EVALUATION OF A NOVEL DEVICE TO ASSESS COMBINED KNEE FLEXION AND HIP EXTENSION, AND HIP FLEXION FORCE PRODUCTION CAPABILITY

BRIEF RUNNING HEAD: *HIP AND KNEE FORCE PRODUCTION CAPABILITY*

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CONTENTS

ABBREVIATIONS

FP – Flight phase

IKD – Isokinetic Dynamometer

HHD – Hand held dynamometer

ICC – Intraclass correlation coefficient

CV – Coefficient of variation

ACL – Anterior cruciate ligament

IMTP – Isometric mid thigh pull

HSI – Hamstring strain injury

GCT – Ground contact time

SEM – Standard error of the measurement

SD – Standard deviation

SDD – Smallest detectable difference

ES – Effect size

MDC – Mininum detectable change

TE – Typical error

T – Testing session

Tr – Trial

UB – Upper bound

LB – Lower bound

LoA – Limits of agreement

1.0 OVERARCHING ABSTRACT

Background: The late flight phase (FP) of the sprint running action is essential to enable the 'forward most limb' to prepare for ground contact. Kinetic and kinematic factors during the FP show association to sprinting speed. While isometric assessments are widely used to evaluate sprint metrics, they often replicate weightlifting positions and not sprint positions. However, isometric isokinetic dynamometry (IKD) and handheld dynamometry (HHD) do allow limbs to be manoeuvred into joint angles similar to the FP of sprinting, though they test unilaterally and don't specifically replicate sprinting positions. Therefore, *Performance Biomechanics* created *The Biostrain, an* isometric device that is capable of assessing isometric force-time characteristics in similar positions to the FP of sprinting. ***Aims:*** This thesis provides a systematic review of IKD and HHD literature to investigate reliability and validity (study 1). This thesis also aims to assess the Biostrain (over 150ms, 200ms, 250ms and peak force) reliability, and validity compared to IKD (peak force) (study 2) and assess its correlation with 20 m sprint performance (study 3). ***Study 1 Methods:*** A literature search was conducted using literature databases and assessment of study quality was assessed using a modified Downs and Blacks scale. ***Study 2 and 3 Methods:*** Eighteen healthy active subjects participated (n = 18; age = 23.3 ± 5.1 years; height: 173.9 ± 5.8 cm; mass: 69.4 ± 12.8 kg). ***Biostrain methods:*** Subjects completed three trials with left leg forwards and right leg back and three trials with right leg forward and left leg back without the use of hands to stabilise positions and again repeated with hand stability (study 2 and study 3). ***IKD Methods:*** 3 × 5 s maximum effort trials were carried out in three different positions on each leg that replicated individual limbs during Biostrain testing (study 2). ***Sprinting Methods***: Subjects completed 3 x 20 m maximum effort sprints (study 3). ***Study 1 systematics review resutls:*** Out of an inital 421, 19 articles were deemed eligible. The main overall findings showed IKD was more reliable than HHD (IKD ICC: 0.83 to 0.99; HHD ICC: 0.49 to 0.99). The quality of methods for IKD ranged between 73 to 91% and for HHD ranged between 73 to 82%. **Study 2 *reliability study results:*** Intraclass correlation coefficients (ICC) were mixed but predominantly acceptable (ICC = 0.625 to 0.976). Coefficients of variation (CV) were acceptable on all occasions (1.59 to 10.91%). Correlation between the Biostrain and Kin Com were large to very large Kin Com (*r* = 0.495 to 0.851). ***Study 3 correlation study results:*** The back leg Biostrain data showed large to very large associations with 20 m sprint performance for the majority of time points (*r* = -0.505 to -0.763). Peak forces of the front leg mostly exhibited large correlations with sprint performance (*r* = 0.467 to -0.656). ***Study 1 systematic review conclusion:*** IKD was more reliable than HHD though it was clear that HHD and IKD has been assessed in a range of positions, angles and used different units of measurement making it difficult for between study comparisons to be made. ***Study 2 and 3 Conclusions:*** The Biostrain demonstrates strong reliability and validity coupled with substantial correlations with the gold standard IKD and sprint performance suggesting its potential as a tool for assessing isometric force time characteristics.

Key words: Hip extension; Hip Flexion, Knee flexion, Isometric, flight phase

2.0 OVERARCHING INTRODUCTION TO THE THESIS

It is well known within the sports science industry that improving force generating capacity coupled with emphasising the ability to rapidly produce force not only diminishes the likelihood of injuries but also increases athletic performance (81,97,106,147,154,175). This is attributed to the role of impulse (force × time) (65). As relative force determines acceleration (65), when the time component is added, this determines the duration of acceleration and therefore the resulting velocity of movement. Therefore, the impulse equation plays a key role in the success of sprinting related tasks in competition. Recent years have seen a surge in research dedicated to exploring the force production capabilities of the lower body, specifically muscles that surround the hip and knee, where there has been a strong emphasis on the hamstrings (12,119,153,166) due to the large occurance of hamstring strain injuries (HSI) in sprint related sports. HSI are prevelent in team sports and typically occur during the late flight phase (FP) of the sprinting action (30) and/or the early contact phase (100). In these phases the hamstrings are required to generate significant force to prepare for touchdown. Consequently, poor technique combined with the forceful physical demand, puts the hamstrings at increased risk of injury (100). As sprinting is a common action across most team sports the need to reduce the risk of HSI is important. Additionally, athletes who have experienced lower body injuries such as HSI are more prone to recurring instances, elevating their susceptibility (50). Other injuries related to the hip and knee such as iliotibial band syndrome (57), patellofemoral pain syndrome (47) and anterior cruciate ligament tears (ACL) (130) also pose significant risk during tasks like sprinting and are also a concern for practitioners. Hence, it is of paramount importance to pinpoint athletes who might be predisposed to injuries.

Motions of the hip, knee and pelvis during sprinting have been found to be highly related to hip extensor strength (56) demonstrating the importance of assessing and improving hip and knee function. In order to do so practitioners use a range of assessments. Whilst there are a large body of assessments used in the industry to assess lower body function, many are typically eccentric (such as the Nordic hamstring curl (38)) due to the requirement of eccentric knee flexor strength to control the rate of deceleration of the swing leg prior to ground contact in the sprint running action (129). Training and developing the hamstrings using eccentric modes have been found to significantly reduce the risk of injury, where eccentric training has been found to reduce the risk of secondary HSI by 65 to 85% (27,61). Though this is the case the evaluation of eccentric strength can present challenges when monitoring regularly as eccentric muscle actions are linked to muscle damage and delayed onset muscle soreness (73,136). For instance, the Nordic hamstring exercise has been criticized in research for its inability to accurately assess an individual's peak force (168). This limitation stems from the exercise's design, which prevents participants from achieving the necessary movement range to reach the hamstrings' angle of peak torque. Moreover, the test is bilateral and only measures peak force, which then requires normalisation to body mass and in some cases height, thereby narrowing its practical utility. Furthermore, the exercise's effectiveness diminishes at higher speeds due to restricted isokinetic range, emphasising the challenge in achieving peak force. Additionally, the seated position during the test contributes to its impracticality (168)

The use of isometric assesments are becoming more popular in the industry as they allow multiple repetitions to be performed with short rest periods, large groups to be assessed quickly and are also less likely to induce muscle damage (32,117). However, their primary attraction point is that they offer the advantage of measuring force at sport-specific time intervals allowing insights into an athlete's neuromuscular function, the effectiveness of training programmes and ability to identify injury risk (32). Common lower body isometric tests include: isometric IKD (99,140), HHD (90,93,122), the isometric mid thigh pull (IMTP) (32,135), isometric squat (18,24) and the isometric hip thrust (62). Whilst these tests offer useful information, most of the isometric tests are typically tested in seated, laying or replicate positions similar to weightlifting positions and do not specifically replicate the joint angles exhibited in dynamic sporting actions such as sprinting where injury risk is high. Though this is the case, assesments like the isometric squat could be adapted to align with the positions of the hip, knee and ankle during the mid-stance phase of sprint running at maximal velocity. Bisop et al. (13) demonstrated strong reliability in the single leg isometric squat, suggesting that modifying the test for unilateral use and to evaluate sprinting joint angles may hold promising potential, though research is lacking in this area.

An intriguing point to note, ~~is that~~ certain researchers have presented the idea that the biarticular hamstring muscle operates more in an isometric capacity, rather than eccentric, during the late FP of the sprinting gait cycle (one of the places where HSI are believed to occur). However, this is based on animal models (76). In practice, making direct comparisons between sprinting gait of humans and animals is unrealistic due to the fundamental contrast between their bipedal and quadrupedal locomotion. This distinction may lead to differences in gait patterns and musculotendinous characteristics, but research is lacking in this area. On the other hand, Nagano et al. (131) observed that during the late swing phase of sprinting in humans (between the eccentric and concentric portions, where there is little change in muscle length) the bicep femoris and the gluteus maximus generated their peak force. Consequently, evaluating peak forces in this specific position could prove beneficial. ~~However, if the hamstrings do act isometrically, it could be said that assessing hip and knee~~

~~function in positions similar to the FP isometrically could be useful~~ Though to date, no isometric tests cater for such positions in its entirety (e.g. as seen in figure 4.0).

Although the HSI are known to occur in the late FP and/or early contact, the FP is often neglected due to the stance phase being the ultimate driving force to cause movement during the sprinting action and of course the limited ability to assess airborne positions isometrically. However, whilst this is the case IKD does offer the ability to unilaterally manoeuvre individual limbs into joint angles similar to positions in sprinting gait. When in flight, front leg hip flexion angles have been found to be between 62.0 to 83.8º (relative to the vertical) and front leg knee joint angle between 22.1 to 47.3 º (relative to the vertical) (125). In elite sprinters, the back leg hip angles have been found to range between 3.9 to -16.8 º (142). Interestingly, Boraczynski et al. (20) using IKD reported a large correlation with normalised maximal isometric knee extensor strength on the IKD at 90º of knee flexion and 30 m sprint time (r = -0.596, $p \leq 0.01$). Although angles assessed differ to that of knee angles during FP the correlation could suggest that assessing isometric assessments in positions similar to the late FP of the sprinting action could show greater correlation and thus help better inform methods to assess sprint specific muscle strength qualities. The isometric hip thrust is also an alternative test that allows the hip and knee to be assessed in positions similar to the FP of sprinting. Goodwin and Bull (62) assessed the isometric hip thrust, laying supine with heels on the force plate at joint angles 20º, 30º, 40º and 50º similar to the front leg knee angles during the FP. Researchers found this test and angles measured to be highly reliable and produced low error compared to the gold standard IKD, further suggesting isometrically assessing joint angles in positions similar to the FP of sprinting may provide great insights. However, whilst the IKD and isometric hip thrust are highly valid and reliable they have some drawbacks. These tests only allows testing to be done seated, standing or laying, and thus do not sepcfically replicate the dynamic bi-lateral multi-joint positions of sprinting. In terms of IKD, it is also very expensive and cannot be easiliy transported meaning it does not practically allow for continual monitoring assesments in real life sports settings.

The company *Performance Biomechanics* has created a new novel device *The Biostrain. The Biostrain* was created to assess isometric force production capabilities in positions that aim to replicate the FP of sprinting gait. The bi-lateral device has the ability to provide individual limb feedback and similar to other isometric tests, can assess force characteristics at different time points that have been found to show correlation to a range of dynamic within sport tasks (32). Given the distinct FP position of the device and its ability to generate data akin to established isometric devices in the field, the Biostrain could emerge as a compelling contender for mitigating the risk of critical lower limb hip and knee related injuries. Moreover, if the hamstrings do exhibit isometric traits in the latter stages of the FP, the innovation of this device could be substantial for the industry (76)

Therefore, the aim of this thesis was primarily to assess the reliability and validity of the new Biostrain device versus the gold standard IKD, with postures standardised between devices, and to assess the correlation between performance on the Biostrain device and sprint performance. This thesis also provides a systematic review of IKD and HHD literature to investigate reliability, validity and potential methods of IKD and HHD for the Biostrain studies. To achieve this aim the thesis is presented as a series of three studies (outlined below) the thesis has the following three objectives:

- **Systematic review of isometric isokinetic dynamometry and hand held dynamometry**

  Aims: This study will comprehensively review literature regarding isometric hip and knee extension/flexion strength using IKD and HHD that use joint angles similar to the biostrain. The aim of this systematic review is to explore reliability and validity of IKD and HHD by assessing methods/procedures, and positions. The study will also explore any associations to sprint performance and injury risk.

  Methodology: A literature search will be conducted using literature databases and inputted into a table ready for further exploration.

- **Reliability and validity of the Biostrain versus isometric isokinetic dynamometry**

  Aims: This study will assess the reliability and the validity of the Biostrain device versus the gold standard device (Kin Com) for assessing unilateral isometric lower body function. The study will explore, hip extension, hip flexion and combined hip extension and knee flexion. The study will explore different methods by assessing using the hands to stabilise posture and not using hands to stabilise posture when on the device. To achieve these aims the study will compare force-time data from each leg in the Biostrain test versus the Kin Com which will unilaterally replicate the same position of each leg in standing positions.

  Methodology: On the Biostrain, subjects will carry out trials without using hands to stablise the body whilst in position and with using hands to stablise the body. Data will be taken from both legs whilst in position on the device and force-time data will be taken at 100 ms, 150 ms, 200 ms, 250 ms and peak force. The Biostrain will assess subjects unilaterally using positions that replicate limbs when on the Biostrain device. Metrics taken from the Kin Com will include peak force.

- **The association between Biostrain force parameters and sprint performance**

  Aims: This study will assess the relationship between the Biostrain and sprint performance.

  Methodology: Subjects will complete Biostrain trials in the same way as the reliability and validity study and also complete 20 m sprint trials to allow sprint time to be correlated to the Biostrain performance.

3.0 SYSTEMATIC REVIEW: Systematic review of isometric isokinetic dynamometry and hand held dynamometry

COVER PAGE

Systematic review of isometric isokinetic dynamometry and hand held dynamometry

3.1 ABSTRACT

Background: Strengthening the supporting muscle of the hip and knee is important in sports performance to help maximise athletic performance and reduce the risk of injury. The use of IKD and HHD in isometric conditions are widely used for assessing strength of the hip and knee muscles during single joint unilateral tasks, though methods and joint angles assessed in research vary greatly. ***Aims:*** The aim of this systematic review was to explore reliability and validity of IKD and HHD and determine associations to performance and injury risk. ***Methods:*** A literature search was conducted using literature databases. The Downs and Blacks scale was used to assess the quality of each study's methodology, where an acceptable score was set to ≥ 75%. ***Results:*** 19 articles were eligible for the systematic review. Results for quality assessment ranged from 73 to 91% where 9 studies were deemed unacceptable quality and 10 were deemed acceptable (IKD 73 to 91% and HHD 73 to 82%). ***Conclusions:*** IKD was found to be more reliable compared to HHD though a range of positions and angles have been assessed making it difficult for between study comparisons to be made. No researchers correlated IKD or HHD to performance or injury. Future research should consider using a back rest during testing, maintaining the same testing location on limbs and ensure testers are of a similar body mass/stronger to the subject. Future research should ensure statistical measures are appropriate and enable meaningful comparisons between research.

Key words: Hip extension; Hip Flexion, Knee flexion, Isometric, Hand-held dynamometry, Isokinetic dynamometry

3.2 INTRODUCTION

Hip and knee flexion and extension play an important role in many human movement-based tasks (9) including: sprinting, jumping and change of direction (44,105). Thus, it is vital that strength of the muscles supporting the hip and knee (hamstring group, quadriceps group, gluteals) are developed to maximise athletic performance and potentially help reduce the risk of injuries (98).

Common injuries that occur around the hip and knee include HSI (137), iliotibial band syndrome (57), patellofemoral pain syndrome (47) and ACL injuries (130). Such injuries can be a major concern for practitioners and athletes, in particular HSI can lead to prolonged absence from sport (~ up to 12 months and potentially more) (137). Time out of competition can place a large financial burden on the teams, where Eliakim et al. (48) found that per season, the English premier league loses an average of £45 million due to injury. In addition, researchers have shown the frequency to be more of a concern as athletes who have suffered from a previous injury are more likely to suffer a recurring injury and once a HSI has been sustained the reoccurrence rate can be as high as 34% (49,108,138). Queen et al. (144) also found similar for the ACL, reporting that athletes who had undergone an ACL reconstruction had a 15-fold increased risk of a second ACL injury, substantiating the need to reduce the risk of injuries.

There is a vast amount of evidence indicating that increasing maximum force generating capacity through regular strength training not only reduces the risk of injury but also enhances athletic performance (81,97,106,147,154,175). Opar et al. (136) reported that Australian football players had a reduced risk of HSI of up to 8.9% for every 10 N increase in strength they gained during the season (assessed during a Nordic hamstring exercise). Raya Gonzalez et al. (146) also found that injuries related to gluteal muscle weakness (including HSI, iliotibial band syndrome (57), patellofemoral pain syndrome (47) and anterior cruciate ligament tears (130)) were reduced during their experimental season compared with their control season after the inclusion of a strength training programme (targeting supporting muscles of the hip and knee). Ford et al. (56) also reported moderate correlations between hip strength and the motions of the hip and pelvis during running (hip extensor strength – thorax axial rotation range of motion: r = -0.59, $p < 0.05$; hip abductor strength – pelvic obliquity range of motion = r = -0.5, $p < 0.05$) demonstrating the need to maintain and improve strength of the supporting muscles of the hip and knee.

Impulse is the product of force × time (65) ($F_{mean} \times \Delta t$ (F_{mean} = mean force, Δt = change in time)) and can be measured during isometric tasks and vertical jumping tasks. Net impulse is directly proportional to the change in momentum, $p = mv - mv_0$ (p = momentum, m = mass, v = final velocity, v_0 = initial velocity) thus often these two metrics are used hand in hand ($F_{mean}\,\Delta t = mv - mv_0$). Whilst there is interest in strength and power assessment within strength and conditioning, the impulse-momentum relationship is arguably of greater importance as it perfectly describes the requirements for forceful powerful movements (164). Thus, the metric impulse is a highly important metric in sports performance, where enhanced impulse not only aids sports performance but may also help reduce the risk of injury. Impulse can be examined over critical periods within sport actions, such as 100 to 300 ms (124) and has also been found to have a strong relationships with many sporting tasks therefore, it is a key performance indicator for many sports (92,114,118,120). Hunter et al. (83) found positive correlations between net relative vertical and horizontal impulse and sprint velocity (vertical $r = 0.755$, $p < 0.001$; horizontal $r = 0.781$, p < 0.001), suggesting impulse is likely a determining factor to success within many sports and thus should be a focal point for practitioners.

Consequently, it is common for practitioners to regularly monitor strength and force capacities, to help reduce the risk of injuries that occur around the hip and knee musculature. IKD is a popular method of assessment to assess the hip and knee flexor and extensor muscles and possibly the gold standard method for assessing muscle moments during single joint unilateral tasks (110). As IKD incorporates unilateral tests it allows asymmetries and between limb differences to be observed. However, various postures have been used when evaluating force production using the IKD, including supine (53), prone (53), standing (62) and seated (71) conditions. During isokinetic IKD assessments the resistive moment that is applied to the limb during testing is equal to the net moment applied, so the joint and muscles can only be loaded up to its maximum capacity over the range of movement (51). However, although this is true, at higher angular velocities, the initial and final portion of the range of motion is not isokinetic. This is due to the need to accelerate and decelerate the limb at the start and the end of the motion, therefore reducing the range of motion at which the angular velocity is achieved (6), though positively, this makes IKD one of the safest forms of testing after isometric testing.

Researchers have found a strong correlation between sprint performance and peak isokinetic torque in flexion and extension on the IKD (34). Alexander (1) reported a strong inverse relationship (r = -0.72, $p < 0.01$) between peak isokinetic concentric torque generated by the knee extensor muscles and 100 m sprint performance in elite track and field athletes. Conversely, IKD can also be used isometrically. When used isometrically, the lever arm of the IKD is locked and set at a specified angle allowing isometric flexion and extension at specific joint angles to be tested. Boraczynski et al. (20) reported a large correlation with normalised maximal isometric knee extensor strength on the IKD at 90º of knee flexion and 30 m sprint time (r = -0.596, $p \leq 0.01$). Therefore, as sprinting is a prevalent attribute performed in many sports (which can determine successful performance in many cases (33)) the data from tests on the IKD could provide considerable assistance to identifying potential injury risk, informing training prescriptions and thus preventing long term absence from sport, though further research is needed to conclude this.

HHD is also a popular method for assessing isometric strength. HHD is beneficial as it is portable, convenient, easy to use and much cheaper compared to IKD (46). The typical cost of an IKD is around $40,000 USD whereas a HHD can cost approximately $1000 USD (152). Although reliable, HHD is not quite as reliable as IKD (Knee extension: HHD ICC = 0.76 vs IKD ICC = 0.93) (161) but HHD has been found to have almost perfect reliability for hip extension, hip flexion, knee extension and knee flexion (ICC = 0.988 to 1.000, $p < 0.001$) and an almost perfect correlation ($r = 0.988$ to 1.000, $p < 0.001$) between that of its gold standard competitor (148). Additionally, Tan et al. (156) found a strong positive correlation between knee extension 1 repetition maximum strength and knee extension isometric HHD scores (r = 0.82, $p < 0.001$), explaining for 76% of the shared variance. Further substantiating the practicality and convenience.

Interestingly, researchers have found that isometric testing can be superior to that of eccentric testing/training as the assessment of eccentric strength can be problematic in terms of regular assessments. Eccentric muscle actions are associated with muscle damage and delayed onset muscle soreness (117) whereas, in contrast, isometric assessments/training are far less fatiguing, less likely to cause muscle damage and provide the opportunity to evaluate force at the ‘all-important sports specific time-points, 100 to 300 ms’ (32). However, in contrast, it should be noted that due to the repeated bout effect, although an initial single bout of eccentric exercise causes muscle damage, this gives a protective effect from muscle damage on subsequent bouts (132), therefore a combination of both eccentric and isometric training/testing may be practical and beneficial. Nonetheless, muscle soreness can be exhibited in both eccentric and isometric training if it is a novel stimulus, unprepared for them or dependent on the muscle length at which the exercise is being carried out at. Therefore, it is important a gradual low dose is introduced and caution is maintained (2).

Although based on animal models, Van Hooren and Bosch (76) suggested that the hamstrings in-fact work isometrically during portions of the sprinting cycle, suggesting that maximal isometric training around the optimum length/specific joint angles may arguably be of more benefit. However, whilst isometric training will enhance strength, a combination of eccentric, concentric and even isokinetic modalities will also enhance aspects of strength (74,99,116,170) as it is clear isometric actions do not elicit a change in fascicle length unless carried out at longer muscles lengths. Researchers have shown that a decrease in muscle fascicle length alongside a lack of strength can increase the risk of injury (82). Due to sprinting being a multipart cyclic action, that emcompasses eccentric, concentric and isometric actions, training a combination of muscle actions and lengths will allow for maximum athletic potential (28,29,38,160)

Although IKD shows many benefits, it is clear within research that methods vary for hip and knee extension and flexion assessments using IKD and HHD. It is evident that assessing hip and knee extension and flexion in different positions (supine (58,90,91,148) prone (89,90,122), seated (19,71,85,88,91,102,122), standing (62,75)) and testing at different joint angles, does indeed affect the torque produced due to changes in muscle moment arm length and the length tension relationship (62). The length tension relationship states that the magnitude of force a muscle can generate is dependent on its length, fascicle lengthening/shortening velocity and neurological stimulation. Within the muscles, the actin and myosin attach to form cross bridges which results in sarcomere shortening, creating tension. The cross bridges can only occur where thin and thick filaments already overlap so the length of the sarcomere has a direct influence on the force generated capacity as the sarcomere shortens (25). This was demonstrated by Lee et al. (99) who assessed knee extension at 30°, 50°, 70° and 90° of knee extension and found different torque values in all conditions (30 º: 159.8 ± 23 Nm; 50 º: 228.8 ± 36.5 Nm; 70 º: 294 ± 50.9 Nm; 90 º: 307.7 ± 56.9 Nm). In addition to this, different methods of assessment have also been found to affect results. Research varies, where the use of strapping to fix the torso in position, back support ranges across research. Such differences and lack of control between factors create difficulty when attempting between study comparisons, making incomparable results.

It is clear, that isometric IKD and HHD is an important tool within sports settings and can provide valuble insights for professionals in assessing their athletes. However, it is evident a range of methods have been used such as the variation in joint angles which can affect force outputs. IKD and HHD has been assessed in prone, supine, seated and standing conditions making between study comparisons difficult. Therefore, the purpose of this systematic review was to comprehensively review the available literature regarding isometric hip and knee extension/flexion strength using IKD and HHD. The aim of this systematic review was to explore reliability and validity of IKD and HHD by assessing methods/procedures, and positions. A secondary aim was to determine associations between isometric knee and hip extensor and flexor force production, performance, and injury risk.

3.3 METHODS

3.3.1 Literature search strategy and selection criteria

A literature search was conducted using literature databases (SPORTDiscus and MEDLINE). A flow diagram explaining search methodology in line with PRISMA guidelines (127) can be seen in Figure 3.0. Search words/terms were: [1] ((isometric[Title]) AND (dynamometer[Title])) OR [2] (dynamometry[Title]). After the application of filters (adults, human) bibliographies from articles were hand checked for any relevant studies. The "related studies" and "citation tracker" functions were used on Google Scholar to identify additional research papers. The search date ranged from 01 November 2022 to 01 Feb 2023. Articles were included for the systematic review if they met the criteria in Table 3.0. Studies that failed to meet the criteria were excluded.

Table 3.0. Inclusion and exclusion criteria

Inclusion Criteria	Exclusion criteria
English language	Review papers
Male or Female adult subjects 18-45 years old	Dissertations or thesis papers, due to limited peer review
Healthy and active subjects	Abstract only papers
Isometric hand-held dynamometry of hip/knee flexion/extension	Practitioner articles/magazines
Isometric isokinetic dynamometry of hip/knee flexion/extension	General or aging population
Includes correlations between force production characteristics and performance	Single subjects study design
Includes correlations between force production characteristics and injury risk	Injured
Reports appropriate reliability statistics	Isokinetic assessment mode rather than isometric
Includes appropriate validity statistics	

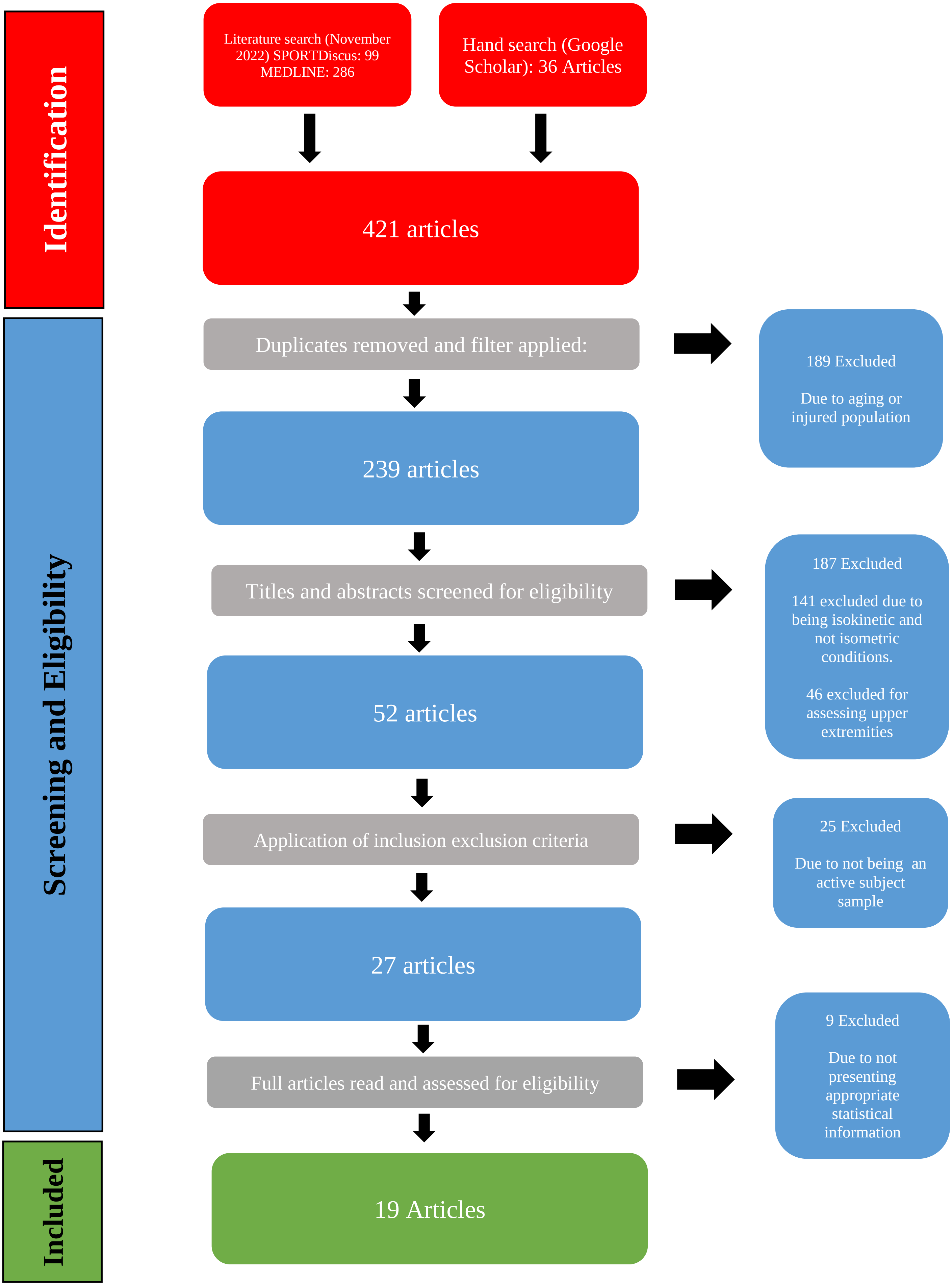


Figure 3.0 Flow diagram displaying literature search process based on PRISMA recommendations (127).

