, outcome, and study design). The studies needed to meet the following criteria: (1) competitive swimmers’ population; (2) exercise therapy interventions; (3) outcome measures including shoulder pain and/or shoulder musculoskeletal risk factors; and (4) any study design were considered, except for conference papers and clinical commentaries. Other inclusion criteria included articles available in full text and published in English. Exclusion criteria included studies conducted on synchronized swimmers, water-polo players, and triathletes. Studies investigating a specific shoulder diagnosis or performing an intervention other than exercise therapy (e.g., corticoid injections) were also excluded. The articles were first assessed for eligibility based on the abstract and title by MY. Then, both MY and LH screened all full text articles for eligibility independently, with TM acting as arbitrator for any disagreements.

Charting, collating and summarizing data

Data related to characteristics of the population and study design, exercise intervention protocol, and measures of shoulder pain or musculoskeletal risk factors were extracted from the included studies. When reporting the findings, p-values, effect sizes, and confidence intervals were included as appropriate; one member of the project team (MY) extracted all the data. Tables were used to organise and synthesise the data. Following the data extraction, a narrative synthesis of the studies was performed to describe the evidence available and identify the gaps in the current literature.

Quality assessment

Although optional in scoping reviews, a critical appraisal of the literature was performed to analyse the quality of the evidence in order to help and guide future research. A risk of bias assessment was separately performed by one author (MY) and one independent researcher (PH) using the Modified Down and Black checklist for both RCT and non-RCT (Downs & Black, 1998) (Appendix 2). Any disagreements were discussed and solved by the two researchers. If disagreements persisted a third person (LH) was consulted. The Modified Down and tool consists of a 27-item scale (maximum score of 28) assessing overall study quality, external validity, internal validity, and power of the study. Studies were categorised as high quality/low risk of bias (≥20), moderate quality/moderate risk of bias (17-19), and low quality/high risk of bias (≤17) (Barton et al., 2016). Case reports were not included in the risk of bias assessment.

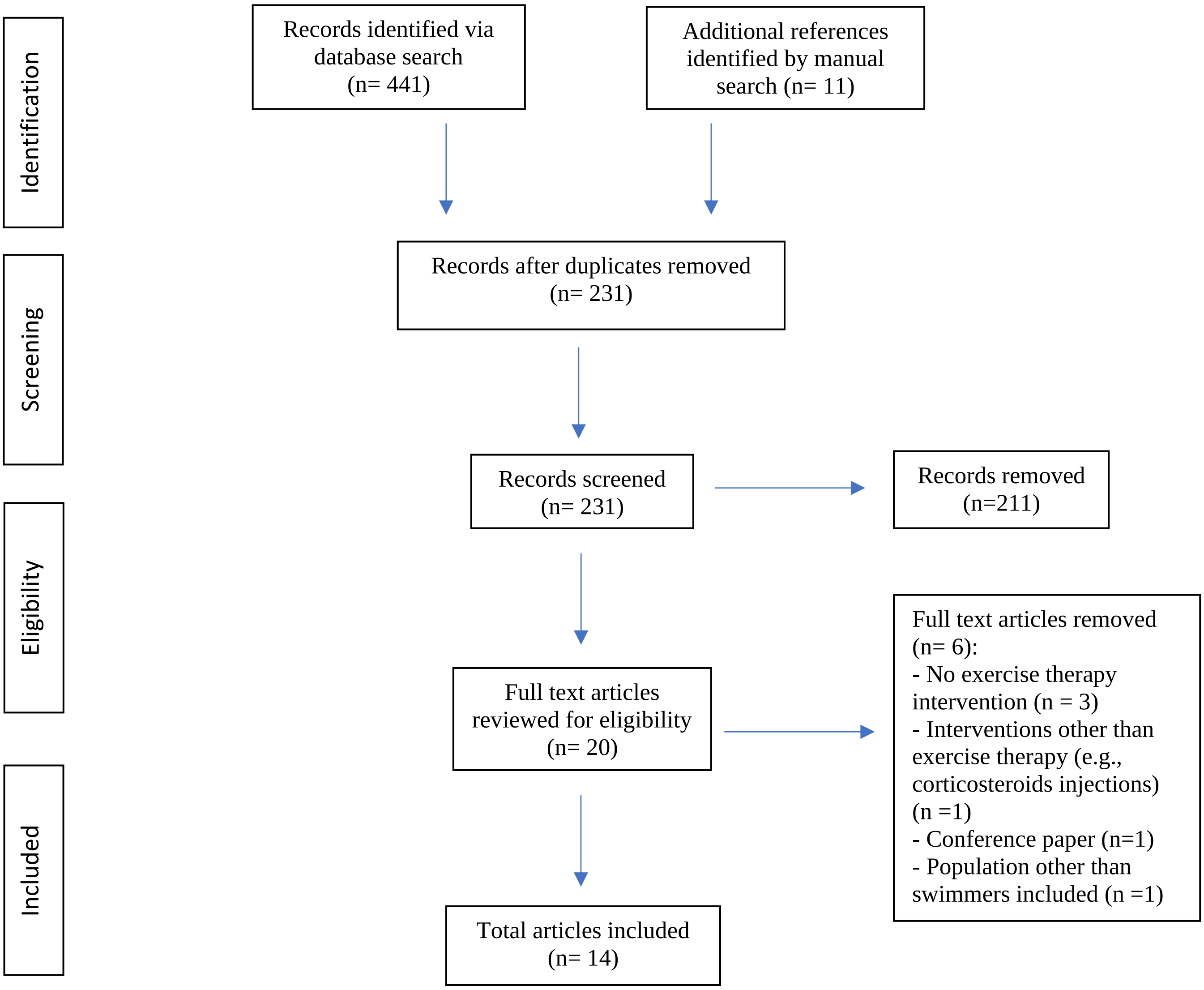

Figure 2.4. PRISMA flow diagram (Moher et al., 2009) of study selection and inclusion process.

2.9.3. Results

Studies and population characteristics

Electronic databases and manual searches returned a total of 452 articles. Screening excluded 432 articles, because they were duplicates or did not meet the inclusion criteria. Finally, data was extracted from 14 studies (Figure 2.4). A total of 354 swimmers from 11 to 24 years were included. The studies included nine RCT, two interventional non-randomized cohort studies, and three case reports (Table 2.3).

Outcome measures

Shoulder pain was reported as an outcome measure in six out of 14 studies (Kurtz JT, 2004; Leão Almeida et al., 2011; Lynch et al., 2010; Manske et al., 2015; Smith et al., 2021; Swanik et al., 2002). Studies measured shoulder pain as pain that interfered with training and competition (Swanik et al., 2002), using the visual analogue pain scale (VAS) (Kurtz JT, 2004; Leão Almeida et al., 2011; Manske et al., 2015), using the numerical pain rating scale (NPRS) (Smith et al., 2021), the American Shoulder and Elbow Surgeons Assessment (ASES) (Lynch et al., 2010), and the Quick Dash Questionnaire (Smith et al., 2021).

Regarding shoulder risk factors, most studies assessed shoulder strength. Shoulder rotator and scapular protractor/retractor muscles were the most common muscle groups studied. They were measured using isokinetic (Batalha et al., 2015; Batalha et al., 2018; Shahpar et al., 2019; Swanik et al., 2002; Van de Velde et al., 2011), HHD (Hibberd et al., 2012; Lynch et al., 2010; Manske et al., 2015; Sawdon-Bea & Benson, 2015; Smith et al., 2021), or manual testing (Kurtz JT, 2004; Leão Almeida et al., 2011). Shoulder flexibility was assessed by seven studies and was obtained by forward shoulder position (FSP) (Kluemper et al., 2006; Laudner et al., 2015; Lynch et al., 2010), pectoralis minor length (Sawdon-Bea & Benson, 2015), and shoulder ROM (Kurtz JT, 2004; Leão Almeida et al., 2011; Sawdon-Bea & Benson, 2015; Smith et al., 2021).

Exercise intervention protocols

The duration of the exercise protocol ranged between two (Laudner et al., 2015) and 16 weeks (Batalha et al., 2015), and a frequency of three sessions per week was chosen among most studies. The interventions included strengthening exercises, stretches, and manual therapy techniques.

Regarding strengthening, all studies except for Laudner et al. (Laudner et al., 2015) included strengthening exercises in the intervention. Different muscle groups were targeted using varied types of exercises. Despite this, emphasis was on shoulder external rotators and scapular retractors. The progression of the exercises was performed increasing the elastic band resistance, weight or the number of repetitions. The criteria for progression was based on perceived difficulty (Batalha et al., 2015; Batalha et al., 2018; Manske et al., 2015; Swanik et al., 2002), time (e.g., weeks) (Batalha et al., 2018; Kluemper et al., 2006; Smith et al., 2021; Van de Velde et al., 2011), assessed by examiners (Hibberd et al., 2012; Sawdon-Bea & Benson, 2015), levels of pain (Leão Almeida et al., 2011), or it was not reported (Kurtz JT, 2004; Lynch et al., 2010; Shahpar et al., 2019). All studies included open kinetic exercises in their programs, while five combined open and closed kinetic chain exercises (Leão Almeida et al., 2011; Sawdon-Bea & Benson, 2015; Shahpar et al., 2019; Swanik et al., 2002; Van de Velde et al., 2011).

Studies using stretches as a therapeutic approach targeted anterior shoulder muscles (e.g., pectoralis minor and major) to decrease SFP (Kluemper et al., 2006; Laudner et al., 2015; Lynch et al., 2010) or used a combination of anterior and posterior shoulder muscle stretches (Hibberd et al., 2012; Kurtz JT, 2004; Sawdon-Bea & Benson, 2015; Smith et al., 2021). However, the applied technique and dose varied across studies: self-stretching (10 x 5 seconds) (Lynch et al., 2010), self-stretching (2 x 30 seconds) (Hibberd et al., 2012), self-stretching (3 x 30 seconds) (Sawdon-Bea & Benson, 2015), peer-assisted (2 x 30 seconds) (Kluemper et al., 2006), muscle energy techniques (4 x 5 seconds) (Laudner et al., 2015), or was not reported (Kurtz JT, 2004; Smith et al., 2021).

Regarding manual therapy techniques, three case reports (Kurtz JT, 2004; Leão Almeida et al., 2011; Smith et al., 2021) included interventions along with strengthening exercises and stretches. These techniques included myofascial release, joint manipulations (thoracic spine and ribs), joint mobilizations (glenohumeral, cervical and thoracic spine), nerve mobilizations, neuromuscular electrical stimulation, and taping.

Exercise protocol effects on shoulder pain

The results showed that studies investigated the effects of exercise therapy to (1) reduce the risk of developing shoulder pain (i.e., injury prevention) and (2) manage shoulder pain in injured swimmers (i.e., treatment).

Regarding the prevention of shoulder pain, two out of three studies reported less incidence of shoulder pain in swimmers performing an exercise intervention compared to swimmers that did not (Lynch et al., 2010; Swanik et al., 2002). Swanik et al. (Swanik et al., 2002) found a lower incidence of shoulder pain that interfered with training in the IG compared to the CG (P = 0.02) after a 6-week strengthening program. Similarly, Lynch et al. (Lynch et al., 2010) reported that the IG had less shoulder pain than the CG after eight weeks of strengthening exercises and stretches. Although a difference in the total score of the ASES was not found, a difference in the pain subsection of the questionnaire was reported. Using a minimal clinical important difference (MCID) of two points, the researchers found that 79% of the subjects in IG decreased two points (> MCID), whereas 50% in CG increased two points. On the contrary, a more recent study reported no between-group differences in shoulder pain measured by the numeric rating scale after a similar intervention program (Manske et al., 2015). The different pain definitions might explain the inconsistencies in the results.

For the management of shoulder pain in injured swimmers, three studies were included. Leao Almeida et al. (Leão Almeida et al., 2011) found that a combination of strengthening, stretching, soft tissue management, manual therapy, and neural tissue techniques decreased shoulder pain in a 10-year-old swimmer. The pain was measured by the visual analogue scale (VAS) and was reduced from 9.5/10 points (at initial assessment) to 0/0 points (end of treatment). Using a similar treatment approach, Kurtz et al. (Kurtz JT, 2004) also found reductions in shoulder pain after four weeks of treatment in a 20-year-old swimmer. Using the VAS scale, the pain decreased from 5-6 at rest and 7-8/10 towards the end of the practice to 0/10 at rest and with swimming up to one hour and at 2–3/10 at the end of swimming practice. Finally, Smith et al. (Smith et al., 2021) reported reductions in shoulder pain after 8 weeks of strengthening exercises, neuromuscular electrical stimulation, manual therapy techniques, and taping. Using the NPRS, the pain decreased from 4/10 at evaluation and from 8/10 while swimming to 0/10. Furthermore, the Dash questionnaire decreased from 29.5 to 0 points after the intervention.

Exercise protocol effects on risk factors for shoulder pain

Regarding shoulder strength, all studies reported an increase at follow-up regardless of the group assigned (IG or CG). However, for between-group comparisons, studies only performing interventions greater than 12 weeks reported increases in shoulder strength compared to the CG (Batalha et al., 2015; Manske et al., 2015). In contrast, studies with interventions less than eight weeks did not find differences between groups (Hibberd et al., 2012; Lynch et al., 2010; Sawdon-Bea & Benson, 2015; Swanik et al., 2002). For instance, Batalha et al. (Batalha et al., 2015) found that swimmers in the IG had a bilateral increase of shoulder external rotation (ER) peak force and endurance compared to the group performing only aquatic training with moderate to large ES (n^2_{p} = 0.117 to 0.247) after a 16-week strengthening program. Likewise, Manske et al. (Manske et al., 2015) found greater increases in ER peak force of the dominant side in the IG after a similar 12-week strengthening program (P= 0.013). Although Manske et al. (Manske et al., 2015) was the only study that investigated if the changes in shoulder strength were associated with decreases in shoulder pain, they did not find a relationship.

Some researchers have also investigated the change of shoulder strength after different interventions. Batalha et al. (Batalha et al., 2018) found that 10 weeks of dry-land strength training was superior to water strengthening exercises in increasing ER endurance (P = 0.150; ηp2 = 0.039) and ER/IR endurance ratio (P = 0.023; ηp2 = 0.168). They also found that open kinetic chain exercises provided greater increases in ER strength and endurance (P < 0.05) than close kinetic chain exercises after eight weeks (Shahpar et al., 2019). However, another study failed to find differences in shoulder rotation strength after endurance or a strengthening program (Van de Velde et al., 2011).

Most studies assessing shoulder flexibility reported differences between the intervention and control group. Kuemper et al. (Kluemper et al., 2006) found that the IG decreased FSP compared to the CG (P < 0.01) after six weeks of strengthening exercises and stretches. Similarly, Lynch et al. (Lynch et al., 2010) found decreases in forward head angle and FSP in the IG compared to CG (P < 0.05; d = 1.2) after eight weeks of a similar intervention. Finally, Laudner et al. (Laudner et al., 2015) reported IG increased PML (P = 0.01: d = 1.6) and decreased forward scapular position (P = 0.01: d = 1.07) after two weeks of muscle energy techniques. In contrast, Sawdon-Bea & Benson (Sawdon-Bea & Benson, 2015) did not find a difference in PML and posterior shoulder flexibility after 6 weeks of strengthening exercises and stretches. Despite this, Lynch et al. (Lynch et al., 2010) was the only study that investigated the relationship with shoulder pain, reporting that increases in PML and decreases in SFP were associated with reductions in shoulder pain.

Risk of bias

Eleven of the 14 articles were eligible for analysis (RCT= 9; interventional non-randomized cohort= 2). According to the Modified Down and Black risk of bias tool, studies have an average of 17.5 points, which corresponds to a moderate quality or risk of bias. The main methodological issues included not reporting confounding factors, allocation concealment, power calculation, and blinding of the study subjects or those measuring the outcome measures. Although confounding factors were partially described, most of the studies did not include important factors, such as history of shoulder injuries, level of competition, and training volume. These are important factors to consider in swimmers (Section 2.5.2). Not considering important demographic factors can introduce bias to the study and lead to misleading conclusions. Also, allocation concealment was not reported in any study, which is important to prevent selection bias. Furthermore, the sample size was not calculated. This could underpower the studies to identify changes. Overall, the studies have methodological limitations, so caution must be used when applying these results in practice.

Table 2.3. Description of included studies: Exercise therapy intervention on shoulder pain and/or musculoskeletal risk factors for shoulder pain in swimmers

Author	Population and study design	Interventions	Outcome measures	Results	Risk of bias
	Studies including shoulder pain and risk factors as an outcome measure				
(Swanik et al., 2002)	Competitive swimmers IG: N= 13 (age NR) CG: N= 13 (age NR) 13F: 13M Design: RCT	Period: 6 weeks, 3 times a week. <u>Strengthening</u>: 3x 10 rep with resistance tubing and weights. Progression increasing loads when completing repetitions with ease. Exercises: Shoulder flexion, extension, IR 90°, ER 90°, diagonal pattern (D2), prone exercises at 120° and 90° abduction, and push-up plus.	Pain: “pain that interferes with practice, while swimming or a feeling of the shoulder being tired” Isokinetic force and endurance: ER, IR, retraction, protraction and diagonal pattern.	Pain: > incidence in CG (episodes = 4.6 ± 4.7) compared to IG (episodes = 1.8 ± 2.1) (P = 0.02). Strength: Both groups increased strength in all muscle groups (P < 0.01), except for ER. But no difference between groups (P > 0.05).	High (12/28)
(Kurtz JT, 2004)	Competitive swimmer with left anterior shoulder pain. N= 1 (20 years old) Gender= Male Design: Case-report	Period: 4 weeks, 3 times a week (first 2 weeks) and 2 times a week (last 2 weeks). <u>Myofascial release</u>: Upper trapezius, pectoralis major and minor, and subscapularis muscles. <u>Joint manipulation</u>: C7-T1, T4-T6, and left 1st and 2nd ribs. <u>Strengthening</u>: 3x 12-15 rep with weights. Progression NR. Exercises: Prone horizontal abduction (Y, T, I) on a Swiss ball. Sitting rowing 0° shoulder ABD. <u>Stretches</u>: Dosage NR. Posterior capsule and upper trapezius, pectoral major and minor, and subscapularis muscles.	Pain: VAS (0-10) Active shoulder ROM (goniometer): movements NR Manual strength testing: muscle groups NR.	Pain: Initially VAS 5-6 constant during last 6 months and 7-8/10 towards the end of practice. After treatment VAS 0/10 at rest and swimming up to one hour and 2-3/10 after swimming > 1 hour. ROM: initially only IR ROM was limited. After treatment, it was within normal limits. Strength Initially +4/5 subscapularis muscle. After treatment was pain-free and within normal limits.	NA
(Lynch et al., 2010)	Competitive swimmers IG: N= 14 (19.29± 1.2 years old) CG: N= 14 (19.29± 1.2 years old) Gender= NR Design: RCT	Period: 8 weeks, 3 times a week <u>Strengthening</u>: 3x10 rep with an elastic band. Progression NR Exercises: Prone horizontal abduction (Ys to Ws, Ls to Ys) Swiss ball <u>Stretching</u>: Pectoralis minor (10x 5s) and chin tucks.	Pain: ASES questionnaire. Forward head angle, forward shoulder position, scapular distance, isometric LT, MT, SA force (HHD).	Pain: No between-group differences in ASSES. But 79% of subjects in IG decrease 2 points in the pain subsection (> MCID) and 50% in CG increase 2 points. IG decreased forward head angle (P =0.005; d = 1.2) and forward shoulder position (P =0.001; d = 1.4) compared to CG Strength: Both groups increased strength in all muscle groups (P < 0.005; d = 1.2-2.4), but no difference between groups (P > 0.05).	High (16/28)

Table 2.3 (continued).

Author	**Population and study design**	**Interventions**	**Outcome measures**	**Results**	**Risk of bias**
(Leão Almeida et al., 2011)	Competitive swimmer with left anterior shoulder pain. N= 1 (10 years old) Gender= Female Design: Case-report	Period: 8 weeks, 3 times a week. The program was divided into four stages. Progression of the stage according to pain and ROM. Manual therapy techniques: 3x30s grade II anterior, posterior, and inferior mobilization of the glenohumeral joint and C5-C6-C7. 3x 1 min mobilization T2-T5 and neural mobilizations. Strengthening: Repetitions depend on the exercise and rehabilitation phase. The patient started with isometric exercises and progressed to isotonic and plyometric exercises. Pain-free exercise for progression. Exercises: Varied exercises including OKC and CKC in different shoulder elevations. Exercises targeting scapulothoracic, glenohumeral, and core muscles (shoulder IR and ER, push-ups, planks, rhythmic stabilization, etc).	Pain: DASH questionnaire and VAS (0-10) Active shoulder ROM (goniometer) for flexion, extension, abduction, and rotations with 90° of ABD. Manual shoulder strength flexion, extension, abduction, adduction, and rotations.	Pain: Dash score decreased from 26.6 to 5 points. The Dash sport module decreased from 68.75 to 6.25 points. VAS decreased from 9.5/10 to 0/10. ROM: Initially full but pain at the end-range of each movement. Pain-free after treatment. Strength: Initially 4/5 for flexion, extension, abduction, and ER. Normal after treatment.	NA
(Manske et al., 2015)	Competitive swimmers IG: N=11 (11.20 ± 2.44 years old) CG: N=10 (11.31 ± 2.24 years old) Gender= NR Design: RCT	Period: 12 weeks, 3 times a week Strengthening: 3x 15 rep with resistance bands. Progression changing band colour when difficulty > 6/10. Exercises: Standing shoulder flexion, extension, IR, ER, and abduction.	Pain: VAS (0-10) Isometric force (HHD) of shoulder flexion, abduction, ER, IR, and extension.	Pain: No difference between groups. Strength: IG increased ER force in the dominant side compared to CG (mean difference 0.73kg CI 95%= 0.174-1.292; P = 0.013).	Moderate (18/28)
(Smith et al., 2021)	Competitive swimmer with right superior shoulder pain. N= 1 (15 years old) Gender= Male Design: Case-report	Period: 8 weeks, 2 times a week Program and swim training was progressed according to pain. Manual therapy techniques: Dosage NR. Soft tissue techniques, joint mobilizations to target tight tissues (pectorals, latissimus, posterior shoulder) or ROM deficits. Neuromuscular electrical stimulation: Mid and low trapezius stimulation while doing exercises. Taping: Scapula reposition taping. Stretches: Dosage NR. Pectorals, latissimus dorsi, and posterior shoulder. Strengthening: Resistance bands and cables. Repetitions NR. Progressions according to pain and time in weeks. Exercises: shoulder rotations in neutral 45°, and 90° ABD, prone Ts and Ys, freestyle and breaststroke simulation exercises with bands and cables, and rhythmic stabilization drills.	Pain: NPRS (0-10) and Quick Dash Active shoulder ROM (measurement instrument NR) for flexion and abduction. Passive shoulder ROM for flexion, abduction, and rotations. Isometric force (HHD) for flexion 90°, abduction neutral, rotations, middle trapezius, lower trapezius and PSET.	Pain: Quick Dash score decreased from 29.5 to 0 points. NPRS decreased from 4/10 at evaluation and 8/10 while swimming to 0/10 and 0/10 respectively. ROM: Symmetric and pain-free ROM of all movements after the intervention. Force: Pain-free force of all muscle groups after the intervention.	NA

Table 2.3 (continued).

Author	**Population and study design**	**Interventions**	**Outcome measures**	**Results**	**Risk of bias**
	Studies only including risk factors as outcome measures				
(Kluemper et al., 2006)	Competitive swimmers IG: N=24 (16± 2.0 years old), 14F: 10M CG: N=15 (16± 2.0 years old), 11F: 4M Design: RCT	Period: 6 weeks, 3 times a week Strengthening: Elastic band: week 1 (3x10rep), week 2 (3x15rep), week 3 (3x20rep) increase band resistance, week 4 (3x10rep), week 5 (3x15rep), week 5 (3x20rep). Exercises: standing scapular retraction at 90° ABD, standing ER at 90° ABD, and forward flexion in standing. Stretching: Peer-assisted pectoralis minor and major stretch (2x 30s hold).	Forward shoulder position	IG decreased forward shoulder position compared to the CG (-9.6 ± 7.3 mm vs –2.0 ± 6.9 mm, $P < 0.01$).	Moderate (17/28)
(Van de Velde et al., 2011)	Competitive swimmers N= 9 strength training group N = 9 endurance training group Age: 14.7 ± 1.3 years old. 11F: 7M Design: Interventional non-randomized cohort	Period: 12 weeks, 3 times a week Strengthening: 3x10 rep (strengthening group); 3x20 rep (endurance group), Examiner re-evaluates weights and band resistance after 6 weeks for progression. Exercises: dynamic hug variation, elbow push-up, side-lying ER 0°, bilateral prone horizontal abduction with 90° elbow flexion and shoulder abduction.	Isokinetic protraction-retraction peak force and endurance	Both groups increased protraction ($P < 0.05$) and retraction ($P < 0.01$) peak force but not endurance. No difference in peak force and endurance between groups.	High (16/27)
(Hibberd et al., 2012)	Competitive Swimmers IG: N=20 (19.0 ±1.2 years old) 10F: 10M CG: N= 17 (19.4 ±1.2 years old) 8:9 Design: RCT	Period: 6 weeks, 3 times a week Strengthening: 2x 15 rep with resistance tubing, Progression changing resistance assessed by examiners. Exercises: Shoulder flexion, extension, IR 90°, ER 90°, throwing acceleration, throwing deceleration, low rows, scapular punches, Ys, Ts, Ws, Stretches: 2x30s. Sleeper stretch and corner stretch	Isometric force (HHD): shoulder flexors, extensors, adductors, abductors, ER, IR, retraction, retraction with upward and downward rotation.	Shoulder extension and IR increased in both groups ($P < 0.005$). No significant differences between groups in strength.	Low (20/28)
(Batalha et al., 2015)	Competitive swimmers. IG (exercise protocol): N= 20 (14.65± 0.49 years old). TG (only aquatic training): N= 20 (14.45± 0.51 years old) CG: N= 16 (14.69± 0.48 years old) Gender: males Design: RCT	Period: 16 weeks, 3 times a week Strengthening: 2 sets of 20 reps and last set with an elastic band until fatigue (red band initially), changing band resistance when 30 reps achieved in the final set. Exercises: Standing abduction in ER below 90° and above 90°, and shoulder flexion above 90°	Isokinetic shoulder rotators peak force and endurance	IG increased ER force compared to TG for dominant (2.94 Nm CI 95%= 0.10-5.76; P= 0.008; $n^2_p = 0.117$) and non-dominant side (3.23 Nm CI 95%= 1.55-4.91; P= 0.0015; $n^2_p = 0.247$). IG increases of ER force compared to CG for dominant (3.32 Nm CI 95%= 1.08-5.56; P= 0.001: $n^2_p = 0.220$) and non-dominant side (4.44 Nm CI 95%= 1.26-7.62; P= 0.002; $n^2_p = 0.255$).	Low (20/28)

Table 2.3 (continued).

Author	**Population and study design**	**Interventions**	**Outcome measures**	**Results**	**Risk of bias**
(Laudner et al., 2015)	Competitive swimmers IG: N= 20 (19.6± 1.2 years old). CG: N= 20 (19.6± 2 years old) Gender: female Design: RCT	Period: 2 weeks, 2 times per week MET: Arm positioned in end-range of horizontal abduction. Four cycles of 5s of shoulder isometric adduction	Scapular upward rotation, pectoralis minor length, forward shoulder position	IG increased pectoralis minor length (change= 0.9 ± 0.5 cm; P = 0.01: d = 1.6) and decreased forward scapular position (change= -1.5 ± 1.1cm; P = 0.01: d = 1.07) but no changes were reported in the CG.	Moderate (18/28)
(Sawdon-Bea & Benson, 2015)	Competitive swimmers IG: N= 16 (15.0 years old). CG: N= 16 (15.0 years old) 16F: 16M Design: RCT	Period: 6 weeks, 3 times a week Strengthening: 3x 30 seconds with resistance bands, Progression increasing the resistance of the band approved by examiners or researchers. Exercises: Shoulder, ER 0° of ABD, squat with scaption, ER with trunk rotation in the four-point kneeling position, serratus punch in supine, diagonal pulls, and planks. Stretches: 3x30s. Sleeper stretch and pectoralis minor stretch.	Isometric force (HHD): lower trapezius, serratus anterior, latissimus dorsi, ER, and IR. Pectoralis minor muscle length. Posterior shoulder tightness (horizontal adduction ROM). Core strength (McGill Trunk Flexor Test).	No significant difference between groups in shoulder strength and flexibility. The IG increased core strength compared to the CG (P< 0.001)	Moderate (19/28)
(Batalha et al., 2018)	Competitive swimmers. Land-group (LG): N= 13 (13.52 ± 0.92 years old). Water-group (WG): N= 12 (13.28 ± 0.96 years old) Gender: males Design: Interventional non-randomized cohort	Period: 10 weeks, 3 times per week Strengthening: LG: 2 sets of 20 rep and last set with an elastic band until fatigue (red band initially), changing band resistance when achieved 30 reps in the final set. Exercises: Standing abduction in ER until 50°-60° and 160°, and shoulder ER 90° WG: Progression every two weeks: Week 1 – 3 x 30 s; Week 3 – 4 x 30 s; Week 5 – 3 x 45 s; Week 7 – 4 x 45 s; Week 9 – 5 x 30 s. Exercises: ER 0° with a band, paddles, and without implements.	Isokinetic shoulder rotators peak force and endurance	WG increased bilateral IR peak torque and endurance for dominant (P= 0.028-0.023; ηp2= 0.157-0.147) and nondominant side (P= 0.013-0.036; ηp2= 0.221-0.167) compared to LG. LG increased ER endurance (P = 0.150; ηp2 = 0.039) and ER/IR endurance ratio (P = 0.023; ηp2 = 0.168) in dominant side compared to the WG.	Moderate (19/28)
(Shahpar et al., 2019)	Competitive swimmers. N= 45 Open chain exercise group (OCG): 23.2_± 3.3 years old. Closed chain exercise group (CCG): 24.2_± 4.2 years old. CG (no dry-land workout, only aquatic training): 23.4 ± 3.8 years old. Gender: males Design: RCT	Period: 8 weeks, 3 times per week Strengthening: CCG: 3 sets of 10-15 rep. Progression= NR Exercises: Push up, scapular push up, scapular dip, crab walk. OCG: 3 sets of 8 rep for ER and IR; 3 sets of 6 rep (80% 1 rm) for dumbbell fly and reverse dumbbell fly. Progression= NR.	Isokinetic shoulder rotators peak torque and endurance	OCG and CCG increased IR and ER peak torque and endurance (P < 0.05). But, the OCG increased more than the CCK (P < 0.05). OCG and CCG increased ER and IR peak torque and endurance compared to CG (P < 0.05).	Moderate (18/28)

Abbreviations: N=number of participants; F=female: M=male; IG=intervention group; CG=control group; TG=training group; s=seconds; rep=repetitions; RCT=randomized controlled trial; LT=lower trapezius;

MT=middle trapezius; SA=serratus anterior; ASSES=American Association of Shoulder and Elbow Surgeons; CI=confidence interval; MCID=minimal clinical important difference; ROM=range of motion; MET=muscle energy techniques; PSET= posterior shoulder endurance test; Nm=newtons-meter; ER=external rotation; IR=internal rotation; ABD=abduction; HHD=hand-held dynamometer; VAS=visual analogue scale; NPRS=numerical pain rating scale; NR=not reported; NA=not applicable. Risk of bias using the Modified Downs and Black quality checklist.

2.9.4. Discussion

Understanding the evidence for the effectiveness of exercise interventions on shoulder pain and risk factors can help practitioners to choose the most appropriate treatment. The heterogeneity of the populations, outcome measures and exercises protocols (e.g., dose and progression) across studies make comparisons difficult. This supports the use of a scoping review instead of a systematic review with meta-analysis to gain some context based insight (Tricco et al., 2018).

Effect of exercise therapy on shoulder pain

One finding of this review was that swimmers performing six to eight weeks of shoulder and scapular strengthening exercises in combination with pectoralis minor stretches have less incidence of shoulder pain (Lynch et al., 2010; Swanik et al., 2002). It is important to consider that the different pain definitions across these studies might have influenced the results. Swanik et al. (Swanik et al., 2002) was the only study including a pain definition based on training modification. Since most shoulder injuries in swimmers are caused by an overuse mechanism and few stop training due to pain, the International Olympic Committee in injury surveillance (Mountjoy et al., 2016) recommends injury definitions that record sport participation, training modifications, performance reductions and symptoms (discussed in Section 2.1.2). Considering this, studies investigating the incidence of shoulder pain should include this type of definition using scales such as the Oslo Sports Trauma Research Centre Questionnaire on Health Problems [OSTRC-H]) (Clarsen et al., 2020) to monitor shoulder pain.

Another finding was that the combination of strengthening exercises and stretches with other therapeutic modalities such as manual therapy techniques can decrease shoulder pain in injured swimmers (Kurtz JT, 2004; Leão Almeida et al., 2011; Smith et al., 2021). The most common interventions included were myofascial release and joint mobilizations, with the latest research incorporating novel approaches such as neuromuscular electrical stimulation (Smith et al., 2021). The evidence supports this, suggesting that combining manual therapy with exercises is better than exercise or manual therapy alone for the management of other musculoskeletal conditions (Hidalgo et al., 2014). However, since the studies investigating these interventions in swimmers are case reports, is not possible to determine whether exercise alone or in combination with manual therapy is better or the superiority of one technique over the other (e.g., joint mobilizations vs myofascial release). Despite this, our findings showed that performing a scoping review (i.e., not excluding case reports) can provide important and valuable information about the management of shoulder pain in swimmers.

Effect of exercise therapy on musculoskeletal risk factors

Another interesting finding of our study was that strengthening programs of more than 12 weeks increased shoulder ER force and endurance in competitive swimmers when compared to interventions of less duration (Batalha et al., 2015; Manske et al., 2015). Regarding the duration of the intervention, studies (Androulakis-Korakakis et al., 2020; Prokopy et al., 2008) support these findings showing that athletes increase their strength after a similar period. Importantly, the changes were reported in shoulder ER endurance and force. These results might be relevant as several studies (Beach et al., 1992; Feijen, Struyf, et al., 2020; Tate et al., 2020) have shown that shoulder ER endurance is a modifiable risk factor for shoulder pain in swimmers. Furthermore, investigators (Labriola et al., 2005) have indicated that decreased infraspinatus activity led to glenohumeral instability, which may result in functional impingement. Despite this, Manske et al. (Manske et al., 2015) did not find a relationship between shoulder strength improvement and reductions in shoulder pain.

Findings of our study also highlight that a combination of pectoralis major and minor stretches with strengthening exercises increased PML and decreased SFP in uninjured competitive swimmers (Kluemper et al., 2006; Lynch et al., 2010). Lynch et al. (Lynch et al., 2010) was the only study that investigated this relationship with shoulder pain, reporting that improvements in these physical qualities were associated with reductions in shoulder pain. Importantly, PML (i.e., an indirect measure of FSP) has been reported as a potential modifiable risk factor for shoulder pain in swimmers (Harrington et al., 2014; Tate et al., 2012). Reductions of the PML can alter scapular position (e.g., increase anterior tilt and internal rotation) decreasing the subacromial space and possibly increasing the risk of shoulder pain (Lynch et al., 2010). Interestingly, the seven studies including flexibility exercises performed anterior shoulder stretches and only four posterior shoulder stretches. This is supported by Matzkin et al. (Matzkin et al., 2016) suggesting that stretches to the posterior shoulder are often neglected. These investigators (Matzkin et al., 2016) highlight the importance of maintaining a balance between anterior and posterior muscle stretches to allow proper scapular motion and posture. Importantly, since overstretching might increase the risk of injury, it is recommended to only stretch if ROM deficits are identified (Blanch, 2004).

Another important finding was that open kinetic chain exercises and a dry-land program are superior to close kinetic exercises and water training for improving shoulder ER strength and endurance (Batalha et al., 2018; Shahpar et al., 2019). Open kinetic exercises incorporating overhead positions might be more relevant as simulates the swimming stroke. Interestingly, the studies reporting pain reductions (Lynch et al., 2010; Swanik et al., 2002) included only open kinetic chain exercises in their interventions. Furthermore, dry-land should be chosen over water strengthening training to improve shoulder ER endurance (Batalha et al., 2018). These findings may support the use of dry-land training in swimmers to reduce shoulder injury risk (Tessaro et al., 2017). However, it seems more important to understand when to perform the dry-land training. In a recent study, Batalha et al. (Batalha et al., 2020) found that strength training program did not have a significant acute effect on shoulder rotators strength and endurance in swimmers, suggesting that the implementation of strength exercises before an in-water swim session are appropriate. However, it may be also important to consider the intensity of the swim session associated to the dry-land training. Studies have shown that swimmers decrease their shoulder rotation force after a high-intensity session (Yoma et al., 2021) but not after a low to moderate intensity session (Batalha et al., 2021; Yoma et al., 2021). Thus, performing a dry land training along with a high-intensity swim session might augment the drops in strength, potentially increasing the risk of injury.

Clinical meaningfulness of the results

We need to consider the clinical meaningfulness of these results. Clinical meaningfulness reflects the degree to which the study results are relevant to practice and can be determined by the effect size, confidence intervals, measurement error, and minimal clinical important difference (MCID) (Riemann & Lininger, 2018b). For instance, only four studies (Batalha et al., 2015; Batalha et al., 2018; Laudner et al., 2015; Lynch et al., 2010) reported the effect size (i.e., magnitude of change) of the results. Regarding measurement error (i.e., reliability), only two studies reported whether the results exceeded or not the standard error of measurement (Laudner et al., 2015) or minimal detectable change (Hibberd et al., 2012). Reporting reliability of the results is important as it refers to the extent to which a test or instrument provides a measure that is free of error over repeated trials (Riemann & Lininger, 2018b). Furthermore, only Lynch et al. (Lynch et al., 2010) reported if the reductions of shoulder pain exceeded the MCID. When assessing the results of an intervention on pain, the MCID is an important parameter to report as reflects the quantity of change that the patient perceives as worthwhile (Riemann & Lininger, 2018b). Finally, four studies (excluding case reports) (Batalha et al., 2018; Laudner et al., 2015; Manske et al., 2015) reported confidence intervals of the results. Confidence intervals are necessary as they provide a range of possible values obtained from samples to estimate the population (Riemann & Lininger, 2018b). Overall, these findings demonstrate a lack of clinical meaningfulness in the results.

Review strengths and limitations

This review presents strengths and weaknesses. Although scoping reviews employ a rigorous and structured method consistent with a systematic review process, the inclusion and exclusion criteria are more flexible (Tricco et al., 2018). This allowed the identification of various study designs assessing the effects of exercise therapy interventions in shoulder pain in swimmers. We delimit our search to "exercise therapy" interventions. This was a strength as it showed the wide range of techniques used to prevent and manage shoulder pain in this population. However, this might be also a weakness as we excluded other treatments (e.g., corticoid injections) or specific shoulder conditions (e.g., postoperative management, painful os acromiale, etc) that were found in the literature. Another possible strength is that we performed a critical appraisal of the literature. Despite this is optional for scoping reviews, we believe that this was appropriate to perform as most of the studies (11 out of 14) were eligible. Thus, along with a broader and more contextual overview of a scoping review, the methodological assessment of the literature might inform and guide future research.

The studies analysed present limitations. First, all the studies present methodological limitations which inhibit generalizing results with confidence. Second, the lack of efficacy of the interventions might also be explained because only musculoskeletal factors were included in the intervention programs. As previously discussed in Section 2.4, other factors (e.g., training loads, behavioural, and psychological) are also important in the aetiology of shoulder pain, and thus, need to be included in the intervention programs. Third, studies assessing the incidence of shoulder pain performed a single measurement of shoulder pain and musculoskeletal risk factors, without considering the dynamic interaction between factors over time (Meeuwisse et al., 2007). A recent study showed that shoulder musculoskeletal risk factors in swimmers are dynamically changing according to the training load applied (Yoma et al., 2021). Fourth, the studies only included a primary prevention intervention (avoidance of injury through an intervention program). An important concept is secondary injury prevention, which involves the early detection and interventions addressing clinical signs which may result in injury (e.g. decreases in strength after training or competition) (van Dyk & Clarsen, 2017; Wollin et al., 2019). Recent research has suggested that in-season monitoring of physical qualities is a promising injury prevention strategy (Baroni & Oliveira Pena Costa, 2021). An example of this is a RCT (Wollin et al., 2019) reporting that in-season monitoring of hamstring strength after football games during a season reduced the risk of injury.

More high-quality studies investigating primary injury prevention of shoulder pain in swimmers are necessary to confirm the findings of this review. Furthermore, future RCT should monitor shoulder pain using scales such as the OSTRC-H and perform repeated measures of multidimensional risk factors when comparing groups to analyse the risk of developing shoulder pain (i.e., secondary injury prevention). Although regular in-season monitoring seems to be the most appropriate approach, challenges of competitive athletes, such as training schedules, travel, competitions, among other issues, need to be considered (Baroni & Oliveira Pena Costa, 2021). Finally, comparing the efficacy of different protocols in injured swimmers is necessary to determine the most appropriate treatment to manage shoulder pain.

2.9.5. Conclusions

Through this scoping review, we have found that an exercise program including strengthening exercises and stretches can decrease the incidence of shoulder pain and improve shoulder musculoskeletal risk factors in swimmers. Also, that a combination of exercises and stretches with manual therapy techniques can help to decrease shoulder pain in injured swimmers. Due to the methodological limitations of the studies and the lack of clinical meaningfulness of the results, caution must be used when applying these results in practice. Future research in injury prevention should monitor shoulder pain and multiple risk factors more repeatedly. Finally, high-quality RCTs are needed to determine the best intervention to manage shoulder pain in swimmers.

2.10. Reliability of outcome measures

This section will assess the literature regarding the reliability of the outcome measures (i.e., shoulder physical qualities) that are going to be used in this thesis (the rationale of why these tests were chosen will be explained in Chapter 3).

Athletes are often assessed to identify potential risk factors that may predispose them to injury (Dennis et al., 2008). These measurements are also used to quantify the amount of change of the risk factors over time and to evaluate treatment progression and effectiveness (Møller et al., 2018). However, before monitoring an intervention, clinicians and researchers need reliable methodologies to accurately assess the status of the athlete. It has been recommended that reliability of the outcome measures need to be established before the evaluation of the study subjects (Holt, Raper, Boettcher, Waddington, & Drew, 2016). Reliability concerns the extent to which repeated measurements provide similar results over time (De Vet et al., 2006). Reliability of outcome measures provide clinicians with the information to differentiate between a real change observed or a measurement error (De Vet et al., 2006).

Reliability is divided into two categories: relative and absolute (Riemann & Lininger, 2018b). Relative reliability is reported by the intraclass correlation coefficient (ICC). Although relative reliability is important, absolute reliability has more clinical relevance (Cools et al., 2014; Riemann & Lininger, 2018). Absolute reliability is measured by parameters, such as the standard error of measurement (SEM) and minimal detectable change (MDC), limits of agreement (LOA) and coefficient of variation (CV) (De Vet et al., 2006). These parameters are easy to interpret by clinicians, as they are expressed in the actual scale of measurement (De Vet et al., 2006). Importantly, along with other parameters (i.e. effect size, minimal important difference, and confidence intervals) the SEM and MDC are used to determine the clinical meaningfulness of the results (Riemann & Lininger, 2018b). Furthermore, the MDC is considered one of the most important values when using objective outcome measures (Carter & Lubinsky, 2015).

Studies analysing the results obtained by the same examiner (e.g., intrarater) in the same session were classified as within-session reliability. Whereas, studies analysing the results obtained by the same examiner at different periods were defined as test-retest reliability, which included within-day and between-day reliability. When appropriate, comparisons of the results obtained by different examiners (interrater) were also performed. Finally, considering its clinical relevance, the MDC was the main parameter reported.

2.10.1. Shoulder rotation range of motion

The reliability of shoulder rotation ROM has been widely studied (Table 2.3). For within-session reliability, ICCs ranged from 0.79 to 0.99 and SEM values ranging from 1.9° to 4.27° (Cools et al., 2014; Kolber et al., 2011; Kolber & Hanney, 2010; Shin et al., 2012). However, only two of these studies reported MDC in their analyses (4.5° to 6.4°) (Cools et al., 2014; Kolber et al., 2011).

Test-retest reliability for shoulder rotation ROM has been calculated from different time points ranging from 30 minutes to one week. The results depend on the time between measurements, the protocol performed, and the population of interest. Large variability for test-retest reliability (ICC=0.41-0.98) has been reported in the literature (Da Silva et al., 2018; Fieseler et al., 2017, 2015; Furness, Johnstone, Hing, Abbott, & Climstein, 2015; Møller et al., 2018; Walker et al., 2016). Regarding agreement parameters, these studies reported SEM values ranging from 1.07° to 8.1°. For the detection of the minimal clinical difference, different parameters were used, such as MDC (Da Silva et al., 2018; Furness et al., 2015; Walker et al., 2016), LOA (Fieseler et al., 2015; Møller et al., 2018) and CV (Fieseler et al., 2017), which has enabled the comparison between all the studies. Studies reporting MDC have found values ranging from 5.0° to 22.4°. The highest values were found in the Da Silva et al. (2018) study (MDC= 16.9°-22.4°), which measured symptomatic subjects over a week. Whilst, the lowest values were reported in the Walker et al. (2016) study (MDC= 5.0°-12°), which measured healthy participants twice with 30 minute intervals. It seems that longer intervals of time between measurements and the assessment of symptomatic population negatively affect the test-retest reliability of shoulder ROM.

There is also evidence that interrater testing for shoulder range provides lower reliability than intrarater testing (Cools et al., 2014; Kolber et al., 2011; Møller et al., 2018; Muir et al., 2010; Shin et al., 2012). Considering this, the same researcher or clinician should perform the repeated measurements on the patients to decrease the probability of measurement error (Mullaney et al., 2010). The different results found may be due to the different methodologies reported. Overall, there is no consensus of the best method to assess shoulder rotation range, which is reflected in the varied results reported.

Table 2.4 - Test-retest, intrarater and interrater reliability of shoulder rotation ROM.

Author	Population	Movement type/position	Stabilization	Instrument	Method	Reliability
(Furness et al., 2015)	AS N= 15 (22-48 years old) 7F: 8M	Active rotation ROM in supine and prone 90° shoulder ABD	IR: Scapular stabilization ER: No stabilization (end-fell)	Non-digital inclinometer	Test-retest reliability after 3 hours Intrarater reliability (within-session)	Test-retest: ICC3,2= 0.82-0.96 SEM= 2.7°-3.5° MDC95= 7.5°-9.7° Intrarater: ICC3,1= 0.93-0.99 SEM= 1.5°-2.4° MDC95= 4.2- 6.7°
(Higson et al., 2018)	AS N= 15 elite swimmers Age = NR Sex: NR	Active rotation ROM in supine 90° shoulder ABD	IR: Humeral head stabilization ER: No stabilization (end-fell)	Digital inclinometer	Test-retest reliability after 10 minutes same examiner	Test-retest: ICC3,2= 0.94-0.96 SEM= 1.5°-1.9° MDC95= 4.2°-5.2°
(Walker et al., 2016)	AS competitive swimmers N= 16 (12-24 years old) 8F: 8M	Active rotation ROM in supine 90° shoulder ABD	ER/IR= caudal-posterior force to scapula.	Inclinometer (attached to the forearm)	Test-retest reliability after 30 minutes (same examiner)	Test-retest: ICC2,3= 0.90-0.95 SEM= 2°-5° MDC90= 5-12°
(Møller et al., 2018)	AS elite handball players N= 162 players (14-18 years old). 82F: 80M	Active rotation ROM in supine 90° shoulder ABD	IR= Scapular stabilization ER= Scapular stabilization	Inclinometer	Test-retest reliability after 1 week Intrarater reliability (within-session) Interrater reliability (within-session)	Test-retest: ICC3,1= 0.41-0.46 LOA= -8.4° to 9.9° Intrarater: ICC3,1= 0.81-0.88 LOA= -4.1° to 4.4° Interrater: ICC3,1= 0.35-0.47 LOA= -14.3° to 6.3°
(Fieseler et al., 2017)	AS and S (SIS) N= 25 (60.4 ±7.84 years old) 14F: 11M	Active ROM in supine 90° shoulder ABD	Scapular stabilization both	Goniometer	Test-retest reliability after 1 week (same examiner)	ICC model NR Test-retest: ICC= 0.79-0.94 SEM= 6.04°-7.86° CV= 24.5°-39.8°
(Fieseler et al., 2015)	AS handball players N= 22 (21±3.7 years old) 22F	Active ROM supine 90° shoulder ABD	IR: Scapular stabilization ER: Scapular stabilization	Goniometer	Test-retest reliability after 1 week (same examiner)	Test-retest: ICC model NR 0.96-0.98 SEM= 1.07°-2.16° LOA= -9° to 8.85°
(Cools et al., 2014)	AS N= 30 (22±1.4 years old) 15M: 15F	Passive rotation ROM supine 90° shoulder ABD	IR: Scapular stabilization ER: Scapular stabilization	Inclinometer	Intrarater and interrater reliability (within-session)	Intrarater: ICC3, k= 0.95- 0.99 SEM= 1.9-2.7°. MDC90= 4.5-6.4° Interrater: ICC 2, k= 0.98 SEM= 1.65-1.85°. MDC90: 4.59-5.14°

Table 2.4 (continued).

Author	**Population**	**Movement type/position**	**Stabilization**	**Instrument**	**Method**	**Reliability**
(Da Silva et al., 2018)	S: SIS N=30 (18-45 years old) M12: F18	Active in supine 90° shoulder ABD	Stabilization NR	Fleximeter attached	Test-retest reliability after 1 week (Same examiner) Interrater reliability after 1 week (between examiners)	Test-retest: ICC2,3= 0.85-0.89 SEM= 6.1-8.1° MDC95= 16.9-22.4° Interrater: ICC2,3= 0.85-0.93 SEM= 5.30-7.12° MDC95= 14.71°-19.74°
(Kolber & Hanney, 2010)	AS N=30 (26 ± 4.2 years old) 21F: 9M	Active ROM ER= supine IR= prone 90° shoulder ABD	ER= no stabilization IR= no stabilization	Inclinometer	Intrarater (within-session)	Intrarater: ICC3, k= 0.98-0.97 SEM= 2° MDC= NR
(Kolber et al., 2011)	AS N= 30 (25.9 ± 3.1 years old) 18F: 12M	Active ROM ER= supine IR= prone 90° shoulder ABD	ER= no stabilization IR= no stabilization	Digital inclinometer	Intra and interrater reliability (within-session)	Intrarater: ICC3, k= 0.87-0.94 SEM= 2.63°-4.27° MDC= NR Interrater: ICC2, k= 0.88-0.93 SEM= 3.39°-3.98° MDC90= 8°-9°
(Muir et al., 2010)	S and AS N=17 (41.5 years old) 14F: 3M	Active and passive ROM supine 90° shoulder ABD	ER= no stabilization IR= Scapular stabilization (verbal)	Goniometer	Interrater and intrarater reliability (within-session)	Intrarater AS: ICC model NR = 0.81-0.87 SEM= 5-4° MDC90= 11-14° Interrater AS: ICC= 0.62-0.72 SEM= 6° MDC90= 18°
(Shin et al., 2012)	S N=41 (52.7± 17.5 years old) 21F: 20M	Active and passive ROM supine 90° shoulder ABD	No stabilization	Smartphone inclinometer	Intrarater (within-session) Interrater (after 30 minutes)	Intrarater: ICC3,1= 0.79-0.99 SEM= 1.86-3.18° MDC90= 2-3° Interrater: ICC2,1= 0.63-0.90 SEM= 7.15-11-54° MDC90= 17-27

Abbreviations: S=symptomatic; AS=asymptomatic; SIS=shoulder impingement syndrome; F=female: M=male; ER=external rotation; IR=internal rotation; ABD=abduction; ICC=intraclass correlation coefficient; SEM=standard error of measurement; MDC=minimal detectable change; LOA=limit of agreement; CV=coefficient of variation; NR=not reported.

2.10.2. Latissimus dorsi length

Few studies have assessed the reliability of LD length (Table 2.4). Some important aspects of the test include the initial arm positioning, end-feel determination, and the supervision of the pelvic position during the test. For within-session reliability, ICCs between 0.91 to 0.94 and SEM from 1.2° to 3.59° have been reported (Feijen, Tate, Kuppens, Struyf, et al., 2020; Herrington & Horsley, 2014). Feijen et al. (2020) also reported MDC values ranging from 7.49° to 9.94°. Although these studies have slightly different protocols, both clearly defined the procedures making them replicable.

Regarding test-retest analysis, no studies have investigated within-day reliability. Between-day reliability has been calculated in two studies. Shahidi et al. (2012) reported excellent interrater reliability (ICC = 0.91-0.93) in healthy participants and poor interrater reliability (ICC= 0.19-0.23) in subjects with neck pain. In this study, the LD length was assessed by the distance from the lateral epicondyle to the surface of the examination table. This study presents methodological limitations, as the rotation of the arm to determine the end-feel was not reported, making it difficult to be replicated. In another study, Borstad et al. (2010) found poor test-retest reliability (ICC= 0.19) in healthy participants measured by the same examiner over a six-week interval period using an inclinometer. The complexity of the end-feel determination and interval period between sessions might explain the poor results. Due to different measurement units used (cm or degrees), it is not possible to compare SEM and MDC values between studies.