3.3.2 Assessment of study quality

The Downs and Blacks scale (45) was used to assess the quality of each study's methodology. The scale assessed: [1] Reporting - whether the information was sufficient to allow for unbiased assessments. [2] External validity- the extent to which the findings could be generalised to the population. [3] Bias - biases in the measurement of the intervention and the outcome. [4] Power - whether the negative findings from a study were because of chance. Not all items of the scale were appropriate, so a modified version of the downs and blacks scale was used where 13 of the possible 27 items were selected from the scale. No questions from the confounding section of the downs and blacks scale were used in the study. The power question and scale were adapted for the study. All questions were scored 0 or 1 (where 0 equates to no, 1 equates to yes). All scores were converted in a percentage ranging from 0 to 100%. To be sure of an appropriate level of quality, an acceptable score was set to ≥ 75% in line with previous research (14).

3.4 RESULTS

SPORTDiscus database search presented 99 articles and MEDLINE database search presented 286 with a further 36 articles identified via hand selection through bibliographies and the "citation tracking" and "related articles" functions on Google scholar (Figure 3.0). Therefore, a total of 421 articles were initially presented. Duplicates were then removed, and filters applied, excluding a further 189 articles, which were all excluded due to incorrect age. 189 papers included subjects who were over 65 years old or injured. Thus, leaving 239 articles present. Next, initial screening was conducted. Titles and abstracts were screened for eligibility where 187 articles were excluded leaving 52 articles. Of the 187 excluded, 141 were excluded due to being isokinetic and not isometric. 46 of the 187 articles excluded were excluded for assessing upper extremities. Next, the inclusion and exclusion criteria were applied excluding a further 25 articles leaving 27 articles present. The 25 articles excluded were excluded due to athletes not being physically active subjects. All 27 articles were read thoroughly and assessed for eligibility and only a further 9 articles were removed due to not presenting appropriate statistical data. Leaving a final total of 19 articles eligible for the systematic review. A flow diagram of this process can be seen in Figure 3.0. A summary of the modified Downs and Blacks scale and results can be seen in Table 3.1. A summary of the research used in the study can be seen in Tables 3.2 – 3.3. Some studies assessed both IKD and HHD where some just assessed IKD and HHD in isolation (Reliability of IKD: (41,52,71,107,113,122,140,161) ; Reliability of HHD (10,58,71,85,89–91,93,102,122,148,161,167) Validity of HHD (71,88,89,91,102,122,139,148,156)). Results for quality assessment ranged from 73 to 91% (Table 3.1) where 9 studies were deemed unacceptable quality and 10 were deemed acceptable. It was clear that there was variation in units of measurement where some papers presented results in N, Nm, Kg, Nm/kg*m and pounds of force. Also, many papers presented raw reliability scores including standard error of the measurement (SEM) and smallest detectable difference (SDD), thus % scores have been calculated for the current study to allow for between study comparisons. It should also be noted that the majority of the studies did not provide the ICC 95% CI LB or UB so point estimate has been used.

Table 3.1 Modified Downs and Blacks scale to assess the quality of methods of research papers.

	Question criteria	Romero-Franco et al. (148)	Katoh et al. (88)	Hirano et al. (71)	Kim et al. (91)	Mentiplay et al. (122)	Ferri-Morales et al. (52)	Toonstra et al. (161)	Maffiuletti et al. (107)	Dirnberger et al. (41)	Mau-Moeller et al. (113)	Padulo et al. (139)	Carvalho Froufe Andrade et al. (140)	Kawaguchi et al., (89)
Reporting	**Is the hypothesis/aim/objective of the study clearly described?**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**1**
	Are the main outcomes to be measured clearly in the introduction or methods section?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Are the characteristics of the subjects included in the study clearly described?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**1**
	Are the main findings of the study clearly described?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Does the study provide estimates of the random variability in the data for the main outcomes?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Have actual probability values been reported? (e.g. 0.035 rather than <0.05)	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**1**	**0**

External validity	**Were the subjects asked to participate in the study representative of the entire population from which they were recruited?**	**0**	**0**	**0**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**
Bias	**If any of the results of the study were based on data dredging was this made clear?**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Were the statistical tests used to assess the main outcomes appropriate?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Were the main outcome measures used accurate (valid and reliable)?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Power	**Did the study justify a sufficient power to detect a clinically important effect for sample size?**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**
SCORE		**8 (73%)**	**8 (73%)**	**8 (73%)**	**9 (82%)**	**9 (82%)**	**9 (82%)**	**9 (82%)**	**10 (91%)**	**10 (91%)**	**9 (82%)**	**9 (82%)**	**8 (73%)**	**8 (73%)**

Table 3.1 continued.

	Question criteria	Kelln et al. (90)	Lu et al. (102)	Kodesh et al. (93)	Jackson et al. (85)	Bazett-Jones et al. (10)	Whiteley et al., (167)	Katoh et al., (88)	Fulcher et al. (58)
Reporting	**Is the hypothesis/aim/objective of the study clearly described?**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Are the main outcomes to be measured clearly in the introduction or methods section?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Are the characteristics of the subjects included in the study clearly described?	**1**	**1**	**1**	**1**	**1**	**0**	**1**	**0**
	Are the main findings of the study clearly described?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Does the study provide estimates of the random variability in the data for the main outcomes?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Have actual probability values been reported? (e.g. 0.035 rather than <0.05)	**0**	**1**	**0**	**0**	**1**	**1**	**0**	**0**

External validity	**Were the subjects asked to participate in the study representative of the entire population from which they were recruited?**	**1**	**0**	**0**	**1**	**0**	**1**	**1**	**0**
Bias	**If any of the results of the study were based on data dredging was this made clear?**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Were the statistical tests used to assess the main outcomes appropriate?	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
	Were the main outcome measures used accurate (valid and reliable)?	**1**	**0**	**1**	**1**	**1**	**1**	**0**	**1**
Power	**Did the study justify a sufficient power to detect a clinically important effect for sample size?**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**
SCORE		**9 (82%)**	**8 (73%)**	**8 (73%)**	**9 (82%)**	**9 (82%)**	**9 (82%)**	**8 (73%)**	**8 (73%)**

Table 3.2 Reliability measures isometric muscle performance via an Isokinetic Dynamometry

AUTHOR	SYSTEM & ANGLE	KNEE EXTENSION	KNEE FLEXION	HIP EXTENSION	HIP FLEXION
Hirano et al. (71)	Biodex Systems Pro 4 No angles reported	**Mixed males and females (n=42)** **ICC (LB-UB 95%CI):** 0.93 (0.87-0.96) **Males (n=22)** **ICC (LB-UB 95%CI):** 0.88 (0.73-0.95) **Females (n=20)** **ICC (LB-UB 95%CI):** 0.83 (0.62-0.93)			
Mentiplay et al. (122)	KinCom For hip and knee flexion and knee extension, subjects were seated with hip and knee angle at 90° For hip extension, the subjects was lay prone with hips and knees extended	**ICC (LB-UB 95%CI):** 0.98 (0.94-0.99) **SEM:** 5.67% **MDC:** 15.72%	**ICC (LB-UB 95%CI):** 0.94 (0.86-0.98) **SEM:** 6.67% **MDC:** 18.48%	**ICC (LB-UB 95%CI):** 0.92 (0.81-0.97) **SEM:** 7.03% **MDC:** 19.49%	**ICC (LB-UB 95%CI):** 0.95 (0.89-0.98) **SEM:** 6.45% **MDC:** 17.89%
Ferri- Morales et al. (52)	Biodex Systems 3 Pro Seated with hip angle 85°, knee	**Women** ***p*** **=** 0.66 **Systematic bias, Mean Difference:** -0.9 ± 10.4 Nm **Men**			

	extension angle 60º	***p*** **=** 1.0 **Systematic bias, Mean Difference:** 1.1 ± 13.7 Nm **SEM:** 4.8% **ICC:** > 0.8			
Toonstra et al. (161)	Cybex II Seated 90° of knee flexion. No hip angle reported	**ICC:** 0.93 **SEM:** 0.11 Nm (5.2%) **95% MDC:** 0.30 Nm (14.3%)	**ICC:** 0.89 **SEM:** 0.09 Nm (4.3%) **95% MDC:** 0.25 Nm (11.9%)		
Maffiuletti et al. (107)	Con-Trex Seated, hip flexion angle 85º and knee extension angle 60º	**Within session reliability:** **CV%:** 4.4 **ICC:** 0.983 **Between session reliability:** **CV%:** 5.5 **ICC:** 0.972	**Within session reliability:** **CV%:** 3.4 **ICC:** 0.991 **Between session reliability:** **CV%:** 4.7 **ICC:** 0.975		
Dirnberger et al. (41)	Isomed 200 dynamometer Knee flexion angle 85º of knee flexion Knee extension 95º of knee extension	**Main effect *p* value:** 0.473 **ICC T1-T2 (LB-UB 95% CI):** 0.966 (0.933-0.983) **ICC T2-T3 (LB-UB 95% CI):** 0.969 (0.939-0.984) **SEM T1-T2:** 9.1 Nm (3.9%) **SEM T2-3:** 9.0 Nm (3.8%)	**Main effect *p* value:** 0.084 **ICC T1-T2 (LB-UB 95% CI):** 0.924 (0.852-0.961) **ICC T2-T3 (LB-UB 95% CI):** 0.941 (0.886-0.970) **SEM T1-T2:** 8.2 Nm (3.5%) **SEM T2-3:** 7.5 Nm (3.2%)		
Mau-Moeller et al. (113)	Isoforce dynamometer Seated, hip flexion angle 90 º	**Intrasession Reliability:** **TE (LB-UB 95% CI) Nm:** 10.6 (8.5-14.3) **CV% (LB-UB 95% CI):** 5.3 (4.2-7.1)	**Intrasession Reliability:** **TE (LB-UB 95% CI) Nm:** 44 (3.5-6.0) **CV% (LB-UB 95% CI):** 4.0 (3.2-5.4)		

	and knee flexion angle 60º	**ICC (LB-UB 95% CI):** 0.97 (0.94-0.99) **Intersession Reliability:** **TE (LB-UB 95% CI):** 15.1 (12.1-20.3) **CV% (LB-UB 95% CI):** 8.3 (6.6-11.4) **ICC (LB-UB 95% CI):** 0.94 (0.88-0.97)	**ICC (LB-UB 95% CI):** 0.98 (0.97-0.99) **Intersession Reliability:** **TE(LB-UB 95% CI):** 11.4 (9.1-15.3) **CV% (LB-UB 95% CI):** 10.8 (8.5-14.8) **ICC (LB-UB 95% CI):** 0.93 (0.87-0.97)		
Carvalho Froufe Andrade et al. (140)	RE V9000 Isokinetic Dynamometer (Technogym) Seated hip flexion angle at 85º and 60 º knee angle			**<u>Right Leg:</u>** **Within session (T2-T3) ICC:** 0.99 **Between session (T1-T2) ICC:** 0.92 **All ICC (LB-UB 95% CI):** 0.96 (0.92-0.98) ***p* value:** 0.210 **MDC%:** 4.2 ± 11.6 **<u>Left Leg:</u>** **Within session (T2-T3):** **Between session (T1-T2) ICC:** 0.94 **All ICC (LB-UB 95% CI):** 0.93 (0.87-0.97) ***p* value:** 0.688 **MDC%:** 4.8 ± 13.3	**<u>Right leg</u>** **Within session (T2-T3) ICC:** 0.99 **Between session (T1-T2) ICC:** 0.93 **All ICC (LB-UB 95% CI):** 0.96 (0.92-0.98) ***p* value:** 0.660 **MDC%:** 4.8 ± 13.3 **<u>Left Leg:</u>** **Within session (T2-T3) ICC:** 0.91 **Between session (T1-T2) ICC:** 0.91 **All ICC (LB-UB 95% CI):** 0.94 (0.89-0.97) ***p* value:** 0.755 **MDC%:** 5.7 ± 15.8

Key: CI – Confidence interval; ICC – Intraclass correlation coefficient; SEM – Standard error of the measurement; MDC – Minimum detectable change; T: Testing session; TE: Typical error; LOA: Limits of agreement; Tr: Tester; CV – Coefficient of variation; SD – Standard deviation; HDD – Hand Held Dynamometry; IKD: Isokinetic dynamometer; SE – Standard error; LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; 1RM: 1 Repetition maximum. *Note: All hip angles are relative anatomical position = 0°; To allow between study comparisons, %SEMs and MDC% in red were calculated based off raw means, where authors failed to present % SEMs and %MDC*

Table 3.3 Reliability of Handheld Dynamometry

AUTHOR	SYSTEM & ANGLES	KNEE EXTENSION	KNEE FLEXION	HIP EXTENSION	HIP FLEXION
Romero-Franco et al. (148)	Precision digital dynamometer Knee flexion and extension: Seated, 90° hip and knee flexion Hip flexion and extension: Supine, 90º Hip flexion with 90º Hip extension *Angles are based off visual inspection of Figures. No angles reported.*	**Intra-tester reliability:** **ICC (LB-UB):** 0.938 (0.789–0.983) ***p*** < 0.001 **SEM:** 10.4 N (4.67%) **Inter-tester reliability:** **ICC (LB-UB):** 0.983 (0.920–0.997) ***p*** < 0.001 **SEM:** 10.6 N (4.76%)	**Intra-tester reliability:** **ICC (LB-UB):** 0.979 (0.924–0.994) ***p*** < 0.001 **SEM:** 8.9 N (6.56%) **Inter-tester reliability:** **ICC (LB-UB):** 0.991 (0.957 –0.998) ***p*** < 0.001 **SEM:** 6.8 N (5.01%)	**Intra-tester reliability:** **ICC (LB-UB):** 0.984 (0.941-0.9996) ***p*** < 0.001 **SEM:** 3.9 N (1.65%) **Inter-tester reliability:** **ICC (LB-UB):** 0.993 (0.964-0.999) ***p*** < 0.001 **SEM:** 4.8 N (2.03%)	**Intra-tester reliability:** **ICC (LB-UB):** 0.984 (0.941–0.99) ***p*** < 0.001 **SEM:** 3.9 N (2.02%) **Inter-tester reliability:** **ICC (LB-UB):** 0.993 (0.964-0.999) ***p*** < 0.001 **SEM:** 4.8 N (2.49%)
Hirano et al. (71)	HHD (μTas F-1) fixed on the Biodex system 3 Upright seated, No back rest, knee flexed to 90º Hands on the bench, non-measurement leg resting on the floor.	**Mixed males and females (n=42)** **ICC (LB-UB):** 0.94 (0.89-0.97) **Males (n=22)** **ICC (LB-UB):** 0.93 (0.83-0.97) **Females (n=20)** **ICC (LB-UB):** 0.75 (0.48-089)			

Kim et al. (91)	JTECH Medical HHD Fixed *vs* non-Fixed Seated condition: Seated upright. No back rest, knee flexion to 35° Supine condition: Laying supine, knee flexion 35°	**<u>Fixed:</u>** **Supine Right ICC:** 0.984 **Supine Right SEM:** 2.9 Nm (4.39%) **Seated Right ICC:** 0.984 **Seated Right SEM:** 2.16 Nm (3.65%) **Supine Left ICC:** 0.952 **Supine Left SEM:** 3.88 Nm (5.91%) **Seated Left ICC:** 0.983 **Seated Left SEM:** 2.09 Nm (3.60%) **<u>Fixed (intra-rater reliability):</u>** **Supine Right ICC:** 0.976 **Supine Right SEM:** 2.48 Nm (4.98%) **Seated Right ICC:** 0.985 **Seated Right SEM:** 1.96 Nm (4.19%) **Supine Left ICC:** 0.981 **Supine Left SEM:** 2.20 Nm (3.90%) **Seated Left ICC:** 0.985 **Seated Left SEM:** 1.96 Nm (3.72%) **<u>Non-fixed:</u>** **Supine Right ICC:** 0.963 **Supine Right SEM:** 2.53 Nm (5.08%) **Seated Right ICC:** 0.94 **Seated Right SEM:** 2.28 Nm (4.88%) **Supine Left ICC:** 0.95 **Supine Left SEM:** 3.39 Nm (6.02%) **Seated Left ICC:** 0.962 **Seated Left SEM:** 2.61 Nm (4.37%)			

Kelln et al. (90)	MicroFET 2 HHD (Hoggan Health Industries) Hip flexion: laying supine. Legs extended Hip extension: laying prone, legs extended Knee flexion and extension: laying prone, knee flexed, to 90° *No angles presented, positions are based off visual representation of images*	**Intratester Reliability** Day 1 **Tr1 ICC:** 0.93 **Tr1 SEM:** 0.44 kg (1.55%) **Tr2 ICC:** 0.82 **Tr2 SEM:** 0.32 kg (1.34%) **Tr3 ICC:** 0.82 **Tr3 SEM:** 0.22 kg (0.78%) **Intratester Reliability** Day 2 **Tr1 ICC:** 0.92 **Tr1 SEM:** 0.21 kg (0.7%) **Tr2 ICC:** 0.82 **Tr2 SEM:** 0.09 kg (0.4%) **Tr3 ICC:** 0.88 **Tr3 SEM:** 0.12 kg (0.4%) **Intertester reliabilty:** **ICC:** 0.77 **SEM:** 1.05 kg (3.93%) **Intersession Reliability** Day 1 **Tr1 ICC:** 0.89 **Tr1 SEM:** 0.49 kg (1.73%) **Tr2 ICC:** 0.70 **Tr2 SEM:** 0.40 kg (1.7%) **Tr3 ICC:** 0.77 **Tr3 SEM:** 0.68 kg (2.4%) **Intersession Reliability** Day 2 **Tr1 ICC:** 0.92 **Tr1 SEM:** 0.36 kg (1.3%)	**Intratester Reliability (kg):** Day 1 **Tr1 ICC:** 0.93 **Tr1 SEM:** 0.08 kg (0.3%) **Tr2 ICC:** 0.91 **Tr2 SEM:** 0.13 kg (0.5%) **Tr3 ICC:** 0.93 **Tr3 SEM:** 0.05 kg (0.2%) **Intratester Reliability:** Day 2 **Tr1 ICC:** 0.94 **Tr1 SEM:** 0.06 kg (0.2%) **Tr2 ICC:** 0.96 **Tr2 SEM:** 0.03 kg (0.1%) **Tr3 ICC:** 0.95 13.4 **Tr3 SEM:** 0.06 kg (0.42%) **Intertester reliability:** **ICC:** 0.85 **SEM:** 0.25 kg (1.87%) **Intersession Reliability** Day 1 **Tr1 ICC:** 0.86 **Tr1 SEM:** 0.10 kg (0.4%) **Tr2 ICC:** 0.91 **Tr2 SEM:** 0.11 kg (0.5%) **Tr3 ICC:** 0.83 **Tr3 SEM:** 0.12 kg (0.4%) **Intersession Reliability** Day 2 **Tr1 ICC:** 0.84 **Tr1 SEM:** 0.05 kg (0.2%)	**Intratester Reliability:** Day 1 **Tr1 ICC:** 0.76 **Tr1 SEM:** 0.14 kg (1.1%) **Tr2 ICC:** 0.77 **Tr2 SEM:** 0.11 kg (0.9%) **Tr3 ICC:** 0.72 **Tr3 SEM:** 0.15 kg (1.2%) **Intratester Reliability:** Day 2 **Tr1 ICC:** 0.79 **Tr1 SEM:** 0.10 kg (0.8%) **Tr2 ICC:** 0.73 **Tr2 SEM:** 0.08 kg (0.6%) **Tr3 ICC:** 0.69 **Tr3 SEM:** 0.11 kg (0.9%) **Intertester reliability:** **ICC:** 0.65 **SEM:** 0.64 kg (4.9%) **Intersession Reliability** Day 1 **Tr1 ICC:** 0.76 **Tr1 SEM:** 0.14 kg (1.1%) **Tr2 ICC:** 0.77 **Tr2 SEM:** 0.11 kg (0.9%) **Tr3 ICC:** 0.72 **Tr3 SEM:** 0.15 kg (1.2%) **Intersession Reliability** Day 2 **Tr1 ICC:** 0.79 **Tr1 SEM:** 0.10 kg (0.8%)	**Intratester Reliability:** Day 1 **Tr1 ICC:** 0.75 **Tr1 SEM:** 0.20 kg (1.5%) **Tr2 ICC:** 0.74 **Tr2 SEM:** 0.19 kg (1.4%) **Tr3 ICC:** 0.79 **Tr3 SEM:** 0.19 kg (1.4%) **Intratester Reliability:** Day 2 **Tr1 ICC:** 0.65 **Tr1 SEM:** 0.26 kg (2.0%) **Tr2 ICC:** 0.66 **Tr2 SEM:** 0.18 kg (1.4%) **Tr3 ICC:** 0.74 **Tr3 SEM:** 0.16 kg (1.2%) **Intertester reliability:** ICC: 0.84 SEM: 0.11 kg (0.8%) **Intersession Reliability** Day 1 **Tr1 ICC:** 0.75 **Tr1 SEM:** 0.20 kg (1.5%) **Tr2 ICC:** 0.74 **Tr2 SEM:** 0.19 kg (1.4%) **Tr3 ICC:** 0.79 **Tr3 SEM:** 0.19 kg (1.4%) **Intersession Reliability** Day 2 **Tr1 ICC:** 0.65 **Tr1 SEM:** 0.26 kg (2.0%)

		Tr2 ICC: 0.70 **Tr2 SEM:** 0.39 kg (1.6%) **Tr3 ICC:** 0.79 **Tr3 SEM:** 0.81 kg (2.9%)	**Tr2 ICC:** 0.92 **Tr2 SEM:** 0.08 kg (0.3%) **Tr3 ICC:** 0.78 **Tr3 SEM:** 0.11 kg (0.4%)	**Tr2 ICC:** 0.73 **Tr2 SEM:** 0.08 kg (0.6%) **Tr3 ICC:** 0.69 **Tr3 SEM:** 0.11 kg (0.9%)	**Tr2 ICC:** 0.66 **Tr2 SEM:** 0.18 kg (1.4%) **Tr3 ICC:** 0.74 **Tr3 SEM:** 0.16 kg (1.2%)
Mentiplay et al. (122)	Lafayette Manual Muscle Testing System And Hoggan micro FET For hip flexion, knee flexion and knee extension subjects were seated, no back rest, with hip and knee angles of 90° For hip extension, the subjects was lay prone with hips and knees extended	**(Assessor A)** **Lafayette** **Intrarater reliability** **ICC (LB-UB):** 0.91 (0.80-0.96) **SEM:** 7.73% **MDC:** 21.42% **Inter-rater reliability ICC (LB-UB):** 0.89 (0.77-0.95) **SEM:** 9.30% **MDC:** 18.23% **Hoggan** **Intrarater reliability** **ICC (LB-UB):** 0.90 (0.76-0.96) **SEM:** 8.54% **MDC:** 23.67% **Inter-rater reliability ICC (LB-UB):** 0.90 (0.77-0.96) **SEM:** 9.30% **MDC:** 17.18%	**(Assessor A)** **Lafayette** **Intra rater reliability** **ICC (LB-UB):** 0.92 (0.83-0.96) **SEM:** 6.93% **MDC:** 19.21% **Inter rater reliability** **ICC (LB-UB):** 0.82 (0.62-0.91) **SEM:** 12.53% **MDC:** 24.56% **Hoggan** **Intra rater reliability:** **ICC (LB-UB):** 0.89 (0.71-0.96) **SEM:** 8.59% **MDC:** 23.81% **Inter rater reliability:** **ICC (LB-UB):** 0.92 (0.77-0.97) **SEM:** 7.40% **MDC:** 14.51%	**(Assessor a)** **Lafayette** **Intra rater reliability** **ICC (LB-UB):** 0.92 (0.82-0.96) **SEM:** 6.77% **MDC:** 18.76% **Inter-rater reliability** **ICC (LB-UB):** 0.92 (0.82-0.96) **SEM:** 7.29% **MDC:** 14.29% **Hoggan** **Intra rater reliability** **ICC (LB-UB):** 0.95 (0.90-0.98) **SEM:** 5.22% **MDC:** 14.48% **Inter-rater reliability** **ICC (LB-UB):** 0.95 (0.89-0.98) **SEM:** 5.34% **MDC:** 10.46%	**(Assessor a)** **Intra rater reliability** **Lafayette** **ICC (LB-UB):** 0.94 (0.88-0.97) **SEM:** 6.15% **MDC:**17.05% **Inter-rater reliability** **ICC (LB-UB):** 0.93 (0.85-0.97) **SEM:** 6.39% **MDC:** 12.53% **Hoggan** **Intra rater reliability** **ICC (LB-UB):** 0.95 (0.89-0.98) **SEM:** 5.43% **MDC:** 15.05% **Inter-rater reliability** **ICC (LB-UB):** 0.92 (0.80-0.96) **SEM:** 6.71% **MDC:** 13.15%

Lu et al. (102)	Resisted enhanced dynamometer system Using straps to stabilise trunk and hip, knee and hip flexed to 90°, non-use leg hanging free, hands holding the sides of the seat.	**Male HHD Cohens d:** 3.745 **Female HHD Cohens d:** 5.036 **Male Resisted enahanced dynamometer Cohens d:** 0.292 **Female Resisted enahanced dynamometer Cohens d:** 0.391	**Male HHD Cohens d:** 0.213 **Female HHD Cohens d:** 1.530 **Male Resisted enahanced dynamometer Cohens d:** 0.060 **Female Resisted enahanced dynamometer Cohens d:** 0.214		
Toonstra et al. (161)	BTE Evaluator portable fixed dynamometer And Lafayette HHD 90° knee flexion, no back rest	**BTE** **ICC:** 0.92 **SEM:** 0.15 Nm (0.15%) **95% MDC:** 0.42 Nm (0.43%) **Lafayette** **ICC:** 0.76 **SEM:** 0.18 Nm (0.11%) **95% MDC:** 0.50 Nm (0.31%)	**BTE** **ICC:** 0.96 **SEM:** 0.05 Nm (0.09%) **95% MDC:** 0.14 Nm (0.26%) **Lafayette** **ICC:** 0.49 **SEM:** 0.12 Nm (0.15%) **95% MDC:** 0.33 Nm (0.41%)		
Kodesh et al.(93)	Lafayette HHD Laying in a bed with the dominant limb was positioned over a wedge which maintained a hip and knee of approx. 60° flexion	**Intratester reliability** **95% Repeatability (LB-UB):** ± 10.46 (-11.09-9.84) **ICC:** 0.87 **Intertester reliability** **95% Repeatability (LB-UB):** ± 11.96 (-10.22-13.70) **ICC:** 0.82			
Jackson et al.(85)	Micro- FET II (Hoggan health industries) portable HHD	**ICC (LB-UB):** 0.93 (0.82-0.98) **SE:** 17.20 N (6.4%) **MDC:** 47.48 N (17.6%)			

	Subjects seated on the edge of the table, no back support, with hips and knees flexed to 90°.				
Bazett-Jones et al. (10)	Lafayette Handheld dynamometer Prone position, straps and folding bed to allow constant controlled hip angle 0°: Prone, hip at 0° and knee flexed to 90° 30°: Prone, hip at 30° and knee flexed to 90° 90°: Prone, hip at 90° and knee flexed to 90°			***p* values** 0° v 30°: <0.001* 0° v 90°: <0.001 30° v 90°: 0.002 **Cohens *d*** 0° v 30°: 0.914 0° v 90°: 1.468 30° v 90°: 0.659	
Whitely et al. (167)	Baseline Electronic Push/Pull dynamometer. No back support, 30º of knee flexion seated			**$ICC_{(2,1)}$ (LB-UB):** 0.96 (0.90-0.98)	**$ICC_{(2,1)}$ (LB-UB):** 0.91 (0.78-0.96)

Kawaguchi et al. (89)	Micro FET2 HHD Prone knee flexed to 90° with pillow placed under anterior thigh to maintain hip extension angle of 30° Waist strap			<u>**Intraclass correlation coefficient and SEM of HHD**</u> **Hip extension Right ICC:** 0.93 **Hip extension Right SEM:** 7.68 **Hip extension Left ICC:** 0.85 **Hip extension Left SEM**: 11.22 *Failed to state means or %SEM*	
Fulcher et al. (58)	Electronic HHD (Industrial research limited) Laying Supine hip at 0°, test leg hanging free off the end of bed.				<u>**Intrarater reliability**</u> **Dominant Leg** **ICC (LB-UB):** 0.70 (0.52-0.88) **Non dominant Leg** **ICC (LB-UB):** 0.78 (0.64-0.92) <u>**Interrater reliability**</u> **Dominant Leg** **ICC (LB-UB):** 0.66 (0.46-0.87) **Non dominant Leg** **ICC (LB-UB):** 0.71 (0.53-0.89)

Key: CI – Confidence interval; ICC – Intraclass correlation coefficient; SEM – Standard error of the measurement; MDC – Minimum detectable change; T: Testing session; TE: Typical error; LOA: Limits of agreement; Tr: Tester; CV – Coefficient of variation; SD – Standard deviation; HDD – Hand Held Dynamometry; IKD: Isokinetic dynamometer; SE – Standard error; LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; 1RM: 1 Repetition maximum. *Note: All hip angles are relative anatomical position = 0°; To allow between study comparisons, %SEMs and MDC% in red were calculated based off raw means, where authors failed to present % SEMs and %MDC*

Table 3.4 The validity of handheld dynamometry versus the isokinetic dynamometry

AUTHOR	SYSTEM & ANGLES	KNEE EXTENSION	KNEE FLEXION	HIP EXTENSION	HIP FLEXION
Padulo et al. (139)	Portable IKD (Isometric Bench) ***vs*** Biodex system 3 pro Seated, 90 º knee flexion angle (no other angles provided)	**Left LOA:** -19.76/+61.03 N **Left *p*:** 0.62 **Left difference:** 5.1% **Right LOA:**-24.26/+71.04 **Right *p* :** 0.14 **Left difference:** 5.9%	**Left LOA:** -15.35/+28.43 N **Left *p*:** 0.68 **Left difference:** 3.9% **Right LOA:** -13.14/+23.86 **Right *p*:** 0.64 **Left difference:** 3.1%		
Romero-Franco et al. (148)	Precision digital dynamometer ***vs*** Biodex system Pro 4 Knee flexion and extension: Seated, 90º hip and knee flexion Hip flexion and extension: Supine, 90º Hip flexion with 90º Hip extension *Angles are based off visual inspection of Figures. No angles reported.*	***r* (LB-UB)** = 0.996 (0.980–1.000) ***p*** < 0.001	***r* (LB-UB)** = 1.000 (0.998–1.000) ***p*** < 0.001	***r* (LB-UB)** = 0.988 (0.878 - 0.999) ***p*** < 0.001	***r* (LB-UB)** = 0.998 (0.996–1.000) ***p*** < 0.001

Katoh et al. (88)	HHD (μ TasF-1) and belt *vs* Cybex Norm Hip flexion: Seated Upright, hip flexed to 90º Hip extension: Prone, Hip at 0º	**Pearson's r correlation coefficients for the two methods** = 0.75 ($p < 0.01$) **Pearson's r correlation coefficients for the reference of measurements by the two methods and measurements by IKD** = 0.91 ($p < 0.05$)	**Pearson's r correlation coefficients for the two methods** = 0.88 ($p < 0.01$) **Pearson's r correlation coefficients for the reference of measurements by the two methods and measurements by IKD** = 0.49 ($p < 0.05$)	**Pearson's r correlation coefficients for the two methods** = 0.84 ($p < 0.01$) **Pearson's r correlation coefficients for the reference of measurements by the two methods and measurements by IKD** = 0.68 ($p < 0.01$)	**Pearson's r correlation coefficients for the two methods** = 0.52 ($p < 0.01$) **Pearson's r correlation coefficients for the reference of measurements by the two methods and measurements by IKD** = 0.79 ($p < 0.01$)
Hirano et al. (71)	HHD (μTas F-1) on the fixed to the Biodex system 3 *vs* Biodex system 3 Upright seated, knee flexed to 90 º. Hands on the bench, non-measurement leg resting on the floor.	**Mixed males and females (n=42)** r = 0.78 ($p < 0.01$) **Males (n=22)** r = 0.71 ($p < 0.01$) **Females (n=20)** r = 0.39 (p <			
Kim et al. (91)	JTECH Medical HHD *vs* Biodex Fixed and Non Fixed Seated condition: Seated upright knee flexed from maximal extension angle by 35º. No back rest in HHD conditions	**Fixed** **Supine Right:** r = 0.806 ($p < 0.05$), $R^2 = 0.6493$ **Seated Right:** r = 0.524 ($p < 0.05$), $R^2 = 0.2242$ **Supine Left:** r = 0.473 ($p < 0.05$), $R^2 = 0.2743$ **Seated Left:** r = 0.294, $R^2 = 0.0862$			

	Supine condition: Laying supine, knee flexed from maximal extension angle by 35°	<u>**Non-fixed**</u> **Supine Right:** r = 0.185 ($p < 0.05$), R^2 = 0.0342 **Seated Right:** r = 0.001, R^2 = error in paper, not reported **Supine Left:** r = 0.384 ($p < 0.05$), R^2 = 0.01478 **Seated Left:** r = 0.016, R^2 = 0.0003			
Mentiplay et al. (122)	Lafayette Manual Muscle Testing System Model-01165 ***and*** Hoggan micro FET ***vs*** KinCom Hip flexors with the subjects seated and hips and knees flexed at 90°. Dynamometer placed on the anterior aspect of the thigh, proximal to the knee joint. Hip extensors with the subject lying prone and hips and knees	**Assessor A – Assessor B** <u>**Lafayette v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.82 (0.63-0.92) **Assessor B**: 0.90 (0.78-0.96) **R concordance value for validity (LB-UB):** **Assessor A:** 0.48 (0.28-0.64) **Assessor B**: 0.61 (0.42-0.75) <u>**Hoggan v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.87 (0.71-0.94) **Assessor B**: 0.86 (0.70-0.94) **R concordance value for validity (LB-UB):** **Assessor A:** 0.71 (0.51-0.84)	**Assessor A – Assessor B** <u>**Lafayette v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.68 (0.40-0.84) **Assessor B**: 0.76 (0.53-0.89) **R concordance value for validity (LB-UB):** **Assessor A:** 0.64 (0.37-0.81) **Assessor B**: 0.72 (0.49-0.85) <u>**Hoggan v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.66 (0.25-0.87 **Assessor B**: 0.76 (0.48-0.90) **R concordance value for validity (LB-UB):**	**Assessor A – Assessor B** <u>**Lafayette v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.80 (0.59-0.91) **Assessor B**: 0.88 (0.74-0.95) **R concordance value for validity (LB-UB): Assessor A:** 0.72 (0.49-0.85) **Assessor B**: 0.88 (0.74-0.94) <u>**Hoggan v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.82 (0.62-0.92) **Assessor B**: 0.89 (0.76-0.95)	**Assessor A – Assessor B** <u>**Lafayette v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.92 (0.83-0.96) **Assessor B**: 0.90 (0.79-0.95) **R concordance value for validity (LB-UB): Assessor A:** 0.80 (0.65-0.89) **Assessor B**: 0.87 (0.76-0.93) <u>**Hoggan v KinCom**</u> **R value for validity (LB-UB):** **Assessor A:** 0.90 (0.77-0.96) **Assessor B**: 0.88 (0.74-0.95)

	extended. Dynamometer placed on the posterior aspect of the shank, proximal to the ankle joint	**Assessor B**: 0.62 (0.42-0.77)	**Assessor A:** 0.65 (0.25-0.86) **Assessor B**: 0.73 (0.44-0.88)	**R concordance value for validity (LB-UB): Assessor A:** 0.77 (0.57-0.89) **Assessor B**: 0.86 (0.71-0.93)	**R concordance value for validity (LB-UB): Assessor A:** 0.84 (0.68-0.92) **Assessor B**: 0.81 (0.64-0.91)
Lu et al. (102)	Resisted enhanced dynamometer system ***vs*** KinCom All the tests were carried out with the subject sitting with their trunk and thighs stabilized using straps, the knee and hip flexed to 90° , non use leg hanging free, while holding the sides of the seat with their hands.	**Male examiner Knee Ext (HHD)** r: 0.405 R^2: 0.164 p: 0.045 **Female examiner Knee Ext (HHD** r: -0.086 R^2: 0.007 p: 0.683 **Male examiner Knee Ext (Resistance enhanced dynamometer)** r: 0.899 ($p < 0.05$, significant correlation with KinCom) R^2: 0.808 p: <0.001 **Female examiner Knee Ext (HHD** r: 0.886 ($p < 0.05$, significant correlation with KinCom) R^2: 0.784 p: <0.001	**Male examiner Knee Flex (HHD)** r: 0.664 ($p < 0.05$, sig correlation with Kincom) R^2: 0.441 p: <0.001 **Female examiner Knee Flex (HHD** r: 0.214 R^2: 0.046 p: 0.305 **Male examiner Knee flex (Resistance enhanced dynamometer)** r: 0.937 ($p < 0.05$, significant correlation with KinCom) R^2: 0.879 p: <0.001 **Female examiner Knee flex (HHD** r: 0.984 ($p < 0.05$, significant correlation with KinCom) R^2: 0.899 p: <0.001		

Tan et al. (156)	Correlation between 1RM and HHD	**R value between HHD and 1RM:** (r = 0.82, p <0.001) 17 kg discrepancy between 1RM and HHD **R^2 value between HHD and 1RM:** 0.672 **SEM:** 8.17 kg SEM to estimate 1RM: 7.5 kg			
Kawaguchi et al. (89)	Micro FET2 HHD ***vs*** Biodex Hip extension: prone leg at 90°, pillow places under anterior thigh to maintain 30° of extension, assessed with a goniometer. Waist strap			**Pearson moment correlation between measures of strength**: 0.419 (*p* = 0.05)	

Key: CI – Confidence interval; ICC – Intraclass correlation coefficient; SEM – Standard error of the measurement; MDC – Minimum detectable change; T: Testing session; TE: Typical error; LOA: Limits of agreement; Tr: Tester; CV – Coefficient of variation; SD – Standard deviation; HDD – Hand Held Dynamometry; IKD: Isokinetic dynamometer; SE – Standard error; LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; 1RM: 1 Repetition maximum. *Note: All hip angles are relative anatomical position = 0°; To allow between study comparisons, %SEMs and MDC% in red were calculated based off raw means, where authors failed to present % SEMs and %MDC*

3.5 DISCUSSION

The aim of this systematic review is to explore reliability and validity of IKD and HHD by assessing methods/procedures, joint angles and positions. The secondary aim was to determine associations between isometric knee and hip extensor and flexor force production, performance, and injury risk. The main overall findings showed that evaluating isometric strength via IKD was more reliable than HHD as demonstrated by the higher reliability scores inline with the Koo and Li scale where an ICC of ≥ 0.75 is interpreted as reliable (94), (IKD ICC: 0.83 to 0.99; HHD ICC: 0.49 to 0.99). No researchers appear to have correlated IKD/HHD to performance or injury. The quality of methods for IKD ranged between 73 to 91% and for HHD ranged between 73 to 82% based on the modified downs and black's scale. Whilst current research may provide avenues for practitioners in practice, research is highly variable and inconsistent.

Dynamometer fixation and position

A range of positions and angles have been used across research, making it difficult for between study comparisons to be made (Table 3.2 – 3.4) . Researchers using IKD have assessed subjects in seated and prone positions. HHD has been used to assess in prone, supine and seated positions. All with varying angles ranging from hip flexion angles of 0 - 90° and knee extension angles of 0 - 95°, where some authors failed to report joint angles all together. Testing at differing angles undoubtedly affects the magnitude of forces that can be produced due to the length-tension relationship of muscle. The length-tension relationship states that the magnitude of force a muscle can generate, dependends on its length (25). Since the length of a muscle directly impacts its ability to generate force when the sarcomere shortens, it becomes evident that in both IKD and HHD testing, greater forces can be generated at smaller joint angles (25), although a 'one size fits all' approach to joint angles in isometric testing may not be feasible. Therefore, specific individualisation would allow for even more accurate results. Inline with this, the selection of joint angles may not only be specific from person to person but also may differ based on athlete type/sport. This was supported by Calderbank et al. (28,29) who found that sprint mechanics vary from the track and field compared to team sport athletes such as rugby players.

Within the current review it is evident that there is a greater array of variability in angles tested for HHD compared to isometric IKD with some failure to report joint angles completely. In many HHD cases, research has reported a hip angle but failed to use a back rest in order to ensure this hip angle is maintained and controlled throughout the test. Zapparoli and Marcelo (174) stated similar. Although Zapparoli and Marcelo investigated IKD in isokinetic conditions, they concluded that the IKD back rest provides greater stability during testing, compared to no back rest. The use of a back rest enables subjects to maintain full support along their dorsal area, preventing compensatory movements thus promoting better stabilization of joints (174). This is likely the case during isometric IKD and HHD conditions. Therefore, it is probable that a back rest would also allow joint angles such as the hip to be maintained and controlled throughout testing. Mentiplay et al. (122) assessed knee extension and knee flexion in a seated position with a hip and knee angle of 90° using both isometric HHD and IKD. Mentiplay's (122) results displayed more reliable measures in IKD versus the HHD for knee extension and flexion in all analysis conditions, where Mentiplay et al. (122) had the use of a back rest in IKD conditions and did not in HHD conditions. Authors produced more reliable ICCs, SEMs and MDC for IKD results (Table 3.2 and Table 3.3). Based off knee flexion and extension assessments, this also suggests that the use of back rest could be used to control and produce more accurate results. However, further research is needed to substantiate this. Interestingly, Kelln et al. (90) produced the most reliable SEMs compared to other HHD results in the current review. Kelln tested athletes in a prone and supine positions, meaning that the entire dorsum could be supported during testing allowing for hip angles to be controlled more accurately compared to 'seated without a back rest' conditions. Changes in hip angle can be problematic during testing, causing a muscle length to change and thus effecting muscle tension developed (due to the length-tension relationship). By not having a back rest during seated conditions, subjects simply have the ability to lean back during testing thus increasing hip angle, therefore this could likely cause an increased ability to produce greater maximal forces. Failure to have a back rest will also cause inconsistencies between subjects, creating incomparable results. In support of this, Bazett-Jones et al. (10) went on to find that large significant differences between changes in hip angles. Bazett-Jones assessed hip extension in a prone position with a constant knee angle of 90º but with differing hip angles (0º, 30º and 90º) using a hinged bed to allow change in hip angle (with straps). Bazett-Jones et al. (10) found a large effect between 0º vs 30º and 0º vs 90º (Table 3.2 and 3.3) and a medium effect between 30º v 90º. Authors concluded that hip flexion angle has a significant effect on torque produced and thus practitioners should ensure consistency between joint angles tested between trials and sessions. This substantiates the importance of the back rests and straps, or to test in a position where the entire dorsum can be supported (supine/prone), allowing all joint angles to be controlled.

The significance of this factor was further reinforced by the comparison between Lee et al. (99) and Hirano et al. (71). Authors assessed knee extension in seated conditions but produced a 180.3 Nm difference in mean torque values (307.7 ± 56.9 Nm *vs* 127.4 ± 53.3 Nm). This could be due to a range of factors, though Hirano et al. (71) failed to use a strap to fix the torso in position whereas Lee et al. (99) used both straps and a back support, suggesting a possible reason for the large difference in torque produced. The variations and absence of control among factors lead to challenges when trying to compare studies, further emphasising the importance of a back rest and straps.

It is clear, the location of dynamometer varies within research which again can affect torque produced. In HHD, some researchers use ‘person held’ manual resistance HHD whilst others used strapping to fix the HHD in position. Hirano et al. (71) used a HHD where the sensor of the HHD was fastened using a Velcro tape on the distal front portion of the lower leg (with the lower end of the sensor placed just above the malleolus) and found highly reliable results (Table 3.3). Kim et al. (91) also tested using similar conditions, however they also assessed non fixed conditions (where non fixed conditions were ‘person held’ manual resisted without the use of strapping or Velcro). Kim et al. (91) found more reliable ICCs and SEMs in fixed conditions versus non fixed conditions in all cases. Authors also found a higher validity in all fixed conditions finding higher correlations in supine conditions versus seated conditions without a back rest when testing against IKD. Again supporting that in supine conditions, where the body is more supported (compared to seated without a back rest) the more stable the device and subjects is, the more reliable the results. Kim et al. (91) also went on to find that in HHD fixed conditions and in IKD conditions, peak forces were higher and therefore it is probable that the stability also gave the potential for higher peak forces to be produced. Interestingly, authors also concluded that the reliability of the HHD is dependent on the strength of the assessor and that the reliability of HHD is known to increase if the assessor is stronger as they can produce more stable conditions for the user (39,91). This was also supported by Lu et al. (102) who specifically assessed assessor strength during HHD testing. Lu et al. (102) found large differences in r values in males versus females where males who were stronger displayed higher r values. This could be problematic for practitioners particularly in sports where athletes are heavier such as men’s Rugby union where average body masses range between 92 – 113 kg (163) and thus have ability to produce more force against a resistance which the examiner may not be able to resist against to ensure isometric conditions(59). This is problematic for weaker practitioners or practitioners lighter in body mass and thus suggests fixed HHD or IKD will provide more accurate results. Interestingly, Fulcher et al.(58) assessed with 'person held HHD' and concluded similar.

Fulcher et al. (58) assessed hip flexion and hip abduction but displayed one of the lowest reliability results in the current review. Fulcher et al. (58) went on to conclude that, in their study, the stronger muscle groups assessed (hip flexors) were less reliable compared to weaker muscle groups assessed (hip adductors) where lower ICCs were produced in the stronger muscle group (hip flexors) and stronger/more dominant side compared to the weaker muscle group (hip adductors) and non-dominant side. This again could highlight assessor strength as an important aspect as it is likely that the reason for the lower reliability scores in stronger muscle groups (hip flexors) compared to weaker muscle groups (hip adductors) may be due to the lowered stability in conditions where higher forces can be produced. Future research should consider practitioners strength and fixation position/stability as a key aspect when using HHD to allow for the best results.

Dynamometer placement on the limb

In terms of dynamometer placement on the limb, there are large differences within research. Although Allred et al. (3) assessed upper body isometric strength function using HHD (forearm strength), it is likely their conclusions will apply in all HHD and IKD conditions. Authors found that reliable results can be expected as long as the dynamometer is placed at the same point on the limb for each trial. Authors noted significant difference in torque values when the dynamometer was placed at distal wrist crease compared to the mid-point wrist crease. Zapparoli et al., (174) stated that a deviation of up to 1 centimetre can lead to errors of approximately 2.5 to 5.0%. It is also clear in the current review there are variations in the placement of dynamometer, in particular, for hip extension. Mentiplay et al. (122) assessed hip extension in a prone position and placed the dynamometer on the posterior aspect of the shank, proximal to the ankle joint whereas in comparison, Kawaguchi et al. (89) (who also assessed hip extension) placed the dynamometer more distally over the posterior thigh, directly two-thirds of the distance between the greater trochanter and the lateral femoral condyle. It is likely that moving the HHD or testing pad closer to the centre of the muscle belly will increase the likelihood for higher peak forces, due to being closer to the centre of mass. However, whilst this is the case as stated above higher peak forces have been shown to reduce reliability therefore it could be suggested that moving the testing device further distally on the limb will increase reliability, meaning the subject to produce lower peak forces. McMahon et al. (121) also concluded that moving the HHD further away from the joint centres increases the reliability for testing, therefore this could be a consideration for future research.

Methodological, statistical and data analysis differences

It is clear within research that there are varying force and peak force units reported. In the current study five papers reported in kg, eight papers reported in Nm, two papers reported in N whilst one paper reported in Nm/kg*m and one reported in pounds of force. This variability poses challenges when attempting to compare results. For instance, reporting in relative units (e.g.Nm/kg*m) necessitates making all other research relative in order to facilitiate comparisons with this unit. This can become difficult, if attempting to make research relative as much of the research only provides average body mass results for their subject group and fails to report lever arm measurements. Thus a standardised approach would be beneficial. It also becomes difficult when comparing SEM values. For example, some authors have reported raw SEM (e.g., in kg, Nm/Kg*m or N or Nm) whilst others have reported as a percentage. A percentage SEM gives indication as to how much the error is relative to the typical magnitude of measurement, this allows a better incation as to how reliable and sensitive devices are therefore, percentage should be preferrable for practitioners. Practitioners should also be cautious when obtaining ICCs and comparing reliability values with other studies as it has been found that measuring these parameters from a single peak force or creating a mean for several repetitions has been reported to give low relative reliability (67). Therefore, alternative approaches have been proposed in the literature, for example, polynomial regression (26) from torque-angle curves or averaging the torque values at given angles (17)

It has become apparent within the current review that many statistical methods to assess validity of HHD versus IKD are somewhat inappropriate. Many researchers have used correlational analysis to assess the validity of HHD (Table 3.4). Though a correlational analysis may be useful in some cases, it is not an appropriate measure of validity and merely tells us the relationship between IKD and HHD and not whether a device is valid. Though this is the case, several correlational research papers included in the review do show strong results (Table 3.4). This shows some positivity for results in the current study and it is clear that HHD is far more easily accessible, simpler to use and cheaper than that of its gold standard competitor IKD. Encouragingly, the positive correlations between HHD and IKD give practitioners a more convenient option for assessing interlimb asymmetries and single limb strength capacities on both small and large scales. However, in order to more appropriately assess validity (to allow practitioners to gain an even stronger insight into the usefulness of HHD) future research could consider assessing the mean differences between HHD and IKD with the use of more appropriate statistical tests such as t-tests or using bland altman plots to plot mean versus difference of the two devices (e.g. to identify whether the data is heteroscedastic).

Across the review in terms of methods, it is evident that cueing is often neglected. Halperin et al. (66) found in that cueing and verbal encouragement throughout testing as an external attentional focus has been shown to affect force production based on the contrained-action hypothesis e.g. task execution becomes more autonomous rather than interrupting movement control processes) (87). Halperin et al. (66) found that external focus of *push hard and as fast as possible* has been shown to increase peak force production compared to other internal cues. For IKD and HHD no studies have assessed cueing and cueing clearly varies across research. Hirano et al. (71) instructed practitioners to “put in their best effort during testing” and Toonstra et al. (161) stated that “subjects were told to put in 3 maximal efforts” but failed to state whether verbal encouragement was provided during testing. Failure to use the correct verbal cueing could result in varying intentions by subjects thus giving the potential for submaximal efforts rather than maximal efforts and/or even incorrect interpretation of testing execution. Therefore, practitioners should ensure consistently strong verbal encouragement is given from subjects to subjects to ensure maximum effort and consistency (66).

IKD and HHD and sports performance

No paper has assessed sprint performance in relation to isometric strength measured via HHD or IKD. This is a clear gap in the research. Although not isometric, researchers have found a strong correlation between sprint performance and peak isokinetic torque in flexion and extension on the IKD (34). Alexander (1) reported a strong inverse relationship ($r = -0.72$, $p < 0.01$) between peak isokinetic concentric torque generated by the knee extensor muscles and 100 m sprint performance in elite track and field athletes. This shows some positivity as researchers have found correlation between IKD in kinetic conditions and isometric HHD (167), therefore it could be likely correlation would also be seen between isometric HHD/IKD and sprint performance. Future research could consider assessing this. The convenience of isometric IKD/HHD may be more attractive to practitioners as a training/assessment tool but whilst this is true, it should be noted that multi-joint tests may be more reliable. However, only Isokinetic IKD studies have considered the correlation with performance also these studies only use peak torque. The corresponding angle of peak torque may be useful to inform the angle at which isometric assessments should be applied though isokinetic analysis is limited with the correlations only using peak torque, as the angle of peak torque may have little functional relevance. In addition to this, many previous studies use an angle that is reflective of peak torque, and not stated the exact angle at which peak torque is produced, which can vary from person to person, again emphasising that angles used in IKD studies may lack functionality in relation to sports performance.

3.5 CONCLUSION

In conclusion, the aim of this systematic review was to explore reliability and validity of IKD and HHD, determine associations to performance and injury risk. The main overall findings showed that IKD was more reliable than HHD though the range of positions and angles tested in research make it difficult for between study comparisons to be made. Much of the research fails to use a back rest meaning joint angles cannot be completely controlled. Future research should consider testing in supine, prone or seated conditions with a back rest. Using a fixed dynamometer rather than ‘person held’ manual resisted should be preferred to allow both joint angles to be controlled and more stable conditions to be exhibited, ensuring the same testing location on the limb is used (also with testers of a similar body mass/strength to that of the user). When reporting results, using one relative unit and avoiding average measures will enhance reliability of results E.g. using polynomial regression (26) from torque-angle curves or averaging the torque values at given angles may provide more meaningful results (17). Additionally, using bland altman plots of mean versus difference between the two devices and exploring hetroscedascity should be considered. It is clear that no researcher has assessed sprint performance in relation to isometric IKD, though current isokinetic research (167) shows optimism for relationships to be exhibited between sprint. Therefore, specific research should consider assessing this to allow a more convenient way of exploring relationship between single limb strength and sprint performance.

~~(particularly in HHD)~~

~~. To further enhance reliability of results, practitioners should maintain~~ ensuring

~~Testing with across tests and~~

~~ensure testers are of a~~

~~and or stronger than the subject to create stable testing conditions. Ensuring strong verbal encouragement is given thoughout testing will also help to yield the best results. In terms of statisitcs, future research should consider r~~

~~and reporting SEM values as a %. Practitioners should also be mindful when obtaining ICCs and comparing reliability due to average measures and single measures causing lowered reliability.~~

~~HHD or IKD. C regarding isokinetic IKD~~

4.0 RELIABILTY AND VALDITY STUDY: Reliability and validity of the Biostrain versus isometric isokinetic dynamometry

COVER PAGE

Reliability and validity of the Biostrain versus isometric isokinetic dynamometry

4.1 ABSTRACT

Background: Isometric assessments enable professionals to assess neuromuscular abilities relating to a range of sports specific tasks such as sprinting. Sprinting is a cyclical action and involves the ground contact phase and the FP. The FP is highly important as it is the preparation phase prior to ground contact and thus ground force application. Whilst the IMTP and IKD offer insights into the neuromuscular function such tests do not specifically replicate sprinting positions. Therefore, the company Performance Biomechanics created *The Biostrain. The Biostrain* assesses isometric force production capabilities in a static FP position. ***Aims:*** Therefore, the primary aim of the current study was to assess the between and within session reliability and the validity of the Biostrain device versus the gold standard device for assessing unilateral isometric force-time capabilities, the IKD (Kin Com) via hip extension, combined hip extension and knee flexion, and hip flexion. ***Methods:*** Eighteen healthy active subjects participated (n = 18; age = 23.3 ± 5.1 years; height: 173.9 ± 5.8 cm; mass: 69.4 ± 12.8 kg). ***Biostrain methods:*** Subjects completed three trials with left leg forwards and right leg back and three trials with right leg forward and left leg back without the use of hands to stabilise positions and again repeated with hand stability. ***IKD Methods:*** 3 × 5 s maximum effort trials were carried out in three different positions on each leg that replicated individual limbs during Biostrain testing ***Results:*** Varied reliability was found (ICC = 0.625 to 0.976). CVs displayed acceptable variability on all occasions (1.59 to 10.91 %). Correlations between the Biostrain and Kin Com were large to very large Kin Com (r = 0.495 to 0.851). ***Conclusions:*** The Biostrain demonstrates reliable and valid data and shows correlation with the gold standard IKD suggesting the Biostrain could be a potential tool for assessing isometric force time characteristics in sports specific positions.