The measurement of the LD length by different examiners (interrater) also provides lower reliability (ICC = 0.54-0.57) compared to one examiner (ICC = 0.91-0.94) (Feijen, Tate, Kuppens, Struyf, et al., 2020). Overall, the number of examiners is an important factor for within-session reliability. Furthermore, longer periods might affect the test-retest reliability of the LD length measurement. Finally, it is also important to consider that the different procedures used (i.e., end-feel and arm positioning) may explain the varied results.

Table 2.5 - Test-retest, intrarater and interrater reliability of latissimus dorsi length

Author	**Population**	**Movement type/position**	**Procedure/ End-feel**	**Instrument**	**Method**	**Reliability**
(Feijen, Tate, Kuppens, Struyf, et al., 2020)	AS swimmers N= 26 (15.46 ± 2.98 years old) 16F: 10M .	Passive shoulder flexion in supine	Active abdominal contraction during the procedure End-fell: resistance to movement in shoulder ER position.	Inclinometer The angle between the humerus and horizontal line	Intrarater (within-session) Interrater (within-session)	Intrarater: ICC (3,2) = 0.91-0.94 SEM= 2.70°-3.59° MDC= 7.49°-9.94° Interrater: ICC (2,4) = 0.54-0.57. SEM= 6.48-6.89° MDC= 17.95°-19.10°
(Herrington & Horsley, 2014)	AS N= 10 (24.5 ± 3.7 years old) 10M .	Passive shoulder flexion in supine	Posterior pelvic tilt with pressure biofeedback under the spine End-fell: resistance to movement from full IR and full ER.	Goniometer The angle between the humerus and horizontal line	Intrarater (within-session) Pilot study	Intrarater: ICC (3,1) = 0.9 SEM= 1.2°-1.8° MDC= NR
(Shahidi et al., 2012)	AS (control) N= 20 (34 ±10.4 years old) 10F: 10M S (neck pain) N= 19 (34.9 ±9.9 years old) 9F:10M	Shoulder flexion in the supine position (the type of movement NR)	knees bent and lumbar spine full contact with the table. End-fell NR	Ruler Distance from the lateral epicondyle to the table. Rotation position of shoulder NR	Interrater reliability after 9 days (different examiners)	Interrater (control group): ICC3,1 = 0.91-0.93 SEM= NR MDC95= 3.8-4.2cm. Interrater (neck pain): ICC3,1 = 0.19-0.23 SEM= NR MDC95= 7.4-7.6cm
(Borstad & Briggs, 2010)	AS N= 30 (23.3 years old) 7F: 23M	Passive shoulder flexion in supine	knees bent and lumbar spine full contact with the table. End-feel: Shoulder flexion or onset of medial rotation	Goniometer The angle between the humerus and horizontal line	Test-retest reliability after 6 weeks (same examiner)	Test-retest: ICC (3,1) = 0.19 SEM= 10.5° MDC= NR

Abbreviations: N=number of participants; S=symptomatic; AS=asymptomatic; SIS=shoulder impingement syndrome; F=female: M=male; ICC=intraclass correlation coefficient; SEM=standard error of measurement; MDC=minimal detectable change; NR=not reported.

2.10.3. Shoulder joint position sense

Few studies assessing the reliability of shoulder JPS have been reported (Table 2.5). No studies have investigated the within-session reliability of this test. Regarding test-retest analysis, two studies have assessed within-day reliability with time intervals of 10 minutes (Higson et al., 2018) and 30 minutes (Herrington et al., 2010). These studies reported high ICCs (0.89 to 0.92) and low MDC values (0.9° to 1.8°). The similar results between these studies might be explained by the same measurement protocol used. Only one study has assessed the between-day reliability of shoulder JPS. Dover et al. (2003) reported excellent test-retest reliability (ICC= 0.98) measured in two consecutive days (Dover & Powers, 2003). However, SEM and MDC parameters were not reported.

Overall, the measurement protocol performed in the Herrington et al. (2010) and Higson et al. (2018) studies provide excellent reliability for this test. Furthermore, no studies have investigated the within-session reliability, and no absolute reliability parameters have been reported in the between-day analysis.

Table 2.6 - Test-retest, intrarater and interrater reliability of shoulder joint positions sense.

Author	**Population**	**Movement type and positioning**	**Procedure and angle**	**Instrument**	**Method**	**Reliability**
(Higson et al., 2018)	AS, elite swimmers N= 15 (20 ±1.8 years old) 7F:9M	Active in supine and 90° of shoulder ABD	Mid-range (45°) of ER ROM	iPhone attached	Test-retest reliability after 10 minutes (pilot study)	Test-retest: ICC model NR= 0.89 SEM= 0.7° MDC95= 1.8°
(Herrington et al., 2010)	AS N=5 Age=NR Males	Active in supine and 90° of shoulder ABD	Mid-range (45°) and end-range (80°) of ER ROM	Digital camera	Test-retest reliability after 30 minutes (pilot study)	Test-retest: ICC2,1= 0.92 SEM= NR MDC= 0.9°
(Dover & Powers, 2003)	AS N= 31 (22±2.8 years old) Gender: NR	Active standing and 90° shoulder ABD	End-range (90%) of ER and IR ROM	Inclinometer	Test-retest after 1 day	Test-retest: ICC2,3= 0.98 SEM= NR MDC= NR

Abbreviations: AS=asymptomatic; F=female: M=male; ER=external rotation; IR=internal rotation; ABD=abduction; ICC=intraclass correlation coefficient; SEM=standard error of measurement; MDC=minimal detectable change; NR=not reported.

2.10.4. Combined elevation test

Few studies have investigated the reliability of the CET (Table 2.6). There is no consensus of the measurement unit to report to quantify shoulder elevation. The tape measurement method uses the perpendicular distance from the base of the metacarpal of the thumb or third finger to the floor, whereas, the humeral angle method uses the angle between the humeral line and the horizontal line.

Only one study has assessed within-session reliability (Furness, Schram, Cottman-Fields, et al., 2018). Using the tape measurement method, Furness et al. (2018) reported ICCs of 0.99 and SEM values of 1.46 cm. Regarding within-day test-retest reliability, two studies have been reported. Using the tape measurement, Dennis et al. (2008) reported excellent reliability (ICC=0.97) measured twice with a 10-minute interval (Dennis et al., 2008). Similarly, Walker et al. (2016) found excellent reliability (ICC= 0.91-0.95) with an interval of 30 minutes between sessions using the humeral angle method (Walker et al., 2016). However, the different measurement units are unable to compare absolute reliability parameters between studies. Overall, both methods provide similar reliability for the test. However, no studies have assessed the between-day reliability of the CET.

Table 2.7 - Test-retest, intrarater and interrater reliability of combined elevation test.

Author	**Population**	**Movement type/position**	**Chin position**	**Instrument**	**Method**	**Reliability**
Walker et al., 2016	AS competitive swimmers N= 16 (12-24 years old) 8F: 8M	Active shoulder elevation in prone	Chin in contact with the plinth	Inclinometer attached to the right arm (below deltoid insertion) The measure of the humeral angle.	Test-retest reliability after 30 minutes	Test-retest: ICC (2,3) = 0.91-0-95 SEM= 2° MDC90= 5°
Dennis et al. (2008)	AS cricket players N= 10 Age= NR Gender= NR	Active shoulder elevation in prone	The forehead in contact with the floor	Tape measure. The perpendicular distance from the base of the metacarpal of the thumb to the floor.	Test-retest reliability after 10 minutes (same examiner) Interrater within-day (10 minutes)	Test-retest: ICC (model NR) 0.97 SEM= 1.0 cm MDC= 2.7 cm Interrater: ICC (model NR) 0.87 SEM= 1.9 cm MDC= 5.4 cm

Table 2.7 (continued).

Author	**Population**	**Movement type/position**	**Chin position**	**Instrument**	**Method**	**Reliability**
Furness et al. (2018)	AS N= 23 Age= NR Gender= NR	Active shoulder elevation in prone	The forehead in contact with the floor	Tape measure. The perpendicular distance from the base of the third metacarpal to the floor.	Intrarater within-session (pilot study)	Intrarater: ICC (3,1) = 0.99 SEM= 1.46cm MDC= NR

Abbreviations: N=number of participants; AS=asymptomatic; F=female: M=male; ICC=intraclass correlation coefficient; SEM=standard error of measurement; MDC=minimal detectable change; NR=not reported.

2.10.5. Shoulder rotation isometric peak force

The reliability of shoulder rotation force has been widely studied (Table 2.7). Within-session ICCs ranged between 0.93 to 0.98 and SEM values from 3.37N to 7.35N (Cools et al., 2014; Furness et al., 2018). Only Cools et al. (2014) reported MDC values ranging from 7.87 to 22.11N, depending on the body position.

Between-day reliability for shoulder rotation isometric peak force has been calculated from different time points ranging from one day to one week. The results depend on the time between measurements, body position, and the population of interest. Large variability for test-retest reliability (ICC=0.42-1.00) has been reported in the literature (Fieseler et al., 2017, 2015; Hayes, Walton, Szomor, & Murrell, 2002; Holt et al., 2016; Møller et al., 2018; Riemann et al., 2010). Regarding agreement parameters, studies reporting SEM values ranged from 2.59N to 9.08N (Fieseler et al., 2017, 2015; Holt et al., 2016). The lower values were reported by Holt et al. (2016) in asymptomatic subjects measured twice over a week (SEM= 2.59N-2.95N). Whereas the highest values (SEM= 4.84N-9.08N) were found in participants with SIS measured with a similar interval of time (Fieseler et al., 2017). It seems that the population of interest (symptomatic) affects the reliability of force measurements. For the detection of the minimal clinical difference, some studies did not calculate any parameter (Hayes et al., 2002; Riemann et al., 2010), whereas others used different statistical analysis, such as MDC (Holt et al., 2016), LOA (Fieseler et al., 2015; Møller et al., 2018) and CV (Fieseler et al., 2017), which enable comparison between studies.

Similar to ROM and LD length assessments, interrater testing for shoulder rotation force results in worse reliability and agreement parameters compared to intrarater analysis (Cools et al., 2014; Furness et al., 2018; Møller et al., 2018). Furthermore, longer time intervals between measurements increase the error. The different results found may be due to the different methodologies reported. Interestingly, all the studies included measured isometric peak force of the shoulder rotators using a HHD.

Table 2.8 - Test-retest, intrarater and interrater reliability of shoulder rotation isometric peak torque

Author	Population	Movement type/position	Instrument/ contraction	Method	Reliability
(Møller et al., 2018)	AS elite handball players N= 162 players (14-18 years old). 82F: 80M	ER and IR Supine with shoulder 90° ABD	HHD 5-seconds isometric contraction Resting period NR	Test-retest reliability after 1 week (same examiner) Interrater reliability (within-session)	<u>Test-retest</u>: ICC3,1= 0.42-0.79 LOA= -35.7N to 56.5N <u>Interrater</u>: ICC3,1= 0.64-0.78 LOA= -42.2 to 64.4N
(Fieseler et al., 2017)	S (SIS) N= 25 (60.4 ±7.84 years old) 14F: 11M	ER and IR Supine with shoulder 90° ABD	HHD 10 seconds isometric contraction Resting period NR	Test-retest reliability after 1 week (same examiner)	ICC model NR <u>Test-retest (SIS)</u>: ICC= 0.90-0.97 SEM= 4.83N-9.08N CV= 14.3N-21.7N
(Fieseler et al., 2015)	AS handball players N= 22 (21±3.7 years old) 22F	ER and IR Supine with shoulder 90° ABD	HHD 10-seconds contraction Resting period NR	Test-retest reliability after 1 week (same examiner)	<u>Test-retest (Handball players)</u>: ICC model NR= 0.96-0.98 SEM= 3.63N-4.76N LOA= -18.5N to 19.4N <u>Test-retest (Control group)</u>: ICC model NR= 0.99-1.00 SEM= 0N-4.48N LOA= -11.8N to 15.4N
(Cools et al., 2014)	AS N= 30 (22±1.4 years) 15M: 15F	ER and IR sitting, supine and prone with the shoulder in 90° ABD	HHD 5-seconds contraction and 10-seconds rest	Intra and interrater reliability (within-session)	<u>Intrarater</u>: ICC 3, k= 0.93- 0.98 SEM= 3.37-9.48N MDC90= 7.87-22.11N <u>Interrater</u>: ICC 2, k= 0.94-0.99 SEM= 3.54-9.60N. MDC90= 9.82-26.6N
(Hayes et al., 2002)	AS and S N= 19 (29-74 years old) 8M: 11F	ER and IR Supine with shoulder 90° ABD	HHD 5 seconds contraction Resting time NR	Test-retest reliability after 48 hrs (same examiner)	<u>Test-retest</u>: ICC model NR= 0.85-0.92 SEM, MDC=NR
(Riemann et al., 2010)	AS N= 181 (23.3± 4.8 years old) 90F:91M	ER and IR prone (90° of ABD), seated (neutral) and seated (30° of shoulder ABD, scaption).	HHD 5-seconds contraction Resting period NR	Test-retest reliability after 48 hours (same examiners)	<u>Test-retest:</u> ICC3,1= 0.570-0.938 SEM, MDC= NR
(Holt et al., 2016)	AS N=20 (M= 31.2± 9.0, F= 30.1± 8.0 years old) 10F:10M	ER and IR in standing with shoulder in neutral position (0°)	HHD 5-seconds contraction and 10 seconds rest	Test-retest reliability 1 week (same examiner)	<u>Test-retest</u>: ICC3,1= 0.94-0.96 SEM= 2.59N-2.95N MDC95= 7.19N-8.18N

Table 2.8 (continued).

Author	Population	Movement type/position	Instrument/ contraction	Method	Reliability
(Furness, Schram, Cottman-Fields, et al., 2018)	AS N=21 (Male 31.2± 9.0 years old, Female 30.1± 8.0 years old) 10F:10M	ER and IR in prone with shoulder 90° ABD	HHD 3-seconds contraction and 10-seconds rest	Intrarater and interrater reliability (within-session)	Intrarater: ICC3,1= 0.97-0.98 SEM= 7.08-7.35N MDC: NR Interrater: ICC3,2= 0.80-0.96 SEM= 8.88-24.00N MDC=NR
(Conceição et al., 2018)	AS swimmers N=29 (16.2 ± 1.2 years old) 21F:8M	ER and IR in prone with shoulder 90° ABD	HHD 5-seconds contraction and 30-seconds rest	Test-retest reliability (same examiner) 7 days apart.	Intrarater: ICC3,1= 0.92-0.98 SEM= 5.21-6.55N MDC= 14.45-18.16N

Abbreviations: S=symptomatic; AS=asymptomatic; SIS=shoulder impingement syndrome; F=female: M=male; ER=external rotation; IR=internal rotation; ABD=abduction; HHD=hand-held dynamometer ICC=intraclass correlation coefficient; SEM=standard error of measurement; MDC=minimal detectable change; LOA=limit of agreement; CV=coefficient of variation; NR=not reported.

2.10.6. Handgrip peak force

Due to a large number of studies reporting the reliability of HGF, only the studies in which testing reliability was the main aim were included in the analysis (Table 2.8). Also, studies using correlation coefficients instead of ICC in their statistical analysis were excluded. It has been suggested that using correlation coefficient for reliability studies is not appropriated, as the extent of the differences between tests (higher or lower) is not reflected (Essendrop et al., 2001; Trevethan, 2017). For within-session reliability, ICCs varied from 0.96 to 0.99 (Gerodimos & Karatrantou, 2013; Lindstrom-Hazel et al., 2009; Stephens et al., 1996). Regarding absolute reliability, SEM and MDC are either not reported or expressed in different units, such as Lb and Kg, which impedes the comparison between studies.

Regarding test-retest analysis, no studies have reported within-day reliability. For between-day reliability, HGF has been calculated from different time points ranging from 1 to 66 days. ICC values for test-retest reliability ranged between 0.72 to 0.99 (Clerke et al., 2005; Essendrop et al., 2001; Gerodimos, 2012; Gerodimos & Karatrantou, 2013; Molenaar et al., 2008; Silva et al., 2019; Svensson et al., 2008). The high consistency in reliability across studies is probably because almost all the studies follow the guidelines from the American Society of Hand Therapists (Mathiowetz et al., 1984). Regarding agreement parameters, there is no consensus on which measurement unit to report; Kg or N. Regarding SEM, these studies reported values ranging from 0.42Kg to 2.75Kg and 3.4N to 20.6N. For the detection of minimal detectable difference, several studies did not calculate any parameter (Clerke et al., 2005; Gerodimos &

Karatrantou, 2013). Some studies reported MDC values ranging from 4.71 to 4.80 Kg (Silva et al., 2019) and 9.3 to 51.7N (Svensson et al., 2008; (Ties) Molenaar et al., 2008). Whilst, others, reported LOA (Essendrop et al., 2001; Gerodimos, 2012). The differences in some studies may probably be due to the interval of time between measurements and the different age groups measured (range 4-82 years).

Similar results were found in studies measuring intra-examiner and inter-examiner reliability (Lindstrom-Hazel, Kratt, & Bix, 2009; Peolsson, Rune Hedlund, Birgitta Ob, 2001; Silva et al., 2019; Stephens, Pratt, & Michlovitz, 1996). This could be explained because the examiner skills are not involved in the measurement of HGF and depend more on participant performance. No studies have investigated the within-day reliability of HGF.

Table 2.9 - Test-retest, intrarater and interrater reliability of handgrip peak force.

Author	**Participants**	**Body and Shoulder positioning**	**Contraction**	**Instrument**	**Statistical method**	**Reliability outcome**
(Silva et al., 2019)	AS N= 100 (82.32 ± 8.12 years old) 62F: 38M	Sitting with back and arms supported with the shoulder in a neutral position	NR	Handgrip dynamometer	Interrater (after 2 to 7 days interval)	Interrater: ICC2,3= 0.96-0.97 SEM= 1.70Kg-1.73Kg MDC95= 4.71Kg-4.80Kg
(Gerodimos, 2012)	AS basketball players N= 90 (9.85-26.06 years old) Gender= Male	Sitting with the shoulder in a neutral position	5s contraction with 60 s of rest	Handgrip dynamometer (Jamar)	Test-retest after 1 day	Test-retest: ICC model NR= 0.94-0.99 SEM= 0.82Kg-1.60Kg LOA95= -4.35Kg-4.79Kg
(Clerke et al., 2005)	AS N= 149 (13 to 17 years old) 75F: 74M	Sitting with shoulder in neutral position (ASHT protocol)	2.5 to 3s contraction with 15s rest	Handgrip dynamometer (Grip Track)	Test-retest after 1 to four weeks (mean 15.51 days)	Test-retest: ICC3,1=0.95-0.97 SEM= 1.63Kg-2.75Kg.
(Peolsson, Rune Hedlund, Birgitta Ob, 2001)	AS N= 32(20-64 years old) 24F: 8M	Standing with the shoulder in a neutral position	5s contraction, rest period NR	Handgrip dynamometer (Jamar)	Intrarater and interrater (within 1-week)	Test-retest: ICC model NR= 0.94-0.98 SEM and MDC= NR Interrater: ICC model NR=0.98 SEM and MDC= NR
(Stephens et al., 1996)	AS N= 48 (32.4 ± 10.51 years old) Gender= NR	Sitting with shoulder in neutral position (ASHT protocol)	Contraction time NR, 30s rest period	Handgrip dynamometer (Jamar)	Intrarater (within-session)	Intrarater: ICC3,1= 0.96-0.98 SEM= 4.09Lb-5.24Lb

Table 2.9 (continued).

Author	**Participants**	**Body and Shoulder positioning**	**Contraction**	**Instrument**	**Statistical method**	**Reliability outcome**
(Essendrop et al., 2001)	AS N= 19 (35 ± 6.9 years old) 13F: 6M	Sitting with the shoulder in a neutral position	NR	Handgrip dynamometer (Jamar)	Test-retest after 1 week	Test-retest: ICC model NR= 0.98 LOA= -60.1-26.5N
((Ties) Molenaar et al., 2008)	AS N= 104 (4-12 years old) 59F: 45M	Sitting with the shoulder in neutral position (ASHT protocol)	NR	Lode dynamometer (Electronic Jamar-like dynamometer)	Test-retest after a mean of 29 days (range 3-66 days)	Test-retest: ICC model NR= 0.95-0.97 SEM= 10.5N-11.5N MDC 95= 29.2N-32N
(Svensson et al., 2008)	AS N= 58 (6-14 years old) 32F: 26M	Sitting with the shoulder in a neutral position (ASHT protocol)	10s contraction and 2min of rest.	Dynamometer Grippit	Test-retest after 1 week	Test-retest (mean of 3 trials): ICC 2,1= 0.72-0.97 SEM= 3.4N-20.6N MDC 95= 9.3N-57.1N
(Lindstrom-Hazel et al., 2009)	AS N= 73 (6-14 years old) Gender= NR	Sitting with the shoulder in neutral position (ASHT protocol)	NR	Jamar hand dynamometer	Interrater reliability (within-session)	Interrater: ICC1,1= 0.99
(Gerodimos & Karatrantou, 2013)	AS Wrestlers N= 45 Age= NR Gender= Male	Sitting with the shoulder in a neutral position (ASHT protocol)	5s contraction and 1min of rest.	Jamar hand dynamometer	Test-retest after 1 day Intrarater (same session)	Mean of 3 trials Test-retest: ICC3,1= 0.96-0.99 SEM= 0.70Kg-0.75Kg Intrarater: ICC3,1=0.98-0.99 SEM= 0.43Kg-0.70Kg

Abbreviations: N=number of participants; AS=asymptomatic; F=female: M=male; ASHT=American Society of Hand Therapists; ICC=intraclass correlation coefficient; SEM=standard error of measurement; MDC=minimal detectable change; NR=not reported.

2.10.7. Summary reliability of the outcome measures

Overall, there is no consensus on the best method to assess shoulder musculoskeletal risk factors. Results vary due to different measurement devices, the number of examiners, the interval of time between measurement, movement type (passive or active), testing position, and the population of interest (symptomatic and asymptomatic). In general intrarater reliability provides better results than interrater, thus the same researcher or clinician should preferably perform the measurements on the patients to decrease the probability of measurement error

(Mullaney et al., 2010). Regarding test-retest reliability, it was negatively influenced by longer intervals of time between measurements. This is supported by the literature, which suggests that measures performed close in time are commonly more correlated than measurements performed farther apart (Guo et al., 2013). Finally, considering that different methodologies provide different results, researchers and clinicians should use a consistent methodology throughout the time when assessing changes in the same individuals.

There are methodological inconsistencies and limitations in studies reporting relative and absolute reliability values. For example, studies reporting relative reliability (ICC) did not report the model, type and form used in their analysis. There are different forms of ICC, which can lead to different results when applied to the same data (Trevethan, 2017). Therefore, it is suggested that the ICC (model, form, type) should be accurately described and reported by the researchers to avoid different interpretations (Koo & Li, 2016). With regards to absolute reliability parameters, some studies did not include them in the analysis. It has been stated that determining reliability only based on ICC values may lead to erroneous conclusions, as ICC is affected by the variability between subjects (Atkinson & Nevill, 1998; De Vet et al., 2006). A high ICC may be due to a heterogeneous sample (i.e. high variability in physical qualities being measured), regardless of the poor trial to trial consistency (Lexell & Downham, 2005). For this reason, parameters such as SEM, MDC, LOA and CV are often reported along with the ICC. These parameters are not effected by subjects´ variability and are easy to interpret by clinicians, as they are expressed in the actual scale of measurement (De Vet et al., 2006). However, there is no consensus on which parameters to report, which would enable the comparison between all the studies. Understanding the reliability of the outcome measures allows researchers and clinicians to use the best method based on informed decisions.

Chapter 3

Methodology

This thesis is divided into two stages. The first stage consists of a pilot study to determine the reliability of the outcome measures, while the second stage assesses the impact of training loads on factors associated to shoulder pain in swimmers. The second stage includes four studies: 1) The acute impact of training intensity on shoulder physical qualities, 2) The acute impact of a high-intensity training session on shoulder physical qualities in different levels of competition, 3) The cumulative effects of training loads on shoulder physical qualities and wellness factors, and 4) The recovery of physical qualities after a training session. This chapter includes the methodology of the pilot study, which provides the basis for the main tests undertaken in the second stage.

Reliability of Tests of Shoulder Function

3.1. Aims

The aims of this study are:

1. Examine the intrarater and test-retest reliability of tests that assess the shoulder function.
2. Establish the final tests for the following studies.
3. Assess the symmetry between the dominant and non-dominant side.

3.2. Introduction

Athletes are often assessed to identify potential risk factors that may predispose them to injury (Dennis et al., 2008). Clinicians routinely assess changes in the status of patients over time to evaluate the treatment effectiveness and progression, to quantify the amount of change on risk factors, and to assess readiness to train and compete (Cools et al., 2014). As discussed in Sections 2.7 and 2.5.2.2 of Chapter 2, modifiable risk factors have received much interest in the athletic population as they might help to identify athletes at risk of injury (Eckard et al., 2018; Windt & Gabbett, 2017). It is proposed that modifiable risk factors are dynamically changing as a result of the training loads applied, and thus the risk of injury (Windt & Gabbett, 2017). Importantly, they can also be changed through therapeutic interventions (Section 2.9, Chapter 2). Considering this, the understanding of modifiable risk factors might have the potential to reduce the risk of injury.

Shoulder pain is frequent among swimmers with a prevalence reported as high as 91% (Sein et al., 2010). As a result of this, shoulder pain is the main cause of missed or modified training in this population (Chase et al., 2013; Weldon & Richardson, 2001). Several potential musculoskeletal modifiable risk factors for shoulder pain in swimmers have been proposed, such as impairments in shoulder range of motion (ROM), flexibility, and strength (discussed in Section 2.5 of Chapter 2). Since training loads seem to be the main cause of injuries, including shoulder pain in swimmers (Section 2.3 of Chapter 2), quantifying how these factors change in response to training might help to identify swimmers at risk.

Before assessing the changes in these factors, clinicians and researchers need reliable tools and methodologies to accurately assess the status of the athlete (Møller et al., 2018). If the assessment has a considerable amount of measurement error, it would be difficult to establish a relationship between the assessment and the possible risk of injury. It is therefore recommended that the reliability of the outcome measures need to be established before the evaluation of the study subjects (Holt, Raper, Boettcher, Waddington, & Drew, 2016). Reliability concerns the extent to which repeated measurements provide similar results over time (De Vet et al., 2006). Reliability of outcome measures provide clinicians with the information to differentiate between a real change observed or a measurement error (De Vet et al., 2006). This allows for the use of the tests with confidence when assessing the effects of an intervention or to identify athletes at risk of injury.

Considering the large number of musculoskeletal factors for shoulder pain in swimmers (Section 2.5 of Chapter 2), assessing all of the factors is not feasible in the clinical setting. As discussed in Section 2.4.1 of Chapter 2, measures have to be chosen according to the sports context, objectives, financial constraints, and psychometric characteristics of the measurement tools. Six physical qualities were included in this thesis. The rationale for their choice was that in combination they assess important features, such as shoulder ROM or flexibility, shoulder force or control, and upper limb function (Figure 3.1). The high amount of repetitive shoulder movements during swimming can lead to several musculoskeletal adaptations, which might increase the risk of injury (reviewed in Section 2.5.2.2 of Chapter 2).

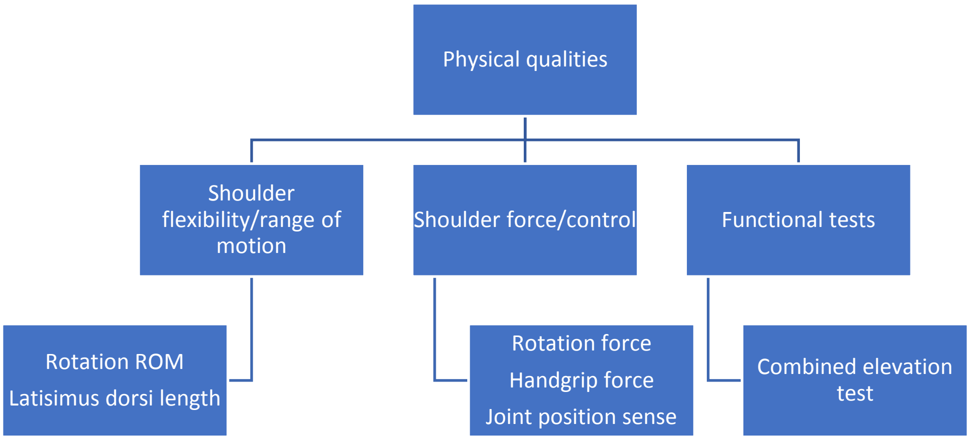

Figure 3.1 - Shoulder physical qualities included in this thesis.

The repetitive load of propulsive muscles (i.e. shoulder internal rotators, extensors, and adductors) can increase their muscular stiffness and thus the resistance to elongation (Wilson et al., 1994). Restrictions in shoulder flexion (Tate et al., 2012) and rotation ROM (Tate et al., 2012; Walker et al., 2012) have been reported as potential risk factors for shoulder pain in swimmers. These two movements are essential for an adequate stroke technique. Before the propulsive phase, sufficient shoulder flexion is necessary to provide the maximum available reach, which is mainly provided by the latissimus dorsi (LD) length (Herrington & Horsley, 2014). Whilst, shoulder rotation ROM is necessary throughout the stroke. Especially, an adequate shoulder external rotation (ER) ROM is needed during the mid-recovery phase when the arm is abducted at 90° (Pink et al., 1991). Importantly, the alterations of these movements have been associated with alterations in scapular kinematics, and consequently, shoulder pain.

The repetitive activity of propulsive muscles during swimming can also result in muscle fatigue and consequently increase the risk of shoulder injury. As a result of the predominant internal rotation (IR) forces during swimming, the assessment of shoulder internal rotator force is necessary. Decreases of IR force have been found in swimmers with shoulder pain (Bak & Magnusson, 1997; Tate et al., 2012). Although shoulder ER are less activated than IR during swimming, they control the IR forces during the stroke (Pink et al., 1991). Reduction in ER endurance have been associated to shoulder pain in this population (Beach et al., 1992). For these reasons, shoulder rotation force will be investigated. Rotator cuff function can also be indirectly assessed by the handgrip force (HGF) (Horsley et al., 2016). Furthermore, this test provides an assessment of performance in swimmers (Geladas et al., 2005; Zampagni et al., 2008). Finally, it has been shown that swimming can result in fatigue and negatively affect shoulder joint position sense (JPS) (Higson et al., 2018; Matthews et al., 2017), potentially increasing the risk of injury. Considering this, JPS was included to assess the dynamic stability of the shoulder.

Since it is more specific for swimmers, the combined elevation test (CET) was chosen to assess the upper quarter function. This test measures scapula retraction and shoulder flexion (Blanch, 2004). Additionally, it assesses thoracic extension ROM; decreases of thoracic extension ROM have been found in subjects with shoulder pain (Hunter et al., 2020). More importantly, the movement performed in this test is essential for achieving a high elbow position during a swimming stroke (Blanch, 2004), which is the main swimming error reported (Virag et al., 2014).

Reliability of shoulder physical qualities

A search was done in the literature for studies reporting the reliability of the tests assessing shoulder function for this thesis (Section 2.10 of Chapter 2). Overall, there is no consensus on the best assessment method, and the results vary due to different measurement devices, the number of examiners, the time interval between measurements, testing position, and the population of interest. Furthermore, the reliability of the tests is negatively influenced by longer intervals of time between measurements. Considering future studies, this thesis will assess the impact of a single session or weekly training loads on these factors; it is therefore important to determine the measurement error at different time points. This information will help to determine with confidence whether the changes in shoulder tests are real or due to measurement error.

Importantly, methodological issues were found in some studies, including the no report of absolute reliability values, such as standard error of measurement (SEM) and minimal detectable change (MDC). It is important to report these parameters as they are expressed in the actual scale of measurement (De Vet et al., 2006) and help to express the clinical meaningfulness of the results (Riemann & Lininger, 2018b). Also, shoulder ROM, rotator force, and HGF have been widely studied, whereas, few studies have assessed LD length, the CET, and shoulder JPS reliability. To our knowledge, no studies have reported within-session and between-day reliability of shoulder JPS, within-day reliability of the CET, and within-day reliability and between-day reliability of LD length. Thus, further investigation is needed to assess the reliability of these physical qualities.

3.3. Methods

The Guidelines for Reporting Reliability and Agreement Studies (GRRAS) were followed to improve the quality and transparency of this study (Kottner et al., 2011). The GRRAS checklist was included in Appendix 3.

Participants and recruitment

Participants were recruited during September-November, 2018. Recruitment methods involved in-person recruitment and advertisement posters placed around the Allerton site of Salford University. Participants interested in participating in the study voluntarily contacted the researchers by email. The researchers replied to the email and provided the participants with an information sheet. Once participants accepted to participate, an appointment to undertake the clinical examination was arranged. A sample of 10 healthy participants (6 females and 4 males; age = 23.8 ± 3.0 years) were included in this study. The number of participants was based on a convenient sample for the main researcher to check the methodology. Table 3.1 shows the demographic characteristics of the participants. Exclusion criteria included history of shoulder or neck pain or injury in the past three months or at the time of data collection, previous shoulder or neck surgery, shoulder or elbow ROM restriction, and current participation in overhead sports at a competitive level (more than three training sessions per week) (Cools et al., 2014; Vafadar et al., 2016).

Table 3.1 - Participant characteristics

	Female	**Male**	**Total**
Number of participants	6	4	10
Age (years)	24.3 ± 2.3	23.0 ± 4.1	23.8 ± 3.0
Height (cm)	165.6 ± 7.2	182.1 ± 7.4	172.2 ± 11
Body mass (Kg)	61.6 ± 2.3	78.4 ± 14.4	68.3 ± 12.2

Mean ± standard deviation

Ethics

As the project involved the assessment of human subjects, the ethical framework “Ethical principles for medical research involving human subjects” (Declaration of Helsinki 2013) was followed throughout the PhD project. Also, all data obtained during this project was subjected to the provisions of the General Data Protection Regulation guidelines of 2018. The study was approved by the University of Salford Ethics Committee (HSR1718-100) on the September 13, 2018 for adult participants (Ethical approval form p.204). For all the studies, written informed consent was obtained from each participant before data collection.

Procedures

Data collection was performed during October-November, 2018 in the University of Salford Human Performance Laboratory. All the tests were performed by one physiotherapist with eight years of clinical experience (main researcher). On the testing day, general demographic information of participants, such as gender, age, arm dominance, height, body mass, and forearm length were recorded. A screening to determine any elbow or shoulder movement restriction was also performed. Before the testing procedure, a standard warm-up consisting of multiplanar shoulder movements with an elastic band was performed (Cools et al., 2014). The warm-up included 10 repetitions of external and internal rotation (at 0° of shoulder abduction) with a yellow TheraBand. Immediately after the warm-up, baseline measurements were recorded in the following order: shoulder ROM, shoulder JPS, shoulder rotation isometric peak force, LD length, CET, and HGF. The tests were standardised assessing the dominant arm first. Three subsequent testing trials of each test were performed in both arms and the results were averaged for further analysis. The same testing procedure was repeated 2 hours and one week later.

Measurement instruments and outcome measures

The measurement instruments are shown in Figure 3.2. The iPhone app ‘Goniometer Pro’ digital inclinometer application for the iPhone was used to measure shoulder ROM, JPS, LD length, and CET. Mobile telephone applications are widely used in clinical practice (Green et al., 2013; Matthews et al., 2017; Shin et al., 2012). They are reliable and valid compared to the universal goniometer (Jones et al., 2014; Melian et al., 2017; Werner et al., 2014). Specifically, Melian et al. (2017) found that the ‘Goniometer Pro’ digital inclinometer application was reliable and valid.

Regarding force assessment, a hand-held dynamometer (HHD) (Hoggan MicroFET2; Scientific LLC, Salt Lake City, UT, USA) was used to measure shoulder-rotation isometric peak torque, which is reliable and valid in different populations compared to the gold standard isokinetic dynamometry (Stark et al., 2011). Also, because of its portability and low cost, it is often used in clinical practice. For the HGF assessment, a hand dynamometer was used (Takei

Physical Takei Physical Fitness test Grip-A; Grip Strength Dynamometer Japan). Hand dynamometers are the gold standard tool for assessing HGF and have been shown to be reliable in several populations and positions (Cronin et al., 2017). Finally, for the LD length assessment, pressure biofeedback (Stabilizer, pressure biofeedback, Chattanooga) was used to supervise the posterior pelvic tilt during the procedure.

Figure 3.2 – Measurement instruments: a) Goniometer Pro app; b) handgrip dynamometer; c) pressure biofeedback; d) hand-held dynamometer.

<u>Shoulder rotation range of motion</u>

Although there is no consensus on the best method to assess shoulder ROM, the methodology chosen was based on the best available evidence. Participants were situated in a supine position with 90° shoulder abduction, 90° elbow flexion, the forearm in full supination, and wrist in a neutral position with the olecranon 10 cm from the edge of the plinth (Herrington et al., 2010). Full supination allowed the iPhone to be placed on a bony surface rather than the muscle belly, which can affect the accuracy of the recordings. Body positioning has been shown to influence ROM recordings; gravity dependant positions, such as standing or sitting, may limit the available ROM due to greater muscular activation (Muir et al., 2010). Supine position has been recommended, because it does not depend on gravity, providing greater trunk and scapular stabilization (Cools et al., 2014; Muir et al., 2010).

A towel roll was placed under the humerus to ensure a correct alignment in the frontal plane (Furness et al., 2015; Kolber et al., 2011). This was based on visual inspection, making sure that the humerus was levelled to the acromion process. Shoulder ROM was assessed actively. Researchers have shown that active assessment is more reliable than passive, as the latter depends on the ability of the examiner to determine the end-feel (Muir et al., 2010). Furthermore, active ROM was measured, because it reflects the ability of swimmers to use their available movement (Holt, Boettcher, Halaki, & Ginn, 2017).

To assess IR ROM, the scapular stabilization method was performed (Figure 3.3, a). This method is more reliable than other methods, such as humeral head and visual stabilization (Wilk et al., 2009). The aim of the scapular stabilization method is to assess pure glenohumeral rotation, avoiding compensatory movements of the scapulothoracic joint (Wilk et al., 2009). The examiner palpated the coracoid process of the examined scapula with the thumb and the spine of the scapula posteriorly with the four fingers. The end-range was defined as the point that the coracoid process of the scapula was perceived to move under the researcher's thumb, which indicates compensatory scapulothoracic movement (Wilk et al., 2009). Participants were instructed to actively internally rotate the limb and stop when the coracoid movement was perceived. The examiner placed the iPhone in the lateral border of the radius, proximal to the crease of the radioulnar joint. The examiner ensured that 90° shoulder abduction was maintained during the whole procedure, avoiding any elbow extension or shoulder horizontal extension (Furness et al., 2015).

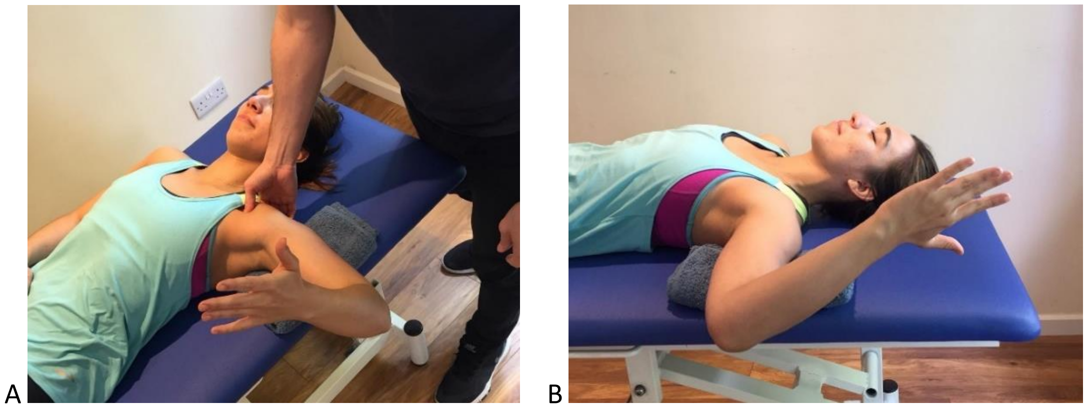

Figure 3.3 – Shoulder rotation range of movement: a) internal rotation; b) external rotation.

For the ER ROM assessment (Figure 3.3, b), the end-range was determined by the available range without any stabilization (Furness et al., 2015; Higson et al., 2018). Researchers have reported that ER is less affected than IR by the stabilization (Boon & Smith, 2000). Participants were instructed to actively rotate the limb back until the available end-range without extending or lifting the lumbar or thoracic spine during the measurement (Kolber et al., 2011). The examiner placed the iPhone on the lateral border of the ulna, proximal to the crease of the radioulnar joint.

Latissimus dorsi length

LD length was assessed measuring shoulder flexion ROM in the supine position. Several procedures have been reported in the literature (Borstad & Briggs, 2010; Feijen, Tate, Kuppens, Struyf, et al., 2020; Herrington & Horsley, 2014; Shahidi et al., 2012; Tate et al., 2012). Despite this, LD length assessment was based on the protocol of Herrington and Horsley (2014), because it has shown the highest reliability.

Participants were positioned in supine with hips flexed to 45°, knees flexed to 90°, and feet flat on the plinth. A pressure biofeedback (Stabilizer, pressure biofeedback, Chattanooga) inflated at 20 mm Hg was placed under the lumbar spine. Participants were instructed to maintain full posterior pelvic tilt during the procedure, “pushing biofeedback down or keeping the back flat”. The examiner visually ensured that the cuff pressure was maintained during the measurement. Importantly, the amount of pressure achieved in the first attempt was recorded and repeated in the following trials. This was performed to ensure that shoulder flexion ROM was not affected by the amount of pressure applied by the participant.

The examiner held the shoulder in 90° flexion (with the elbow flexed to 90°) and in ER (aligned to the sagittal plane, palm facing medially, and olecranon facing down). Next, the shoulder in the sagittal plane was passively flexed until the flexion end-feel range was perceived (Figure 3.4). The initial limb rotation was maintained during the whole measurement without allowing any medial rotation of the arm. The examiner placed the iPhone on the posterior surface of the upper arm, proximal to the olecranon.

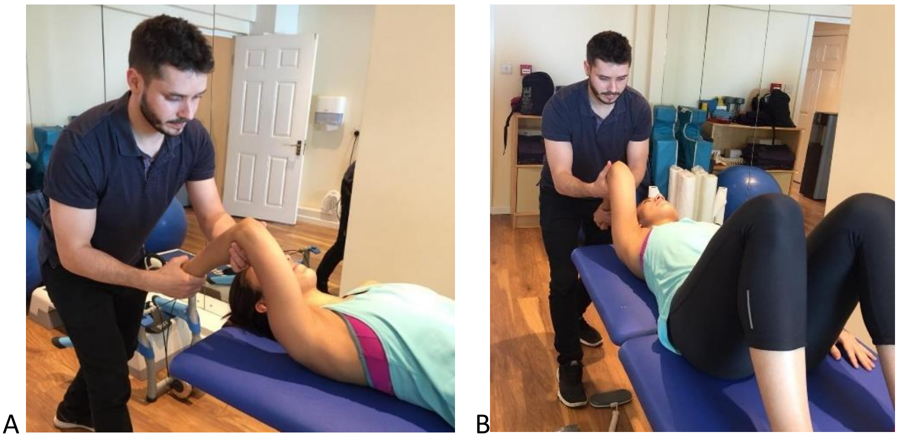

Figure 3.4 – Latissimus dorsi length: a) lateral view; b) sagittal view.

<u>Joint position sense</u>

JPS is assessed by the active reproduction of a joint position (Sahin et al., 2017). We followed the protocol of Herrington et al. (2010) to assess JPS. This protocol has been shown to be reliable and has been used in several studies (Green et al., 2013; Higson et al., 2018; Morgan & Herrington, 2014). Regarding the measurement instrument, inclinometers, motion analysis systems, isokinetic dynamometers, and digital cameras have been used to assess JPS. We chose the iPhone inclinometer because it is easy to use in the clinical setting and has been shown to be a reliable tool for the assessment of shoulder JPS in swimmers (Higson et al., 2018).

Participant positioning was the same as in the shoulder ROM measurement (Figure 3.5). The testing position of 90° shoulder abduction was used to recreate the limb position of swimmers during the freestyle stroke. JPS error is affected by the angle in which the measurement is taken; there is lower error in end-range than mid-range position (Herrington et al., 2010; Janwantanakul et al., 2001; Morgan & Herrington, 2014). Researchers suggest that lower errors in end-range are due to the greater feedback provided by the skin and capsule-ligamentous structures tension. For this reason, JPS was measured at both mid and end-range of shoulder rotation. The target angles included: 90% of total ER ROM, 20% of total ER ROM, and 90% of total IR ROM.

Participants were instructed to close their eyes during the measurement. The limb was passively rotated to the first target angle and held in that position for five seconds. Next, they were instructed to remember this position, and the examiner passively returned the limb to the initial position. Participants actively returned the limb to the target angle; they were instructed to say "OK" when the angle was achieved; and they held the position for five seconds, while the angle was measured. The examiner placed the iPhone on the lateral border of the ulna for ER and the lateral border of the radius for IR, proximal to the crease of the radioulnar joint. The number of degrees away from the target angle indicated the absolute error score. Absolute error scores (magnitude only) rather than relative error scores (magnitude and direction) were chosen as their assessment is more reliable and are less time consuming (Relph & Herrington, 2015).

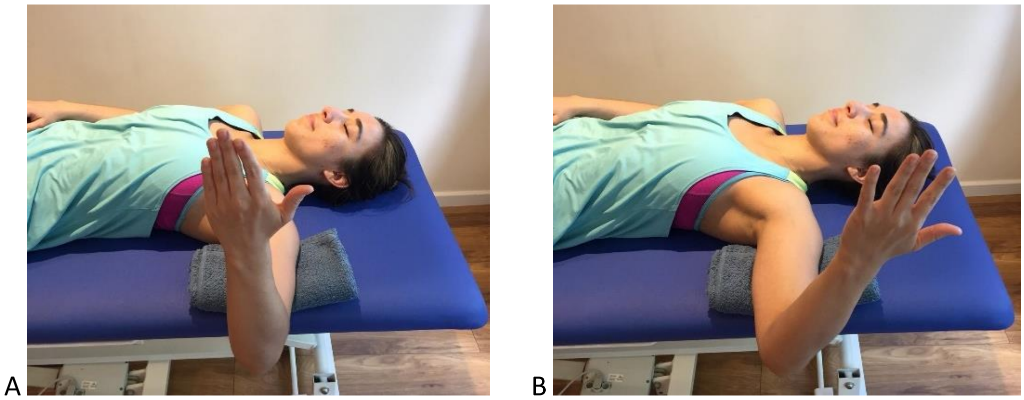

Figure 3.5 – Shoulder joint position sense: a) initial position; b) final position for mid-range external rotation.

<u>Combined elevation test</u>

The CET is a screening test used to assesses the strength and mobility of the upper limb and the thoracic spine (Dennis, Finch, Elliott, & Farhart, 2008). The CET was performed using the Blanch et al. (2004) protocol in a swimmer population. Participants were positioned in prone with the shoulders in full flexion, elbows extended, and palms facing down into a streamline swim position (Figure 3.6). Participants were instructed to lift the limbs as high as possible from the plinth while keeping elbow extension. They kept the forehead, chest, legs, and feet in contact with the surface during the whole procedure (Blanch, 2004). Forehead contact was used rather than chin contact, as the latter has been found to limit shoulder flexion and scapular retraction movement (Allen et al., 2017).

Once the final position was achieved, the examiner placed the iPhone on the posterior surface of the forearm of the hand on top, proximal to the wrist crease. The angle between the line of the humerus and the horizontal was measured. Two techniques have been reported to measure the CET. Blanch et al. (2004) used the humeral angle method, which measures the angle between the line of the humerus and the horizontal plane. Other studies (Dennis, Finch, McIntosh, & Elliott, 2008; Furness, Schram, Corea, Turner, & Cairns, 2018) have used the tape method, which measures the perpendicular distance between the base of the fifth metacarpal or the ulnar styloid process and the floor. Although Allen et al. (2017) found a strong correlation between these two techniques (r= 0.93, p < 0.001), we chose the humeral angle method, because it has been used in swimmers (Blanch, 2004; Walker et al., 2016).

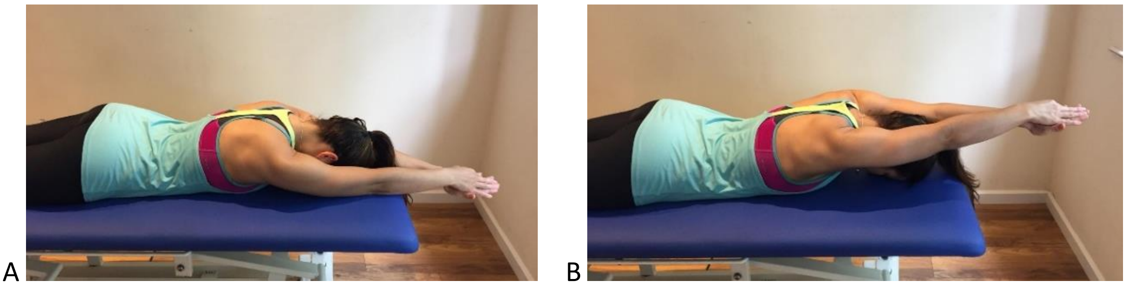

Figure 3.6 – Combined elevation test: initial position (a), final position (B).

Shoulder rotation isometric peak torque

Shoulder internal and external peak force were tested. Participants were tested in the same position as JPS and ROM measurements, except that the forearm was placed in a neutral position, rather than in full supination. The testing position of 90° shoulder abduction recreates swimmers mid-pull-through and recovery phases performed during the stroke (McLaine, Ginn, et al., 2018). Before testing, one submaximal trial was performed to ensure correct technique (McLaine, Ginn, et al., 2018). The HHD was placed on the palmar surface of the forearm for IR and on the dorsal aspect of the forearm for ER (Figure 3.7), proximal to the radioulnar joint crease (Cools et al., 2014). Participants were instructed to push against the HHD as hard as possible for three seconds, with a resting period of 10 seconds (Cools et al., 2014). Force was recorded in newtons.

Figure 3.7 – Shoulder isometric peak force: a) internal rotation; b) external rotation.

Most of the literature investigating the reliability of shoulder force use newtons as the measurement unit. Considering this, force was reported in newtons to make comparisons with the literature. However, it has been shown that the development of force is affected by lever arm length (Krause et al., 2007) and body mass (Riemann et al., 2010). Therefore, force was converted into torque (in newtons meter) by multiplying the force (in newtons) by the lever arm length (meters) of the dominant and non-dominant sides. Next, torque was normalized to body mass (Nm/Kg) and expressed as the percentage of change between measurements. This will allow more accurate comparisons between participants and for future studies. Lever arm length was measured from the olecranon process to the proximal aspect of the styloid process of the ulna (Holt et al., 2016). Despite that force will be measured isometrically, it has been suggested that to accurately report muscle output using a hand-held dynamometer, it needs to be expressed as torque (Alvarenga et al., 2019; Garcia et al., 2021). For this reason, the term isometric torque will be used to report the results of our studies.

Handgrip peak force

HGF was quantified measuring the amount of static force the hand can perform by squeezing a hand dynamometer (Massy-Westropp et al., 2011). HGF was measured with the limb in two different positions: neutral and 90° of shoulder abduction (Figure 3.8) (Horsley et al., 2016). Participants were standing with their feet placed a shoulder-width apart, elbow in 90° flexion and mid-prone and wrist in neutral flexion-extension and radio-ulnar deviation (Horsley et al., 2016). The examiner instructed participants to squeeze the handle of the handgrip dynamometer as hard as possible and hold for five seconds, with a resting period of 15 seconds between measurements (Mathiowetz, 2002; Tsang, 2005). The grip was adjusted to the participant´s comfort.

The average of three scores was used for further analysis. The mean of the three trials has been shown to be more reliable than the maximum value of three trials for HGF assessment (Mathiowetz, 2002; Tsang, 2005). Considering that researchers have shown that HGF is affected by body position (El-Sais & Mohammad, 2014), the standing position was consistent during all the measurements. Most of the literature investigating the reliability of HGF use kilograms as the measurement unit. Because of this, HGF was reported in kilograms to make comparisons with the literature. As previously discussed, the development of force is affected by body mass. Therefore, HGF was normalized to body mass (Kg/body mass) and expressed as the percentage of change between sessions.

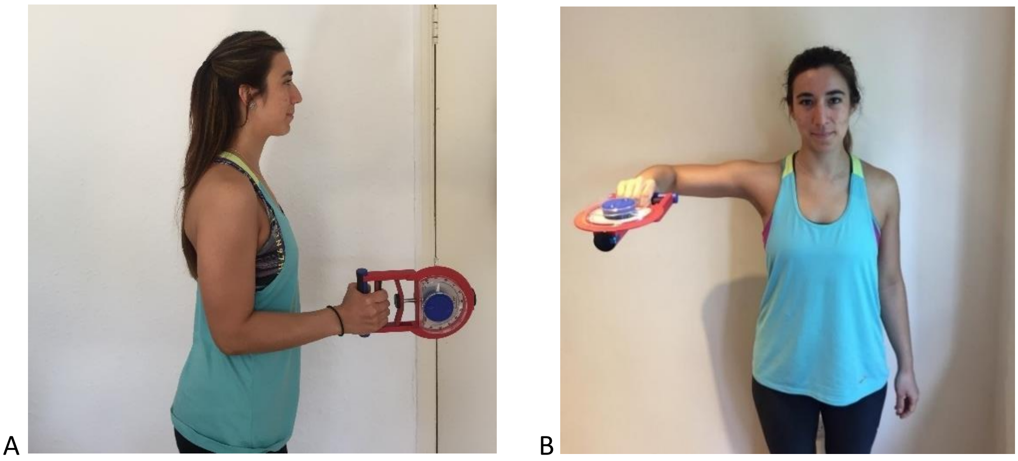

Figure 3.8 – Handgrip force: a) 0° shoulder abduction; b) 90° shoulder abduction.