Key words: Hip extension; Hip Flexion, Knee flexion, Isometric, flight phase

4.2 INTRODUCTION

Isometric assessments have become an invaluable tool for assessing a number of performance-based metrics in sports world-wide (5,18,23,32,99,113,139). Isometric assessments such as the IMTP and IKD allow practitioners to assess neuromuscular capabilities on intricate levels. Based on isometric assessments, practitioners have the ability to make data driven conclusions; thus, facilitating with the prevention of injuries and improvement of sports performance.

Isometric assessments are particularly useful in sports performance as they allow the assessment of force-time characteristics through a range of different timepoints (32). In competition and game-time scenarios the ability to produce high forces through dynamic tasks such as sprinting (in particular sprinting ground contact phases and FPs) is essential for ultimate performance (28,169). However, the ability to produce force under the shortest possible timeframe (< 250 ms) can be the difference between successful and unsuccessful in game-time outcomes (162).

It is widely known within research that sprinting is one of the most commonly performed actions in sports as a whole (15,28,36,68,151,155,169). Sprinting is a fast-multipart repeated action (cyclical), where the limbs undergo a switching action (31). Within sprinting, the ground contact phase is an important aspect, as this is the point of force application into the ground and thus is the driving cause for movement during the sprint. Whilst this is true, sprinting is also a primary mechanism of injury (173) substantiating the need to not only improve sprinting performance but also prevent the risk of injuries.

During a sprinting step, a ground contact time (GCT) < 250 ms has been found to be superior (134), where shorter GCTs relate to faster running speeds (103). Mattes et al. (112) found a large correlation between GCT and sprint performance, where athletes in their study exhibited GCTs as low as between 85 to 110 ms. Therefore, it is clear GCT is an important aspect in sporting success and thus improving GCT is usually a key training focus for practitioners and athletes. In addition to this GCT is crucial in top end sprinting permitting sufficient force can be produced, specifically for sprinting it is in the first 50% of the stance. High top speeds are characterised by the retraction velocity of the limb prior to ground contact (ability to produce a stiff stance limb upon ground contact) allowing high initial ground reaction forces and thus short GCTs (31).

But whilst the ground contact phase is highly important, the FP is arguably of equal importance as this is the preparation phase prior to ground contact and thus ground force application. The FP has been found to be negatively correlated to running speed (22) and thus is also a determining factor to game-time successes. Furthermore, whilst short GCTs are a necessity, there is a need to produce high impact ground reaction forces to enable sufficient impulse generation within each footfall. In order to enable this, the preparation of the leg for touchdown during the FP (rapid forward swing from the hip followed by rapid leg retraction from the hip) is an essential part of the sprint cycle (31).

During the FP, Miyashiro et al. (125) found that maximal thigh lift angle (hip angle of the front leg during the FP) ranged between 62.0 to 83.8º (relative to anatomical position = 0 º) and knee joint angle of the front leg during the FP ranged between 22.1 to 47.3 º (measured from the joint behind the knee) in a group of athletes. When in flight the back leg hip angles have been found to be 3.9 to -16.8 º (142). Typical flight times during sprinting are said to be between 120 to 140 ms (8,96,123,128) where during this time the limbs undergo substantial muscle activity. The hamstrings, quadricep group and gluteus maximus are all active during the late FP (80), including the gastrocnemius and soleus immediately prior to ground contact. Intriguingly, Van Hooren and Bosch (76) introduced the isometric hamstring phenomenon. Van Hooren and Bosch (76) suggested that following passive lengthening of the active muscles in the initial-and mid-FPs of sprinting, the hamstrings actually behave isometrically in the late-FP immediately prior to ground contact in order to prepare for ground force application. This could suggest that isometric training and assessment of the hamstring muscle group in positions similar to the FP could be a revolution for the industry. Van Hooren and Bocsh (77) suggested specific isometric exercises that could be carried out that mimic specific components of the action of the hamstrings during the flight phase. Although these suggestions are in place, the length of muscles/joint angles used have been approximated and the fascle length has not been evaluated via 3D motion analysis meaning it will likely differ from person to person. Initially, Van Hooren and Bosch (76) based their suggestions on animal models who have different gait patterns to human gait, while the animals exhibit different musculotendinous properties and interactions compared to humans. However, it was also found by Thelen et al. (157) within the hamstrings, at approximately 80% of the gait cycle, the EMG activity in the bicep femoris increased rapidly, causing the contractile element to stay close to isometric and even shorten. Therefore, the isometric hamstring phenomenon could be likely though further research is needed.

Interestingly, isometric IKD (the gold standard) and handheld dynamometry has been used to assess lower body function in positions where joint angles are similar to the individual limbs during the FP of sprinting. Kawaguchi et al. (89) assessed isometric hip extension function in a prone position with a hip extension angle of 30º (similar to the position of the front leg during the FP) and found high reliability producing ICCs 0.85 to 0.93. Similarly, Goodwin and Bull (62) assessed the isometric hip thrust with hip flexion angles, similar to the front leg of the FP in sprinting (20º, 30º, 40º and 50º relative to anatomical 0°) and found the hip thrust had high reliability and repeatability compared to the gold standard IKD in isometric conditions. These angles show strong reliability and exhibit similar angles to the joint angles during the FP of sprinting, thus could be interesting for practitioners to explore. However, no assessment has specifically assessed both front and back legs simultaneously in FP positions of sprinting, due to no device currently catering for this. As sprinting is a multipart rotary opposing action, assessing in bilateral positions may be of more interest, but to date, this has not been able to be assessed.

Although the gold standard device (the IKD) is a highly valid and reliable test, the machine is very expensive, where some IKD devices have an extremely long testing procedure and extraction process, is large and cannot be transported easily. Additionally, many isometric assessments in research including the IKD, although reliable, do not specifically replicate positions to dynamic real-life sports tasks and instead replicate seated or laying positions. Therefore, the introcution of the *The Biostrain* created by Performance Biomechanics could be a tool that could bridge this gap with its ability to assess isometric force production capabilities of individual limbs via bi-lateral multi-joint assessment (Figure 4.0). Similar to other isometric tests, the Biostrain can assess force at different time points from zero to peak force which have been found to be valid and reliable timepoints of assessments in research evaluating multi-joint isometric performance, also showing large associations with an array of dynamics tasks including, sprint performance, change of direction ability, weightlifting, jump performance (32). Due to the unique positions of the device, and similarities to already successful devices in research this device could transform isometric testing for sprint related sports. Additionally, due to the Van Hooren and Bosch (76) isometric hamstring theory, if the hamstrings do indeed act isometrically during the FP of sprinting, this device could prove as meaningful.

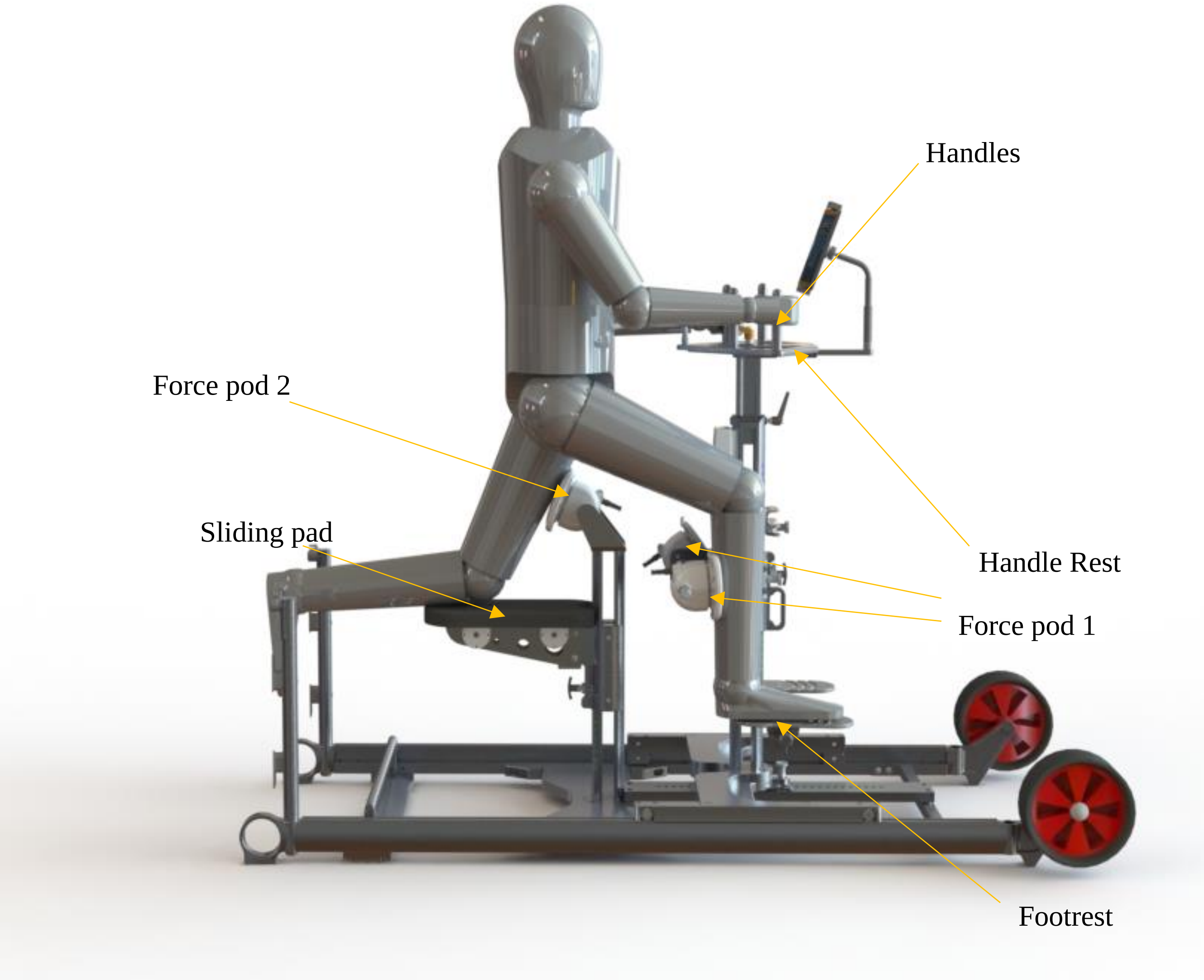


Figure 4.0 Biostrain device and subject set up

Therefore, the primary aim of the current study was to assess the reliability and the validity of the Biostrain device versus the gold standard isokinetic dynamometer device (the Kin Com) by assessing combined hip extension and knee flexion, and hip flexion. The study assesses between session and within session reliability. A secondary aim was to assess technique variation when using the Biostrain device, evaluating conditions without using the hands to stabilise posture versus using the hands to stabilise positions. To achieve these aims the study compared force-time characteristics from each leg using the Biostrain test versus the Kin Com, which replicated the same position of each leg in standing positions.

The study has the following hypotheses:

- [1] Force output from the front and back legs whilst using the Biostrain will be correlated to hip extension and flexion force derived from isokinetic dynamometry.
- [2] Force output from the front and back leg will demonstrate acceptable relative and absolute reliability with ICCs and CVs (ICC $\geq$ 0.7, CV $<$ 15%).
- [3] Force output from the front and back legs using the Biostrain without hands will demonstrate higher reliability compared to using hands for stability.
- [4] Differences in force time characteristics between session one and session two would be exhibited

4.3 METHODS

4.3.1 Experimental approach to the problem

A quantitative experimental approach, incorporating between subjects, cross sectional design was used to assess the reliability and validity of the Biostrain test versus a gold standard device, isokinetic dynamometry (Kin Com, Chattanooga, TN). On the Biostrain, subjects completed three trials in each condition (Table 4.0) and on the Kin Com isokinetic dynamometer, subjects also completed three trials in each condition (Table 4.1). This allowed hip extension, combined hip and knee extension and hip flexion for both right and left legs unilaterally to be assessed on the Kin Com and combined hip extension and hip flexion, and hip extension to be assessed on the Biostrain device. Metrics taken from the Biostrain test included forces at 100 ms, 150 ms, 200 ms, 250 ms and peak force for both left and right legs in each condition. Metrics taken from the Kin Com included peak forces in each condition tested (Table 4.1). Force at the time points listed above have been selected as these timepoints are the ‘all important within sport critical’ time points , demonstrate high within and between session reliability during isometric testing (32,37) and have also been reported to be excellent time point impulse predictors of athletic performance where the time frame for force application is generally limited to below < 300 ms (32).

The Biostrain was assessed with front leg hip flexion angle 30º relative to anatomical 0° and rear leg hip extension angle at -15º relative to anatomical 0°. These angle were replicated on the IKD thus replicating the Biostrain positions. These angles have been chosen as they exhibit angles similar to the late FP of sprinting and have been found to be safe, valid and reliable in previous research (62,86,171).

Subjects carried out two testing sessions. Testing session one included both the Biostrain tests and the IKD tests and testing session two consisted of a repeat of the Biostrain test. Subjects completed each testing session 3 to 7 days apart to allow for between session reliability to be assessed on the Biostrain.

Table 4.0 Biostrain positional condition definitions

Biostrain Conditions	
Condition A	Left leg forwards and right leg back. No hands in use.
Condition B	Right leg forward and left leg back. No hands in Use
Condition C	Left leg forwards and right leg back. Hands in Use
Condition D	Right leg forward and left leg back. Hands in Use

Table 4.1 Isometric testing conditions on the Kin Com

Kin Com Conditions	
Condition 1	Left hip extension, with the attachment cuff above the knee
Condition 2	Right hip extension, with the attachment cuff above the knee
Condition 3	Combined left hip and knee extension, with the attachment cuff below the knee
Condition 4	Combined right hip and knee extension, with the attachment cuff below the knee
Condition 5	Left hip flexion, with the attachment cuff above the knee
Condition 6	Right hip flexion, with the attachment cuff above the knee

4.4 PARTICIPANTS

Eighteen healthy active subjects (n = 18; age = 23.3 ± 5.1 years; height: 173.9 ± 5.8 cm; mass: 69.4 ± 12.8 kg) were selected via convenience sampling to take part in the study. N = 18 was selected as this was determined as an acceptable sample number based on Borg et al. (21)Data from Goodwin and Bull (62) was used through methods by Borg et al. (21) with expected reliability 0.87, a precision level of ± 0.15 and a confidence level of 95%, the minimum sample size required was 12. ~~a *priori* power analysis using G*Power (Version 3.1.9.2, University of Dusseldorf, Germany) This was based upon a previously reported Cohens *d* effect size of 1.69 Wild et al~~. All subjects currently or previously had experience in competitive team sports and individual sports, regularly partook in physical activity a minimum of three times a week and were familiar with structured strength and conditioning training and testing. Ethical approval was obtained from the University of Salford ethics board (ethics: 9356). Subjects received a letter of invitation outlining the full requirements of the study and were also provided with written informed consent to partake in the study. Subjects were given 72 hrs to decide whether they wanted to partake in the study or not. Prior to testing, all subjects completed a physical activity readiness questionnaire to check eligibility and ensure safety. All subjects were injury free and were informed they could not partake if they have had a lower body injury in the past 6 months.

4.5 PROCEDURES

4.5.1 Biostrain assessments

First subjects were shown the device and set-up position. They were then given the opportunity to mount the device to familiarise themselves with the positions. They were instructed to place their back knee on the sliding pad ensuring their quadricep was in contact with force pod 2 and place their front leg over force pod 1 ensuring their calf was in contact with force pod 1 and their front foot was placed on the footrest (Figure 4.0). After brief familiarisation subjects undertook three (each side) submaximal 2 second efforts of the test (50% perceived maximum intent, 75% perceived maximum intent and 95% perceived maximal intent) this acted as a priming warm up to ensure the body was ready for maximal efforts in this position. As the Biostrain was completed post isometric testing on the dynamometer, a mobility warm up was not required. The Biostrain was set up to replicate postures associated with the FP of sprinting gait as seen in Figure 4.0. The subject was set into the device with a front leg hip flexion angle of 30º relative to anatomical 0° and rear leg hip extension angle of -15º relative to anatomical 0°. In order to achieve these joint angles, the device was adjusted using the pulleys and stoppers and joint angles were checked using a goniometer. Posture and joint angles were recorded and replicated between sessions.

After the familiarisation and priming warm up trials, testing initiated. Subjects were asked to get into position on the device in the same way they did during familiarisation. Testing took place using two different protocols. During protocol one, subjects could not use their hands to stabilise themselves (Table 4.0, condition a and b). During protocol two, subjects could hold the handles to help stabilise themselves (Table 4.0, condition c and d). Subjects were instructed to remain as upright as possible during testing and abstain from leaning forwards where possible, during both protocol one and protocol two. Once in position, protocol one took place first. Subjects were instructed to keep completely still to allow a stable baseline force trace at the start of the test. They were instructed to rest their hands with thumbs towards the ceiling and little finger on the hand rest (thus palms facing each other) next to the handles. Subjects were given a countdown of "3-2-1 go" and were instructed to "squeeze" their legs together and towards each other (driving back with the front leg and forwards with the back leg) as "*fast and as hard as they could"* in line with previous successful isometric force testing cues (32) for a duration of 5 seconds. Strong verbal encouragement was given throughout the trial. When subjects perceived themselves to be recovered the next trial initiated, subjects were given a maximum of 3-minute rest periods between trials. Six trials were carried out in total (for each protocol) where three trials with subjects left leg forwards and right leg back and three trials with subjects' right leg forward and left leg back were carried out, where each trial alternated positions. The same testing protocols were used for protocol two, however subjects used the handles for stability during testing. During protocol two subjects were instructed to hold the handles with their right hand on the right handle and their left hand on the left handle. Subjects were *solely* instructed to hold onto the handles and *"use their hands to keep themselves in an upright and stable position".*

After the first testing session, subjects were given a usability questionnaire (Appendix 2) in order to gain insight into their experience on the device, allowing Biostrain to adapt and improve user experience.

Similar to the Isometric Kin Com protocols, data was collected for a duration of 8 seconds where each maximal isometric trial was only carried out for a maximum of 5 seconds allowing sufficient time for a stable baseline trace at the start, a peak force to be met, and a stable baseline trace at the end of the trial to be collected (32). To ensure consistency between

IKD and Biostrain testing a difference in PF of ≤10% between trials was considered acceptable (4). The data was collected using the custom-built software which was interfaced within the Biostrain computer setup. Raw unfiltered data was exported. An average of the three trials for each condition was created for each person for each time point. As the data was in kilograms, kilograms were converted into Newtons to allow comparisons to the isometric Kin Com measurements, by multiplying by 9.81.

Initiation of force production was identified as a progressive increase in force over 50 ms using a 10 ms moving average window which was automatically calculated within the custom-built software (appendix 1) interfaced within the computer set up. The highest force recorded across each trial was recorded as peak force. Force at 150 ms was recorded as the force at 150 ms from initiation of the effort. Force at 200 ms was recorded as the force at 200 ms from initiation of the effort. Force at 250 ms was recorded as the force at 250 ms from initiation of the effort.

4.5.2 Isometric testing on the Isokinetic Dynamometer

Subjects carried out a standard protocol warm up similar to recommendations made in research for other reliable isometric tests (32). The warm-up included: a series of 90/90 hip rolls, laying body weight leg extensions, body weight lunges, body weight glute bridges and world’s greatest stretch. All subjects were already familiar with isometric testing, however, to ensure familiarisation subjects received an explanation and demonstration of tests before testing initiated. They were also given the opportunity to carry out some practice trials in each position. Once set in position for initiation of each test, subjects carried out submaximal trials to ensure readiness for testing (explained later in this section)

Using procedures similar to Goodwin and Bull (62) assessments took place in the order of: left hip extension, left combined hip and knee extension, right hip extension, right combined hip and knee extension, left hip flexion, right hip flexion. Subjects were instructed to stand in an anatomical position to allow alignment of the dynamometer hip pad to be moved in line with the greater trochanter of their hip joint. Their test leg was then strapped in. For hip extension and for hip flexion the cuff was strapped in just above the knee (Figure 4.1). For combined hip and knee extension flexion the cuff was strapped in just below the knee (Figure 4.1). To ensure joint angles were consistent between trials, tape was placed on the ground. Subjects were instructed to keep their non test leg on the tape throughout testing.

On the Kin Com, isometric conditions were selected and anatomical zero was set where ‘0º’ was standing upright in an anatomical position, with feet behind the testing tape position on the floor. Next the lever arm was read and inputted into the Kin Com computer system before setting the start and stop angles. For hip extension and combined hip and knee flexion and extension the stop angle was set to 35º and the start angle was set to 30º. For hip flexion, stop angle was set to -20º and the start angle was set to -15º. Minimum isometric forces were set to 20 N for all trials. Next warm up trials were carried out before testing initiated. Subjects completed two submaximal practice efforts for 2 seconds at each position on each side (hip extension, combined hip and knee extension and hip flexion) one at 75% perceived max effort and one at 95%+ of perceived maximum effort.

Next 3 × 5s maximum effort trials were carried out in each position for each side. For the hip extension trials subjects were instructed to drive their leg back as hard as they could against the pad, for combined hip and knee extension the subject was instructed to drive their leg back and up against the pad. For hip flexion, the subject was instructed to drive their quadricep forwards as hard as they could against the pad. Subjects were told to hold onto the side of dynamometer to allow them to maintain stability and balance, allowing them to maximally push. Subjects were also instructed to remain as upright as possible with their torso during testing and to keep the toes of their standing leg behind the tape, to ensure a comparable posture to assessment on the Biostrain device. Subjects were given 2–3-minute rest periods between trials or until they perceived to be recovered and they stated they felt ready for the next trial.

Data was collected for a duration of 8 seconds where each maximal isometric trial was only carried out for a maximum of 5 seconds. The 8 second duration allowed sufficient time for a stable baseline trace at the start, a peak force to be met, and a stable baseline trace at the end of the trial to be collected (32). A difference in PF of ≤10 % between trials was considered acceptable as this has been used in previous successful IKD research in maintaining consistent results (4). The data was collected using the custom-built software which is interfaced within the computer setup. Initiation of force production was identified when peak force exceeded 20 N and the highest force recorded across each trial was recorded as PF. Raw unfiltered data was exported for further analysis.

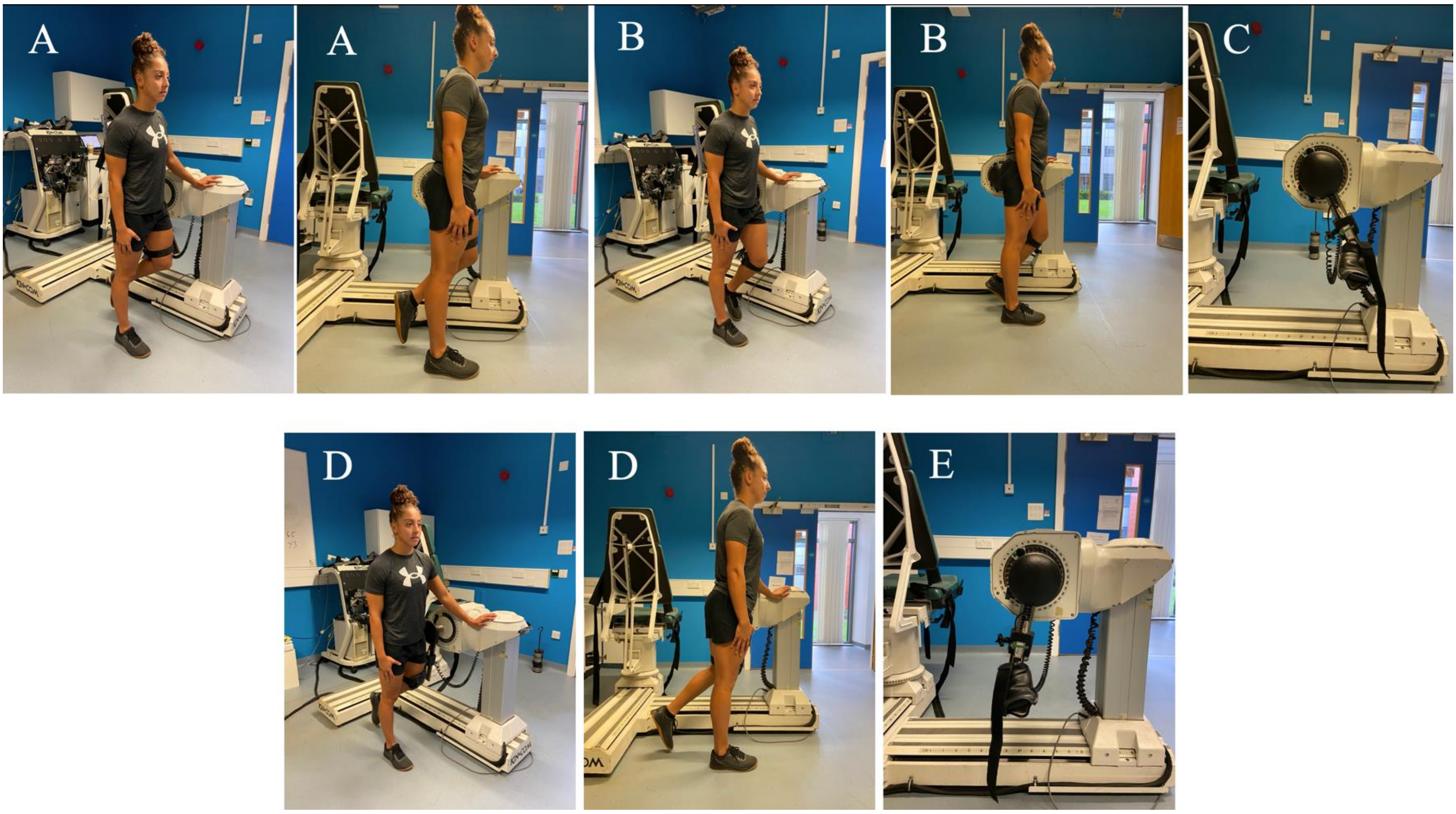


Figure 4.1 Images of Kin Com testing set up. **(A)** Hip extension, with attachment cuff above the knee; **(B)** Combined hip extension and knee extension with attachment cuff below the knee; **(C)** Angle set up of dynamometer lever arm for hip extension and combined hip and knee extension; **(D)** Hip flexion with attachment cuff above the knee; **(E)** Angle set up of dynamometer lever arm for hip flexion *Note: Images show left leg, the same was replicated for the right leg*

4.6 STATISTICAL ANALYSES

For each test, using SPSS (Version 23; SPSS Inc., Chicago, IL, USA) an Intraclass Correlation Coefficient ($ICC_{3,k}$) was used to examine relative reliability (e.g., rank order of consistency between trials) An ICC of ≥ 0.75 was interpreted as reliable, based on the ~~lower bound 95% CI~~ point estimate (94), 95% CIs were also calculated to determine reliability. %CV was calculated to determine the variability of the trials for each test using 'Standard deviation (SD) / mean × 100' an average was then calculated (with an acceptable CV set to CV ≤ 10 %). The SEM and smallest detectable difference (SDD) allowed identification of whether a change in a subjects performance was statistically significant/meaningful (42,95). SEM was calculated using SEM = $SD_{\text{pooled}} \times \sqrt{1 - ICC}$), where $SD_{\text{pooled}} = \sqrt{((SD_1{}^2 + SD_2{}^2)/2)}$. SDD was calculated using SDD = SEM × $\sqrt{2}$ × 1.96 (11,165). Within SPSS, p values were calculated using T-Tests to determine whether there are any significant differences between sessions on the Biostrain for each timepoint. A series of T-tests were also performed to determine differences between 'hand' versus 'no hands' conditions. Using estimationstats.com (72) Hedge's g effect sizes (ES) were calculated and plotted using Cumming's estimation plots with values interpreted as; trivial (≤ 0.19), small (0.20 to 0.59), moderate (0.60 to 1.19), large (1.20 to .99) and very large (2.0 to 4.0) and extremely large + 4.0 (78). To determine bias ~~agreement~~ between isometric testing on the Kin Com and Biostrain, limits of agreements were calculated and to explore fixed or proportional bias Bland-Altman plots (16) were created using Microsoft excel which compared mean versus the difference, a trend line was added to see the agreement between the two devices. The mean was calculated by calculating the average of the peak forces between the two devices: (peak force Kin Com / Peak force Biostrain) / 2. The difference was calculated by calculating the difference in peak force between the two devices. The bias was calculated between the two devices by averaging the difference between two devices for each subject. Limits of agreement were calculated using: the ±SD of mean difference × 1.96 (145). For correlational analysis of the Biostrain and the IKD, using SPPS, a Shapiro-Wilks test was performed to determine the normality of data. Using Pearson's correlation coefficient significance was set to $p \leq 0.05$ correlations were conducted. P values were multiplied by the number of correlations to adjust for familywise error. Pearson's correlation coefficient values were interpreted as < 0.10, 0.10 to 0.29 0.30 to 0.49, 0.50 to 0.69, 0.7 to 0.89 and ≥ 0.90 as trivial, small, moderate, large, very large and nearly perfect, respectively following Hopkins (26) guidelines. Using JAMOVI, correlations were plotted with standard error.

4.7 RESULTS

ICCs and CVs for all time points for each condition can be seen in Table 4.2 to 4.5. Varied reliability was found (ICC = -0.625 to 0.976). CVs displayed almost acceptable acceptable variability on all occasions (1.59 to 10.91%). SEM% ranged between 4.21 to 14.4% and SDD% ranged between 11.7 to 39.9% (Table 4.2 to 4.5). T-test results between testing session one and testing session two displayed varied results where some time points displayed significant differences, and some did not (Table 4.2 to 4.5). Raw differences can be seen in cummings plots (Figure 4.14 to 4.17). Tables 4.6 to 4.7 displays T-test results between hands versus no hands conditions. Right no hands versus right hand conditions displaying significant differences on all occasions, whereas left no hands versus left hands displayed varied results. Hedges *g* displayed trivial to small effect between first and second testing sessions (Table 4.2 to 4.5 and Figures 4.14 to 4.17). Bland Altman plots of difference versus mean for the two devices and their positions can be seen in Figure 4.2 to 4.13 with bias and error limits displayed. Correlation between the Biostrain and that of its retrospective condition in the KINCOM can be seen in Tables 4.12 to 4.15. Correlations displayed strong association, ranging between large to very large correlations (r = 0.495 to 0.851).

Table. 4.2 - 4.5 Between session reliability of the biostrain measures in different conditions

Table 4.2 Condition A: Left leg forwards and right leg back. No hands in use.

Biostrain Limb Force (N)								
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	277.0 ± 74.8	301.4 ± 84.8	314.0 ± 85.9	429.3 ± 114.8	280.7 ±83.2	298.4 ±94.4	300.6 ± 91.7	400.5 ± 121.5
% CV	7.24	7.49	6.67	7.02	4.71	3.75	3.06	4.08
ICC (LB-UB)	0.824 (0.531 - 0.934)	0.838 (0.567 - 0.939)	0.845 (0.585 - 0.942)	0.890 (0.706 - 0.959)	0.860 (0.625 - 0.948)	0.874 (0.662 - 0.953)	0.862 (0.631 - 0.948)	0.926 (0.803 - 0.972)
SEM%	10.39	10.40	9.95	8.25	10.35	10.49	10.64	7.81
SDD%	31.3	28.8	27.6	22.9	28.7	29.1	29.5	21.6
Sig. (2-tailed)	0.052	0.047	0.062	0.022	0.196	<0.001	0.403	0.145
Hedges *g* (95%CI)	0.372 (0.041 - 0.735)	0.369 (0.064 - 0.695)	0.337 (0.035 - 0.666)	0.365 (0.099 - 0.695)	0.218 (0.085 - 0.571)	0.162 (0.124 - 0.511)	0.137 (0.154 - 0.525)	0.184 (0.058 - 0.427)

Key: LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; ICC: Intraclass correlation coefficient; CV: Coefficient of variation; SEM: Standard error of the measurement; SDD: Smallest detectable difference. Sig. (2-tailed): signifance level between 1st and 2nd testing session Hedges g: session 1 vs session 2. Effect sizes interpreted as:

Trivial ES	Small ES	Moderate ES	Large ES	Very Large ES	Extremely Large ES

Table 4.3 Condition B: Right leg forwards and left leg back. No hands in use.

Biostrain Limb Force (N)								
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	265.4 ± 71.1	281.09 ± 79.1	293.06 ± 79.4	423.29 ± 114.6	261.8 ± 71.5	281.4 ± 73.5	292.7 ± 73.8	422.9 ± 103.6
% CV	9.76	10.91	9.70	4.40	9.25	9.33	8.21	3.43
ICC (LB-UB)	0.625 (-0.003 - 0.860)	0.688 (0.166 - 0.883)	0.837 (0.564 - 0.939)	0.903 (0.741 - 0.964)	0.710 (0.226 - 0.892)	0.739 (0.302 - 0.902)	0.790 (0.438 - 0.921)	0.897 (0.726 - 0.962)
SEM%	14.4	13.7	9.79	8.03	13.1	12.0	10.6	7.54
SDD%	39.9	37.9	27.1	22.3	36.4	33.3	29.3	20.9
Sig. (2-tailed)	0.047	0.026	0.009*	0.121	0.043	0.028	0.030	0.188
Hedges *g* (95%CI)	0.486 (0.074 - 0.959)	0.452 (0.111 – 0.883)	0.339 (0.046 - 0.770)	0.389 (0.054 - 0.709)	0.324 (0.078 - 0.529)	0.455 (0.237 - 0.657)	0.406 (0.199 - 0.624)	0.138 (-0.012 - 0.286)

Key: LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; ICC: Intraclass correlation coefficient; CV: Coefficient of variation; SEM: Standard error of the measurement; SDD: Smallest detectable difference. Sig. (2-tailed): signifance level between 1st and 2nd testing session Hedges g: session 1 vs session 2. Effect sizes interpreted as:

Trivial ES	Small ES	Moderate ES	Large ES	Very Large ES	Extremely Large ES

Table 4.4 Condition C: Left leg forwards and right leg back. Hands in use.

	Biostrain Limb Force (N)							
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	284.8 ± 72.0	317.7 ± 86.9	340.5 ± 101.5	538.0 ± 142.2	326.66 ± 90.6	367.25 ± 93.5	398.71 ± 102.6	596.33 ± 165.7
% CV	8.72	8.83	7.29	7.39	6.50	8.27	7.50	2.81
ICC (LB-UB)	0.684 (-0.156 - 0.882)	0.779 (0.410 - 0.917)	0.832 (0.550 - 0.937)	0.853 (0.606 - 0.945)	0.929 (0.811 - 0.973)	0.938 (0.834 - 0.977)	0.941 (0.843 - 0.978)	0.976 (0.935 - 0.991)
SEM%	12.7	11.60	11.30	9.40	6.90	5.90	5.90	4.21
SDD%	35.1	32.1	31.2	26.0	19.2	16.3	16.2	11.7
Sig. (2-tailed)	0.047	0.034	0.070	0.031	0.014	<0.001	0.002	0.068
Hedges *g* (95%CI)	0.514 (0.042 – 1.02)	0.550 (0.121 – 1.06)	0.505 (0.70 - 0.931)	0.223 (-0.003 - 0.494)	0.476 (0.074 - 0.880)	0.504 (0.148 - 0.937)	0.456 (0.128 - 0.869)	0.192 (-0.036 - 0.522)

Key: LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; ICC: Intraclass correlation coefficient; CV: Coefficient of variation; SEM: Standard error of the measurement; SDD: Smallest detectable difference. Sig. (2-tailed): signifance level between 1st and 2nd testing session Hedges g: session 1 vs session 2. Effect sizes interpreted as:

Trivial ES	Small ES	Moderate ES	Large ES	Very Large ES	Extremely Large ES

Table 4.5 Condition D: Right leg forwards and left leg back. Hands in use.

Biostrain Limb Force (N)								
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	344.1 ± 94.0	383.9 ± 102.3	414.1 ± 109.2	608.0 ± 159.8	291.4 ± 69.8	320.3 ± 80.0	341.0 ± 85.1	551.3 ± 148.6
% CV	2.40	1.89	4.19	3.80	2.08	1.59	2.63	3.61
ICC (LB-UB)	0.894 (0.717 - 0.960)	0.928 (0.807 - 0.973)	0.923 (0.974 - 0.971)	0.940 (0.840 - 0.978)	0.725 (0.264 - 0.897)	0.709 (0.223 - 0.891)	0.709 (0.223 - 0.891)	0.904 (0.744 - 0.964)
SEM%	8.36	6.80	6.84	6.08	11.70	12.50	12.4	7.90
SDD%	23.2	18.9	19.0	16.9	32.3	34.5	34.5	21.8
Sig. (2-tailed)	0.407	0.424	0.091	0.083	0.580	0.695	0.514	0.191
Hedges *g* (95%CI)	0.122 (0.212 - 0.395)	0.098 (0.191 - 0.320)	0.221 (0.016 - 0.491)	0.201 (-0.026 - 0.473)	0.120 (-0.249 - 0.604)	0.088 (0.311 - 0.576)	0.145 (-0.265 - 0.604)	0.185 (-0.088 - 0.441)

Key: LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; ICC: Intraclass correlation coefficient; CV: Coefficient of variation; SEM: Standard error of the measurement; SDD: Smallest detectable difference. Sig. (2-tailed): signifance level between 1st and 2nd testing session Hedges g: session 1 vs session 2. Effect sizes interpreted as:

Trivial ES	Small ES	Moderate ES	Large ES	Very Large ES	Extremely Large ES

Table 4.6 – 4.7 T-test results comparing hands versus no hands conditions.

Table 4.6 Condition A: Left leg forwards and right leg back. No hands in use *versus* Condition C: Left leg forwards and right leg back. Hands in use.

Biostrain Limb Force (N)								
	Left 150ms	Left 200ms	Left 250ms	Left Peak	Right 150ms	Right 200ms	Right 250ms	Right Peak
Sig 2. Tailed	0.306	0.166	0.065	0.010	0.010	<0.001	<0.001	<0.001

Table 4.7 Condition B: Right leg forwards and left leg back. No hands in use versus Condition D: Right leg forwards and left leg back. Hands in use.

Biostrain Limb Force (N)								
	Left 150ms	Left 200ms	Left 250ms	Left Peak	Right 150ms	Right 200ms	Right 250ms	Right Peak
Sig 2. Tailed	<0.001	<0.001	<0.001	<0.001	0.017	<0.001	<0.001	<0.001

Table 4.8 – 4.11 Correlation Coefficients with *p* values of Biostrain peak force versus the Kin Com peak force

Table 4.8

	r (p)	
	Biostrain Left hip extension no hands *(Left Leg during condition A)*	Biostrain Left hip extension with hands *(Left Leg during condition C)*
KINCOM Left hip extension *(condition 1)*	0.693** (0.002)	0.791** (0.002)
KINCOM Left combined hip and knee extension *(condition 3)*	0.547* (0.038)	0.620** (0.012)

Table 4.9

	r (p)	
	Biostrain Right hip extension no hands *(Right Leg during condition B)*	Biostrain Right hip extension with hands *(Right Leg during condition D)*
KINCOM Right hip extension *(condition 2)*	0.724** (0.002)	0.669** (0.004)
KINCOM Right Combined hip and knee extension *(condition 4)*	0.495 (0.074)	0.497 (0.072)

Table 4.10

	r (p)	
	Biostrain Left hip flexion no hands *(Left Leg during condition B)*	Biostrain Left hip flexion with hands *(Left Leg during condition D)*
KINCOM Left hip flexion (condition 5)	0.665** (0.003)	0.642** (0.004)

Table 4.11

	r (p)	
	Biostrain Right hip flexion no hands (Right Leg during condition A)	Biostrain Right hip flexion with hands (Right Leg during condition C)
KINCOM Right hip flexion (condition 6)	0.647** (0.004)	0.851** (<0.001)

Key: * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)

Figure 4.2 Left hip extension Biostrain (no hands) versus Left hip extension KINCOM

(Biostrain left leg condition A versus KINCOM condition 1)

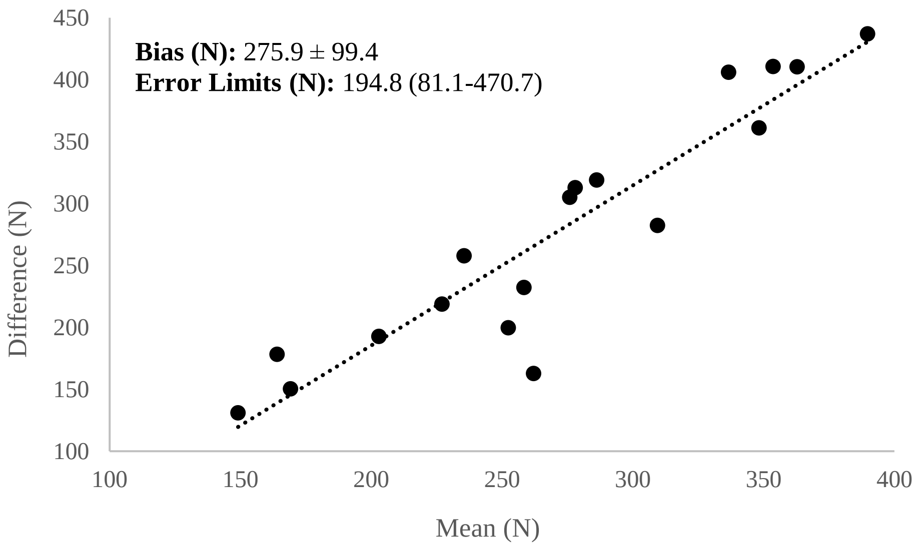


Figure 4.3 Left hip extension Biostrain (hands) versus Left hip extension KINCOM

(Biostrain left leg condition C versus KINCOM condition 1)

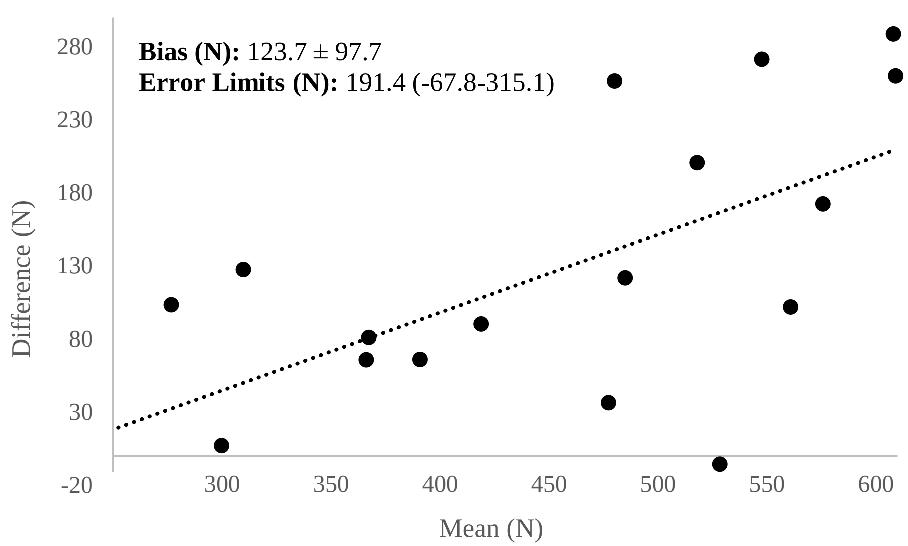


Figure 4.2 – 4.13 Bland altmon plots of difference (N) versus mean (N) for the Biostrain and KINCOM in each paired condition tested. With bias and error limits

Figure 4.4 Left hip extension Biostrain (no hands) versus combined Left hip and knee extension KINCOM

(Biostrain left leg condition A versus KINCOM condition 3)

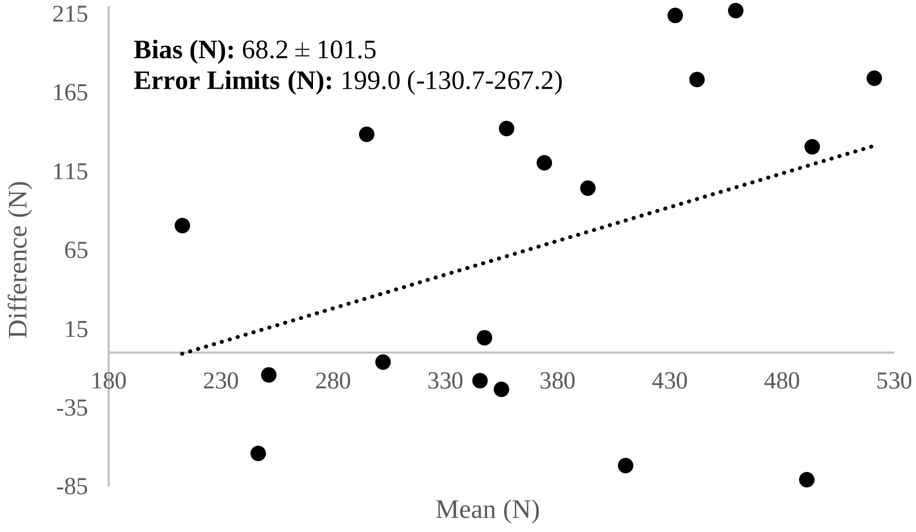


Figure 4.5 Left hip extension Biostrain (hands) versus Left combined hip and knee extension KINCOM

(Biostrain left leg condition C versus KINCOM condition 3)

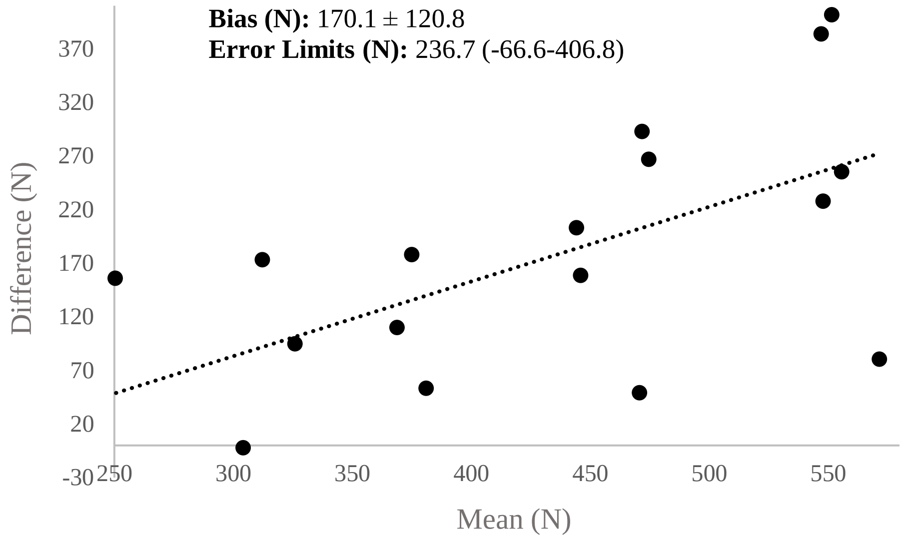


Figure 4.6

Right hip extension Biostrain (no hands) versus Right hip extension KINCOM
(Biostrain right leg condition B versus KINCOM condition 2)

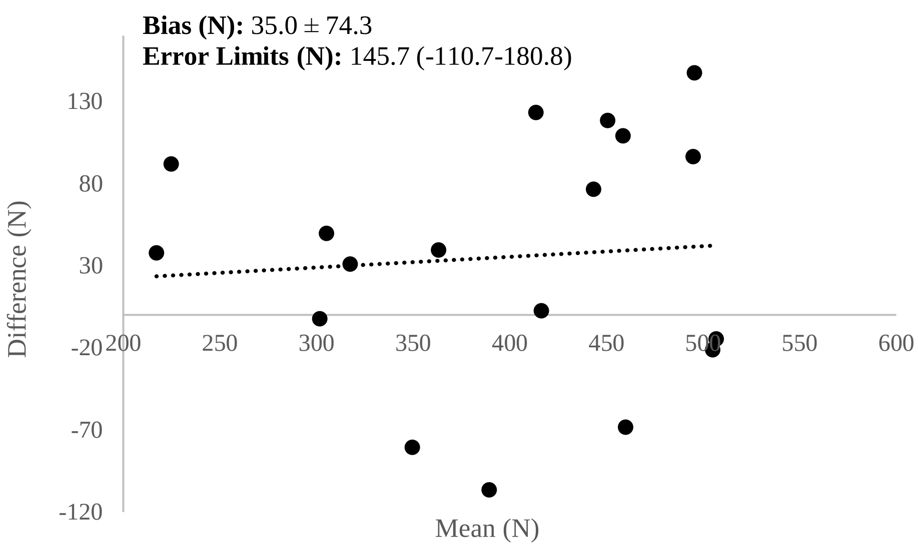


Figure 4.7

Right hip extension Biostrain (hands) versus Right combined hip and knee extension KINCOM
(Biostrain right leg condition B versus KINCOM condition 4)

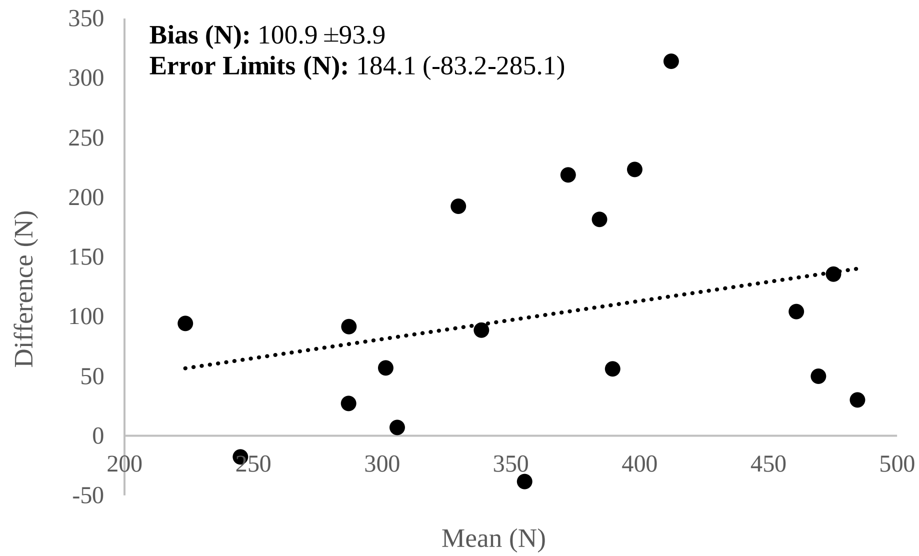


Figure 4.8 Right hip extension Biostrain (hands) versus Right hip extension KINCOM

(Biostrain right leg condition D versus KINCOM condition 2)

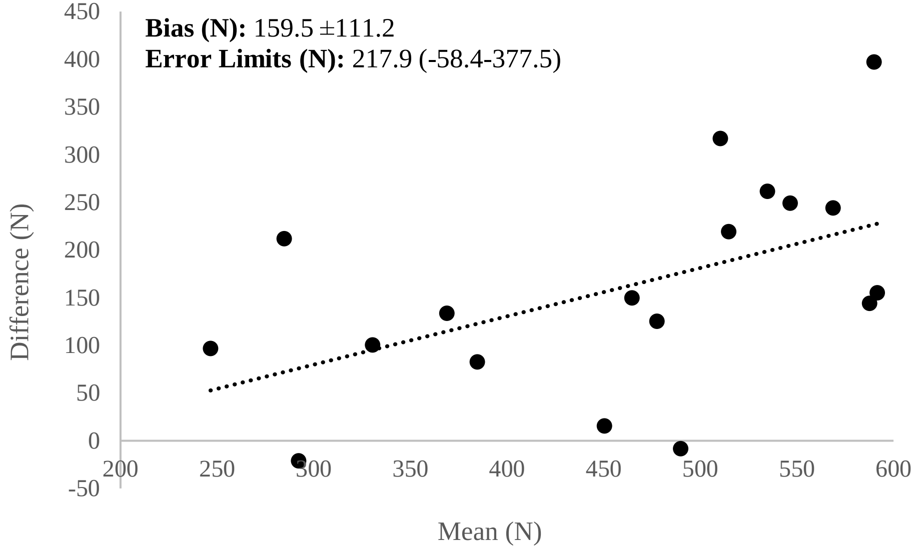


Figure 4.9 Right hip extension Biostrain (hands) versus Right combined hip and knee extension KINCOM

(Biostrain right leg condition D versus KINCOM condition 4)

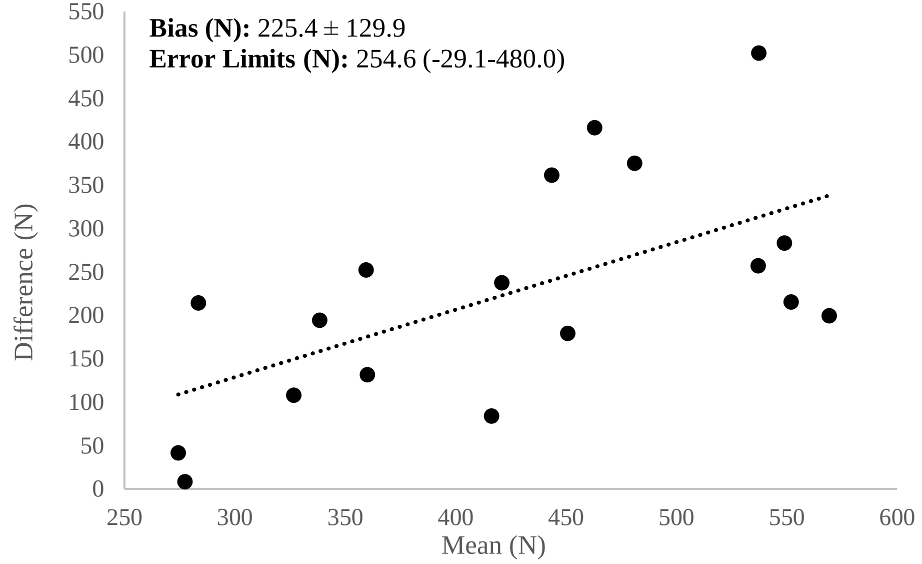


Figure 4.10 Left hip flexion Biostrain (no hands) versus Left hip flexion KINCOM
(Biostrain left leg condition B versus KINCOM condition 5)

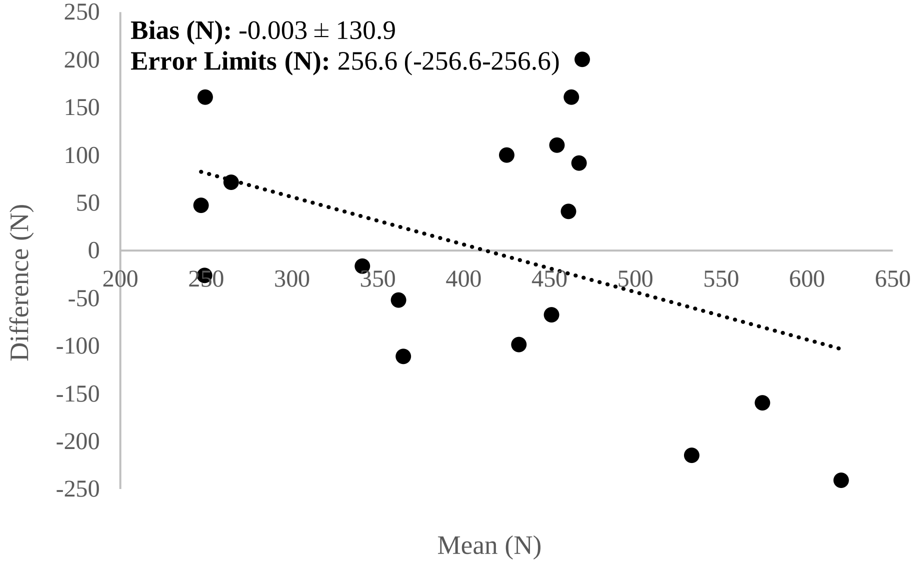


Figure 4.11 Left hip flexion Biostrain (hands) versus Left hip flexion KINCOM
(Biostrain left leg condition D versus KINCOM condition 5)