Statistical analysis

For statistical analysis, SPSS (version 25 for Windows; Inc, Chicago, IL) was used. The analysis of participants was performed separately on dominant and non-dominant sides.

1) Intrarater and test-retest reliability analysis

For the first objective, intrarater and test-retest reliability of the shoulder tests were calculated. Data from the initial session was used for intrarater reliability analysis. Intrarater reliability was calculated to assess the consistency of the results obtained by the examiner in the same session. Test-retest reliability was calculated from repeated measurements performed at different time points: two hours and one week. Test-retest reliability was calculated to assess how time influences the reliability of the outcome measures. Data from the initial and two-hour sessions was used for within-day reliability. The rationale for this time frame is because a normal swimming session lasts around two hours (Higson et al., 2018). This information will determine whether the changes in the physical qualities after a swimming training session are real or due to measurement error (Chapters 4, 5, and 7). Data from the initial and one-week sessions was used for between-day analysis. This will determine whether the effects of cumulative swimming training loads during a week are a result of measurement error or due to a real change (Chapter 6) (Figure 3.9).

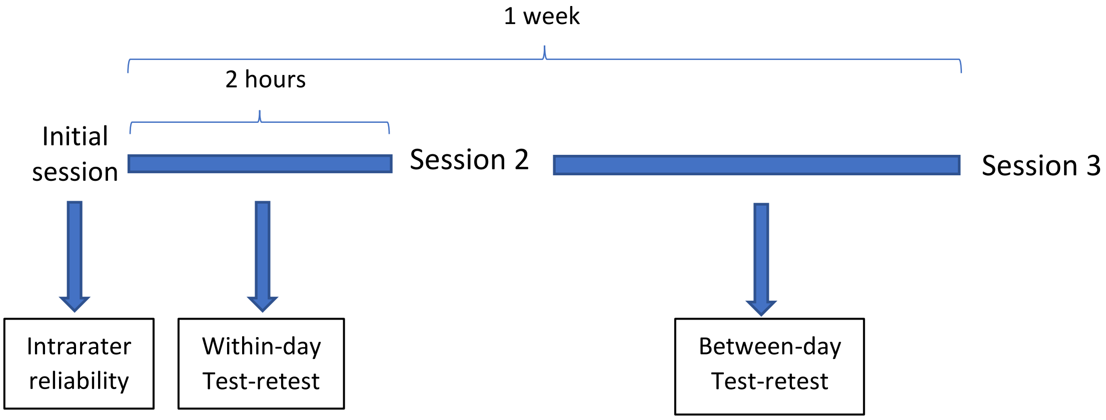

Figure 3.9 - Methodological approach of the pilot study

Statistical methods to report reliability

Three statistical methods were used to report reliability: relative reliability, absolute reliability, and systematic bias (Riemann & Lininger, 2018a). Each method will be discussed.

Relative reliability

To determine relative reliability, intraclass correlation coefficients (ICC) with a 95% confidence interval (CI) were calculated (Lexell & Downham, 2005). The ICC is denoted by two numbers: the first number indicates the model (testers) and the second number the form (number of measurements) (Riemann & Lininger, 2018a). Model 3 (two-way mixed) was chosen because the main investigator was the only examiner of interest. This model is appropriate for a pilot study where the consistency of the results of one examiner is assessed before the main study (Hayen et al., 2007). Furthermore, three measurements or readings for each test were performed. Thus, an average measures two-way mixed model (3,3) type absolute agreement was used to calculate the ICCs. The ICC ranges from 1 (perfect relative reliability) to 0 (no relative reliability) (Riemann & Lininger, 2018a). ICC interpretation was based on the guidelines provided by Fleiss: ICC >0.90 will be defined as excellent reliability, 0.80-0.90 as good reliability, 0.70-0.79 moderate and <0.70 low reliability (Shrout & Fleiss, 1979).

Absolute reliability

It has been stated that determining reliability only based on ICC values may lead to erroneous conclusions, as ICC is affected by the variability between subjects (Atkinson & Nevill, 1998; De Vet et al., 2006). If there is a high inter-subject variability, high ICC values may be reported despite the poor trial to trial consistency (Lexell & Downham, 2005). For this reason, absolute reliability including parameters, such as SEM and MDC, was also calculated. These parameters are not affected by subjects variability and are easy to interpret by clinicians as they are expressed in the actual scale of measurement (De Vet et al., 2006). The SEM was calculated for each outcome measure using the following formula (Vafadar et al., 2016):

$$SEM = SD \times \sqrt{1-ICC}.$$

The SEM is equivalent to the SD of the measurement error, reflecting the variability in the distribution of the measurement (De Vet et al., 2006). It provides a range for the observed scores within which a true score of a measure is likely to lie (Walter & Eliasziw, 1998). The smaller the range of the SEM, the more precise the measurement capacity of the assessment. The SD was calculated as the pooled SD (combined or average) between sessions (Fritz et al., 2012; Lininger & Riemann, 2016). Also, the MDC was calculated to determine the change needed to indicate statistical significance between repeated measures (Atkinson & Nevill, 1998). The MDC is the minimum value that should be exceeded to report a real change and distinguish from measurement error between measurements (Atkinson & Nevill, 1998). MDC with a 95% confidence level was calculated using the following formula (Vafadar et al., 2016; Weir, 2005):

$$MDC_{95} = SEM \times 1.96 \times \sqrt{2}$$

Importantly, SEM and MDC are often used to determine the clinical meaningfulness of the results (Riemann & Lininger, 2018b). The SEM and MDC were expressed as absolute values and percentages of change. SEM% and MDC% were calculated by dividing their respective value with the related average of the test and re-test value multiplied by 100 (Wollin et al., 2016). This may provide information that can be easily interpreted in the clinical practice, especially for tests measuring force (Wollin et al., 2016).

Systematic bias

To examine systematic bias we assessed the differences between trials (initial vs 2-hour session and initial vs 1-week session) using paired student t-test for normally distributed data and Wilcoxon signed-rank test for non-normally distributed data (rotation force only) (Riemann & Lininger, 2018b). The alpha level was set at 0.05. Before the analysis, Shapiro-Wilk's test was performed to determine if the variables had a normal distribution.

2) Correlational analysis to determine the final tests for the main study

For the second objective, a correlation analysis between some of the outcome measures was performed. For this, data from the initial session was used. Considering that JPS and HGF had more than one target angle, a correlational analysis between the angles of each test was carried out. This will help to choose the most appropriate target angles of each outcome measure to reduce the testing time. Since JPS and HGF were normally distributed, the Pearson correlation coefficient was used. Also, a correlational analysis was performed to confirm whether the development of force (e.g., shoulder rotation force and HGF) was affected by body mass and lever arm length. This will help to determine the measurement units for the next studies. Considering that body weight was not normally distributed, Spearman’s Rho was used to examine the correlations between these variables. The correlation values considered were: < 0.3 (low), between 0.30 and 0.65 (moderate) and >0.65 (high) (Stief et al., 2014). The alpha level was set at 0.05.

3) Symmetry between the dominant and non-dominant side

For the third objective, baseline data were screened to assess differences between the dominant and non-dominant arm. Paired student t-test was used for normally distributed data and Wilcoxon signed-rank for non-normally distributed data (rotation force only).

3.4. Results

Ten participants were analysed at the initial session. One participant was unable to complete the 1-week session due to unknown reasons. The rest of the participants completed the three sessions with no drop-outs. Regarding the baseline side to side differences, only JPS at 20% of total ER (p = 0.020) reported a significant difference (Table 3.2). Despite this, all tests were similar in the dominant and non-dominant sides of all participants. Tables 3.3 to 3.5 present the intrarater and test-retest reliability for the outcome measures expressed in degrees (ROM, LD length, JPS, and CET), rotation isometric torque, and HGF.

Table 3.2 - Mean, standard deviation, and maximum-minimum value for each outcome measure by arm dominance (taken from the average of the initial session). The results of comparative analysis between sides are summarized in p-value.

Outcome measures	Side	Mean ± SD	Max-min	P-value
ROM ER, °	D	104 ± 17	141.3- 83.7	0.663
	ND	102.8 ± 17.3	134.3- 81	
ROM IR, °	D	54.8 ± 7.9	65.3- 40.5	0.973
	ND	54.8 ± 7.1	65.5- 43.3	
JPS error 90% of ER, °	D	4.8 ± 2.8	10.8- 1.4	0.770
	ND	4.6 ± 3.3	11.9- 0.6	
JPS error 20% of ER, °	D	6.6 ± 6.9	20.2- 1.1	0.022*
	ND	11.5 ± 7.4	22.1- 2.3	
JPS error 90% of IR, °	D	5.1 ± 2.4	9.2- 2.8	0.301
	ND	7.0 ± 4.3	15.3- 2.4	
ER Peak Torque, Nm/Kg	D	0.41 ± 0.17	0.76-0.24	0.093
	ND	0.37 ± 0.17	0.75-0.20	
IR Peak Torque, Nm/Kg	D	0.42 ± 0.15	0.70-0.27	0.959
	ND	0.42 ± 0.17	0.77- 0.20	
HGF 0° Shoulder ABD, Kg/body mass	D	0.31 ± 0.07	0.43- 0.20	0.480
	ND	0.32 ± 0.08	0.44- 0.18	
HGF 90° Shoulder ABD, Kg/body mass	D	0.33 ± 0.08	0.43- 0.19	0.285
	ND	0.32 ± 0.08	0.45- 0.20	
LD length, °	D	155.8 ± 12.5	172.3- 136.4	0.658
	ND	155.3 ± 13.5	174.5- 138.3	
CET, °	NA	4.3 ± 8.5	18.3- (-7.0)	N.A.

Abbreviations: SD=standard deviation; Max=maximum; Min=minimum; D=dominant; ND=non-dominant; ER=external rotation; IR=internal rotation; JPS=joint position sense; HGF=handgrip force; LD=latissimus dorsi; CET=combined elevation test; ABD=abduction; N=newton; sec=seconds; °= degrees; N.A.=not applicable; *= p-values <0.05. T test conducted on mean values from dominant and non-dominant arm.

Intrarater reliability

ICC analysis showed good to excellent values (ICC > 0.80) for most of the tests (20/21). Only one test reported low ICC values: dominant JPS at 90% of IR (0.645). For tests expressed in degrees (ROM, JPS, CET, LD length), SEM varied from 1.0° to 1.9° and MDC from 2.6° to 4.3°. For shoulder rotation torque, SEM and MDC varied from 0.012 to 0.015 Nm/Kg (2.9 to 3.7%) and 0.033 to 0.042 Nm/Kg (8.2 to 10.1%), respectively. For HGF, SEM varied from 0.009 to 0.014 Nm/Kg (3.2 to 4.4%) and MDC from 0.025 to 0.028 Nm/Kg (7.5 to 12.2%).

Within-day test-retest reliability

ICC analysis showed good to excellent results (> 0.80) for most of the tests (19/21). Two tests reported low ICC values: dominant JPS at 90% of ER (0.576), non-dominant JPS at 90% of IR (0.249). For tests expressed in degrees (ROM, JPS, CET, LD length), SEM varied from 1.2° to 2.8° and MDC from 3.3° to 7.9°. For shoulder rotation torque, SEM and MDC varied from 0.011 to 0.026 Nm/Kg (2.0 to 6.0%) and 0.021 to 0.072 Nm/Kg (5.6 to 17.6%), respectively. Regarding HGF, SEM varied from 0.015 to 0.020 Nm/Kg (3.7 to 6.0%) and MDC from 0.042 to 0.054 Nm/Kg (10.2 to 16.6%). Regarding the systematic difference between sessions, four out of 21 tests reported a significant difference ($p < 0.05$). The tests included: non-dominant ER ROM ($p = 0.022$), dominant JPS 20% of ER ($p = 0.041$), dominant ER peak torque ($p = 0.013$), and non-dominant peak HGF force at 0° shoulder abduction ($p = 0.037$).

Between-day test-retest reliability

ICC analysis showed good to excellent results (>0.80) for most of the tests (16/21). Two tests had moderate ICC: dominant ER ROM (0.785) and dominant JPS ER 90% (0.714). Whilst, four tests reported low ICC: dominant JPS 20% ER (0.683), dominant JPS 90% ER (0.490), non-dominant JPS IR (0.357), and dominant JPS IR (0.140). For tests expressed in degrees (ROM, JPS, CET, LD length), SEM ranged from 1.6° to 3.8° and MDC from 4.4° to 10.6°. With respect to shoulder rotation torque, SEM and MDC ranged from 0.016 to 0.021 Nm/Kg (4.0 to 5.2%) and 0.045 to 0.060 Nm/Kg (11 to 13.5%), respectively. For HGF, SEM values ranged from 0.011 to 0.023 Nm/Kg (3.4 to 7.3%) and MDC from 0.031 to 0.065 Nm/Kg (9.3 to 20.3%). Regarding the systematic difference between sessions, only the dominant LD length reported a significant difference between sessions ($p = 0.014$).

Table 3.3 - Intrarater and test-retest reliability for shoulder rotation range of motion, joint position sense, latissimus dorsi length, and combined elevation test. The results of a comparative analysis between the initial session with the 2-hour and 1-week sessions are summarized in p-value.

Reliability	Side	ICC (95% CI)	SEM	MDC	P-values
Intrarater					
ER ROM, °	D	0.996 (0.987-0.999)	1.1	3.0	NA
	ND	0.994 (0.984-0.998)	1.3	3.7	NA
IR ROM, °	D	0.958 (0.880-0.989)	1.7	4,7	NA
	ND	0.944 (0.841-0.985)	1.8	4.9	NA
JPS 90% of ER, °	D	0.838 (0.549-0.956)	1.3	3.5	NA
	ND	0.906 (0.721-0.975)	1.1	3.1	NA
JPS 20% of ER, °	D	0.953 (0.864-0.987)	1.6	4.3	NA
	ND	0.939 (0.773-0.985)	1.9	5.3	NA
JPS 90% of IR, °	D	0.645 (0.060-0.900)	1.9	5.3	NA
	ND	0.862 (0.600-0.963)	1.8	5.1	NA
LD length, °	D	0.985 (0.959-0.996)	1.6	4.3	NA
	ND	0.988 (0.965-0.997)	1.5	4.1	NA
CET, °	NA	0.988 (0.966-0.997)	1.0	2.6	NA
Within-day test-retest					
ER ROM, °	D	0.980 (0.922-0.995)	2.4	6.6	0.744
	ND	0.990 (0.919-0.998)	1.7	4.7	0.022*
IR ROM, °	D	0.903 (0.602-0.976)	2.2	6	0.788
	ND	0.877 (0.536-0.969)	2.3	6.3	0.326
JPS 90% of ER, °	D	0.576 (-0.04-0.870)	1.9	5.3	0.575
	ND	0.820 (0.335-0.954)	1.2	3.3	0.256
JPS 20% of ER, °	D	0.943 (0.498-0.988)	1.7	4.8	0.041*
	ND	0.886 (0.570-0.971)	1.9	5.2	0.352
JPS 90% of IR, °	D	0.825 (0.450-0.950)	1.3	3.6	0.804
	ND	0.249 (-0.42-0.678)	2.8	7.9	0.245
LD length, °	D	0.965 (0.858-0.991)	2.4	6.7	0.886
	ND	0.975 (0.898-0.994)	2	5.5	0.809
CET; °	NA	0.950 (0.791-0.998)	2.1	5.9	0.111

Table 3.3 (continued).

Reliability	Side	ICC (95% CI)	SEM	MDC	P-values
Between-day test-retest					
ER ROM, °	D	0.958 (0.815-0.991)	2.2	6.2	0.146
	ND	0.947 (0.783-0.988)	3.8	10.6	0.246
IR ROM, °	D	0.785 (0.000-0.952)	3.5	9.6	0.666
	ND	0.804 (0.109-0.956)	3.1	8.7	0.606
JPS 90% of ER, °	D	0.490 (-0.16-0.840)	3.0	8.4	0.799
	ND	0.714 (0.200-0.92)	1.8	4.9	0.393
JPS 20% of ER, °	D	0.683 (0.460-0.950)	3.3	9.0	0.374
	ND	0.806 (0.095-0.957)	3.3	9.1	0.708
JPS 90% of IR, °	D	0.140 (-0.50-0.680)	2.6	7.1	0.678
	ND	0.357 (-0.30-0.790)	1.9	5.3	0.689
LD length, °	D	0.966 (0.624-0.994)	1.6	4.4	0.014*
	ND	0.951 (0.743-0.989)	1.9	5.3	0.074
CET, °	NA	0.929 (0.677-0.984)	2.1	5.7	0.893

Abbreviations: ICC=intraclass correlation coefficient; SEM=standard error of measure; 95% CI=95% confidence interval; MDC95%=minimal detectable change with 95% confidence; D=dominant; ND=non-dominant; NA=not applicable; ER=external rotation; IR=internal rotation; ROM=range of movement; JPS=joint position sense; LD=latissimus dorsi; CET=combined elevation test; °=degrees; *= p-values <0.05. T-test and Wilcoxon Rank Test compare mean values between initial session with 2-hour session and initial session with 1-week session.

Table 3.4 - Intrarater and test-retest reliability for shoulder rotation isometric peak torque. The results of a comparative analysis between the initial session with 2-hours and 1-week sessions are summarized in p-value.

Reliability	Side	ICC (95% CI)	SEM			MDC$_{95}$			P value
			N	Nm/Kg	% change	N	Nm/Kg	% change	
Intrarater									
ER torque	D	0.990 (0.972-0.997)	5.5	0.012	3.3	15.2	0.034	9.2	NA
	ND	0.995 (0.985-0.999)	3.9	0.012	3.2	10.9	0.033	8.8	NA
IR torque	D	0.990 (0.970-0.997)	5.1	0.015	3.7	14.2	0.042	10.1	NA
	ND	0.995 (0.986-0.999)	4.2	0.012	2.9	11.5	0.034	8.2	NA
Within-day									
ER torque	D	0.992 (0.905-0.998)	3.9	0.018	4.5	10.8	0.050	12.4	0.013*
	ND	0.999 (0.994-1.000)	1.8	0.008	2.0	4.9	0.021	5.6	0.799
IR torque	D	0.982 (0.925-0.996)	6.6	0.026	6.3	18.2	0.072	17.6	0.114
	ND	0.997 (0.990-0.999)	3.2	0.011	2.6	9.0	0.030	7.3	0.799
Between-day									
ER torque	D	0.984 (0.928-0.996)	6.4	0.020	4.8	17.7	0.054	13.4	0.953
	ND	0.988 (0.950-0.997)	6.0	0.018	4.9	16.5	0.049	13.5	0.441
IR torque	D	0.982 (0.913-0.996)	6.9	0.021	5.2	19.0	0.060	14.3	0.086
	ND	0.991 (0.959-0.998)	5.4	0.016	4.0	15.0	0.045	11.0	0.859

Abbreviations: ICC=intraclass correlation coefficient; SEM=standard error of measure; 95% CI=95% confidence interval; MDC95%=minimal detectable change with 95% confidence; D=dominant; ND=non-dominant; ER=external rotation; IR=internal rotation; N=newton. *= p-values <0.05. T-test and Wilcoxon Rank Test compare mean values between initial session with 2-hour session and initial session with 1-week session.

Table 3.5 - Intrarater and test-retest reliability for handgrip force. The results of a comparative analysis between the initial session with 2-hour and 1-week sessions are summarized in p-value.

Reliability	Side	ICC (95% CI)	SEM			MDC95			P value
			Kg	Kg/body mass	% change	Kg	Kg/body mass	% change	
Intrarater									
HGF 0° shoulder ABD	D	0.970 (0.916-0.992)	1.4	0.014	4.4	3.9	0.038	12.2	NA
	ND	0.985 (0.926-0.996)	1.0	0.010	3.0	2.9	0.027	8.4	NA
HGF 90° shoulder ABD	D	0.988 (0.966-0.997)	1.0	0.009	2.7	3.0	0.025	7.5	NA
	ND	0.984 (0.953-0.996)	1.2	0.010	3.2	3.3	0.028	8.9	NA
Within-day test-retest									
HGF 0° shoulder ABD	D	0.942 (0.732-0.986)	2.2	0.020	6.0	6.1	0.054	16.6	0.037*
	ND	0.949 (0.799-0.987)	2.1	0.018	5.7	5.8	0.051	15.7	0.508
HGF 90° shoulder ABD	D	0.980 (0.919-0.995)	1.4	0.017	3.7	3.9	0.048	10.2	0.646
	ND	0.987 (0.948-0.997)	1.2	0.015	4.7	3.2	0.042	12.9	0.799
Between-day test-retest									
HGF 0° shoulder ABD	D	0.950 (0.702-0.989)	1.9	0.018	5.6	5.3	0.050	15.5	0.066
	ND	0.900 (0.592-0.977)	2.5	0.023	7.3	7.0	0.065	20.3	0.314
HGF 90° shoulder ABD	D	0.977 (0.868-0.995)	1.3	0.011	3.4	3.6	0.031	9.3	0.139
	ND	0.978 (0.943-0.997)	1.3	0.011	3.6	3.6	0.032	10.1	0.515

Abbreviations: ICC=intraclass correlation coefficient; SEM=standard error of measure; 95% CI=95% confidence interval; MDC95%=minimal detectable change with 95% confidence; D=dominant; ND=non-dominant; HGF=handgrip force; °=degrees; Kg=kilograms; ABD=abduction. *= p-values <0.05. T-test and Wilcoxon Rank Test compare mean values between initial session with 2-hour session and initial session with 1-week session.

Effect of time on reliability

MDC is one of the most important values to consider in clinical practice when using objective outcome measures (Cools et al., 2014). For this reason, Figures 3.10 to 3.12 present how the time between measurements affected the MDC of the outcome measures. Among the tests, 16 of 21 (76.2%) showed the lowest MDC value in the initial session and 12 of 21 (57.1%) showed the highest MDC in the 1-week session. Figure 3.10 shows the effect of time in tests expressed in degrees (ROM, JPS, LD length, and CET). Eleven out of 13 tests (84.6%) reported the lowest MDC values in the initial session and 8 of 13 (61.5%) the higher MDC values in the 1-week session.

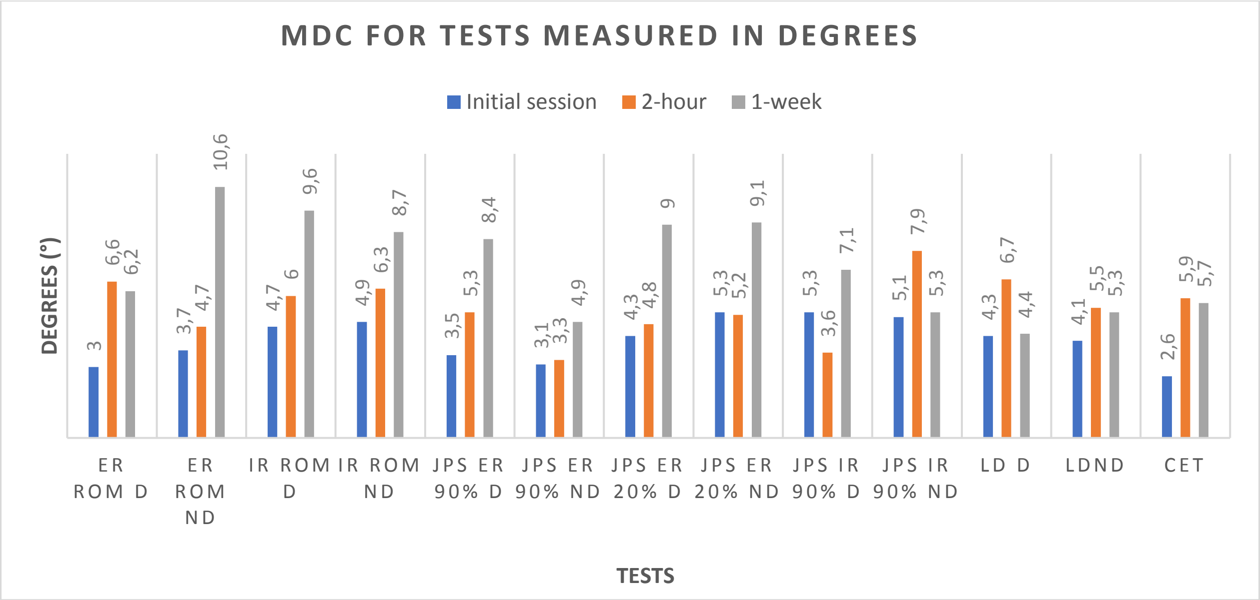

Figure 3.10 - Minimal detectable change of tests expressed in degrees during the different testing sessions. Abbreviations: D=dominant; ND=non-dominant; ER=external rotation; IR=internal rotation; ROM=range of movement; JPS=joint position sense; LD=latissimus dorsi; CET=combined elevation test; °=degrees.

Regarding shoulder rotation torque, two out of four tests (50%) reported the lowest MDC value in the initial session and three out of four tests (75%) showed the highest MDC in the one-week session (Figure 3.11). For HGF, four out of four tests (100%) reported the lowest MDC value in the initial session and one out of four (25%) reported the higher MDC value in the last session (Figure 3.12).

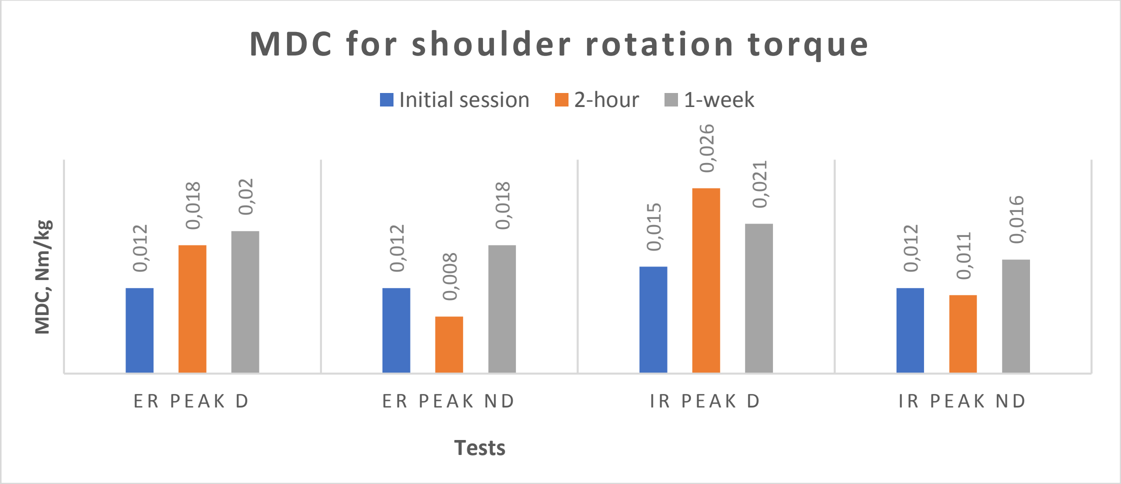

Figure 3.11 - Minimal detectable change for shoulder rotation isometric peak torque during the different testing sessions. Shoulder rotation torque was normalized to body mass and expressed as Nm/Kg. Abbreviations: MDC=minimal detectable change; D=dominant; ND=non-dominant; ER=external rotation; IR=internal rotation; N=newton; sec=seconds.

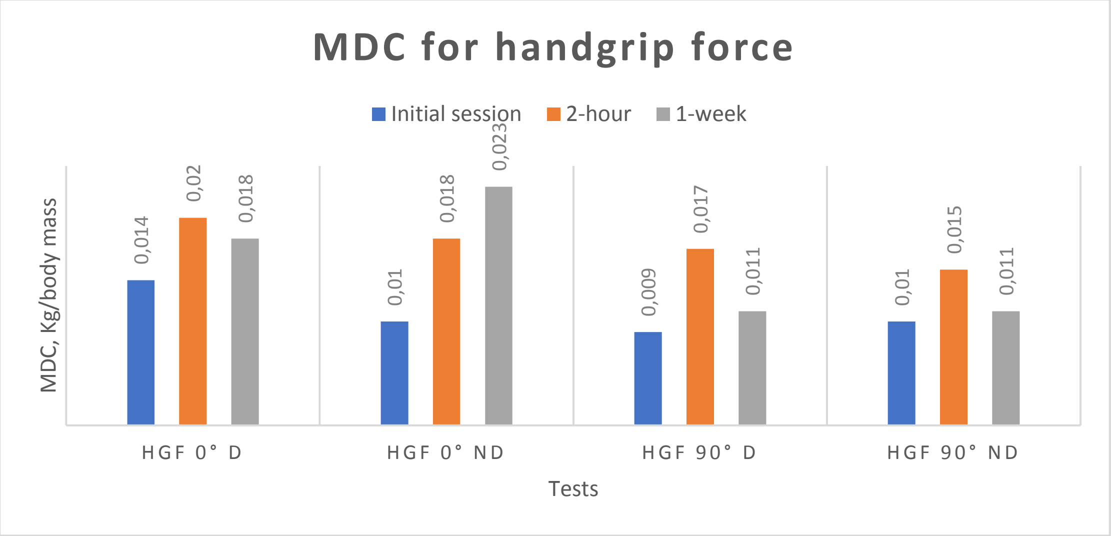

Figure 3.12 - Minimal detectable change for peak handgrip force during the different testing sessions. Handgrip force was normalized to body mass. Abbreviations: MDC=minimal detectable change; D=dominant; ND=non-dominant; HGF=handgrip force; °=degrees; Kg=kilograms; ABD=abduction.

Correlational analysis

The results of the correlational analysis for JPS and HGF target angles are shown in Appendix 4. For JPS, the analysis showed low negative nonsignificant correlations for most tests (r= -0.449 to -0.047; P < 0.05). Only one target angle reported positive moderate correlation: JPS 90% of ER with JPS 90% of IR (r = 0.393) of the non-dominant side. However, it was not significant. Regarding HGF, both shoulder positions (0° and 90° abduction) were strongly correlated for dominant (r = 0.969, p < 0.01) and non-dominant (r = 0.910, p < 0.01) sides.

The results of the correlational analysis between force, lever arm, and body mass are shown in Appendix 5. Moderate to high correlations between HGF and body mass (r_s = 0.624 to 0.830) were reported. Furthermore, moderate to high correlations between rotation peak force and body mass (r_s = 0.370 to 0.697) and high correlations between rotation peak force and lever arm length (r_s = 0.553 to 0.703) were found.

3.5. Discussion

The primary aim of this pilot study was to establish intrarater and test-retest reliability of tests that assess shoulder function. The majority of the tests reported good to excellent intrarater reliability confirming the consistency of the results obtained by the same examiner. Also, longer intervals of time between measurements increased the measurement error. These results are relevant for future studies to determine whether the changes in shoulder tests are real or due to measurement error. The secondary aim was to establish the final tests for the next studies using a correlational analysis for JPS and HGF. The results showed that these tests are redundant and that they can be simplified to decrease the measurement time. The tertiary aim was to assess the symmetry between dominant and non-dominant sides. The subtest of JPS (20% of total ER) was the only reporting differences between sides. Despite this, the results demonstrated the symmetry of the participants.

Effect of time on measurements

The results show that longer periods increase the measurement error, negatively affecting the consistency of the measurements. Most of the tests showed the lowest MDC value in the initial session (76.2%) and the highest in the 1-week session (57.1%). It has been suggested that measurements performed closer in time are usually more correlated than measurements performed farther apart (Guo et al., 2013). Our results are supported by Furness et al. (2015) that investigated the reliability of shoulder rotation ROM at two periods of time: within-session and after three hours. MDC values in the 3-hour session (7.5°-9.7°) were greater than the values obtained in the same session (4.2°-6.7°). A similar pattern was found in our study. Shoulder rotation ROM reported greater MDC values in the 2-hour session (4.7°-6.6°) compared to the initial session (3°-4.9°). This is further evidenced by even higher values found in the 1-week session (MDC=6.2°-10.6°). Considering this, MDC values obtained in the same session should be used with caution to assess changes after an intervention or sport-related activity, since the measurement error of the time between measurements is not considered. Not considering this might lead to misleading conclusions, as the changes could probably be due to a measurement error and not a real change.

Reliability of the outcome measures

For intrarater comparisons, studies calculating reliability from the same session will be included. For test-retest reliability, studies assessing reliability the same day and on different days will be used for within-day and between-day analysis, respectively. For each test relative (ICC) and absolute reliability (SEM and MDC) will be discussed. For comparisons to the literature, only studies assessing asymptomatic population were included.

Shoulder rotation range of motion

Our results for intrarater reliability revealed ICCs between 0.96 and 0.99, which are higher than previous studies investigating shoulder rotation ROM in the same session (0.81 to 0.99) (Cools et al., 2014; Kolber et al., 2011; Kolber & Hanney, 2010; Møller et al., 2018). For measurement error and what might constitute a real change, SEM values ranged from 1.1° to 1.8° and MDC values from 3.0° to 4.9° in the present study. Cools et al. (2014) reported slightly higher SEM (1.65°-2.7°) and MDC (4.5°-6.4°) for passive rotation shoulder ROM measured with an inclinometer. Also, higher SEM values (2°-4.27°) were reported in two studies (Kolber et al., 2011; Kolber & Hanney, 2010) measuring active shoulder rotation ROM with an inclinometer. However, these studies did not report MDC. Using a similar methodology, our study provides more consistent results for shoulder ROM measurements performed by the same examiner in the same session.

For test-retest reliability (within-day), our study reported ICCs ranging from 0.88 to 0.99. Two studies have measured shoulder ROM reliability twice the same day, reporting similar ICC values using an inclinometer as measurement instrument (0.90 to 0.98) (Furness et al., 2015; Walker et al., 2016). Although our study reported excellent relative reliability, SEM and MDC are more important parameters to consider. SEM values varied from 1.7° to 2.4° and MDC from 4.7° to 6.6°. For MDC (calculated with 95% confidence interval), this means that a value of change in shoulder rotation ROM greater than 6.6° is required to be 95% certain that the change after two hours is real and not due to measurement. Slightly higher SEM (2.7° to 3.2°) and MDC values (7.5° to 8.9°) were found in the Furness et al. (2015) study measuring shoulder rotation ROM twice the same day with an interval of three hours. Interestingly, a study performed in elite swimmers also found higher SEM (2°-5°) and MDC values (5°-12°) between two sessions separated by 30 minutes (Walker et al., 2016).

Regarding between-day analysis, ICCs between 0.76 and 0.96 were found in our study. These values are lower than intrarater and within-day test-retest analysis, showing that more time between testing increases the measurement error. Few studies have assessed shoulder rotation ROM reliability in different days in asymptomatic subjects (Fieseler et al., 2015; Møller et al., 2018). Higher ICC values (0.96-0.98) were found in the Fieseler et al (2015) study measuring active rotation ROM in handball players with a goniometer over a week. In contrast, Moller et al. (2018) found lower ICCs varying from 0.41 to 0.46 in elite handball player over a week using an inclinometer. For absolute reliability, our study found SEM values ranging from 2.2° to 3.8° and MDC from 6.2° to 10.6°. Regarding SEM, Fieseler et al. (2015) reported slightly lower values measured (1.07°-2.16°), whereas Moller et al. (2018) did not include the SEM in their analysis. Because these studies did not calculate MDC and used other statistical analysis, such as limits of agreement, we have no more literature with which to compare our results.

Shoulder IR ROM assessment is considered a problematic test due to the difficulties in isolating glenohumeral joint movement (Wilk et al., 2009). Several methods to isolate glenohumeral movement have been reported, such as the humeral head, the scapular, and visual stabilization (Wilk et al., 2009). Within these methods, scapular stabilization is the most reliable (Wilk et al., 2009). An example will be provided to show the relevance of the stabilization method for IR ROM measurement: Walker et al. (2016) reported MDC values of IR (12°) in elite swimmers between two sessions separated by 30 minutes. These values were higher compared to ER ROM measurement (5°). This might be explained by the stabilization method used for IR: caudal-posterior force to the scapula. Our study performed the scapula stabilization method, providing similar MDC values between IR (5.7°) and ER ROM (6.2°). Current studies in the athletic population use the scapular stabilization method for the assessment of shoulder IR ROM (Asker et al., 2019; Williams & Hebron, 2018).

Overall, the methodology used in the current study provides similar to superior results compared to the literature for intrarater and test-retest reliability of shoulder rotation ROM. Importantly, the test-retest results demonstrate that the time between measurement is an important factor to consider in ROM measurement. Furthermore, it supports the use of the scapula stabilization method as a reliable and consistent measure of shoulder IR ROM.

Latissimus dorsi length

Our results for within-session analysis revealed ICCs of 0.99, SEM ranging from 1.5° to 1.6°, and MDC from 4.1° to 4.3°. Similarly, Herrington et al. (2014) found ICCs of 0.9 and SEM values ranging from 1.2° to 1.8° for LD length in healthy controls within a single session. Unfortunately, the MDC was not calculated, which inhibits more comparisons. Despite this, similar results might be explained by the comparable methodology used in both studies. The arms were initially placed in ER and the procedure was supervised by a pressure cuff to ensure posterior pelvic movement. A recent study in competitive swimmers (Feijen, Tate, Kuppens, Struyf, et al., 2020) found slightly lower ICCs (0.91 to 0.94) for LD length measured in the same session. Furthermore, higher SEM (2.70 to 3.59°) and MDC values (7.49 to 9.94°) were reported. Although the initial shoulder positioning was similar, the supervision of the abdominal contraction was different. In the Feijen et al. (2020) study, participants were asked to maintain an abdominal contraction during the procedure, while in our study, the abdominal contraction was objectively supervised by a pressure cuff. This ensured that the same contraction was performed during the procedure, which might explain the better results.

To our knowledge, this is the first study to assess the within-day reliability of the LD length. For between-day reliability, only one study has been reported using degrees as the measurement unit. Using an inclinometer, Borstad et al. (2010) assessed the reliability of the LD length with an interval of six weeks. The authors reported low ICCs (0.19) and high SEM values (10.5°). However, the MDC was not reported. The complexity of the end-feel determination (either flexion or the onset of humerus medial rotation) and the 6-week interval between sessions might explain the poor results. Compared to Borstad et al. (2010), our study found ICCs between 0.95 to 0.97 and SEM ranging from 1.6° to 1.9° for between-day analysis. The superior results are probably explained by the decreased time between measurements (one week vs. six weeks) and the easiest determination of the end-feel; shoulder flexion with the arm in the ER (aligned in the sagittal plane) without allowing any medial rotation of the arm during the procedure.

Overall, the methodology for LD length assessment is reliable. Within-session reliability obtained in this study is comparable to studies using the same methodology. Importantly, this study provides preliminary evidence for the test-retest reliability of LD length assessment in the asymptomatic population. We would like to practically interpret the SEM values obtained in our study. Considering that the LD length in the dominant side reported a mean of 155.8° and a SEM of 1.6°, there is a 68% chance that the true score lies between 154.2° and 157.4° (± 1 SEM), and a 95% chance that the true score lies between 152.6° and 159° (± 2 SEM).

Shoulder joint position sense

Our study found that JPS error is affected by the rotational angle in which the shoulder is tested. For instance, greater errors were found in mid-range positions of ER (6.6°-11.5°) compared to end-range positions (4.6°-4.8°). These findings are supported by several studies (Herrington et al., 2010; Janwantanakul et al., 2001; Morgan & Herrington, 2014) suggesting that the less mechanical deformation of the mechanoreceptors at a mid-range position result in a lower stimulation, and therefore less joint position feedback.

To our knowledge, this is the first study to report within-session reliability of shoulder JPS. For within-day test-retest reliability, two pilot studies have been reported (Herrington et al., 2010; Higson et al., 2018). Herrington et al. (2010) found ICC values of 0.92 and MDC values of 0.9° for shoulder JPS measured at mid (45°) and end-range (80°) of ER in rugby players. Two measurements were performed the same day (30 min) and analysed with a digital camera.

The lower ICC (0.84- 0.95) and higher MDC (3.1°- 5.3°) for ER at mid and end-range found in our study might be explained by the longer interval between measurements and the less accurate measuring instrument (iPhone device vs digital camera). In a later study, Higson et al. (2017) found ICCs of 0.89 for shoulder JPS at mid-range position (45° of ER) in 15 elite swimmers measured twice the same day (10 minutes) using a smartphone device. Lower ICCs for mid-range were found in our study (20% of total ER) (0.58-0.82) measured with an interval of two hours. Furthermore, Higson et al. (2017) also reported lower SEM (0.7°) and MDC values (1.8°) compared to our study (SEM= 1.7°-1.9°, MDC= 4.8°-5.2°). Since both studies used a similar protocol and measurement device, the longer interval between measurements and population of interest (non-athletic subjects vs elite athletes) might to some extent explain the differences.

Regarding between-day analysis, only one study has been published. Dover et al. (2003) found ICCs of 0.98 for shoulder JPS measured at end-range (ER and IR) in two consecutive days with an inclinometer (Dover & Powers, 2003). Our analysis showed lower ICC values (0.14-0.71) for end-range positions measured twice over a longer period (one week). However, absolute reliability values were not reported, which inhibits more comparisons with the present study. Overall, we found higher measurement errors compared to the literature. Importantly, the time between measurements is an important factor to consider in JPS measurement, as it increases the measurement error. Finally, this study provides preliminary evidence of within-session reliability and SEM and MDC values for between-day reliability.

Combined elevation test

Only one study has investigated the reliability of the CET using the humeral angle method. Walker et al. (2016) reported excellent test-retest reliability (ICC= 0.91-0.95) measured twice the same day with an interval of 30 minutes in competitive swimmers. Similarly, our study found excellent within-day test-retest reliability (ICC= 0.95) measured with an interval of two hours. Regarding absolute reliability, Walker et al. (2016) found SEM values of 2° and MDC values of 5°, which are similar to our results (SEM= 2.1°, MDC= 5.9°). Despite the different populations tested between the studies (non-athletic vs swimmers), the results are similar. Since no studies have assessed the within-session and between-day reliability of the CET, our study provides preliminary evidence in the non-athletic population.

Shoulder rotation isometric peak torque

Since all the studies investigating the reliability of shoulder rotation force are expressed in Newtons, the comparison was performed in N. Regarding intrarater analysis, our study found ICCs values of 0.99, SEM ranging from 3.9 to 5.5 N, and MDC from 10.9 to 15.2 N. Likewise, Cools et al. (2014) reported ICCs ranging from 0.95 to 0.98 for rotation shoulder force measured in the same session with HHD. Furthermore, similar SEM (4.09-6.67N) and MDC (9.55-17.62N) values were found by Cools et al. (2014). A recent study in surfers (Furness, Schram, Cottman-Fields, et al., 2018) found similar ICCs (0.97 to 0.98) measured in the same session with a HHD. However, in comparison to our study, higher SEM values (7.08 to 7.35N) were reported.

Regarding test-retest analysis, no studies have assessed the reliability of rotation isometric shoulder force the same day in an asymptomatic population. For between-day analysis, ICCs varying from 0.98 to 0.99 were found in the present study. Compared to the literature, lower ICCs (0.42 to 0.94) for shoulder rotation force have been reported in studies using a HHD (Fieseler et al., 2015; Hayes, Walton, Szomor, & Murrell, 2002; Holt et al., 2016; Møller et al., 2018; Riemann et al., 2010). For absolute reliability, this study found SEM values ranging from 5.4 to 6.9N and MDC from 15 to 19N. Fieseler et al. (2015) reported slightly lower SEM values (1.45N to 4.48N) for rotation shoulder force measured with a HHD in handball players over a one-week period. However, the MDC was not calculated. In a later study, Holt et al. (2016) reported lower SEM and MDC values ranging from 2.59 to 2.95N and 7.19 to 8.18N respectively. The measurements were performed in a standing position with an interval of one week. Finally, using a HHD, similar ICC (0.92-0.98), SEM (5.21N-6.55N), and MDC values (14.45N-18.16N) were reported in swimmers measured twice during a week (Conceição et al., 2018). Since other studies examining the reliability of shoulder force did not calculate MDC (Hayes et al., 2002; Riemann et al., 2010) and used other statistical analysis, such as limits of agreement (Fieseler et al., 2015; Møller et al., 2018), we have no more literature with which to compare our results. Overall, our results are comparable to the literature regardless of the population and the testing position, demonstrating that the protocol performed is reliable.

For future studies in swimmers, force will be reported as torque normalized to body weight (Nm/Kg). As discussed in the literature review (Section 3.3), shoulder peak force is reported in varied measurement units. Some examples of this include pounds (Lb) (Ramsi et al., 2004), torque (Nm) (Batalha et al., 2013; Batalha et al., 2015), force normalized to body mass (N/Kg)

(Habechian et al., 2018), and torque normalized to body mass (Nm/Kg) (Bak & Magnusson, 1997), which impedes the comparison between studies. Importantly, it has been shown that force development is affected by body mass and lever arm (Krause et al., 2007; Riemann et al., 2010). The results of our correlational analysis support this, showing moderate to high correlations between rotation peak force and body mass (r_s = 0.370 to 0.697) and high correlations between rotation peak force and lever arm length (r_s = 0.553 to 0.703) (Appendix 5). Considering this, expressing force as torque normalized to body mass (Nm/Kg) will be more accurate to determine the force changes in future studies. Furthermore, reporting SEM and MDC as percent of change will allow better understanding of the measurement error. For example, a change in shoulder ER torque greater than 12.4% (0.050 Nm/Kg) in body weight is necessary to be 95% certain that the change after two hours is real and not due to measurement.

Handgrip peak force

There is no consensus of the measurement unit to report HGF; Kg, Lb or N. Considering that our study reported in Kg, SEM and MDC results were compared only to studies reporting in Kg. Regarding within-session reliability, ICCs ranged from 0.97 to 0.99 for HGF measured at both 0° and 90° shoulder abduction. Similar ICC values (0.96-0.99) have been reported in the literature for HGF measured the same session by the same examiner (Gerodimos & Karatrantou, 2013; Stephens et al., 1996). Regarding absolute reliability, our study reported SEM values varying from 1.0 to 1.4 Kg and MDC from 2.9 to 3.9 Kg. Only Gerodimos et al. (2013) expressed their results in Kg, reporting slightly lower SEM values (0.43-0.70 Kg) than our study. However, the MDC was not reported.

Regarding test-retest reliability, no studies have investigated HGF reliability on the same day. Most of the studies have analysed the changes between-days. This study reported ICCs between 0.90 and 0.98 with an interval of one week. Similar values (ICC = 0.94-0.97) have been reported for HGF measured with different intervals of time ranging from one to 66 days (Clerke et al., 2005; Gerodimos, 2012; Gerodimos & Karatrantou, 2013; Molenaar et al., 2008; Peolsson, Rune Hedlund, Birgitta Ob, 2001; Silva et al., 2019; Svensson et al., 2008). Our study found SEM values ranging from 1.1 to 2.2 Kg, which are similar to the SEM values reported in the literature (0.70 to 2.75 Kg) (Clerke et al., 2005; Gerodimos, 2012; Gerodimos & Karatrantou, 2013; Silva et al., 2019). Regarding the minimal value to determine a true change, only one study included the MDC in their analysis, whereas the other studies did not report any parameter or used LOA as statistical analysis. Silva et al. (2019) reported MDC between 4.71 to 4.80 Kg measured with an interval of two to seven days. Our study reported similar MDC values ranging from 3.2 to 6.1 Kg using a time interval of seven days. Overall, our results are similar to the literature and support the reliability of HGF measured at 0° and 90° shoulder abduction.

The results of our correlational analysis showed moderate to high correlations between HGF and body mass ($r_s = 0.624$ to 0.830) (Appendix 5). This supports the normalization of HGF to body mass for future studies.

Pilot study results compared to swimmer population

Participants in this pilot were a non-swimming population. This was due to the difficulties performing reliability testing in competitive swimmers (tight training regime and different training locations). This is a potential limitation, as it might not reflect the reliability of the tests in swimmers. However, if we compare our results to studies assessing swimmers, they are similar. For instance, reliability values for rotation ROM, LD length, CET, and rotation peak force are comparable to studies involving swimmers (Conceição et al., 2018; Feijen, Tate, Kuppens, Struyf, et al., 2020; Higson et al., 2018; Walker et al., 2016). For more details, refer to Tables 2.4, 2.5, 2.7, and 2.8 (Chapter 2). Regarding HGF, we did not find any reliability studies in swimmers. However, when our results were compared to other athletic populations (handball and basketball), the results are similar (Gerodimos, 2012; Gerodimos & Karatrantou, 2013). For more details, refer to Table 2.9 (Chapter 2). Regarding shoulder JPS, only one study has assessed this on swimmers reporting better reliability (Higson et al., 2018). Despite this, the results of this study can be used in the swimming population.

Measurement error

There are two types of measurement error: systematic bias and random error (Bialocerkowski & Bragge, 2008; Riemann & Lininger, 2018a). Atkins et al. (1998) stated that both sources of errors can be controlled, however, that random error contributes more than systematic bias in the total measurement error. Systematic bias occurs in the same direction and magnitude, caused mainly by learning effects or participant fatigue across multiple trials (Atkinson & Nevill, 1998). To mitigate this, participants performed a practice trial to familiarize themselves with the tests (Riemann & Lininger, 2018a). Additionally, sufficient resting periods were performed between trials to avoid fatigue in tests assessing force. Riemann et al. (2018a) suggested the use of paired t-test for the detection of large systematic bias between repeated measurements. Only four out of 21 tests presented a significant difference ($p < 0.05$) between the initial session and the 2-hour session, whereas only one out of 21 tests presented a significant difference between the initial session and 1-week session. Regarding the random error, it is not predictable, and it differs in magnitude and direction (Atkinson & Nevill, 1998). This error is caused by mechanical or biological variation and inconsistencies in the measurement protocol (Atkinson & Nevill, 1998). To decrease this source of error, the tests were performed by the same examiner and practised before the pilot study (Riemann & Lininger, 2018a). The SEM and MDC values obtained in the study were similar and sometimes lower compared to the ones reported in the literature, showing an overall low measurement error.

Statistical approach commentary

As stated above, the determination of reliability only based on ICC values may lead to erroneous conclusions, as ICC is affected by the variability between subjects (Atkinson & Nevill, 1998; De Vet et al., 2006). Our results are a good example of this. In the initial session, JPS at 90% of ER ROM reported good reliability (ICC=0.83), whereas ER ROM presented almost perfect reliability values (ICC=0.99). Based on these results, we might assume that ER ROM test is more reliable than JPS. However, based on absolute reliability parameters, both tests present almost the same values: ER ROM (SEM= 1.1°-1.3°, MDC=3.0°-3.7°) and JPS (SEM= 1.1°-1.3°, MDC=3.1°-3.5°). The higher ICC found in ER ROM might be explained by the higher variance in the results (SD= ±17°) compared to significantly lower variance in the JPS test (SD= ±2.8°). If there is a high inter-subject variability, high ICC values may be reported despite the poor trial to trial consistency (Lexell & Downham, 2005). This explains why only relying on ICC values leads to misleading conclusions. Furthermore, as the ICC relies on the sample variability, caution should be taken when generalizing ICC values obtained in one study to a new sample of individuals with different characteristics (Atkinson & Nevill, 1998). On the contrary, SEM and MDC are more stable over different population samples, as they are less affected by sample variability (De Vet et al., 2006). Hence, SEM and MDC should be calculated along with the ICC to provide more accurate information about the reliability of the assessments and to allow the comparison between different samples.

Definition of the final methodology

The secondary aim of the pilot study was to determine the final tests for the main study. It is important to consider that performing all the tests took approximately 35 minutes per participant. Since competitive swimmers are exposed to a strict training regime, this might not be feasible in the sporting setting. During the testing, we noticed that JPS and HGF had more than one testing position. Considering this, a correlational analysis was performed to determine the definitive testing position for these tests. For JPS, all the target angles reported a non-significant correlation ($P < 0.05$). These results suggest that all the target angles measure different JPS features (appendix 4). Despite this, only JPS at mid-range (20% of ER ROM) will be used in the subsequent study. The rationale for this is because in the mid-range position, the skin and capsule-ligamentous structures are less tense, and therefore JPS rely more on the feedback provided by muscular-tendinous structures (Herrington et al., 2010; Janwantanakul et al., 2001). Since muscle fatigue plays a crucial role in the aetiology of shoulder pain in swimmers, JPS at the mid-range position can provide more information about muscular feedback than end-range positions. Regarding HGF, both shoulder positions (0° and 90° abduction) were strongly correlated ($r = 0.91$-0.97, $p < 0.01$), suggesting that both tests assess similar features (Appendix 4). Only HGF at 90° shoulder abduction will be used for the main study as it is a more functional position for swimmers. Furthermore, it showed lower MDC values (3-3.9 Kg) compared to HGF at 0° (2.9-7 Kg), further supporting our decision. Finally, rotation ROM (ER and IR), JPS (20% of total ER), rotation peak torque (ER and IR), LD length, HGF (90° shoulder abduction), and the CET will be the definite tests for future studies.