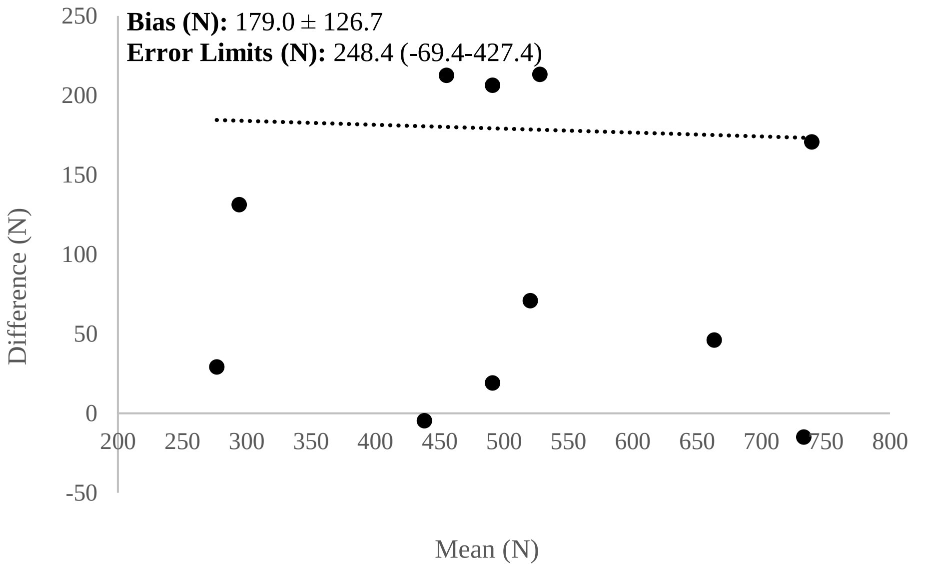


Figure 4.12 Right hip flexion Biostrain (no hands) versus Right hip flexion
(Biostrain right leg condition A versus KINCOM condition 6)

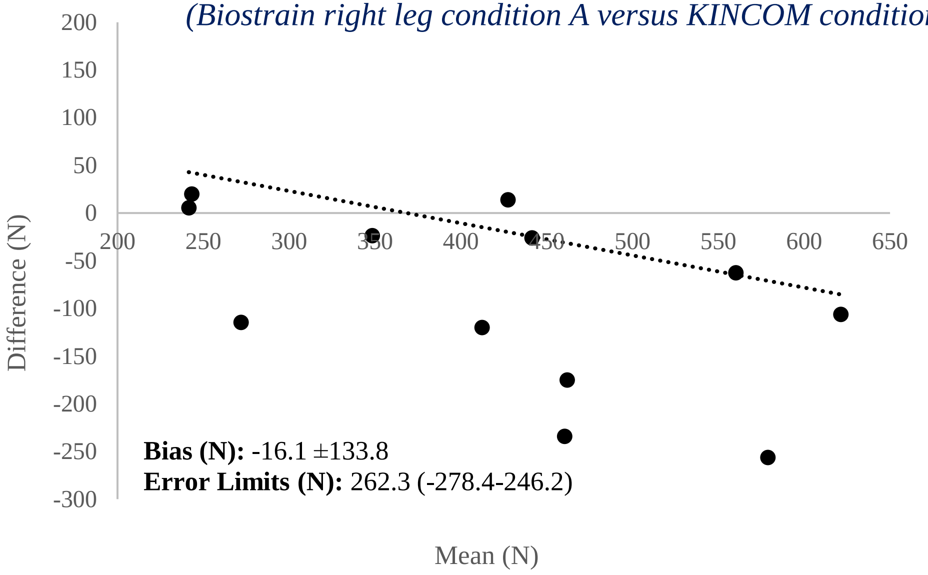
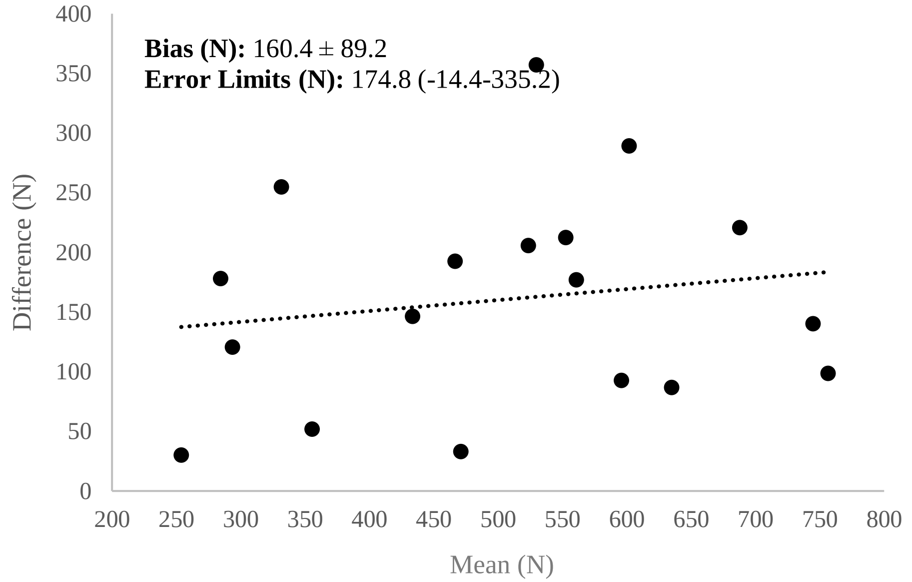


Figure 4.13 Right hip flexion Biostrain (hands) versus Right hip flexion
(Biostrain right leg condition C versus KINCOM condition 6)



Condition A: Left leg forwards and right leg back. No hands in use.

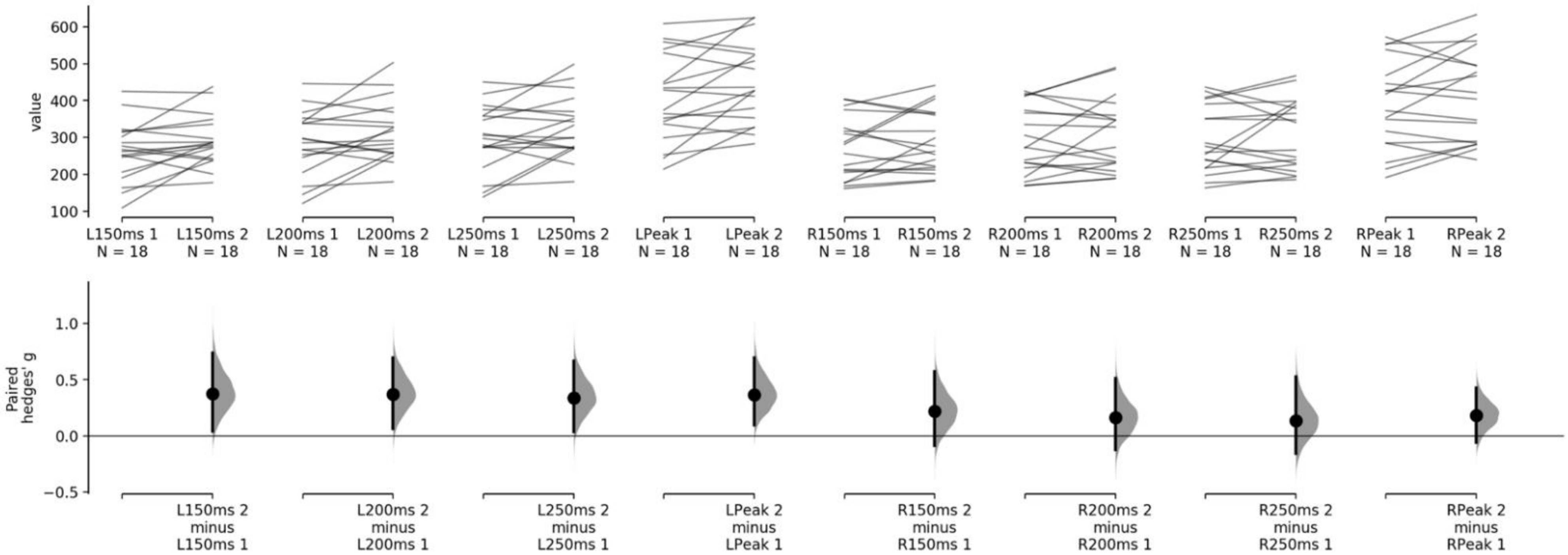


Figure 4.14 Cumming plots of force outputs for session 1 versus session 2 and hedges *g* effect sizes, Condition A

Condition B: Right leg forwards and left leg back. No hands in use.

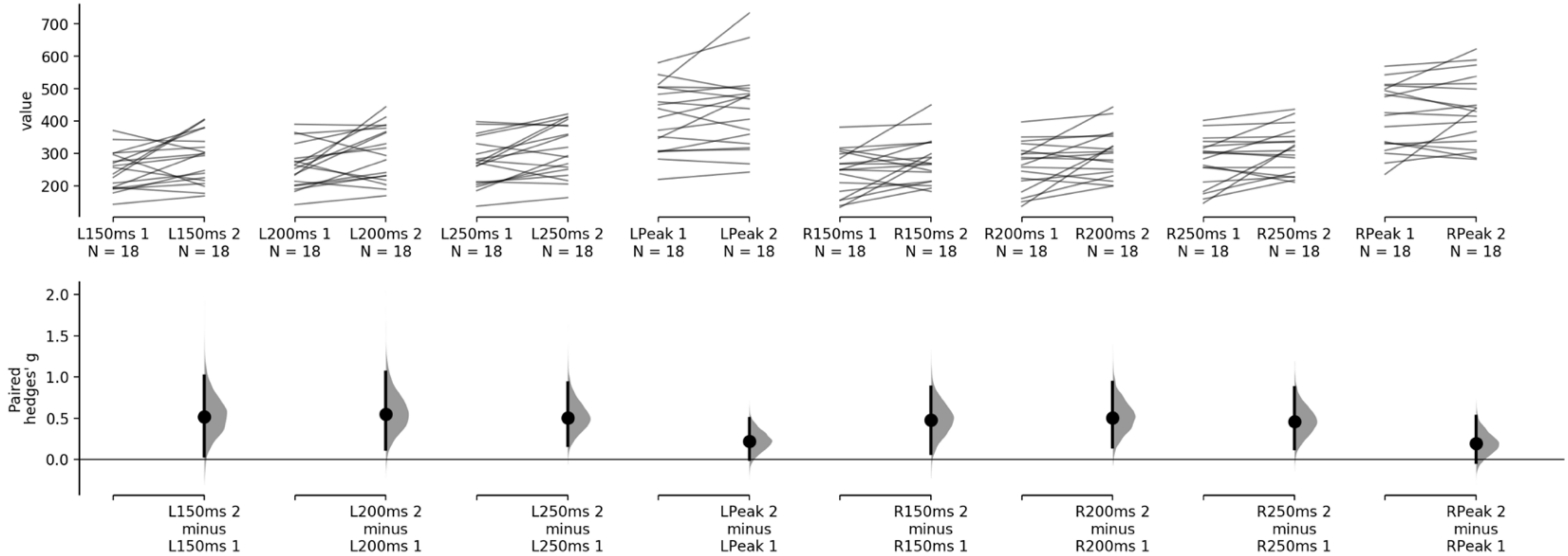


Figure 4.15 Cumming plots of force outputs for session 1 versus session 2 and hedges *g* effect sizes, Condition B

Condition C: Left leg forwards and right leg back. Hands in use.

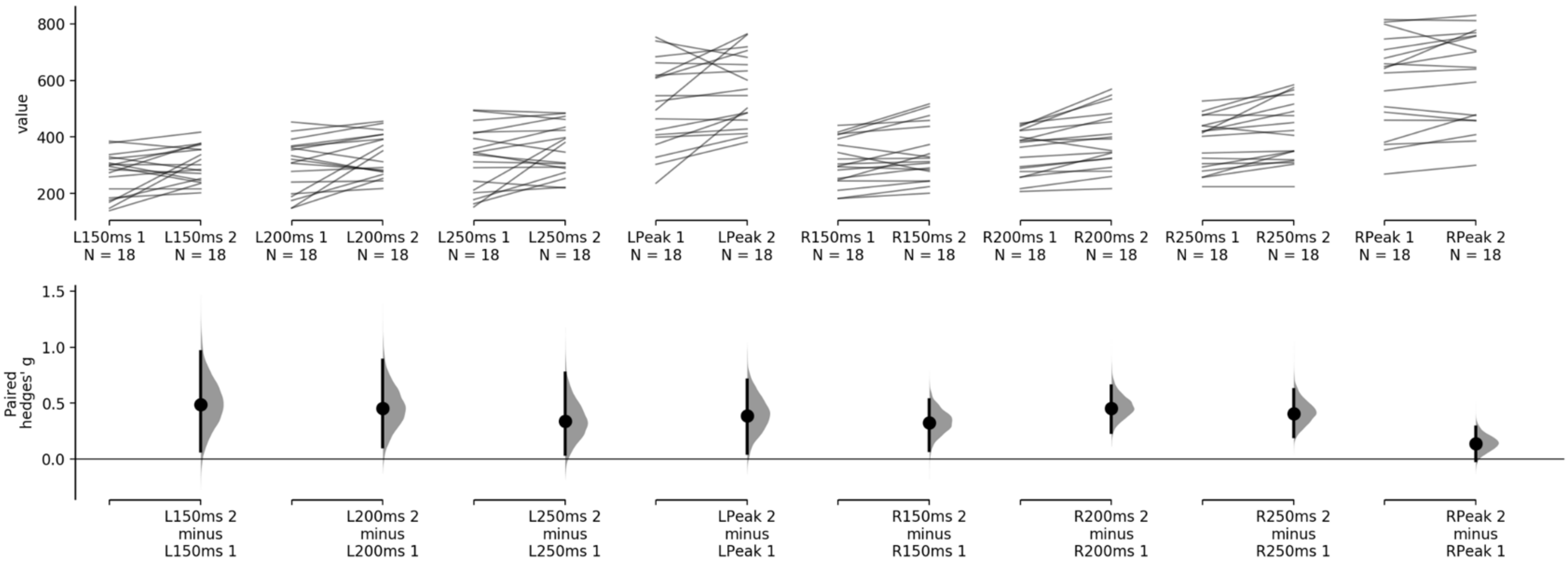


Figure 4.16 Cumming plots of force outputs for session 1 versus session 2 and hedges g, Condition C

Condition D: Right leg forwards and left leg back. Hands in use.

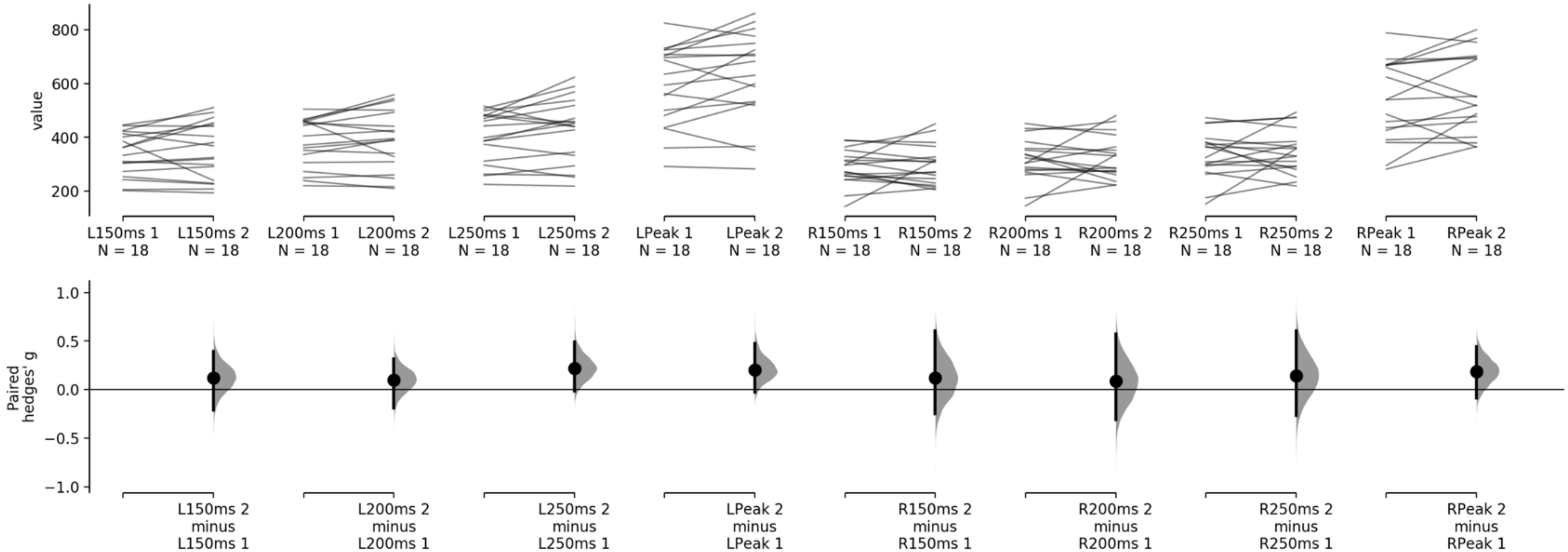


Figure 4.17 Condition D: Right leg forwards and left leg back. Hands in use. Condition D

4.8 DISCUSSION

The primary aim of the current study was to assess the reliability and the validity of the Biostrain device versus the isometric testing on the Kin Com IKD by assessing the Biostrain versus combined hip extension and knee flexion and hip flexion on the Kin Com. A secondary aim was to compare using the Biostrain, without using the hands to stabilise position versus using the hands to stabilise position.

On the whole CV% were acceptable as only condition B, left leg was deemed unacceptable. Upon further exploration of the results, it is evident that having the right leg either at the front or at the back, consistently yields more reliable results in all conditions compared to the left leg, producing lower CV% than the left on all occasions. This may be due to the fact that most subjects stated they were right foot dominant (3 left versus 15 right). Research has shown that the dominant limb can produce more reliable results due to increased motor control, strength, and power in the dominant side (64,84) therefore this may explain the reason for lower CV% in the right-side compared to the left. In two conditions, left 150 ms ICCs were deemed unacceptable (b and c). ~~Where the right leg was deemed to have acceptable ICCs in all conditions at all timepoints.~~ Where the right leg was deemed to have acceptable This again provides support for the above statement regarding limb dominance and reliability. Further research may be needed to understand on deeper levels the reliability of each limb versus limb dominance. Future research could also consider assessing an equal number of left foot dominant subjects compared to an equal number of right foot dominant subjects to explore side dominance versus variability on deeper levels. Though a longitudinal study monitoring the reliability of each limb may be useful to explore whether reliability strengthens as familiarity with the device increases. ~~Assessing asymmetries may also be useful to help prevent the risk of long-term injuries.~~

In the current study, there was a clear pattern whereby as the time point increased, the reliability (ICC) also increased. This suggests that the Biostrain could be a reliable method of assessment at higher timepoints (250 ms and peaks). Though, for the timepoint 200 ms, scores were acceptable in all conditions except for left 200 ms in condition b. This could suggest that 200 ms may also be a reliable timepoint, but further research is needed to confirm this point. Reliability patterns in the current study also agree with other isometric tests in research that conclude higher timepoints produce more reliable ICCs. The Biostrain results agreeing with both bilateral isometric tests and unilateral tests such as the IMTP (43,55) and single limb Isometric knee extension (strain guage) (35). This provides positivity for the device showing similarities to already successful devices in the industry, though further research is needed to provide more solid conclusions.

It is widely known within research that the ability to examine, monitor, and improve maximal force production capabilities of the lower limbs is an essential part in allowing athletes to reach their maximum potential (26,33,38,43,98,147). However, in game-time scenarios, as previously mentioned, whilst there is importance in the ability to express force maximally, the ability to express force quickly can be the difference between successful and unsuccessful results (69). Though the ability to produce force quickly at timepoints < 250 ms is important in sports performance (69,159) isometric strength assessments in research have found the timepoints 200 ms to peak force appear to show more correlation to sprint performance compared to lower time points (e.g., below 150 ms) due to higher reliability and validity at higher time points (104). Although this is the case, Mason et al. (111) assessed IMTP force

150 ms versus sprint performance and found that the strength of the correlation began to strengthen as sprinting speed increases. Therefore, this show potential that the timepoint 150 ms may also be useful in the Biostrain and may show association to sprint performance similar to the IMTP. Though further research is needed at lower time points to confirm this.

Clark et al. (31) found that leg angular velocity was positively related to running speed in human sprinting helping to gain greater ground reaction force and velocity at touchdown. Clark et al. (31) found a 91% shared variance with running speed and angular velocity of the thigh during the full gait cycle. Therefore, as there are associations between the FP and the ground contact phases (109) it is likely that the same isometric force time points associated with the ground contact phase in sprinting (200 ms to peak) may also show association with the FP. The valid and reliable results at timepoints 200 ms to peak in the current study provide optimism for such correlation study to take place.
Additionally, Preece et al. (143) found that faster running speeds is characterised by increased vertical impulse, increased velocity at toe-off and longer flight times. Therefore, it could be suggested that greater impulse generation of the front and back leg during Biostrain testing, could enable greater forces at touchdown leading to greater vertical impulse generation and thus, greater take-off velocity and flight times thus better sprint performance. Investigations into the associations between time points 200 ms to Peak through impulse with kinetic and kinematic parameters of the FP in sprinting may prove useful.

Within the current study, SEMs range between 4.21 to 14.4% and SDD were high ranging between 11.7 to 39.9%. Where in all conditions, the SEM% for the peaks (in both front and back legs) exhibited the lowest SEM%. There was a clear pattern, whereby as the timepoint increased the SEM% lowered in all conditions. SEM% (SEM% = 4.21 to 14.4%) results in the current study show positivity for the Biostrain device exhibiting low SEMs on the whole, suggesting the Biostrain could be a reliable test for longitudinal assessments. SEM% and SDD% results in the current study are also in agreement with other isometric assessment studies. Mentiplay et al. (122) assessed isometric IKD and HHD and found SEM% ranged between 5.67 to 7.03% and 5.22 to 8.59% (IKD and HHD retrospectively) across hip and knee extension and flexion. Interestingly Mentiplay et al. (122) also found high SDDs (called Minial detectable change in their study, calculated by MDC 1⁄4 z SEM 2, where z = 1.96 (based on 95% confidence) and SEM is the standard error of measurement, SEM = SEM 1⁄4 SD1 1 ICC) results (Kin Com: 15.72 to 19.49%; HHD: 14.48 to 23.81%, intra rater) , similar to the current study. Additionally, McCall et al. (115) assessed isometric hamstring function (using similar joint angles to the current study) via an isometric hip thrust at 30º and 90º. Though the hip thrust has been found to be a reliable and valid test, similar to the current study McCall et al. (115) found large SDD (Called minimal detectable change in their study caluted by TE × 1.96 × √2) ranging between 26.2 to 36.9 . Mentiplay et al. (122) concluded that SEM% may be more informative for a clinical population compared to the healthy athletic population as a clinical population are more likely to exhibit larger improvements/change. It is possible that may be the case in the current study in terms of SEM% and SDD% results though further research is needed for the current device. An additional factor that could have influenced such factors may relate to the rest intervals allocated between trials. Athletes were permitted a maximum of 3 minutes recovery between each trial. However, they were allowed to initiate the subsequent trial once perceived recovered. This practice may have lead to inconsistencies in rest durations, potentially introducing a degree of acute fatigue. Thus possibly impacting metrics such as SDD% and SEM%.

The Biostrain clearly exhibits large to very large correlations with its retrospective hip extension (front leg) and hip flexion (back leg) condition on the Kin Com. Therefore, results of the current study show that the Biostrain does indeed assess hip extension, combined hip and knee extension and hip flexion as there are strong associations with the gold standard. In the strongest correlation (right hip flexion Biostrain (with hands) versus right hip flexion Kin Com) results show that 72% of the variance is accounted for by the Kin Com.This suggests that the Biostrain could be an alternative option to assess hip flexion, hip extension and combined hip flexion and extension. The Biostrain is far more convenient compared to IKD as it is much more transportable, provides instant test results, has a quicker data extraction process and is cheaper in price. Thus, the Biostrain may be a more attractive device for practitioners. With this in mind, to further enhance attractiveness researchers could consider assessing the Biostrain longitudinally to gain deeper insight into the effect of training on the Biostrain.

Researchers have found a strong correlation between sprint performance and peak isokinetic torque in flexion and extension on the IKD (34). Alexander (1) reported a strong inverse relationship (r = -0.72, $p < 0.01$) between peak isokinetic concentric torque generated by the knee extensor muscles and 100 m sprint performance in elite track and field athletes. However, Alexander (1) assessed IKD in isokinetic conditions, not isometric therefore whilst these suggestions may be true further research is needed to conclude this. But promisingly, a broad array of research has explored the associations between IKD with isometric HHD and found strong associations therefore enhancing the likelihood that the Biostrain (also isometric like HHD) is correlated to sprint performance (71,88,89,91,102,122,148). Additionally, as the Biostrain exhibits angles and positions even more similar to sprinting compared to IKD, this provides further support that the Biostrain may show correlation to sprint performance. As previous research has found the FP positively influences the force and the velocity at which the limbs contact the ground at (31,109) the high reliability and high correlations with the gold standard suggest that the Biostrain could be a potential device to help aid the preparatory phase prior to ground contact. Thus, helping to enable rapid and high force production during ground contact. Further research could consider assessing correlating sprint performance versus the Biostrain. However, it is important to recognise that even in the strongest correlations of the current study 28% of the variance was not accounted for by the Kin Com. This may be due to the employment of predetermined specific joint angles for assessment for every athlete. As previously discussed (in the systematic review section of the thesis), a universal approach for joint angle selection is unlikely to be suitable for everyone. Calderbank et al. (28,29) discovered differences in technical models between track and field athletes and team sport athletes. This suggests that the joint angles selected in the current study might not accurately represent the optimal angles for the late swing phase of sprinting across all athletes. A more precise approach could involve conducting biomechanical analyses of athletes sprint performances, capturing their late swing phase joint angles and then applying these specific joint angles to the biostrain. This method could potentially yield more accurate results although this wouldn't be practical in a real life setting due to being too time consuming.

It is clear that in the current study when assessing results between testing session one and testing session two there are differences, supported by *p* values. Hedge's *g* results show a trivial to small effect between testing sessions one and two. Although raw results are mixed, overall, it seems that during testing session two, subjects displayed higher scores suggesting a learning effect. *P* values, SEM% and Hedge's g Cummings plots in the current study suggest future research could consider testing longitudinally to assess changes. Testing subjects across > 4-week period could help to identify how long it will take to stabilise performance or alternatively testing multiple efforts in one session to see if results stabilise (which may be more practically logistical). The use of a learning curve may be insightful for future users of the device in order to measure the number of trials required to deem familiarity.

When assessing Bland-Altman plots of mean versus differences of the two devices, it is clear that results vary and hetereoschedasticity is evident in most conditions. This may be due to differences in stability of the two devices. During Biostrain testing, both limbs were tested at the same time thus, both limbs were producing force against the device/force pods and used multiple muscle groups to do so. Whereas on the Kin Com, though testing was isolated and more specific to one limb, the testing procedures were less stable thus meaning a representation of true maximal force generating capacity may not have been exhibited and thus further research may be needed ensuring athlete familiarity with both testing procedures.