3.6. Conclusions

Compared to the literature, all tests showed to be reliable for both intrarater and test-retest analysis. Intrarater analysis demonstrated consistency of the results obtained by the same examiner, suggesting that the main researcher can perform the tests with confidence in the following studies. Test-retest analysis corroborated that longer intervals of time between measurements negatively affect reliability. Since future studies will include pre-post testing at different time points (e.g., a single training session and a training week), the SEM and MDC values obtained in this study will help to determine with confidence whether the changes in shoulder tests are real or due to measurement error. Also, these values will help to establish clinical meaningfulness of the results. Importantly, this methodology is replicable and easy to perform in any clinical practice. Considering the time consumption of the tests, the definitive tests were determined along with the most adequate measurement units. Finally, our results provide preliminary evidence of LD length, shoulder JPS, and CET reliability.

3.7. Considerations for future studies

Swimmers from Manchester, Stockport, Salford, and Warrington swimming clubs were contacted to participate in future studies using a letter of support from British Swimming (Appendix 6). Considering that swimming clubs participating involved young swimmers, amendments to include participants less than 18 years old were submitted to the ethics committee. The amendments were approved by November 22, 2018 (Ethical approval form p.205). To address this ethical issue, the University of Salford Safeguarding policy V.2.2 was followed (Recommended behaviour when dealing with Children or Vulnerable Adults) to ensure the welfare of the children during all procedures. Thus, this study was ethically approved for both adult and youth participants. Finally, Chapters 4, 5, and 6 were reported according to the Strengthening the Reporting of Observational Studies in Epidemiology checklist (STROBE) (https://www.strobe-statement.org/index.php?id=available-checklists). The STROBE checklist for each chapter was included in Appendix 7.

Chapter 4

Training intensity and shoulder musculoskeletal physical quality responses in competitive swimmers

Context: Shoulder pain is the main cause of missed or modified training in competitive swimmers. Shoulder musculoskeletal maladaptations occur to some extent as a consequence of training loads during swimming that may increase the risk of shoulder injury. Further evidence is needed to understand the training intensities at which these maladaptations occur.

Objective: To determine the acute effect of training intensity on shoulder musculoskeletal physical qualities associated with shoulder injury in competitive swimmers.

Design: Cross-sectional study.

Setting: Indoor swimming pool.

Patients or Other Participants: Sixteen asymptomatic national- and regional-level swimmers (7 females, 9 males; age = 14.6 ± 3.9 years, height = 160.5 ± 12.7 cm, mass = 55.3 ± 12.5 kg).

Main Outcome Measure(s): Bilateral active shoulder-rotation range of motion (ROM), joint position sense, latissimus dorsi length, combined elevation test, and shoulder-rotation isometric peak torque and handgrip peak force normalized to body weight were measured before and immediately after low-and high-intensity swim-training sessions. The intensity of the sessions was determined by the distance swam over or at the pace threshold and confirmed by the swimmer's rating of perceived exertion.

Results: After the high-intensity training session, shoulder external-rotation ROM (dominant side: $P < 0.001$; change = -7.8°; $d = 1.10$; nondominant side: $P = 0.002$; change = -6.5°; $d = 1.02$), internal-rotator isometric peak torque (dominant side: $P < 0.001$; change = -11.4%; $d = 0.42$; nondominant side: $P = 0.027$; change = -6.6%; $d = 0.20$), and external-rotator isometric peak torque (dominant side: $P = 0.004$; change = -8.7%; $d = 0.27$; nondominant side: $P = 0.019$; change = -7.6%; $d = 0.25$) were reduced. No changes were found in any of the outcome measures after the low-intensity session.

Conclusions: Shoulder active external-rotation ROM and rotation isometric peak torque were decreased immediately after a high-intensity training session, possibly increasing the risk of injury during subsequent training. Monitoring these variables may help practitioners adjust and manage training loads to decrease the risk of shoulder injury.

Key Words: shoulder pain, shoulder injury, swimming, fatigue, training loads.

Key Points:

- The intensity of the swim-training session, which can be easily measured by the rating of perceived exertion, may be an important factor that leads to maladaptive changes in shoulder physical qualities of the shoulder,
- Active shoulder external-rotation range of motion and rotation isometric peak torque were immediately decreased after a high-intensity but not after a low-intensity training session, with predominant changes on the dominant side.
- The maladaptive changes in physical qualities of the shoulder after a high-intensity session probably increase the risk of shoulder injury during the training that follows.

4.1. Introduction

The shoulder is the most commonly injured body part in swimmers, accounting for 31% to 39% of all injuries (Chase et al., 2013; Kerr et al., 2015). This might be explained by the fact that 90% of the propulsive forces during swimming are generated by the upper limbs (Pink & Tibone, 2000). In addition, competitive swimmers swim approximately 10,000 to 14,000 m/day six or seven times per week (Pink & Tibone, 2000). This amount of training volume combined with the repetitive nature of the sport predisposes athletes to many shoulder overuse injuries (Chase et al., 2013; Kerr et al., 2015). The prevalence of shoulder pain in competitive swimmers has been reported to be between 26% and 91% (Hibberd & Myers, 2013; Sein et al., 2010; Tate et al., 2012). Despite this high prevalence, most swimmers do not discontinue training because of shoulder pain (Hibberd & Myers, 2013). This is reflected in the low amount of time loss from training and competition reported as a consequence of shoulder concerns (Kerr et al., 2015; Sein et al., 2010). Therefore, shoulder pain might interfere with training and competition performance, leading to the development of chronic injuries and in some cases to retirement from sport participation (Hibberd & Myers, 2013).

The cause of musculoskeletal injuries in sport is dynamic and multifactorial (Bittencourt et al., 2016). Emerging evidence (Soligard et al., 2016) has indicated that inadequate management of training loads is a major risk factor for injury. In their workload-injury etiology model, Windt and Gabbett (2017) suggested that the risk of injury changes dynamically as a result of the training loads applied and their effects on modifiable risk factors. Training loads can cause positive physiological adaptations (e.g., fitness) that alter modifiable risk factors positively, decreasing the risk of injury. However, training loads can also cause negative physiological effects (e.g., fatigue), altering modifiable risk factors and increasing the injury risk during subsequent training (Windt & Gabbett, 2017). The authors suggested the importance of understanding the interactions between training loads and modifiable risk factors for decreasing the risk of injury (Windt & Gabbett, 2017). This is supported by the complex-systems approach to sports injuries proposed by Bittencourt et al. (2016), who emphasized understanding the interactions among risk factors so as to identify injury risk profiles of an athlete or group of athletes. Several potential modifiable risk factors for shoulder pain, such as alterations in the physical qualities of the shoulder (e.g., range of motion [ROM], flexibility, and strength), have been identified in swimmers. Regarding ROM and flexibility, reduced internal-rotation (IR) ROM (Tate et al., 2012), increased (Bansal et al., 2007; Walker et al., 2012) and decreased external-rotation (ER) ROM (Walker et al., 2012), reduced latissimus dorsi (LD) length (Tate et al., 2012), and reduced pectoralis minor length (Tate et al., 2012) have been reported. Furthermore, reduced shoulder internal-rotator force (Bak & Magnusson, 1997; Tate et al., 2012) and external-rotator endurance (Beach et al., 1992) have been found in swimmers with shoulder pain.

Other physical qualities, such as shoulder joint position sense (JPS), results of the combined elevation test (CET), and handgrip force (HGF), are also considered important when clinicians examine swimmers. Although these have not been reported as risk factors for shoulder pain in this population, they are regularly used in clinical practice. Joint position sense is a submodality of proprioception and is defined as the ability to consciously recognize the position of a joint in space (Myers & Lephart, 2000). Proprioception is essential for the practice of sport-related activities, providing neuromuscular control and joint stability (Myers & Lephart, 2000). The CET is a screening tool used to assess the strength and mobility of the upper limb and thoracic spine (Blanch, 2004). The movement performed during the CET is essential for achieving a high elbow position during a swimming stroke (Blanch, 2004). This is important, because a dropped elbow has been suggested as a sign of potential shoulder injury (Pink & Tibone, 2000). Finally, the HGF provides an objective indicator of the functional status of the upper limb and has also been proposed as an indirect assessment of posterior cuff function (Horsley et al., 2016). Considering that training intensity is an important component of training loads (Windt & Gabbett, 2017), it is important to understand the effects of training intensity on these physical qualities.

To date, the effect of swim-training loads on the physical qualities of the shoulder in competitive swimmers has been investigated in only two studies (Higson et al., 2018; Matthews et al., 2017). Matthews et al. (2017) found a bilateral decrease in ER ROM and an increase in JPS error in the dominant extremity after swim training in 17 national youth swimmers. In a later study, Higson et al. (2018) observed reduced ER ROM and pectoralis minor length and increased JPS errors after swim training in 16 elite swimmers. Based on the current evidence, shoulder maladaptation occurs immediately after swim training, which may increase the risk of shoulder injury. However, these researchers measured the effect of only one type of training and, thus, only one training intensity. No one has investigated the effect of different training intensities on the physical qualities of the shoulder. Understanding how the physical qualities of the shoulder are affected by training intensity could help inform researchers and clinicians on the appropriate management of training loads. The aim of appropriate load management is to maximize adaptation and performance while minimizing the risk of injury (Soligard et al., 2016). This includes adequate prescription, monitoring, and adjustment of training loads (Soligard et al., 2016). Our study may provide information about which physical qualities need to be monitored. Monitoring might help to inform researchers on the appropriate timing of high-intensity training for enhancing load capacity and performance without increasing the detrimental effects on these physical qualities. It may also help to identify post-swim deficits and permit early interventions to reduce the susceptibility to shoulder injury. Furthermore, considering the multifactorial nature of sport injuries, assessment of more physical qualities is needed to support the current findings. To our knowledge, no authors have addressed the effect of training loads on LD length, CET, and HGF in swimmers.

The aim of our study was to determine the acute effect of training intensity on shoulder musculoskeletal physical qualities associated with shoulder injury in competitive swimmers. The null hypothesis was that shoulder physical qualities will be unaffected by a low and high-intensity swim training session.

4.2. Methods

Participants

We conducted this cross-sectional study among a swimming squad to assess the effects of swim-training intensity on the physical qualities of the shoulder. Sixteen regional- and national-level swimmers were part of a convenience sample. According to an a priori power analysis (version 3.1.9.2; G*Power, Heinrich-Heine-Universität, Dusseldorf, Germany) using the t test for means (one group), a sample size of 15 participants would be required to detect a large effect size (0.8) after swim training, with a power of 0.80 and an α level of 0.05. The sample consisted of seven female and nine male participants (age = 14.6 ± 3.9 years [range = 11–20 years], height = 160.5 ± 12.7 cm, mass = 55.3 ± 12.5 kg). All swimmers trained in the same group during the year and completed the same practices regularly, regardless of age and level of competition. The participants had a mean of 6 years of regular swimming experience (range = 4–8 years), performed a mean of 5.5 days of swim training per week (range = 5–6 days), and completed a swimming volume of 35,000 ± 5,000 m/week. All swimmers were regularly active in regional and national championships. The exclusion criteria were a history of shoulder surgery, shoulder pain at the time of the study, and any pain in the two weeks before the study that interfered with the ability to train or compete fully (Higson et al., 2018). All participants provided written informed consent. For participants <18 years old, parental or guardian signed consent was obtained. The study was approved by our university’s ethics board.

Procedures

All tests were performed by the same researcher (M.Y.), who had eight years of clinical experience. For each swimmer, measurements were recorded before and after low- and high-intensity training sessions. On the testing day, general demographic information of participants, such as sex, age, limb dominance, height, mass, and forearm length, were recorded. Limb dominance was determined by asking participants if they were right- or left-hand dominant. Before the testing, participants performed a standardized land-based warm-up consisting of multiplanar shoulder movements using an elastic band that was supervised by the tester. The warm-up consisted of 10 repetitions of ER and IR (0° of shoulder abduction) with a yellow TheraBand (The Hygenic Corporation, Akron, OH). Immediately after the warm-up, baseline measurements were recorded in the following order: shoulder-rotation ROM, shoulder JPS, shoulder-rotation isometric peak torque, LD length, CET, and handgrip peak force. All tests were standardized, and the dominant side was assessed first. Three trials of each test were performed on both limbs, and the results were averaged for further analysis. Immediately after completion of the training, swimmers exited the pool and repeated the baseline testing. The testing was conducted over eight weeks because of the availability of only one researcher, and participants completed both sessions at least eight times. Data were collected on the same days each week to ensure that the swimming sessions were the same. The tests were performed in block order: the high-intensity session data were collected on Wednesday afternoons, whereas the low-intensity session data were collected on Friday afternoons of the same week. All swimmers completed an aerobic-kick–focused session on Thursday morning between sessions. No weight training was performed before or after the testing sessions.

Instrumentation and outcome measures

The same procedure for shoulder-rotation ROM, shoulder JPS, shoulder-rotation isometric peak torque, LD length, CET, and handgrip peak force were used as previously described in Section 3.3 of Chapter 3. Furthermore, the same measurement error values found in Chapter 3 (pilot study) were used for this study (Tables 3.3 to 3.5).

Training intensity definition

Training intensity can be categorized into relative zones (i.e., low, moderate, high) based on the stimulus from the training load (Bourdon et al., 2017). Training load has been defined as ‘‘the cumulative amount of stress placed on an individual from a single or multiple training sessions (structure or unstructured) over a period of time.’’(Soligard et al., 2016) (pg1). According to consensus statements on training loads (Bourdon et al., 2017; Soligard et al., 2016), the recommendation is that a combination of external (amount of work performed by the athlete) and internal (athlete’s response to external load) training loads should be used to monitor an athlete’s response to training. The intensity of the training sessions was based on the external training loads and categorized as low or high. Considering that each session lasted one hour and consisted of comparable total volumes of 3 km, the intensity was determined by the volume swum at or above the threshold pace. Threshold pace was previously determined by the coach, and all athletes were familiar with and had experience swimming at this intensity (a hard sustainable pace).

During the low-intensity training session, 0% of the swimming was completed at or above the threshold pace. The session was evenly balanced among the four swimming strokes, with the athletes instructed to complete the entire volume at a low-intensity recovery pace. Conversely, during the high-intensity training session, one-third of the volume was dedicated to performing the athlete’s number one stroke at or above the threshold pace. The remaining swim volume was designated for warm-up, dedicated skill practice, and swim down. A detailed description of each session can be found in Appendix 8. The intensity of the session was confirmed by the swimmer’s perception of intensity (internal load). Internal loads were quantified by the rating of perceived exertion (RPE) based on the modified version of the category-ratio scale of Borg (Foster et al., 2001). Immediately after completing the training, the swimmers were asked, ‘‘How hard was your workout?’’ The RPE is a valid and simple measurement for assessing training intensity in athletes and is commonly used to monitor athletes’ physiological stress during or after training or competition (Foster et al., 2001). The RPE method has also been shown to be consistent with objective physiological indices, such as heart rate, in athletes (Borresen & Lambert, 2008).

Statistical analysis

For statistical analysis, SPSS (version 25 for Windows; Inc, Chicago, IL) was used. The Shapiro Wilks test was performed to determine if the variables had a normal distribution. All the results were analysed by statistical significance and clinical meaningfulness. Statistical significance (as reflected by the P-value associated with a statistical test) indicates the influence of chance on the outcome, whereas clinical meaningfulness reflects the degree to which the study results are relevant to practice (Riemann & Lininger, 2015).

To determine if a statistical difference in the physical qualities was present before and after a training session, we used the paired *t* test as the sample was normally distributed. The α level was set at ≤ 0.05 (i.e., 5% likelihood of making a type I error) (Riemann & Lininger, 2015). Furthermore, as we wanted to determine the relationship between variables in each direction (i.e., physical qualities increase or decrease after a training session), we used two-tailed tests for the analysis (Ruxton & Neuhäuser, 2010). This was also performed in the following chapters.

Clinical meaningfulness was determined by the effect size and whether the change values exceeded the SEM and MDC (Riemann & Lininger, 2018b). These same parameters were used in the following studies to assess clinical meaningfulness. We calculated the Cohen d effect size to determine the magnitude of any difference among measurements using the following formula: pre session mean - post session mean/ SD pooled (Fritz et al., 2012; Lininger & Riemann, 2016). The following effects size values were considered: > 0.8 (large), between 0.5 and 0.79 (moderate), between 0.49 and 0.20 (small), and < 0.2 (trivial) (Cohen, 1988). Results were presented in boxplots to examine data distribution (Weissgerber et al., 2017).

4.3. Results

Sixteen swimmers were analysed before and after the low- and high-intensity training sessions. All swimmers completed both sessions with no dropouts. Regarding the RPE, we observed a difference between sessions ($P < 0.001$). Swimmers demonstrated RPE averages of 2.44 ± 1.2 (minimum–maximum = 1–4) and 7.44 ± 1.3 (minimum– maximum = 5–9) for the low- and high-intensity session, respectively. No swimmers experienced shoulder pain during either session. The comparison between pre- and post-swim tests for both the low- and high-intensity training sessions are shown in Tables 4.1 and 4.2.

Table 4.1 - Mean results from pre-swim and post-swim of high and low-Intensity training sessions for rotational range of motion, joint position sense, latissimus dorsi length, and combined elevation test (N = 16).

Session intensity/Test	Side	Pre-swim	Post-swim	Mean difference	Effect size	P Value[a]
High-Intensity						
External rotation ROM, °	D	101 ± 6.5	93.2 ± 7.5	-7.8	1.10	<0.001[b]
	ND	101.3 ± 7.2	94.8 ± 5.5	-6.5	1.02	0.002[b]
Internal rotation ROM, °	D	57.5 ± 5.8	59.7 ± 7.4	+2.3	0.33	0.19
	ND	59.9 ± 8.6	61.5 ± 5.7	+1.6	0.22	0.36
Joint position sense, °	D	5.9 ± 3.1	6.1 ± 3.4	+0.2	0.06	0.83
	ND	6.2 ± 3.2	6.1 ± 3.1	-0.1	0.03	0.92
Latissimus dorsi length, °	D	134.1 ± 8.5	132.3 ± 8.4	-1.7	0.21	0.24
	ND	137.4 ± 8.8	135 ± 9.3	-2.4	0.27	0.12
Combined elevation test, °	NA	2.9 ± 5.4	2.1 ± 4.2	-0.8	0.17	0.28
Low-Intensity						
External rotation ROM, °	D	98.8 ± 7.8	100.5 ± 8.1	+1.7	0.21	0.19
	ND	97.2 ± 7.3	96.7 ± 5.8	-0.5	0.08	0.66
Internal rotation ROM, °	D	59.6 ± 6.2	59.0 ± 6.1	-0.6	0.10	0.60
	ND	59.1 ± 7.9	61.9 ± 5.7	+2.8	0.41	0.12
Joint position sense, °	D	5.7 ± 2.3	7.4 ± 4.1	+1.7	0.53	0.21
	ND	6.4 ± 2.8	6.6 ± 3.6	+0.3	0.06	0.73
Latissimus dorsi length, °	D	137.3 ± 12.2	135.6 ± 10.2	-1.7	0.15	0.39
	ND	138.2 ± 10.2	136.6 ± 9.9	-1.6	0.16	0.39
Combined elevation test, °	NA	2.8 ± 3.8	2.9 ± 4.5	+0.1	0.02	0.83

Abbreviations: D, dominant; ND, non-dominant; ROM, range of motion; °, degrees; NA, not applicable.

[a] P value was calculated from independent samples t-test comparing the average number of pre-swim and post-swim scores obtained in each test.

[b] Denotes statistical significance ($P < 0.05$).

Table 4.2 - Mean results from pre-swim and post-swim of high and low-intensity training sessions for isometric peak torque and handgrip force normalized to body weight (N = 16).

Session intensity/Test	Side	Pre-swim	Post-swim	Mean difference	Mean % change[c]	Effect size	P Value[a]
High-intensity							
External rotator torque, Nm/kg	D	0.40 ± 0.11	0.37 ± 0.11	-0.03	-8.7 ± 9.4	0.27	0.004[b]
	ND	0.37 ± 0.12	0.34 ± 0.11	-0.03	-7.6 ± 11.6	0.25	0.019[b]
Internal rotator torque, Nm/kg	D	0.46 ± 0.13	0.41 ± 0.12	-0.05	-11.4 ± 8.6	0.42	<0.001[b]
	ND	0.44 ± 0.16	0.41 ± 0.14	-0.03	-6.6 ± 10.2	0.20	0.027[b]
Handgrip force, Kg/body mass	D	0.43 ± 0.09	0.43 ± 0.10	0	0.3 ± 11.2	0	0.92
	ND	0.43 ± 0.10	0.41 ± 0.10	-0.02	-3-3 ± 11.5	0.20	0.23
Low-intensity							
External rotator torque, Nm/kg	D	0.44 ± 0.15	0.42 ± 0.13	-0.02	-1.8 ± 10	0.14	0.15
	ND	0.40 ± 0.12	0.39 ± 0.11	-0.01	-3.1 ± 9.1	0.08	0.16
Internal rotator torque, Nm/kg	D	0.49 ± 0.15	0.49 ± 0.14	0	-0.8 ± 8.4	0	0.89
	ND	0.50 ± 0.16	0.48 ±0.14	-0.02	-1.7 ± 9.5	0.13	0.36
Handgrip force, Kg/body mass	D	0.44 ± 0.12	0.43 ± 0.11	-0.01	-0.5 ± 15.7	0.08	0.59
	ND	0.44 ± 0.10	0.43 ± 0.09	-0.01	-2.9 ± 5.2	0.10	0.015[b]

Abbreviations: D, dominant; ND, non-dominant; Nm/kg, newtons meter per kilogram; Kg, kilograms.

[a] P value was calculated from independent samples t-test comparing the average number of pre-swim and post-swim scores obtained in each test.

[b] Denotes statistical significance (P < 0.05).

[c] Values of change between sessions expressed as percentage of body weight.

High-intensity training session

We observed changes in ER ROM and rotation isometric peak torque that were different. Box plots showing the differences between the low- and high-intensity sessions for ER ROM and isometric peak torque are displayed in Figures 4.1 and 4.2, respectively. Decreases were present in ER ROM, with large effect sizes for the dominant (P < 0.001; change = -7.88; d = 1.10) and nondominant (P = 0.002; change = -6.58; d = 1.02) sides. Based on the pilot study results, the values of change in ER ROM on the dominant and nondominant sides exceeded the SEM and MDC. A decrease in ER ROM below 93° has been reported as a cut-off value for the development of shoulder pain in swimmers (Walker et al., 2012). After the training session, 8 of 16 (50%) and 7 of 16 (43.8%) swimmers exhibited a decrease in ER ROM below this value on the dominant and nondominant sides, respectively.

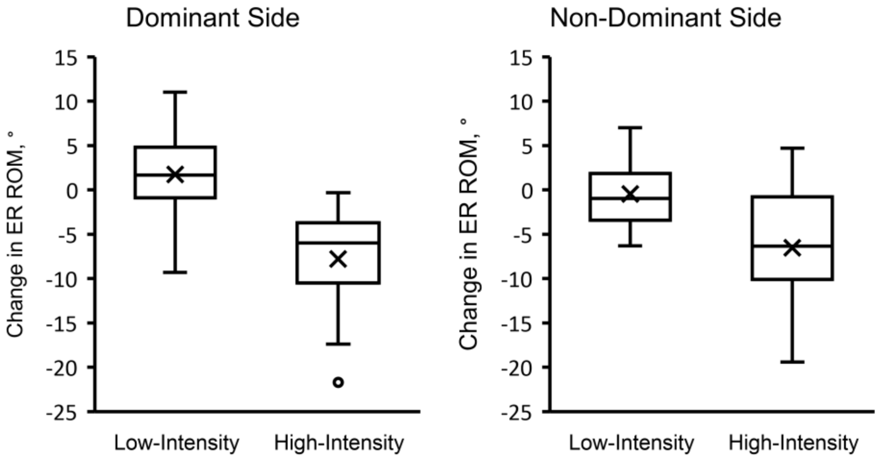

Figure 4.1 - Box plots showing the change in ER ROM following a low and a high-intensity swimming session, on the dominant and nondominant shoulder. The lower and upper edge of the box indicates the 25th and 75th percentile of the sample respectively. The height of the box indicates the interquartile range and the line inside the box shows the median. The X inside the box represents the mean. The whiskers represent extreme data point that is no more than 1.5 times the interquartile range from the lower and upper edges of the box. The circles beyond the whiskers represent outliers. Abbreviations: ROM, range of movement; ER, external rotation; °, angle.

Regarding isometric peak torque, we found decreases in the internal rotators, with small effect sizes for the dominant (P < 0.001; d = 0.42) and nondominant (P = 0.03; d = 0.20) sides. The changes represented mean decreases of 11.4% (0.05 Nm/kg) and 6.6% (0.03 Nm/kg) in body weight for the dominant and nondominant sides, respectively. For both sides, the value of change exceeded the SEM but not the MDC. With respect to external-rotator isometric peak torque, we observed a decrease for the dominant side, with a small effect size (P = 0.004; d = 0.27). The change represented a mean decrease of 8.7% (0.03 Nm/ kg) of body weight. The value of change exceeded the SEM but not the MDC. Regarding the nondominant side, external-rotator isometric peak torque decreased, with a small effect size (P = 0.02; d = 0.25). The change represented a mean decrease of 7.6% (0.03 Nm/kg) of body weight. In this case, the value of change exceeded the SEM and MDC. We observed no differences between pre-swim and post-swim measurements for the IR ROM, JPS, LD length, CET, or HGF outcomes.

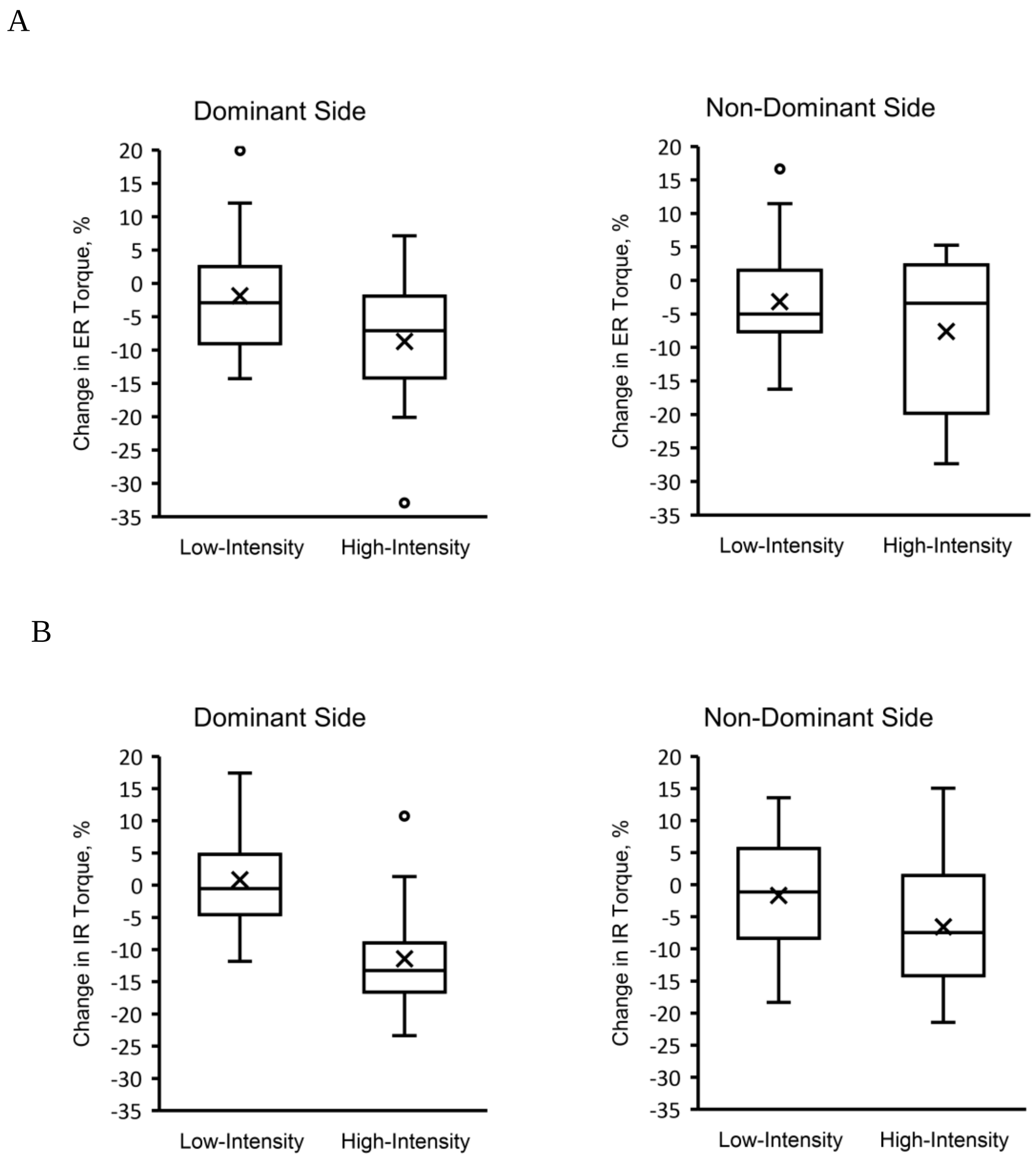

Figure 4.2- Box plots showing the percentage of change in shoulder isometric peak torque following a low and a high-intensity swimming session, on the dominant and nondominant shoulder. A, External rotators. B, Internal rotators. Torque was normalized to body weight and expressed as a percentage of change between sessions. The lower and upper edge of the box indicate the 25th and 75th percentiles respectively. The height of the box indicates the interquartile range and the line inside the box shows the median. The X inside the box represents the mean. The whiskers represent extreme data point that is no more than 1.5 times the interquartile range from the lower and upper edges of the box. The circles beyond the whiskers represent outliers. Abbreviations: IR, internal rotators; ER, external rotators.

Low-intensity training session

After the session, only the HGF on the nondominant side decreased, with a trivial effect size ($P = 0.02$; $d = 0.10$). The change represented a mean decrease of 2.9% (0.01 kg/body mass) in body weight. The change did not exceed the SEM or the MDC, probably indicating that it was due to chance or random error. We noted no differences between pre-swim and post-swim measurements in any of the other measurements. Regarding ER ROM, 1 of 16 (6.2%) and 4 of 16 (25%) swimmers displayed decreases below 93° on the dominant and nondominant sides, respectively.

4.4. Discussion

The aim of this study was:

- To determine the acute effect of training intensity on shoulder musculoskeletal physical qualities associated with shoulder injury in competitive swimmers

The null hypothesis was partially rejected. After high-intensity sessions, active ER ROM and rotation isometric peak torque were reduced, but IR ROM, JPS, LD length, CET score, and HGF did not change. However, after the low-intensity session, we identified no changes in any of the physical qualities. Considering the changes in certain physical qualities after the high-intensity session, it was important to establish whether these changes were clinically meaningful (Riemann & Lininger, 2018b). For ER ROM, we observed large effect sizes, with change values that exceeded the MDC, whereas isometric peak torque had small effect sizes, with only the external-rotator isometric peak torque of the nondominant side exceeding the MDC (a detailed explanation of the clinical meaningfulness of each variable is provided in the following subsection). We showed that musculoskeletal adaptations varied in response to training intensity over a short period (i.e., one training session). This suggests that some physical qualities are in constant fluctuation due to the training loads being applied. Bittencourt et al. (2016) proposed that athletes are open and dynamic systems that interact with the environment and evolve over time. Thus, our results provided information about the short-term interaction between training intensity and the physical qualities of the shoulder in competitive swimmers. We suggest that the intensity of the swim training may be an important factor that influences acute changes in the physical qualities of the shoulder and, therefore, dynamically modifies the potential risk of injury.

In addition to the mean decreases in ER ROM and isometric peak torque after the high-intensity training, the variability of the responses among swimmers was important (Figures 4.1 and 4.2).

Windt and Gabbett (2017) proposed that a specific external load elicits different internal responses. Our results support this concept: the same training intensity produced different responses among swimmers. Thus, the shoulder physical qualities need to be regularly monitored, and training loads need to be progressed individually (Soligard et al., 2016).

Training intensity

The intensity of the sessions was defined by the coach and determined by the volume swum at or above the pace threshold. The swimmers exhibited higher RPE values after the high-intensity session (7.44 ± 1.3) than the low-intensity session (2.44 ± 1.2). Based on the modified version of the category-ratio scale of Borg (Foster et al., 2001), the low-intensity session was perceived as easy, whereas the high-intensity session was perceived as very hard. A mean RPE value of 7 ± 1.3 has been associated with the onset of blood lactate accumulation in female distance runners (Abe et al., 2015). Hence, the high-intensity session would probably result in the accumulation of blood lactate, leading to fatigue. This might explain the negative effects on ER ROM and rotation isometric peak torque after the high-intensity but not the low-intensity session.

Shoulder-rotation ROM

Internal-rotation ROM was not affected after the high- or low-intensity training session. These results are in accordance with those of Matthews et al. (2017) and Higson et al. (2018), who reported no changes in IR ROM after a swim-training session. In contrast, acute reductions in IR ROM of the dominant side have been described after tennis (Moore-Reed et al., 2016) and baseball (Reinold et al., 2008) training. Researchers (Moore-Reed et al., 2016) have indicated that the high levels of eccentric stress placed on the external rotators to decelerate the throwing or striking motion may increase posterior rotator cuff stiffness and consequently decrease IR ROM. The lack of changes found in the studies of swimmers might be explained by the low activation level of the external rotators during the freestyle stroke (Pink et al., 1991) combined with the endurance nature of the sport. Regarding ER ROM, we observed reductions after the high-intensity but not the low-intensity training session. After the high intensity session, ER ROM decreased by 7.8° on the dominant side and 6.5° on the nondominant side with large effect sizes (dominant side: $d = 1.10$; nondominant side: $d = 1.02$). An effect size of 1.0 indicates that the mean of the postsession is at the 84th percentile of the presession; thus, a swimmer with an average score in the postsession had a lower ER ROM score than 84% of the swimmers in the presession (Coe, 2002). Also, the probability of correctly guessing if a swimmer performed a low- or high-intensity session was 69% based on the ER ROM score alone (Coe, 2002). Furthermore, post-swim changes in ROM exceeded the MDC on both sides. Therefore, we can be 95% confident that the changes in ER ROM after a high-intensity training session were attributable to the swim training and not due to measurement error. The large effect sizes reported and the values exceeding the MDC confirmed the clinical meaningfulness of the changes in ER ROM.

Authors of two studies of swimmers (Higson et al., 2018; Matthews et al., 2017) have noted reductions in ER ROM after a training session. Matthews et al. (2017) found ER ROM decreases of 5.29° on the dominant side and 3.18° on the nondominant side after a fatiguing protocol consisting of 8 sets of a 100-m swim. The effect sizes were moderate for the dominant side ($d = 0.75$) and small for the nondominant side ($d = 0.42$). The larger effect sizes in our study may be explained by the greater total training volume (3000 m versus 1000 m). However, given the different definitions of training intensity and measures used to confirm fatigue, it is difficult to compare studies. Matthews et al. (2017) set the swimming intensity at 85% of the swimmers' best 100-m times, and blood lactate levels were used as an objective measure to confirm fatigue. In contrast, in our study, the intensity was set in relation to the threshold pace, and RPE was used as a subjective measure of fatigue. In a later study, Higson et al. (2018) demonstrated a decrease in ER ROM of 3.4°, with a moderate effect size ($d = 0.34$) after a 2-hour training session. Higson et al. (2018) defined the external training load only in terms of time (2 hours), without specifying the distance or intensity. Furthermore, the internal loads were not measured; therefore, the swimmers' response to the training was unknown. Consensus statements on training loads and injury (Bourdon et al., 2017; Soligard et al., 2016) recommended combining internal and external training loads to monitor an athlete's response to training. Moreover, subjective measures of internal loads, such as the RPE, could be preferable because they are easily used in the clinical setting (Soligard et al., 2016).

The acute reductions in ER ROM after swim training may be explained by the biomechanics of the stroke. The repetitive forces during swimming can lead to hypertrophic changes and muscular tightness of the internal rotators, consequently decreasing ER ROM (Higson et al., 2018). Deficits in shoulder ER ROM have been shown to be a potential risk factor for shoulder pain in competitive swimmers (Walker et al., 2012). In a 1-year prospective study, Walker et al. (2012) found that competitive swimmers with ER ROM values < 93° measured actively at the beginning of the season were at 12.5 times greater risk of developing shoulder pain that resulted in missed or modified training. The authors (Walker et al., 2012) suggested that limited

ER ROM during the recovery phase may contribute to shoulder pathomechanics. Interestingly, after the high-intensity training session, half of our swimmers (8/16) decreased their ER ROM to < 93° in the dominant limb. In contrast, after the low-intensity session, only one swimmer had an ER ROM of < 93° on the dominant side. After a high-intensity training session, active ER ROM decreased to values associated with the risk of shoulder injury in a significant number of swimmers.

Shoulder-rotation isometric peak torque

Isometric peak torque decreased for both the internal and external rotators after the high-intensity but not the low-intensity session. After the high-intensity session, torque decreased between 6.6% and 11.4% of body weight. In spite of the changes, the effect sizes were small, ranging from 0.20 to 0.42. This indicated that a swimmer with an average score in the postsession had less rotation torque than 58% to 66% of the swimmers in the presession (Coe, 2002). Furthermore, the probability of correctly guessing if a swimmer performed a low- or high-intensity session was between 54% and 58% based on test score alone (Coe, 2002). Only the changes in the external rotators of the nondominant side exceeded the MDC. Therefore, we can be 95% confident that the changes were attributable to the swim training and not to measurement error. The changes in the internal-rotator torque on both sides and external-rotator torque on the dominant side exceeded the SEM but not the MDC. Hence, we can be confident only 68% of the time that the changes were not due to an error. The interpretation of these results indicated that the small effect sizes for isometric peak torque might weaken their clinical meaningfulness. Furthermore, only the changes in the external rotators on the nondominant side exceeded the MDC and, consequently, reflected clinical meaningfulness.

Matthews et al. (2017) were the sole researchers to investigate the effect of swim training on shoulder isometric force, and they reported contradictory findings. Although fatigue was confirmed by blood lactate levels, rotation isometric force did not change after a swim-training session in 17 national-level swimmers (Matthews et al., 2017). Given the different training protocols performed, it is difficult to explain the variable findings between studies. Considering that the participants' ages and levels of competition were similar, the different testing positions might have influenced the results. We assessed force in the supine position, whereas Matthews et al. (2017) measured it in the standing position. Authors (El-Sais & Mohammad, 2014) have suggested that upper limb strength assessments performed in the standing position are influenced by the synergistic effects of the lower limb muscles. The lack of change in shoulder force described by Matthews et al. (2017) may have been due to compensation of the lower limbs.

The acute decrease in internal-rotator torque that we noted may be explained by the predominant internal-rotator forces that occur during swimming (Pink et al., 1991). Because of the repetitive internal-rotator forces, the subscapularis muscle is constantly active during all stroke phases, stabilizing the glenohumeral joint (Pink et al., 1991). However, this constant activity may render the subscapularis muscle susceptible to fatigue (Pink et al., 1991). Deficits in internal-rotator forces have been shown to be a potential risk factor for shoulder pain in swimmers (Bak & Magnusson, 1997; Tate et al., 2012). Bak and Magnusson (1997) and Tate et al. (2012) identified decreases in internal-rotator force in the injured shoulders of competitive swimmers, suggesting that internal-rotator deficits may affect stroke dynamics. These findings are supported by Scovazzo et al. (1991), who used electromyography to demonstrate decreased subscapularis activity during the midrecovery phase in the painful shoulders of swimmers.

Regarding external-rotator torque, we reported decreases after the high-intensity session on both the dominant and nondominant sides. The infraspinatus muscle is mainly active during the midrecovery phase to control the internal-rotator forces of the subscapularis muscle, whereas the teres minor muscle controls the internal-rotator forces of the pectoralis major muscle during the pull phase (Pink et al., 1991). With respect to the relationship between external-rotator weakness and risk of shoulder injury in swimmers, Beach et al. (1992) determined that swimmers with shoulder pain displayed decreased external-rotator endurance as measured using isokinetic dynamometry. Investigators (Labriola et al., 2005) have indicated that decreased infraspinatus activity led to glenohumeral instability, which may result in functional impingement. However, given the cross-sectional designs of studies addressing the relationship between shoulder pain and rotator force, whether the force deficits seen were due to pain inhibition or a compensatory strategy to remain pain free is unknown. In addition to ER ROM, we found greater mean reductions in rotation isometric peak torque on the dominant than the nondominant side. An explanation for these findings may be that during swimming, the dominant limb is mainly used for propulsion and the nondominant limb for control and support (Higson et al., 2018). Despite the greater mean reductions on the dominant side, the changes on the nondominant side were more variable (Figures 4.1 and 4.2).

Limitations

Our study had limitations. Although we calculated the necessary sample size, it was small for the competitive swimmer population and probably limits the generalization of the results. The large age range could also have been a limitation because it might not have represented the adaptations of a specific age group. A history of shoulder pain was a nonmodifiable risk factor for shoulder pain in swimmers (Chase et al., 2013; Tate et al., 2012). We excluded only swimmers with shoulder pain at the time of the study or any pain in the two weeks before the study that had interfered with the ability to train or compete fully and did not exclude swimmers with a history of shoulder pain. A history of shoulder pain might have been a confounding factor that affected the results. However, studying swimmers without a history of shoulder pain is challenging because most describe either a history of shoulder pain or shoulder symptoms at the time of testing (Higson et al., 2018). Another limitation of our study was that all swimmers were not all measured on the same day because only one researcher was available. To mitigate this, the measurements were taken on the same days and at the same times every week. Yet other uncontrollable factors could have influenced the results. Despite the pre- and postswim differences in rotation torque and values exceeding the SEM, the reader must be aware of the small effect sizes. This might be a problem with respect to determining a true difference between pre- and postswim scores. Another possible limitation was that swimmers were not randomized to the different intensity sessions. Instead, we performed the tests in block order: the high-intensity session on Wednesday and the low-intensity session on Friday of the same week. It is possible that the results of the Friday sessions could have been affected by the Wednesday sessions. Still, no changes occurred in the Friday sessions; therefore, carryover effects did not appear to have influenced the Friday sessions, regardless of the activity on Thursday. In addition, we focused only on the acute postswim adaptations as a result of training intensity without including other training-load variables, such as time and volume. Finally, we assessed only the interactions between training loads and musculoskeletal risk factors. Bittencourt et al. (2016) suggested that the athlete should be analysed as a complex system, with a focus on multilevel risk factors, including biomechanical, behavioural, psychological, and physiological factors.

Further research is needed to analyse the adaptations in different age groups and levels of competition. Also, larger sample sizes will allow swimmers to be subdivided into groups according to their training responses so that we can understand specific group adaptations. It may also be necessary to investigate how other components of training loads, such as training time and volume, affect these physical qualities. Furthermore, it is important to evaluate the cumulative effects of training loads on these physical qualities. Ideally, longitudinal research should be done to monitor ER ROM and isometric peak torque, which will allow us to understand changes over time and their relationship with the development of shoulder pain. Additional work is needed to evaluate the recovery time of these variables after a high-intensity session. Finally, investigating the interactions of training loads with psychological and behavioural factors may also be necessary.

4.5. Conclusions

Our results demonstrated that the intensity of a training session may be an important factor that leads to maladaptive changes in the physical qualities of the shoulder. A high-intensity training session immediately decreased shoulder active ER ROM and rotation isometric peak torque in competitive swimmers, particularly on the dominant side. However, we observed no changes in any of the physical qualities after the low-intensity session. We showed that these physical qualities changed dynamically as a result of the training load applied. This provides information about the short-term interaction between training intensity and the physical qualities of the shoulder in competitive swimmers. Shoulder ER ROM and rotator force have been described as potential modifiable risk factors for shoulder pain in this population; hence, their maladaptive changes may increase the risk of shoulder injury in subsequent training. Considering this, the application of appropriate training loads may be required to minimize the risk of injury associated with these changes. High training loads are necessary to increase load capacity and tolerate further loads (Windt & Gabbett, 2017); nevertheless, it is essential to know when to train hard. Understanding the appropriate timing of a strenuous training session can enhance load capacity and performance without increasing the detrimental effects on shoulder physical qualities. Clinically, our findings suggested the importance of individual in-season monitoring of ER ROM and rotation isometric peak torque. Regular monitoring can ensure that swimmers have restored these qualities before or after undertaking high-intensity training. If these qualities are impaired before a high-intensity session, practitioners and coaches can adjust the training loads to avoid further maladaptations and reduce the potential risk of injury. Furthermore, identifying deficits in post-swim rotation torque and ER ROM may permit early interventions and serve as a practical way to reduce the athlete’s susceptibility to shoulder injury. In addition, an individualized regular exercise program to maintain ER ROM and improve shoulder-rotation torque should be performed to minimize these post-swim adaptations. Finally, training intensity can be easily quantified in clinical practice by the RPE, which provides an individual perspective of the training load.

4.6. The rationale for Chapter 5

Despite the efforts to reduce the time of the measurement procedure in the pilot study (Chapter 3), the testing took around 20 minutes per swimmer (measuring six shoulder physical qualities). Considering the large amount of time, only the tests that showed a significant change in the present study (shoulder ER ROM and isometric peak torque) will be included in the next investigations. For the next chapter, the response to training will also be investigated in different levels of competition. This is important as the level of competition has been reported as an important non-modifiable risk factor for shoulder pain in swimmers (Section 2.5.2.1 of Chapter 2).

Chapter 5

The effects of a differing swim-training session density on shoulder range of motion and isometric torque production in national and university level swimmers

ABSTRACT

Background: Well-developed physical qualities (i.e., greater load capacity) in athletes can provide protection against injuries. Although higher competitive level swimmers have more developed physical qualities, no studies have investigated how physical qualities of the shoulder respond to a swim-training session in different competitive levels.

Purpose: To compare baseline shoulder external rotation range of motion (ER ROM) and rotation isometric peak torque between national and university level swimmers with differing training volumes. A secondary objective was to compare the post-swim changes of these physical qualities between groups.

Study design: Cross-sectional.

Setting: Indoor swimming pool.

Methods: Ten healthy male swimmers were included. Based on their level of competition, they were divided into high-load (N = 5 national level; age = 18.0 ± 1.2 years) and low-load groups (N = 5 university level; age = 19.4 ± 0.9 years). For each group, shoulder ER ROM and shoulder-rotation isometric peak torque were measured before and after a high-intensity swim-training session. Session rating of perceived exertion (sRPE) was calculated after the swim session.

Results: University swimmers had lower baseline ER torque (P= 0.007-0.006; d= 2.50-2.55) and internal rotation (IR) torque (P= 0.011-0.014; d= 2.12-2.42). For post-swim analysis, ER ROM decreased more in university swimmers (change= 6.3°-8.4°; d= 0.75-1.05) than national counterparts (change= 1.9°-5.7°; d= 0.43-0.95). Greater drops in rotation torque were also found in university swimmers (IR change= 15%-21.0%; d= 0.83-1.66; ER change = 9.0%-17.0%; d= 1.14-1.28) compared to national counterparts (IR change= 10.0%-13.0%; d= 0.61-0.91; ER change = 3.7%-9.1%; d= 0.50-0.96). The average change of all tests in university swimmers exceeded the minimal detectable change (MDC), whereas in national level swimmers (depending on the test) some exceeded the MDC and others only the standard error of measurement. Despite this, only post-swim ER torque in the dominant side (P= 0.003; d= 1.18) and sRPE^{km} (P < 0.001; d= 3.75) were lower in university swimmers. Individual analysis showed that the physical qualities in most participants in both groups (> 80%) decreased after the session, with a greater number of university swimmers exceeding the MDC.

Conclusions: University swimmers have less baseline shoulder rotator torque and had greater drops in shoulder physical qualities after a swim-training session, which may have implications for injury risk, but, due to the sample size, the results have to be interpreted with caution.

Key Words: shoulder pain, swimming, load capacity, physical qualities.

Highlights:

- Baseline shoulder ER ROM was similar between groups; however, shoulder rotator torque was lower in university-level swimmers compared to national-level counterparts.
- University-level swimmers experienced greater drops in shoulder external rotation ROM and rotation isometric peak torque after a high-intensity training session.
- Higher chronic loads and better developed shoulder physical qualities in swimmers might be protective against drops in shoulder strength and ROM after a high-intensity swim-training session.

5.1. Introduction

The shoulder is the most common body part injured in swimmers with a prevalence reported as high as 91% (Sein et al., 2010). The level of competition has been reported as a potential nonmodifiable risk factor for shoulder pain in this population (Hill et al., 2015). This might be explained as swimmers of a higher competitive level are exposed to greater chronic loads (e.g. weekly swim-training volume and number of training sessions) (Feijen, Tate, Kuppens, Claes, et al., 2020). However, higher levels of competition have also been associated with more developed physical qualities, such as aerobic capacity and shoulder strength (Bae et al., 2016; Cheung et al., 2018), which might also protect against injury in swimmers ('training load-injury paradox') (Gabbett, 2016). A recent study (Feijen, Struyf, et al., 2020) found that club-level swimmers had a higher risk of shoulder pain than regional-level counterparts during a two-year follow-up. A possible explanation for this is that fitter and stronger athletes (i.e., higher load capacity) can better tolerate the amount of and changes in workloads (Malone et al., 2019; Møller et al., 2017).

Some studies have investigated how swimmers respond to training loads (Higson et al., 2018; Matthews et al., 2017; Yoma et al., 2021). These researchers found that a swim-training session negatively affect shoulder physical qualities, such as rotation strength (Yoma et al., 2021), rotation ROM (Higson et al., 2018; Matthews et al., 2017; Yoma et al., 2021), pectoralis minor length (Higson et al., 2018), and joint position sense (Higson et al., 2018; Matthews et al., 2017). Since some of these physical qualities have been considered potential risk factors for shoulder pain in swimmers (Hill et al., 2015; Struyf et al., 2017), their acute impairments can increase the risk of shoulder injury (Windt & Gabbett, 2017). The injury-aetiology model proposed by Windt & Gabbett (2017) suggested that the risk of injury can increase as a result of training loads applied and the negative effects on modifiable risk factors (e.g., physical qualities). Although these studies investigated different levels of competition, it is difficult to make comparisons as the studied swim-sessions varied in terms of volume, intensity, and time. Therefore, it is unknown whether higher-level swimmers (i.e., stronger and fitter athletes) have less significant decreases in physical qualities than lower-level counterparts after a similar swim-training session.

To date, some studies have shown that swimmers of a higher competitive level have more developed shoulder physical qualities (Bae et al., 2016; Cheung et al., 2018). However, no studies have compared the post-swim changes in shoulder physical qualities between different levels of competition. Investigating this could help to understand whether higher chronic loads and well-developed physical qualities affect post-training shoulder responses. This might have implications in the prevention of shoulder pain in specific groups.

The primary aim of this study was to compare the baseline differences in shoulder ER ROM and rotation isometric peak torque between university and national level swimmers with different training volumes. A secondary aim was to compare the post-swim changes of these physical qualities within and between groups. The null hypothesis was that there will be no significant difference between groups in baseline shoulder ER ROM and isometric peak torque. Also, there will not be a significant difference in post-swim changes in these physical qualities within and between groups.

5.2. Methods

Participants

A sample of ten male participants was included in the study. Participants were divided into two groups according to their level of competition: university level (N = 5) and national level swimmers (N = 5). Participants of both groups were matched by gender, age, and years of swimming experience, but differed in training volume (Table 5.1). All swimmers trained within the same group during the year, completed the same practices regularly, and participated in either university or national championships. The exclusion criteria included a history of shoulder surgery, shoulder pain at the time of the study, and any pain in the two weeks before the study that interfered with the ability to train or compete fully (Higson et al., 2018). All participants provided written informed consent. This study was approved by our university's ethics board and conducted in accordance with the Declaration of Helsinki (Ref.no.HSR1718-100).

Table 5.1 - Descriptive and baseline characteristics of participants

	University swimmers (n = 5)		National swimmers (n = 5)		Between group
	Mean ± SD	Range (min-max)	Mean ± SD	Range (min-max)	P Value
Age (y)	19.4 ± 0.9	2.0 (19 – 21)	18.0 ± 1.2	3.0 (17.0 – 20.0)	0.062
Body mass (kg)	83.2 ± 5.2	14.0 (75.0 – 89.0)	69.9 ± 6.9	19.1 (60.3 – 79.4)	0.009[a]
Height (cm)	176.0 ± 12.3	30.0 (155.0 – 185.0)	171.8 ± 10.5	27.0 (155.0 – 182.0)	0.578
Weekly swim-volume (km)	6.8 ± 1.8	4.0 (6.0 – 10.0)	37.0 ± 2.7	5.0 (35.0 – 40.0)	<0.001[a]
Weekly training sessions (n)	2.6 ± 0.9	2.0 (2- 4)	8.2 ± 1.1	2.0 (8-9)	<0.001[a]
Weekly training hours (hr)	5.2 ± 1.8	4.0 (4-8)	16.8 ± 1.1	2.0 (16-18)	<0.001[a]
Swimming experience (y)	8.8 ± 1.6	3.0 (7.0 – 10.0)	8.0 ± 0.84	2.0 (7.0 – 9.0)	0.260
History of shoulder pain (yes: no)	4:1		4:1		1.0

[a] Significant difference between groups ($P < 0.05$).

Procedures

The same researcher (MY) performed all the tests in both groups. For each swimmer, measurements were recorded before and after a swim-training session. On the testing day, participants´ general demographic information, such as sex, age, limb dominance, height, mass, and forearm length, was recorded. Before the testing procedure, participants performed a standardized land-based warm-up consisting of shoulder movements. Immediately after the warm-up, baseline measurements were recorded in the following order: shoulder ER ROM and shoulder-rotation isometric peak torque. All the tests were standardized, and the dominant arm was assessed first. Three subsequent testing trials of each test were performed in both limbs, and the results were averaged for further analysis. Immediately after completion of the training, swimmers exited the pool and repeated baseline testing.

Instrumentation and outcome measures

The same procedure for shoulder ER ROM and rotation isometric peak torque was used, as previously described in Section 3.3 of Chapter 3. Furthermore, the same measurement error values found in Chapter 3 (pilot study) were used for this study (Tables 3.3 to 3.5).

Description of the training sessions

For each group, the hardest swim-session of the week was analysed. The rationale for this was because a study (Yoma et al., 2021) found changes in shoulder physical qualities only after a high-intensity swim-training. Based on the coaches´ perception, Wednesday evening session was chosen. Data of both groups was collected on the same day of the week, time, and period of the year. Both sessions lasted one hour. The only difference between sessions was the total swim-volume performed; national level swimmers performed a greater volume (3 km) than university swimmers (2 km). To assess how swimmers perceived the intensity of the training, the session-RPE (sRPE) was calculated. sRPE is a valid and reliable method to monitor training load in various sports and populations (Haddad et al., 2017). Two methods of sRPE were used to quantify the internal training load: $sRPE^{h}$ and $sRPE^{km}$ (Collette et al., 2018).

First, the intensity of the session was quantified by the RPE based on the modified version of the category-ratio scale of Borg (Foster et al., 2001). Immediately after completing the training, the swimmers were asked, “How hard was your workout?” using an 11-point scale with 0 corresponding to ‘rest’ and 10 to ‘maximal’ effort. For $sRPE^{h}$, the RPE score was multiplied by the session duration (min) and expressed in arbitrary units (AU). Whereas, for $sRPE^{km}$, the RPE was multiplied by the volume (km) and also expressed in arbitrary units (AU). This method has been used especially in swimmers to quantify internal training loads as it includes the volume swam (Collette et al., 2018; Nagle et al., 2015). Collette er al. (2018) found that the $sRPE^{km}$ was the strongest measure associated with the recovery-stress status of swimmers during a training season.

Statistical analysis

For statistical analysis, SPSS version 25 for Windows (Inc, Chicago, IL) was used. The Shapiro Wilks test was performed to determine if the variables had a normal distribution. Demographic data were screened for between-group differences using independent sample t-tests for normally distributed (weight and height) data and Mann Whitney test for non-normally distributed data (age, swimming distance, training time, number of sessions, swimming experience, and history of shoulder pain).

Regarding the outcome measures (shoulder ROM and rotation torque), all presented normal distribution. For the first objective, independent sample t-tests were used to assess baseline differences between groups. For the second objective, paired student t-test was used to assess within-group differences between pre-and post-measurements, and independent sample t-tests were used to assess between-group differences in post-swim changes. Differences were considered significant when p values were ≤ 0.05. Also, Cohen’s d effect size (ES) was calculated to determine the magnitude of any difference between measurements (Cohen, 1988). The following ES values were considered: > 0.8 (large), between 0.5 and 0.79 (medium), between 0.49 and 0.20 (small), and < 0.2 (trivial). Given the small sample size (n ≤ 10), results were presented in scatterplots to examine data distribution (Weissgerber et al., 2017).

5.3. Results

No differences were found between groups based on age, sex, height, years of swim, and history of shoulder pain (Table 5.1). The high-level group reported greater swim-training volume (P < 0.001), hours of training (P < 0.001), training sessions (P < 0.001), and less body mass (P = 0.009) than the low-level group. Table 5.2 and 5.3 show baseline and pre-post differences of the outcome measures, respectively. Figures 5.1 and 5.2 present the results for shoulder ER ROM and rotator peak torque, respectively.

Baseline differences between groups

University swimmers presented a lower baseline torque than national counterparts for external rotators (dominant side: P = 0.007; d = 2.50 and nondominant side: P = 0.006; d = 2.55) and internal rotators (dominant side: P = 0.011; d = 2.12 and nondominant side: P = 0.014; d = 2.42). There was no significant difference between groups for ER ROM and ER: IR ratio. Individual analysis showed that 80% (4 out of 5) and 100% (5 out of 5) of national swimmers had higher baseline rotator torque than university counterparts in the dominant and nondominant side, respectively.

Table 5.2 - Baseline difference between groups for shoulder external rotation range of motion and rotation isometric peak torque normalized to body weight.

Test		University swimmers	National swimmers	Mean difference	P Value	Effect size
External Rotation ROM, °	D	105.3 ± 10.9	100.3 ± 3.3	5.0	0.376	0.70
	ND	97.4 ± 5.6	98.2 ± 4.0	0.8	0.973	0.17
External rotator torque, Nm/kg	D	0.43 ± 0.05	0.53 ± 0.03	0.10	0.007[a]	2.50
	ND	0.39 ± 0.05	0.53 ± 0.06	0.14	0.006[a]	2.55
Internal rotator torque, Nm/kg	D	0.41 ± 0.08	0.59 ± 0.09	0.18	0.011[a]	2.12
	ND	0.40 ± 0.06	0.63 ± 0.13	0.24	0.014[a]	2.42
ER: IR ratio	D	1.08 ± 0.11	0.92 ± 0.14	0.16	0.081	1.28
	ND	0.97 ± 0.12	0.85 ± 0.12	0.12	0.167	1.0

[a] Significant difference between groups (P < 0.05).

Post-swim shoulder external rotation ROM

University swimmers reported mean decrease with moderate ES for the dominant side (P = 0.003; change = -8.4°; d = 0.74). Although decreases on the nondominant side had large ES (d = 1.05; change = -6.4°), the difference was not significant (P = 0.062). The mean value of change on both sides exceeded the MDC. Individual analysis showed that all participants in this group reduced the ER ROM on both sides. Furthermore, that 80% (4 out of 5) of the participants exceeded the MDC on the dominant side and 40% (2 out of 5) on the nondominant side.

In national swimmers, no significant pre-post differences were found on either side. Despite this, the ES was large for the dominant side (d = 0.95) and moderate for the nondominant side (d = 0.43). The value of change on the dominant side only exceeded the SEM, whereas, on the nondominant side, it did not exceed the measurement error. Individual analysis showed that all participants reduced ER ROM on the dominant side and 80% (4 out of 5) on the nondominant side. Furthermore, 20% (1 out of 5) of the participants exceeded the MDC on both sides. There was no significant difference between groups.

Table 5.3 - Mean results from pre-swim and post-swim of high-Intensity training sessions for rotation range of motion and isometric peak torque normalized to body weight.

Test	Side	Pre-swim	Post-swim	Mean difference	Mean % change	Effect size	P Value	Between group	Effect size
University swimmers									
External rotation ROM, °	D	105.3 ± 10.9	96.9 ± 11.9	-8.4	-8.1 ± 3.0	0.74	0 .003[a]	0.444	0.35
	ND	97.4 ± 5.6	91.1 ± 6.3	-6.3	-6.4 ± 5.5	1.05	0.062	0.200	0.85
External rotator torque, Nm/kg	D	0.43 ± 0.05	0.36 ± 0.04	-0.07	-17.2 ± 6.0	1.28	0.004[a]	0.003[b]	1.18
	ND	0.39 ± 0.05	0.35 ± 0.04	-0.04	-9.0 ± 8.8	1.14	0.075	0.914	0.19
Internal rotator torque, Nm/kg	D	0.41 ± 0.08	0.32 ± 0.06	-0.09	-21.5 ± 9.4	1.66	0.024[a]	0.160	0.13
	ND	0.40 ± 0.06	0.35 ± 0.03	-0.05	-15.1 ± 18.1	0.83	0.108	0.615	0.33
ER: IR ratio	D	1.08 ± 0.11	1.14 ± 0.11	+0.06	+6.3 ± 10.8	0.57	0.273	0.329	0.41
	ND	0.97 ± 0.12	0.99 ± 0.06	+0.03	+3.9 ± 11.3	0.12	0.600	0.763	0.18
National swimmers									
External rotation ROM, °	D	100.3 ± 3.3	94.6 ± 4.5	-5.7	-5.7 ± 6.9	0.95	0.127	NA	NA
	ND	98.2 ± 4.0	96.4 ± 4.5	-1.8	-1.9 ± 4.6	0.43	0.421	NA	NA
External rotator torque, Nm/kg	D	0.53 ± 0.03	0.51 ± 0.05	-0.02	-3.7 ± 4.0	0.50	0.103	NA	NA
	ND	0.53 ± 0.06	0.48 ± 0.06	-0.05	-9.1 ± 9.6	0.96	0.145	NA	NA
Internal rotator torque, Nm/kg	D	0.59 ± 0.09	0.51 ± 0.09	-0.08	-13.9 ± 4.0	0.91	0.002[a]	NA	NA
	ND	0.63 ± 0.13	0.55 ± 0.14	-0.08	-10.7 ± 5.1	0.61	0.001[a]	NA	NA
ER: IR ratio	D	0.92 ± 0.14	1.03 ± 0.13	+0.11	+12.0 ± 5.2	0.80	0.004[a]	NA	NA
	ND	0.85 ± 0.12	0.90 ± 0.15	+0.05	+6.2 ± 11.9	0.35	0.311	NA	NA

Abbreviation: NA, not applicable

[a] Significant difference within group ($P < 0.05$).

[b] Significant difference between groups ($P < 0.05$).

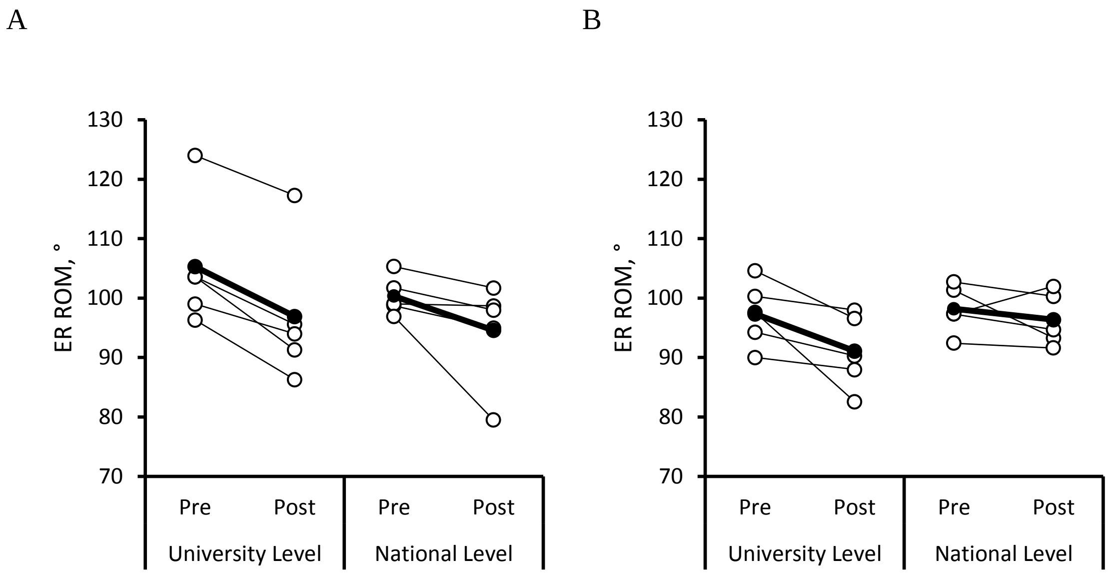

Figure 5.1 - Scatterplots showing pre-swim and post-swim changes in shoulder ER ROM for university and national swimmers. A, dominant shoulder. B, nondominant shoulder. The lines indicate the mean value.

<u>Post swim shoulder rotation isometric torque</u>

Regarding internal rotator torque, university swimmers reported a mean decrease with large ES for the dominant side (P = 0.024; change = 21.5%: d = 1.66). Although the decreases on the nondominant side had large ES (change = 15.1%: d = 0.83) the difference was not significant (P = 0.108). On both sides, the value of change exceeded the MDC. Individual analysis showed torque reductions in all participants on the dominant side and 80% (4 out of 5) on the nondominant side. Furthermore, 60% (3 out of 5) of the participants exceeded the MDC values in both sides. National swimmers had significant decreases with large ES for the dominant side (P = 0.002; change = 13.9%: d = 0.91) and moderate ES for the nondominant side (P = 0.001; change = 10.7%: d = 0.61). The value of change exceeded the MDC on the nondominant side and only exceeded the SEM on the dominant side. Individual analysis showed torque reductions in all participants on both sides. Furthermore, 20% (1 out of 5) of the participants exceeded the MDC in the dominant side and 80% (4 out of 5) in the nondominant side.

For external rotator torque, university swimmers reported a mean decrease with large ES for the dominant side (P = 0.004; change = 17.2%: d = 1.28). Although reductions on the nondominant side had large ES (change = 9.0%: d = 1.14), the difference was not significant (P = 0.075). On both sides, the value exceeded the MDC. Individual analysis showed torque reductions in all participants on the dominant side and 80% (4 out of 5) on the nondominant side. Furthermore, 80% (4 out of 5) of the participants exceeded the MDC on the dominant side and 60% (3 out of 5) on the nondominant side. National swimmers had no significant differences on the dominant (P = 0.103; change = 3.7%: d = 0.50) and nondominant sides (P = 0.145; change = 9.1%: d = 0.96). On the dominant side, the value of change did not exceed the measurement error. Whilst, on the nondominant side, it exceeded the MDC. Individual analysis showed torque reductions in 80% (4 out of 5) of the participants on both sides. Furthermore, none of the participants exceeded the MDC on the dominant side and 60% (3 out of 5) on the nondominant side.

There was no significant difference between groups for internal rotator (both sides) and for external rotator of the nondominant side. However, external rotator torque of the dominant side was significantly lower in university swimmers compared to national counterparts (P = 0.003; d = 1.18).

Shoulder ER: IR ratio

University swimmers reported no significant differences in any side. Individual analysis showed increases in 80% (4 out of 5) of the participants on the dominant side and 60% (3 out of 5) on the nondominant side. National swimmers reported a significant increase on the dominant side with large ES (P = 0.004; d = 0.80) but no differences on the nondominant side (P = .311). Individual analysis showed ratio increases in all participants on the dominant side and 80% (4 out of 5) on the nondominant side. There was no significant difference between groups.

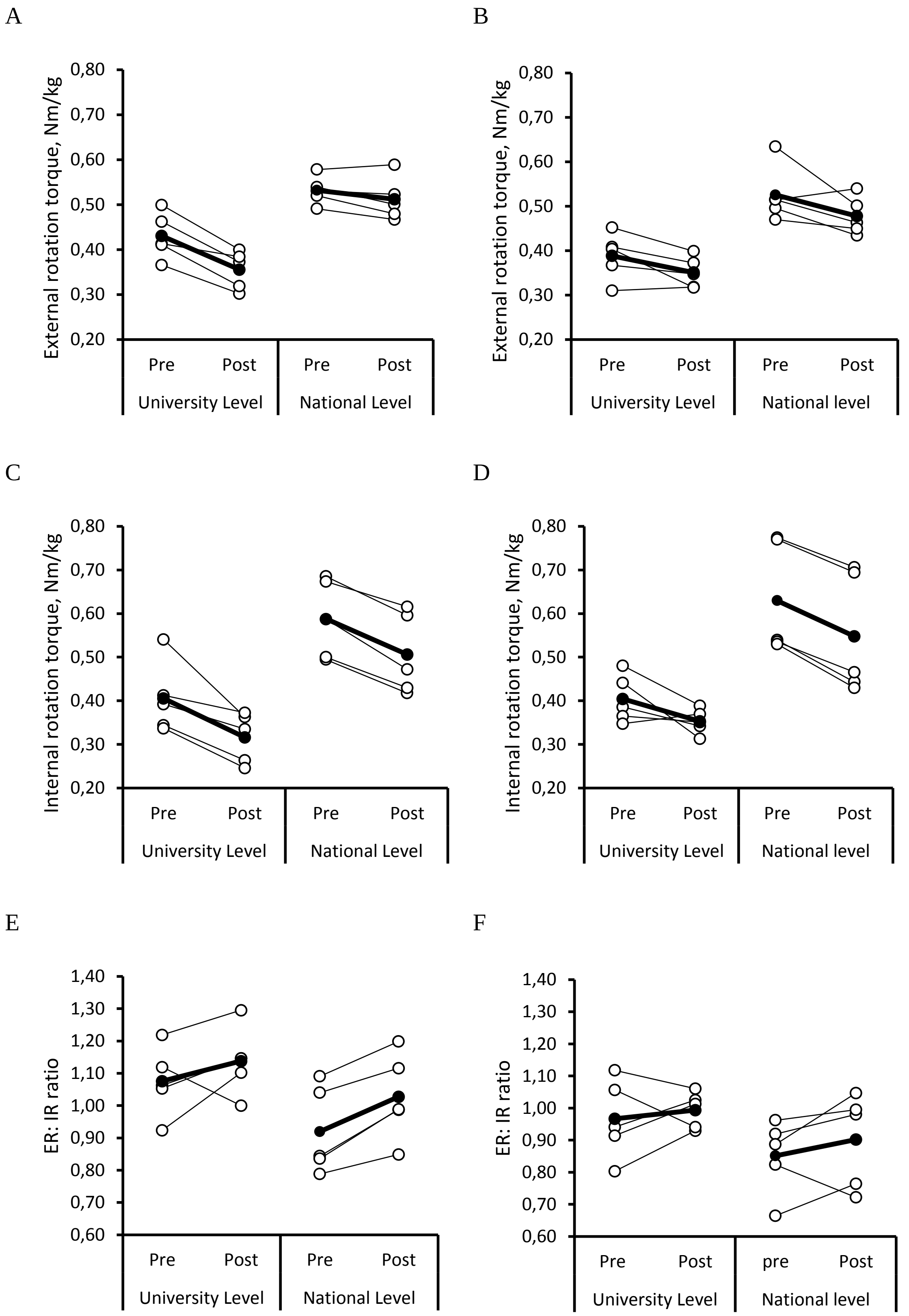

Figure 5.2 - Scatterplots showing pre-swim and post-swim changes in shoulder rotation torque for national and university swimmers. A, External rotators on the dominant shoulder. B, External rotators on the nondominant shoulder. C, Internal rotators on the dominant shoulder. D, Internal rotators on the nondominant. E, ER:IR ratio on the dominant side. F, ER:IR ratio on the nondominant side. The lines indicate the mean value.

Session-RPE

University swimmers reported an RPE average of 6.4 ± 1.5 (min-max = 5-9), whereas national counterparts reported an average of 8.2 ± 1.1 (min-max = 7-9). Considering that both groups performed a 60-minute session, $sRPE^{h}$ average was 384 ± 91 AU (min-max = 300 – 540 AU) for university swimmers and 492 ± 65.7 AU (min-max = 420 – 540 AU) for national counterparts. The difference between groups was not significant (P = 0.064). Individual analysis showed that 80% (4 out of 5) of national swimmers reported higher RPE and $sRPE^{h}$ than university. Regarding $sRPE^{km}$, university swimmers reported an average of 12.8 ± 3.0 AU (min-max = 10 – 18 AU) and national swimmers an average of 24.6 ± 3.3 AU (min-max = 21 -27 AU). In this case, the difference was significant with large ES ($P < 0.001$; $d = 3.75$). Furthermore, all national swimmers reported higher $sRPE^{km}$ than university counterparts.

5.4. Discussion

The aims of this study were two-fold:

- To compare the baseline differences in shoulder ER ROM and rotation isometric peak torque between university and national level swimmers with differing training volumes.
- To compare the post-swim changes of these physical qualities within and between groups.

For the first objective, the null hypothesis was partially rejected. University swimmers had significantly less shoulder rotator torque at baseline. However, there was no baseline difference in shoulder ER ROM between groups. For the second objective, the null hypothesis was also partially rejected. University swimmers had a significant post-swim decrease of shoulder ER ROM and rotation torque of the dominant side, whereas, national swimmers had significant decreases in bilateral internal rotator torque. For differences in between-groups, only external rotator torque of the dominant side was significantly lower in university swimmers. The lack of significance of some variables might be explained by the small sample size (type II error). If we compare groups using ES and whether the results exceeded the measurement error or not, university swimmers showed more meaningful decreases in physical qualities after the training session (this will be discussed in detail in the following subsection). This is important as the ES is not heavily affected by the sample size (Lininger & Riemann, 2018). Our results suggest that swimmers of a lower competitive level have less shoulder rotation torque, which might then predispose them to greater changes after a high-intensity swim-session. However, the results must be interpreted with caution due to the small sample size.

Group characteristics

Both groups were composed of male swimmers of a similar age and years of swimming experience. The main differences between groups were the amounts of training to which they had been exposed. As competitive level increases, so does the number of sessions and swim-training volume (Feijen, Tate, Kuppens, Claes, et al., 2020). In our study, national swimmers performed on average 37.0 ± 2.7 km per week, which is 5.4 times more than the university swimmers (average = 6.8 ± 1.8 km). Furthermore, national swimmers performed an average of 11.6 hours and 5.6 sessions of extra training per week compared to university counterparts. This shows that national swimmers were exposed to higher chronic loads.

Shoulder rotation torque

Baseline rotation torque was significantly higher in national swimmers than university counterparts with large ES. All national swimmers were stronger than university swimmers on the dominant side and 80% on nondominant side. This is supported by Bae et al. (2016) who found that international swimmers had greater shoulder rotator force measured by isokinetic dynamometry than national swimmers. A later study (Cheung et al., 2018) reported that elite swimmers also had greater strength in the shoulder extensor, flexor, abductor, and adductor muscles than recreational counterparts measured by a handheld dynamometer. Our results are in accordance with these studies showing that swimmers of a higher competitive level have greater baseline shoulder force, which might be explained by the greater chronic loads they endure. This is important as greater upper body strength has been associated with swimming performance (Garrido et al., 2012; Gola et al., 2014; Saavedra et al., 2010).

For post-swim changes, internal rotation torque was significantly decreased in both groups, particularly on the dominant arm. Despite this, university swimmers reported greater mean decreases as a percentage of body weight (15% to 21%) than national swimmers (10% to 13%). Furthermore, they had more meaningful drops (large ES and values exceeding MDC) than national counterparts (moderate to large ES and only the nondominant side exceeding MDC). Importantly, a higher percentage of university swimmers had drops exceeding the MDC. Despite this, there was no significant difference between groups, which might be explained by the small sample size. Shoulder internal rotator muscles are constantly activated during the pull-through phase of the stroke (Pink et al., 1991), which can lead to muscle fatigue after a high-intensity swim-session (Yoma et al., 2021). Two cross-sectional studies have found deficits of internal rotator force in swimmers with shoulder pain (Bak & Magnusson, 1997; Tate et al., 2012). However, due to the cross-sectional design of these studies, it is unclear whether the decrease in internal rotator force is the cause or consequence of shoulder pain.

External rotation torque was also decreased in both groups. Although none of the groups reported significant decreases on the nondominant side, the percentage of change (9.0% and 9.1%), ES (large), and swimmers exceeding the MDC value (60%) were similar between groups. The main difference was seen on the dominant side. Reductions in university swimmers (17% of body weight) were significant, with large ES, and with 80% of participants exceeding the MDC. On the contrary, national swimmers reported non-significant drops (3.7% of body weight) with small ES and none of the swimmers exceeding the MDC. These results support why external rotation torque on the dominant side was the only variable significantly different between groups. Although shoulder external rotator muscles are less activated during swimming, their role is to control internal rotator forces (Pink et al., 1991).

A recent study showed acute decreases of shoulder external rotator torque after a high-intensity swim-session (Yoma et al., 2021). Importantly, it has been shown that overhead athletes with lower external rotation force tolerate fewer changes in training load, which leads to a higher incidence of shoulder pain (Møller et al., 2017). Despite this, deficits in shoulder external rotator endurance, rather than peak force, have been reported as a potential risk factor for shoulder pain in swimmers in a cross-sectional (Beach et al., 1992) and two prospective studies (Feijen, Struyf, et al., 2020; Tate et al., 2020). Considering this, we recommend that future research explore post-swim changes in shoulder external rotator endurance in this population.

Regarding muscular balance, both groups increased their ER: IR ratio after the swim-session, mainly on the dominant side. This means that proportionally internal rotator torque was more affected than external rotator after a single training. Interestingly, we found that national swimmers had greater increases in this ratio (6.2% to 12%) than university counterparts (3.9% to 6.3%). However, only the changes on the dominant side of national swimmers were significant. To our knowledge, no studies have investigated the acute changes of shoulder ER: IR ratio in swimmers. Several studies have investigated the changes in this ratio over a longer period (Batalha et al., 2015; Batalha et al., 2013; Ramsi et al., 2004), reporting reductions between 4% to 14% during a training period in young competitive swimmers. This shows that internal rotator force increases proportionately more than external rotator force during a training season (Batalha et al., 2015). Therefore, while a training season decreases the ER: IR ratio, a single swim-session increases it. However, cross-sectional studies have found no relationship between the ER: IR ratio and shoulder pain (history and current) in competitive swimmers (Beach et al., 1992; Boettcher et al., 2020).

In summary, our results showed that a high-intensity swim-session decreased shoulder rotator torque and increased the ER: IR ratio in both groups. However, university-level swimmers reported more meaningful changes. We suggest that lower-level swimmers have less tolerance to maintain loads during a high-intensity swim-session, which result in greater fatigue of shoulder rotator muscles. Possibly, lower competitive level swimmers might be at higher risk of shoulder injury after a high-intensity swim-session.

Shoulder ER ROM

Baseline shoulder ER ROM was similar between groups. Although one university swimmer presented more range on his dominant side, this was not consistent (Figure 5.1). To our knowledge, this is the first study to investigate baseline differences of shoulder ER ROM between levels of competition in swimmers. One study found that elite swimmers had more shoulder ER ROM (average of 15°) compared to a non-swimmer group (Holt et al., 2017). The greater ROM found in swimmers was explained by the repetitive shoulder elevation during the stroke (Holt et al., 2017). Although in our study national swimmers were exposed to greater chronic loads (i.e., more repetitive shoulder elevation), the results showed no baseline difference between groups. This probably indicates that higher chronic loads in swimmers are more related to baseline differences in shoulder rotation force than ER ROM.

Regarding post-swim changes, both groups reduced their shoulder ER ROM, predominantly in the dominant arm. However, the average decrease in university swimmers was greater (6.3° to 8.4°) and more meaningful (large ES and values exceeding MDC) than national counterparts (1.9° to 5.7° with small to large ES and values exceeding the SEM only). Despite this, only the changes in the dominant arm of university swimmers were significant. Individually, almost all swimmers reduced their ROM after the training session in both groups. Only one national swimmer increased the ROM on the nondominant side, which might explain the less significant result in this group. Interestingly, university swimmers presented a higher proportion of swimmers exceeding the MDC (40 to 80%) than national counterparts (20%). Despite this, the difference between groups was not significant. Our results showed that, after a high-intensity swim-session, shoulder ER ROM decreased in both groups with more meaningful changes in low-level swimmers.

Our findings are consistent with previous studies reporting decreases in shoulder ER ROM after a swim-training session in elite (Higson et al., 2018) and national level swimmers (Matthews et al., 2017; Yoma et al., 2021). Interestingly, the study assessing the highest level of competition (i.e. elite) found the lowest drops in ER ROM (average = 3.4°) (Higson et al., 2018). Whilst, the highest drops were found in the university group of the present study (average = 8.4° on the dominant side). This supports our results and suggests that higher competitive levels have less post-swim reductions of shoulder ER ROM. However, it is difficult to make comparisons since the intensity and distance of the sessions are different. More studies with bigger sample sizes comparing the effect of the same session in different groups might be necessary to confirm our findings.

Intensity of training sessions

Despite national swimmers reporting less post-swim changes in shoulder physical qualities, this group perceived the training session as harder. Both groups performed a one-hour session, but the national swimmers completed more volume (3 km) than university counterparts (2 km). To illustrate this, in the same period, national swimmers performed 33% more volume, which implies a higher intensity of the session and probably less recovery. This was expected as higher levels of competition perform greater swim-volumes and intensities. However, both training sessions were the hardest of the week which is proportional to the level of competition.

Comparing the $sRPE^{h}$, national swimmers perceived the session slightly harder, however, the differences between groups were not significant ($P = 0.064$; $d = 1.35$). Yet, if we compare the $sRPE^{km}$, national swimmers perceived the session harder with significant differences and larger ES ($P < .000$; $d = 3.75$). The difference obtained between the two methods might be explained because $sRPE^{km}$ considers the volume instead of time. This shows that, in this study, $sRPE^{km}$ was more appropriate than $sRPE^{h}$ to compare internal training loads between groups. This is supported by Collette et al. (2018) who recommended the use of $sRPE^{km}$ to monitor internal training loads as the influence of volume on the perceived exertion is greater than the training time in swimmers. Another explanation for the higher RPE found in national swimmers is the accumulation of training loads over the week. Although both groups were assessed the same day (Wednesday evening), on the testing day, national swimmers had already performed five training sessions that week (average = 8.2 training sessions/week). Furthermore, they had done a morning session on the same day. Whilst, university swimmers only performed one or two sessions before the Wednesday session (average = 2.6 training sessions/week) and did not have a morning training on the testing day.

Limitations

This study presents limitations. First, while the swim-sessions were the hardest for each group, there might have been some differences in terms of structure that could have influenced the results. Second, although the study reported some findings (e.g., level of competition presenting more developed physical qualities and less post-swim changes), it is underpowered (Type II error). To be confident of the post-swim changes and differences between groups, we would have needed at least 16 participants per group (version 3.1.9.2; G*Power). Because of the small sample size, we tried to increase the statistical power in several ways (Lininger & Riemann, 2018). We investigated a homogeneous sample: males between 17 and 20 years old with similar swimming experience. Although this can decrease the between-subject variability and increase the power of the study, the results cannot be generalized to other populations. We also performed repeated measures of the dependent variables (shoulder physical qualities) to increase the statistical power. Finally, we used reliable tools to measure the participants. Unreliable tools can increase variability and decrease statistical power (Lininger & Riemann, 2018). Further research should investigate a larger sample size, including other levels of competition and development of physical qualities (e.g., elite group). Also, understanding whether post-swim changes of shoulder physical qualities are related to the development of shoulder pain might be necessary.

5.5. Conclusions

University level swimmers have lower baseline shoulder rotator torque than national level counterparts, which might be explained by the lower chronic loads they are exposed to. This might, to some extent, explain the greater post-swim drops of shoulder physical qualities in this group. However, due to the small sample size, the results have to be interpreted with caution. Our results might have practical implications for recreational swimmers and triathletes (lower chronic loads). Since higher baseline shoulder rotator torque and chronic loads seem to be a protective factor of post-swim drops in shoulder physical qualities (mainly external rotation torque of the dominant side), we suggest that lower-level swimmers might benefit from a shoulder strengthening program. However, it is unknown whether the post-swim impairments on shoulder force and ROM are associated to shoulder injury in this population.

5.6. The rationale for Chapter 6

Although the findings of Chapter 4 and 5 are relevant and novel, it is still unknown whether the changes in shoulder ER ROM and rotation isometric torque are transient or long-lasting. The next study will investigate how the accumulation of training loads (i.e., swim-volume) affect these physical qualities. We also acknowledged that the previous chapters only included physical qualities as outcome measures. Since the nature of injuries in sport is multifactorial, the next study will also investigate the impact of training loads on wellness factors (e.g., self-reported fatigue, sleep quality, muscle soreness, and stress). Alterations in these factors have been associated with overtraining in swimmers and predictors of injuries in other sports (Section 2.5.2.2.2 of Chapter 2). Incorporating a multifactorial approach would provide a broader picture of the swimmers’ response to training.

Chapter 6

Cumulative effects of a week´s training loads on shoulder physical qualities and wellness in competitive swimmers

Abstract

Context: Competitive swimmers are exposed to high training loads, which can contribute to the development of shoulder pain. There is a lack of research investigating the interactions between the accumulation of training loads and factors associated to shoulder pain in competitive swimmers.

Objective: The primary aim of this study was to assess the impact of a week´s training loads on shoulder physical qualities and wellness factors. A secondary aim was to determine the impact of different training volumes on these factors.

Design: Cross-sectional study.

Setting: Indoor swimming pool

Participants: Thirty-one national and regional-level swimmers were included (18 females, 13 males; age = 15.5 ± 2.2 years).

Main outcome measures: Shoulder external rotation (ER) range of motion (ROM), shoulder-rotation isometric torque, and wellness factors (muscular soreness, fatigue, sleep quality, stress, and overall wellness) were measured twice over the week: a baseline measurement (before Monday´s training session) and a follow-up during the week. Participants were divided into a high-volume group (HVG) and low-volume group (LVG) based on the day follow-up was performed. HVL (n = 15) was tested at the end of the training week (after Saturday´s session, volume > 30 km) and LVG (n = 16) during the week (after Thursday or Friday´s session, volume < 30km). Weekly rating of perceived exertion (RPE) was recorded after the follow-up session.

Results: LVG and HVG decreased shoulder ER ROM on dominant ($P = 0.002$; $P = 0.006$) and nondominant sides ($P = 0.001$; $P = 0.004$), increased muscular soreness ($P = 0.001$; $P = 0.007$) and worsened overall wellness ($P < 0.001$; $P = 0.010$). Fatigue ($P = 0.008$) and poor sleep quality were increased ($P = 0.023$) in HVG, but not in LVG. There were no changes in shoulder-rotation torque and stress in any group. Regarding between-groups differences, only weekly RPE was higher (P = 0.004) in the HVG.

Conclusions: This study showed that the accumulation of training loads over the week negatively affect physical and wellness factors in swimmers. Although greater swim-volumes were associated with an increase perception of training loads, this was not reflected by significant differences in physical and wellness factors between groups. We recommend the regular monitoring of multiple factors to assess swimmers' response to training.

Key words: Fatigue, Musculoskeletal, Overtraining, Training.

Highlights

- The accumulation of training loads during the week negatively affects shoulder physical qualities and wellness factors in competitive swimmers.
- Active shoulder external rotation range of motion, perceived muscular soreness, and overall wellness are negatively affected over a training week regardless of the swim-training volume performed.
- Although self-reported fatigue and sleep quality were only impaired in the high-volume group, the difference between groups was not significant.
- Weekly training loads are perceived as harder towards the end of the week (RPE), in relation to greater swim-training volumes.

6.1. Introduction

The aetiology of injuries in sports is multifactorial including the dynamic interaction among biomechanical, psychological, behavioural, and training-related factors (Bittencourt et al., 2016). Competitive swimmers are exposed to large training loads, swimming up to 14,000 m/day (Pink & Tibone, 2000). Given that 90% of the propulsive force comes from the upper limbs (Pink & Tibone, 2000), the shoulder is the most common body part injured (Chase et al., 2013). With a prevalence as high as 91% (Sein et al., 2010), shoulder pain is the main reason for missed training in competitive swimmers (Chase et al., 2013). Injuries in this population occur mainly from repetitive strain and microtrauma as a result of high training intensity or volume (Gaunt & Maffulli, 2012). A systematic review supported this, reporting moderate associations between training volume and shoulder pain in adolescent competitive swimmers (Feijen, Tate, Kuppens, Claes, et al., 2020). Considering the dynamic and multifactorial nature of sports injuries and the importance of training loads on the development of shoulder pain in swimmers, it is necessary to understand the interaction between training loads and other risk factors.

It has been shown that the stress induced by training loads in swimmers have a negative effect on shoulder physical qualities. Researchers have reported immediate decreases of shoulder external rotation (ER) range of movement (ROM) (Higson et al., 2018; Matthews et al., 2017; Yoma et al., 2021), pectoralis minor length (Higson et al., 2018), and isometric rotation torque (Yoma et al., 2021) after a single swim session. Since these physical qualities have been reported as potential risk factors for shoulder pain in swimmers (Hill et al., 2015), their acute maladaptation can potentially increase the predisposition to shoulder injury. The intensity of the training session has been shown to be an important component of training loads leading to some of these changes (Yoma et al., 2021). To date, there is evidence that a single swim-practice can lead to acute shoulder maladaptations (Higson et al., 2018; Matthews et al., 2017; Yoma et al., 2021), however, it is unknown whether these maladaptations are affected by the accumulation of multiple sessions. Also, training intensity is the only component of training loads that has been investigated (Yoma et al., 2021); no studies have examined the effect of swim-training volume on physical qualities of the shoulder.

General wellness in swimmers is also affected by training loads. The peak swim-training volume during a season has been associated with mood (O'Connor et al., 1989) and sleep disturbances (Taylor et al., 1997). It has been also shown that acute increases in swim-training volume negatively affect muscular soreness, mood, perception of training loads, and psychological well-being (Morgan et al., 1988; O'Connor et al., 1991; Tomar & Allen, 2019). Importantly, impairments of wellness factors have been found in overtrained swimmers (Hooper et al., 1995). Although wellness factors have not been directly associated with shoulder pain in swimmers, they have been reported as injury predictors in other sports (Hamlin et al., 2019; Laux et al., 2015; Watson et al., 2017). There is evidence of a dose-response relationship between training loads and wellness in swimmers (Morgan et al., 1988; O'Connor et al., 1989; O'Connor et al., 1991; Taylor et al., 1997); the peak swim-volume during a season and acute increases in swim-volume negatively affect wellness factors. However, it is unknown how they are affected by different swim-training volumes performed during a week.

There is a lack of information about the interaction between training loads and risk factors for shoulder pain in swimmers. Importantly, no studies have simultaneously monitored shoulder physical qualities and wellness factors in this population. Given the dynamic and multifactorial nature of injuries in sports and the role of training loads, it is important to understand how the accumulation of training loads affect factors associated to shoulder pain in swimmers and how different swim-training volumes influence these changes. This might help coaches and practitioners to know which factors and when they need to be monitored. Monitoring can help to understand a swimmer's response to training to adequately prescribe and manage training loads, minimising the risk of injury and maximizing performance.

The primary objective of our study was to analyze the changes in shoulder physical qualities and wellness factors over a week of training in competitive swimmers. A secondary objective was to compare the changes in these variables between different swim-training volumes performed during the week. The null hypothesis was that shoulder physical characteristics and wellness factors will be unaffected by the accumulation of training loads over a week. Also, there will not be a significant difference between the effects of different training volumes on these factors.

6.2. Methods

Experimental approach to the problem

A cross-sectional study was conducted to assess the impact of a week´s training loads on shoulder physical qualities and wellness factors and to determine the impact of different training volumes on these factors. For the first objective, participants were measured twice over a week: a baseline measurement at the beginning of the week (before Monday´s training session) and a follow-up during the week. The rationale for this was to assess the effect of multiple swimming sessions on these factors. For the second objective, participants were divided into the high-volume group (HVG) and low-volume group (LVG) according to the day the follow-up measurement was performed. The HVG group was measured after Saturday´s training session. This implied that this group was tested after completing all the sessions of the week and thus performed the total weekly swim-volume. Conversely, the LVG was measured during the week (after the Thursday or Friday session). This indicated that, at the time of follow-up, this group had performed less than the total weekly swim-volume.

Participants

Thirty-four national and regional level swimmers from the same club were recruited to participate in the study. According to a priori power analysis (version 3.1.9.2; G*Power, Heinrich-Heine-Universität, Düsseldorf, Germany), using the t-tests for means (two independent groups), a sample size of 32 participants (16 per group) would be required to detect a large effect size (0.90) with a power of 0.80 and an α level of 0.05. Three participants were unable to complete the follow-up testing; one developed shoulder pain during the testing week, whereas two missed the session due to other reasons. Thirty-one participants were included in final analysis (18 females and 13 males; age = 15.5 ± 2.2 years, range 12-21 years). All swimmers trained in year-round and completed a similar number of practices regularly, regardless of the age and level of competition. The participants performed an average training volume of 35,600 ± 4,000 meters per week and average swim sessions of 8.5 ± 0.5 per week. The exclusion criteria included a history of shoulder surgery, shoulder pain at the time of the study, and any pain in the two weeks before the study that interfered with the ability to train or compete fully (Higson et al., 2018). All participants provided written informed consent before data collection. For participants under 18 years of age, parental or guardian signed consent was obtained. This study was approved by our university's ethics board and conducted in accordance with the Declaration of Helsinki (Ref.no.HSR1718-100).

Procedures

Baseline measurements included general demographic information, such as sex, age, limb dominance, height, mass, forearm length, and history of shoulder pain. Considering the high number of swimmers that do not discontinue training due to shoulder pain (Mountjoy et al., 2016), history of shoulder pain was recorded as the presence of significant interfering pain that caused the swimmer to miss or modify training or competition within the previous 12 months.

Before testing, participants performed a standardized warm-up consisting of shoulder movements (10 repetitions of ER and IR [0° shoulder abduction] with a yellow TheraBand [The Hygenic Corporation, Akron, OH]). After the warm-up, participants were asked about their readiness to train and completed a wellness questionnaire. Readiness to train was measured by asking "Do you feel ready to train at 100% this week?" on a seven-point Likert ranging from 1 (strongly agree) to 7 (strongly disagree). Then, shoulder rotation ROM and shoulder rotation isometric peak torque were measured, assessing the dominant side first. Three trials of each test were performed on both limbs, and the results were averaged for further analysis. For the follow-up session, participants were tested on different days according to the swim-volume group (low-volume or high-volume). Immediately after completion of the training, swimmers exited the pool and repeated baseline testing. Additionally, weekly RPE was recorded after the follow-up session.

Training loads monitoring

According to a consensus statement in training loads (Soligard et al., 2016), a combination of external (amount of work performed by the athlete) and internal (athlete's physical and psychological response to external loads) training loads should be used to monitor an athlete's response to training. External training loads were measured by the swim-training volume performed during the testing week. For internal training loads monitoring, it has been recommended to include objective and subjective measures (Saw et al., 2016). Objective measures included shoulder physical qualities, whereas subjective measures included self-reported wellness factors and weekly RPE.

Swim-training volume

Swim-training volume was defined as "the average distance or average time swum per week" (Feijen, Tate, Kuppens, Claes, et al., 2020) (p. 33). The swim-volume for each swimmer was reported by the coaches at the end of each week and was based on the distance covered at the time of the follow-up measurement. If a participant missed a training session, the volume of the missed session was deducted from the total weekly volume.

Shoulder physical qualities

The same procedure for shoulder ER ROM and rotation isometric peak torque was used as previously described in Sections 3.3 of Chapter 3. Intrarater test-retest reliability for shoulder ER ROM and rotation torque was also established previously in Chapter 3. Each measurement was performed on two sessions separated by seven days. The intraclass correlation coefficient, standard error of measurement (SEM), and minimal detectable change (MDC) with 95% of confidence interval for each test were calculated (Table 3.3).

Wellness factors

This subsection will provide the rationale for the questionnaire used in this chapter. Because of their practical and economic advantages, there is an increasing interest in wellness questionnaires for athlete monitoring (Coutts et al., 2007; Saw et al., 2016). Furthermore, subjective measures, such as wellness questionnaires, have been shown to be more sensitive than objective measures to assess the athlete´s response to training (Saw et al., 2016).

A systematic review (Saw et al., 2016) found that the most common instruments to assess athlete’s wellness in practice are the Stress-Recovery Questionnaire for Athletes (RESTQ-Sport) (Kellmann & Kallus, 2001), the Profile of Mood States (POMS), and the Multicomponent Training Distress Scale (MTDS) (Main & Grove, 2009). Although they are valid and reliable, they are long and time-consuming (e.g., 76 items in RESTQ-S), which limits their implementation in the sports setting. Because of this, several studies have incorporated elements of these questionnaires into short, customized, and easy-to-use self-reported measures (Clemente et al., 2017, 2019; Gastin et al., 2013; Hamlin et al., 2019; Hooper et al., 1995; Malone et al., 2018; Mcgahan et al., 2020; Nobari et al., 2020; Rabbani et al., 2019). A survey conducted among practitioners in a wide variety of high-performance sports showed that customized wellness questionnaires were the preferred method to monitor athlete’s recovery-stress status due to the low time needed for completion (Taylor et al., 2012). These short questionnaires are usually administered on a regular basis and assess the current state of the athlete using a 5-, 7-, or 10-point Likert scale.

In the swimming population, some studies have used long questionnaires (Collette et al., 2018; Morgan et al., 1987; Nagle et al., 2015; O’Connor et al., 1989; Zanini et al., 2018), while others have used short-customized surveys to assess the athlete´s wellness (Hooper et al., 1995; O’Connor et al., 1991). Due to the limited time for assessment in our study (e.g., tight training schedule) and the numerous tests included (e.g., wellness factors and physical qualities), we chose to use a short-customized questionnaire. Within these questionnaires, a specific set of questions (Hooper questionnaire) have been used in several studies (Chamari et al., 2016; Charlot et al., 2016; Clemente et al., 2017, 2019; Haddad et al., 2013; Hooper et al., 1995; Nobari et al., 2020; Rabbani et al., 2019), which include self-reported ratings of muscular soreness, fatigue, sleep quality, and stress in a Likert scale ranging from 1 (very, very good) to 7 (very, very bad). Importantly, the Hooper questionnaire has provided an efficient method of monitoring both overtraining and recovery in swimmers (Hooper et al., 1995). In combination, these questions can predict overtraining and decreases in swimming performance during a season (Hooper et al., 1995). Furthermore, moderate to large relationships have been reported between the Hooper questionnaire and acute load in other sports (Nobari et al., 2020). Considering this, we included the Hopper questionnaire to assess the changes in wellness as a result of training loads.

For better comprehension, some words of the questionnaire were modified (Table 6.1). Some studies have also changed the wording of customized wellness questionnaires to monitor athletes (Hamlin et al., 2019; Mcgahan et al., 2020). Before the implementation of the modified questionnaire, the main researcher contacted three physiotherapists based on their expertise on athlete monitoring in both clinical practice and research. They were asked whether the proposed changes were adequate in terms of wording and logic. The physiotherapists agreed unanimously that the changes contributed to a better understanding of the questionnaire. This was based on a similar methodology used to update the Oslo Sport Trauma Research Centre Questionnaire (Clarsen et al., 2020).

Finally, we used a coefficient of variation (CV) of 20% to determine whether the changes in wellness exceeded the measurement error. This was based on Rabbani et al. (2019) study that reported a week-to-week CV of 19.6% for The Hooper questionnaire in football players.

Table 6.1 - Wellness questionnaire, each question scored on a seven-point scale with 1 and 7 representing very good to very poor wellness ratings.

	1	2	3	4	5	6	7
Muscular soreness	Full free movement	Free movement	Fairly free movement	Neutral	Fairly sore/tight	Sore	Very sore
Sleep quality	Very restful	Restful	Fairly restful	Neutral	Fairly restless	Restless	Very restless
Fatigue	Very fresh	Fresh	Fairly fresh	Neutral	Fairly tired	Tired	Very tired
Stress	Very relaxed	Relaxed	Fairly relaxed	Neutral	Fairly stressed	Stressed	Very stressed

Weekly RPE

The perception of training loads was quantified by the weekly RPE based on the modified version of the category-ratio scale of Borg (Foster et al., 2001). Immediately after completing the follow-up session, the swimmers were asked, “On average how hard was your training week?”, on a scale from 0 (rest) to 10 (maximal effort) (Foster et al., 2001). Researchers have recommended that RPE should be monitored daily (Foster et al., 2001). However, as a result of the various training locations of each athlete, the daily measurement of the RPE was not possible. It has been shown that the RPE reported at the end of the week (weekly RPE) has a strong correlation with the RPE reported daily after 24 hours of training (0.87 [CI, 0.78 – 0.93]) (Phibbs et al., 2017).

Statistical analysis

For statistical analysis, SPSS version 25 for Windows (Inc, Chicago, IL) was used. The Shapiro Wilks test was performed to determine if the variables had a normal distribution. Demographic data were screened for between-group differences using independent sample t-tests for normally distributed data (weight) and Mann Whitney test for non-normally distributed data (age, sex, height, swim-volume, readiness to train, level of competition, and history of shoulder pain).

Regarding the outcome measures (shoulder physical qualities, wellness factors, and weekly RPE), all presented normal distribution. For the first objective, a paired t-test was used to assess within-group differences between pre-and post-measurements. For the second objective, independent sample t tests were used to assess between-group differences. We calculated the Cohen d effect size (ES) to determine the magnitude of any difference among measurements: >0.8 (large), 0.5-0.79 (medium), 0.49-0.20 (small), and <0.2 (trivial) (Cohen, 1988). Differences were considered significant when p values were ≤ 0.05. Results are presented in boxplots for shoulder physical qualities (e.g., shoulder ER ROM) and with bar graphs for wellness factors and RPE. Additionally, a swim-volume threshold was calculated to determine the percentage of swimmers above or below a specific swim-volume in each group. In the LVG, 2 SD were added to the average value of the swim-volume obtained, whereas, in the HVG, 2 SD were subtracted from the average of the swim-volume. This will determine a swim-volume threshold where 95% of the participants in each group lie.

6.3. Results

Table 6.2 shows the baseline characteristics of the participants. The HVG reported greater swim-volume (P < 0.001) and training hours (P < 0.001) at follow-up. The LVG averaged a volume of 26.2 ± 2.2 km, whereas the HVG averaged a volume of 37.5 ± 3,.7 km. The swim-volume threshold was set at 30 km, identifying that 95% of swimmers in the HVG performed more than 30 km (37.5 - 2 SD [3.7]) and 95% of swimmers in the LVG performed less than 30 km (26.2 + 2 SD [2,2]) at follow-up.

Table 6.2 - Descriptive and baseline characteristics of participants (N = 31)

	Low-Volume Group (n = 16)		High-Volume Group (n = 15)		Between Group
	Mean ± SD	Range (min-max)	Mean ± SD	Range (min-max)	P Value
Swim-volume at follow-up, km	26.2 ± 2.2	5.0 (25.0 - 30.0)	37.5 ± 3.7	8.0 (32.0 – 40.0)	< 0.001*
Training hours at follow-up, h	12.0 ± 0.6	2.5 (10.9 – 13.4)	15.3 ± 0.7	1.4 (14.4 – 15.8)	< 0.001*
Age, y	15.1 ± 2.2	7.0 (12.0 – 19.0)	15.9 ± 2.2	8.0 (13.0 – 21)	0.32
Body mass, kg	54.8 ± 9.6	29.0 (40.0 – 69.0)	62.8 ± 9.2	30.0 (45.0 – 75.0)	0.025*
Height, cm	166.6 ± 10.2	32.0 (150.0 – 182.0)	170.5 ± 10.4	27.0 (155.0 – 1.82.0)	0.23
Readiness to train, scale 1-7	2.1 ± 0.9	3.0 (1.0 – 4.0)	2.0 ± 0.9	3.0 (1.0 – 4.0)	0.77
Sex, male: female	5: 11		8: 7		0.30
Level of competition	7 national, 8 regional, 1 county		11 national, 3 regional, 1 county		0.20
History of shoulder pain, yes: no	6:10		4:11		0.54

* Abbreviations: SD, standard deviation.
* Difference between groups (P < .05).

For shoulder ER ROM, the LVG reported decreases with large ES for the dominant (P = 0.002; d = 1.22) and nondominant sides (P = 0.001; d = 0.82). The HVG reported decreases with large ES for the dominant (P = 0.006; d = 0.99) and nondominant sides (P = 0.004; d = 1.25) (Table 6.3 and figure 6.1). In both groups, the average change on the dominant side exceeded the MDC, whereas it only exceeded the SEM on the nondominant side. There was no significant difference between groups. For isometric peak torque, there was no significant pre-post and between-group difference in external rotator, internal rotator, and ER: IR ratio (Table 6.3).

Table 6.3 - Mean results for within-group and between-group comparison for shoulder external rotation range of motion and shoulder rotation isometric peak torque (N = 31).

Test	Side	Low-volume group n =16						High-volume group n = 15						Between group
		Initial Session, Mean ± SD	Follow-up, Mean ± SD	Mean Difference	% Change	Effect Size	P Value	Initial Session, Mean ± SD	Follow-up, Mean ± SD	Mean Difference	% Change	Effect Size	P Value	P Value
External rotation ROM, °	D	99.0 ± 5.7	86.8 ± 14.3	-12.2	-16.5 ± 18.0	1.22	0.002[*]	98.3 ± 7.9	89.9 ± 8.9	-8.4	-10.2 ± 13.2	0.99	0.006*	0.32
	ND	93.3 ± 9.4	84.7 ± 11.5	-8.6	-11.1 ± 11.3	0.82	0.001[*]	99.9 ± 6.8	91.3 ± 6.9	-8.6	-10.0 ± 11.8	1.25	0.004*	0.71
Internal rotator torque, Nm/kg	D	0.53 ± 0.13	0.58 ± 0.18	+0.05	+5.0 ± 19.9	0.31	0.12	0.50 ± 0.12	0.51 ± 0.12	+0.01	+1.2 ±18.8	0.08	0.60	0.57
	ND	0.51 ± 0.17	0.56 ± 0.17	+0.05	+9.0 ± 17.5	0.29	0.058	0.51 ± 0.12	0.50 ± 0.10	-0.01	-1.0 ± 11.7	0.09	0.78	0.22
External rotator torque, Nm/kg	D	0.48 ± 0.12	0.47 ± 0.11	-0.01	-0.8 ± 12.6	0.08	0.94	0.45 ± 0.08	0.43 ± 0.07	-0.02	-5.2 ± 16.1	0.25	0.35	0.36
	ND	0.40 ± 0.12	0.43 ± 0.14	+0.03	+6.9 ± 14.5	0.23	0.067	0.40 ± 0.08	0.41 ± 0.08	+0.01	+1.8 ± 15.2	0.12	0.54	0.45
ER:IR ratio	D	0.89 ± 0.08	0.84 ± 0.14	-0.05	-9.4 ± 19.8	0.43	0.18	0.92 ± 0.11	0.87 ± 0.19	-0.05	-8.8 ± 22.3	0.33	0.40	1.0
	ND	0.81 ± 0.20	0.77 ± 0.12	-0.04	-5.4 ± 26.7	0.27	0.48	0.79 ± 0.13	0.81 ± 0.12	+0.02	2.3 ± 11.8	0.15	0.40	0.45

Abbreviations: D, dominant; ND, nondominant; SD, standard deviation.