Participant usability

Post initial testing, subjects completed a usability/feedback sheet. A summary of feedback can be seen in appendix 2. On the whole, it was clear subjects deemed the Biostrain to be a comfortable usable device, with 78% of subjects stating the Biostrain position was comfortable, and they didn't feel too far stretched (into the splits) or in too narrow of a position. Positively, when rating comfort, 56% of users scored the device a '1 out of 5' and stated the pods on the device weren't uncomfortable at all (where 1 is not uncomfortable at all and 5 is very uncomfortable). 33% of users scored the device a '2' stating the pods were a little uncomfortable but didn't affect their test. Only 11% of subjects stated a '3' signifying the pods were moderately uncomfortable. Therefore, on the whole, based on feedback, the Biostrain could be deemed as a strong alternative to IKD. When asked what subjects focused on during the test, 50% of subjects stated they felt they squeezed equally whilst 33% of users stated that they felt it was more back leg dominant. Interestingly, 17% of users said, that when comparing ‘no hand’ conditions versus ‘hands in use’ conditions they felt they could apply an equal amount of force with both legs during the ‘no hands’ conditions. But opposingly, felt that when their ‘hands’ were in use it became more back leg dominant. Whilst this was said, correlations in the current study in both front and back legs in each condition versus its retrospective position with the Kin Com still shows large to very large correlation. This shows positivity for the Biostrain again suggesting it could be a valid and reliable option within sports science as opposed to the Kin Com.

In terms of intention, subjects all stated they felt it was purely lower body dominant, again showing positivity for the device which also agrees with correlations in the current study (Table 4.3- 4.6). It goes without saying, subjects exhibited more stability when hands were in use versus not in use with 39% of subjects stating they felt more stable and upright when their hand were in use though 39% of subjects also stated that felt their posture remained the same throughout all tests, whether hands were in use or not. Though 22% of subjects did recall some kind of postural change including leaning forwards. Subject feedback is encouraging for future users of the device, as no subjects stated that the pods were completely uncomfortable (scoring it a 4 or 5 out of 5) and the majority of users stated the device was lower body dominant. Additionally in all conditions whether the hands were in use or not, ≥ large correlations were shown between the gold standard. Therefore, the Biostrain could be an alternative to its gold standard competitor, IKD which is very expensive and not easily transportable.

4.9 CONCLUSION

In conclusion, the Biostrain displayed acceptable reliability on most occasions and acceptable variability on all occasions, where the higher the timepoint the higher the reliability. Hypothesis [1] was accepted on all occasions as the Biostrain displayed correlations with the Kin Com in all conditions (large to very large correlations) where the strongest associations were found between right hip flexion Biostrain (with hands) versus right hip flexion Kin Com (r = 0.851**, p <0.001). Hypothesis [2] was partially accepted as the Biostrain displayed acceptable relative and absolute reliability on most occasions (ICC = 0.625 to 0.976) Variability CV% was accepted on all occasions. Hypothesis [3] was not accepted as conditions 'hands in use' conditions displayed higher reliability than 'hands not in use'. Hypothesis [4] was also partially accepted displaying trivial to small effect between testing session one and testing session two (g = 0.088 to 0.550). Based on current results and associations, future investigations could consider exploring associations between Biostrain time at points 200 ms to Peak with kinetic and kinematic parameters of the FP in sprinting. Exploring associations of the Biostrain with sprint performance would allow practitioners to determine whether the Biostrain could aid sprint performance enhancement. Conducting biomechanical sprint analyses of athletes late swing phase via video analysis then applying these specific joint angles to the biostrain could be considered to potentially yield more accurate results. Assessing such metrics longitudinally may be insightful to help gain deeper understanding into the change of metrics over time. Testing subjects across weekly periods or completing multiple efforts in one session could help to identify time periods to stabilise performance. The use of a learning curve may be insightful for this investigation.

~~where only condition B left 150 ms, condition B left 200 ms and condition C left 150 ms failed to accept the hypothesis.~~

~~Timepoints 250 ms to peaks were reliable in all conditions for both front and back legs. For the timepoint 200 ms, scores were acceptable in all conditions only except from left 200 ms condition b suggesting 200 ms may also be a reliable timepoint for measurement.~~

~~The Biostrain displayed large to very large correlations with the Kin Com in all conditions, where the strongest associations were found between right hip flexion Biostrain (with hands) versus right hip flexion Kin Com (r = 0.851**, p <.001)~~

~~Hypothesis [1] was accepted on all occasions as the Biostrain showed large to very large correlations with the Kin Com in all conditions, where the strongest associations were found between right hip flexion Biostrain (with hands) versus right hip flexion Kin Com (r = 0.851**, p <0.001). Hypothesis [2] was partially accepted as the Biostrain displayed acceptable relative and absolute reliability on most occasions (ICC = 0.625 to 0.976) where only condition B left 150 ms, condition B left 200 ms and condition C left 150 ms failed to accept the hypothesis. Variability CV% was accepted on all occasions thus accepting this part of the hypothesis (CV = 1.59 to 10.91%). Hypothesis [3] was not accepted as conditions where 'hands in use' conditions displayed higher reliability than 'hands not in use' conditions. Hypothesis [4] was also partially accepted displaying trivial to small effect between testing session one and testing session two (g = 0.088 to 0.550).~~

5.0 CORRELATIONAL STUDY: The association between Biostrain force parameters and sprint performance

COVER PAGE

The association between Biostrain force parameters and sprint performance

5.1 ABSTRACT

Background: Within sprinting, the FP occurs when the feet have left the ground, and the body is in flight. Commonly assessments are carried out using isometric devices to monitor force-time parameters related to sprinting. Many isometric assessment devices are designed around weightlifting positions and not dynamic positions such as the FP. The Biostrain is a new device that exhibits positions similar to the FP of sprinting and assesses isometric force-time characteristics. ***Aims:*** The aim of the study was to assess the relationship between the Biostrain and sprint performance. ***Methods:*** Eighteen healthy active subjects participated (n = 18; age = 23.3 ± 5.1 years; height: 173.9 ± 5.8 cm; mass: 69.4 ± 12.8 kg). ***Biostrain methods:*** Subjects completed three trials with left leg forwards and right leg back and three trials with right leg forward and left leg back without the use of hands to stabilise positions and repeated with hand stability. ***Sprint Methods***: Subjects completed 3 x 20 m maximum effort sprints, splits also taken at 10 m. ***Results:*** Reliability and variability of 10 m and 20 m sprints were deemed acceptable in all occasions (ICC = 0.991 and 0.989 respectively; %CV = 15.59 and 8.77 % respectively). Biostrain reliability was varied (ICC = 0.367 to 0.957) and variability was unacceptable on all occasions (%CV = 21.12 to 31.99). The back leg Biostrain (hip flexions) showed large to very large associations with 20 m sprint performance for all time points in three conditions (A to C) (r = -0.505 to -0.763) and moderate to very large correlations with 10 m sprint performance (r = -0.401 to -0.702) . Peak forces of the front leg (hip extensions) exhibited large correlations with 20 m sprint performance on three occasions (A to C) (r = -0.554 to 0.505). Forces of the front leg showed large correlation with 200 ms and 250 ms with 10 m sprint performance in condition C (r = -0.592** and -0.589

respectively). ***Conclusions:*** The Biostrain ~~could be a tool for~~ emerges as a strong tool for evaluating force-time characteristics related to sprinting in FP positions. Future research could consider assessing the relationship of the Biostrain and kinetic and kinematic parameters of the FP to gain deeper insight into the Biostrains capabilities.

Key words: Hip extension; Hip Flexion, Knee flexion, Isometric, flight phase

5.2 INTRODUCTION

Sprinting is a complex multipart aspect within sports performance that can be the determining factor in many game-time outcomes (28). Understanding the biomechanics of sprinting at deeper more intricate levels can help practitioners to adapt training programmes and make informed decisions, tailoring to their athletes' individual needs. Given that sprinting frequently involves high speeds, substantial force and rapid change in direction, it acts as a major contributor to injury (173) . This highlights the crucial need to not only enhance sprinting capabilities but also to mitigate injury risk.

The sprinting stride is typically broken down into two main phases including: the stance phase and the FP (133). The stance phase involves all ground contact aspects. It therefore encompasses the initial ground contact, support and force application into the ground (133). The FP occurs when the feet have left the ground and therefore the body is in flight (133). During flight, the limbs undergo a switching action in preparation for ground contact (40). During the stance phase, it has been found that the time the foot is on the ground for lowers as sprinting speed progresses (103), where the ability to produce maximal force in the shortest possible timeframe results in ultimate performance (112). However, whilst the stance phase is important the importance of the FP is debatably of more importance due it being the preparation phase prior to ground contact.

During the FP, a skilled sprinter can adapt their positioning ensuring they are in an optimal position at ground contact ready for force application into the ground, where front leg hip flexion angles during the FP have been found to range between 62.0 to 83.8º (relative to vertical) and front leg knee angles between 22.1 to 47.3 º (measured from the joint behind the knee) (125). In elite sprinters, the back leg hip angles have been found to be 3.9 to -16.8 º (142) when the leg is airbourne. Clark et al. (31) found that greater top speeds are characterised by ones ability to immediately retract the limb prior to ground contact (retraction velocity) to produce a stiff stance limb upon impact enabling high initial ground reaction forces and short ground contact times and permitting the hip to continuously extend throughout ground contact. It is clear that the FP encompasses a number of factors which affect subsequent portions of the sprint, thus further emphasising the complexity and importance of the FP.

Due to step length × step frequency = step velocity (54), thus step length is directly proportional to flight time (101), longer flight times have been found to result in enhanced sprint velocity (28). Mattes et al. (112) found a number of metrics that occur during the FP to be highly correlated to sprinting speed. Mattes et al. (112) found that during the (late) FP hip extension angular velocity showed large significant correlations with sprinting speed ($r = 0.63$, $p < 0.01$). Mattes et al. (112) also found large correlations with the vertical foot velocity of the foot on approach to ground contact ($r = 0.77$, $p < 0.01$). Due to the importance of force-time metrics in sprinting already ~~it could be suggested that~~ maximising force-time metrics in positions similar to the FP of sprinting ~~may~~ will ~~allow enhanced these metrics and~~ result in even greater sprint performance outcomes.

In elite sports clubs, commonly strength training is carried out in order to enhance sprint performance and reduce the risk of injury (70). It is typical for strength to be monitored using biomechanical testing such as isometric testing. Popular isometric strength testing used in research and professional organisations includes the IMTP (32), the isometric squat (18), isometric hand-held dynamometry (152), and isometric IKD (41). Isometric testing has been found to be superior compared to traditional concentric testing (such as one repetition maximum strength testing) due to the ‘no change in muscle length’. During isometric testing, there is zero change in muscle length compared to eccentric training, meaning ~~practitioners~~ multiple efforts can be carried out with a lowered risk of severe delayed onset muscle soreness (73). Additionally, the stationary conditions of isometric testing allow athletes to acquire proficiency quickly and easiliy, making it possible for people with limited prior experience and even children to carry out isometric testing (32,126). Isometric testing has also been found to show significant correlations with sprint performance within research. Thomas et al. (158) found large to very large (r = 0.57 to 0.78) correlation with 5 and 20 m sprint performance and isometric force at different time points during an IMTP. Though it could be argued that the IMTP positions replicates phases of the gait cycle when the hips and knees are extended, the bilateral position of the IMTP does not specifically replicate the unilateral positions of the dynamic task sprinting. To date, no papers have correlated isometric strength testing metrics with sprint performance using angles similar to that of the FP, a clear gap in the research. However, a number of researchers have assessed the reliability and validity of angles similar to the FP via isometric tasks using HHD and IKD (34,41,51,90,93,99,152,167,174), therefore suggesting a relationship may be evident between isometric tasks at angles similar to the FP of sprinting with sprint performance. Though further research is needed.

It is clear that there is a gap in research for the assessment of FP joint angles versus sprint performance. Though this is true, many of the isometric tests in research are limited and do not allow such position to be accurately replicated. The Biostrain is a new device that exhibits positions similar to the FP of sprinting (Figure 4.0). The Biostrain assesses isometric strength and is capable of assessing force at different timepoints similar to the other reliable and successful isometric tests like the IMTP. Therefore, the Biostrain may have the potential to show more correlation to dynamic tasks such as sprinting due to exhibiting more similar positions as opposed to IMTP weightlifting positions used in research. The Biostrain may assist with leg angular velocity due to associations being exhibited between leg angular velocity during the FP with running speed and ground reaction force at touchdown (31). Prior to such examinations being carried out it would be appropriate to first examine the relationship between the Biostrain and sprinting as a while. Thus, the primary aim of the current study was to assess the relationship between the Biostrain and sprint performance.

- Hypothesis [1] is that the Biostrain shows association to 20 m sprint performance (≥ large correlation).
- Hypothesis [2] is that the back leg shows higher correlations with sprint performance compared to the front leg.
- Hypothesis [3] is that 20 m sprint performance would be more highly correlated to the Biostrain force timepoints than 10 m sprint performance.

5.3 METHODS

5.3.1 Experimental approach to the problem

The data collection used a quantitative experimental approach, incorporating between subjects, cross sectional design. Subjects completed three trials in each condition (Table 4.0). Subjects performed three 20 m sprints, to determine sprint performance. Metrics taken from the Biostrain test included force at 150 ms, 200 ms, 250 ms and peak force for both left and right legs in each condition.These metrics were chosen because these time points are the 'all important within sport critical' time points and show high within and between session reliability during isometric testing (32,37). Additionally, these timepoints have been reported to be excellent time point impulse predictors of athletic performance for force application at timepoionts < 300 ms (32). Also, based on the previous study, ICCs and CVs were deemed acceptable on most and timepoints produced small standard deviations. Metrics taken from the sprint including 10 m sprint time (s) and 20 m sprint time (s). ~~Reasoning for choosing timepoints and assessed joint angles on the Biostrain can be seen in section 4.1.~~ The 20 m sprint test was chosen to allow associations between the Biostrain and sprint performance to be explored. The 20 m was chosen as the test is a popular reliable test used in research versus isometric testing (158). Additionally, team sport athletes have an adapted running style in order to allow them to reach maximum speed by 20 m (7,8,28) therefore exploring this association may be useful for future target end-users. Assessing the Biostrain at maximum speed (distances 20 – 60 m) may be interesting for the current study, however due to lab constraints, the indoor track facility was limited to 20 m.

5.4 PARTICIPANTS

See section 4.4

5.5 PROCEDURES

5.5.1 Biostrain assessments

Testing procedures and data analysis/extraction for the Biostrain can be seen in section 4.5.1. However, due to this testing session not occurring prior to any other physical activity a warm-up was carried out. Subjects completed a standard protocol warm up consisting of a series of 90/90 hip mobility rolls, bodyweight leg extensions, body weight glute bridges and world's greatest stretch. Subjects then carried out the same priming trials outlined in section 7.3.1 to ensure readiness for testing.

5.5.2 20 m sprint assessments

As subjects completed the 20 m sprints post Biostrain test, subjects were already sufficiently warmed up and thus were only required to carry out build up sprint efforts. Subjects undertook four build up sprint efforts (<50% effort, 50% effort; 75% effort; 95% + effort) from a standing start on an indoor artificial athletic track surface.

Testing took place indoors using similar to methods to Calderbank et al. (28). Using a measuring tape, a 20 m track was marked out in a straight line along the artificial running track. Brower photocell timing gates (BRO001; Brower, Draper, UT, USA) were placed at the 0 m, 10 m and 20 m along the track, timing to the nearest 0.001 s. Timing gates were set up to approximately hip height to ensure the lower torso broke the beam as Yeadon et al. (172) found that setting up timing gates at hip height was the most accurate for reducing the risk of the arms or legs breaking the beam prematurely. Subjects were cued to start 0.5 m behind the first timing gate in a 2-point staggered athletic start in order to prevent the timing beam from breaking prematurely. Each subject then completed 3 maximum effort trials of the 20 m sprint each interspersed with rest periods between 3 to 4 minutes (169). Subjects were told not to decelerate until they pass the final timing gate and were given strong verbal encouragement throughout each trial. Sprint times were taken and averaged in a Microsoft excel spreadsheet (Microsoft Corp., Redmond, WA, USA) for each subject ready for further data and statistical analysis.

5.6 STATISTICAL ANALYSIS

Using SPSS (Version 23; SPSS Inc., Chicago, IL, USA) an ICC was used ($ICC_{3,k}$) was used to inspect relative reliability of all timespoints during biostrain testing 10 m and 20 m sprint times (e.g., rank order of consistency between trials). An ICC of ≥ 0.75 was interpreted as reliable, based on the ICC point estimate (94), 95% CIs were also calculated to determine reliability. %CV was calculated to determine the variability of the trials for each Biostrain conditioning, the 10 m sprints and the 20 m sprints using 'SD / mean × 100' an average was then calculated (with an acceptable CV set to CV $\leq$ 10%). For correlational analysis, using SPPS, a Shapiro-Wilks test was performed to determine the normality of data. Associations were determined using Pearson's correlation coefficient with the associatied 95% CI calculated significance was set to $p \leq 0.05$. p values were multipled by the number of correlation to adjust for familywise error. *r* values were interpreted as < 0.10, 0.10-0.29 0.30-0.49, 0.50-0.69, 0.7-0.89 and ≥ 0.90 as trivial, small, moderate, large, very large and nearly perfect, respectively following Hopkins (26) guidelines. Using JAMOVI, correlations were plotted with standard error.

5.7 RESULTS

Reliabilty and variability results for both 10 m and 20 m sprints in the current study were deemed acceptable in all occasions (ICC = 0.991 and 0.989 respectively; CV% = 13.58 and 15.59% respectively), reliability for timepoints of the Biostrain was varied (ICC = 0.367 to 0.957), though peaks for both legs in all conditions were acceptable. Variability was deemed unacceptable in all occasions for Biostrain timepoints in this testing session (CV% = 21.12 to 31.99) (Table 5.0). The back leg Biostrain showed large to very large associations with 20 m sprint performance for all time points in three conditions A to C (where condition A is right hip flexion no hands, condition B is left hip flexion no hands and condition C is right hip flexion hands) (r = -0.505 to -0.763) (Table 5.1 – 5.4). In condition D, left 150ms and left 200ms (left hip flexion with hands) showed moderate correlations (r = -0.448, p = 0.062, r = -0.466, p = 0.051). The peak forces of the front leg (hip extensions) exhibited large correlations with sprint performance on three occasions (A to C) (where condition A is right hip flexion no hands, condition B is left hip flexion no hands and condition C is right hip flexion hands) (r = -0.554 to 0.505). During condition D (left hip extension with hands) only moderate correlations were exhibited (r = 0.467, p = 0.050). Large to very large correlations were found between the the back leg and 10 m sprint performance in three conditions; A, C and D (right hip flexion no hands, right hip flexion hands, left hip extension hands; respectively) (r = 0.534 to -0.702). Moderate correlations were found in conditions B (left hip flexion no hands) between 10 m sprint performance and the back leg (r = -0.401, p = 0.099). Large correlations were found between 10 m sprint performance and the front leg in one condition, conditions C (right hip flexion hands) at two timpoints Left 200 ms and Left 250 ms (r = -0.592 to -0.588). Figure 5.0 displays correlations of the peak forces of each leg during each condition versus 20 m sprint time with standard error.

Table 5.0 Descriptive statistics and reliability measures of 20 m sprint times.

Sprint Times		
	10 m (s)	20 m (s)
Mean ± SD	1.82 ± 0.28	3.32 ± 0.29 s
%CV	15.59	8.77
ICC (LB-UB 95%CI)	0.991 (0.981 - 0.996)	0.989 (0.975 - 0.995)
m = metres; s = seconds; SD = standard deviation; CV = coefficient of variation; ICC = intraclass correlation coefficient; LB = lower bound; UB = upper bound; CI = confidence interval		

Key: LB: 95% Confidence interval lower bound; UB: 95% Confidence interval upper bound; ICC: Intraclass correlation coefficient; CV: Coefficient of variation

Table. 5.1 – 5.4 Descriptives and correlation coefficients of sprint performance with Biostrain.

Table 5.1 Condition A: Left leg forwards and right leg back. No hands in use.

	Biostrain Limb Force (N)							
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	291.16 ± 68.62	317.34 ± 81.67	328.83 ± 82.83	450.64 ± 109.67	290.05 ± 83.79	306.29 ± 97.99	307.11 ± 94.89	412.00 ± 124.81
ICC (UB-LB)	0.630 (0.372-0.824)	0.713 (0.488 – 0.869)	0.675 (0.433 – 0.849)	0.884 (0.768-0.951)	0.863 (0.729-0.941)	0.894 (0.786-0.955)	0.902 (0.800-0.959)	0.897 (0.791-0.957)
CV%	23.57	25.74	25.19	24.34	28.89	31.99	30.90	30.29
r value versus 10 m sprint	-0.114 (0.652)	-0.145 (0.566)	-0.184 (0.464)	-0.357 (0.146)	-0.549* (0.018)	-0.532* (0.023)	-0.499* (0.035)	-0.534* (0.022)
r value versus 20 m sprint	-0.245 (1.288)	-0.320 (1.568)	-0.338 (1.360)	-0.548 (0.144)	-0.575 (0.104)	-0.549 (0.144)	-0.583 (0.880)	-0.656* (0.024)

Key: *P* value is stated in brackets after *r* value, ICC: Intraclass correlation coefficient: UB-LB: 95% upperbound and lower bound Biostrain, CV%: coefficient of variation; * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)

Table 5.2 Condition B: Right leg forwards and left leg back. No hands in use.

Biostrain Limb Force (N)								
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	283.71 ± 77.22	302.78 ± 85.04	313.16 ± 81.74	436.45 ± 127.13	278.91 ± 71.10	300.00 ± 71.08	309.72 ± 70.08	433.18 ± 106.5
ICC (UB-LB)	0.602 (0.337-0.809)	0.687 (0.451-0.856)	0.619 (0.358-0.819)	0.880 (0.759-0.949)	0.680 (0.440-0.852)	0.657(0.409-0.840)	0.554 (0.277-0.781)	0.880 (0.759-0.949)
CV%	27.22	28.09	26.10	29.13	25.49	23.69	22.63	24.59
r value versus 10 m sprint	-0.464 (0.052)	-0.412 (0.089)	-0.443 (0.066)	-0.401 (0.099)	-0.191 (0.447)	-0.193 (0.443)	-0.208 (0.408)	-0.310 (0.210)
r value versus 20 m sprint	-0.541 (1.600)	-0.507 (0.256)	-0.538 (0.168)	-0.655* (0.024)	-0.405 (0.760)	-0.380 (0.952)	-0.406 (0.752)	-0.554 (0.136)

Key: *P* value is stated in brackets after *r* value, ICC: Intraclass correlation coefficient: UB-LB: 95% upperbound and lower bound Biostrain, CV%: coefficient of variation; * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)

Table 5.3 Condition C: Left leg forwards and right leg back. Hands in use.

Biostrain Limb Force (N)								
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	302.38 ± 63.85	337.57 ± 76.27	358.01 ± 90.42	566.13 ± 128.20	341.68 ± 98.35	388.71 ± 102.69	419.85 ± 110.25	608.18 ± 166.88
ICC (UB-LB)	0.367 (0.076-0.658)	0.462 (0.173-0.723)	0.551 (0.274-0.779)	0.896 (0.790-0.956)	0.815 (0.647-0.920)	0.787 (0.601-0.906)	0.814 (0.645-0.919)	0.936 (0.865-0.973)
CV%	21.12	22.59	25.26	22.64	28.79	26.42	26.26	27.44
r value versus 10 m sprint	-0.480* (0.044)	-0.592** (0.010)	-0.588* (0.010)	-0.418 (0.084)	-0.589* (0.010)	-0.603** (0.008)	-0.678** (0.002)	-0.702** (0.001)
r value versus 20 m sprint	-0.314 (1.640)	-0.372 (1.024)	-0.389 (0.888)	-0.539 (0.168)	-0.505 (0.264)	-0.548 (0.152)	-0.763** (0.008)	-0.763** (0.008)

Key: *P* value is stated in brackets after *r* value, ICC: Intraclass correlation coefficient: UB-LB: 95% upperbound and lower bound Biostrain, CV%: coefficient of variation; * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)

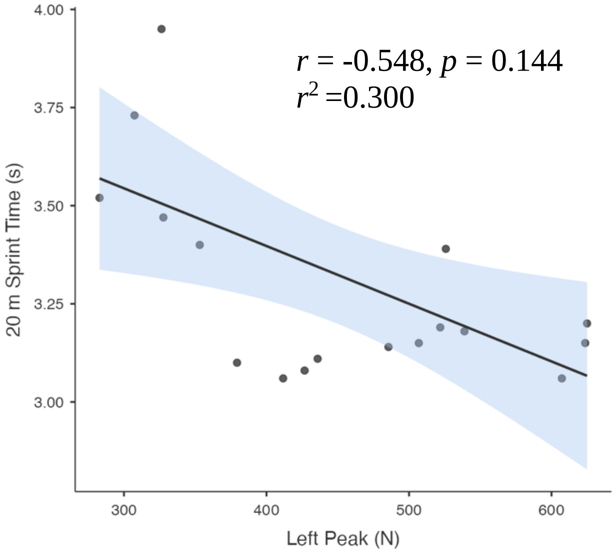
Table 5.4 Condition D: Right leg forwards and left leg back. Hands in use.

Biostrain Limb Force (N)								
	Left 150 ms	Left 200 ms	Left 250 ms	Left Peak	Right 150 ms	Right 200 ms	Right 250 ms	Right Peak
Mean ± SD	349.94 ± 105.42	389.04 ± 112.16	426.52 ± 120.37	624.35 ± 168.87	295.68 ± 73.61	323.86 ± 79.22	347.31 ± 82.23	565.31 ± 148.06
ICC (UB-LB)	0.825 (0.663-0.924)	0.744 (0.533-0.885)	0.721 (0.499-0.873)	0.957 (0.909-0.982)	0.516 (0.233-0.758)	0.455 (0.165-0.719)	0.385 (0.094-0.671)	0.880 (0.759-0.949)
CV%	30.12	28.83	28.22	27.05	24.89	24.46	23.68	26.19
r value versus 10 m sprint	-0.633** (0.005)	-0.652** (0.003)	-0.692** (0.001)	-0.660** (0.003)	-0.299 (0.228)	-0.389 (0.111)	-0.463 (0.053)	-0.380 (0.120)
r value versus 20 m sprint	-0.448 (0.496)	-0.466 (0.408)	-0.544 (0.160)	-0.668** (0.016)	-0.276 (2.144)	-0.342 (1.320)	-0.411 (0.720)	0.467 (0.400)

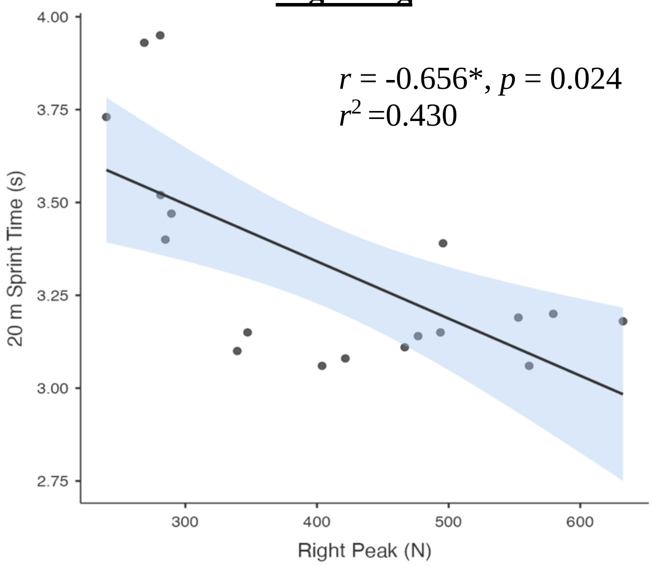
Key: *P* value is stated in brackets after *r* value, ICC: Intraclass correlation coefficient: UB-LB: 95% upperbound and lower bound Biostrain, CV%: coefficient of variation; * Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed)

Condition A: Left leg forwards and right leg back. No hands.

Left Leg

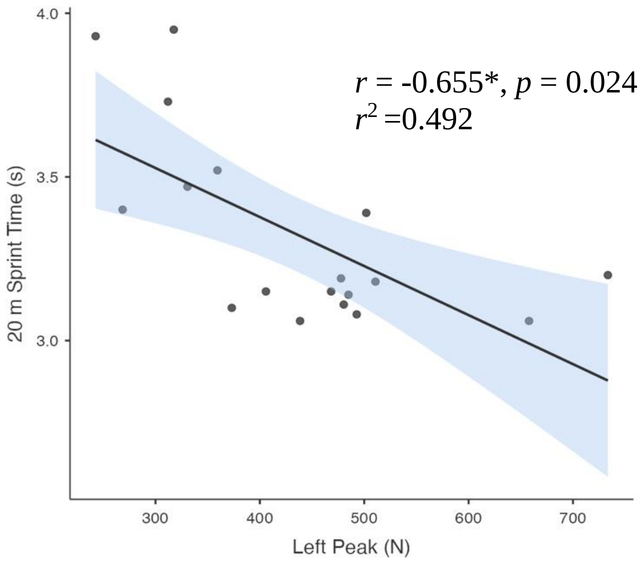


Right Leg



Condition B: Right leg forwards and left leg back. No hands.

Left Leg



Right Leg

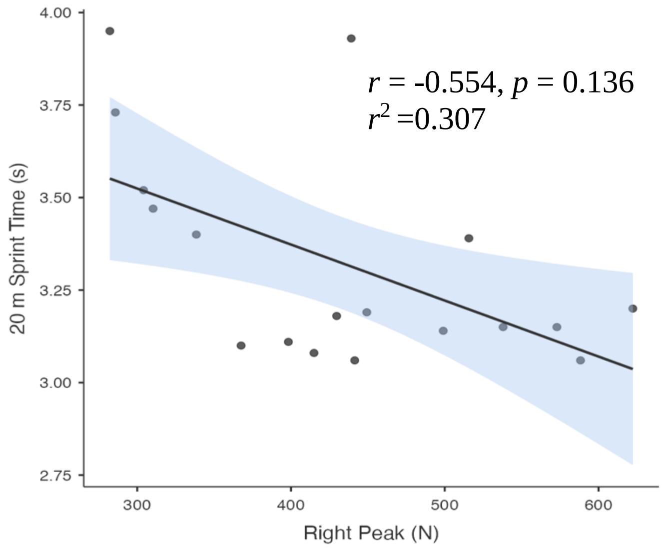
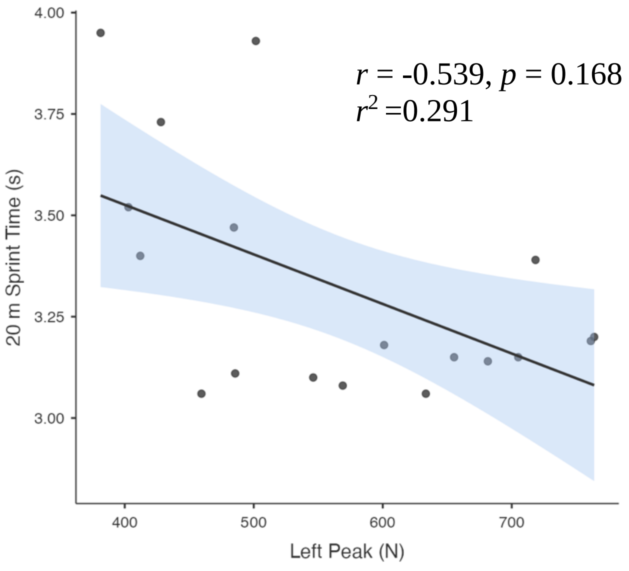


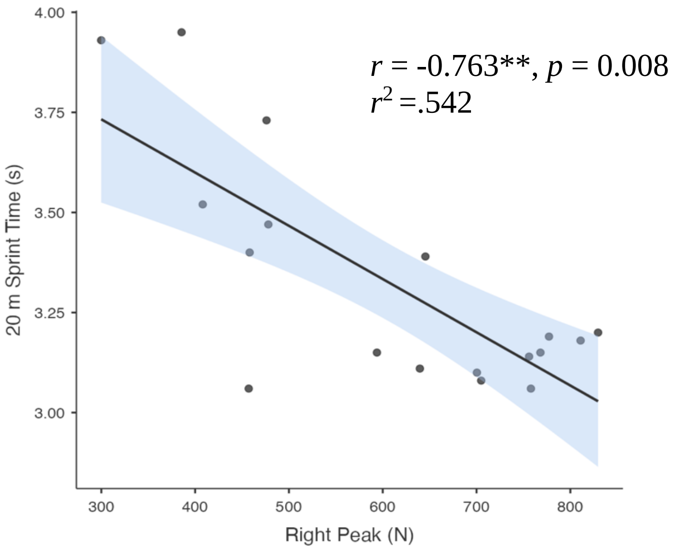
Figure 5.0 Correlations of the peak forces of each leg during each condition on the Biostrain device versus 20 m sprint time with standard error

Condition C: Left leg forwards and right leg back. Hands in use.

Left Leg

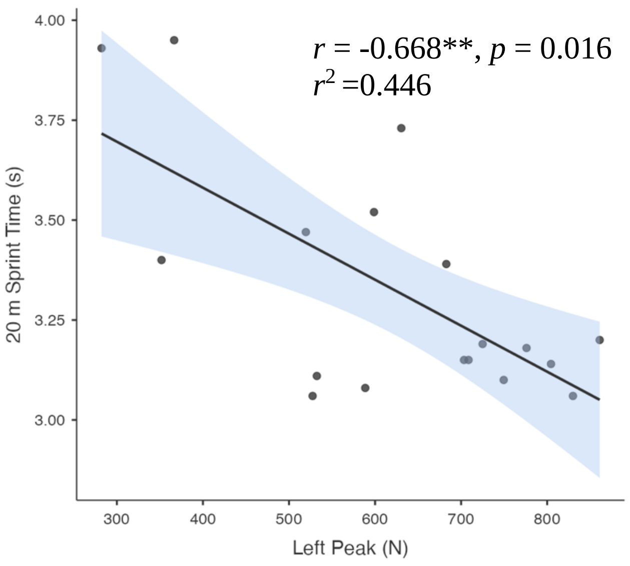


Right Leg

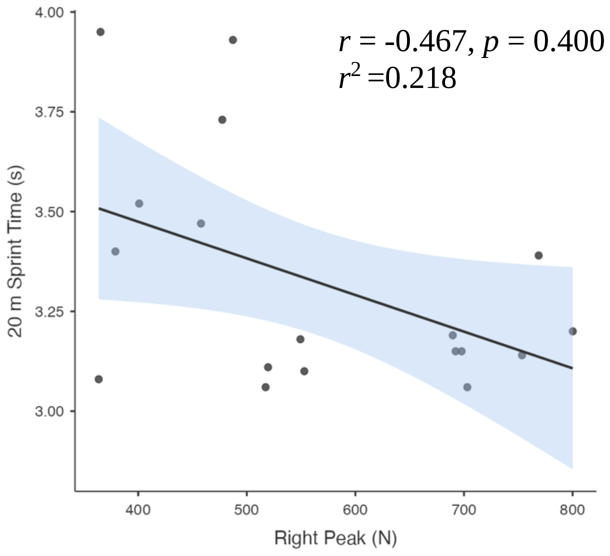


Condition D: Right leg forwards and left leg back. Hands in use.

Left Leg



Right Leg



5.8 DISCUSSION

The primary aim of the current study was to assess the relationship between the Biostrain and sprint performance. Correlation coefficients results showed that the Biostrain has small to very large associations to sprint performance and thus could be a potential tool for strength profiling in relation to sprint performance.

In the current study, although results were mixed it was clear that 20 m sprint performance showed correlations to the Biostrain (partially accepting the first part of the hypothesis). The back leg showed higher correlations than the front leg in all occasions, displaying large to very large associations for 20 m sprint performance versus the Biostrain (accepting the second part of the hypothesis). The peaks for the back leg versus 20 m sprint performance showed ≥ large correlations in all occasions. Such results show similarities to the current gold standard for single limb isometrics/isokinetic assessments. The large – very large associations found in the current study show resemblances to Alexander (1) who reported a strong inverse relationship (r = -0.72, $p < 0.01$) between peak isokinetic concentric torque generated by the knee extensor muscles and 100 m sprint performance in elite track and field athletes. This provides some optimism for the Biostrain. Even more so as it replicates positions even more similar to sprinting than the IKD can cater for. Earlier suggestions that the Biostrain may be related to thigh angular velocity could be evident (31). On the Biostrain, due to the limb being in a replicated position to the sprinting position at which thigh angular retraction typically occurs it is likely that force expression on the Biostrain would assist with generating greater ground reaction force at touchdown. Therefore, exploring the association between rear leg Biostrain with thigh angular velocity during sprinting may be informative for practitioners and should be considered in future work. If associations were found, exploring such associations longitudinally may be interesting. In regards to the 20 m sprint performance and the Biostrain back leg, whilst associations were large to very large the highest correlation of the current study (condition C, right leg hip flexion, figure 5.0) only 54% of the correlation can be explained by the Biostrain and thus the flight phase position. Gleadhill and Nagahara (60) found large to very large correlations with ground reaction force variables and running speed. Variables in their study included just some of the following: support time, propulsive mean force, braking mean force and step. Such research suggests that in the current study the remaining 46% of the association not explained by the Biostrain/flight phase are likely explained by ground reaction force metrics. Therefore, training to improve both ground and flight phase based metrics should be considered by practitioners. Another point to note is that Brady et al. (23) found significant correlations between sprint performance and ground based isometric tests/metrics. Brady et al. (23) found that during the IMTP and isometric squat, peak force, relative peak force, rate of force development and impulse showed ≥ large correlations to sprint performance. Therefore, it could be said that remaining associations not explained by the Biostrain could also be attributed to such factors.

During condition D for the 20 m sprint, the back leg (left hip flexion with hands) was only correlated at timepoints left 250 ms and left peak. Condition D involved the use of the hands whereas condition Ds ‘non-hand’ alternative (condition B) produced ≥ large correlations. A potential reason for mixed findings with ‘hands in use’ conditions may be due to perceived intention. 17% of subjects stated they felt they emphasised producing force with the back leg when their hands were in use compared to when the hands were not in use (appendix A). Subjects stated that when the hands weren’t in use, they felt they could apply equal amount of force with both legs. This bias and unequal intention during conditions could suggest a reason for opposing findings in condition D. But whilst this is the case condition C (right hip flexion with hands) produces some optimism for ‘hands in use’ conditions. Further research could consider exploring longitudinal changes using the Biostrain with both ‘hands’ and ‘no hands’ conditions to determine the best possible methodology.

The correlations in the current study followed a pattern whereby the strength of the correlation increased as the time points increased. This shows similarities to other isometric assessments used in research, where Mason et al. (111) explored the relationship of the IMTP versus maximum sprinting speed (taken during 65 m sprint) and found that as the IMTP timepoint increased, the strength of the correlation increased. Mason et al. (111) found ≥ large correlations between relative IMTP forces at only 150 ms, 200 ms and PF timepoints, where lower timepoints lower than 150 ms appeared to non-significant correlations (likely due to lowered reliability at lower timepoints). In the current study, timepoints assessed were 150 ms to PF, however, the Biostrain software is capable of assessing lower time points. Similar to Mason et al. (111) it is likely that timepoints lower than 150 ms will also show insignificant correlations. Lower reliability at lower time points is typically due to identification of the onset being more difficult with measures with shorter time frames. Also, subjects’ ability to intend to apply maximal force in such short time frames is often difficult. Therefore, whilst assessing lower timeframes is possible, it is highly likely results will be insignificant and unreliable at timepoints lower than 150 ms. Therefore, future research should consider assessing similar timepoints to the current study.

It is clear the Biostrain back leg correlated with 10 m sprint performance though slightly weaker than the 20 m sprint performance showing moderate to very large correlations. Similar patterns have been found in previous isometric assessment research. Thomas et al. (158) explored the correlation between IMTP metrics and sprint performance. Thomas et al. (158) found that as the sprint interval increased, correlations with IMTP were further strengthened in a range of metrics including peak force, maximum rate of force development, impulse at 100 Ns and impulse at 300 Ns. The IMTP is one of the most successful, reliable, and valid tests in the industry, and the fact the Biostrain shows similar results and conclusions to the IMTP shows real potential for the device, suggesting the Biostrain could also be a valid and reliable piece of equipment in the industry.

It is likely that the strength correlations will increase as the sprint distance increases closer to maximum velocity. Future research could consider correlating maximum sprint performance to the Biostrain using distances of 20 to 60 m to explore whether correlations strengthen. Though whilst the Biostrain may be better suited to the maximum velocity phase of sprinting, rapid leg switching is important for early, mid and late acceleration phases and thus, the Biostrain offers an assessment of simultaneous hip flexion and extension similar to acceleration requirements hence the findings of this study.

In the current study, regarding the front leg, the front leg force production characteristics only correlated at later timepoints for 20 m sprint performance in three conditions (A to C) (250 ms and PF). Although this shows some optimism that the Biostrain could evaluate force outputs relating to front flight leg mechanics. However, positively, for the 10 m sprint performance, in condition C the front leg exhibited large correlations at Left 200 ms and Left 250 ms giving potential that both front and back legs may correlate with further familiarity and longitudinal testing. Intriguingly, Clark et al. (31) found that during the FP, a rapid thigh angular retraction velocity (rapid retraction of the limb causing a stiff impact upon touchdown, thus referring to the forward leg) results in faster running speeds. During this phase of sprinting, the elastic energy storage in the stretch shortening cycle function serves to improve the horizontal propulsion by aiding the forward flight and benefitting leg retraction upon touchdown (141,149,150). Further research could consider exploring thigh angular retraction velocity and even potentially touchdown with the Biostrain to gain deeper insight into the ability of the Biostrain. Additionally, again referring to the front leg, Morin et al. (129) found that subjects who produced the greatest amount of horizontal force were both able to highly activate their hamstring muscles just before ground contact and present high eccentric peak torque capability, therefore with this in mind it is possible the Biostrain could aid with evaluating this mechanism.

5.9 CONCLUSION

In conclusion, the Biostrain displayed large to very large correlations with sprint performance. Hypothesis [1] was partially accepted as the back leg (e.g., rear thigh pushing into load cell) Biostrain showed small to very large associations with 20 m sprint performance across all time points across both legs in three conditions A to C (condition A right hip flexion no hands, condition B left hip flexion no hands, condition C right hip flexion hands). Where the back leg showed large to very large associations with 20 m sprint performance in the same three conditions (A to C). Hypothesis [2] was accepted, as the back leg did exhibit higher correlations than the front leg. Hypothesis [3] was accepted as 20 m sprint performance was more highly correlated to the Biostrain, than the 10 m sprint performance. Therefore, in summary, the correlations from the current study suggest that the Biostrain may show associations to the kinetics and kinematics of the FP in sprinting. Future research could consider assessing the relationship of the Biostrain back leg versus thigh angular velocity and the Biostrain front leg with thigh angular retraction velocity. If associations were found, the Biostrain could serve as an important testing feedback tool which could then inform training programmes for practitioners and athletes. Assessing all future research suggestions longitudinally may also be useful to help determine firmer conclusions. Overall, it is evident there is a clear pattern in correlations whereby as the sprint distance increases, the strength of the correlation increases (for both front and back legs). Therefore, future research could also consider assessing the Biostrain at higher distances above 60 m (through maximal speed) to determine if correlations are further strengthened. It should be noted that, to date, this is the only study to have explored the Biostrains usability, reliability, validity, and associations to performance. Further research is also needed to create a greater collection of data and determine best methods of practice.

~~In condition D, (left hip flexion with hands), left 150 ms and left 200 ms (this was the back leg in this condition) only showed moderate correlations (r = -0.448, p = 0.062, r = -0.466, p = 0.051) and in the front leg, only peaks were correlated.~~

~~with thigh angular velocity, thigh angular retraction velocity and touchdown.~~

~~The back leg of the Biostrain showed large to very large associations with 20 m sprint performance for all time points in conditions A to C, though in condition D, the back leg at left 150 ms and left 200 ms only showed moderate correlations. The front leg of the Biostrain exhibited ≥ large correlations with 20 m sprint performance but solely at peaks on three occasions, where, during condition D only moderate correlations were exhibited.~~

~~training aid to helping improve this important aspect of performance~~.

6.0 OVERARCHING CONCLUSION TO THE THESIS

COVER PAGE

6.1 CONCLUSION

The purpose of this thesis was to assess the reliability and validity of the new Biostrain device in comparison to the established gold standard IKD whilst also examining its relationship to sprint performance. The thesis additionally conducted a systematic review of literature on IKD and HHD to explore reliability, validity, and possible applications in the Biostrain studies. The findings of the study revealed promising outcomes that highlight the Biostrain's capacity to effectively gauge isometric force-time attributes during FP positions. Therefore, it seems the Biostrain, ~~holds the potential to emerge~~ is a strong contender in the sports science industry in contributing to the prevention of sprint-related injuries. In examining the literature it became clear that research has explored a wide variety of joint angles leading to noticeable differences in the length tension relationship. Consequently many researchers adopted a standard joint angle for the entire sample group this one-size-fits-all strategy fails to account for consistent length-tension relationships across participants complicating comparisons across studies. Additionally the setup positions used by researchers varied with some conducting tests in seated positions with back support and others in prone or supine positions facilitating controlled hip joint angles in contrast test conducted in seating positions without back support could not maintain consistent hip joint angles again affecting the length-tension relationship

Results from the systematic review also displayed a clear lack of uniformity for the location of the dynamomter on the limb. Some researchers use 'person held' whilst others used strapping to fix the HHD in position. Fixed conditions yielded more reliable results than non fixed conditions this inconsistency was also evident in the practitioners ability to provide a stable testing environment which varied significantly making it challenging to compare results across studies accurately.

In the current review, an additional key finding was the variation in the units of measurement used by studies with some reporting relative units another absolute units hindering direct comparison. Many of these aforementioned issues will be mitigated with use of the Biostrain. This device permits the evaluation of specific, fixed joint angles, with stable subject set up positions.The device has the ability to be manouvered into individualised positions meaning specific length tension relationships could be found. The device also removes the need for assessor strength indicating that the Biostrain device appears to show many strengths in comparison to IKD and HHD.

Regarding the assessment of reliability and validity for the Biostrain the results were consistently positive showing acceptable reliability in most instances and consistent acceptability in terms of variability. In all test conditions the Biostrain demonstrated strong correlations with the Kin Com underscoring its comparative effectiveness overall the biostrain was found to be reliable and valid exhibiting acceptable CV percentages in almost all conditions. Specifically the right leg produced more consistent results than the left across all test scenarios given the predominance of right leg dominance among participants this discrepancy might have been attributed to limb dominance therefore future studies should consider including a balance of mixed participants with right and left leg dominance to determine the influence of limb dominance. Additionally it was noted that as time points progressed the biostrains reliability improved and the SEM% decreased especially at later time points. The reason for lowered reliability and SEM% at lower time points was suggested to be due to the variability in rest intervals. Athletes were allowed up to 3 minutes of recovery between trials potentially introducing varying levels of acute fatigue future studies could obtain even more consistent results by standardising rest intervals more rigorously.

In the current study the Biostrain showed strong correlations with the Kin Com, explaining 72% of the variance, indicating its potential as a competitive tool. However it's important to acknowledge that 28% of the variance was not explained by the Kin Com. This discrepancy might have been due to the predetermined joint angles for assessments which may not have been optimal for all athletes. Promisingly, the Kin Com does allow for a more individual tailored approach to be used. Mechanical analysis to identify and use athlete specific joint angles could be implemented although this may not always be feasible.

An addiotnal point to note is that, it was clear when reviewing differences between the first and second testing session results, p values and hedges *g* suggest a possible learning effect, meaning longitudual studies will likely produced positive results.

In terms of the biostrains relation to sprint performance, strong associations were found with 20 m sprint times, with the strength of the correlation increasing over time similar to other successful isometric assessments in research (111). This suggests the biostrains relevance to aspects such as thigh angular velocity and the potential to enhance ground reaction force upon contact. However, whilst these correlations are promising, they explain only 54% of the variance pointing to other physical factors related to ground reaction metrics that also contribute to performance. Hence, practitioners are encouraged to consider training that improves both ground and flight phase metrics.

It was observed that the 10 m sprint times also exhibited some correlations with the Biostrain though lower than the 20 m sprint performance. Nonetheless, a distinct pattern in correlations emerged, indicating that as the sprint distance increased, the strength of correlation also increased, observed for both the front and rear legs. In summary, findings implied that the Biostrain device holds potential as a monitoring tool of lower body sprint related force-time characteristics, and thus it is encouraging that the biostrain may show associations to leg angular velocity during the FP. Thus the Biostrain could potentially help contribute to the mitigation of risks related to sprint-related injuries.

To summarise, for improved results, the findings of the present study suggest that forthcoming research should explore associations of kinetics and kinematics during the FP of sprinting with the Biostrain device. Kinetic and kinematic parameters such as thigh angular velocity, thigh angular retraction velocity and touchdown could offer intriguing insights. It the current study sprints were limited to 20 m due to the constraints of the facility but given the apparent trend in correlations, whereby as the sprint distance increases, the strength of the correlation increases future research could also explore Biostrain assessments at distances beyond 60 m to determine whether correlations are further strengthened. Additionally, conducting longitudinal assessments in accordance with these suggestions could provide valuable insights into the change of metrics changes over time.

Across the whole thesis with all suggestions in mind, future research should be cautious of units reported and SEM percentage/raw when comparing results. Practitioners should also ensure statistical tests are appropriately chosen for validity tests to allow accurate between study comparisons to be made. Practitioners should also take into account when comparing ICCs (average measures versus single measures) to ensure reliable comparisons are made. Though it should be noted that, to date, this study is the only study to have explored the Biostrains usability, reliability, validity, and associations to performance. Further research is also needed to create more data and determine best methods of practice as previous research (46,63) has found that factors such as training history, level of farmiliarisation, cues and understanding of protocols can affect the reliability and level of error of results. Therefore, a greater bank of data to explore potential best practices could be insightful.

On the whole, when reviewing participant usability it was clear subjects deemed the Biostrain to be a comfortable usable device, with the majority of practicipants rating the device as comfortable. In terms of intention, results were mixed, though whilst this is varied, only a short farmiliarisation took place and subjects only saw and tried the device for the first time on the day of the testing. Further farmiliarsation could cause differing feedback. Whilst this was said, correlations in the current study in both front and back legs in each condition versus the Kin Com still shows large to very large correlation. This shows positivity for the Biostrain again suggesting it could be a valid and reliable option within sports science as opposed to the Kin Com. Therefore, the Biostrain could be an alternative to its expensive not easily transportable gold standard competitor.

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8.0 APPENDICES

Appendix 1: Biostrain software contraction detection algorithm

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Outline:

1. The peak detection logic is applied to the data after recording has finished.
2. The algorithm creates three threshold values (low, medium, high) based on the maximum and minimum recorded forces during the test.
3. The algorithm iterates through each sample (front and back leg force) and calculates the gradient in 10ms intervals using a linear gradient calculation.
4. For each sample, the algorithm checks if 5 conditions are satisfied. The conditions ensure that the gradient is increasing for at least 50ms (stops random spikes triggering contractions).
5. If all conditions are met and the force value at the sample is less than the low threshold, begin assigning samples to a contraction.
6. A contraction will be successfully recorded if the maximum (peak) force exceeds the high threshold and there is no drop in gradient below -1.0 across any 50ms interval.
7. Samples are assigned to a contraction until the force value drops below the medium threshold. Beyond this point, the algorithm begins to look for the next contraction.

Pseudocode:

- Gradient is calculated as:-
  - (Sample B reading - Sample A reading) / (Sample B timestamp - Sample A timestamp)
- So an increase in readings from 60 to 100 over a 10ms period would result in a gradient of (40 / 10) = 4.0

- Calculate maximum/minimum readings for the captured data.
- From this, calculate 3 thresholds: -
  - Low threshold (33%): min + ((max-min) / 3)
  - Medium threshold (50%): min + ((max-min) / 2)
  - High threshold (66%): max - ((max-min) / 3)

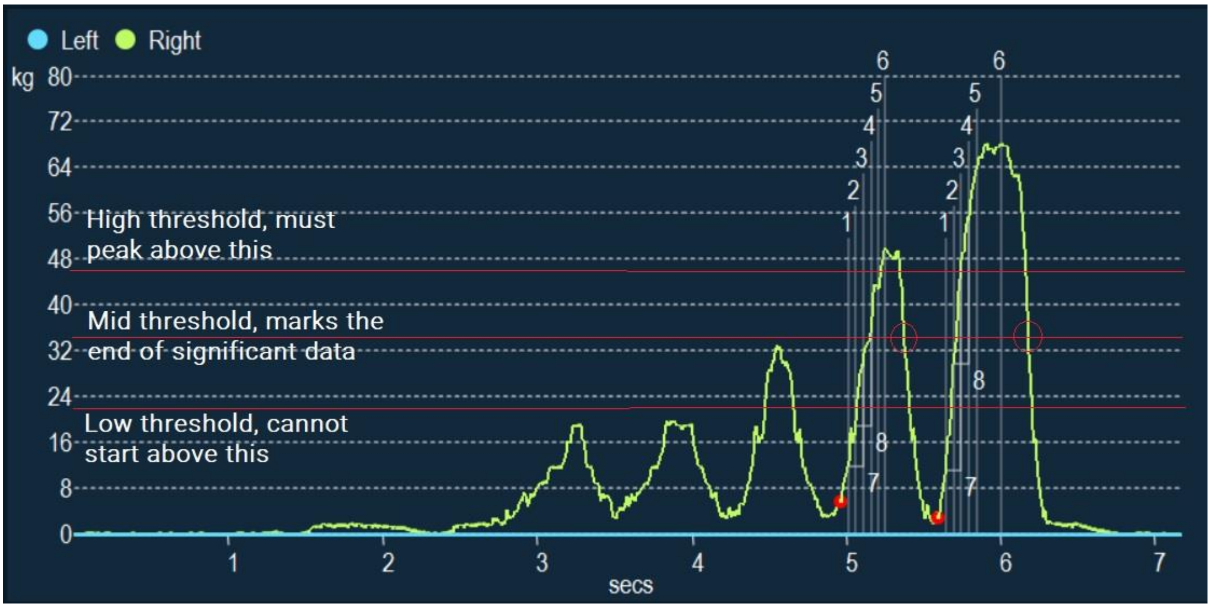
*** A contraction will only be recognised if the starting force is below low threshold ***

- Iterate through every recorded sample, looking for a sustained increase in gradient over a 50ms period
- The following 5 conditions must be satisfied: -
  - Gradient between Sample(now) and Sample(now + 10ms) > 0.3
  - Gradient between Sample(now + 10ms) and Sample(now + 20ms) > 0.4
  - Gradient between Sample(now + 20ms) and Sample(now + 30ms) > 0.5
  - Gradient between Sample(now + 30ms) and Sample(now + 40ms) > 0.6
  - Gradient between Sample(now + 40ms) and Sample(now + 50ms) > 0.7

- Assuming all 5 conditions were satisfied and Sample(now) < low threshold, continue to iterate through remaining samples.
- A contraction has been recorded if the following conditions are satisfied:-
  - Force exceeds high threshold
  - There are no dips in gradient below -1.0 over any 50ms interval from the contraction start to the point at which force exceeds high threshold

- When a contraction has been recorded, continue to iterate through remaining samples.
- When force drops below mid threshold, start looking for next contraction.

- The Peak Force stat is the maximum reading recorded from the contraction start to the contraction end.



Appendix 2: Usability of the Biostrain feedback sheet

A summary of feedback from subjects is below with collation of similar themes tallied. [X] states the number of subjects, with percentages.

Was the position comfortable?

Yes: [14] 78%

No: [4] 12%

Did you feel stretched too far into the splits or too narrow?

Yes: (three stated stretched too far into the splits and one stated too narrow) [4] 12%

No: [14] 78%

Were the pods uncomfortable?

1: No, no uncomfortable at all [10] 56%

2: A little uncomfortable, but it didn't affect my test [6] 33%

3: Moderately uncomfortable. Only affected my test a little [2] 11%

4: Uncomfortable, I feel it affected my test somewhat

5: Very uncomfortable to the point it massively affected my test

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What did you focus on during the test? Did you favour one side more than the other?

Easier to push with the back leg than to pull with the front leg [6] 33%

I focussed on squeezing equally as hard as possible [9] 50%

Felt I could equally push better with no hands. When hands were in use, it became more back leg dominant [3] 17%

Did you feel it was solely lower body?

I felt it was solely lower body [5] 28%

Yes, but I felt I could apply more pressure when my hands were in use as I was more stable [8] 44%

Yes, I felt it mainly in my hip flexors [1] 6%

Felt core engage [4] 22%

Did you feel your posture change during the task?

Felt more stable and more upright when my hands were in use [7] 39%

No, I felt my posture remained upright and the same throughout all tests, with and without hands [7] 39%

I felt I tended to lean forwards during testing [2] 11%

I felt my general posture changed a little [2] 11%