[*] Difference (P < .01).

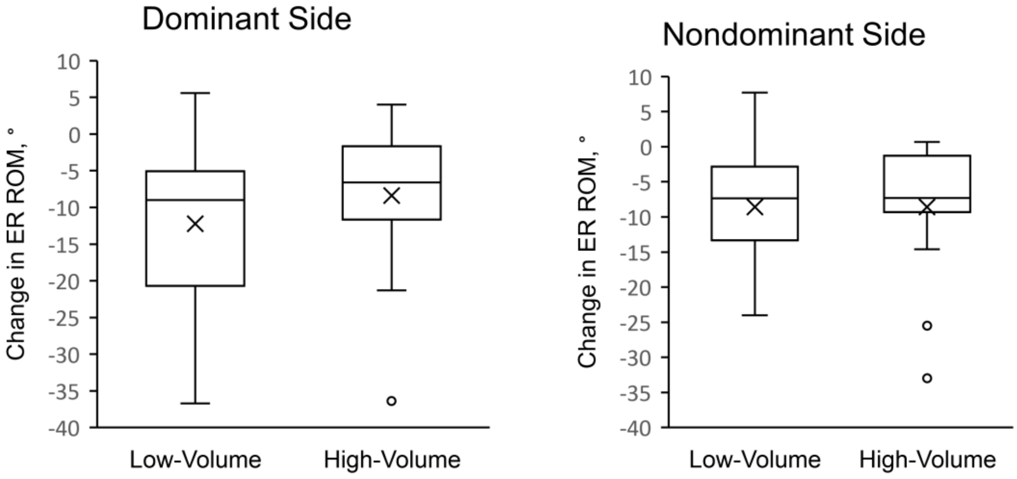

Figure 6.1 - Box plots showing the change in ER ROM for low and high-volume groups, on the dominant and nondominant shoulder. The lower and upper edge of the box indicates the 25th and 75th percentile of the sample respectively. The height of the box indicates the interquartile range, and the line inside the box shows the median. The X inside the box represents the mean. The whiskers represent extreme data points that are no more than 1.5 times the interquartile range from the lower and upper edges of the box. The circles beyond the whiskers represent outliers. Abbreviations: ROM, range of motion; ER, external rotation; °, angle.

Regarding wellness factors (Table 6.4 and Figure 6.2), both muscular soreness (P = 0.001; d = 0.81) and overall poor wellness scores increased with large ES (P = < 0.001; d = 1.33) in the LVG, with both exceeding the CV value. There was no difference between testing sessions for sleep quality, fatigue, and stress. In the HVG, both muscular soreness (P = 0.007; d = 0.63) and poor sleep quality increased with moderate ES (P = 0.023; d = 0.69). Fatigue (P = 0.008; d = 0.96) and overall poor wellness (P = 0.010; d = 0.80) increased with a large ES. Fatigue, muscular soreness and overall wellness exceeded the CV value, but sleep quality did not. No difference was reported in stress. There was no difference for muscular soreness, sleep quality, fatigue, stress, and overall score between groups.

Table 6.4 - Mean results for within-group and between-group comparison for wellness factors (N = 31)

Test	Low-volume group (n = 16)						High-volume group (n = 15)						Between group
	Initial Session Mean ± SD	Follow-up Mean ± SD	Mean Difference	% change	Effect Size	P Value	Initial Session Mean ± SD	Follow-up Mean ± SD	Mean Difference	% change	Effect Size	P Value	P Value
Muscular soreness	2.75 ± 1.1	4.25 ± 1.1	+1.50	32.5 ± 27.9	1.33	0.001*	3.00 ± 1.4	3.87 ± 1.3	+0.87	22.7 ± 28.6	0.63	0.007*	0.17
Sleep quality	3.25 ± 1.6	3.69 ± 1.0	+0.44	12.6 ± 36.3	0.33	0.21	2.53 ± 0.8	3.13 ± 0.9	+0.60	15.2 ± 27.7	0.69	0.023*	0.70
Fatigue	3.38 ± 1.2	4.06 ± 1.1	+0.68	13.0 ± 34.5	0.60	0.052	3.00 ± 1.0	4.27 ± 1.6	+1.27	21.7 ± 33.3	0.96	0.008*	0.27
Stress	2.69 ± 1.1	3.13 ± 1.0	+0.53	8.9 ± 38.2	0.43	0.069	2.47 ± 1.0	2.60 ± 1.2	+0.13	2.8 ± 39.9	0.12	0.63	0.39
Overall wellness	12.3 ± 4.3	15.3 ± 3.0	+3.00	22.0 ± 17.4	0.81	<0.001*	11.0 ± 3.4	13.9 ± 3.8	+2.90	19.8 ± 23.7	0.80	0.010*	0.31

* Difference (P < 0.05).

Weekly RPE differed significantly between groups with moderate effect size (P = 0.004; d = 1.15) (Figure 2). The HVG reported higher weekly RPE scores (mean = 7.13 points, SD =1.3; range = 5-9) than the LVG (mean = 5.63 points, SD =1.3; range = 3-7).

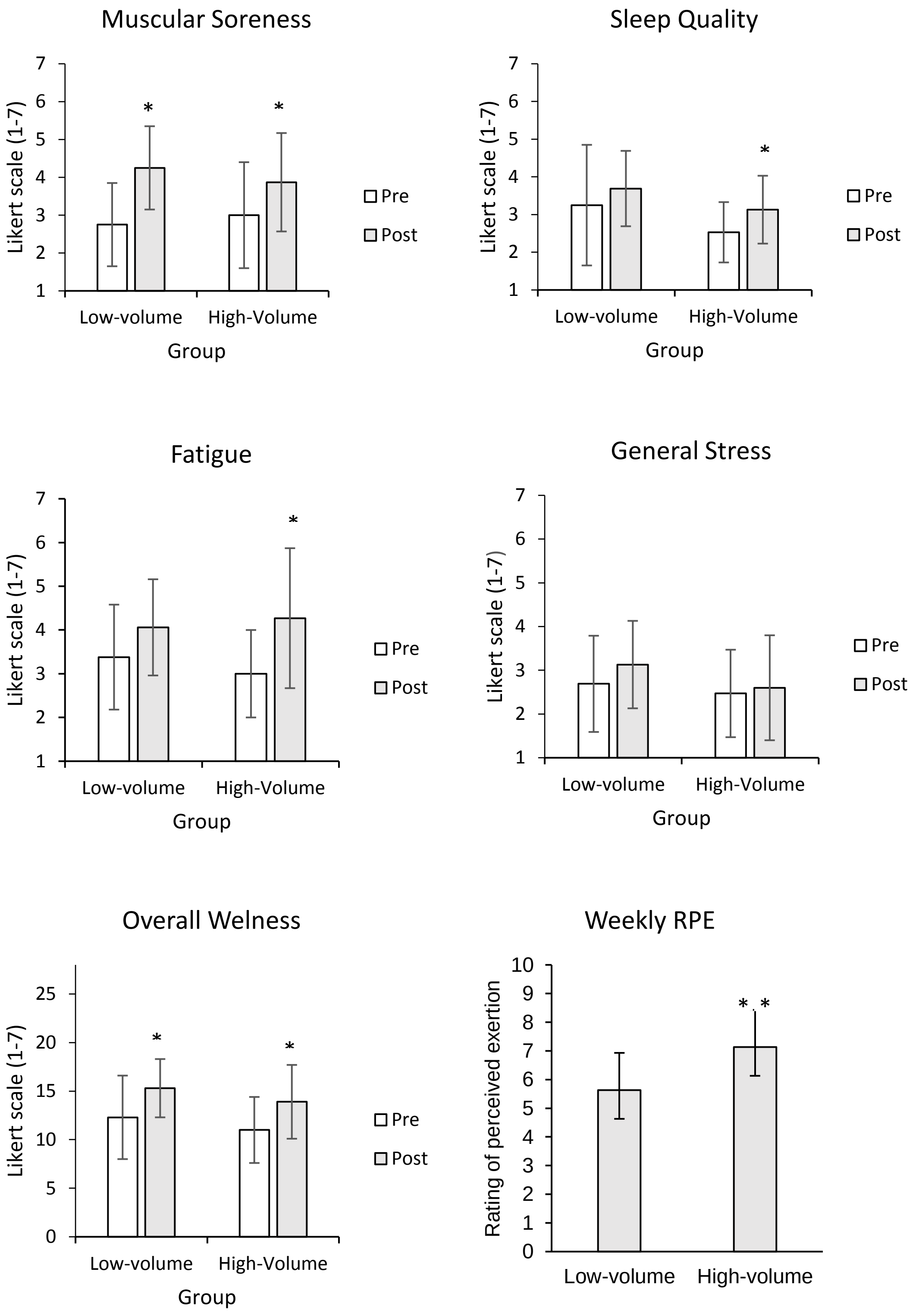

*Figure 6.2 - Graphs showing the mean changes between baseline and follow-up scores in self-reported wellness and weekly RPE for low-volume and high-volume groups. A) Muscular Soreness, B) Fatigue, C) Sleep Quality, D) General Stress, E) Overall Wellness, and F) Weekly RPE. Error bars represent the standard deviation. *Significant difference between pre- and post-measurements (P < .05). **Significant difference between groups (P < .05).*

6.4. Discussion

The aims of this study were two-fold:

- To analyze the changes in shoulder physical qualities and wellness factors over a week of training in competitive swimmers.
- To compare the changes in these variables between different swim-training volumes performed during the week

For the first objective, the null hypothesis was partially rejected. Shoulder ER ROM and self-reported muscular soreness, sleep quality, fatigue, and overall wellness were negatively affected over a week's training, but isometric peak torque and self-reported stress were not. Within-group analysis showed that both groups reported decreases in shoulder ER ROM and increases in self-reported muscular soreness; however, only the HVG reported impairments in fatigue and sleep quality at follow-up. For the second objective, the null hypothesis was also partially rejected. The HVG reported higher weekly RPE scores compared to the LVG at follow-up. However, there were no significant differences in shoulder physical qualities and wellness factors between groups. Our results show that the accumulation of training loads over a week negatively affect physical and wellness factors in swimmers. Also, higher swim-volumes were mainly associated with an increased perception of training loads.

Weekly RPE

The weekly RPE was significantly higher in the HVG than the LVG with large ES (d = 1.15). The LVG perceived the training week as "hard" (RPE mean = 5.63 points), whereas the HVG perceived the training week as "really hard" (RPE mean = 7.13 points). This shows that as the swim-training volume increases towards the end of the week, training loads are perceived as harder. O' Connor et al. (O'Connor et al., 1991) found increases in RPE values after an acute increase in training volume over 3 days in competitive swimmers. Interestingly, these changes were associated with increases in self-reported fatigue, muscular soreness and mood (O'Connor et al., 1991). Although our study showed changes in most of the wellness and physical factors during the week, there were no significant differences between groups. This shows that higher swim-volumes performed during the week (over 30 km) have no additional impact on these factors. These findings might suggest that these factors are more affected by the acute changes in swim-volume rather than the total volume performed.

Shoulder physical qualities

To our knowledge, this is the first study investigating cumulative effects of training loads on shoulder ER ROM and rotation isometric torque over a training week in swimmers. Both groups reported reductions in ER ROM with large ES. The LVG reported a mean decrease of 12.2° on the dominant and 8.6° on the nondominant side, while the HVG reported a mean decrease of 8.6° on the dominant and 8.4° on the nondominant side. However, the difference between groups was not significant. Our results showed that ER ROM is negatively affected by the accumulation of training loads but higher swim-training volumes provide no additional impact. The large ES and values exceeding the MDC in the dominant side for both groups support the clinical meaningfulness of ER ROM changes. Therefore, we can be 95% confident that the changes in ER ROM in the dominant side during a training week are attributed to the swim training and not due to measurement error. Although the ES for the nondominant side was large, the values of change only exceeded the SEM, which weakens its clinical significance.

Studies in swimmers have only investigated the impact of a single training session on shoulder ER ROM (Higson et al., 2018; Matthews et al., 2017). Matthews et al. (2017) found decreases of 5.29° on the dominant side and 3.18° on the nondominant side after a fatigue protocol consisting of eight sets of 100m swim in national level swimmers. Higson et al. (Higson et al., 2018) reported decreases in ER ROM of 3.4° after a two-hour training session in elite swimmers. More recently, Yoma et al. (2021) found decreases in ER ROM of 7.8° on the dominant side and 6.5° on the nondominant side after a high-intensity session of 3.0 km in regional and national level swimmers. The greater changes found in our study may be explained by the cumulative effects of swim-volume over multiple training sessions. In our study, all participants performed between seven and nine sessions and completed a total swim-volume over 25 km, which is a significantly higher volume than in the studies of Mathews et al. (2017) (800 m) and Yoma et al. (2021) (3.0 km). Probably, the acute reductions of ER ROM after a single session are not completely recovered before the following training, which might explain the greater changes found in this study. Deficits in shoulder ER ROM is a risk factor for shoulder pain in competitive swimmers (Walker et al., 2012), therefore, the regular monitoring of shoulder ER ROM might be important to reduce the susceptibility of shoulder injuries due to the accumulation of training loads.

Contrary to what we expected, the accumulation of training loads over the week did not affect shoulder rotation peak torque in any group. In a recent study, Yoma et al. (2021) found that shoulder rotation isometric peak torque was immediately reduced after a high-intensity session but not after a low-intensity session in competitive swimmers. As part of the regular week, swimmers usually perform a combination of high and low-intensity sessions. The absence of changes in this study might be explained by the possible recovery of force between sessions. Another explanation is that we only assessed the maximal peak force, which may not reflect the demands of swimming. Swimming is an endurance sport that does not reach peak levels of force; thus, it is possible that testing multiple repetitions rather than maximal force could have given different results (Beach et al., 1992; Feijen, Struyf, et al., 2020; Tate et al., 2020). Considering ours and the previous studies´ results (Yoma et al., 2021), we can suggest that changes in rotation force are possibly more affected by the intensity of a single session than the accumulation of swim-volume.

Wellness factors

All wellness factors were affected by training performed during the week, except for general stress. Muscular soreness was increased in both groups with moderate to large ES and values exceeding the CV. Studies have reported increases in muscular soreness after acute increases of swim-volume during three (O'Connor et al., 1991) and ten days (Morgan et al., 1988) of training. Furthermore, Hooper et al. (Hooper et al., 1995) found increases in muscular soreness during the peak volume period of a season in competitive swimmers. Although our study did not assess the impact of acute increases of swim-volume or the effects of a specific period of the season, we found that the accumulation of training loads over a regular training week also increases the perception of muscular soreness. However, the different swim-volumes performed did not influence the perception of muscular soreness. Laux et al. (2015) found an association between the feeling of stiff muscles and feeling vulnerable to injuries in professional football players. The stress-injury model (Andersen & Williams, 1988) proposes that generalised muscle tension is an important mediating factor between psychological stress and injury; an elevated stress response increases muscle tension narrowing the visual field and increasing distractibility and consequently the risk of injury.

Perceived fatigue and sleep quality were significantly affected in the HVG, but not in the LVG. These results might be explained by the higher RPE in the HVG. However, the non-significant difference between groups for fatigue (P = .27) and sleep quality (P = .70) weaken this relationship. The changes in fatigue in the HVG were more meaningful (large ES and changes exceeding the CV) than sleep quality (moderate ES and changes not exceeding the CV). Fatigue and sleep disorders have been found in overtrained swimmers; during the peak swim-volume period of the season, self-reported impairments in sleep and fatigue predicted overtraining before the deterioration in performance became evident several weeks later (Hooper et al., 1995). Furthermore, both have been reported as injury predictors in team sports (Laux et al., 2015). Our results showed that the changes in both variables might be sensitive to higher swim-training volumes performed. The increases in stress (fatigue) and simultaneous decreases in recovery (sleep) might increase the susceptibility to injury and overtraining. However, as a result of the non-significant differences between groups, swim-volume might weaken its contribution to these changes.

Overall wellness score was affected in both groups with large ES and exceeding the measurement error. Hooper et al. (1995) found that this battery of tests accounted for 49%, 78%, and 76% of the variance to predict overtraining in swimmers in early, late and midseason respectively. Training loads can impose stress on the athlete, shifting their physical and psychological wellness along a continuum that progresses from acute fatigue to functional overreaching, non-functional overreaching, and ultimately overtraining syndrome (Meeusen et al., 2013). Therefore, we support the importance of regularly monitoring these factors of potential overtraining in competitive swimmers. Finally, general stress was not affected over the week in any group. Likewise, a study in rowers (Jürimäe et al., 2004) found that a six-day heavy training camp negatively affected perceived fatigue and sleep quality but not the levels of general stress. This might be explained as increases in stress values related to training volume need longer periods to be affected (Jürimäe et al., 2004).

Finally, it is important to consider the variability of the responses among swimmers. Although most swimmers decreased their shoulder physical qualities and wellness factors at follow-up, the responses were varied (Figures 6.1 and 6.2). This is similar to the findings in Chapter 4 and 5. Therefore, we further support the individual monitoring and management of training loads in competitive swimmers.

Limitations

We recognize several limitations to our study. First, athletes usually experienced stress from sources other than training loads, such as academic, social, lifestyle, and athlete coach-relationship. Some of these factors could have also influenced the changes found in physical and wellness factors. Second, the monitoring period was short (one week) and does not reflect the long-term adaptations of the swimmers to training loads. Third, the age range of the participants (12-21 years) may have affected the results as maturational age can influence the response to training (Lloyd et al., 2014). Although the age frequency and average were similar between groups, it is not possible to determine biological maturation based on chronological age (Lloyd et al., 2014). Thus, we are not sure how many swimmers in each group had reached or not reached biological maturation. Lastly, we calculated the average of the results, which does not represent the individual responses to training. Future research performing repeated measurements should investigate prospectively the individual changes in physical and wellness factors and examine how they are related to the development of shoulder pain in swimmers. Furthermore, it would be important to understand how long these factors take to recover after the stress induced by training loads.

6.5. Conclusions

The accumulation of training loads over a week negatively affected shoulder ER ROM and wellness factors (muscular soreness, fatigue, and sleep quality) in swimmers. Considering that shoulder ER ROM is a potential risk factor for shoulder pain and wellness factors have been associated with overtraining in swimmers, their regular monitoring might be necessary. This can potentially help to identify swimmers at greater risk of shoulder injury and overtraining. Regarding swim-volume, only the perception of training loads was different between groups. This shows that, although performing higher swim-volumes was perceived as harder, this did not reflect significant differences in general wellness and shoulder physical qualities between groups. We recommend the regular monitoring of subjective wellness along with objective physical qualities to assess swimmers’ response to the accumulation of training loads.

Chapter 7

Recovery of shoulder physical qualities after a high-intensity training session in competitive swimmers

7.1. Introduction

Recovery is defined as a “multifaceted (e.g., physiological, psychological) restorative process relative to time,” (Kellmann et al., 2020). An inadequate balance between stress and recovery might result in an increased risk of injury (Eckard et al., 2018; Windt & Gabbett, 2017). Recovery can be assessed by performance (sport-specific outcomes), physiological and psychological measures (Kellmann et al., 2020). Importantly, the measures used to assess recovery need to be practical and relevant for the athlete (Kellmann et al., 2020). For this chapter, we are going to focus on physical recovery, specifically, shoulder musculoskeletal factors.

Studies in swimmers (Higson et al., 2018; Matthews et al., 2017) have found that a training session has immediate effects on the physical qualities of the shoulder. Chapter 4 and 5 supported these findings by showing that shoulder external rotation (ER) range of motion (ROM) and rotation isometric peak torque decreased after high-intensity training. Despite this, it is still unknown how long these physical qualities take to recover after a swim-training session. Considering the frequency and amount of training swimmers are exposed to (six or seven times per week and sometimes two sessions a day), some of these qualities might not completely recover before the next training, therefore possibly increasing the risk of shoulder injury.

To our knowledge, no studies have investigated the recovery of shoulder physical qualities in swimmers. This has been investigated in other overhead sports, such as tennis (Moore-Reed et al., 2016) and baseball (Reinold et al., 2008). These studies showed that shoulder rotation ROM decreases after a training session with the changes lasting more than 24 hours. Importantly, they also showed that the responses vary among athletes. For example, Moore-Reed et al. (2016) found that around 50% of the participants decreased their shoulder IR ROM beyond the minimal detectable change (MDC) immediately after the training session, as well as 24 hours later. This individual response to training and consequent recovery has also been reported in other sports, such as football (Bueno et al., 2021). Chapters 4, 5 and 6 support this by showing the responses to acute training loads and the accumulation of training loads varied among swimmers (box plots, scatterplots, and bar graphs). Therefore, understanding the individual characteristics of the swimmers who do not recover might be important to determine injury risk.

The aim of this study is to investigate if shoulder ER ROM and rotation isometric peak torque recover after a high-intensity training session by the next training session in competitive swimmers who show a negative response to a high-intensity training session. The null hypothesis was that shoulder ER ROM and rotation peak torque will have recovered by the evening training session on the same day.

7.2. Methods

Data collection for this study was supposed to be performed in June 2020 at Warrington and Salford Swimming Clubs. However, due to the current Covid-19 pandemic, this was not possible; the swimmers were not in training as they were not able to access swimming pools due to the government restrictions. Other swimming clubs around Manchester (Manchester Aquatic Centre and British Swimming (programmes with elite sport exemptions) were also contacted but without success (sport-based restrictions would not allow the researcher access to the swimmers). Then, we tried to establish collaboration for data collection in other countries that didn´t have the same level of restrictions. We contacted physiotherapists working with swimmers in the USA, Australia, and New Zealand, but unfortunately none were willing to participate in the study. Despite not collecting the data, the methodology of the study is presented in the following section.

Experimental approach to the problem

A cross-sectional study will be conducted among swimmers of the same squad to assess the recovery of shoulder ER ROM and isometric peak torque after a high-intensity session. Three measurements at different time points will be performed during a training day (Figure 7.1). First, the measurements will be performed before (T1) and after (T2) the morning training session. This will provide information about the swimmers who do and who do not decrease their physical qualities beyond the measurement error (i.e., MDC). Swimmers decreasing their physical qualities will be assessed again before the evening session of the same day (T3). This will inform whether they have recovered or not the physical qualities of the shoulder before the training. Together, this will help to know the characteristics of the swimmers who do not recover and to inform from a physical perspective (shoulder strength and ROM) if they are ready to train in the evening.

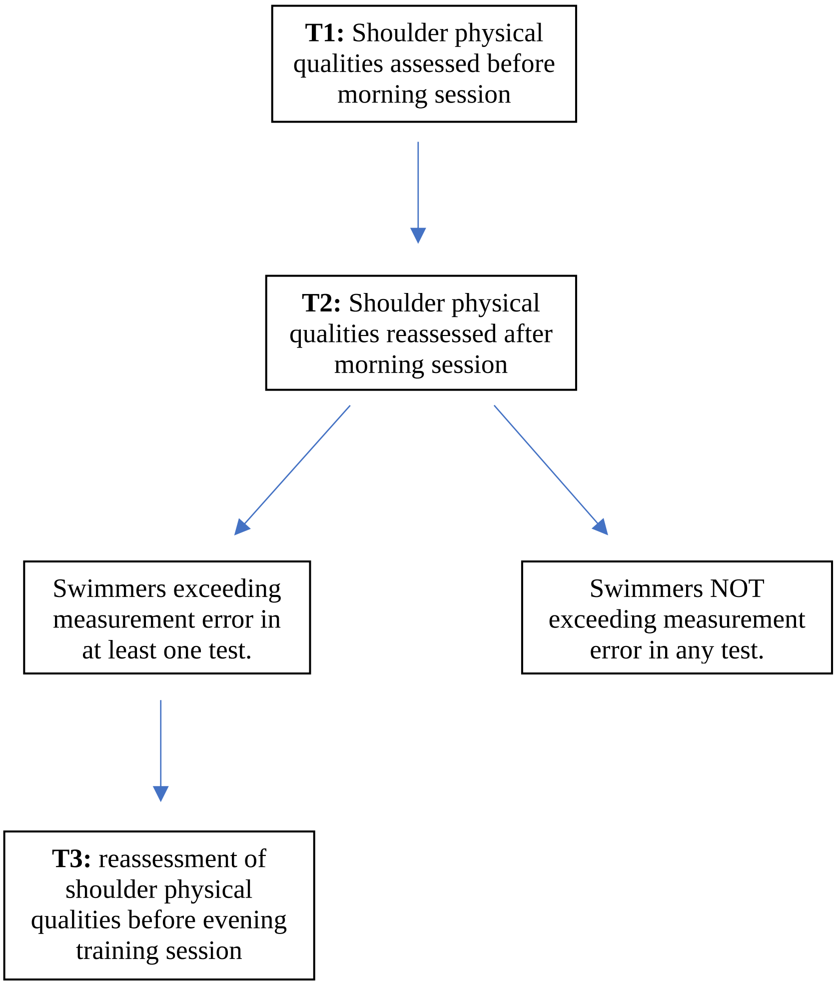

Figure 7.1 - Flow diagram of recovery study.

Participants

The sample will include national and regional level swimmers. According to an a priori power analysis (version 3.1.9.2; G*Power) using the F-test (one group and three measurements), a sample size of nine participants would be required to detect a medium effect size (0.5), with a power of 0.80 and an α level of 0.05. Based on the results of Chapter 4, not all swimmers decreased their physical qualities beyond the MDC after a high-intensity training session. Between 31.2% and 50% of them decreased rotation torque and between 53.3% and 68.8% ER ROM beyond the MDC. Considering the lowest threshold exceeding the MDC (31.2%), 27 participants will be needed. The inclusion and exclusion criteria will be the same as in previous chapters.

Procedures and outcome measures

The same demographic characteristics and procedures for shoulder physical qualities (ER ROM and rotation isometric peak torque) will be used as previously described in Section 3.3 of Chapter 3. Furthermore, the same measurement error values found in Chapter 3 (pilot study) will be used for this study (Tables 3.3 to 3.5).

Statistical analysis

For statistical analysis, SPSS version 25 for Windows (Inc, Chicago, IL) will be used. The Shapiro Wilks test will be performed to determine if the variables had a normal distribution. Data from T1 and T2 will be used to determine the swimmers who decreased their physical qualities beyond the MDC after the morning session. Then, data from T2 and T3 will be used in this subgroup to assess whether these physical qualities are recovered before the afternoon session. Depending on the sample distribution, paired student t-test or Wilcoxon signed-rank test will be used to assess within-group differences between measurements (T1 vs T2 and T2 vs T3).

Differences will be considered significant when p values were ≤ 0.05. Also, Cohen's d effect size (ES) will be calculated to determine the magnitude of any difference between measurements (Cohen, 1988). The following ES values were considered: > 0.8 (large), between 0.5 and 0.79 (medium), between 0.49 and 0.20 (small), and < 0.2 (trivial). The results will be presented in scatterplots or boxplots to show data distribution (Weissgerber et al., 2017).

Chapter 8

Summary, clinical interpretation and recommendations for future work

8.1. Summary

Following the literature review, it was concluded that training loads are the main cause of shoulder pain in swimmers. To reduce the risk of injury, aetiology injury models in sports suggest a better understanding of the interactions among multiple factors in order to identify injury risk profiles of an athlete or group of athletes (Bittencourt et al., 2016; Windt & Gabbett, 2017). However, it was acknowledged that few studies have investigated the interactions between training loads and risk factors for shoulder pain in swimmers. Increasing this knowledge would help to know which risk factors need to be monitored to manage training loads and decrease the risk of injury. This would also help to incorporate these factors in injury prevention programs.

Therefore, the aims of this thesis were:

1. Examine the intrarater and test-retest reliability of tests that assess the shoulder function.
2. Determine the acute effect of training intensity on shoulder musculoskeletal physical qualities in competitive swimmers.
3. Compare the baseline differences and post swim changes in shoulder ER ROM and rotation isometric peak torque between university and national level swimmers.
4. Analyze the changes in shoulder physical qualities and wellness parameters over a week of training in competitive swimmers, and compare the changes in these variables between different swim-training volumes.
5. Investigate if physical qualities of the shoulder recover after a high-intensity training session by the next training session in competitive swimmers who show a negative response to a high-intensity training session.

Regarding aim one, Chapter 3 investigated the intrarater (within-session) and test-retest (within-day and between-day) reliability of tests that assess shoulder function. Since the following studies assessed the impact of a single swim session and weekly swim-training loads on these factors, it was important to determine the measurement error at different time points. Based on the literature review, six tests were included: shoulder rotation range of motion, joint position sense, rotation isometric torque, latissimus dorsi length, handgrip force, and combined elevation test. The rationale of this was that, in combination, these tests measure important features of the shoulder. The majority of the tests showed good to excellent reliability for both intrarater and test-retest analysis. Intrarater analysis demonstrated the consistency of the results obtained by the same examiner, suggesting that the main researcher could perform the tests with confidence in the following studies. Test-retest analysis corroborated that longer intervals between measurements negatively affected the reliability of the tests. The SEM and MDC values obtained in this study were used to determine whether the changes in physical qualities in the following studies were meaningful or due to measurement error. Moreover, these values helped to establish the clinical meaningfulness of the results in swimmers.

With respect to aim two, Chapter 4 presented a cross-sectional study, which investigated the acute impact of swim-training intensity on shoulder physical qualities in swimmers. Sixteen regional and national level swimmers were tested before and immediately after a low and a high-intensity swim-training session. The outcome measures included were the same physical qualities of the shoulder as in Chapter 3. The results showed that a high-intensity training session immediately decreased shoulder active ER ROM and rotation isometric torque. However, after the low-intensity session, no changes in any of the physical qualities were identified. Our results demonstrated that the intensity of a training session may be an important factor that leads to maladaptive changes in the physical qualities of the shoulder in competitive swimmers.

In regards to aim three, Chapter 5 presented a cross-sectional study comparing the baseline differences and post-swim changes in shoulder ER ROM and rotation isometric peak torque between university and national level swimmers. Five university and five national level swimmers were measured before and immediately after a high-intensity swim-training session. The physical qualities and the intensity of the session were chosen based on the results of the previous chapter. Furthermore, due to its importance as a non-modifiable risk factor, the level of competition was studied. The results showed that university swimmers had less shoulder rotator torque at baseline. Only decreases in ER torque of the dominant side were significantly higher in university swimmers. Despite this, university swimmers showed more meaningful decreases in physical qualities after the training session (based on ES and values exceeding the measurement error) than national-level counterparts. Overall, our results suggest that swimmers of a lower competitive level have less shoulder rotation torque, which might then predispose them to greater changes after a high-intensity swim session, especially of ER force. The results must be interpreted with caution due to the small sample size. (This will be discussed in the limitations subsection.)

With respect to aim four, Chapter 6 presented a cross-sectional study that investigated the cumulative effects of training loads on physical qualities of the shoulder and wellness factors in swimmers. Thirty-one national and regional level swimmers were measured at the beginning and during the training week, and they were assigned to either the LVG or the HVG. Since injuries are multifactorial, wellness factors were also included as an outcome measure. Both groups reported decreases in shoulder ER ROM and increases in self-reported muscular soreness; however, only the HVG reported impairments in fatigue and sleep quality at follow-up. For between-group analysis, there were no differences in physical qualities of the shoulder and wellness factors. The HVG only reported higher weekly RPE scores compared to the LVG at follow-up. Our results show that the accumulation of training loads over a week negatively affect physical and wellness factors in swimmers and that higher swimming volumes were mainly associated with an increased perception of training loads.

Regarding aim five, the objective of Chapter 7 was to investigate if shoulder ER ROM and isometric peak torque recover after a high-intensity training session by the next training session in competitive swimmers who show a negative response to a high-intensity training session. However, data collection was not possible.

8.2. Limitations and strengths

Reliability study

One main strength of this thesis is that the measurement error of the outcome measures was calculated prior to conducting the study in the swimmers. This helped us to determine with confidence whether the changes in swimmers were real and meaningful or due to measurement error. It is also a strength that the same examiner performed all the tests throughout the thesis, decreasing the probability of measurement error (generally, intrarater reliability is higher than interrater). However, this can be also seen as a limitation, as the results cannot be generalized or be used by other examiners. Accounting for time between measurements was also an important strength of this study. This was corroborated by the fact that most of the tests had higher MDC after a week compared to within-session or within-day analysis. For instance, if we had analyzed the results in swimmers based only on within-session reliability, we would have probably had false positives (i.e., finding a value exceeding the measurement error, that in fact, did not exceed the error). Finally, performing the reliability study in a non-swimmer population might have been a limitation. However, since the measurement error found in our study was similar to the studies assessing swimmers, this might have not affected the results.

Outcome measures

A primary strength of this thesis was that the outcome measures included are appropriate for the clinical setting. The fact that all the tests were performed poolside support this, making them feasible and relevant to practice. Also, the measurement instruments included (smartphone and hand-held dynamometer) are easy to use and accessible for most clinicians, and thus the measurement protocol can be replicated in any clinical practice.

Another strength was that we examined various risk factors, including physical, behavioral, and training-related factors. This was important as injuries in sports arise from the interaction between multiple factors. Although the physical qualities chosen for this thesis tried to assess the most relevant features of the shoulder (e.g., flexibility, strength, and function), not including factors, such as pectoralis minor length, shoulder extension strength, and scapular dyskinesis, might be a limitation. In addition, wellness factors were included to provide a better understanding of swimmers' response to training loads (Chapter 6). However, not assessing factors, such as academic pressure, anxiety, and mood, was also a limitation, as they can affect the response to training and injury risk in athletes (Haischer et al., 2019; Hamlin et al., 2019).

Regarding specific outcome measures, shoulder rotation peak torque was a test used across studies. The fact that force was normalized to body weight and lever arm is an advantage as it can be compared across studies and populations. However, we have to consider that we only assessed peak force and not endurance. Swimming is an endurance sport that does not reach peak levels of force (Beach et al., 1992); thus, this might be a limitation. The rationale for choosing peak force over an endurance measure was based on the test reliability and practicability. The reliability of shoulder rotator peak force has been widely reported in the literature (Chapter 2), whereas the reliability of shoulder endurance (i.e., posterior shoulder endurance test [PSE]) has only been reported in a few studies (Day et al., 2015; Moore et al., 2013; Powell et al., 2021). Regarding test practicability, the PSE is a failure test. Thus, performing this test before a training session could have negatively influenced swimming performance and, possibly, increased the risk of shoulder injury. Despite this, we are aware that shoulder endurance is an important factor that was not assessed.

Regarding the type of contraction, swimmers perform repeated concentric and eccentric contractions during the stroke (Pink et al., 1991). A possible limitation is that we assessed force isometrically (make test). To assess force concentrically, we should have used an isokinetic dynamometer, which was not realistic at poolside. To our knowledge, concentric strength measurements have not been performed using a HHD (Cools et al., 2016). Regarding eccentric assessment (brake test), excellent reliability has been reported for shoulder rotator muscles using a HHD (Johansson et al., 2015). Despite this, we decided that assessing force eccentrically was not appropriate after a training session due to possible increased injury risk. Pragmatically, even testing shoulder strength isometrically after a training session was perceived as unsafe among coaches due to the potential increase risk of injury. Therefore, performing a brake test was not feasible in practice.

Finally, shoulder ROM and rotation torque were tested in supine rather than in prone. The rationale of this was to increase the internal validity of the study. Performing the tests in a supine position was an advantage as they provide more shoulder stability and assess more specifically the glenohumeral joint. However, this might be a potential limitation, as prone is a more functional position for swimmers. Therefore, we are aware that this can affect the generalization of the results (external validity).

Methodology and interpretation of the findings

This thesis presents some methodological limitations. First, the heterogeneity of the swimming stroke and distance could be a potential limitation. However, the training was homogeneous among swimmers; the majority of swimmers swim a single stroke (freestyle) for high proportions of any training sessions, and no differences were made for different swimming distances. Second, we did not divide groups by gender. Although there is no sufficient evidence that gender is a risk factor for shoulder pain in swimmers, this might be a potential limitation. Thus, to reduce gender differences, we normalized strength to body mass and lever arm. Third, our study included swimmers with an age range between 11 to 21 years old, because the swimming clubs included in this study had swimmers of this age range. This can be a strength as it represents the most common age range in competitive swimming squads. However, it does not provide information about specific age groups.

Not accounting biological maturation of the participants might be also a limitation. It has been shown that maturity status is a contributor to aerobic fitness, anaerobic power, and speed in young athletes (Lloyd et al., 2014). As we included swimmers from 11 to 21 years of age, some of them had probably not reached their biological maturation, which might have affected the comparison between participants. In Chapter 4, we only did a within-participants analysis, thus maturational age did not affect the results. Although in Chapter 6 we compared two groups; however, this was not a problem as the participants had probably already reached maturity (over 18 years). Chapter 6 compared two groups with an age range between 12 and 21 years old. In this case, biological maturational could have affected force development and, therefore, the comparison between groups. Although the age frequency and average were similar between groups, it is not possible to determine biological maturation based on chronological age (Lloyd et al., 2014). Thus, we are not sure how many swimmers in each group had reached or not reached biological maturation. Other measures, such as skeletal age and pubertal status, can inform this data (Malina et al., 2015); however, this was not an aim of this thesis.

Not including swimmers with low levels of pain/soreness might also be a limitation. Since competitive swimmers often train with low levels of shoulder pain (Section 2.1.2 of Chapter 2), this can limit the degree to which the results can be extrapolated to a pain population. The rationale for not including this group of swimmers was to minimize the negative effects of shoulder pain in the assessments (Section 2.5.2.2 of Chapter 2). Considering that the thesis aimed to assess the impact of training loads on the physical qualities of the shoulder, shoulder pain was identified as a confounding factor. However, we are aware that excluding this population can limit the generalizations of our findings

The sample size needed for each study was calculated. Chapter 4 and Chapter 6 were performed with an adequate number of participants. However, Chapter 5 (comparison between levels of competition) was underpowered increasing the probability of type II error. In this study, we found only significant between-groups differences in ER torque of the dominant side. It is possible that the non-significant differences in the others factors might be explained by the small sample size (failed to reject the null hypothesis).

According to the GRRAS checklist (Appendix 3), blinding of the examiner and the participants was not performed in any study. First, not blinding the outcome assessor might have introduced bias. It is recommended that the person performing the assessment is blinded to the participants' characteristics and interventions. However, considering that only one researcher performed all the measurements (pre- and post-swim session) blinding the rater to the participants characteristics (e.g., age, gender, level of competition) or training session (e.g., low or high intensity) was not possible. To minimize the awareness of the outcome assessor to the participants' characteristics, the results were written in a different spread sheet in the follow-up session to avoid comparisons. Furthermore, participants were given a number instead of a name. Regarding the bias from not blinding the participants, it is difficult to avoid in Physiotherapy studies (Opara et al., 2013). As the participants were aware of the measurements and training sessions they were performing, this was not possible to prevent. Overall, we are conscious of the potential blinding bias.

8.3. Clinical relevance

Certainly, athlete monitoring is a current topic of interest in sports, as it can provide useful information about injury risk, readiness to train and compete, and performance. The literature suggests the importance of regular monitoring of modifiable risk factors for injury risk. However, due to a large number of risk factors for shoulder pain in swimmers, when and what to monitor might sometimes be challenging.

Chapter 4 contributed to the understanding of which physical qualities of the shoulder to observe and when they need to be monitored in competitive swimmers. We suggest the importance of in-season monitoring of shoulder ER ROM and rotation isometric peak torque before and after a high-intensity swim-training session. If these qualities are impaired before a high-intensity session, practitioners can adjust the training loads (e.g., decrease training intensity or volume) to avoid further maladaptations and reduce the potential risk of injury. Also, identifying post-training deficits in these qualities may permit early interventions and might be a practical way to reduce the susceptibility to shoulder injury. Previous researchers have found that these shoulder physical qualities are potential risk factors for shoulder pain in this population (Hill et al., 2015; Struyf et al., 2017); therefore, their maladaptive changes after high-intensity training can increase the risk of shoulder injury.

Clinically, Chapter 5 highlights the importance of high chronic loads and well-developed physical qualities (i.e., load capacity) in swimmers' response to high-intensity training. Our results might have practical implications for recreational swimmers and triathletes (lower chronic loads). Since higher baseline shoulder rotator torque and chronic loads seem to be a protective factor of post-swim drops in shoulder physical qualities, we suggest that lower-level swimmers might benefit from a shoulder strengthening program. More specifically, exercise programs should target external shoulder rotator muscles, particularly of the dominant arm. Importantly, decreases in ER force and endurance have been reported as potential risk factors for shoulder pain in swimmers (Beach et al., 1992; Feijen, Struyf, et al., 2020; Tate et al., 2020). Furthermore, it has been shown that overhead athletes with lower ER force tolerate fewer changes in training load, which leads to a higher incidence of shoulder pain (Møller et al., 2017).

Clinically, Chapter 6 highlights the importance of the multifactorial monitoring of competitive swimmers. It further supports the importance of regular in-season monitoring of shoulder ER ROM, and it also recommends the use of well-being measures (e.g., self-reported muscular soreness, fatigue, and sleep quality) to assess swimmers' response to the accumulation of training loads. Since these factors have been associated with overtraining in swimmers, their regular monitoring can potentially help to identify swimmers at greater risk of injury. We also found that only swimmers performing more volume perceived training as harder along with impairments in fatigue and sleep quality (stress-recovery relationship). Decreases in sleep quality might reflect impairments in recovery. Therefore, interventions to improve sleep quality should be considered to decrease the fatigue sensation and enhance swimmers' recovery. However, due to the lack of significant difference between groups, this finding has to be interpreted with caution.

The results highlight the complex and multifactorial interaction among risk factors for shoulder pain in swimmers. First, we recommend the in-season monitoring of multiple factors (secondary prevention) to reduce the risk of shoulder injury. ER ROM and rotation force should be monitored when performing a high-intensity session. When the training loads accumulate over the week, a multifactorial monitoring approach, including physical qualities (shoulder ER ROM) along with wellness factors, should be preferred. Second, incorporating these factors in exercise prevention programs (primary prevention) might be necessary. Importantly, swimmers of a lower competitive level (i.e., reduced load capacity) might benefit more from a strengthening program focused on shoulder external rotator muscles. However, there are some important considerations before translating these findings into practice.

Compliance issues have been reported in self-monitoring and injury prevention programs (Andersson et al., 2017; Saw et al., 2017; Thorborg et al., 2017). This is important as higher compliance has been associated with greater reductions of injuries (Silvers-Granelli et al., 2017). We also have to consider the variability of the responses among swimmers. Although most swimmers showed impairments as a result of training loads, the amount of change varied among them (presented in boxplots and scatterplots throughout the thesis). This demonstrates that swimmers respond differently to a similar training input. Therefore, the actions to take after athlete monitoring (e.g., management of training loads and exercise intervention programs) should be prescribed individually.

8.4. Recommendation for future work

The findings of this thesis and subsequent discussion raise several questions for investigation in future work. Following the results in Chapter 4, it is recommended to investigate how other components of training loads (e.g., time and volume) impact these physical qualities after a high-intensity training session. This would help to understand whether these parameters are also important for the swimmers' response to training.

Following the results in Chapter 5, a larger study is warranted to confirm the findings. Future research including more participants should investigate how different levels of competition (including an elite group) respond to a similar training session. This might provide information about load capacity in different groups. Following the results in Chapter 6, future work on the changes in physical and well-being factors concerning acute changes in volume (rather than total volume) is necessary. Recent literature in swimmers emphasizes the importance of the acute changes in training volume in the aetiology of shoulder pain (Feijen, Struyf, et al., 2020; Feijen, Tate, Kuppens, Claes, et al., 2020). Further investigation will help to gain understanding of how change in swimming volume impacts these factors and, therefore, injury risk.

The recovery study (Chapter 7) aimed to investigate how long physical qualities of the shoulder take to recover after a high-intensity session and to know the characteristics of the swimmers whose physical qualities do not recover before the subsequent session. As we could not collect the data, these questions require further investigation. Understanding how long these physical qualities take to recovery can inform when swimmers can safely perform another training session. Furthermore, investigating the individual responses to training (due to the variable responses across studies) can help to subdivide swimmers and, thus, understand specific group adaptations.

Having established the main musculoskeletal factors that are affected by training in swimmers (or that interact with training loads) can help to reduce the factors to be monitored in future research. A prospective study using time series (repeated measures) of these factors should be performed to determine their association with shoulder pain. This information can complement the few studies that have assessed this association prospectively using more than one measurement (Feijen, Struyf, et al., 2020; Tate et al., 2020). Ideally, shoulder pain should be monitored by non-time loss questionnaires, such as The Oslo Sports Trauma Research Centre. Together, this can advance the knowledge of the complex and dynamic aetiology of shoulder pain in swimmers.

It might also be important to perform a RCT investigating whether the monitoring of shoulder ER ROM and isometric peak torque after a high-intensity training session (secondary prevention) can decrease the risk of shoulder pain in swimmers. Recent research has suggested that in-season monitoring of physical qualities is a promising injury prevention strategy (Baroni & Oliveira Pena Costa, 2021; Wollin et al., 2019). Finally, after increasing the knowledge of shoulder pain in swimmers, computational methods, such as agent-based modelling and system dynamics modelling, can be used (Hulme, Mclean, et al., 2019). These approaches are very useful as they can simulate the interactions between multiple factors without collecting data (Hulme, Thompson, et al., 2019).

8.5. Conclusions

The work undertaken in this thesis has widened the knowledge of the interaction between training loads and potential risk factors for shoulder pain in swimmers. To our knowledge, these are the first studies to investigate the impact of training intensity, training volume, and level of competition on risk factors for shoulder pain in competitive swimmers.

The results show that shoulder ER ROM and rotation isometric torque decreased after a high-intensity session. They also conclude that the accumulation of training loads over a week negatively affects physical and wellness factors. Finally, low-level swimmers have greater changes in shoulder ER ROM and rotation isometric torque after a high-intensity swim session than higher-level counterparts. Together, these findings recommend the regular monitoring of objective physical qualities of the shoulder and subjective well-being factors to assess the swimmer’s response to training loads. Monitoring these factors could potentially help to decrease the risk of shoulder pain in this population.

Collectively, this work demonstrates the complex, multifactorial, and dynamic interactions between training loads and risk factors for shoulder pain in swimmers. Furthermore, it emphasizes the importance of the regular monitoring of modifiable risk factors individually.

Finally, this work helped to understand which factors and when it might be more appropriate to monitor in future prospective studies.

Appendices

Preferred Reporting Items for Systematic and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) (Chapter 2)

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	45
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	45
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	47-48
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	48
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	It was not registered
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	48-49
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	48-49
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	48-49
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	49
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	49
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	49
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	49
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	49

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	50-51
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	51-55
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	55
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	56-59
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	56-59
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	60-63
Limitations	20	Discuss the limitations of the scoping review process.	63-64
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	64
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	NA

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

Appendix 2

Modified Downs and Black quality checklist to assess the methodology of interventional studies in swimmers' population (Downs & Black, 1998; Wright et al., 2018) **(Chapter 2).**

	Score
Reporting	
1. Is the hypothesis/aim/objective of the study clearly described?	Yes = 1 No = 0
2. Are the main outcomes to be measured clearly described in the introduction or methods section?	Yes = 1 No = 0
3. Are the characteristics of the patients included in the study clearly described?	Yes = 1 No = 0
4. Are the intervention of interest clearly described?	Yes = 1 No = 0
5. Are the distributions of principal confounder in each group of subjects to be compared clearly described?	Yes = 2 Partially = 1 No = 0
6. Are the main findings of the study clearly described?	Yes = 1 No = 0
7. Does the study provide estimates of the random variability in the data for the main outcomes?	Yes = 1 No = 0
8. Have all of the important adverse events that may be a consequence of the intervention been reported?	Yes = 1 No = 0
9. Have the characteristics of patients lost to follow-up been described?	Yes = 1 No = 0
10. Have actual probability values been reported for the main outcomes except where the probability value is less than 0.001?	Yes = 1 No = 0
External validity	
11. Were the subjects asked to participate in the study representative of the entire sample from which they were recruited?	Yes = 1 No = 0 Unable to determine = 0
12. Were those subjects who were prepared to participated representative of the entire population from which they were recruited?	Yes = 1 No = 0 Unable to determine = 0
13. Were the staff, places, and facilities where the patients were treated, representative of the treatment the majority of patients receive?	Yes = 1 No = 0 Unable to determine = 0
Study bias	
14. Was an attempt made to blind study subjects to the intervention they received?	Yes = 1 No = 0 Unable to determine = 0
15. Was an attempt made to blind those measuring the main outcomes of the intervention?	Yes = 1 No = 0 Unable to determine = 0
16. If any of the results of the study were based on "data dredging", was this made clear?	Yes = 1 No = 0 Unable to determine = 0

17. In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, is the time period between the intervention and outcome the same for cases and controls?	Yes = 1 No = 0 Unable to determine = 0
18. Were the statistical tests used to assess the main outcomes appropriate?	Yes = 1 No = 0 Unable to determine = 0
19. Was compliance with the intervention/s reliable?	Yes = 1 No = 0 Unable to determine = 0
20. Were the main outcome measures used accurate (valid and reliable?	Yes = 1 No = 0 Unable to determine = 0
Confounding (selection bias)	
21. Were the patients in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population?	Yes = 1 No = 0 Unable to determine = 0
22. Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same time?	Yes = 1 No = 0 Unable to determine = 0
23. Were study subjects randomized to intervention groups?	Yes = 1 No = 0 Unable to determine = 0
24. Was the randomized intervention assignment concealed from both patients and health care staff until recruitment was complete and irrevocable?	Yes = 1 No = 0 Unable to determine = 0
25. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?	Yes = 1 No = 0 Unable to determine = 0
26. Were losses of patients to follow-up taken into account?	Yes = 1 No = 0 Unable to determine = 0
Power	
27. Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance is < 5%	Yes = 1 No = 0 Unable to determine = 0

Note: Item 27 was modified to a Yes =1, No = 0, UTD = 0 scoring metric from the original 1 to 5 scoring range

Appendix 3

GRRAS checklist for reporting of studies of reliability and agreement (Chapter 2)

Version based on Table I in: Kottner J, Audigé L, Brorson S, Donner A, Gajeweski BJ, Hróbjartsson A, Robersts C, Shoukri M, Streiner DL. Guidelines for reporting reliability and agreement studies (GRRAS) were proposed. J Clin Epidemiol. 2011;64(1):96-106

Section	**Item #**	**Checklist item**	**Reported on page #**
Title/Abstract	1	Identify in title or abstract that interrater/intrarater reliability or agreement was investigated.	79
Introduction	2	Name and describe the diagnostic or measurement device of interest explicitly.	82
	3	Specify the subject population of interest.	79
	4	Specify the rater population of interest (if applicable).	79
	5	Describe what is already known about reliability and agreement and provide a rationale for the study (if applicable).	82
Methods	6	Explain how the sample size was chosen. State the determined number of raters, subjects/objects, and replicate observations.	83
	7	Describe the sampling method.	83
	8	Describe the measurement/rating process (e.g. time interval between repeated measurements, availability of clinical information, blinding).	84-92
	9	State whether measurements/ratings were conducted independently.	NA
	10	Describe the statistical analysis.	92-95
Results	11	State the actual number of raters and subjects/objects which were included and the number of replicate observations which were conducted.	96
	12	Describe the sample characteristics of raters and subjects (e.g. training, experience).	84
	13	Report estimates of reliability and agreement including measures of statistical uncertainty.	96-102
Discussion	14	Discuss the practical relevance of results.	102
Auxiliary material	15	Provide detailed results if possible (e.g. online).	NA

Correlation analysis between shoulder joint position sense target angles and between handgrip peak force target angles (Chapter 3)

Shoulder joint position sense correlational analysis between target angles for the dominant side calculated from initial session of pilot study.

Target angle	JPS ER 90%	JPS ER 20%	JPS IR 90%
JPS 90% ER	1	-0.290	-0.187
JPS 20% ER	-0.290	1	-0.449
JPS IR 90%	-0.187	-0.449	1

Abbreviations: D=dominant; ND=non-dominant; ER=external rotation; IR=internal rotation; JPS=joint position sense.

Shoulder joint position sense correlational analysis between target angles for the non-dominant side calculated from initial session pilot study.

Target angle	JPS ER 90%	JPS ER 20%	JPS IR 90%
JPS 90% ER	1	-0.142	0.393
JPS 20% ER	-0.142	1	-0.047
JPS IR 90%	0.393	-0.047	1

Abbreviations: D=dominant; ND=non-dominant; ER=external rotation; IR=internal rotation; JPS=joint position sense.

Handgrip peak force correlational analysis between angles dominant and non-dominant sides calculated from initial session pilot study.

Target angles	HGF 90° of Shoulder abduction D (Kg)	HGF 90° of Shoulder abduction ND (Kg)
HGF 0° of Shoulder abduction D (Kg)	0.969**	-
HGF 0° of Shoulder abduction ND (Kg)	-	0.910**

Abbreviations: D=dominant; ND=non-dominant; Kg=kilograms; HGF=handgrip force; ABD=abduction; **= < 0.01

Appendix 5

Correlational analysis between force development, lever arm, and body mass

(Chapter 3)

Correlation between handgrip force development and body mass calculated from the initial session of pilot study.

Target angle	Body weight
HGF 0° D	0.626
HGF 0° ND	0.782**
HGF 90° D	0.624
HGF 90° ND	0.830**

**= < 0.01

Correlation between shoulder rotational isometric force and body mass and lever arm calculated from the initial session of pilot study.

Target angle	Body weight	Lever arm
ER torque D	0.636*	0.615
ER torque ND	0.370	0.553
IR torque D	0.697*	0.615
IR torque ND	0.442	0.703*

**= < 0.01

Appendix 6

Support letter from British Swimming (Chapter 3)

British Swimming
Pavilion 3
SportPark
3 Oakwood Drive
Loughborough
LE11 3QF

24th Jan 2019

Dear Club coach

Re: Research into shoulder health in Swimmers

I am writing to provide the support of British Swimming for a research project that is taking place to further our knowledge about shoulder health in swimmers. I have had close contact with the supervisor of this project, and am comfortable that the research is closely aligned to the work we are doing at British Swimming. Collecting a large data set in this area would be very useful, so I encourage you to participate in the study if at all possible.

Below are the details of the study:

- Research Student:
    - Matias Galleguillos, Physiotherapist
- Supervisor:
    - Dr Lee Herrington
- Ethics:
    - Approved by university of Salford (for both adults and adolescents)
- Study title:
    - Impact of swimming on shoulder physical qualities related to injury predisposition
- Aim:
    - To investigate the impact of swim training on various shoulder physical qualities which have been reported to predispose to shoulder injury.

Kind regards

Matt Ashman
Athlete Health Lead
British Swimming

Appendix 7

STROBE Statement--Checklist of items that should be included in reports of cross-sectional studies (Chapter 4)

	Item No	Recommendation	
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	P.114
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	p.114
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	p.116
Objectives	3	State specific objectives, including any prespecified hypotheses	p.117
Methods			
Study design	4	Present key elements of study design early in the paper	p.118
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	p.118
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	p.118
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	p.118 p.120
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	p.119
Bias	9	Describe any efforts to address potential sources of bias	p.118 p.120
Study size	10	Explain how the study size was arrived at	p.118
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	p.121
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	p.121
		(*b*) Describe any methods used to examine subgroups and interactions	NA
		(*c*) Explain how missing data were addressed	NA
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	NA
		(*e*) Describe any sensitivity analyses	NA
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	p.121
		(b) Give reasons for non-participation at each stage	NA
		(c) Consider use of a flow diagram	NA
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	p.118
		(b) Indicate number of participants with missing data for each variable of interest	NA
Outcome data	15*	Report numbers of outcome events or summary measures	
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	p.121-125
		(*b*) Report category boundaries when continuous variables were categorized	NA
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	NA

Discussion			
Key results	18	Summarise key results with reference to study objectives	P.126
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	p.131
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	P.131
Generalisability	21	Discuss the generalisability (external validity) of the study results	p.131
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	NA

STROBE Statement--Checklist of items that should be included in reports of cross-sectional studies (Chapter 5)

	Item No	Recommendation	
Title and abstract	1	*(a)* Indicate the study's design with a commonly used term in the title or the abstract	P.134
		(b) Provide in the abstract an informative and balanced summary of what was done and what was found	p.134
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	p.136
Objectives	3	State specific objectives, including any prespecified hypotheses	p.137
Methods			
Study design	4	Present key elements of study design early in the paper	p.137
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	p.137
Participants	6	*(a)* Give the eligibility criteria, and the sources and methods of selection of participants	p.137
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	p.137 p.138
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	p.138
Bias	9	Describe any efforts to address potential sources of bias	p.138
Study size	10	Explain how the study size was arrived at	NA
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	p.138
Statistical methods	12	*(a)* Describe all statistical methods, including those used to control for confounding	p.139
		(b) Describe any methods used to examine subgroups and interactions	p.139
		(c) Explain how missing data were addressed	NA
		(d) If applicable, describe analytical methods taking account of sampling strategy	NA
		(e) Describe any sensitivity analyses	NA
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	p.140
		(b) Give reasons for non-participation at each stage	NA
		(c) Consider use of a flow diagram	NA
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	p.138
		(b) Indicate number of participants with missing data for each variable of interest	NA
Outcome data	15*	Report numbers of outcome events or summary measures	
Main results	16	*(a)* Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	p.140-146
		(b) Report category boundaries when continuous variables were categorized	NA
		(c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	NA

Discussion			
Key results	18	Summarise key results with reference to study objectives	P.146
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	p.151
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	P.151
Generalisability	21	Discuss the generalisability (external validity) of the study results	p.151
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	NA

STROBE Statement--Checklist of items that should be included in reports of cross-sectional studies (Chapter 6)

	Item No	Recommendation	
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	P.153
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	p.153
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	p.155
Objectives	3	State specific objectives, including any prespecified hypotheses	p.156
Methods			
Study design	4	Present key elements of study design early in the paper	p.156
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	p.156
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants	p.157
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	p.157 p.158
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	p.158-161
Bias	9	Describe any efforts to address potential sources of bias	p.157-p.158
Study size	10	Explain how the study size was arrived at	p.157
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	p.158
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	p.161
		(*b*) Describe any methods used to examine subgroups and interactions	p.161
		(*c*) Explain how missing data were addressed	p.157
		(*d*) If applicable, describe analytical methods taking account of sampling strategy	NA
		(*e*) Describe any sensitivity analyses	NA
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	p.162
		(b) Give reasons for non-participation at each stage	NA
		(c) Consider use of a flow diagram	NA
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	p.162
		(b) Indicate number of participants with missing data for each variable of interest	NA
Outcome data	15*	Report numbers of outcome events or summary measures	
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	p.162-165
		(*b*) Report category boundaries when continuous variables were categorized	NA
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	NA

Discussion			
Key results	18	Summarise key results with reference to study objectives	P.166
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	p.169
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	P.170
Generalisability	21	Discuss the generalisability (external validity) of the study results	p.170
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	NA

Appendix 8

Description of Training Sessions (Chapter 4)

High-Intensity Session Functional Threshold Training (2 Min Recovery Between Sets)	**Low-Intensity Session** Active Recovery / Drill & Skill (2 Min Recovery Between Sets)
2x 150 as FR 150 as BR, BK, FLY KICK (ALL STREAMLINED ROLL TO BREATH) 150 as FR, No1 STK no FR, CH x 50 (PULL, no PADS) 150 as FR (Progressive pace/distance U/W) Recovery Interval 15 Seconds, Intensity Progression 2nd Round	2x 150 as FR 150 as BR, BK, FLY KICK (ALL STREAMLINED ROLL TO BREATH) 150 as FR, No1 STK no FR, CH x 50 (PULL, no PADS) 150 as FR (Progressive pace/distance U/W) Recovery Interval 15 Seconds, Intensity Progression 2nd Round
8 x 25 alternate No1/No2 Build to Pace over 25 Recovery Interval +30	8 x 25 alternate No1/No2 Underwater - Slowest possible travel Recovery Interval +30
5 x 200 No1 Functional Threshold Pace - Descending Recovery Recovery Interval (1. +20, 2. +15, 3. +10, 4. +5, 5. N/A)	5 x 200 as 1 Each STK Rev IM Order + 200 IM, DR/SW x 25 Recovery Interval +30
8 x 25 No1 Race Start (Dedicated Underwater Kick Practice) - 14.5m Break Out Target Walk Back Recovery	8 x 25 No1 Race Start (Dedicated Underwater Kick Practice) - 14.5m Break Out Target Walk Back Recovery
4 x 100 as 2x100 IM, 2x100 FR alt DR/SW x 100 Recovery Interval +15	4 x 100 as 2x100 IM, 2x100 FR alt DR/SW x 100 Recovery Interval +15

Abbreviations: STK, Stroke; NO1, Number 1 Stroke; FR, Freestyle; BR, Breaststroke; BK, Backstroke; FLY, Butterfly; IM, Individual Medle; DR, Drill; SW, Swim; U/W, Underwater. On the sessions, all recovery intervals refer to seconds rest e.g. +15 means the athlete is to take 15 seconds after finishing one interval before commencing the next.

References

Abe, D., Yoshida, T., Ueoka, H., Sugiyama, K., & Fukuoka, Y. (2015). Relationship between perceived exertion and blood lactate concentrations during incremental running test in young females. *BMC Sports Science, Medicine and Rehabilitation*, *7*. https://doi.org/10.1186/2052-1847-7-5

Alizadehkhaiyat, O., Fisher, A. C., Kemp, G. J., Vishwanathan, K., & Frostick, S. P. (2011). Shoulder muscle activation and fatigue during a controlled forceful hand grip task. *Journal of Electromyography and Kinesiology*, *21*(3), 478–482. https://doi.org/10.1016/j.jelekin.2011.03.002

Allen, S., Phillips, G., & McCaig, S. (2017). A biomechanical evaluation of the combined elevation test. *Physical Therapy in Sport*, *25*, 1–8. https://doi.org/10.1016/j.ptsp.2016.11.001

Alvarenga, G., Kiyomoto, H. D., Martinez, E. C., Polesello, G., & Alves, V. L. dos S. (2019). NORMATIVE ISOMETRIC HIP MUSCLE FORCE VALUES ASSESSED BY A MANUAL DYNAMOMETER. *Acta Ortopédica Brasileira*, *27*, 124–128. https://doi.org/10.1590/1413-785220192702202596

Andersen, M. B., & Williams, J. M. (1988). A Model of Stress and Athletic Injury: Prediction and Prevention. *Journal of Sport and Exercise Psychology*, *10*(3), 294–306. https://doi.org/10.1123/jsep.10.3.294

Anderson, V. B., & Wee, E. (2011). Impaired Joint Proprioception at Higher Shoulder Elevations in Chronic Rotator Cuff Pathology. *Archives of Physical Medicine and Rehabilitation*, *92*(7), 1146–1151. https://doi.org/10.1016/j.apmr.2011.02.004

Andersson, S. H., Bahr, R., Clarsen, B., & Myklebust, G. (2017). Preventing overuse shoulder injuries among throwing athletes: A cluster-randomised controlled trial in 660 elite handball players. *Br J Sports Med*, *51*(14), 1073–1080. https://doi.org/10.1136/bjsports-2016-096226

Androulakis-Korakakis, P., Fisher, J. P., & Steele, J. (2020). The Minimum Effective Training Dose Required to Increase 1RM Strength in Resistance-Trained Men: A Systematic Review and Meta-Analysis. *Sports Medicine*, *50*(4), 751–765. https://doi.org/10.1007/s40279-019-01236-0

Antony, N. T., & Keir, P. J. (2010). Effects of posture, movement and hand load on shoulder muscle activity. *Journal of Electromyography and Kinesiology*, *20*(2), 191–198. https://doi.org/10.1016/j.jelekin.2009.04.010

Arksey, H., & O'Malley, L. (2005). Scoping studies: Towards a methodological framework. *International Journal of Social Research Methodology*, *8*(1), 19–32. https://doi.org/10.1080/1364557032000119616

Asker, M., Waldén, M., Källberg, H., Holm, L. W., & Skillgate, E. (2019). Preseason Clinical Shoulder Test Results and Shoulder Injury Rate in Adolescent Handball: A Prospective Study on Female and Male Elite Players. *Journal of Orthopaedic & Sports Physical Therapy*. https://doi.org/10.2519/jospt.2020.9044

Atkinson, G., & Nevill, A. M. (1998). Statistical Methods For Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine: *Sports Medicine*, *26*(4), 217–238. https://doi.org/10.2165/00007256-199826040-00002

Auvinen, J. P., Tammelin, T. H., Taimela, S. P., Zitting, P. J., Mutanen, P. O. A., & Karppinen, J. I. (2008). Musculoskeletal Pains in Relation to Different Sport and Exercise Activities in Youth: *Medicine & Science in Sports & Exercise*, *40*(11), 1890–1900. https://doi.org/10.1249/MSS.0b013e31818047a2

Aydin, T., Yildiz, Y., Yanmis, İbrahim, Yildiz, C., & Kalyon, T. A. (2001). Shoulder proprioception: A comparison between the shoulder joint in healthy and surgically repaired shoulders. *Archives of Orthopaedic and Trauma Surgery*, *121*(7), 422–425. https://doi.org/10.1007/s004020000245

Bae, Y.-H., Yu, J.-H., & Lee, S. M. (2016). Comparison of basic physical fitness, aerobic capacity, and isokinetic strength between national and international level high school freestyle swimmers. *Journal of Physical Therapy Science*, *28*(3), 891–895. https://doi.org/10.1589/jpts.28.891

Bahr, R. (2016). Response to ‘Screening for risk factors: If you liked it then you should have put a number on it.’ *British Journal of Sports Medicine*, *50*(21), 1354.2-1354. https://doi.org/10.1136/bjsports-2016-096465

Bahr, R., Clarsen, B., Derman, W., Dvorak, J., Emery, C. A., Finch, C. F., Hägglund, M., Junge, A., Kemp, S., Khan, K. M., Marshall, S. W., Meeuwisse, W., Mountjoy, M., Orchard, J. W., Pluim, B., Quarrie, K. L., Reider, B., Schwellnus, M., Soligard, T., … Chamari, K. (2020). International Olympic Committee consensus statement: Methods for recording and reporting of epidemiological data on injury and illness in sport 2020 (including STROBE Extension for Sport Injury and Illness Surveillance (STROBE-SIIS)). *British Journal of Sports Medicine*, *54*(7), 372–389. https://doi.org/10.1136/bjsports-2019-101969

Bak, K., & Magnusson, S. P. (1997). Shoulder Strength and Range of Motion in Symptomatic and Pain-Free Elite Swimmers. *The American Journal of Sports Medicine*, *25*(4), 454–459. https://doi.org/10.1177/036354659702500407

Bansal, S., Sinha, A. G. K., & Sandhu, J. S. (2007). SHOULDER IMPINGEMENT SYNDROME AMONG COMPETITIVE SWIMMERS IN INDIA—PREVALENCE, EVALUATION AND RISK FACTORS. *J Exerc Sci Fit*, *5*(2), 7.

Baroni, B. M., & Oliveira Pena Costa, L. (2021). Evidence-Based Prevention of Sports Injuries: Is the Sports Medicine Community on the Right Track? *Journal of Orthopaedic & Sports Physical Therapy*, *51*(3), 91–93. https://doi.org/10.2519/jospt.2021.0104

Barry, L., Lyons, M., McCreesh, K., Powell, C., & Comyns, T. (2021). The Relationship Between Training Load and Pain, Injury and Illness in Competitive Swimming: A Systematic Review. *Physical Therapy in Sport*. https://doi.org/10.1016/j.ptsp.2021.01.002

Barton, C. J., Bonanno, D. R., Carr, J., Neal, B. S., Malliaras, P., Franklyn-Miller, A., & Menz, H. B. (2016). Running retraining to treat lower limb injuries: A mixed-methods study of current evidence synthesised with expert opinion. *British Journal of Sports Medicine*, *50*(9), 513–526. https://doi.org/10.1136/bjsports-2015-095278

Batalha, N., Dias, S., Marinho, D. A., & Parraca, J. A. (2018). The Effectiveness of Land and Water Based Resistance Training on Shoulder Rotator Cuff Strength and Balance of Youth Swimmers. *Journal of Human Kinetics*, *62*(1), 91–102. https://doi.org/10.1515/hukin-2017-0161

Batalha, N. M., Raimundo, A. M., Tomas-Carus, P., Barbosa, T. M., & Silva, A. J. (2013). Shoulder Rotator Cuff Balance, Strength, and Endurance in Young Swimmers During a Competitive Season: *Journal of Strength and Conditioning Research*, *27*(9), 2562–2568. https://doi.org/10.1519/JSC.0b013e31827fd849

Batalha, N., Marmeleira, J., Garrido, N., & Silva, A. J. (2015). Does a water-training macrocycle really create imbalances in swimmers’ shoulder rotator muscles? *European Journal of Sport Science*, *15*(2), 167–172. https://doi.org/10.1080/17461391.2014.908957

Batalha, N., Paixão, C., Silva, A. J., Costa, M. J., Mullen, J., & Barbosa, T. M. (2020). The Effectiveness of a Dry-Land Shoulder Rotators Strength Training Program in Injury Prevention in Competitive Swimmers. *Journal of Human Kinetics*, *71*(1), 11–20. https://doi.org/10.2478/hukin-2019-0093

Batalha, N., Parraca, J. A., Marinho, D. A., Conceição, A., Louro, H., Silva, A. J., & Costa, M. J. (2021). The Acute Effects of a Swimming Session on the Shoulder Rotators Strength and Balance of Age Group Swimmers. *International Journal of Environmental Research and Public Health*, *18*(15), 8109. https://doi.org/10.3390/ijerph18158109

Batalha, N., Raimundo, A., Tomas-Carus, P., Paulo, J., Simão, R., & Silva, A. J. (2015). Does a land-based compensatory strength-training programme influences the rotator cuff balance of young competitive swimmers? *European Journal of Sport Science*, *15*(8), 764–772. https://doi.org/10.1080/17461391.2015.1051132

Beach, M. L., Whitney, S. L., & Dickoff-Hoffman, S. A. (1992). Relationship of Shoulder Flexibility, Strength, and Endurance to Shoulder Pain in Competitive Swimmers. *Journal of Orthopaedic & Sports Physical Therapy*, *16*(6), 262–268. https://doi.org/10.2519/jospt.1992.16.6.262

Bialocerkowski, A. E., & Bragge, P. (2008). Measurement error and reliability testing: Application to rehabilitation. *International Journal of Therapy and Rehabilitation*, *15*(10), 422–427. https://doi.org/10.12968/ijtr.2008.15.10.31210

Bittencourt, N. F. N., Meeuwisse, W. H., Mendonça, L. D., Nettel-Aguirre, A., Ocarino, J. M., & Fonseca, S. T. (2016). Complex systems approach for sports injuries: Moving from risk factor identification to injury pattern recognition—narrative review and new concept. *British Journal of Sports Medicine*, *50*(21), 1309–1314. https://doi.org/10.1136/bjsports-2015-095850

Blanch, P. (2004). Conservative management of shoulder pain in swimming. *Physical Therapy in Sport*, *5*(3), 109–124. https://doi.org/10.1016/j.ptsp.2004.05.002

Boettcher, C., Halaki, M., Holt, K., & Ginn, K. A. (2020). Is the Normal Shoulder Rotation Strength Ratio Altered in Elite Swimmers?: *Medicine & Science in Sports & Exercise*, 1. https://doi.org/10.1249/MSS.0000000000002177

Boon, A. J., & Smith, J. (2000). Manual scapular stabilization: Its effect on shoulder rotational range of motion. *Archives of Physical Medicine and Rehabilitation*, *81*(7), 978–983. https://doi.org/10.1053/apmr.2000.5617

Borresen, J., & Lambert, M. I. (2008). Quantifying training load: A comparison of subjective and objective methods. *International Journal of Sports Physiology and Performance*, *3*(1), 16–30. https://doi.org/10.1123/ijspp.3.1.16

Borstad, J. D., & Briggs, M. S. (2010). Reproducibility of a measurement for latissimus dorsi muscle length. *Physiotherapy Theory and Practice*, *26*(3), 195–203. https://doi.org/10.3109/09593980903015250

Bourdon, P. C., Cardinale, M., Murray, A., Gastin, P., Kellmann, M., Varley, M. C., Gabbett, T. J., Coutts, A. J., Burgess, D. J., Gregson, W., & Cable, N. T. (2017). Monitoring Athlete Training Loads: Consensus Statement. *International Journal of Sports Physiology & Performance*, *12*, S2-161.

Bradley, J., Kerr, S., Bowmaker, D., & Gomez, J.-F. (2019). A Swim-Specific Shoulder Strength and Conditioning Program for Front Crawl Swimmers: *Strength and Conditioning Journal*, *41*(4), 1–17. https://doi.org/10.1519/SSC.0000000000000457

Bueno, C. A., de Araujo Ribeiro-Alvares, J. B., Oliveira, G. dos S., Grazioli, R., Veeck, F., Pinto, R. S., Cadore, E. L., & Baroni, B. M. (2021). Post-match recovery of eccentric knee flexor strength in male professional football players. *Physical Therapy in Sport*, *47*, 140–146. https://doi.org/10.1016/j.ptsp.2020.11.032

Bullock, G. S., Brookreson, N., Knab, A. M., & Butler, R. J. (2017). Examining Fundamental Movement Competency and Closed-Chain Upper-Extremity Dynamic Balance in Swimmers: *Journal of Strength and Conditioning Research*, *31*(6), 1544–1551. https://doi.org/10.1519/JSC.0000000000001627

Bullock, M. P., Foster, N. E., & Wright, C. C. (2005). Shoulder impingement: The effect of sitting posture on shoulder pain and range of motion. *Manual Therapy*, *10*(1), 28–37. https://doi.org/10.1016/j.math.2004.07.002

Butler, R., Arms, J., Reiman, M., Plisky, P., Kiesel, K., Taylor, D., & Queen, R. (2014). Sex Differences in Dynamic Closed Kinetic Chain Upper Quarter Function in Collegiate Swimmers. *Journal of Athletic Training*, *49*(4), 442–446. https://doi.org/10.4085/1062-6050-49.3.17

Butler, R. J., Bullock, G., Arnold, T., Plisky, P., & Queen, R. (2016). Competition-Level Differences on the Lower Quarter Y-Balance Test in Baseball Players. *Journal of Athletic Training*, *51*(12), 997–1002. https://doi.org/10.4085/1062-6050-51.12.09

Cahalan, R., Kearney, P., Ni Bhriain, O., Redding, E., Quin, E., McLaughlin, L. C., & O' Sullivan, K. (2018). Dance exposure, wellbeing and injury in collegiate Irish and contemporary dancers: A prospective study. *Physical Therapy in Sport*, *34*, 77–83. https://doi.org/10.1016/j.ptsp.2018.09.006

Carter, R., & Lubinsky, J. (2015). *Rehabilitation Research- E-Book: Principles and Applications*. Elsevier Health Sciences.

Cassella, M., Gustafson, C., & d'Hemecourt, P. A. (2014). Principles of Rehabilitation. In L. Micheli, C. Stein, M. O'Brien, & P. d'Hemecourt (Eds.), *Spinal Injuries and Conditions in Young Athletes* (pp. 115–124). Springer. https://doi.org/10.1007/978-1-4614-4753-5_12

Cejudo, A., Sánchez-Castillo, S., Sainz de Baranda, P., Gámez, J. C., & Santonja-Medina, F. (2019). Low Range of Shoulders Horizontal Abduction Predisposes for Shoulder Pain in Competitive Young Swimmers. *Frontiers in Psychology*, *10*. https://doi.org/10.3389/fpsyg.2019.00478

Chamari, K., Briki, W., Farooq, A., Patrick, T., Belfekih, T., & Herrera, C. (2016). Impact of Ramadan intermittent fasting on cognitive function in trained cyclists: A pilot study. *Biology of Sport*, *33*(1), 49–56. https://doi.org/10.5604/20831862.1185888

Charlot, K., Zongo, P., Leicht, A. S., Hue, O., & Galy, O. (2016). Intensity, recovery kinetics and well-being indices are not altered during an official FIFA futsal tournament in Oceanian players. *Journal of Sports Sciences*, *34*(4), 379–388. https://doi.org/10.1080/02640414.2015.1056822

Chase, K. I., Caine, D. J., Goodwin, B. J., Whitehead, J. R., & Romanick, M. A. (2013). A Prospective Study of Injury Affecting Competitive Collegiate Swimmers. *Research in Sports Medicine*, *21*(2), 111–123. https://doi.org/10.1080/15438627.2012.757224

Cheung, A. T. H., Ma, A. W. W., Fong, S. S. M., Chung, L. M. Y., Bae, Y.-H., Liu, K. P. Y., Kam, K. W. K., & Chung, J. W. Y. (2018). A comparison of shoulder muscular performance and lean mass between elite and recreational swimmers. *Medicine*, *97*(47). https://doi.org/10.1097/MD.0000000000013258

Clarsen, B., Bahr, R., Myklebust, G., Andersson, S. H., Docking, S. I., Drew, M., Finch, C. F., Fortington, L. V., Harøy, J., Khan, K. M., Moreau, B., Moore, I. S., Møller, M., Nabhan, D., Nielsen, R. O., Pasanen, K., Schwellnus, M., Soligard, T., & Verhagen, E. (2020). Improved reporting of overuse injuries and health problems in sport: An update of the Oslo Sport Trauma Research Center questionnaires. *British Journal of Sports Medicine*, *54*(7), 390–396. https://doi.org/10.1136/bjsports-2019-101337

Clemente, F. M., Mendes, B., Bredt, S. da G. T., Praça, G. M., Silvério, A., Carriço, S., & Duarte, E. (2019). Perceived Training Load, Muscle Soreness, Stress, Fatigue, and Sleep Quality in Professional Basketball: A Full Season Study. *Journal of Human Kinetics*, *67*(1), 199–207. https://doi.org/10.2478/hukin-2019-0002

Clemente, F. M., Mendes, B., Nikolaidis, P. T., Calvete, F., Carriço, S., & Owen, A. L. (2017). Internal training load and its longitudinal relationship with seasonal player wellness in elite professional soccer. *Physiology & Behavior*, *179*, 262–267. https://doi.org/10.1016/j.physbeh.2017.06.021

Clerke, A. M., Clerke, J. P., & Adams, R. D. (2005). Effects of Hand Shape on Maximal Isometric Grip Strength and its Reliability in Teenagers. *Journal of Hand Therapy; Philadelphia*, *18*(1), 19–29.

Coe, R. (2002, September 25). *It's the effect size, stupid: What effect size is and why it is important*.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. L. Erlbaum Associates.

Collette, R., Kellmann, M., Ferrauti, A., Meyer, T., & Pfeiffer, M. (2018). Relation Between Training Load and Recovery-Stress State in High-Performance Swimming. *Frontiers in Physiology*, *9*. https://doi.org/10.3389/fphys.2018.00845

Conceição, A., Parraca, J., Marinho, D., Costa, M., Louro, H., Silva, A., & Batalha, N. (2018). Assessment of isometric strength of the shoulder rotators in swimmers using a handheld dynamometer: A reliability study. *Acta of Bioengineering and Biomechanics / Wroclaw University of Technology*, *20*. https://doi.org/10.5277/ABB-01210-2018-02

Cook, C. (2016). Predicting future physical injury in sports: It's a complicated dynamic system. *British Journal of Sports Medicine*, *50*(22), 1356–1357. https://doi.org/10.1136/bjsports-2016-096445

Cools, A. M., De Wilde, L., Van Tongel, A., Ceyssens, C., Ryckewaert, R., & Cambier, D. C. (2014). Measuring shoulder external and internal rotation strength and range of motion: Comprehensive intra-rater and inter-rater reliability study of several testing protocols. *Journal of Shoulder and Elbow Surgery*, *23*(10), 1454–1461. https://doi.org/10.1016/j.jse.2014.01.006

Cools, A. M. J., Vanderstukken, F., Vereecken, F., Duprez, M., Heyman, K., Goethals, N., & Johansson, F. (2016). Eccentric and isometric shoulder rotator cuff strength testing using a hand-held dynamometer: Reference values for overhead athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(12), 3838–3847. https://doi.org/10.1007/s00167-015-3755-9

Coutts, A. J., Wallace, L. K., & Slattery, K. M. (2007). Monitoring Changes in Performance, Physiology, Biochemistry, and Psychology during Overreaching and Recovery in Triathletes. *International Journal of Sports Medicine*, *28*(2), 125–134. https://doi.org/10.1055/s-2006-924146

Cronin, J., Lawton, T., Harris, N., Kilding, A., & McMaster, D. T. (2017). A Brief Review of Handgrip Strength and Sport Performance: *Journal of Strength and Conditioning Research*, *31*(11), 3187–3217. https://doi.org/10.1519/JSC.0000000000002149

Culham, E., & Peat, M. (1994). Spinal and shoulder complex posture. II: Thoracic alignment and shoulder complex position in normal and osteoporotic women. *Clinical Rehabilitation*, *8*(1), 27–35. https://doi.org/10.1177/026921559400800104

Da Silva, I. H., da Silva Junior, J. M., Santos-de-Araújo, A. D., de Paula Gomes, C. A. F., da Silva Souza, C., de Souza Matias, P. H. V. A., & Dibai-Filho, A. V. (2018). Intra- and inter-reliability of fleximetry in individuals with chronic shoulder pain. *Physical Therapy in Sport*, *32*, 115–120. https://doi.org/10.1016/j.ptsp.2018.05.011

Day, J. M., Bush, H., Nitz, A. J., & Uhl, T. L. (2015). Scapular Muscle Performance in Individuals With Lateral Epicondylalgia. *Journal of Orthopaedic & Sports Physical Therapy*, *45*(5), 414–424. https://doi.org/10.2519/jospt.2015.5290

De Almeida, M. O., Hespanhol, L. C., & Lopes, A. D. (2015). PREVALENCE OF MUSCULOSKELETAL PAIN AMONG SWIMMERS IN AN ELITE NATIONAL TOURNAMENT. *International Journal of Sports Physical Therapy*, *10*(7), 1026–1034.

De Martino, I., & Rodeo, S. A. (2018). The Swimmer's Shoulder: Multi-directional Instability. *Current Reviews in Musculoskeletal Medicine*, *11*(2), 167–171. https://doi.org/10.1007/s12178-018-9485-0

De Vet, H. C. W., Terwee, C. B., Knol, D. L., & Bouter, L. M. (2006). When to use agreement versus reliability measures. *Journal of Clinical Epidemiology*, *59*(10), 1033–1039. https://doi.org/10.1016/j.jclinepi.2005.10.015

Delbridge, A., Boettcher, C., & Holt, K. (2017). An Inside look at "Swimmers Shoulder": Antero-superior Internal Impingement (ASII) 'A Cause of "Swimmer's Shoulder." *Aspetar Journal*.

Dennis, R. J., Finch, C. F., Elliott, B. C., & Farhart, P. J. (2008). The reliability of musculoskeletal screening tests used in cricket. *Physical Therapy in Sport*, *9*(1), 25–33. https://doi.org/10.1016/j.ptsp.2007.09.004

Dennis, R. J., Finch, C. F., McIntosh, A. S., & Elliott, B. C. (2008). Use of field-based tests to identify risk factors for injury to fast bowlers in cricket. *British Journal of Sports Medicine; London*, *42*(6). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsm.2008.046698

Dorssen, E., Whiteley, R., Mosler, A., Ortega Cebrian, S., & Dijkstra, P. (2020). *SHOULDER INJURIES IN SWIMMING MEETING THE CHALLENGE SPORTS MEDICINE*. *4*.

Dover, G., & Powers, M. E. (2003). Reliability of Joint Position Sense and Force-Reproduction Measures During Internal and External Rotation of the Shoulder. *Journal of Athletic Training*, *38*(4), 304–310.

Downs, S. H., & Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *Journal of Epidemiology & Community Health*, *52*(6), 377–384. https://doi.org/10.1136/jech.52.6.377

Drew, M. K., & Finch, C. F. (2016). The Relationship Between Training Load and Injury, Illness and Soreness: A Systematic and Literature Review. *Sports Medicine*, *46*(6), 861–883. https://doi.org/10.1007/s40279-015-0459-8

Eckard, T. G., Padua, D. A., Hearn, D. W., Pexa, B. S., & Frank, B. S. (2018). The Relationship Between Training Load and Injury in Athletes: A Systematic Review. *Sports Medicine*, *48*(8), 1929–1961. https://doi.org/10.1007/s40279-018-0951-z

El-Sais, W. M., & Mohammad, W. S. (2014). *INFLUENCE OF DIFFERENT TESTING POSTURES ON HAND GRIP STRENGTH*. 12.

Esculier, J.-F., Maggs, K., Maggs, E., & Dubois, B. (2020). A Contemporary Approach to Patellofemoral Pain in Runners. *Journal of Athletic Training*, *55*(12), 0. https://doi.org/10.4085/1062-6050-0535.19

Essendrop, M., Schibye, B., & Hansen, K. (2001). Reliability of isometric muscle strength tests for the trunk, hands and shoulders. *International Journal of Industrial Ergonomics*, *28*(6), 379–387. https://doi.org/10.1016/S0169-8141(01)00044-0

Exercise Therapy—MeSH - NCBI. (n.d.). Retrieved August 10, 2021, from https://www.ncbi.nlm.nih.gov/mesh/?term=exercise+therapy

Feijen, S., Struyf, T., Kuppens, K., Tate, A., & Struyf, F. (2020). Prediction of Shoulder Pain in Youth Competitive Swimmers: The Development and Internal Validation of a Prognostic Prediction Model. *The American Journal of Sports Medicine*, 0363546520969913. https://doi.org/10.1177/0363546520969913

Feijen, S., Tate, A., Kuppens, K., Barry, L. A., & Struyf, F. (2020). Monitoring the swimmer's training load: A narrative review of monitoring strategies applied in research. *Scandinavian Journal of Medicine & Science in Sports*, *30*(11), 2037–2043. https://doi.org/10.1111/sms.13798

Feijen, S., Tate, A., Kuppens, K., Claes, A., & Struyf, F. (2020). Swim-Training Volume and Shoulder Pain Across the Life Span of the Competitive Swimmer: A Systematic Review. *Journal of Athletic Training*, *55*(1), 32–41. https://doi.org/10.4085/1062-6050-439-18

Feijen, S., Tate, A., Kuppens, K., Struyf, T., Claes, A., & Struyf, F. (2020). Intrarater and Interrater Reliability of a Passive Shoulder Flexion Range of Motion Measurement for Latissimus Dorsi Flexibility in Young Competitive Swimmers. *Journal of Sport Rehabilitation*, 1–4. https://doi.org/10.1123/jsr.2019-0294

Fieseler, G., Laudner, K. G., Irlenbusch, L., Meyer, H., Schulze, S., Delank, K.-S., Hermassi, S., Bartels, T., & Schwesig, R. (2017). Inter- and intrarater reliability of goniometry and hand held dynamometry for patients with subacromial impingement syndrome. *Journal of Exercise Rehabilitation*, *13*(6), 704–710. https://doi.org/10.12965/jer.1735110.555

Fieseler, G., Molitor, T., Irlenbusch, L., Delank, K.-S., Laudner, K. G., Hermassi, S., & Schwesig, R. (2015). Intrarater reliability of goniometry and hand-held dynamometry for shoulder and elbow examinations in female team handball athletes and asymptomatic volunteers. *Archives of Orthopaedic and Trauma Surgery*, *135*(12), 1719–1726. https://doi.org/10.1007/s00402-015-2331-6

Fonseca, S. T., Souza, T. R., Verhagen, E., van Emmerik, R., Bittencourt, N. F. N., Mendonça, L. D. M., Andrade, A. G. P., Resende, R. A., & Ocarino, J. M. (2020). Sports Injury Forecasting and Complexity: A Synergetic Approach. *Sports Medicine*. https://doi.org/10.1007/s40279-020-01326-4

Foster, C., Florhaug, J. A., Franklin, J., Gottschall, L., Hrovatin, L. A., Parker, S., Doleshal, P., & Dodge, C. (2001). A New Approach to Monitoring Exercise Training. *Journal of Strength*, *15*(1), 109–115.

Fritz, C. O., Morris, P. E., & Richler, J. J. (2012). Effect size estimates: Current use, calculations, and interpretation. *Journal of Experimental Psychology: General*, *141*(1), 2–18. https://doi.org/10.1037/a0024338

Fuller, C. W. (2006). Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *British Journal of Sports Medicine*, *40*(3), 193–201. https://doi.org/10.1136/bjsm.2005.025270

Furness, J., Johnstone, S., Hing, W., Abbott, A., & Climstein, M. (2015). Assessment of shoulder active range of motion in prone versus supine: A reliability and concurrent validity study. *Physiotherapy Theory and Practice*, *31*(7), 489–495. https://doi.org/10.3109/09593985.2015.1027070

Furness, J., Schram, B., Corea, D., Turner, Z., & Cairns, H. (2018). The Combined Elevation Test (CET) in Adolescent School Children: A Pilot Study. *Sports*, *6*(3), 64. https://doi.org/10.3390/sports6030064

Furness, J., Schram, B., Cottman-Fields, T., Solia, B., Secomb, J., Furness, J., Schram, B., Cottman-Fields, T., Solia, B., & Secomb, J. (2018). Profiling Shoulder Strength in Competitive Surfers. *Sports*, *6*(2), 52. https://doi.org/10.3390/sports6020052

Gabbett, T. J. (2016). The training-injury prevention paradox: Should athletes be training smarter and harder? *British Journal of Sports Medicine; London*, *50*(5). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsports-2015-095788

Gabbett, T. J. (2018). Debunking the myths about training load, injury and performance: Empirical evidence, hot topics and recommendations for practitioners. *British Journal of Sports Medicine*, bjsports-2018-099784. https://doi.org/10.1136/bjsports-2018-099784

Gabbett, T. J. (2020). The Training-Performance Puzzle: How Can the Past Inform Future Training Directions? *Journal of Athletic Training*, *55*(9), 874–884. https://doi.org/10.4085/1062/6050.422.19

Gabbett, T. J., Nassis, G. P., Oetter, E., Pretorius, J., Johnston, N., Medina, D., Rodas, G., Myslinski, T., Howells, D., Beard, A., & Ryan, A. (2017). The athlete monitoring cycle: A practical guide to interpreting and applying training monitoring data. *Br J Sports Med*, *51*(20), 1451–1452. https://doi.org/10.1136/bjsports-2016-097298

Gabbett, T. J., Nielsen, R. O., Bertelsen, M. L., Bittencourt, N. F. N., Fonseca, S. T., Malone, S., Møller, M., Oetter, E., Verhagen, E., & Windt, J. (2019). In pursuit of the 'Unbreakable' Athlete: What is the role of moderating factors and circular causation? *British Journal of Sports Medicine*, *53*(7), 394–395. https://doi.org/10.1136/bjsports-2018-099995

Gabbett, T. J., Ullah, S., & Finch, C. F. (2012). Identifying risk factors for contact injury in professional rugby league players – Application of a frailty model for recurrent injury. *Journal of Science and Medicine in Sport*, *15*(6), 496–504. https://doi.org/10.1016/j.jsams.2012.03.017

Galambos, S. A., Terry, P. C., Moyle, G. M., & Locke, S. A. (2005). Psychological predictors of injury among elite athletes. *British Journal of Sports Medicine; London*, *39*(6). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsm.2005.018440

Garcia, M. A. C., Fonseca, D. S., & Souza, V. H. (2021). Handheld dynamometers for muscle strength assessment: Pitfalls, misconceptions, and facts. *Brazilian Journal of Physical Therapy*, *25*(3), 231–232. https://doi.org/10.1016/j.bjpt.2020.09.003

Garrido, N. D., Silva, A. J., Fernandes, R. J., Barbosa, T. M., Costa, A. M., Marinho, Daniela., & Marques, M. C. (2012). High Level Swimming Performance and its Relation to Non-Specific Parameters: A Cross-Sectional Study on Maximum Handgrip Isometric Strength. *Perceptual and Motor Skills*, *114*(3), 936–948. https://doi.org/10.2466/05.10.25.PMS.114.3.936-948

Gastin, P. B., Meyer, D., Huntsman, E., & Cook, J. (2015). Increase in injury risk with low body mass and aerobic-running fitness in elite Australian football. *International Journal of Sports Physiology and Performance*, *10*(4), 458–463. https://doi.org/10.1123/ijspp.2014-0257

Gastin, P. B., Meyer, D., & Robinson, D. (2013). Perceptions of Wellness to Monitor Adaptive Responses to Training and Competition in Elite Australian Football: *Journal of Strength and Conditioning Research*, *27*(9), 2518–2526. https://doi.org/10.1519/JSC.0b013e31827fd600

Gaudet, S., Tremblay, J., & Begon, M. (2018). Muscle recruitment patterns of the subscapularis, serratus anterior and other shoulder girdle muscles during isokinetic internal and external rotations. *Journal of Sports Sciences*, *36*(9), 985–993. https://doi.org/10.1080/02640414.2017.1347697

Gaunt, T., & Maffulli, N. (2012). Soothing suffering swimmers: A systematic review of the epidemiology, diagnosis, treatment and rehabilitation of musculoskeletal injuries in competitive swimmers. *British Medical Bulletin*, *103*(1), 45–88. https://doi.org/10.1093/bmb/ldr039

Geladas, N. D., Nassis, G. P., & Pavlicevic, S. (2005). Somatic and Physical Traits Affecting Sprint Swimming Performance in Young Swimmers. *International Journal of Sports Medicine*, *26*(02), 139–144. https://doi.org/10.1055/s-2004-817862

Gerodimos, V. (2012). Reliability of Handgrip Strength Test in Basketball Players. *Journal of Human Kinetics*, *31*, 25–36. https://doi.org/10.2478/v10078-012-0003-y

Gerodimos, V., & Karatrantou, K. (2013). Reliability of Maximal Handgrip Strength Test in Pre-Pubertal and Pubertal Wrestlers. *Pediatric Exercise Science*, *25*(2), 308–322.

Gissane, C., White, J., Kerr, K., & Jennings, D. (2001). An operational model to investigate contact sports injuries: *Medicine & Science in Sports & Exercise*, *33*(12), 1999–2003. https://doi.org/10.1097/00005768-200112000-00004

Gola, R., Urbanik, C., Iwańska, D., & Madej, A. (2014). Relationship between Muscle Strength and Front Crawl Swimming Velocity. *Human Movement*, *15*(2), 110–115. https://doi.org/10.2478/humo-2014-0011

Green, C. M., Comfort, P., & Herrington, L. (2013). Shoulder Joint Position Sense in Injured and Noninjured Judo Athletes. *International Journal of Athletic Therapy and Training*, *18*(2), 29–33. https://doi.org/10.1123/ijatt.18.2.29

Guo, Y., Logan, H. L., Glueck, D. H., & Muller, K. E. (2013). Selecting a sample size for studies with repeated measures. *BMC Medical Research Methodology*, *13*(1). https://doi.org/10.1186/1471-2288-13-100

Gw, N., Fw, J., J, P., Dr, M., & D, A. (1986). Fine wire electromyography analysis of muscles of the shoulder during swimming. *The American Journal of Sports Medicine*, *14*(1), 7–11. https://doi.org/10.1177/036354658601400102

Habechian, F. A. P., Van Malderen, K., Camargo, P. R., & Cools, A. M. (2018). Changes in shoulder girdle strength in 3 consecutive years in elite adolescent swimmers: A longitudinal cohort study. *Brazilian Journal of Physical Therapy*, *22*(3), 238–247. https://doi.org/10.1016/j.bjpt.2018.01.001

Haddad, M., Chaouachi, A., Wong, D. P., Castagna, C., Hambli, M., Hue, O., & Chamari, K. (2013). Influence of fatigue, stress, muscle soreness and sleep on perceived exertion during submaximal effort. *Physiology & Behavior*, *119*, 185–189. https://doi.org/10.1016/j.physbeh.2013.06.016

Haddad, M., Stylianides, G., Djaoui, L., Dellal, A., & Chamari, K. (2017). Session-RPE Method for Training Load Monitoring: Validity, Ecological Usefulness, and Influencing Factors. *Frontiers in Neuroscience*, *11*, 612. https://doi.org/10.3389/fnins.2017.00612

Haik, M. N., Camargo, P. R., Zanca, G. G., Alburquerque-Sendín, F., Salvini, T. F., & Mattiello-Rosa, S. M. (2013). Joint position sense is not altered during shoulder medial and lateral rotations in female assembly line workers with shoulder impingement syndrome. *Physiotherapy Theory and Practice*, *29*(1), 41–50. https://doi.org/10.3109/09593985.2012.676722

Haischer, M. H., Cooke, D. M., Carzoli, J. P., Johnson, T. K., Shipherd, A. M., Zoeller, R. F., Whitehurst, M., & Zourdos, M. C. (2019). Impact of Cognitive Measures and Sleep on Acute Squat Strength Performance and Perceptual Responses Among Well-Trained Men and Women:

Journal of Strength and Conditioning Research, 1. https://doi.org/10.1519/JSC.0000000000003202

Halson, S. L. (2014). Monitoring Training Load to Understand Fatigue in Athletes. *Sports Medicine*, *44*(2), 139–147. https://doi.org/10.1007/s40279-014-0253-z

Hamlin, M. J., Wilkes, D., Elliot, C. A., Lizamore, C. A., & Kathiravel, Y. (2019). Monitoring Training Loads and Perceived Stress in Young Elite University Athletes. *Frontiers in Physiology*, *10*, 34. https://doi.org/10.3389/fphys.2019.00034

Harrington, S., Meisel, C., & Tate, A. (2014). A Cross-Sectional Study Examining Shoulder Pain and Disability in Division I Female Swimmers. *Journal of Sport Rehabilitation*, *23*(1), 65–75. https://doi.org/10.1123/JSR.2012-0123

Hayen, A., Dennis, R. J., & Finch, C. F. (2007). Determining the intra- and inter-observer reliability of screening tools used in sports injury research. *Journal of Science and Medicine in Sport*, *10*(4), 201–210. https://doi.org/10.1016/j.jsams.2006.09.002

Hayes, K., Walton, J. R., Szomor, Z. L., & Murrell, G. A. C. (2002). Reliability of 3 methods for assessing shoulder strength. *Journal of Shoulder and Elbow Surgery*, *11*(1), 33–39. https://doi.org/10.1067/mse.2002.119852

Herrington, L., & Horsley, I. (2014). Effects of latissimus dorsi length on shoulder flexion in canoeists, swimmers, rugby players, and controls. *Journal of Sport and Health Science*, *3*(1), 60–63. https://doi.org/10.1016/j.jshs.2013.01.004

Herrington, L., Horsley, I., & Rolf, C. (2010). Evaluation of shoulder joint position sense in both asymptomatic and rehabilitated professional rugby players and matched controls. *Physical Therapy in Sport*, *11*(1), 18–22. https://doi.org/10.1016/j.ptsp.2009.10.001

Hibberd, E. E., & Myers, J. B. (2013). Practice Habits and Attitudes and Behaviors Concerning Shoulder Pain in High School Competitive Club Swimmers: *Clinical Journal of Sport Medicine*, *23*(6), 450–455. https://doi.org/10.1097/JSM.0b013e31829aa8ff

Hibberd, E. E., Oyama, S., Spang, J. T., Prentice, W., & Myers, J. B. (2012). Effect of a 6-Week Strengthening Program on Shoulder and Scapular-Stabilizer Strength and Scapular Kinematics in Division I Collegiate Swimmers. *Journal of Sport Rehabilitation*, *21*(3), 253–265.

Hidalgo, B., Detrembleur, C., Hall, T., Mahaudens, P., & Nielens, H. (2014). The efficacy of manual therapy and exercise for different stages of non-specific low back pain: An update of systematic reviews. *The Journal of Manual & Manipulative Therapy*, *22*(2), 59–74. https://doi.org/10.1179/2042618613Y.0000000041

Hidalgo-Lozano, A., Calderón-Soto, C., Domingo-Camara, A., Fernández-de-las-Peñas, C., Madeleine, P., & Arroyo-Morales, M. (2012). Elite Swimmers With Unilateral Shoulder Pain Demonstrate Altered Pattern of Cervical Muscle Activation During a Functional Upper-Limb Task. *Journal of Orthopaedic & Sports Physical Therapy*, *42*(6), 552–558. https://doi.org/10.2519/jospt.2012.3875

Hidalgo-Lozano, A., Fernández-de-las-Peñas, C., Calderón-Soto, C., Domingo-Camara, A., Madeleine, P., & Arroyo-Morales, M. (2013). Elite swimmers with and without unilateral shoulder pain: Mechanical hyperalgesia and active/latent muscle trigger points in neck-shoulder muscles. *Scandinavian Journal of Medicine & Science in Sports*, *23*(1), 66–73.

Higson, E., Herrington, L., Butler, C., & Horsley, I. (2018). The short-term effect of swimming training load on shoulder rotational range of motion, shoulder joint position sense and pectoralis minor length. *Shoulder & Elbow*, 175857321877353. https://doi.org/10.1177/1758573218773539

Hill, L., Collins, M., & Posthumus, M. (2015). Risk factors for shoulder pain and injury in swimmers: A critical systematic review. *The Physician and Sportsmedicine*, *43*(4), 412–420. https://doi.org/10.1080/00913847.2015.1077097

Hodder, J. N., & Keir, P. J. (2012). Targeted gripping reduces shoulder muscle activity and variability. *Journal of Electromyography and Kinesiology*, *22*(2), 186–190. https://doi.org/10.1016/j.jelekin.2011.11.011

Holt, K., Boettcher, C., Halaki, M., & Ginn, K. A. (2017). Humeral torsion and shoulder rotation range of motion parameters in elite swimmers. *Journal of Science and Medicine in Sport*, *20*(5), 469–474. https://doi.org/10.1016/j.jsams.2016.10.002

Holt, K. L., Raper, D. P., Boettcher, C. E., Waddington, G. S., & Drew, M. K. (2016). Hand-held dynamometry strength measures for internal and external rotation demonstrate superior reliability, lower minimal detectable change and higher correlation to isokinetic dynamometry than externally-fixed dynamometry of the shoulder. *Physical Therapy in Sport*, *21*, 75–81. https://doi.org/10.1016/j.ptsp.2016.07.001

Hooper, S. L., Mackinnon, L. T., Howard, A., Gordon, R. D., & Bachmann, A. W. (1995). Markers for monitoring overtraining and recovery. *Medicine & Science in Sports & Exercise*, *27*(1), 106–112.

Horsley, I., Herrington, L., Hoyle, R., Prescott, E., & Bellamy, N. (2016). Do changes in hand grip strength correlate with shoulder rotator cuff function? *Shoulder & Elbow*, *8*(2), 124–129. https://doi.org/10.1177/1758573215626103

Hulin, B. T., Gabbett, T. J., Blanch, P., Chapman, P., Bailey, D., & Orchard, J. W. (2014). Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *British Journal of Sports Medicine; London*, *48*(8). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsports-2013-092524

Hulme, A., Mclean, S., Salmon, P. M., Thompson, J., Lane, B. R., & Nielsen, R. O. (2019). Computational methods to model complex systems in sports injury research: Agent-based modelling (ABM) and systems dynamics (SD) modelling. *British Journal of Sports Medicine*, *53*(24), 1507–1510. https://doi.org/10.1136/bjsports-2018-100098

Hulme, A., Thompson, J., Nielsen, R. O., Read, G. J. M., & Salmon, P. M. (2019). Towards a complex systems approach in sports injury research: Simulating running-related injury development with agent-based modelling. *British Journal of Sports Medicine*, *53*(9), 560–569. https://doi.org/10.1136/bjsports-2017-098871

Hunter, D. J., Rivett, D. A., McKeirnan, S., Smith, L., & Snodgrass, S. J. (2020). Relationship Between Shoulder Impingement Syndrome and Thoracic Posture. *Physical Therapy*, *100*(4), 677–686. https://doi.org/10.1093/ptj/pzz182

Impellizzeri, F. M., McCall, A., Ward, P., Bornn, L., & Coutts, A. J. (2020). Training Load and Its Role in Injury Prevention, Part 2: Conceptual and Methodologic Pitfalls. *Journal of Athletic Training*, *55*(9), 893–901. https://doi.org/10.4085/1062-6050-501-19

Impellizzeri, F. M., Menaspà, P., Coutts, A. J., Kalkhoven, J., & Menaspà, M. J. (2020). Training Load and Its Role in Injury Prevention, Part I: Back to the Future. *Journal of Athletic Training*, *55*(9), 885–892. https://doi.org/10.4085/1062-6050-500-19

Janwantanakul, P., Magarey, M. E., Jones, M. A., & Dansie, B. R. (2001). Variation in shoulder position sense at mid and extreme range of motion. *Archives of Physical Medicine and Rehabilitation*, *82*(6), 840–844. https://doi.org/10.1053/apmr.2001.21865

Johansson, F. R., Skillgate, E., Lapauw, M. L., Clijmans, D., Deneulin, V. P., Palmans, T., Engineer, H. K., & Cools, A. M. (2015). Measuring Eccentric Strength of the Shoulder External Rotators Using a Handheld Dynamometer: Reliability and Validity. *Journal of Athletic Training*, *50*(7), 719–725. https://doi.org/10.4085/1062-6050-49.3.72

Jones, A., Sealey, R., Crowe, M., & Gordon, S. (2014). Concurrent validity and reliability of the Simple Goniometer iPhone app compared with the Universal Goniometer. *Physiotherapy Theory and Practice*, *30*(7), 512–516. https://doi.org/10.3109/09593985.2014.900835

Jones, C. M., Griffiths, P. C., & Mellalieu, S. D. (2017). Training Load and Fatigue Marker Associations with Injury and Illness: A Systematic Review of Longitudinal Studies. *Sports Medicine*, *47*(5), 943–974. https://doi.org/10.1007/s40279-016-0619-5

Junge, A., & Dvorak, J. (2000). Influence of Definition and Data Collection on the Incidence of Injuries in Football. *The American Journal of Sports Medicine*, *28*(5_suppl), 40–46. https://doi.org/10.1177/28.suppl_5.s-40

Jürimäe, J., Mäestu, J., Purge, P., & Jürimäe, T. (2004). Changes in stress and recovery after heavy training in rowers. *Journal of Science and Medicine in Sport*, *7*(3), 335–339. https://doi.org/10.1016/S1440-2440(04)80028-8

Kakavas, G., Malliaropoulos, N., Pruna, R., & Maffulli, N. (2020). Artificial intelligence: A tool for sports trauma prediction. *Injury*, *51*, S63–S65. https://doi.org/10.1016/j.injury.2019.08.033

Kalkhoven, J. T., Watsford, M. L., Coutts, A. J., Edwards, W. B., & Impellizzeri, F. M. (2021). Training Load and Injury: Causal Pathways and Future Directions. *Sports Medicine*. https://doi.org/10.1007/s40279-020-01413-6

Kalkhoven, J. T., Watsford, M. L., & Impellizzeri, F. M. (2020). A conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury. *Journal of Science and Medicine in Sport*, *23*(8), 726–734. https://doi.org/10.1016/j.jsams.2020.02.002

Kellmann, M., Bertollo, M., Bosquet, L., Brink, M., Coutts, A. J., Duffield, R., Erlacher, D., Halson, S. L., Hecksteden, A., Heidari, J., Kallus, K. W., Meeusen, R., Mujika, I., Robazza, C., Skorski, S., Venter, R., & Beckmann, J. (2020). Recovery and Performance in Sport: Consensus Statement. *International Journal of Sports Physiology and Performance*, *13*(2), 240–245. https://doi.org/10.1123/ijspp.2017-0759

Kellmann, M., & Kallus, K. W. (2001). *Recovery-stress Questionnaire for Athletes: User Manual*. Human Kinetics.

Kennedy, J. C., Hawkins, R., & Krissoff, W. B. (1978). Orthopaedic manifestations of swimming. *The American Journal of Sports Medicine*, *6*(6), 309–322. https://doi.org/10.1177/036354657800600602

Kerr, Z. Y., Baugh, C. M., Hibberd, E. E., Snook, E. M., Hayden, R., & Dompier, T. P. (2015). Epidemiology of National Collegiate Athletic Association men's and women's swimming and diving injuries from 2009/2010 to 2013/2014. *British Journal of Sports Medicine*, *49*(7), 465–471. https://doi.org/10.1136/bjsports-2014-094423

King, D. (1995). 1995 Student Writing Contest Winner. *Journal of Athletic Training*, *30*(4), 333–337.

Kluemper, M., Uhl, T. L., & Hazelrigg, H. (2006). Effect of Stretching and Strengthening Shoulder Muscles on Forward Shoulder Posture in Competitive Swimmers. *Journal of Sport Rehabilitation*, *15*(1), 58.

Kolber, M. J., & Hanney, W. J. (2010). The reliability, minimal detectable change and construct validity of a clinical measurement for identifying posterior shoulder tightness. *North American Journal of Sports Physical Therapy: NAJSPT*, *5*(4), 208–219.

Kolber, M. J., Vega, F., Widmayer, K., & Cheng, M.-S. S. (2011). The reliability and minimal detectable change of shoulder mobility measurements using a digital inclinometer. *Physiotherapy Theory and Practice*, *27*(2), 176–184. https://doi.org/10.3109/09593985.2010.481011

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *Journal of Chiropractic Medicine*, *15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Kottner, J., Audigé, L., Brorson, S., Donner, A., Gajewski, B. J., Hróbjartsson, A., Roberts, C., Shoukri, M., & Streiner, D. L. (2011). Guidelines for Reporting Reliability and Agreement Studies (GRRAS) were proposed. *Journal of Clinical Epidemiology*, *64*(1), 96–106. https://doi.org/10.1016/j.jclinepi.2010.03.002

Krause, D. A., Schlagel, S. J., Stember, B. M., Zoetewey, J. E., & Hollman, J. H. (2007). Influence of Lever Arm and Stabilization on Measures of Hip Abduction and Adduction Torque Obtained by Hand-Held Dynamometry. *Archives of Physical Medicine and Rehabilitation*, *88*(1), 37–42. https://doi.org/10.1016/j.apmr.2006.09.011

Kruger, P. E., Dressler, A., & Botha, M. (2012). Incidence of shoulder injuries and related risk factors among master swimmers in South Africa. *African Journal for Physical Activity and Health Sciences*, *18*(1), 57-76–76.

Kurtz JT. (2004). A chiropractic case report in the treatment and rehabilitation of swimmer's shoulder. *Journal of the American Chiropractic Association*, *41*(10), 32–38.

Labriola, J. E., Lee, T. Q., Debski, R. E., & McMahon, P. J. (2005). Stability and instability of the glenohumeral joint: The role of shoulder muscles. *Journal of Shoulder and Elbow Surgery*, *14*(1, Supplement), S32–S38. https://doi.org/10.1016/j.jse.2004.09.014

Lanese, R. R., Strauss, R. H., Leizman, D. J., & Rotondi, A. M. (1990). Injury and disability in matched men's and women's intercollegiate sports. *American Journal of Public Health*, *80*(12), 1459–1462. https://doi.org/10.2105/AJPH.80.12.1459

Laudner, K. G., Wenig, M., Selkow, N. M., Williams, J., & Post, E. (2015). Forward Shoulder Posture in Collegiate Swimmers: A Comparative Analysis of Muscle-Energy Techniques. *Journal of Athletic Training*, *50*(11), 1133–1139. https://doi.org/10.4085/1062-6050-50.11.07

Laudner, K. G., & Williams, J. G. (2013). The relationship between latissimus dorsi stiffness and altered scapular kinematics among asymptomatic collegiate swimmers. *Physical Therapy in Sport*, *14*(1), 50–53. https://doi.org/10.1016/j.ptsp.2012.02.007

Laux, P., Krumm, B., Diers, M., & Flor, H. (2015). Recovery–stress balance and injury risk in professional football players: A prospective study. *Journal of Sports Sciences*, *33*(20), 2140–2148. https://doi.org/10.1080/02640414.2015.1064538

Leão Almeida, G. P., De Souza, V. L., Barbosa, G., Santos, M. B., Saccol, M. F., & Cohen, M. (2011). Swimmer's shoulder in young athlete: Rehabilitation with emphasis on manual therapy and stabilization of shoulder complex. *Manual Therapy*, *16*(5), 510–515. https://doi.org/10.1016/j.math.2010.12.012

Levac, D., Colquhoun, H., & O'Brien, K. K. (2010). Scoping studies: Advancing the methodology. *Implementation Science*, *5*(1), 69. https://doi.org/10.1186/1748-5908-5-69

Lexell, J. E., & Downham, D. Y. (2005). How to Assess the Reliability of Measurements in Rehabilitation: *American Journal of Physical Medicine & Rehabilitation*, *84*(9), 719–723. https://doi.org/10.1097/01.phm.0000176452.17771.20

Lindstrom-Hazel, D., Kratt, A., & Bix, L. (2009). Interrater Reliability of Students Using Hand and Pinch Dynamometers. *The American Journal of Occupational Therapy; Bethesda*, *63*(2), 193–197. http://dx.doi.org.salford.idm.oclc.org/10.5014/ajot.63.2.193

Lininger, M. R., & Riemann, B. L. (2018). Statistical Primer for Athletic Trainers: Understanding the Role of Statistical Power in Comparative Athletic Training Research. *Journal of Athletic Training*, *53*(7), 716–719. https://doi.org/10.4085/1062-6050-284-17

Lininger, M., & Riemann, B. L. (2016). Statistical Primer for Athletic Trainers: Using Confidence Intervals and Effect Sizes to Evaluate Clinical Meaningfulness. *Journal of Athletic Training*, *51*(12), 1045–1048. https://doi.org/10.4085/1062-6050-51.12.14

Lloyd, R. S., Oliver, J. L., Faigenbaum, A. D., Myer, G. D., & De Ste Croix, M. B. A. (2014). Chronological Age vs. Biological Maturation: Implications for Exercise Programming in Youth. *The Journal of Strength & Conditioning Research*, *28*(5), 1454–1464. https://doi.org/10.1519/JSC.0000000000000391

López-Valenciano, A., Ayala, F., Puerta, Jos. M., De Ste Croix, M. B. A., Vera-Garcia, F. J., Hernández-Sánchez, S., Ruiz-Pérez, I., & Myer, G. D. (2018). A Preventive Model for Muscle Injuries: A Novel Approach based on Learning Algorithms. *Medicine & Science in Sports & Exercise*, *50*(5), 915–927. https://doi.org/10.1249/MSS.0000000000001535

Lynch, S. S., Thigpen, C. A., Mihalik, J. P., Prentice, W. E., & Padua, D. (2010). The effects of an exercise intervention on forward head and rounded shoulder postures in elite swimmers. *British Journal of Sports Medicine; London*, *44*(5). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsm.2009.066837

Main, L., & Grove, J. R. (2009). A multi-component assessment model for monitoring training distress among athletes. *European Journal of Sport Science*, *9*(4), 195–202. https://doi.org/10.1080/17461390902818260

Malina, R. M., Rogol, A. D., Cumming, S. P., Silva, M. J. C. e, & Figueiredo, A. J. (2015). Biological maturation of youth athletes: Assessment and implications. *British Journal of Sports Medicine*, *49*(13), 852–859. https://doi.org/10.1136/bjsports-2015-094623

Malone, S., Hughes, B., Doran, D. A., Collins, K., & Gabbett, T. J. (2019). Can the workload–injury relationship be moderated by improved strength, speed and repeated-sprint qualities? *Journal of Science and Medicine in Sport*, *22*(1), 29–34. https://doi.org/10.1016/j.jsams.2018.01.010

Malone, S., Owen, A., Newton, M., Mendes, B., Tiernan, L., Hughes, B., & Collins, K. (2018). Wellbeing perception and the impact on external training output among elite soccer players. *Journal of Science and Medicine in Sport; Belconnen*, *21*(1), 29–34. http://dx.doi.org.salford.idm.oclc.org/10.1016/j.jsams.2017.03.019

Malone, S., Roe, M., Doran, D. A., Gabbett, T. J., & Collins, K. (2017). High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *Journal of Science and Medicine in Sport*, *20*(3), 250–254. https://doi.org/10.1016/j.jsams.2016.08.005

Mandalidis, D., & O'Brien, M. (2010). Relationship between hand-grip isometric strength and isokinetic moment data of the shoulder stabilisers. *Journal of Bodywork and Movement Therapies*, *14*(1), 19–26. https://doi.org/10.1016/j.jbmt.2008.05.001

Manske, R. C., Lewis, S., Wolff, S., & Smith, B. (2015). Effects of a Dry-Land Strengthening Program in Competitive Adolescent Swimmers. *International Journal of Sports Physical Therapy*, *10*(6), 858–867.

Martens, J., Figueiredo, P., & Daly, D. (2015). Electromyography in the four competitive swimming strokes: A systematic review. *Journal of Electromyography and Kinesiology*, *25*(2), 273–291. https://doi.org/10.1016/j.jelekin.2014.12.003

Martin, J. A., Brandon, S. C. E., Keuler, E. M., Hermus, J. R., Ehlers, A. C., Segalman, D. J., Allen, M. S., & Thelen, D. G. (2018). Gauging force by tapping tendons. *Nature Communications*, *9*(1), 1592. https://doi.org/10.1038/s41467-018-03797-6

Massy-Westropp, N. M., Gill, T. K., Taylor, A. W., Bohannon, R. W., & Hill, C. L. (2011). Hand Grip Strength: Age and gender stratified normative data in a population-based study. *BMC Research Notes*, *4*(1), 127. https://doi.org/10.1186/1756-0500-4-127

Mathiowetz, V. (2002). Comparison of Rolyan and Jamar dynamometers for measuring grip strength. *Occupational Therapy International*, *9*(3), 201–209. https://doi.org/10.1002/oti.165

Mathiowetz, V., Weber, K., Volland, G., & Kashman, N. (1984). Reliability and validity of grip and pinch strength evaluations. *The Journal of Hand Surgery*, *9*(2), 222–226. https://doi.org/10.1016/S0363-5023(84)80146-X

Matijevich, E. S., Scott, L. R., Volgyesi, P., Derry, K. H., & Zelik, K. E. (2020). Combining wearable sensor signals, machine learning and biomechanics to estimate tibial bone force and damage during running. *Human Movement Science*, *74*, 102690. https://doi.org/10.1016/j.humov.2020.102690

Matsuura, Y., Hangai, M., Koizumi, K., Ueno, K., Hirai, N., Akuzawa, H., & Kaneoka, K. (2020). Injuries and physical characteristics affecting swimmer participation in the Olympics: A prospective survey. *Physical Therapy in Sport*, *44*, 128–135. https://doi.org/10.1016/j.ptsp.2020.05.001

Matthews, M. J., Green, D., Matthews, H., & Swanwick, E. (2017). The effects of swimming fatigue on shoulder strength, range of motion, joint control, and performance in swimmers. *Physical Therapy in Sport*, *23*, 118–122. https://doi.org/10.1016/j.ptsp.2016.08.011

Matzkin, E., Suslavich, K., & Wes, D. (2016). Swimmer's Shoulder: Painful Shoulder in the Competitive Swimmer. *JAAOS - Journal of the American Academy of Orthopaedic Surgeons*, *24*(8), 527. https://doi.org/10.5435/JAAOS-D-15-00313

McFarland, E. G. M. D., & Wasik, M. A. T. C. (1992). INJURIES IN COMPETITIVE FEMALE SWIMMERS DUE TO CROSS-TRAINING: 749. *Medicine & Science in Sports & Exercise*, *24*(5).

Mcgahan, J., Burns, C., Lacey, S., Gabbett, T., & O'Neill, C. (2020). *RELATIONSHIP BETWEEN LOAD AND READINESS TO TRAIN IN A GAELIC FOOTBALL PRE-COMPETITION TRAINING CAMP*. *27*.

McLaine, S. J., Bird, M.-L., Ginn, K. A., Hartley, T., & Fell, J. W. (2018). Shoulder extension strength: A potential risk factor for shoulder pain in young swimmers? *Journal of Science and Medicine in Sport*. https://doi.org/10.1016/j.jsams.2018.11.008

McLaine, S. J., Ginn, K. A., Fell, J. W., & Bird, M.-L. (2018). Isometric shoulder strength in young swimmers. *Journal of Science and Medicine in Sport*, *21*(1), 35–39. https://doi.org/10.1016/j.jsams.2017.05.003

McMaster, W. C., & Troup, J. (1993). A survey of interfering shoulder pain in United States competitive swimmers. *The American Journal of Sports Medicine*, *21*(1), 67–70. https://doi.org/10.1177/036354659302100112

Meeusen, R., Duclos, M., Foster, C., Fry, A., Gleeson, M., Nieman, D., Raglin, J., Rietjens, G., Steinacker, J., & Urhausen, A. (2013). Prevention, diagnosis and treatment of the overtraining syndrome: Joint consensus statement of the European College of Sport Science (ECSS) and the American College of Sports Medicine (ACSM). *European Journal of Sport Science*, *13*(1), 1–24. https://doi.org/10.1080/17461391.2012.730061

Meeuwisse, W. (1994). Assessing Causation in Sport Injury: A Multifactorial Model. *Clinical Journal of Sport Medicine*, *4*(3), 166–170.

Meeuwisse, W. H., Tyreman, H., Hagel, B., & Emery, C. (2007). A Dynamic Model of Etiology in Sport Injury: The Recursive Nature of Risk and Causation: *Clinical Journal of Sport Medicine*, *17*(3), 215–219. https://doi.org/10.1097/JSM.0b013e3180592a48

Melian, A., Laguarta, S., & Varillas, D. (2017). Reliability and Concurrent Validity of the Goniometer-Pro App vs a Universal Goniometer in determining Passive Flexion of Knee. *International Journal of Computer Applications*, *173*, 30–34. https://doi.org/10.5120/ijca2017915229

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *BMJ*, *339*, b2535. https://doi.org/10.1136/bmj.b2535

Møller, M., Attermann, J., Myklebust, G., Lind, M., Sørensen, H., Hebert, J. J., Nielsen, R. O., Bertelsen, S. L., & Wedderkopp, N. (2018). The inter- and intrarater reliability and agreement for field-based assessment of scapular control, shoulder range of motion, and shoulder isometric strength in elite adolescent athletes. *Physical Therapy in Sport*, *32*, 212–220. https://doi.org/10.1016/j.ptsp.2018.04.005

Møller, M., Nielsen, R. O., Attermann, J., Wedderkopp, N., Lind, M., Sørensen, H., & Myklebust, G. (2017). Handball load and shoulder injury rate: A 31-week cohort study of 679 elite youth handball players. *British Journal of Sports Medicine*, *51*(4), 231–237. https://doi.org/10.1136/bjsports-2016-096927

Moore, S. D., Uhl, T. L., & Kibler, W. B. (2013). Improvements in Shoulder Endurance Following a Baseball-Specific Strengthening Program in High School Baseball Players. *Sports Health*, *5*(3), 233–238. https://doi.org/10.1177/1941738113477604

Moore-Reed, S. D., Kibler, W. B., Myers, N. L., & Smith, B. J. (2016). ACUTE CHANGES IN PASSIVE GLENOHUMERAL ROTATION FOLLOWING TENNIS PLAY EXPOSURE IN ELITE FEMALE PLAYERS. *International Journal of Sports Physical Therapy*, *11*(2), 230–236.

Morgan, R., & Herrington, L. (2014). The effect of tackling on shoulder joint positioning sense in semi-professional rugby players. *Physical Therapy in Sport*, *15*(3), 176–180. https://doi.org/10.1016/j.ptsp.2013.10.003

Morgan, W. P., Brown, D. R., Raglin, J. S., O'Connor, P. J., & Ellickson, K. A. (1987). Psychological monitoring of overtraining and staleness. *British Journal of Sports Medicine; London*, *21*(3). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsm.21.3.107

Morgan, W. P., Costill, D. L., Flynn, M. G., Raglin, J. S., & O'connor, P. J. (1988). Mood disturbance following increased training in swimmers. *Medicine & Science in Sports & Exercise*, *20*(4), 408–414.

Mountjoy, M., Junge, A., Alonso, J. M., Clarsen, B., Pluim, B. M., Shrier, I., Hoogenband, C. van den, Marks, S., Gerrard, D., Heyns, P., Kaneoka, K., Dijkstra, H. P., & Khan, K. M. (2016). Consensus statement on the methodology of injury and illness surveillance in FINA (aquatic sports). *Br J Sports Med*, *50*(10), 590–596. https://doi.org/10.1136/bjsports-2015-095686

Mountjoy, M., Junge, A., Alonso, J. M., Engebretsen, L., Dragan, I., Gerrard, D., Kouidri, M., Luebs, E., Shahpar, F. M., & Dvorak, J. (2010). Sports injuries and illnesses in the 2009 FINA World Championships (Aquatics). *British Journal of Sports Medicine*, *44*(7), 522–527. https://doi.org/10.1136/bjsm.2010.071720

Mountjoy, M., Junge, A., Benjamen, S., Boyd, K., Diop, M., Gerrard, D., van den Hoogenband, C.-R., Marks, S., Martinez-Ruiz, E., Miller, J., Nanousis, K., Shahpar, F. M., Veloso, J., van Mechelen, W., & Verhagen, E. (2015). Competing with injuries: Injuries prior to and during the 15th FINA World Championships 2013 (aquatics). *British Journal of Sports Medicine*, *49*(1), 37–43. https://doi.org/10.1136/bjsports-2014-093991

Muir, S. W., Corea, C. L., & Beaupre, L. (2010). Evaluating change in clinical status: Reliability and measures of agreement for the assessment of glenohumeral range of motion. *North American Journal of Sports Physical Therapy: NAJSPT*, *5*(3), 98–110.

Mullaney, M. J., McHugh, M. P., Johnson, C. P., & Tyler, T. F. (2010). Reliability of shoulder range of motion comparing a goniometer to a digital level. *Physiotherapy Theory and Practice*, *26*(5), 327–333. https://doi.org/10.3109/09593980903094230

Munn, Z., Peters, M. D. J., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Medical Research Methodology*, *18*(1), 143. https://doi.org/10.1186/s12874-018-0611-x

Myers, J. B., & Lephart, S. M. (2000). The Role of the Sensorimotor System in the Athletic Shoulder. *Journal of Athletic Training*, *35*(3), 351–363.

Nagle, J., Mcmillan, J., Munkasy, B., Joyner, B., Roorda, A., Scott, M., & Rossi, S. (2015). Changes in Swim Performance and Perceived Stress, and Recovery in Femaile Collegiate Swimmers across a Competitive Season. *Journal of Swimming Research*, *volume 23*, 44–53.

Newton, L., & McCaig, S. (2018). The effect of a cricket fielding session on glenohumeral range of motion and active joint position sense. *Physical Therapy in Sport*, *31*, 52–57. https://doi.org/10.1016/j.ptsp.2018.04.002

Nielsen, R. O., Bertelsen, M. L., Møller, M., Hulme, A., Mansournia, M. A., Casals, M., & Parner, E. T. (2020). Methods matter: Exploring the ‘too much, too soon’ theory, part 1: causal questions in sports injury research. *British Journal of Sports Medicine*, bjsports-2018-100245. https://doi.org/10.1136/bjsports-2018-100245

Nobari, H., Aquino, R., Clemente, F. M., Khalafi, M., Adsuar, J. C., & Pérez-Gómez, J. (2020). Description of acute and chronic load, training monotony and strain over a season and its relationships with well-being status: A study in elite under-16 soccer players. *Physiology & Behavior*, *225*, 113117. https://doi.org/10.1016/j.physbeh.2020.113117

Noffal, G. J. (2003). Isokinetic Eccentric-to-Concentric Strength Ratios of the Shoulder Rotator Muscles in Throwers and Nonthrowers. *The American Journal of Sports Medicine*, *31*(4), 537–541. https://doi.org/10.1177/03635465030310041001

Oberlander, M. A., Chisar, M. A., & Campbell, B. (2000). Epidemiology of Shoulder Injuries in Throwing and Overhead Athletes: *Sports Medicine and Arthroscopy Review*, *8*(2), 115–123. https://doi.org/10.1097/00132585-200008020-00001

O’Connor, P. J., Morgan, W. P., & Raglin, J. S. (1991). Psychobiologic effects of 3 d of increased training in female and male swimmers. *Medicine & Science in Sports & Exercise*, *23*(9), 1055–1061.

O’Connor, P. J., Morgan, W. P., Raglin, J. S., Barksdale, C. M., & Kalin, N. H. (1989). Mood state and salivary cortisol levels following overtraining in female swimmers. *Psychoneuroendocrinology*, *14*(4), 303–310. https://doi.org/10.1016/0306-4530(89)90032-2

Opara, J., Kucio, C., Małecki, A., & Pilch, J. (2013). Methods of blinding clinical trials in physiotherapy. *Physiotherapy*, *21*. https://doi.org/10.2478/physio-2013-0006

Owoeye, O. B. A. (2020). Digging Deep into the Etiology of Basketball Injuries: A Complex Systems Approach for Risk Mitigation. In L. Laver, B. Kocaoglu, B. Cole, A. J. H. Arundale, J. Bytomski, & A. Amendola (Eds.), *Basketball Sports Medicine and Science* (pp. 665–671). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-61070-1_52

Pensgaard, A. M., Ivarsson, A., Nilstad, A., Solstad, B. E., & Steffen, K. (2018). Psychosocial stress factors, including the relationship with the coach, and their influence on acute and overuse injury risk in elite female football players. *BMJ Open Sport & Exercise Medicine*, *4*(1), e000317. https://doi.org/10.1136/bmjsem-2017-000317

Peolsson, Rune Hedlund, Birgitta Ob, A. (2001). INTRA- AND INTER-TESTER RELIABILITY AND REFERENCE VALUES FOR HAND STRENGTH. *Journal of Rehabilitation Medicine*, *33*(1), 36–41. https://doi.org/10.1080/165019701300006524

Phibbs, P. J., Roe, G., Jones, B., Read, D. B., Weakley, J., Darrall-Jones, J., & Till, K. (2017). Validity of Daily and Weekly Self-Reported Training Load Measures in Adolescent Athletes: *Journal of Strength and Conditioning Research*, *31*(4), 1121–1126. https://doi.org/10.1519/JSC.0000000000001708

Pink, M. M., & Tibone, J. E. (2000). THE PAINFUL SHOULDER IN THE SWIMMING ATHLETE. *Orthopedic Clinics of North America*, *31*(2), 247–261. https://doi.org/10.1016/S0030-5898(05)70145-0

Pink, M., Perry, J., Browne, A., Scovazzo, M. L., & Kerrigan, J. (1991). The normal shoulder during freestyle swimming: An electromyographic and cinematographic analysis of twelve muscles. *The American Journal of Sports Medicine*, *19*(6), 569–576. https://doi.org/10.1177/036354659101900603

Porter, K., Talpey, S., Pascoe, D., Blanch, P., Walker, H., & Shield, A. (2020). The effect of swimming volume and intensity on changes in supraspinatus tendon thickness. *Physical Therapy in Sport*. https://doi.org/10.1016/j.ptsp.2020.12.002

Powell, A., Levy, E., Heneghan, N. R., & Horsley, I. (2021). Intra-rater reliability, inter-rater reliability and minimal detectable change of the Posterior Shoulder Endurance Test in elite athletes. *Physical Therapy in Sport*. https://doi.org/10.1016/j.ptsp.2021.02.004

Pozzi, F., Plummer, H. A., Shanley, E., Thigpen, C. A., Bauer, C., Wilson, M. L., & Michener, L. A. (2020). Preseason shoulder range of motion screening and in-season risk of shoulder and elbow injuries in overhead athletes: Systematic review and meta-analysis. *British Journal of Sports Medicine*, *54*(17), 1019–1027. https://doi.org/10.1136/bjsports-2019-100698

Prokopy, M. P., Ingersoll, C. D., Nordenschild, E., Katch, F. I., Gaesser, G. A., & Weltman, A. (2008). Closed-Kinetic Chain Upper-Body Training Improves Throwing Performance of NCAA Division I Softball Players. *The Journal of Strength & Conditioning Research*, *22*(6), 1790–1798. https://doi.org/10.1519/JSC.0b013e318185f637

Rabbani, A., Clemente, F. M., Kargarfard, M., & Chamari, K. (2019). Match Fatigue Time-Course Assessment Over Four Days: Usefulness of the Hooper Index and Heart Rate Variability in Professional Soccer Players. *Frontiers in Physiology*, *10*, 109. https://doi.org/10.3389/fphys.2019.00109

Raglin, J. S., Koceja, D. M., Stager, J. M., & Harms, C. A. (1996). Mood, neuromuscular function, and performance during training in female swimmers. *Medicine & Science in Sports & Exercise*, *28*(3), 372–377.

Ramsi, M., Swanik, K. A., Swanik, C., Straub, S., & Mattacola, C. (2004). Shoulder-Rotator Strength of High School Swimmers Over the Course of a Competitive Season. *Journal of Sport Rehabilitation*, *13*(1), 9–18.

Reinold, M. M., & Gill, T. J. (2010). Current Concepts in the Evaluation and Treatment of the Shoulder in Overhead-Throwing Athletes, Part 1. *Sports Health*, *2*(1), 39–50. https://doi.org/10.1177/1941738109338548

Reinold, M. M., Wilk, K. E., Macrina, L. C., Sheheane, C., Dun, S., Fleisig, G. S., Crenshaw, K., & Andrews, J. R. (2008). Changes in Shoulder and Elbow Passive Range of Motion after Pitching in Professional Baseball Players. *The American Journal of Sports Medicine*, *36*(3), 523–527. https://doi.org/10.1177/0363546507308935

Relph, N., & Herrington, L. (2015). Interexaminer, Intraexaminer, and Test-Retest Reliability of Clinical Knee Joint-Position-Sense Measurements Using an Image-Capture Technique. *Journal of Sport Rehabilitation*, *24*(2). https://doi.org/10.1123/jsr.2013-0134

Riemann, B. L., Davies, G. J., Ludwig, L., & Gardenhour, H. (2010). Hand-held dynamometer testing of the internal and external rotator musculature based on selected positions to establish normative data and unilateral ratios. *Journal of Shoulder and Elbow Surgery*, *19*(8), 1175–1183. https://doi.org/10.1016/j.jse.2010.05.021

Riemann, B. L., & Lephart, S. M. (2002). The Sensorimotor System, Part II: The Role of Proprioception in Motor Control and Functional Joint Stability. *Journal of Athletic Training*, *37*(1), 80–84.

Riemann, B. L., & Lininger, M. (2015). Statistical Primer for Athletic Trainers: The Difference Between Statistical and Clinical Meaningfulness. *Journal of Athletic Training*, *50*(12), 1223–1225. https://doi.org/10.4085/1062-6050-51.1.04

Riemann, B. L., & Lininger, M. R. (2018a). Statistical Primer for Athletic Trainers: The Essentials of Understanding Measures of Reliability and Minimal Important Change. *Journal of Athletic Training; Dallas*, *53*(1), 98–103. http://dx.doi.org.salford.idm.oclc.org/10.4085/1062-6050-503-16

Riemann, B. L., & Lininger, M. R. (2018b). Principles of Statistics. *Clinics in Sports Medicine*, *37*(3), 375–386. https://doi.org/10.1016/j.csm.2018.03.004

Ristolainen, L., Kettunen, J., Waller, B., Heinonen, A., & Kujala, U. (2014). Training-related risk factors in the etiology of overuse injuries in endurance sports. *THE JOURNAL OF SPORTS MEDICINE AND PHYSICAL FITNESS*, *54*(1), 10.

Rodeo, S. A., Nguyen, J. T., Cavanaugh, J. T., Patel, Y., & Adler, R. S. (2016). Clinical and Ultrasonographic Evaluations of the Shoulders of Elite Swimmers. *The American Journal of Sports Medicine*, *44*(12), 3214–3221. https://doi.org/10.1177/0363546516657823

Rosen, P. von, Frohm, A., Kottorp, A., Fridén, C., & Heijne, A. (2017). Multiple factors explain injury risk in adolescent elite athletes: Applying a biopsychosocial perspective. *Scandinavian Journal of Medicine & Science in Sports*, *27*(12), 2059–2069. https://doi.org/10.1111/sms.12855

Rupp, S., Berninger, K., & Hopf, T. (1995). Shoulder Problems in High Level Swimmers—Impingement, Anterior Instability, Muscular Imbalance? *International Journal of Sports Medicine*, *16*(08), 557–562. https://doi.org/10.1055/s-2007-973054

Ruxton, G. D., & Neuhäuser, M. (2010). When should we use one-tailed hypothesis testing? *Methods in Ecology and Evolution*, *1*(2), 114–117. https://doi.org/10.1111/j.2041-210X.2010.00014.x

Saavedra, J. M., Escalante, Y., & Rodríguez, F. A. (2010). A Multivariate Analysis of Performance in Young Swimmers. *Pediatric Exercise Science*, *22*(1), 135–151.

Sahin, E., Dilek, B., Baydar, M., Gundogdu, M., Ergin, B., Manisali, M., Akalin, E., & Gulbahar, S. (2017). Shoulder proprioception in patients with subacromial impingement syndrome. *Journal of Back & Musculoskeletal Rehabilitation*, *30*(4), 857–862.

Sallis, R. E., Jones, K., Sunshine, S., Smith, G., & Simon, L. (2001). Comparing Sports Injuries in Men and Women. *International Journal of Sports Medicine*, *22*(6), 420–423. https://doi.org/10.1055/s-2001-16246

Saw, A. E., Kellmann, M., Main, L. C., & Gastin, P. B. (2017). Athlete Self-Report Measures in Research and Practice: Considerations for the Discerning Reader and Fastidious Practitioner. *International Journal of Sports Physiology and Performance*, *12*(s2), S2-127-S2-135. https://doi.org/10.1123/ijspp.2016-0395

Saw, A. E., Main, L. C., & Gastin, P. B. (2016). Monitoring the athlete training response: Subjective self-reported measures trump commonly used objective measures: a systematic review. *British Journal of Sports Medicine*, *50*(5), 281–291. https://doi.org/10.1136/bjsports-2015-094758

Sawczuk, T. (2019). *Training loads and player wellness in youth sport: Implications for illness*. https://doi.org/10.13140/RG.2.2.16012.95363

Sawdon-Bea, J., & Benson, J. (2015). The Effects of a 6-Week Dry Land Exercise Program for High School Swimmers. *Journal of Physical Education and Sports Management*, *2*(1). https://doi.org/10.15640/jpesm.v2n1a1

Scovazzo, M. L., Browne, A., Pink, M., Jobe, F. W., & Kerrigan, J. (1991). The painful shoulder during freestyle swimming: An electromyographic cinematographic analysis of twelve muscles. *The American Journal of Sports Medicine*, *19*(6), 577–582. https://doi.org/10.1177/036354659101900604

Sein, M. L., Walton, J., Linklater, J., Appleyard, R., Kirkbride, B., Kuah, D., & Murrell, G. A. C. (2010). Shoulder pain in elite swimmers: Primarily due to swim-volume-induced supraspinatus tendinopathy. *British Journal of Sports Medicine*, *44*(2), 105–113. https://doi.org/10.1136/bjsm.2008.047282

Shahidi, B., Johnson, C. L., Curran-Everett, D., & Maluf, K. S. (2012). Reliability and group differences in quantitative cervicothoracic measures among individuals with and without chronic neck pain. *BMC Musculoskeletal Disorders*, *13*(1). https://doi.org/10.1186/1471-2474-13-215

Shahpar, F. M., Rahnama, N., & Salehi, S. (2019). The Effect of 8 Weeks Open and Closed Kinetic Chain Strength Training on the Torque of the External and Internal Shoulder Rotator Muscles in Elite Swimmers. *Asian Journal of Sports Medicine*, *10*(2), 1–6. https://doi.org/10.5812/asjsm.82158

Shanley, E., Kissenberth, M. J., Thigpen, C. A., Bailey, L. B., Hawkins, R. J., Michener, L. A., Tokish, J. M., & Rauh, M. J. (2015). Preseason shoulder range of motion screening as a predictor of injury among youth and adolescent baseball pitchers. *Journal of Shoulder and Elbow Surgery*, *24*(7), 1005–1013. https://doi.org/10.1016/j.jse.2015.03.012

Shin, S. H., Ro, D. H., Lee, O.-S., Oh, J. H., & Kim, S. H. (2012). Within-day reliability of shoulder range of motion measurement with a smartphone. *Manual Therapy*, *17*(4), 298–304. https://doi.org/10.1016/j.math.2012.02.010

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin*, *86*(2), 420–428. https://doi.org/10.1037/0033-2909.86.2.420

Silva, A. G., Cerqueira, M., Santos, A. R., Ferreira, C., Alvarelhão, J., & Queirós, A. (2019). Inter-rater reliability, standard error of measurement and minimal detectable change of the 12-item WHODAS 2.0 and four performance tests in institutionalized ambulatory older adults. *Disability and Rehabilitation*, *41*(3), 366–373. https://doi.org/10.1080/09638288.2017.1393112

Silvers-Granelli, H., Bizzini, M., Arundale, A., Mandelbaum, B., Pohlig, R., & Snyder-Mackler, L. (2017). Does Higher Compliance to the Fifa 11+ Injury Prevention Program Improve Overall Injury Rate in Male Soccer (football) Players? *British Journal of Sports Medicine*, *51*(4), 389–390. https://doi.org/10.1136/bjsports-2016-097372.268

Smith, N., Hotze, R., & Tate, A. R. (2021). A Novel Rehabilitation Program Using Neuromuscular Electrical Stimulation (NMES) and Taping for Shoulder Pain in Swimmers: A Protocol and Case Example. *International Journal of Sports Physical Therapy*, *16*(2), 579–590. https://doi.org/10.26603/001c.21234

Soligard, T., Schwellnus, M., Alonso, J.-M., Bahr, R., Clarsen, B., Dijkstra, H. P., Gabbett, T., Gleeson, M., Hägglund, M., Hutchinson, M. R., Rensburg, C. J. van, Khan, K. M., Meeusen, R., Orchard, J. W., Pluim, B. M., Raftery, M., Budgett, R., & Engebretsen, L. (2016). How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *British Journal of Sports Medicine*, *50*(17), 1030–1041. https://doi.org/10.1136/bjsports-2016-096581

Sørensen, A. K. B., & Jørgensen, U. (2000). Secondary impingement in the shoulder. *Scandinavian Journal of Medicine & Science in Sports*, *10*(5), 266–278. https://doi.org/10.1034/j.1600-0838.2000.010005266.x

Sporrong, H., Palmerud, G., & Herberts, P. (1995). Influences of handgrip on shoulder muscle activity. *European Journal of Applied Physiology and Occupational Physiology*, *71*(6), 485–492. https://doi.org/10.1007/BF00238549

Stark, T., Walker, B., Phillips, J., Fejer, R., & Beck, R. (2011). *Hand-held Dynamometry Correlation With the Gold Standard Isokinetic Dynamometry: A Systematic Review* (Vol. 3). https://doi.org/10.1016/j.pmrj.2010.10.025

Stephens, J. L., Pratt, N., & Michlovitz, S. (1996). The reliability and validity of the tekdyne hand dynamometer: Part II. *Journal of Hand Therapy*, *9*(1), 18–26. https://doi.org/10.1016/S0894-1130(96)80007-X

Stern, B. D., Hegedus, E. J., & Lai, Y.-C. (2019). Injury prediction as a non-linear system. *Physical Therapy in Sport*. https://doi.org/10.1016/j.ptsp.2019.10.010

Stief, F., Böhm, H., Dussa, C. U., Multerer, C., Schwirtz, A., Imhoff, A. B., & Döderlein, L. (2014). Effect of lower limb malalignment in the frontal plane on transverse plane mechanics during gait in young individuals with varus knee alignment. *The Knee; Amsterdam*, *21*(3), 688–693. http://dx.doi.org.salford.idm.oclc.org/10.1016/j.knee.2014.03.004

Stocker, D., Pink, M., & Jobe, F. W. (1995). Comparison of Shoulder Injury in Collegiate- and Master's-Level Swimmers. *Clinical Journal of Sport Medicine*, *5*(1), 4–8.

Struyf, F., Tate, A., Kuppens, K., Feijen, S., & Michener, L. A. (2017). Musculoskeletal dysfunctions associated with swimmers' shoulder. *British Journal of Sports Medicine*, *51*(10), 775–780. https://doi.org/10.1136/bjsports-2016-096847

Svensson, E., Waling, K., & Häger-Ross, C. (2008). Grip strength in children: Test–retest reliability using Grippit. *Acta Paediatrica*, *97*(9), 1226–1231. https://doi.org/10.1111/j.1651-2227.2008.00895.x

Swanik, K. A., Swanik, C. B., Lephart, S. M., & Huxel, K. (2002). The Effect of Functional Training on the Incidence of Shoulder Pain and Strength in Intercollegiate Swimmers. *Journal of Sport Rehabilitation*, *11*(2), 140–154.

Tate, A., Harrington, S., Buness, M., Murray, S., Trout, C., & Meisel, C. (2015). Investigation of In-Water and Dry-Land Training Programs for Competitive Swimmers in the United States. *Journal of Sport Rehabilitation*, *24*(4), 353–362.

Tate, A., Sarver, J., DiPaola, L., Yim, J., Paul, R., & Thomas, S. J. (2020). Changes in clinical measures and tissue adaptations in collegiate swimmers across a competitive season. *Journal of Shoulder and Elbow Surgery*, *29*(11), 2375–2384. https://doi.org/10.1016/j.jse.2020.03.028

Tate, A., Turner, G. N., Knab, S. E., Jorgensen, C., Strittmatter, A., & Michener, L. A. (2012). Risk Factors Associated With Shoulder Pain and Disability Across the Lifespan of Competitive Swimmers. *Journal of Athletic Training*, *47*(2), 149–158. https://doi.org/10.4085/1062-6050-47.2.149

Taylor, K.-L., Chapman, D. W., Cronin, J. B., Newton, M. J., & Gill, N. (2012). *FATIGUE MONITORING IN HIGH PERFORMANCE SPORT: A SURVEY OF CURRENT TRENDS*. *20*(1), 13.

Taylor, S. R., Rogers, G. G., & Driver, H. S. (1997). Effects of training volume on sleep, psychological, and selected physiological profiles of elite female swimmers: *Medicine &amp Science in Sports &amp Exercise*, *29*(5), 688–693. https://doi.org/10.1097/00005768-199705000-00016

Tessaro, M., Granzotto, G., Poser, A., Plebani, G., & Rossi, A. (2017). SHOULDER PAIN IN COMPETITIVE TEENAGE SWIMMERS AND IT'S PREVENTION: A RETROSPECTIVE EPIDEMIOLOGICAL CROSS SECTIONAL STUDY OF PREVALENCE. *International Journal of Sports Physical Therapy*, *12*(5), 798–811.

Thorborg, K., Krommes, K. K., Esteve, E., Clausen, M. B., Bartels, E. M., & Rathleff, M. S. (2017). Effect of specific exercise-based football injury prevention programmes on the overall injury rate in football: A systematic review and meta-analysis of the FIFA 11 and 11+ programmes. *British Journal of Sports Medicine*, *51*(7), 562–571. https://doi.org/10.1136/bjsports-2016-097066

Molenaar, H. M., Zuidam, J. M., Selles, R. W., Stam, H. J., & Hovius, S. E. R. (2008). Age-Specific Reliability of Two Grip-Strength Dynamometers When Used by Children: *The Journal of Bone* *and Joint Surgery-American Volume*, *90*(5), 1053–1059. https://doi.org/10.2106/JBJS.G.00469

Tomar, R., & Allen, J. A. (2019). *The Relationship of Training Parameters with Incidence of Injury, Sleep and Well Being of Young University Swimmers*. 14.

Trevethan, R. (2017). Intraclass correlation coefficients: Clearing the air, extending some cautions, and making some requests. *Health Services and Outcomes Research Methodology*, *17*(2), 127–143. https://doi.org/10.1007/s10742-016-0156-6

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., Moher, D., Peters, M. D. J., Horsley, T., Weeks, L., Hempel, S., Akl, E. A., Chang, C., McGowan, J., Stewart, L., Hartling, L., Aldcroft, A., Wilson, M. G., Garritty, C., … Straus, S. E. (2018). PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. *Annals of Internal Medicine*, *169*(7), 467–473. https://doi.org/10.7326/M18-0850

Trinidad, A., González-Garcia, H., & López-Valenciano, A. (2021). An Updated Review of the Epidemiology of Swimming Injuries. *PM & R: The Journal of Injury, Function, and Rehabilitation*, *13*(9), 1005–1020. https://doi.org/10.1002/pmrj.12503

Tsang, R. C. C. (2005). Reference Values for 6-Minute Walk Test and Hand-Grip Strength in Healthy Hong Kong Chinese Adults. *Hong Kong Physiotherapy Journal*, *23*(1), 6–12. https://doi.org/10.1016/S1013-7025(09)70053-3

Vafadar, A. K., Cote, J. N., & Archambault, P. S. (2016). Interrater and Intrarater Reliability and Validity of 3 Measurement Methods for Shoulder-Position Sense. *Journal of Sport Rehabilitation*, *25*(1). https://doi.org/10.1123/jsr.2014-0309

Van de Velde, A., De Mey, K., Maenhout, A., Calders, P., & Cools, A. M. (2011). Scapular-Muscle Performance: Two Training Programs in Adolescent Swimmers. *Journal of Athletic Training*, *46*(2), 160–167. https://doi.org/10.4085/1062-6050-46.2.160

Van Dyk, N., & Clarsen, B. (2017). Prevention forecast: Cloudy with a chance of injury. *British Journal of Sports Medicine; London*, *51*(23). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsports-2017-097861

Verhagen, E., & Gabbett, T. (2019). Load, capacity and health: Critical pieces of the holistic performance puzzle. *British Journal of Sports Medicine*, *53*(1), 5–6. https://doi.org/10.1136/bjsports-2018-099819

Virag, B., Hibberd, E. E., Oyama, S., Padua, D. A., & Myers, J. B. (2014). Prevalence of Freestyle Biomechanical Errors in Elite Competitive Swimmers. *Sports Health*, *6*(3), 218–224. https://doi.org/10.1177/1941738114527056

Walker, H., Gabbe, B., Wajswelner, H., Blanch, P., & Bennell, K. (2012). Shoulder pain in swimmers: A 12-month prospective cohort study of incidence and risk factors. *Physical Therapy in Sport*, *13*(4), 243–249. https://doi.org/10.1016/j.ptsp.2012.01.001

Walker, H., Pizzari, T., Wajswelner, H., Blanch, P., Schwab, L., Bennell, K., & Gabbe, B. (2016). The reliability of shoulder range of motion measures in competitive swimmers. *Physical Therapy in Sport*, *21*, 26–30. https://doi.org/10.1016/j.ptsp.2016.03.002

Wallace, L., Coutts, A., Bell, J., Simpson, N., & Slattery, K. (2008). Using Session-RPE to Monitor Training Load in Swimmers: *Strength and Conditioning Journal*, *30*(6), 72–76. https://doi.org/10.1519/SSC.0b013e31818eed5f

Wallace, L. K., Slattery, K. M., & Coutts, A. J. (2009). The Ecological Validity and Application of the Session-Rpe Method for Quantifying Training Loads in Swimming. *Journal of Strength and Conditioning Research; Champaign*, *23*(1), 33–38. http://dx.doi.org.salford.idm.oclc.org/10.1519/JSC.0b013e3181874512

Walter, S. D., & Eliasziw, M. (1998). Sample size and optimal designs for reliability studies. *Statistics in Medicine*, *17*(1), 101–110. https://doi.org/10.1002/(SICI)1097-0258(19980115)17:1<101::AID-SIM727>3.0.CO;2-E

Wanivenhaus, F., Fox, A. J. S., Chaudhury, S., & Rodeo, S. A. (2012). Epidemiology of Injuries and Prevention Strategies in Competitive Swimmers. *Sports Health: A Multidisciplinary Approach*, *4*(3), 246–251. https://doi.org/10.1177/1941738112442132

Watson, A., Brickson, S., Brooks, A., & Dunn, W. (2017). Subjective well-being and training load predict in-season injury and illness risk in female youth soccer players. *British Journal of Sports Medicine; London*, *51*(3). http://dx.doi.org.salford.idm.oclc.org/10.1136/bjsports-2016-096584

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research*, *19*(1), 231–240. https://doi.org/10.1519/15184.1

Weissgerber, T. L., Savic, M., Winham, S. J., Stanisavljevic, D., Garovic, V. D., & Milic, N. M. (2017). Data visualization, bar naked: A free tool for creating interactive graphics. *The Journal of Biological Chemistry*, *292*(50), 20592–20598. https://doi.org/10.1074/jbc.RA117.000147

Welbeck, A. N., Amilo, N. R., Le, D. T., Killelea, C. M., Kirsch, A. N., Zarzour, R. H., Burgi, C. R., Sell, T. C., & Faherty, M. S. (2019). Examining the link between thoracic rotation and scapular dyskinesis and shoulder pain amongst college swimmers. *Physical Therapy in Sport*, *40*, 78–84. https://doi.org/10.1016/j.ptsp.2019.08.013

Weldon, E. J., & Richardson, A. B. (2001). UPPER EXTREMITY OVERUSE INJURIES IN SWIMMING. *Clinics in Sports Medicine*, *20*(3), 423–438. https://doi.org/10.1016/S0278-5919(05)70260-X

Werner, B. C., Holzgrefe, R. E., Griffin, J. W., Lyons, M. L., Cosgrove, C. T., Hart, J. M., & Brockmeier, S. F. (2014). Validation of an innovative method of shoulder range-of-motion measurement using a smartphone clinometer application. *Journal of Shoulder and Elbow Surgery*, *23*(11), e275–e282. https://doi.org/10.1016/j.jse.2014.02.030

Wilk, K. E., Macrina, L. C., Fleisig, G. S., Porterfield, R., Simpson, C. D., Harker, P., Paparesta, N., & Andrews, J. R. (2011). Correlation of Glenohumeral Internal Rotation Deficit and Total Rotational Motion to Shoulder Injuries in Professional Baseball Pitchers. *The American Journal of Sports Medicine*, *39*(2), 329–335. https://doi.org/10.1177/0363546510384223

Wilk, K. E., Reinold, M. M., Macrina, L. C., Porterfield, R., Devine, K. M., Suarez, K., & Andrews, J. R. (2009). Glenohumeral Internal Rotation Measurements Differ Depending on Stabilization Techniques. *Sports Health: A Multidisciplinary Approach*, *1*(2), 131–136. https://doi.org/10.1177/1941738108331201

Williams, K., & Hebron, C. (2018). The immediate effects of serving on shoulder rotational range of motion in tennis players. *Physical Therapy in Sport*, *34*, 14–20. https://doi.org/10.1016/j.ptsp.2018.08.007

Wilson, G. J., Murphy, A. J., & Pryor, J. F. (1994). Musculotendinous stiffness: Its relationship to eccentric, isometric, and concentric performance. *Journal of Applied Physiology*, *76*(6), 2714–2719. https://doi.org/10.1152/jappl.1994.76.6.2714

Windt, J., & Gabbett, T. J. (2017). How do training and competition workloads relate to injury? The workload—injury aetiology model. *Br J Sports Med*, *51*(5), 428–435. https://doi.org/10.1136/bjsports-2016-096040

Wolf, B. R., Ebinger, A. E., Lawler, M. P., & Britton, C. L. (2009). Injury Patterns in Division I Collegiate Swimming. *The American Journal of Sports Medicine*, *37*(10), 2037–2042. https://doi.org/10.1177/0363546509339364

Wollin, M., Purdam, C., & Drew, M. K. (2016). Reliability of externally fixed dynamometry hamstring strength testing in elite youth football players. *Journal of Science and Medicine in Sport*, *19*(1), 93–96. https://doi.org/10.1016/j.jsams.2015.01.012

Wollin, M., Thorborg, K., Drew, M., & Pizzari, T. (2019). A novel hamstring strain injury prevention system: Post-match strength testing for secondary prevention in football. *British Journal of Sports Medicine*, bjsports-2019-100707. https://doi.org/10.1136/bjsports-2019-100707

Wright, A. A., Hegedus, E. J., Tarara, D. T., Ray, S. C., & Dischiavi, S. L. (2018). Exercise prescription for overhead athletes with shoulder pathology: A systematic review with best evidence synthesis. *British Journal of Sports Medicine*, *52*(4), 231–237. https://doi.org/10.1136/bjsports-2016-096915

Yanai, T., & Hay, J. G. (2000). Shoulder impingement in front-crawl swimming: II. analysis of stroking technique: *Medicine & Science in Sports & Exercise*, 30. https://doi.org/10.1097/00005768-200001000-00006

Yoma, M., Herrington, L., Mackenzie, T. A., & Almond, T. A. (2021). Training Intensity and Shoulder Musculoskeletal Physical Quality Responses in Competitive Swimmers. *Journal of Athletic Training*, *56*(1), 54–63. https://doi.org/10.4085/1062-6050-0357.19

Zampagni, M. L., Casino, D., Benelli, P., Visani, A., Marcacci, M., & De Vito, G. (2008). Anthropometric and Strength Variables to Predict Freestyle Performance Times in Elite Master Swimmers. *Journal of Strength and Conditioning Research; Champaign*, *22*(4), 1298–1307.

Zanini, G. D. S., Filho, D. M. P., Neiva, C. M., Da Silva, D. P., Ciolac, E. G., & Verardi, C. E. L. (2018). Stress and mood states monitoring in a swimming team during a competitive period. *Journal of Physical Education and Sport; Pitesti*, *18*(4), 2466–2471. http://dx.doi.org/10.7752/jpes.2018.04369

Zemek, M. J., & Magee, D. J. (1996). Comparison of glenohumeral joint laxity in elite and recreational swimmers. *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine*, *6*(1), 40–47. https://doi.org/10.1097/00042752-199601000-00009

Ethical approval forms

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13 September 2018

Dear Matias,

RE: ETHICS APPLICATION–HSR1718-100 – ‘Reliability study of shoulder outcome measures. ‘Swimming and Shoulder Joint Position Sense.’

Based on the information that you have provided, I am pleased to inform you that ethics application HSR1718-100 has been approved.

If there are any changes to the project and/or its methodology, then please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,

Professor Sue McAndrew
Chair of the Research Ethics Panel

Amendment Notification Form

Please complete this form and submit it to the Health Research Ethics Panel that reviewed the original proposal: Health-ResearchEthics@Salford.ac.uk

Title of Project: Swimming and Shoulder Joint Position Sense

Name of Lead Applicant: Matias Yoma *School:* Health Sciences

Are you the original Principal Investigator (PI) for this study? ***YES*** *(delete as appropriate)*

If you have selected 'NO', please explain why you are applying for the amendment:

Date when original approval was obtained: 13 September 2018 *Reference No:* HSR1718-100

Please outline the proposed changes to the project. ***NB.*** *If the changes require any amendments to the PIS, Consent Form(s) or recruitment material, then please submit these with this form highlighting where the changes have been made:*

There are no changes to the original documents. One of the swimming clubs participating in the study involve under 18 years old participants. For this reason, we are adding two consent forms and two information sheets (for parents and under 18 years old participants).

Please say whether the proposed changes present any new ethical issues or changes to ethical issues that were identified in the original ethics review, and provide details of how these will be addressed:

The proposed changes present new ethical issues as we are aiming to add children to the study (under 18 years old).
To address this ethical issue, the University of Salford Safeguarding policy V.2.2 will be followed (Appendix D: Recommended behaviour when dealing with Children or Vulnerable Adults). The welfare of the children will be ensured during all the procedures. Children will be measured by the investigators in a safe and open environment (swimming club pool) always in presence of other adults (coaches). In addition, new information sheets and consent forms for under 18 years old participants and for their parents will be provided.

Amendment Approved: ☑

Date of Approval: 22.11.18

Chair's Signature: