

**UNDERSTANDING THE BIOMECHANICAL RISK
FACTORS OF PATELLOFEMORAL PAIN (PFP)
IN MILITARY INDIVIDUALS**

HASAN H. ALRAYANI

Understanding the Biomechanical Risk Factors of Patellofemoral Pain (PFP) in Military Individuals

HASAN H. ALRAYANI

**School of Health Sciences
University of Salford, Salford, UK**

**Submitted in Partial Fulfilment of the Requirements of the
Degree of Doctor of Philosophy 2018**

Table of Contents

List of Figures	vi
List of Tables	ix
Glossary List	xii
Thesis structure	xiii
CHAPTER 1	1
Introduction.....	1
CHAPTER 2	7
Literature review	7
2.1. Introduction	7
2.2. Patellofemoral pain	7
2.3. Functional anatomy and biomechanics of PFJ	9
2.4. Mechanism of PFJ injury	11
2.5. Diagnosis of patellofemoral pain	12
2.6. Risk factors of PFP	17
2.6.1. Lower limb structural and alignment abnormalities	17
Quadriceps Angle.....	17
Foot pronation.....	19
2.6.2. Muscle weakness	21
Handheld dynamometer.....	24
2.6.3. Kinetic Abnormalities.....	25
2.6.4. Kinematic Characteristics and dynamic abnormalities	27
2.7. Two-dimensional motion analysis	29
2.8. Screening tasks	32
2.9. Previous screening and prevention approaches.....	34
2.10. Summary of literature review	35
2.11. Gap in the literature.....	36
2.12. Aims of the project	37
2.13. Research questions	37
2.14. Hypothesis	38
CHAPTER 3	39
Biomechanical risk factors of patellofemoral pain: A systematic review and meta-analysis..	39
3.1. Introduction	39
3.2. Materials and Methods	40
3.2.1. Literature search strategy.....	40

3.2.2. Selection of studies	40
3.2.3. Methodological quality	40
3.2.4. Data extraction.....	40
3.2.5. Data analysis.....	41
3.3. Results	41
3.3.1. Characteristics of the included studies	41
3.3.2. Methodological quality	44
3.3.3. Participants	49
3.3.4. Follow-up periods.....	50
3.3.5. Types of population and participants.....	50
3.3.6. Risk factors	52
3.3.6.1. Demographic characteristics	52
3.3.6.2. Physical fitness.....	53
3.3.6.3. Lower limb alignment and static measurement	54
3.3.6.4. Muscle strength.....	55
3.3.6.5. Muscle timing	59
3.3.6.6. Kinematics	60
3.3.6.7. Kinetics	61
3.3.6.8. Plantar pressure	61
3.4. Discussion	62
3.5. Conclusion.....	65
CHAPTER 4	67
Validity and reliability of 2D analysis and HHD for kinematics and strength assessment of the lower limb	67
4.1. Study 1: The validity and reliability of the FPPA and HADD angle.....	67
4.1.1. Aims	67
4.1.2. Introduction	67
4.1.3. Methods.....	69
4.1.3.1. Participants	69
4.1.3.2. Two-dimensional motion analysis procedure.....	70
4.1.3.3. Three-dimensional motion analysis procedure.....	71
4.1.3.4. Screening Tasks	74
Running.....	75
Single leg squat	75
Single leg land.....	76

4.1.3.5. Data processing.....	77
2D data processing.....	77
3D data processing.....	77
4.1.3.6. Statistical analysis.....	79
Statistical analysis of reliability	79
Statistical analysis of the validity of 2D vs 3D.....	80
4.1.4. Results	81
4.1.4.1. Reliability	81
Within-day reliability.....	81
Between-sessions reliability.....	82
Intra-tester reliability	82
Inter-tester reliability	83
4.1.4.2. 2D Validity	84
Validity of FPPA and HADD during SLS.....	85
Validity of FPPA and HADD during SLL.....	86
Validity of FPPA and HADD during RUN	86
4.1.5. Discussion	87
4.2. Study 2: Validity and reliability of 2D and HHD for kinematics and strength assessment of the lower limb	92
4.2.1. Aims	92
4.2.2. Introduction	92
4.2.3. Methods.....	96
4.2.3.1. Participants	96
4.2.3.2. 3D procedure	97
4.2.3.3. 2D Procedure	97
4.2.3.4. 2D and 3D Marker placement	98
Marker placement and measurement of Q-angle.....	98
Marker placement and measurement of FPPA	98
Marker placement and measurement of knee flexion.....	99
Marker placement and measurement of ankle dorsiflexion.....	99
Marker placement and measurement of rearfoot eversion.....	100
4.2.3.5. Screening tasks	101
4.2.3.6. Data processing.....	101
2D data processing.....	101
3D data processing with QTM analysis	101

4.2.3.7. Isometric strength assessment for hip abductors and knee extensors.....	102
Handheld dynamometer procedure	102
Isokinetic dynamometer procedure	104
4.2.3.8. Statistical analysis.....	106
Reliability.....	106
Validity	106
4.2.4. Results	107
4.2.5. Discussion	114
CHAPTER 5	118
Prospective Investigation of Biomechanical Risk Factors in the Initiation of PFP in Basic Military Training.....	118
5.1. Introduction	118
5.2. Aims	120
5.3. Methods.....	121
5.3.1. Instruments	121
5.3.2. Participants	121
5.3.3. Basic military training	122
5.3.4. Camera setup	122
5.3.5. Baseline for kinematic assessments using 2D analysis	124
5.3.6. Baseline for strengthening assessments using HHD	124
5.3.6.1. Knee extensors	124
5.3.6.2. Hip abductors	125
5.3.7. Data processing.....	127
5.3.8. Assessment and registration of injuries	127
5.3.9. Statistical analysis.....	128
5.4. Results	130
5.4.1. Results (A) all participants of the three groups (315 subjects).....	133
5.4.1.1. Predicted risk factors of lower limbs injuries.	138
5.4.1.2. Predicted risk factors of PFP.....	142
5.4.1.3. Receiver Operation Curve (ROC).....	143
5.4.2. Results (B): First group (203 cadets from KAMA).....	145
5.4.2.1. Predicted risk factors of PFP.....	150
5.4.2.2. Receiver Operation Curve (ROC).....	151
5.4.3. Results (C): All of the three groups without overweight participants.....	152
5.4.3.1. Predicted risk factors of PFP.....	157

5.4.3.2. Receiver Operation Curve (ROC).....	158
5.5. Discussion	159
5.6. Conclusion.....	166
CHAPTER 6	167
Overall discussion, conclusion, and suggestions for future work.....	167
6.1. Overall discussion	167
6.2. Conclusion.....	172
References.....	175

List of Figures

Chapter 2

Figure 2.1 The patella stabilization.....	10
Figure 2.2 Maltracking of the patella.....	11
Figure 2.3 Sits of retinaculum pain in left knee.....	15
Figure 2.4 Sulcus angle.....	16
Figure 2.5 Patellar lateral displacement.....	16
Figure 2.6 The Q-angle	18
Figure 2.7 Measurement of rearfoot eversion.....	21
Figure 2.8 Dynamic Knee valgus.....	28
Figure 2.9 FPPA measurement	30

Chapter 3

Figure 3.1 Flow chart of the process to select the relevant studies.....	43
Figure 3.2 Numbers of participants and injuries.....	49
Figure 3.3 Length of the follow-up period in weeks	50
Figure 3.4 Male and female participants with percentage of injuries.....	51
Figure 3.5 Percentages of types of participants	51
Figure 3.6 Number of participants and injuries in each type.....	51
Figure 3.7 Forest plot: Association between PFP and height grouped according to age and sex	52
Figure 3.8 Forest plot: Association between PFP and age.....	53
Figure 3.9 Forest plot: Association between PFP and mass according to age.....	53
Figure 3.10 Forest plot: Association between PFP and vertical jump (cm)	54
Figure 3.11 Forest plot: Association between PFP and Q-angle (°).....	55
Figure 3.12 Forest plot: Association between PFP and peak torque of knee extensors 60/s...55	
Figure 3.13 Forest plot: Association between PFP and peak torque of knee extensors 240/s56	
Figure 3.14 Forest plot: Association between PFP and peak torque of knee extensors 60/s %BW	56
Figure 3.15 Forest plot: Association between PFP and peak torque of knee extensors 240/s %BW	56
Figure 3.16 Forest plot: Association between PFP and peak torque of knee extensors 60/s %BMI.....	56

Figure 3.17 Forest plot: Association between PFP and peak torque of knee extensors 240/s %BMI.....	56
Figure 3.18 Forest plot: Association between PFP and peak torque of knee flexors 60/s.....	57
Figure 3.19 Forest plot: Association between PFP and peak torque of knee flexors 240/s.....	57
Figure 3.20 Forest plot: Association between PFP and knee extensors muscle strength	58
Figure 3.21 Forest plot: Association between PFP and Peak torque of hip abductors	58
Figure 3.22 Forest plot: Association between PFP and hip abductor strength	59
Figure 3.23 Forest plot: Association between PFP and hip extensor strength.....	59
Figure 3.24 Forest plot: Association between PFP and hip external rotator strength.....	59
Figure 3.25 Forest plot: Association between PFP and hip internal rotation strength	59
Figure 3.26 Forest plot: Association between PFP and knee valgus (°).....	60

Chapter 4

Figure 4.1 100cm square frame	70
Figure 4.2 2D markers placement	71
Figure 4.3 Overview of the procedure set up.....	72
Figure 4.4 Calibration L-shaped frame and T-shaped handheld wand	73
Figure 4.5 Static Trial Marker Tracking Markers.....	74
Figure 4.6 Running Task.....	75
Figure 4.7 Single Leg Squat Task.....	76
Figure 4.8 Single Leg Landing Task.....	76
Figure 4.9 Lower limb segments and rotation according to the X-Y-Z Euler rotation sequence	78
Figure 4.10 Overview of the procedure set-up	98
Figure 4.11 Marker placement for FPPA, Q-angle, and HADD	99
Figure 4.12 Marker placement for KFA and DFA	100
Figure 4.13 Marker placement for RFA	100
Figure 4.14 Process of 3D measurements using QTM	102
Figure 4.15 The wooden frame of HHD	103
Figure 4.16 Isometric strength assessment of knee extensors with HHD.....	103
Figure 4.17 Isometric strength assessment of hip abductors with HHD.....	104
Figure 4.18 Isometric strength assessment of knee extensors with Biodex.....	105
Figure 4.19 Isometric strength assessment of hip abductors with Biodex.....	105
Figure 4. 20 Scatterplot illustrating the linear relationship, with (r^2) value, between the HHD procedure and the isokinetic dynamometer procedure for knee extensors	113

Chapter 5

Figure 5.1 Marker placement	123
Figure 5.2 Overview of the 2D procedure set-up	124
Figure 5.3 Diagram of data collection procedure	126
Figure 5.4 Statistical analysis diagram	130
Figure 5.5 Number of participants of the three groups.....	131
Figure 5.6 Flow chart of groups' identification	132
Figure 5.7 Types and percentages of PFP and other lower limb injuries during the 12 weeks of basic military training	134
Figure 5.8 Percentages of injuries.....	134
Figure 5.9 Types and numbers of lower limb injuries during the 12 weeks of basic military training	135
Figure 5.10 Receiver Operation Curve (ROC) of FPPA during SLL.....	143
Figure 5.11 Types and percentages of PFP and other lower limb injuries during the 12 weeks of basic military training	146
Figure 5.12 Percentages of injuries.....	146
Figure 5.13 Types and numbers of lower limb injuries during the 12 weeks of basic military training	147
Figure 5.14 Receiver Operation Curve (ROC) of FPPA during SLL.....	151
Figure 5.15 and percentages of PFP and other lower limb injuries during the 12 weeks of basic military training	153
Figure 5.16 Percentages of injuries.....	153
Figure 5.17 Types and numbers of lower limb injuries during the 12 weeks of basic military training	154
Figure 5.18 Receiver Operation Curve (ROC) of FPPA during SLL.....	158

List of Tables

Chapter 2

Table 2.1 Differential Considerations for AKP	13
-----------------------------------------------------	----

Chapter 3

Table 3.1 Methodological Quality Rating Score	44
Table 3.2 Summary of included studies.....	46
Table 3.2 Continued.....	47
Table 3.2 Continued.....	48

Chapter 4

Table 4.1 Classification of Intraclass Correlation Coefficient (ICC) values	80
Table 4.2 Grades of correlation ranges	80
Table 4.3 Within-Day Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN	81
Table 4.4 Between-session Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN	82
Table 4.5 Intra-tester Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN	82
Table 4.6 Inter-tester Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN	83
Table 4.7 2D FPPA and 3D variables correlations using Visual3D during SLS, SLL, and running.	84
Table 4.8 2D HADD and 3D variables correlations using Visual3D during SLS, SLL, and running.	85
Table 4.9 Validity and reliability of FPPA and HADD during SLS, SLL, and RUN	87
Table 4.10 Between-session intraclass correlation coefficients (ICC) for lower limb kinematics using 2D analysis during SLS	107
Table 4.11 Between-session intraclass correlation coefficients (ICC) for lower limb kinematics using 2D analysis during SLL	108
Table 4.12 Between-session intraclass correlation coefficients (ICC) for lower limb kinematics using 2D analysis during RUN	109
Table 4.13 2D and 3D correlation using QTM during SLS.....	110
Table 4.14 2D and 3D correlation using QTM during SLL	111
Table 4.15 2D and 3D correlation using QTM during RUN	112

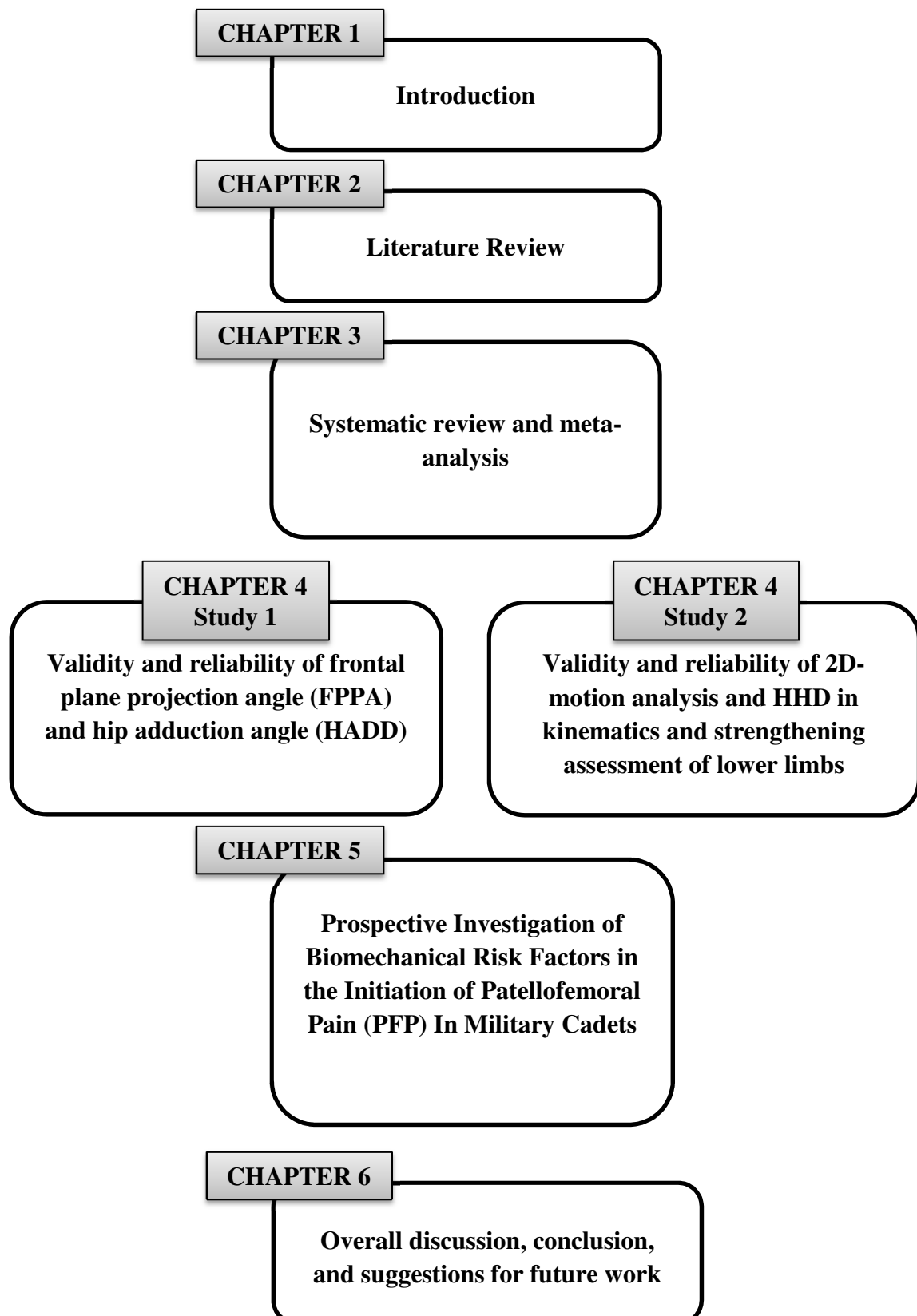
Table 4.16 Between-session intraclass correlation coefficients (ICC) for HHD.....	112
Table 4.17 HHD and Biodex correlation for isometric strength assessment of knee extensors and hip abductors	113
Chapter 5	
Table 5.1 Measurements of the kinematic variables for the lower limb.....	127
Table 5.2 Demographic characteristics of the participants	133
Table 5.3 Numbers and percentages of injured participants and injured limbs in each injury	133
Table 5.4 .Mean, standard deviation, 95% confidence interval (CI), and P value of the demographic characteristics of injured and non-injured groups.....	136
Table 5.5 Mean, standard deviation, 95% confidence interval (CI), and P value of the strength variables of injured and non-injured groups	136
Table 5.6 Mean, standard deviation, 95% confidence intervals (CI), and P value of kinematic variables and sports participation of injured and non-injured groups.....	137
Table 5.7 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable.....	138
Table 5.8 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for regression model	138
Table 5.9 Mean, standard deviation, 95% confidence interval (CI), and P value of the demographic characteristics of injured and non-injured groups.....	140
Table 5.10 Mean, standard deviation, 95% confidence interval (CI), and P value of the strength variables of injured and non-injured groups	140
Table 5.11 Mean, standard deviation, 95% confidence intervals (CI), and P value of kinematic variables and sports participation of injured and non-injured groups.....	141
Table 5.12 Mean, standard deviation, and P value of KOOS for PFP.....	141
Table 5.13 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable.....	142
Table 5.14 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for regression model	143
Table 5.15 Numbers and percentages of injured participants and injured limbs in each injury	145
Table 5.16 Mean, standard deviation, 95% confidence intervals (CI), and P value of the demographic characteristics of injured and non-injured groups.....	148

Table 5.17 Mean, standard deviation, 95% confidence intervals (CI), and P value of the strength variables of injured and non-injured groups	148
Table 5.18 Mean, standard deviation, 95% confidence intervals (CI), and P value of the kinematic variables and sports participation of injured and non-injured groups.....	149
Table 5.19 Mean, standard deviation, and P value of KOOS	150
Table 5.20 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable.....	150
Table 5.21 Numbers and percentages of injured participants and injured limbs.....	152
Table 5.22 Mean, standard deviation, 95% confidence intervals (CI), and P value of the demographic characteristics of injured and non-injured groups.....	155
Table 5.23 Mean, standard deviation, 95% confidence intervals (CI), and P value of the strength variables of injured and non-injured groups	155
Table 5.24 Mean, standard deviation, 95% confidence intervals (CI), and P value of the kinematic variables and participation in sports of injured and non-injured groups.....	156
Table 5.25 Mean, standard deviation, and P value of KOOS	157
Table 5.26 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable.....	157

Glossary List

2D	Two-dimensional motion analysis
3D	Three-dimensional motion analysis
ADL	Activity of Daily Living
AKP	Anterior knee pain
ASIS	Anterior superior iliac spine
BMI	Body mass index
CAST	Calibration anatomical systems technique
DVJ	Drop vertical jump
FPI	Foot posture index
FPPA	Frontal plane projection angle
HABD	Hip abductors
HADD	Hip adduction
HHD	Handheld dynamometer
ICC	Interclass correlation coefficient
KOOS	Knee injury and osteoarthritis outcome
MDD	Minimal detectable differences
NOS	Newcastle-Ottawa quality assessment scale
QTM	Qualisys Track Manager
ROC	Receiver Operation Curve
SLL	Single leg land
SLS	Single leg squat
TSF	Tibial stress fracture

Thesis structure



Acknowledgment

I would like to give special thanks to my supervisor, Prof. Richard Jones, for giving me an opportunity to join this programme. He has spent a lot of time developing this project and guided me to where I am now. Without his support, guidance, and encouragement, I would never have finished this thesis.

I would also like to thank my co-supervisors, Dr Lee Herrington and Dr Anmin Liu. I appreciate their time, input, and assistance in completing this research.

Many thanks to Steve Horton and Laura Smith for their great efforts and cooperation during my project, and I would also like to thank all of my participants who gave up their precious time so that others might benefit.

I would like to express my deepest appreciation to my colleagues and friends, Yousef, Mazen, Faisal, Adel, Yousef, Ahmed, Saud, Hussein, Yasser, Huthaifa, Ali, Sultan, Ihab, Ziyad, Msaad, Ahmed, Omar, Walaa, Abdullah, Ayman, Husam, and Wael, for their support in all matters during my project and my stay in Manchester.

I would like to thank Dr Henrike Greuel for being the second reviewer of the meta-analysis study.

I can never thank my parents who stood for me with their feelings, prayers, and unlimited emotional support.

From the bottom of my heart, I would like to thank my lovely wife and children for their patience and support throughout my study journey. Without their understanding and encouragement this PhD would never have reached completion.

Finally, I would like to thank the Saudi Ministry of Defence for funding my PhD, and I would like to give a special thanks to Authority in Saudi Armed Forces, King Abdul-Aziz Military Academy, Training Centre of Maintenance Institute, Training Centre of Artillery Institute and to all who supported me in the data collection for my project.

Abstract

Patellofemoral pain (PFP) is one of the major sources of chronic knee pain in young athletes, affecting one in four individuals. To progress further in this field, prospective studies are therefore needed in order to gain a better understanding of the biomechanical risk factors of PFP and to develop future treatment and prevention strategies. With this in mind, the main purpose of the present PhD thesis is to prospectively examine individuals' lower limb movements with two-dimensional (2D) video analysis and muscle strength with a handheld dynamometer (HHD) in order to screen for PFP development, in addition to other lower limb injuries. Therefore, a systematic review and meta-analysis in addition to three studies were conducted within this thesis to investigate the factors involved in the development of PFP.

In the first study, 15 healthy subjects (6 male and 9 female) participated in a reliability study (within-day, between-day, intra-rater, and inter-rater reliability) of 2D frontal plane projection angle (FPPA) and hip adduction (HADD) angle. They also participated in a validation study for 2D motion analysis against the gold standard of three-dimensional (3D) motion analysis. In the second study, eight healthy male subjects participated in a between-day reliability and validity study for 2D analysis and HHD strength tests against the gold standard of 3D analysis, using Qualysis Track Manager (QTM) system and an isokinetic dynamometer for the measurements of lower limb kinematics (FPPA, Q-angle, HADD, knee flexion, ankle dorsiflexion, and rearfoot angle) and strength (hip abductors and knee extensors). The main study was undertaken with 315 healthy male infantry cadets and recruits from King Abdul-Aziz Military Academy (KAMA) and two other basic military training centres in Saudi Arabia. Lower limb kinematics and muscle strength were measured during running (RUN), single leg squatting (SLS), and single leg landing (SLL) in the first week of training, and were followed up over the participants' 12 weeks of basic military training for the occurrence of PFP and other lower limb injuries.

Participants who developed PFP had a significantly greater FPPA and Q-angle during SLS, SLL, and RUN, as well as a significantly greater HADD during SLS and SLL, than participants who did not develop PFP. In addition, the injured group had significantly lower knee extensor and hip abductor muscle strength during the baseline assessment when compared to the non-injured group. The logistic regression revealed that FPPA during SLL significantly predicts the development of PFP. Therefore, this appears to be a suitable method for screening of PFP risk before joining basic military training.

CHAPTER 1

Introduction

Basic military training is considered to be the most physically demanding training courses for new recruits across many military institutions in the world (Wilkinson et al., 2008). Several musculoskeletal injuries were recorded during basic military training. These musculoskeletal injuries were reported as the main cause of medical discharge of recruits during the training. Patellofemoral pain (PFP) is one of the most common musculoskeletal injuries that affect young athletes and trainees during basic military training (Brody & Thein, 1998; Piva et al., 2006). The causes of PFP are not clearly established, although it may be related to training load, abnormal biomechanics of lower extremity, poor physical level, previous injury, genetics, and psych-social factors (Lankhorst et al., 2012; Cameron & Owens, 2016; Waryasz et al., 2008). Due to this, definitive prevention and treatment strategies remain elusive as will. Within the field, several researchers have attempted to understand the causes, and the mechanism behind this condition with low-cost equipment. This thesis aims to improve the method of identifying those individuals who are at risk of developing this injury, depending on the knowledge, the experience of positives and the limitations of previous findings.

This introduction provides an overview of the literature relating to PFP and its risk factors, as well as of possible methods with which to identify those who are at risk of developing the injury and which can be used for large-scale screening within the field.

Patellofemoral pain accounts between 25% - 40% of all knee joint problems investigated in sports medicine clinics (Bizzini et al., 2003; Chesworth et al., 1989; Rubin & Collins, 1980). The primary symptom of PFP is pain arising from the anterior of the knee joint (Powers, 1998). It is defined according to Crossley et al., (2016) as a pain around or behind the patella. This pain is commonly reproduced in activities which increase the compressive forces in the patellofemoral joint (PFJ), such as running, walking, ascending and descending stairs, prolonged sitting, and squatting (Levine, 1979; McConnell, 1996; Powers, 1998). Patellofemoral arthritis, prepatellar bursitis, patellar stress fracture and patellar tendinopathy are other conditions that have been reported as having the same symptom as PFP. Hence, misdiagnosis of the condition is potentially troublesome (Waryasz & McDermott, 2008). Although there is no definitive aetiology for PFP, several previous studies have identified predisposing factors, such as increased knee valgus, increased Q-angle, increased hip adduction (HADD) angle, increase in rearfoot eversion, weakness of hip abductors and weakness of knee

extensors (Pappas & Wong-Tom, 2012; Thijs et al., 2007; Waryasz & McDermott, 2008). However, it has been stated that the cause of PFP is multifactorial (Thijs et al., 2007).

It has been recognised that the mechanics of PFJ may be affected by the interaction of the segments of the lower extremity (Powers et al., 2003; Thijs et al., 2007). Abnormal kinematics and kinetics of lower limb have been theorised as potential risk factors for PFP (Powers et al., 2003; Thijs et al., 2007). Gait-related risk factors have therefore been investigated in a number of studies as possible predisposing factors for PFP (Buchbinder et al., 1979; Callaghan & Baltzopoulos, 1994; Duffey et al., 2000; Eng & Pierrynowski, 1993; Hamill et al., 1992; Levinger & Gilleard, 2004; Messier et al., 1991; Powers et al., 2002; Powers et al., 2003; Thijs et al., 2007; Tiberio, 1987). Individuals with PFP demonstrate greater frontal plane knee joint motion and greater loads during dynamic activities, such as running, jumping, squatting, and stepping (Holden et al., 2015; Levinger & Gilleard, 2007; Nakagawa et al., 2013; Theresa et al., 2015; Nakagawa et al., 2012; Willson & Davis, 2008). Interactions of the hip and PFJ have been reported, which may contribute to PFP (Callaghan & Baltzopoulos, 1994; Holden et al., 2015; Laprade & Culham, 2003). A greater Q-angle leads to excessive knee valgus, which may increase the potential risk of PFP (Bennell et al., 2000; Holden et al., 2015). It has also been proposed that excessive foot pronation is predisposing for PFP (Eng & Pierrynowski, 1993; Thijs, Tiggelen, et al., 2007; Tiberio, 1987).

Hip and knee muscle strength play an important role in the stability of the PFJ and muscle dysfunction of hip and knee joints found to be associated with PFP. Weakness of hip abductors and external rotators against hip adductors and internal rotators during dynamic activities may increase knee valgus. This leads to an increase in the lateral quadriceps muscle's force on the patella, causing abnormal tracking of the patella (Mizuno et al., 2001; Powers, 2003). A number of studies have reported a decrease in the isometric strength of the hip abductors and the hip external rotators of PFP subjects (Ireland & Davis, 2003; Robinson & Nee, 2007). Laprade and Culham (2003) found a 26% decrease in hip abductor strength and a 36% decrease in hip external rotation in individuals with PFP, compared with the control group. Previous studies have demonstrated weaknesses in the quadriceps muscles of PFP subjects compared to the healthy group. Boling et al. (2009), DuVigneaud et al. (2008), Witvrouw et al. (2000), and Van Tiggelen et al. (2004) reported significant decreases in quadriceps muscle strength in PFP participants.

The relationship between hip and knee muscle activation during dynamic postural control and PFP has been investigated by Brindle et al. (2003). Subjects with PFP demonstrate a shorter duration and delayed onset of gluteus medius activation while descending and ascending stairs, compared to the onset of Vastus Medialis Oblique (VMO) and Vastus Lateralis (VL) (Brindle et al., 2003). The delayed onset of VMO during the screening task (rocking back on the heels) was associated with PFP (Van Tiggelen et al., 2009).

Most of the previous studies suggest that the PFP individuals are characterised as having an increase in dynamic knee valgus during functional activities, which is a result of contribution of several factors, including the weakness of hip abductors and hip external rotation (ER), the weakness of knee extensor, an increase in HADD angle and internal rotation angle, and an increase in knee abduction. Therefore, selecting the accurate and appropriate method is important in identifying the risk factors of PFP. Several tools and functional tasks for screening tests have been undertaken by researchers in order to evaluate dynamic knee valgus and lower extremity muscle strength.

Running, double or single leg squats, single leg lands, and drop landings were the common functional movement screening tasks used by investigators. The majority of previous studies have used three-dimensional (3D) methods to quantify the biomechanics of the lower limbs. This enables clinicians and researchers to accurately quantify all three planes of joint motion during different tasks. Isokinetic dynamometers such as Cybex or Biodex have been used in many previous studies for strengthening assessments. These methods are considered a gold standard for this type of motion analysis and for strength assessments.

However, in injury prevention programmes, there is a need for large-scale screening within the field in order to identify high-risk athletes. Therefore, while 3D and isokinetic dynamometers should ideally be used, it is not practical to use them in large screening programmes due to the high costs, the space required, and the extra time needed for preparation and marker placement. A method is therefore needed that allows for quick collection of the data in a relatively small space. Two-dimensional (2D) motion analysis and hand held dynamometry (HHD) may provide an alternative solution to 3D and isokinetic dynamometers.

In different types of musculoskeletal injuries, there is a need to perform strengthening evaluations in the clinic. These enable clinicians to determine the baseline level of the athlete's strength in order to generate the differential diagnoses and develop a treatment plan as an addition to following up on the efficacy of the treatment. (Kawaguchi & Babcock, 2010;

Wadsworth et al., 1987). Isokinetic dynamometers such as the Biodex were among the existing strength measurement methods and were accepted for the clinical use of muscle assessment (Martin et al., 2006). The isokinetic dynamometer provides accurate evaluations for dynamic as well as static muscle strength and considered the first choice in clinical studies (Drouin et al., 2004). However, due to its spatial and temporal cost, lack of portability and complexity to set up or use, it is not practical to use for large-scale screenings in epidemiological studies, nor useful to sports. The HHD is therefore the alternative method for muscle strength assessment (Edwards & McDonnell, 1974; Kawaguchi & Babcock, 2010).

The HHD is a device used for strengthening assessments that is preferred for clinical use due to the ease of application, the relatively low cost of its use, and the portability. Good validity and repeatability have been established and it has been used widely (Bassey & Harries, 1993; Martin et al., 2006). However, HHD which is fixed with the examiner hand's is difficult to be used for some muscle groups, particularly lower limb muscle strength assessments (Holmbäck et al., 1999). Various protocols for using HHD have been developed to measure the upper and lower extremities' muscle strength in order to improve their validity and reliability.

Compared to the gold standard in muscle strength measurement (isokinetic dynamometry), several studies investigate the validity of HHD for lower extremity muscle strength. A number of studies report that an evaluation of lower extremity muscle strength for physically active individuals with HHD has some limitations related to the hand stabilisation of the instrument and to changing the angle of the joint. This occurs especially if the subject is stronger than the examiner, or in the case of large-scale screenings (Katoh et al., 2011). However, it has been found that the validity and reliability of isometric muscle strength increased when using HHD with a stick, a steel support and a belt.

3D motion analysis is considered the gold standard for this type of analysis, but given the reasons mentioned above, the use of 2D analysis is on the increase, because it is perceived as easy to use, portable, and less expensive compared to 3D. Previously, 2D has been used for quantifying the knee valgus angle in healthy, injured and athletic populations (Willson & Davis, 2008, Willson et al., 2006).

The 2D frontal plane projection angle (FPPA) was identified as a potential outcome risk factor for the development of PFJ injury during large-scale screenings and in the clinical environment (Willson et al., 2006). FPPA is defined with three markers which are placed on the midpoint of the ankle, centre of the knee joint, and the proximal thigh. FPPA is the angle formed between

the line from the marker of the proximal thigh to the marker of the midpoint of the knee joint and the line from the marker of the knee joint to the marker of the ankle (Willson et al., 2008, Willson et al., 2006). McLean et al. (2005) assessed the validity of 2D video analysis by measuring FPPA and compared it with the gold standard 3D. Two-dimensional FPPA reflected 58% to 64% of the variance in average peak 3D knee abduction angle in side-jump and side-step tasks (McLean et al., 2005). Recently, Sorenson et al. (2015) investigated 2D and 3D relationships between knee and hip kinematics during single leg drop landings and reported that 2D knee FPPA had a strong relationship with 3D knee abduction angle ($r^2=0.72$); additionally, 2D hip adduction angle had a strong correlation with 3D hip adduction angle ($r^2=0.52$). Willson & Davis (2008) found that hip adduction, which is one of the contributing factors of the dynamic knee valgus, was significantly correlated with 2D FPPA. Willson & Davis (2008) conclude that 2D analysis could be a useful method for quantifying knee valgus in order to identify high-risk athletes.

Movement screening has been used increasingly over recent years in both sport and clinical practice, to provide measurements with which to evaluate athletes who return from injuries. In these functional tests, the athlete tries to demonstrate some common actions in sports activities such as running (RUN), Single Leg Squats (SLS), and Single Leg Landing (SLL), vertical jumping (VJ), stepping down, and sprint tests. Screening tasks provides objective measurements for muscle strength, agility, joint laxity, proprioception and pain (Munro et al., 2012; Herrington et al., 2009; Reid et al., 2007; Loudon et al., 2004).

Running, SLL and SLS are the most common tasks used to evaluate the dynamic functioning of the lower limbs, particularly in screening PFP. Running is the most frequently performed task that researchers use to evaluate the dynamic functioning of the lower limb. It has been suggested that the investigation into the biomechanics of running has the potential to identify individuals who are at risk of sustaining running related injuries (Schache et al., 1999). A number of studies have used SLS to distinguish between participants with and without PFP by demonstrating increased dynamic knee valgus (Whatman et al., 2011; Willson & Davis, 2008). Single leg landing is one of the common tasks or techniques in sports and may be better suited than bilateral landing for the assessment of individuals who are at risk of knee injuries (Faude et al., 2005). Due to the increased demand to decelerate landing force in SLL screening task, appears to be more sensitive than the drop jump (DJ) in identifying individuals who demonstrate dynamic knee valgus.

The majority of previous studies investigating the biomechanical risk factors for PFP are retrospective studies in nature, and given the study design, it raises the question whether the results are the effect of the condition and not actually a causation. However, whilst there are a number of military prospective studies have used multiple approaches for screening such as 3D for kinematic kinetic measurements and isokinetic dynamometer for muscle strength evaluation, none one of them have used 2D or stabilised HHD.

Within the Saudi military population, it is notable that there is a high incidence rate for knee injuries during the first three months of military training and that it is one of the common causes of discharge or referral to hospital. In order to further advance the current state of research and gain a better understanding of the risk factors that contribute to the occurrence of PFP, the main aim of this thesis is to conduct the first study investigating the biomechanical risk factors of PFP among Saudi military individuals.

CHAPTER 2

Literature review

2.1. Introduction

Within the rationale of this thesis, this literature review provides information about the definition of PFP, anatomy and biomechanics of the PFJ, incidence and prevalence, mechanism of PFJ injury, risk factors of PFP, 2D, screening tests, and isometric strength assessment with HHD.

2.2. Patellofemoral pain

Patellofemoral pain is one of the sources of chronic knee pain in young athletes (Brody & Thein, 1998; Piva et al., 2006). It accounts for 25 to 40% of all knee joint problems which have been investigated in sports medicine clinics (Bizzini et al., 2003; Chesworth et al., 1989; Rubin & Collins, 1980). Patellofemoral pain is a major problem among physically active populations, such as adolescents, young adults and military recruits (Duffey et al., 2000; Messier et al., 1991; Powers et al., 2003; Witvrouw et al., 2000; Laprade et al., 2003; Cutbill et al., 1997; Thijs et al., 2007). McConnell, (1986) found that one in four individuals is affected by PFP. In a retrospective study of individuals with PFP who were assessed between four and eight years after the presence of injury, the results showed that knee pain was still present in 91% of 22 individuals, while 36% were unable to continue their physical activity (Fulkerson & Shea, 1990). Utting et al., (2005) reported a connection between PFP and the development of patellofemoral arthritis, and found that 22% of 118 individuals with patellofemoral osteoarthritis had anterior knee pain when they were adolescents. There are also high recurrence rates in two-thirds of injured individuals who are assessed one year after the initial diagnosis (Devereaux and Lachmann, 1984; Pappas & Wong-Tom, 2012). However, it has been suggested that PFP is one of the musculoskeletal injuries with a high rate, which is associated with an increase in the volume of exercise or load of physical activities, such as sports or basic military training (Cowan et al., 1996; Almeida, 1999).

The risk of injury is increased with the increase of the intensity of training exercises. Occurrence of injury causes temporary or long-term disability for the athlete or recruit, resulting in loss of training time, and treatment and rehabilitation. Approximately 50% to 75% of lower limb injuries for both sexes occur in a variety of sports and levels of playing (Hootman et al., 2007; Agel et al., 2007; Rauh et al., 2007; Powell et al., 2000). Patellofemoral pain is

commonly diagnosed for knee injuries that are found in sports, such as running, soccer, football, basketball and baseball (Taunton et al., 2002; DeHaven et al., 1986; Devereaux & Lachman, 1984). Patellofemoral pain has high prevalence among runners compared to other knee injuries (DeHaven & Lintner, 1986; Devereaux & Lachman, 1984). Patellofemoral pain has been reported to account for 16% of all runners' injuries and is the most commonly diagnosed injury (Taunton et al., 2002).

Basic military training is considered to be the most physically demanding training courses for new recruits across many military institutions in the world (Wilkinson et al., 2008). It mainly consists of running, battle training, resistance training, and loaded marches to improve muscle strength, endurance and aerobic fitness, in order to reach the maximum level of physical readiness (Greeves et al., 2001; Blacker et al., 2008). The volume and physical load for many recruits is higher than they experienced previously (Cowan et al., 1996; Almeida, 1999). It has been claimed that the risk of musculoskeletal injury is increased due to the failure of adaptation to the sharp and large rise in the physical load (Knapik et al., 2011; Popovich et al., 2000; Sharma, 2007).

However, training load management has been found as one of the factors that plays an important role in incidences of training injuries. Previous research suggested that poor training load management and prescription is a major risk factor for injury (Soligard et al., 2016). The training load injuries are preventable and should be addressed by sports medicine practitioners and sports science by implementing monitoring protocols (Gabbett, 2016). These monitoring protocols should aim to track readiness, improve performance, and prevent injuries. 'Acute: chronic workload ratio' is one of the popular protocols which have been used by practitioners to view a snapshot of an athlete's training load history, in order to measure the readiness of their athletes, improve training periodisation, and act as a flagging value for risk of injury. Acute: chronic workload ratio is calculated by dividing the acute workload (training load information over one week, which is calculated by multiplying the session rating of perceived exertion by session duration in minutes) by chronic work load (the average of acute workload over the training period in weeks) (Hulin et al., 2016; Carey et al., 2016). Comparison between acute work load and chronic work load as a ratio, is a dynamic representation of an athlete's preparedness (Malone et al., 2017). Therefore, training load during basic military training should be managed carefully with as much consideration, as possible, of previous training load history and level of fitness of all participants in order to prevent or reduce the development of injury.

Incidence of musculoskeletal injuries range from 20% to 59% during basic military training (Franklyn et al., 2011; Knapik et al., 2013; Linenger and West, 1992). The medical discharge rate at the Infantry Training Centre Catterick in the UK is over 8%, primarily due to musculoskeletal injuries (Blacker et al., 2008). Incidence of musculoskeletal injuries within military populations has been reported in many studies. Knee injuries were about 203 per 1000 and lower limb injuries comprised 72% of all injuries.

Smith et al., (2017) conducted a systematic review and meta-analysis to investigate the incidence and prevalence of PFP. They classified the participant's population to adult general population, general adolescent population, elite athletes and military population. The incidence rate of PFP in the adult general population (novice female runners) over ten weeks was 1080.5/1000 person-year. In the adolescent population the incidence rate over one season in females was 0.97–1.09 per 1000 athletic exposure and it was 0.51 per 1000 for mixed sex adolescent over one running season. In military populations PFP incidence rates ranged from 9.7–571.4 cases per 1,000 person-years in the male population (Smith et al., 2017). Point prevalence was 13.5% in military populations, 12% to 13% in female general populations, 35% in amateur cyclists and 16.7% to 29.3% in female elite sports. It was calculated through the meta-analysis to be 7.2% in mixed sex adolescents, and 22.7% in female amateur athletes. Therefore, it is clear from the previous, PFP is a common pathology in the general population, adolescents and in those with high levels of activity such as military populations and elite athletes (Smith et al., 2017). However, knowledge of the injuries to the patellofemoral region is crucial for a better understanding of the pathogenesis of injury (Besier et al., 2005; Gerbino et al., 2006).

2.3. Functional anatomy and biomechanics of PFJ

The PFJ consists of the bones of the patella, anterior distal parts of the femur, surfaces of the articulation and surrounding supporting tissues. The patella is a sesamoid bone that helps to improve knee flexion efficiency by increasing the lever arm of the quadriceps and by protecting the tibiofemoral joint (Ficat, 1977; Hughston, 1984; Thomee et al., 1999; Tecklenburg et al., 2006). Most of the posterior surface of the patella is covered by the thickest layer of cartilage in the body (Thomee, et al., 1999). The quadriceps tendon, patella tendon, medial retinaculum and lateral retinaculum are combined to stabilise the patella (Amis, 2007) (Figure 2.1).

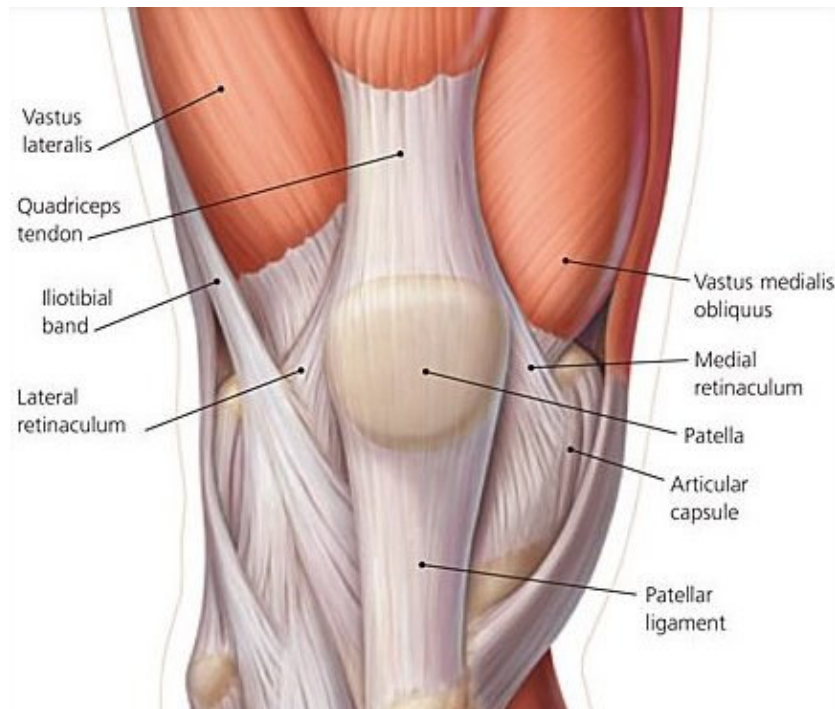


Figure 2.1 The patella stabilization (Dixit et al., 2007)

Several components contribute towards controlling the biomechanics of the PFJ dynamically. These components consist of the four parts of the quadriceps femoris, the adductor longus and magnus, the biceps femoris, the illiotibial band, and the pes anserine group (Tang et al., 2001). In the last 30° of knee extension, the tibia tends to rotate outward and the patella glides by the interacting heads of the quadriceps, moving upward through the trochlea of the femur to the patellar bursa. In contrast, in the first 10° to 20° of knee flexion, the distal part of the patella articulates with the lateral femoral condyle and the patella subsequently moves through the trochlea in an S-shaped curve. Medial tilt of the patella also occurs during the movement of the patella on the femur, proximally and distally. The average angle of this tilt is approximately 11° to 25° within 135° of knee flexion (Norkin & Levangie, 1992; Grelsamer & Klein, 1998).

Joint reaction forces increase with the knee flexion (Norkin & Levangie, 1992; Grelsamer & Klein, 1998). The quadriceps muscle group or particularly the Vastus Medialis Oblique (VMO) and Vastus Lateralis (VL) play an important role in the forces that affect patella tracking (Besier et al., 2009). During knee extension, the quadriceps muscles increase the lateral shifting force of the patella on the frontal plane and the tibia rotates externally in the last 30° degrees (Scuderi, 1995). The VMO apply resistance to this lateral force by the medial retinacular structure and the lateral facet of the trochlea (Herrington & Nester, 2004; Scuderi, 1995).

On the other hand, during knee flexion, the quadriceps action in the horizontal plane separates into two forces; the first acts on the lateral patellar facet and pushes the articular surface against the femoral trochlea, while the second tends to rotate the tibia internally by applying medial tension on the tibial tuberosity (Scuderi, 1995; Norkin and Levangie, 1992; Grelsamer, Klein, 1998; Neumann, 2002; Dixit et al., 2007). To achieve normal patellar tracking, VMO and VL forces have to contract equivalently (Norkin and Levangie, 1992; Grelsamer, Klein, 1998; Neumann, 2002). During knee flexion, the articular surface of the patella that articulates with the femur moves proximally, while patellofemoral compression forces can reach up to eight times the body weight, with an increase in knee flexion up to 90° (Thomee, et al., 1999).

2.4. Mechanism of PFJ injury

The symptom of PFP is a pain arising from the anterior of the knee (Powers, 1998). This pain is commonly produced by activities which increase the compressive forces in the PFJ, such as running, walking, ascending and descending stairs, prolonged sitting and squatting (Powers, 1998; Levine, 1979; McConnell, 1996). This condition is widely believed to be a stress caused by maltracking of the patella on the stable femur during knee movement. Patella malalignment in the femoral trochlea results in decreases of the contact area and leads to increases the contact stress underlying the cartilage of the patella (figure 2.2) (Harilainen, 2005; Powers et al., 2010; Huberti & Hayes, 1984; Lee et al., 2001).

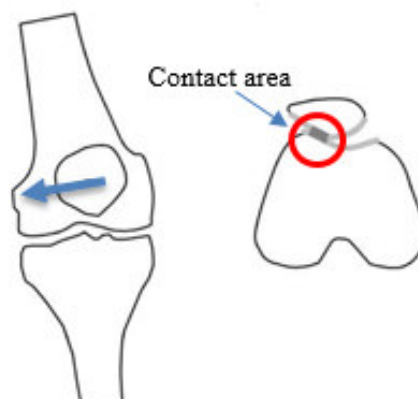


Figure 2.2 Maltracking of the patella

Previous studies reported an association between the increase of HADD and hip internal rotation (HIR), and PFP in female runners (Noehren et al., 2013; Sousa et al., 2009; Willson & Davis 2008). These motions were investigated using experimental models and have been shown by increasing the load of stress on the lateral aspect of patella. Pain may arise due to the repetitive exposure of the patella's underlying cartilage to this type of stress (Huberti & Hayes,

1984; Li et al., 2004). McClay & Manal (1998) found that there is a relationship between excessive rearfoot eversion and PFP. As consequence to that, there is greater tendency to knee valgus results from the increase of knee flexion that associated with excessive rearfoot eversion. Knee valgus is associated with increase in the force of the lateral component of the quad, Q-angle increase and increase in the patellar lateral tracking tendency. Therefore, all these factors lead to greater loads on the lateral aspects of the PFJ (Tiberio, 1987). Thus, if these were the theoretical aspects mechanism of injury, it is important to know, how it could be identified.

2.5. Diagnosis of patellofemoral pain

Patellofemoral pain is an overuse disorder due to increased compressive force on PFJ with activity and is not related to direct injury or intra-articular damage to the knee (Aminaka & Gribble, 2008; Bolgla & Boling, 2011; Crossley et al., 2001; Davis & Powers, 2010; Duffey et al., 2000; Fulkerson, 2002). It is similar to some other conditions which present similar symptoms and which are exacerbated by the same activities, labelled as anterior knee pain (AKP). The subtitle variances in improper interchanging classification therefore creates difficulty in the differential diagnosis (Callaghan & Selfe, 2007; Crossley et al., 2002; Dixit et al., 2007). Anterior knee pain is a generic term for any source of pain from the knee region and has a broad differential diagnosis. Most of common diagnosis for AKP are illustrated in Table 2.1 (Christian et al., 2006). Therefore, careful history, physical examination, and clinical examination are sufficient to make the diagnosis of PFP for most of individuals.

Table 2.1 Differential Considerations for AKP (Brukner et al., 2002)

Cause	Description
Articular cartilage injury	May with history of trauma, mechanical symptoms may occur with presence of loose body. If loose body, possibility of effusion and tenderness of involved structure (e.g., patella, femoral condyles)
Bone tumors	Tenderness may be of bony structures
Chondromalacia patellae	Retropatellar pain, may with history of trauma, may with effusion on examination
Hoffa's disease	Pain and tenderness localized to infrapatellar fat pad
Iliotibial band	Pain and tenderness over and proximal lateral femoral epicondyle
Loose bodies	Variation in the symptoms, may with intermittent sharp pain, locking, or effusion
Osgood-Schlatter disease	Tenderness and swelling over tibial tubercle and at insertion of patellar tendon in an adolescent
Osteochondritis dissecans	Variation in the symptoms, may have intermittent pain, swelling, or locking
Patellar instability/subluxation	Intermittent pain with sensation of instability or movement of patella, tenderness over medial retinaculum, may have swelling, locking can occur due to loose body formation
Patellar stress fracture	Tenderness directly over patella
Patellar tendinopathy	Tenderness of patellar tendon and it may be thickened if chronic
Patellofemoral osteoarthritis	crepitus or effusion
Patellofemoral pain	Pain "behind" or around patella
Pes anserine bursitis	Pain usually described as medial rather than anterior, tenderness over pes anserine bursa
Plica synovialis	May be medial or lateral to patella, if symptomatic, tenderness can be found on examination
Prepatellar bursitis	Swelling following trauma anterior to patella
Quadriceps tendinopathy	Tenderness over quadriceps tendon
Referred pain from the lumbar spine or hip joint pathology	Knee examination usually normal and symptoms depend on origin of pain.
Saphenous neuritis	May be with history of surgery and pain poorly localized but usually medial
Sinding-Larsen-Johansson	Tenderness at insertion of patellar tendon at inferior pole of patella in an adolescent
Symptomatic bipartite patella	May be with tenderness over patella

However, recently in 2016, patellofemoral pain consensus statements have suggested that: PFP syndrome, chondromalacia patella, anterior knee pain and/or syndrome, and runner's knee are synonyms for PFP (Crossley et al., 2016).

Individuals with PFP typically describe pain around or behind the patella. This pain is exacerbated by weight-bearing activities such as squatting, running, and ascending and descending stairs. The symptoms of PFP are presented gradually, but also in some cases it can be caused by trauma and could be bilateral. Symptoms include pain or stiffness, or both in prolonged sitting with flexed knee. Localization of the pain can be difficult to the individual. When asked to point the site of the pain, individuals may draw a circle around the patella or place their hand over the anterior aspect of the knee. Pain described ranged between "achy" and 'sharp' (Crossley et al., 2016; Devereaux et al., 2007; Thijs et al., 2007; Noehren et al., 2013; Post, 1999). In some cases, individual may complain of their knee giving away. This usually does not represent real patellar instability but it may be a transient inhibition of the quadriceps due to pain. However, determining whether patellar dislocation or subluxation has occurred is important, because patellar instability can be linked with PFP. Individuals may report from a stiffness sensation particularly when the knee is flexed describing it as a catching sensation. Knee locking symptoms are not associated with PFP but are likely a meniscal tear or loose bodies (Post, 1999).

Given that PFP is often a consequence of overuse injury, any changes in activities, or in the dose, duration, and frequency of training should be considered. A change of footwear particularly if it was inappropriate or worn excessively, and conditioning activities or resistance training (especially lunges and squats), may be other possible contributors to development of the injury. A history of previous injuries such as patellar dislocation or subluxation, trauma, or surgeries, should be noted. They may cause direct injury to the articular cartilage, or alter the forces across the patellofemoral joint, resulting in AKP (Manske & Davies 2016; Dixit et al., 2007). The 2016 patellofemoral pain consensus statements recommended that, patellar dislocation or subluxation should not be included in studies of PFP, unless there are subgroups evaluation in the study (Crossley et al., 2016).

Whereas, there is no definitive clinical test to diagnose PFP, a complete assessment of the knee, including a careful physical examination of the patellofemoral joint, should be performed. The assessment should aim to recognise features that may change patellofemoral mechanics. This physical examination should include: inspection, palpation, range of motion, and special tests

such as: patellar glide, patellar tilt, and patellar grind (Nunes et al., 2013; Dixit et al., 2007). Patellar grinding and apprehension tests have low sensitivity and limited diagnostic accuracy for PFP (Crossley et al., 2016). Therefore the best available test, according to 2016 patellofemoral pain consensus, is anterior knee pain elicited during a squatting manoeuvre. In this test PFP is evident in 80% of people who are positive on the test (Nunes et al., 2013; Crossley et al., 2016).

In the clinical examination most individuals with PFP presented pain that was localised in the retinaculum (figure 2.3). Fulkerson (1983) investigated the localisation of pain in 78 knees of individuals affected with PFP and reported that 90% of them had pain in the lateral retinaculum area. In 27% of the cases, this was in the lateral epicondylopatellar band and insertion of vastus lateralis, whereas only 10% of the studied knees suffered pain in the medial PFJ (Fulkerson, 1983).

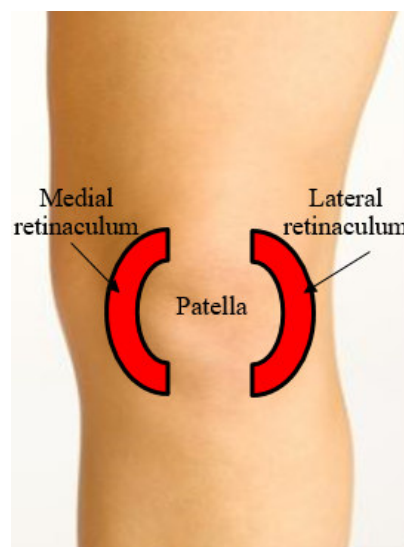


Figure 2.3 Sites of retinaculum pain in left knee

Many of PFP individuals initiated the treatment based on the primarily clinical diagnosis. Imaging or radiography is an adjunct to the history and physical examination. It should be performed in individuals with effusion, or with history of surgery or trauma, or with those whose pain received treatment and does not improved. In addition to the usefulness of radiography in detecting the abnormalities that associated with PFP, it can be helpful to evaluate other causes of anterior knee pain, such as loose bodies, physeal injury, osteochondritis dissecans, and bone tumor (Elias and White, 2004; Natri et al., 1998; Dixit et al., 2007). Trochlear dysplasias, lateral patellar tilt, lateral patellar displacement, can cause PFP and also be deducted in clinical radiography. Trochlear dysplasias occurs when the Sulcus

angle (Figure 2.4), which is the angle of the depth of the trochlea is greater than 142° .(Davies et al., 2000; Fulkerson et al., 2004). Approximately 50% of individuals with PFP who are diagnosed with patellar maltracking were found to have emissive lateral translation of the patella, relative to the femur accurse in the last degrees of knee extension (figure 2.5) (DeHaven & Lintner, 1986).

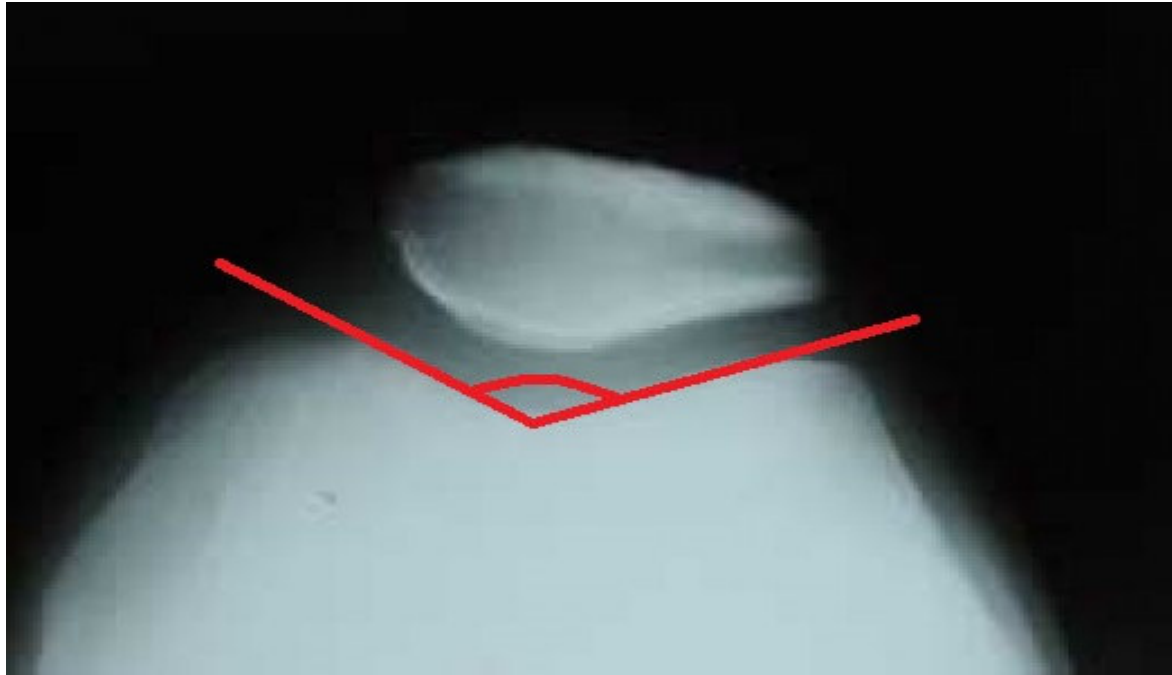


Figure 2.4 Sulcus angle (Healdove, 2017)

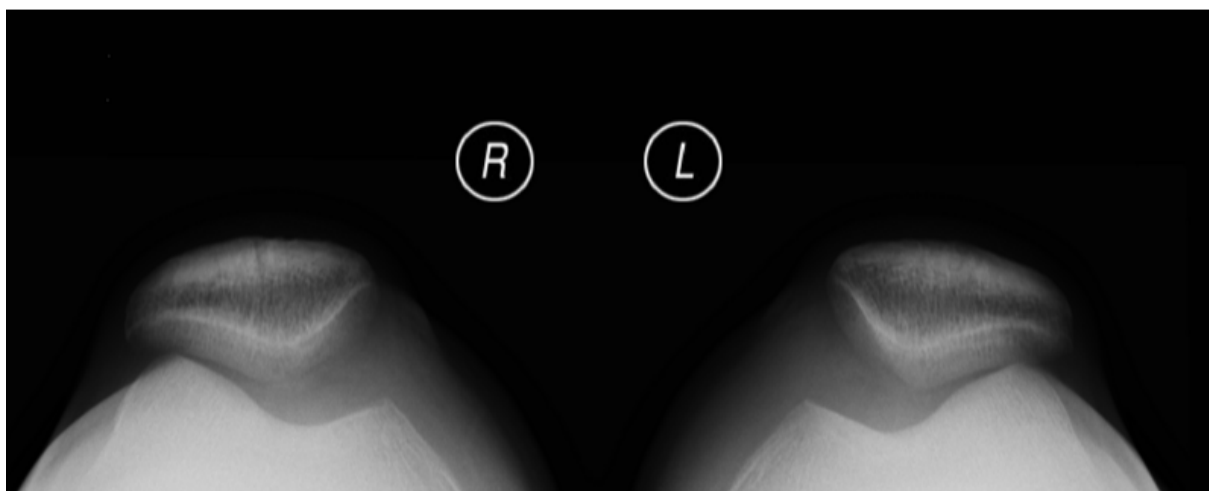


Figure 2.5 Patellar lateral displacement (ShareMyRadiology, 2012)

After knowledge of common diagnostic ways for recognising PFP, it is important in injury prevention programs to identify the risk factors that cause this condition. The development of prevention programs are considered an effective strategy in reducing the occurrence of PFP.

Many studies with several methodological approaches have investigated and attempted to explain the causal relationship for the injury, but conclusive evidence is lacking and various risk factors have been identified (Devereaux & Lachmann, 1984; Pappas & Wong-Tom, 2012).

2.6. Risk factors of PFP

The risk factors of PFP have been described in several studies and have been shown to be multifactorial, and linked to the pathophysiology of PFP (Lankhorst et al., 2012). Intrinsic and extrinsic factors are the two main factors associated with development of PFP via alterations in patellar tracking, increased patellofemoral joint forces, or combinations of these biomechanical features (Witvrouw et al., 2000). The intrinsic factors refer to the physical and psychological characteristics of the individual, and extrinsic factors related to the outside environment of the human body, such as sport activities or the environmental conditions (Witvrouw et al., 2000).

Previous studies have identified a variety of risk factors leading to abnormal tracking of the patella. As a consequence of this abnormal tracking, internal knee pain or PFP has developed (Duffey et al., 2000; Fulkerson & Arendt, 2000; Thomeé et al., 1999). The identified risk factors can be classified into lower limb structural and alignment abnormalities, muscle weakness, and dynamic malalignment. A review of these will be presented next.

2.6.1. Lower limb structural and alignment abnormalities

Quadriceps Angle

The Q-angle is the angle formed by the quadriceps femoris force vector and the patella ligament force vector. The force vector of the quadriceps femoris is represented by a line connecting the anterior superior iliac spine (ASIS) to the centre of the patella. The force vector of the patellar ligament is represented by a line connecting the tibial tuberosity to the centre of the patella. The relative angle that is formed between these two lines defines the Q-angle (figure 2.6) (Livingston, 1998; Melicharek et al., 2011). A greater Q-angle is believed to change the pressure contact area in the PFJ, causing in areas experiencing excessive stress that could not be manageable physiologically (Duffey et al., 2000). An increased Q-angle was reported as a risk factor of PFP by Aglietti et al., (1983); Haim et al., (2006); Messier et al. (1991); Emami et al., (2007). Same finding was found in one systematic review based on nine case control and cross sectional studies (Lankhorst et al., 2012). Q-angle value excess 20 degrees may increase development of PFP (Haim et al., 2006).

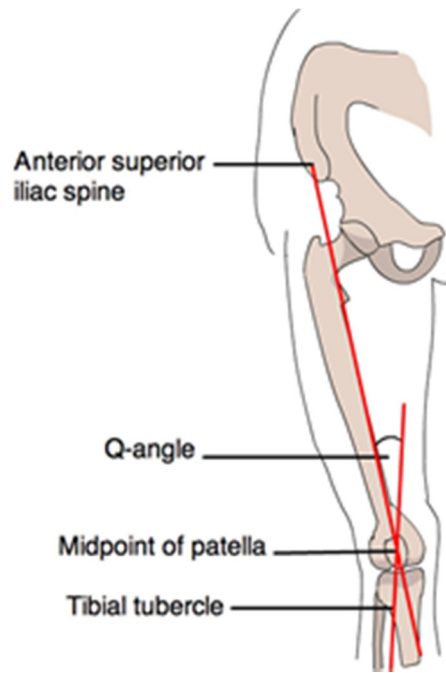


Figure 2.6 The Q-angle (Marra, 2013)

In the literature, Four prospective studies have measured the difference between the Q-angle in individuals who developed PFP and in individuals who did not (Rauh et al., 2010; Boling et al., 2009; Thijs et al., 2011; Witvrouw et al., 2000). Only Rauh et al., (2010) found there was association between static Q-angle that assessed from a standing position and development of PFP. Participants with a right or left Q-angle $\geq 20^\circ$ were nearly two times and more likely to incur a PFP injury, respectively, than recruits with a right or left Q-angle $< 20^\circ$ (right: OR = 2.3; 95% CI: 1.3-4.0; left: OR = 1.9; 95% CI: 1.1-3.3). No significant associations were found between the Q-angle and PFP in any of the other three studies. However, if the Q-angle is seen as a risk factor then the position in which the measurements are taken needs to be appraised. In the study by Witvrouw et al. (2000), the measurement was taken statically for 282 participants from the supine position, which did not reveal changes in the alignment of the lower extremities during weight bearing. In an earlier study, significant differences between the measurement of the Q-angle in standing and supine positions were found by Woodland & Francis (1992) and consequently, standing position was recommended. In another study conducted by Thijs and colleagues, they measured Q-angle of 77 female runners statically from standing position and found no difference between the participants who developed injuries and those who did not. This could be due to the investigated sample size (77 Female runners), which may be too small to elicit the differences between the two groups Thijs et al. (2011). Boling et al. (2009) measured the Q-angle in 1319 midshipman from a standing position and

40 went on to develop the injury. No association was found between the Q-angle and development of PFP. The reason for this result could be the proportion of participants who developed PFP (only 3% of 1319), compared to the number of participants during the study, given the lack of information in the medical records and the self-treatment for PFP, as is stated in the limitations of the study (Boling et al., 2009). Additionally, static clinical measurements have been advocated as non-reliable measurements (Smith et al., 2008).

While clinical Q-angle measurements appear to be not related to PFP in the previous prospective studies, biomechanical dynamic parameters have been proposed with respect to PFP development (De Oliveira et al., 2015; Witvrouw et al., 2014; Thijs et al., 2011; Boling et al., 2009). However, recently several studies have reported that the mechanism of PFP can be better observed in dynamic rather than static position due to the higher muscular demands that are needed to perform the physical activities (De Oliveira et al., 2015; Graci and Salsich, 2014). Powers, (2010) reported that dynamic knee valgus which is corresponded with dynamic Q-angle has been anticipated to contribute to PFP development. Therefore, it may be a useful method to determine the contribution of the Q-angle during performing dynamic tasks. However, there is a recent trend towards measuring the Q-angle dynamically during physical activity (Chen & Powers, 2010; Massada, Aido, Magalhães, & Puga, 2011; Melicharek et al., 2011). Massada et al. (2011) investigated the relationship between the dynamic Q-angles during tasks and PFP, using 3D. The Q-angle was significantly higher in the PFP group compared to the control group (34.9° vs 22.3°) and the relationship between a greater dynamic Q-angle and PFP was ($r = 0.517$) (Massada et al., 2011). Therefore, the measurement approach should be a dynamic Q-angle measurement, but the accuracy and reliability of this measurement has not been established within the current literature.

Foot pronation

It has been proposed that an increase of foot pronation is associated with PFP (Neal et al., 2014). The subtalar and metatarsal joints have triplanar motion, occurs simultaneously in the three main motion planes (Astrom et al., 1995). Movement of the subtalar joint is also coupled with the rotation of the tibia. It is pronated with the internal rotation of the tibia and supinated with its external rotation (Nawoczinski et al., 1998). It is claimed that PFP is a result of an alteration of the dynamic alignment of the tibiofemoral joint, which leads to a decrease in the area of contact in the PFJ. According to this theory, in the neutral condition, foot pronation occurs in the first 30% of the gait cycle in order to help the lower limb with the absorption of ground reaction forces (Tiberio, 1987; Powers et al., 2002). During prolonged foot pronation

after the first 30%, the tibia is rotated internally and due to this rotation, the femur rotates internally during knee extension. This increases hip adduction and lateral PFJ stress (Powers, 2003; Gross & Foxworth, 2003; Tiberio, 1987). Another study demonstrated that an increase in hip adduction is associated with excessive rearfoot eversion (Barton et al., 2012). Therefore, excessive foot pronation may be a risk factor of PFP. Decreases in flexibility of soleus and gastrocnemius muscles are considered to be another potential influencing factor. Foot pronation may be a result of compensatory mechanisms when there is a decrease in flexibility of soleus and gastrocnemius muscles, and when the ankle has to achieve the required range of dorsiflexion during movement (Piva et al., 2005; Witvrouw et al., 2000). However, researchers have measured subtalar joint pronation with several approaches, statically as with navicular drop, rearfoot and forefoot posture (valgus / varus), and arch index, and dynamically with rearfoot eversion angle during weight bearing activities (Earl et al., 2005; Powers et al., 2002; Duffey et al., 2000; Messier et al., 1991).

Earl et al. (2005) reported that the individuals with PFP demonstrated less navicular drop compared to the healthy individuals, and that the same individuals with PFP demonstrated increased pronation during dynamic tasks. Individuals with PFP have been reported with significant increases in the rearfoot varus angle (8.9 vs. 6.8 degrees; $P = .0002$) when measurements were applied with the subtalar joint in neutral, from prone position (Powers et al., 1995). In contrast, another study found a significant decrease in arch index ($F = 3.91$, $P = 0.050$) within the PFP group, compared to the healthy group (Duffey et al., 2000). Very limited evidence has indicated that individuals who exhibit increased pronated foot posture, measured using navicular drop, are more likely to develop patellofemoral pain (Neal et al., 2014; Dowling et al., 2014). These conflicting results from the previous studies may be due to the use of different methods for static measurements of foot pronation, which do not provide sufficient explanation of its connection to PFP, as during dynamic movement (Dierks et al., 2008; Duffey et al., 2000; Powers et al., 1995; Earl, et al., 2005).

Rearfoot angle is the angle that is formed between lower leg line and calcaneus line, in reference to subtalar posture (Powers et al., 1995). Powers et al. (1995) describe rearfoot eversion as one of the anatomical factors that contribute to increases of foot pronation in PFP. They reported significant increases in rearfoot eversion angle during weight bearing for the PFP group compared to the healthy group. A rearfoot angle greater than 4° to 6° is considered to be excessive rearfoot eversion (Kagaya et al., 2013). Rearfoot eversion has been reported to

be correlated with and hip adduction and Q-angle (Dileep et al., 2017; Barton et al., 2012). It has been stated that hip abductor and rearfoot dysfunction are important factors for dynamic knee valgus (Kagaya et al. (2013).

The association between increases in rearfoot eversion and PFP has been investigated prospectively in three studies (Noehren et al., 2013; Witvrouw et al., 2000; Hetsroni et al., 2006). No association was found between rearfoot eversion and PFP in these studies. These results may be partly due to the fact that the measurement of lower leg-heel alignment was based on static measurement using photographs, as in the study of Witvrouw et al. (2000), or due to the fact that the measurement that was used by Hetsroni et al., (2006) was based on walking barefoot on the treadmill using 2D, which may not be valid as more dynamic activities are associated with PFP. They may also be due to the fact that walking may not offer the potential to detect the differences between the injured and non-injured group, or due to the fact that the sample size estimation was based on the potential differences of another variable, as stated by Noehren et al. (2013). However, dynamic rearfoot measurements would reflect the increased loading during activities and examine their association to increased dynamic knee valgus, particularly with valid and reliable measurements (Figure 2.7).

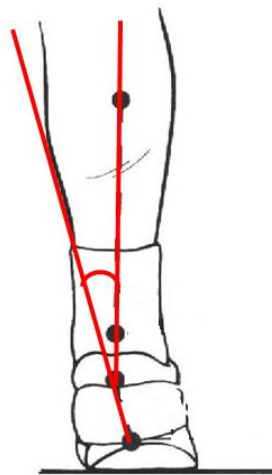


Figure 2.7 Measurement of rearfoot eversion (Hall, 2012)

2.6.2. Muscle weakness

Weakness and imbalance of hip and knee muscles have been reported as a factor of PFP (Dierks et al., 2008; Magalhães et al., 2010; Piva et al., 2005; Willson & Davis, 2008; Lankhorst et al., 2012). Several studies have found significant decreases in hip abductor, hip external rotators and knee extensors strength, in addition to decreases in explosive strength and vertical jump in PFP subjects (Piva et al., 2005; Willson et al., 2008).

Boling et al. (2009); Duvigneaud et al., (2008); Milgrom et al., (1991); Van Tiggelen et al., (2004); Witvrouw et al. (2000); Herbest et al., (2015) prospectively investigated the association between quadriceps muscle strength and development of PFP. Surprisingly, one of these studies reported a 6 % increase in isometric strength of quadriceps muscles for participants who developed PFP, compared to those who did not (Milgrom et al., 1991). In contrast to these results, Boling et al., (2009); Duvigneaud et al., (2008) Witvrouw et al., (2000) and Van Tiggelen et al., (2004) reported significant decreases in quadriceps muscle strength in PFP participants, while, Herbest et al., (2015) study was not able to detect any difference between the two groups. The increase of quadriceps strength that was reported by Milgrom et al. (1991) may due to the limitations resulting from the fact that they did not normalise the data of the quadriceps strength to body mass.

Weakness of hip muscles has been theorised to affects patella movement within the femoral trochlea (Powers, 2003). The results of the PFP group demonstrated 15% to 36% lower strength values in isometric hip abduction and external rotation strength tests, compared with those of healthy participants (Bolgia et al., 2008; Ireland et al., 2003; Willson et al., 2008). A recent systematic review has reported that hip abduction weakness, evaluated by handheld dynamometer, was found to be a significant factor for the development of patellofemoral pain (Mucha et al., 2016).

Four prospective studies have investigated the relationship between PFP and weakness of hip muscles (Boling et al., 2009; Youri Thijs et al., 2011 Finnoff et al., 2011 and Herbest et al., 2015) . Boling et al., (2009) assessed isometric hip abductors and external rotators strength using HHD. Only 3% (40 participants, of which 24 male and 16 female) of a total of 1319 participants developed PFP during a 2.5 years follow-up period and an increase of hip external rotation strength was reported as a risk factor of developing PFP (Boling et al., 2009) whereas, no association was found for hip abductor strength. Opposite findings were reported in Finnoff et al., (2011) study. They assessed isometric hip abductors and external rotators strength in 98 athletes runners participants from 5 high schools (53 male, 45 female), five participants developed the injury. The baseline hip external-to-internal rotation strength ratio was lower in injured than in uninjured subjects ($P = 0.008$) and a trend towards higher baseline hip abduction-to-adduction normalized torque percent ratio was seen in injured subjects ($P = 0.09$). In the third prospective study Thijs et al., (2011) evaluated hip abductors and external rotators with the same previous approach in 77 female runners. 16 participants developed PFP injury, no significant difference was found between hip muscle strength in participants with the injury

and those without. Recent research constructed by Herbest and colleagues, evaluated isokinetic hip abductors and knee extensors muscle strength for 255 female basketball middle school participants and 38 were developed PFP. Hip abductors muscle strength with PFP group was greater than non-injured group ($P < 0.05$) (Herbest et al., 2015).

Increases in the strength of hip abductors and hip external rotator muscles that were reported by prospective studies of Herbest et al., (2015); Boling et al. (2009) in addition to negative results that were reported by Thijs et al., (2011) appear to contradict the previous retrospective studies and Finnoff et al., (2011) prospective study. These conflicting results could be due to errors from HHD used to measure muscle strength, or be a result of conducting measurements with the dynamometer being held by the experimenter, or not being stabilised or secured to provide steadied resistance. The stabilisation of the HHD, for instance by using an immovable belt, would improve the reliability of the measurements and may yield important differences between strength measurements in the group (Katoh & Yamasaki, 2009; Wikholm & Bohannon, 1991). Another reason which may have lead to these results is by testing isokinetic hip abductors muscle strength with fixed dynamometer from standing position which may have been affected from the influence of contralateral limb (Widler et al., 2009) Also the value of isokinetic muscle strength with a high angular velocity during assessment of knee extensors may be lower than the present value because the movement only contains acceleration to maximum velocity (Bartlett and Paton, 1996).

In different types of musculoskeletal injuries, there is a need for a strengthening evaluation in the clinic. Strengthening evaluation enables clinicians to determine the baseline level of the athlete's strength for the generation of deferential diagnoses and for the development of a treatment plan, as an addition to follow up on the efficacy of the treatment (Kawaguchi & Babcock, 2010; Wadsworth et al., 1987). For decades, manual muscle testing was the most common method for muscle strength and function assessment during the clinical evaluation in the presence of disease or pathology (Kendall et al., 2005). However, there are some limitations in using this method. One of them is the deficiency of objective grading of muscle strength (Wadsworth et al., 1987; Frese et al., 1987; Smidt and Rogers, 1982). Another is the difficulty of scale consistency in a typical grading system, particularly with an increasing number of measurements (Kendall et al., 2005). Many attempts have been made by researchers to develop the assessment method for muscle strength. The isokinetic dynamometer was one of these attempts that is accepted for the clinical use of muscle assessment (Martin et al., 2006; Kawaguchi & Babcock, 2010). The isokinetic dynamometer provides an accurate evaluation

for both dynamic and static muscle strength, and it is considered to be the first choice for clinical studies (Drouin et al., 2004; Martin et al., 2006). However, due to its spatial and temporal cost, lack of portability, and complexity to set up or use, it is not practical to use in large-scale screening in epidemiological studies or useful to the field of sport. Thus, HHD is the alternative method for muscle strength assessment (Kawaguchi & Babcock, 2010; Edwards and McDonnell, 1974).

Handheld dynamometer

The HHD is a device used for muscle strength assessment and preferred for clinical use due to the ease of application, the relatively low cost of its use and the portability. In HHD assessments, examiners hold the HHD and apply force against the force of the athlete's tested limb (Kawaguchi & Babcock, 2010; Edwards and McDonnell, 1974). Good validity and repeatability has been established and it has been used widely (Bassey and Harries, 1993; Kuh et al., 2002; Martin et al., 2006). However, HHD cannot be used for certain muscle groups, and has been more difficult particularly for lower limb strength and lower limb muscle strength assessment (Holmback et al., 1999; Symons 2005). Various protocols for using HHD have been developed to measure upper and lower extremities' muscle strength in order to improve the validity and reliability.

Compared to the gold standard in muscle strength measurement of the isokinetic dynamometer, validity of HHD for lower extremity muscle strength has been investigated in several studies. A number of studies reported that evaluating the lower extremity muscle strength for physically active individuals with HHD has some limitations, which are related to the hand stabilisation of the instrument and changing the angle of the joint, especially if the subjects are stronger than the examiner, or in the case of large-scale screening (Vasconcelos et al., 2009; Katoh et al., 2011). However, it has been found that the validity and reliability of isometric muscle strength were increased when using HHD with a stick, steel support, or belt (Vasconcelos et al., 2009; Kolber et al., 2007; Gagnon et al., 2005; Johansson et al., 2005; Brinkmann, 1994; Katoh et al., 2009, 2010, 2011). Katoh et al., (2009) assessed the reliability of isometric muscle strength when using HHD with a belt for lower limbs (abduction, adduction, flexion, extension, internal and external rotation of the hip, knee flexion and extension, and ankle dorsiflexion and planter flexion) and found ICC results ranging from 0.75 to 0.97, SEM and MDD were not reported (Katoh et al., 2009). Interrater reliability using HHD with a belt was found ranging from 0.97 to 0.99, whereas it ranged from 0.21 to 0.88 for measurements without a belt. When the belt was applied, the measurements were significantly higher with paired t-test (Katoh et al., 2009).

Hansen and colleagues assessed within session reliability for knee extensors using HHD with belt and found ICC = 0.93, SEM was 5.4 N.m with a MDD of 15.1 N.m (Hansen et al., 2015). Using the stabilized HHD with belt for knee extensors muscle strength evaluation, has shown excellent reliability and moderate to excellent reliability for knee flexors (Hansen et al., 2015; Toonstra and Mattacola 2017; Katoh, 2015; Kim et al., 2014; Thorborg et al., 2013). For the hip muscle strength, excellent reliability has been observed for flexors, extensors, abductors, adductors, by number of studies (Thorborg et al., 2013; Kramer, 1991; Ieiri et al., 2015).

Several studies have reported the validity of isometric muscle strength measurements obtained with the HHD for various muscles in lower limbs, in comparison with the measurements obtained with the isokinetic dynamometer (Katoh et al., 2009). The knee extensors muscle strength with HHD displayed moderate to high correlation with isokinetic dynamometer (r range = 0.47 – 0.93) (Hansen et al., 2015; Kim et al., 2014; Katoh et al., 2011). Katoh et al., (2012) investigated the correlation between the HHD with belt and isokinetic dynamometer for hip muscle and knee flexors. The investigators observed high correlation for knee flexors (r = 0.88), and moderate to high correlation for hip muscles (r range = 0.52 – 0.86), but correlation was low for hip abductors (Katoh et al., 2011). Recently Martins et al., (2017) observed high correlation between stabilized HHD with belt and isokinetic dynamometer for knee extensors and hip abductors (r range = 0.78 – 0.90).

However, despite the resistance that is provided by using an immovable belt for HHD in the previous studies, they have some limitations in the validity and reliability and not practical to use for large scale screening. It is either, due to that HHD being not stable and secure during maximal force tests as well as the procedure takes more time for adjustment the belt and the HHD position which may limit the number of participants in large scale screening, or it was coupled with isokinetic dynamometer and positions which will not be available in field and will not reflect daily clinic practise, in addition the absence of reporting SEM in some reliability studies or the reliability was assessed within session only, so further evaluation is needed to validate the suitable protocol for the current study.

2.6.3. Kinetic Abnormalities

It has been claimed that altered kinetics of the lower extremity during tasks contribute to the development of PFP. Besier et al., (2009) found that the knee extension moment during running was significantly lower (13 % p = 0.041) in the PFP group, compared with the healthy group. Kinetic variables were investigated prospectively in three studies (Boling et al., 2009; Myer et

al., 2010; Stefanyshyn et al., 2006). Knee valgus load was evaluated in two prospective studies during running and landing tasks (Myer et al., 2010; Stefanyshyn et al., 2006). Myer et al. (2010) investigated landing biomechanics in 240 middle and high school female athletes at the beginning of the competitive school sports season. Three-dimensional hip, knee, and ankle kinematic and kinetics during drop vertical jump (DVJ) were assessed. They reported that nearly 25% of the participants developed PFP and demonstrated an increase in the knee abduction moment at initial contact during landing in those individuals. The generalisability of the results of this study is limited because they are young adolescent girls and it is questionable whether this was true for the majority of the population. Stefanyshyn et al. (2006) investigated the association between knee abduction impulse and PFP prospectively in 80 runners (41 male and 39 female) over a six month running period. Knee abduction impulse is the time effect of the total knee abduction moment load during the stance phase, and is calculated by multiplying the load with length of time (Stefanyshyn et al., 2006). Six participants (3 male and 3 female) developed PFP and the prospective data showed that they had significantly ($P = 0.042$) higher knee abduction impulses (9.2 ± 3.7 Nms) than those who did not develop the injury (4.7 ± 3.5 Nms) during stance phase.

In another aspect, two studies have investigated foot plantar pressure prospectively (Thijs et al., 2008; Thijs et al., 2007). Thijs et al. (2007) evaluated 84 individuals (65 male and 19 female) who entered military academy before the start of the six week basic training. In this study, plantar pressure measurements were used to assess participants during walking. Thirty-six participants (25 male and 11 female, 43%) developed PFP. Statistical analysis revealed that there was a significant increase in the lateral pressure distribution at initial contact of the foot, shorter time to maximal pressure on the fourth metatarsal and slower maximal velocity of the change in lateromedial direction of the centre of pressure during the forefoot contact phase. In the second study, Thijs et al. (2008) evaluated the standing foot posture of 102 novice runners (13 male and 89 female) using the foot posture index (FPI) and plantar pressure measurements in running, before starting a 10 week running program. Seventeen participants who developed PFP were found to have higher vertical peak force underneath the lateral heel and metatarsals two and three. However, in both of the two studies, planter foot pressure was measured with barefoot, which may be not useful for baseline assessment for participants who will be shod during the follow-up period. Barefoot planter pressure will not be equal to shod planter pressure that may be influenced with the shoes which may also effect on the dynamic movement of foot and lower limb of participants.

In one recent study, Luedk et al., (2016) investigated the relationship between step rate and AKP. They measured the step rate for 68 high school cross-country runners in constant speed (3.3 m.s^{-1}) and in self-selected speed (mean, $3.8 \pm 0.5 \text{ m.s}^{-1}$), and followed them prospectively during an interscholastic season. No association was found between the step rate and AKP. However, step rate is influenced with several factors as leg length, participants' height, and other anthropometric characteristics the may have effect on the results.

2.6.4. Kinematic Characteristics and dynamic abnormalities

Dynamic abnormalities of the lower limb are the abnormal patterns of movement during functional screening tasks that may cause improper tracking of the patella within the femoral trochlea (Earl et al., 2010). Many studies have investigated the kinematics of the lower extremities during screening tasks (Barton et al., 2010; Crossley et al., 2002; Dierks et al., 2008; McClinton et al., 2007; Powers et al., 1995).

Increases in hip adduction and internal rotation during landing and running are dynamic malalignments that have been reported to increase the risk of injury (Powers, 2010; Willson & Davis, 2008; Neal et al., 2016). These dynamic malalignments contribute to an increase in knee valgus and affect the patella's normal tracking in the trochlea of the femur, causing decreases in the PFJ contact area and increasing the forces on the joint (Powers, 2010; Salsich & Perman, 2007; Willson & Davis, 2008).

Dynamic knee valgus is a common pattern of the knee movement which has been found to be associated with PFP. It is a result of the combination of hip adduction and internal rotation, tibia abduction with external rotation, and foot pronation movements (Figure 2.8). Increases in dynamic knee valgus during tasks is an important element in identifying those who are at risk of developing PFP (Decker et al., 2003; Ford et al., 2003; Lephart et al., 2002; Malinzak et al., 2001; Pollard et al., 2006). Two prospective studies have assessed the kinematic differences of the hip movement between the participants who developed PFP and those who did not (Boling et al., 2009; B. Noehren et al., 2013). Boling et al. (2009) reported an increase of hip internal rotation with the PFP group, $7.6^\circ (\pm 8.9^\circ)$ injured / $7.2^\circ (\pm 8.4^\circ)$ uninjured, and used a regression model which was able to significantly predict the development of PFP ($P = .04$) with this increase. Noehren et al. (2013) investigated the association between hip adduction and PFP prospectively in 400 female runners using 3D during running, over a two year period. 15 participants developed PFP and the prospective data shows that they observed a significantly

greater HADD angle ($P = 0.007$), ($12.1^\circ \pm 2.8^\circ$) for the PFP group and ($8.1^\circ \pm 4.5^\circ$) for the control group (B. Noehren et al., 2013).

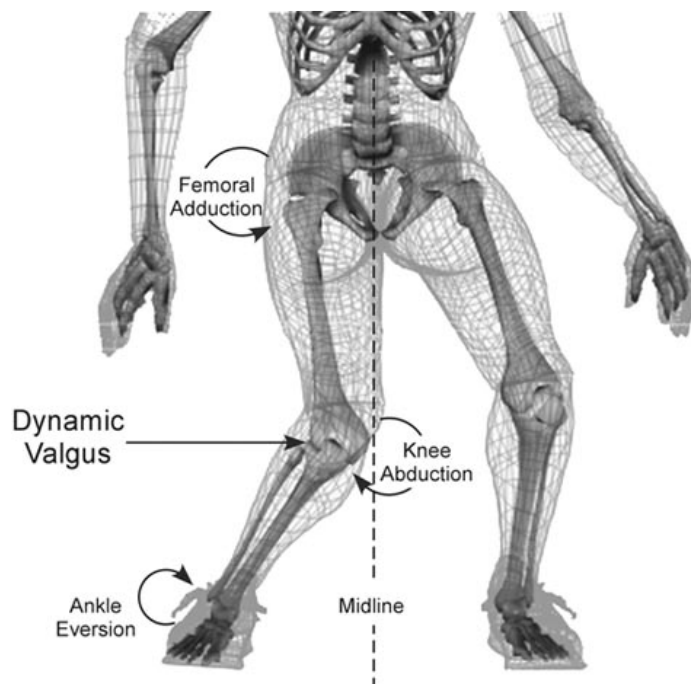


Figure 2.8 Dynamic Knee valgus

Decreased flexibility of the gastrocnemius and/or soleus muscles can cause a decreased range of motion (ROM) of dorsiflexion. This may lead to compensatory foot pronation in order to achieve the required dorsiflexion ROM at the ankle during gait and other activities (Piva et al., 2005). Individuals with PFP demonstrate significant decreases in the length of gastrocnemius and soleus, compared to healthy individuals (Piva et al., 2005). It has been reported that the decrease in dorsiflexion ROM is correlated to increases in knee valgus as a compensatory movement (Sigward & Powers, 2008). Witvrouw et al. (2000) prospectively investigated dorsiflexion ROM and found a significant increase in the gastrocnemius tightness in participants who developed PFP, compared with the healthy group. Therefore, the author hypothesized that any increase in gastrocnemius tightness will be translated in the kinematics of the ankle and foot during movements.

Earl et al., (2005) reported an association between a decrease in knee flexion angle and PFP during the step down task and other studies found similar results during stair ambulation in the individuals with PFP (Crossley et al., 2004; Powers, 1998). Boling et al. (2009) evaluated dynamic knee flexion angle with 3D during a bilateral jump-landing task and reported significant decreases (c.4-5 degrees) in the angle in participants with PFP.

Two previous systematic reviews and meta-analyses in the literature have investigated the prospective evaluation of risk factors for the onset of PFP (Pappas & Wong-Tom, 2012; Lankhorst et al., 2012). Both reviews included seven studies, which were slightly different, due to the variation in the data sources and inclusion and exclusion criteria of the search. Pappas & Wong-Tom, (2012) included (Boling et al., 2009; Milgrom et al., 1991; Thijs et al., 2007; Thijs et al., 2008; Van Tiggelen et al., 2009; Witvrouw et al., 2000; and Myer et al., 2010) and Lankhorst and colleagues included (Boling et al., 2009; Milgrom et al., 1991; Thijs et al., 2007; Van Tiggelen et al., 2004; Van Tiggelen et al., 2009; Witvrouw et al., 2000; and Duivigneaud et al., 2008). Both reviews concluded that lower knee extensor muscle strength may be a predictor for PFP development. However, in the other risk factors, there was a lack of agreement amongst the studies, which are likely due to the differences in the variables considered and measurement methods used. More importantly, the two previous systematic reviews included only seven studies, so only a limited number of variables were possible to be pooled in a meta-analysis and several risk factors were described individually, each in a single study.

Different screening tests have been undertaken by researchers to evaluate dynamic knee valgus. They have included running (RUN), single leg squatting (SLS), single leg landing (SLL) and drop landing tasks. Most of the previous studies have used 3D methods to quantify the biomechanics of lower limb. This enables clinicians and researchers to accurately quantify all three planes of joint motion during different tasks. This method is seen as a gold standard for this type of analysis. However, in injury prevention programmes, there is a need for large-scale screening within the field in order to identify high-risk athletes. Therefore, while 3D should be used, it is not practical to use it in a large screening programme due to the required space and to the extra time for marker placement. A method is needed that allows for a quick collection of data in a relatively small volume and in this, 2D may provide an alternative solution to 3D.

2.7. Two-dimensional motion analysis

Three-dimensional motion analysis is considered the gold standard for this type of analysis, but given the reasons mentioned above, there are increases in the use of 2D, because compared with 3D it is perceived as easy to use, portable and less expensive. Previously, 2D has been used for quantifying the knee valgus angle in healthy, injured, and athletic populations (Willson & Davis, 2008; Willson et al., 2006).

Recently, Sorenson et al. (2015) investigated 2D and 3D relationships between knee and hip kinematics during single leg drop landings and reported that 2D knee frontal plane projection angle (knee abduction angle) had a strong relationship with 3D knee abduction angle ($r^2=0.72$); additionally, 2D hip adduction angle had a strong correlation with 3D hip adduction angle ($r^2=0.52$).

However, there are two major technical errors associated with the limitations of using 2D. The first is the parallax error, which is the error that occurs when an object moves away from the optical axis of the camera. However, this technical error can be minimised by positioning the optical axis of the camera so that it is aligned with the central part of the motion and by focusing on the moving part of the target by zooming the lens of the camera. The second is the perspective error; this occurs when the object moves out of the calibrated plane (closer or away) and appears different in length and angle. Keeping the camera as far from the performer as possible, zooming to compensate the image size and maintaining the optical axis perpendicular to the calibrated plane would reduce this error (Kirtley, 2006; Krebs et al., 1985).

The 2D FPPA has been identified as a potential outcome measure for PFJ injury risk during large-scale screening and in the clinical environment (Willson et al., 2006). Frontal Plane Projection Angle is defined with three markers placed on the midpoint of the ankle, the centre of the knee joint and the proximal thigh. Frontal Plane Projection Angle is the angle that is formed between the line from the marker of proximal thigh to the marker of the midpoint of the knee joint and the line from the marker of the knee joint to the marker of the ankle (Figure 2.9) (Willson et al., 2008; Willson et al., 2006).

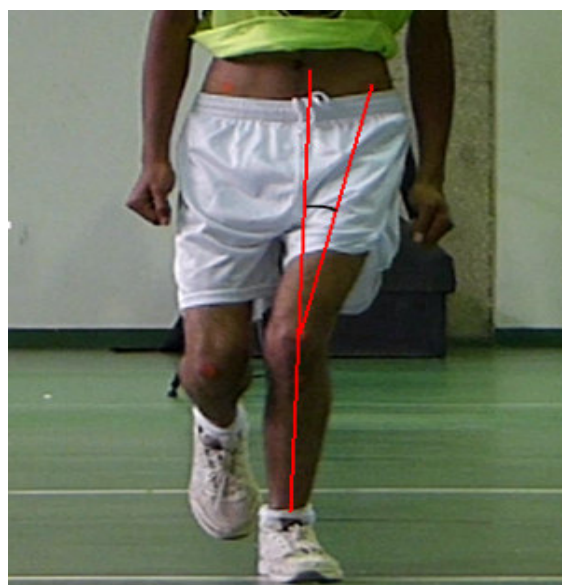


Figure 2.9 FPPA measurement

McLean et al. (2005) assessed the validity of 2D video analysis by measuring FPPA and compared it with the gold standard 3D. Two-dimensional motion analysis FPPA reflected 58% to 64% of the variance in average peak 3D knee abduction angle in side-jump and side-step tasks (McLean et al., 2005). Willson & Davis (2008) found that the two most important factors contributing to the dynamic knee valgus, hip adduction and knee external rotation angle, were significantly correlated with 2D FPPA. They concluded that 2D could be a useful method for quantifying knee valgus in order to identify high-risk athletes. Holden et al., (2015), reported a strong correlation between 2D and 3D measurements for medial knee displacement during DVJ and was statistically significant ($r = 0.946$; $r^2 = 0.894$; $P < 0.001$) (Holden et al., 2015). In a very recent study, Räisänen et al., (2017) assessed the relationship between FPPA and lower extremity injuries during SLS in 306 basketball and volleyball players, they found that it was able to predict the incidence of injury. Athletes displaying a high FPPA were 2.7 times more likely to sustain a lower extremity injury (adjusted OR 2.67, 95% CI 1.23 to 5.83) and 2.4 times more likely to sustain an ankle injury (OR 2.37, 95% CI 1.13 to 4.98). Whereas, there was no statistically significant association between FPPA and knee injury (OR 1.49, 95% CI 0.56 to 3.98). This negative findings of knee injury may due to that SLS task was not has the potential to predict the injury and may be other tasks could predict the knee injury better than SLS.

Despite the simplicity and advantages of using 2D FPPA, there are some factors that may contribute to affect the accuracy of measurements, in relation to either the 2D limitations or the dynamic movement. According to the 2D nature of FPPA, it is sensitive in motion in frontal and transverse planes and particularly during the single leg screening tasks (Willson et al., 2006). Therefore, it has been claimed that 2D FPPA cannot represent the same level of accuracy or magnitude as 3D lower extremity joint rotation during functional tests. However, 2D FPPA provides a valid and reliable measurement for lower extremity kinematics in the absence of 3D measurement (Munro et al., 2012; Willson & Dives, 2008). Multiple attempts have been made by researchers to minimise the variations of 2D FPPA values during screening tasks, by controlling the factors that may cause the occurrence of parallax error of 2D, such as degree of knee flexion angle or lower limb rotation angle (Willson & Davis, 2008; and Gwynne & Curran, 2014; McLean et al., 2005; Maykut et al., 2015; Sorenson et al., 2015). Therefore, selecting the appropriate screening test is crucial, because it is supposed to have the potential of identifying individuals who are at risk of PFP while it is applicable to use with 2D.

2.8. Screening tasks

Movement screening tasks have been used increasingly over recent years to provide an outcome measure to evaluate the athletes who return from injuries in both sport and clinical practice. In these functional movement tests, the athlete tries to mimic certain common actions in sport activities, such as RUN, SLS, SLL, VJ, stepping down and sprint test. Screening tasks provide an objective measurement for muscle strength, agility, joint laxity, proprioception and pain (Herrington et al., 2009; Loudon et al., 2004; Munro et al., 2012; Reid et al., 2007).

Single leg squat is one of the most common tasks used to evaluate dynamic function of lower limb, particularly in screening PFP. The SLS task has previously been used in investigating the correlations between 2D FPPA and 3D angles of lower limb (Willson & Davis, 2008). Hip abductors, hip external rotators, hip extensors and core musculature has demonstrated a significant impact on the FPPA during the single squat (Stickler et al., 2015). Willson & Davis (2008) reported that FPPA values represented medial knee displacement during SLS and it was associated with increased HADD angle ($r = 0.32$ to 0.38 , $P < .044$) and knee external rotation ($r = 0.48$ to 0.55 , $P < .001$), two of the components of dynamic knee valgus. Single leg squat has been used to distinguish between the participants with and without PFP, by demonstrating dynamic knee valgus (Whatman et al., 2011; Willson & Davis, 2008). Frontal Plane Projection Angle of the PFP group during SLS was significantly greater than FPPA of the healthy group ($P = .012$) (Willson & Davis, 2008). Furthermore, it has been suggested that this predicts the kinematics demonstrated during running or that it has mechanics similar to those of running during stance phase. Munro et al. (2012) investigated 2D FPPA for 20 participants (10 male and 10 female) during the SLS and found that the between-days ICC was good, (.88) for men and (.82) for women, with overall mean values of (8.64°) for men and (11.07°) for women.

Running is the most frequently performed task used by researchers to evaluate the dynamic function of lower limb. It has been suggested that the investigation into the biomechanics of running has the potential to identify individuals with risk factors of running injuries (Schache et al., 1999). Frontal Plane Projection Angle measured from PFP participants by Willson & Davis (2008), demonstrated a greater HADD angle during running, jumping, and squatting, compared with the healthy control group. Souza and Powers (2009) found greater peak hip internal rotation during running in individuals with PFP. Another study has found that runners who developed PFP had greater HADD angle, compared with the healthy group (Noehren & Davis, 2007). individuals with PFP have also been reported with greater knee abduction angular

impulse during the stance phase of running, compared with healthy individuals (Stefanyshyn et al., 2006).

Recently, Maykut et al., (2015) reported that 2D testing during running had excellent intrarater reliability for peak of the HADD (ICC = 0.951 – 0.963) and peak of Knee Abduction (KABD) (ICC = 0.955 – 0.976). Moderate correlations were found between 2D and 3D measurements for peak of HADD on the left (0.539; $P = .007$) and the right (0.623; $p = .001$) and peak of KABD on the left (0.541; $p = .006$), which were found only in the lower extremity (Maykut et al., 2015).

Single leg landing is one of the common tasks or techniques in sports, and it may be better than bilateral landing for the assessment of individuals who are at risk of knee injuries (Faude et al., 2005). Studies have shown that during unilateral tasks performers demonstrate an increase of knee valgus and HADD angle compared to bilateral tasks (Myklebust et al., 1998; Pappas et al., 2007). Single leg land screening task appears to be more sensitive than DJ in identifying individuals who demonstrate dynamic knee valgus, due to the increased demand to decelerate landing force, whereas this has not been investigated. The reliability of 2D FPPA during SLL was assessed by Munro et al. (2012), who reported good ICC in within-days and between-days for both men and women, with mean values of (4.69°) for men and (7.33°) for women.

Running, SLS and SLL are three activities that require single leg stance and weight bearing. Mechanics based on muscle function during these types of activities show that hip abductors play an important role to prevent pelvic drops and HADD and angle (Hollman et al., 2009). During motion hip abductors primarily stabilise femur in the frontal plane (McLeish et al., 1970). Therefore, it is logically the presence of an increased HADD angle that is associated with weakness of hip abductors muscles. Hip adductors have been associated with PFP (Ireland et al., 2003). Furthermore, individuals with PFP demonstrated an increased HADD angle and knee valgus (Powers, 2010; Willson & Davis, 2008). Recently, Stickler et al., (2014) investigated the relationship between hip strength (hip abductors, hip external rotators, hip extensors and core musculature) and frontal plane alignment during SLS. They reported that hip abduction strength was the greatest predictor of the variation in FPPA, at $r^2 = 0.22$, $p = 0.002$, with multiple regression analysis. Therefore, since weakness of hip abductors or hip adductors peak torque have been found to be correlated with knee valgus during SLS and landing, the author conclude to select hip abductors and knee extensors isometric strength to

be assessed with stabilized HHD, as the below methodology at the baseline of the study (Kagaya et al., 2013, Claiborne et al., 2006; Jacobs et al., 2007).

2.9. Previous screening and prevention approaches

It is assumed that 3D and isokinetic dynamometer are the gold standard for motion analysis and muscle strength measurement, but they are not practical to use for large scale screening for PFP prevention programmes due to cost, time and space required which will limit the number of screened individuals. Holden et al., (2015) demonstrated in a previous study that may use the appropriate screening measurement in terms of cost and portability of measurement instruments, and duration of data collection which enabled for large scale screening. They found that participants who developed PFP had a greater medial knee displacement. However, this study only used a kinematic assessment for medial knee displacement with 2D for adolescent girls with no strength measurement.

It has been suggested that there is a link between the development of PFP and biomechanical abnormalities (Neal et al., 2016). Several studies have investigated the biomechanical abnormalities thought to be associated with PFP, and targeted them for intervention and injury prevention programmes. Knee valgus, increased hip adduction, hip internal rotation, rearfoot eversion, decrease of hip abductors and external rotators, and decrease of knee extensors are some of the biomechanical characteristics that may lead to PFP development (Aglieetti et al., 1983; Al-Rawi & Nessian, 1997; Aliberti et al., 2010; Anderson & Herrington, 2003; Baker et al., 2002; Barton et al., 2010; Barton et al., 2009; Besier et al., 2008; Callaghan & Oldham, 2004; Cowan et al., 2002; Cowan et al., 2001; Crossley et al., 2004; Dierks et al., 2008; Dorotka et al., 2002; Draper et al., 2009; Noehren et al., 2013; Thijs et al., 2011; Myer et al., 2010; Van Tiggelen et al., 2009; Boling et al., 2009; Thijs et al., 2008; Duvigneaud et al., 2008; Thijs et al., 2007; Stefanyshyn et al., 2006; Van Tiggelen et al., 2004; Witvrouw et al., 2000; Milgrom et al., 1991; Finnoff et al., 2011; Herbst et al., 2015; Holden et al., 2015; Hetsroni et al., 2006; Rauh et al., 2010; Luedke et al., 2016; Neal et al., 2016). A recent study by Selfe et al., (2015) grouped PFP individuals into three subgroups (strong, weak and tighter, and weak and pronated feet) in order to be targeted for the intervention according to the findings of seven clinical tests based on measurements of range of motion, flexibility, strength, and FPI (Selfe et al., 2015). However, there was no kinematic screening or in particular FPPA screening. Therefore, lower limb kinematic should be included in the screening to detect the kinematic abnormalities in order to be one of the targeted intervention subgroups. In two systematic reviews and meta-analyses, aimed to guide treatment and prevent PFP, the results showed that running retraining

and proximal strengthening exercise for hip muscles combined with quadriceps leads to decreased pain, improved function, increased isometric hip strength, reduced peak hip adduction and decreased knee valgus variability during running (Lack et al., 2015; Neal et al., 2016). Herrington et al., (2015) is one of the studies that has been successful with a prevention programme for PFP, where they investigated the effect of six weeks jump-training landing on FPPA and found a significant decrease during the SLL and drop jump landing after the training, which was further decreased in combination with strengthening.

It has been determined that tools for screening studies are supposed to be simple, low cost, portable and easy to apply in order to offer the screening to a large number of individuals in order to identify the ones who are at risk of PFP development. Additionally, in planning for future prevention programmes the individuals that are at high risk of PFP should be grouped according to the finding of screening in order to be the targeted for a particular intervention.

2.10. Summary of literature review

The majority of the previous studies that have investigated the biomechanical risk factors for PFP have been retrospective studies (Aglietti et al., 1983; Al-Rawi & Nessian, 1997; Aliberti et al., 2010; Anderson & Herrington, 2003; Baker et al., 2002; Barton et al., 2010; Barton et al., 2009; Besier et al., 2008; Callaghan & Oldham, 2004; Cowan et al., 2002; Cowan et al., 2001; Crossley et al., 2004; Dierks et al., 2008; Dorotka et al., 2002; Draper et al., 2009). But given the study design, the question arises of whether the results are the effect of the condition, rather than an actual causation.

18 studies were found in the literature that investigated the biomechanical risk factors of PFP prospectively. Several methodology and measurement tools have been used in these studies (Noehren et al., 2013, Thijs et al., 2011; Myer et al., 2010, Van Tiggelen et al., 2009, Boling et al., 2009, Thijs et al., 2008, Duvigneaud et al., 2008, Thijs et al., 2007, Stefanyshyn et al., 2006, Van Tiggelen et al., 2004, Witvrouw et al., 2000, Milgrom et al., 1991, Finnoff et al., 2011, Herbst et al., 2015, Holden et al., 2015, Hetsroni et al., 2006, Rauh et al., 2010, Luedke et al., 2016). Three studies have used static measurements for lower extremities alignment and abnormality, such as Q-angle, genu varum/valgum, and navicular drop (Thijs et al., 2011, Boling et al., 2009, Witvrouw et al., 2000, Rauh et al., 2010). Muscle strength risk factors were assessed in eight studies (Boling et al., 2009; Duvigneaud et al., 2008; Milgrom et al., 1991; Thijs et al., 2011; Tiggelen et al., 2004; Witvrouw et al., 2000; Finnoff et al., 2011 and Herbst et al., 2015). The handheld dynamometer was used in three studies (Boling et al., 2009; Thijs et al., 2011; Finnoff et al., 2011) and fixed dynamometers, such as Cybex or Biodex were used

for strength measurement in four studies (Duvigneaud et al., 2008; Milgrom et al., 1991; Van Tiggelen et al., 2004; Witvrouw et al., 2000). Kinetic kinematic variables were quantified in four prospective studies using 3D motion analysis during RUN, jump-landing, and drop vertical jump (Boling et al., 2009; Myer et al., 2010; Noehren et al., 2013; Stefanyshyn et al., 2006; Holden et al., 2015). Two studies assessed muscle activation with EMG during tasks (Van Tiggelen et al., 2009; Witvrouw et al., 2000). Two studies investigated the relationship between plantar pressure and development of PFP during running and walking using a foot-scan pressure plate (Thijs et al., 2008; Thijs et al., 2007). One study assessed the association between step rate and AKP during running (Luedke et al., 2016). Finally, two studies investigated this association in lower extremity kinematics using 2D motion analysis (Hetsroni et al., 2006; Holden et al., 2015). In the first study, Hetsroni et al. (2006) assessed the kinematics of rearfoot motion walking on the treadmill, while Holden et al. (2015) used 2D FPPA for the first time for large scale screening in order to investigate the association between knee kinematics and incidence of PFP during DVJ.

2.11. Gap in the literature

From the previous prospective studies, several possible conclusions can be drawn. It could be that, since these studies were based on the use of high technology, so they are not practical to use for large-scale screening (Boling et al., 2009; Myer et al., 2010; Stefanyshyn et al., 2006). Further, the results are not generalizable (Myer et al., 2010), as they are based on static measurements (Thijs et al., 2011; Witvrouw et al., 2000; Rauh et al., 2010), or have looked at a single factor or observed during a single task (Thijs et al., 2011; Van Tiggelen et al., 2009). However, none of the studies reported their reliability and there is a lack of validation for the measurement tools (Boling et al., 2009; Thijs et al., 2011), as well as a low incidence rate of PFP in some of the studies (Boling et al., 2009). Only one recent study used 2D in knee valgus displacement during DVJ landing in adolescent females. No study has used stabilised HHD, or investigated the role of the 2D FPPA, dynamic Q-angle, or other lower limb kinematics during specific tasks in PFP risk. Additionally, none of the studies stated the time duration of data collection.

In the Saudi military population, it is notable, there is a high rate of knee injuries during the first three months of military training and that it is one of the common reasons for discharge or referral to hospital. Therefore, in order to further advance the current research and improve our understanding of the risk factors that contribute to the occurrence of PFP, this is the first study established towards investigating the risk factors of PFP among Saudi recruits. It is the first to

employ 2D for FPPA and HHD within the military population in order to screen for potential PFJ injury risk. Furthermore, it will also objectively assess the HADD angle, dynamic Q-angle, knee flexion, dorsiflexion, and knee extensor and hip abductor muscles strength. All of these measures will be explored for any relationship with the incidence of PFP. Aiming to detect the risk factors of PFP with low cost, portable, and easy to use tools, as an alternative valid and reliable solution to the gold standard (3D and isokinetic dynamometer) can increase the ease and capacity of screening individuals who are at risk of PFP.

This will allow for the development of more targeted intervention strategies to reduce injury risk, by identifying the main risk factors that contribute to the increase of the injury's occurrence. This will enable us to apply our future intervention for individuals who are considered to be at risk of PFP, after screening their populations, and working to stop or reduce the predicted negative impact as a risk factor.

2.12.Aims of the project

The aims of this study are therefore to:

- 1- Systemically review the previous prospective studies to establish the biomechanical differences between individuals with and without PFP.
- 2- Prospectively examine:
 - a) The use of 2D in FPPA, HADD, dynamic Q-angle, knee flexion, ankle dorsiflexion, and rearfoot eversion during running, SLS, and SLL to screen for PFP development injury occurrence in addition to the other lower limb injuries.
 - b) The use of HHD in isometric strength tests of hip abductors and knee extensors to screen for PFP development injury occurrence in addition to the other lower limb injuries.
 - c) Identify the risk factors that could be measured and have a clear relationship with the incidence of PFP more than the other risk factors

2.13.Research questions

The following research questions will be examined:

- 1) Are systematic review and meta-analysis of previous prospective studies able to identify the biomechanical differences between individuals with and without PFP?
- 2) Is there any difference between the kinematics of the lower limb joints in individuals who sustain patellofemoral pain and those who do not?

- 3) Is there any difference between hip abductors and knee extensors' strength in individuals who sustain patellofemoral pain and those who do not?
- 4) Which risk factor could be measured and has a clear relationship to the incidence of PFP more than the other risk factors?

2.14.Hypothesis

Therefore, the following null hypotheses will be tested within the study

1. H0₁: systematic review and meta-analysis of previous prospective studies will not be able to identify the biomechanical differences between individuals with and without PFP.
2. H0₂: There will be no significant difference between the kinematics of individuals who sustain patellofemoral pain and any other lower limb injuries, and those who do not.
3. H0₃: There will be no significant difference in muscle strength between the individuals who sustain patellofemoral pain and any other lower limb injuries and those who do not.
4. H0₄: There will be no risk factor that has a clear relationship to the incidence of PFP more than the other risk factors.

CHAPTER 3

Biomechanical risk factors of patellofemoral pain: A systematic review and meta-analysis

This chapter will undertake a systematic review and meta-analysis of previous prospective studies to focus on the literature in a scientific way to reduce bias in all stages of the review, in order to investigate the biomechanical differences between individuals with and without PFP.

3.1. Introduction

Patellofemoral pain is one of the most common sources of chronic knee pain in young athletes (Brody and Thein, 1998; Piva et al., 2006), accounting for 25 to 40% of all knee joint problems investigated in sports medicine clinics (Rubin and Collins, 1980; Chesworth et al., 1989; Bizzini et al., 2003). Patellofemoral pain is a major problem among physically active populations, such as adolescents, young adults, and military recruits (Messier et al., 1991; Cutbill et al., 1997; Duffey et al., 2000; Witvrouw et al., 2000; Laprade et al., 2003; Powers et al., 2003; Thijs et al., 2007). McConnell (1986) reported that one in four individuals is affected by PFP. In a retrospective study of individuals with PFP who were assessed between four and eight years after the initial injury, the results showed that knee pain was still present in 91% of the 22 individuals, while 36% were unable to continue their physical activity (Fulkerson and Shea, 1990). Utting et al. (2005) reported a connection between PFP and the development of patellofemoral arthritis, where 22% of 118 individuals with patellofemoral osteoarthritis had anterior knee pain when they were adolescents.

The primary symptom of PFP is pain arising from the anterior aspect of the knee joint (Powers, 1998), a pain which is commonly the result of activities that increase the compressive forces in the patellofemoral joint (PFJ), such as running, walking, ascending and descending stairs, prolonged sitting, and squatting (Levine, 1979; McConnell, 1996; Powers, 1998). Although there is no definitive aetiology for PFP, previous studies have identified predisposing factors, such as increased knee valgus, Q-angle, hip adduction angle, and rearfoot eversion, in addition to a weakness of hip abductor and knee extensor muscle strength (Thijs et al., 2007; Waryasz & McDermott, 2008; Pappas & Wong-Tom, 2012). However, it has been stated that the causes of PFP is multifactorial (Thijs et al., 2007). Therefore, there is a need to identify individuals who are at high risk of PFP in order to develop injury prevention programmes. The purpose of this study is to systemically review prospective cohort studies on the predictors of PFP.

3.2. Materials and Methods

3.2.1. Literature search strategy

A comprehensive search strategy was devised from the following electronic databases: CINAHL, MEDLINE; PUBMED, and WEB OF SCIENCE, up to February 2017 and using the following keywords: (*patellofemoral* OR *anterior knee*) AND *pain* AND (*risk* OR *predictor*) AND *prospective*. The search was limited to full-text prospective cohort studies written in English.

3.2.2. Selection of studies

Only prospective studies with healthy participants in the baseline assessment in order to monitor for PFP development were included in the systematic review. No limits with regard to age, sex, or physical activity were placed on searching the participants' characteristics. Single reviewer (H.A) screened articles based on their titles and abstracts, according to selection criteria. For the selected articles, a final decision about inclusion was made based on the full text articles.

3.2.3. Methodological quality

Two reviewers (H.A and H.G) independently assessed the quality of the studies using the Newcastle-Ottawa quality assessment scale (NOS) (Appendix A). Although several assessment scales for cohort studies exist, none of these have been fully validated. The Newcastle-Ottawa Scale is one of the assessment tools widely used by researchers for quality assessment of cohort studies in systematic reviews and meta-analyses. The NOS is composed of eight items for quality appraisal, easy to apply, in three main topics (selection, comparability, and outcome). However, the NOS for cohort studies was chosen in the current study because it has been found to be reliable and designed for the quality assessment of cohort studies (Wells et al., 2008). The eight assessment items of NOS rank studies with scores ranging from 0–9. The included studies were awarded point for each item when it corresponded with answer has a star. The NOS classified the included studies as high quality (HQ) with (7 – 9) scores, moderate quality (MQ) with (5 – 6) scores, and low quality (LQ) with (0 – 4) (Wells et al., 2001). Disagreement between the two reviewers was solved by discussion and consensus or consultation with a third reviewer (R.J).

3.2.4. Data extraction

One reviewer (H.A) extracted relevant data from the included studies by means of a standardised form, i.e. the author, year of publication, sample size (injured/non-injured), sex,

age, mass, height, definition of PFP, inclusion criteria, type of participants (e.g. recruits, athletes, or students), follow-up time, loss of follow-up participants, and assessment methods.

3.2.5. Data analysis

A meta-analysis was performed to establish factors associated with the development of PFP that had a consistent definition, and the results were reported for the same outcome measures. A fixed effect model was used to inspect the forest plot. Means and standard deviations (SD's) values for continuous scaled variables were extracted and used to calculate standardised mean differences (SMD) with 95% confidence intervals (CI's). Review Manager 5 (RevMan5) software package was used for the meta-analysis of this review. Statistical heterogeneity level was established using I^2 statistics and its P value. The heterogeneity was defined as $I^2 > 50\%$, $p < 0.05$ (Higgins et al., 2003). Levels of evidence were categorised based on the previous work of van Tulder et al., (2003) to:

- ***Strong evidence:***

Pooled results derived from three or more studies, including at least two high quality studies that are statistically homogenous; may be associated with a statistically significant or non-significant pooled result.

- ***Moderate evidence***

Significant pooled results derived from multiple studies that are statistically heterogeneous, including at least one high quality study; or from multiple moderate quality or low quality studies which are statistically homogenous.

- ***Limited evidence***

Results from one high quality study or multiple moderate or low quality studies that are statistically heterogeneous.

- ***Very limited evidence***

Results from one moderate quality study or one low quality study.

- ***No evidence***

Pooled results are insignificant and derived from multiple studies regardless of quality but are statistically heterogeneous.

3.3. Results

3.3.1. Characteristics of the included studies

560 potentially relevant articles were found from the database search. Using the Endnote system, 204 articles were automatically excluded due to duplication. In addition, 299 articles

were excluded from titles and abstracts because they are not relevant studies. Further, 42 articles were excluded from full text (20 articles for other studies (Cumps et al., 2007, Davis, 2007, Hanna et al., 2007, Berry et al., 2008, Wilson et al., 2009, Brennan et al., 2010, Echegoyen et al., 2010, Song et al., 2011, Peat et al., 2012, Wagemakers et al., 2012, Anhdung et al., 2013, Collins et al., 2013, Rathleff et al., 2013, Stefanik et al., 2013, Attal et al., 2014, Myer et al., 2014, Nielsen et al., 2014, Hsiang-Ling et al., 2015, Kastelein et al., 2015, Altman and Davis, 2016), 4 articles review (Barton et al., 2009a, Rathleff et al., 2014, Weiss and Whatman, 2015, Molloy, 2016), 2 articles with the full text not found (Mohtadi, 2001, Bout-Tabaku et al., 2015), 8 articles where there was no specific data for PFP (Leetun et al., 2004, Lun et al., 2004, Rauh et al., 2007, Zazulak et al., 2007, Lehr et al., 2013, Dingenen et al., 2015, Davis et al., 2016, Kuhman et al., 2016), 2 treatment and intervention studies (Huang et al., 2015, Ramskov et al., 2015), 3 retrospective studies (Duffey et al., 2000b, Tenforde et al., 2011, Barton et al., 2012a), and 3 studies with no data for the control group (Hetsroni et al., 2006a, Rauh et al., 2010, Luedke et al., 2016). Finally, 15 studies met the inclusion criteria (Milgrom et al., 1991, Witvrouw et al., 2000, Van Tiggelen et al., 2004, Stefanyshyn et al., 2006, Thijs et al., 2007d, Duvigneaud et al., 2008, Thijs et al., 2008, Boling et al., 2009, Van Tiggelen et al., 2009, Finnoff et al., 2011, Thijs et al., 2011, Noehren et al., 2013, Herbst et al., 2015, Holden et al., 2015, Myer et al., 2010) (Figure 3.1).

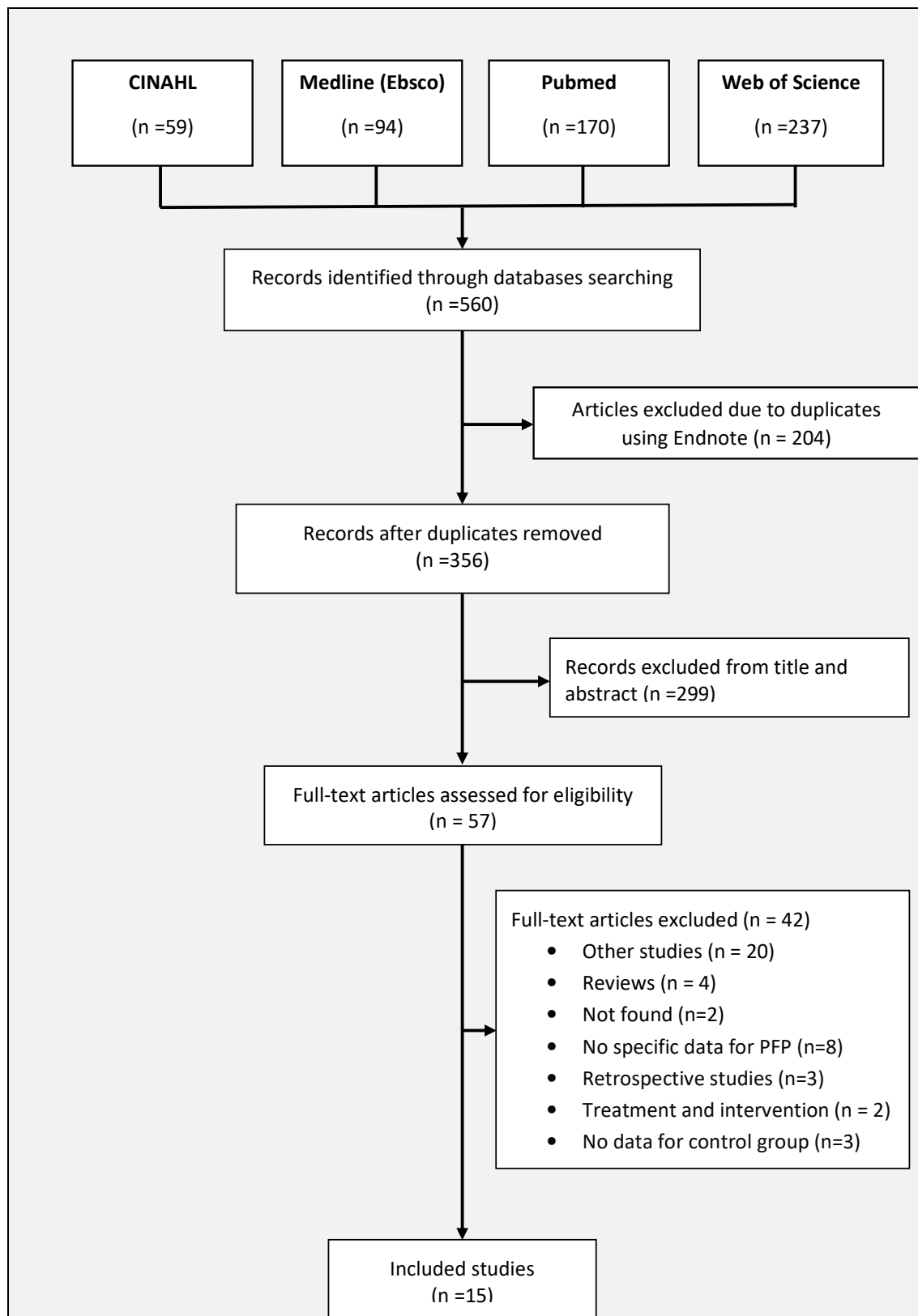


Figure 3.1 Flow chart of the process to select the relevant studies

3.3.2. Methodological quality

Table 3.1 Methodological Quality Rating Score

Study	Selection				Comparability		Outcome			Total
	Representative ness of the exposed cohort	Selection of non-exposed	Ascertainment of exposure	Outcome not present at start	important factor	additional factor	Assessment of outcome	Follow-up length 3m/1m	Adequacy of follow-up >80%	Total
Milgrom 1991	1	1	1	1	1	1	0	1	1	8
Witvrouw 2000	1	1	1	1	1	1	0	1	0	7
Van Tiggelen 2004	1	1	1	1	1	1	0	1	1	8
Stefanyshyn 2006	1	1	1	1	1	0	1	1	1	8
Thijs 2007	1	1	1	1	1	1	1	1	1	9
Thijs 2008	1	1	1	1	1	0	0	1	0	6
Duivgneaude 2008	1	1	1	1	0	1	0	1	1	7
VanTiggelen 2009	1	1	0	1	1	1	0	1	1	7
Boling 2009	1	1	0	1	1	1	0	1	1	7
Myer 2010	1	1	1	1	1	0	0	1	0	6
Finnoff 2011	1	1	1	1	1	0	0	1	0	6
Thijs 2011	1	1	1	1	0	0	1	0	1	6
Noehren 2012	1	1	1	1	0	0	0	1	1	6
Holden 2015	1	1	1	1	1	0	0	1	1	7
Herbst 2015	1	1	1	1	1	0	0	1	0	6

Table 3.1 presents the data about the methodological quality of the included studies. All initial disagreements were discussed until a consensus was reached. The quality scores ranged from 5 – 8 points. All the 15 studies scored positively in three items, including representativeness of the exposed cohort, selection of non-exposed and outcome not present at start. Only three studies (i.e. Stefanyshyn et al., 2006; Thijs et al., 2007; Thijs et al., 2011) obtained positive scores in relation to assessment of outcome and all included studies obtained positive in follow-up length except Thijs et al., (2011). Nine studies scored high quality (HQ) (Milgrom et al., 1991; Witvrouw et al., 2000; Van Tiggelen, 2004; Stefanyshyn et al., 2006; Thijs et al., 2007; Duvigneaud et al., 2008; Van Tiggelen et al., 2009; Boling et al., 2009; Holden et al., 2015) and six studies scored moderate quality (MQ) (Thijs et al., 2008; Myer et al., 2010; Finnoff et al., 2011; Thijs et al., 2011; Noehren et al., 2012; Herbest et al., 2015), and no studies scored low quality (LQ).

Table 3.2 Summary of included studies

No	STUDY	POPULATION	MEASUREMENTS	FINDINGS
1	Milgrom et al. (1991) 14 weeks	390 Infantry recruits	<ul style="list-style-type: none"> • Isometric strength of Quadriceps • 2-km run • Push-ups • Sit-ups in 60s 	<ul style="list-style-type: none"> ➤ Increase of quadriceps strength ➤ Increase medial tibial intercondylar distance
2	Witvrouw et al. (2000) 2 years	282 Physical Education Students Age (17-21) (151M/131F) 9% injured	<ul style="list-style-type: none"> • Isokinetic strength for quad and hams with (Cybex) • EMG • Lower leg Alignment • General joint laxity • Physical fitness assessment • Static patellofemoral alignment • (Q-angle- genu varum/valgum) • Physiological evaluation 	<ul style="list-style-type: none"> ➤ Shortened quadriceps muscle ➤ Altered vastus medialis obliquus muscle reflex response time ➤ Decrease vertical jump ➤ Patella hypermobility ➤ Increase of gastrocnemius tightness
3	Van Tiggelen et al. (2004) 6 weeks	96 male recruits Age (17-27) 31 injured	<ul style="list-style-type: none"> • Isokinetic Strength (Cybex) for knee FLX/EXT 	<ul style="list-style-type: none"> ➤ Decrease of normalised peak extensor torque at 60°/s ➤ Decrease of Peak torque/BMI
4	Stefanyshyn (2006) 6 months	80 runners (41M/39F) Age (F 35.9 ±8.8) (M 39.8 ±8.9) 6 injured (3M/3F)	<ul style="list-style-type: none"> • Kinetics and Kinematics (3D) during running 	<ul style="list-style-type: none"> ➤ Increase Knee Abduction impulses
5	Thijs et al. (2007) 6 weeks	84 cadets (65M/19F) Age (19 ±1.54) 36 injured (25M/11F)	<ul style="list-style-type: none"> • Planter pressure measurement with Footscan pressure plate during walking 	<ul style="list-style-type: none"> ➤ Heel strike in a less pronated position and roll over more on the lateral side

Table 3.3 Continued

No	STUDY	POPULATION	MEASUREMENTS	FINDINGS
6	Thijs et al. (2008) 10 weeks	102 runners (13M/89F) Age (37 ± 9.5) 17 injured	<ul style="list-style-type: none"> • Foot posture index (FPI) • Planter pressure measurements in running 	<ul style="list-style-type: none"> ➤ Increase vertical peak force underneath lateral heel and 2 and 3 metatarsals. ➤ Shorter time of the vertical peak force underneath the lateral heel
7	Duivgneaud et al. (2008) 6 weeks	62 female recruits Age (18-28) 26 injured	<ul style="list-style-type: none"> • Isokinetic strength (Cybex) for knee FLX/EXT • Single-leg horizontal hop test 	<ul style="list-style-type: none"> ➤ Decreased quadriceps strength
8	VanTiggelen et al. (2009) 6 weeks	79 recruits Age (17 – 27) 26 32% injured	<ul style="list-style-type: none"> • EMG for quadriceps muscles timing during (rocking back on the heel) 	<ul style="list-style-type: none"> ➤ Delayed vastus medialis obliquus to vastus lateralis onset timing
9	Boling et al. (2009) 2.5 years	1319 midshipmen (16M / 24F) (790M/489F) 3% 40 injured 1279 non-injured	<ul style="list-style-type: none"> • Kinetics and Kinematics (3D) during jump-landing task • Isometric Strength with Hand Held Dynamometer (HHD) for hip and knee muscles • Postural alignment (navicular drop and Q-angle) 	<ul style="list-style-type: none"> ➤ Increase Hip internal rotation angle ➤ Decrease Knee flexion angle ➤ Decrease Vertical ground-reaction force ➤ Decrease Knee flexion strength ➤ Decrease Knee extension strength ➤ Increase Hip external rotation strength ➤ Increase Navicular drop
10	Myer et al. (2010) School basketball season	240 basketball players, middle and high school student girls Age (mean 13.4) 25% injured	<ul style="list-style-type: none"> • Kinetics and kinematics (3D) during drop vertical jump (DVJ) • Questionnaires to determine familial anthropometrics utilised for maturational estimates 	<ul style="list-style-type: none"> ➤ Increase of knee abduction moment during landing

Table 3.4 Continued

No	STUDY	POPULATION	MEASUREMENTS	FINDINGS
11	Finnoff et al. (2011) Fall 2007 to fall 2009	98 (53M/45F) running athletes From 5 local high schools 5 injured (3F / 2M)	<ul style="list-style-type: none"> Isometric hip strength 	<ul style="list-style-type: none"> ➤ Increase of preinjury hip abductors in relation to hip adduction ➤ Decrease of preinjury hip external rotator in relation to hip internal rotation
12	Thijs et al. (2011) 10 weeks	77 female runners Age (38 ± 9) 16 injured	<ul style="list-style-type: none"> Isometric Strength with Hand Held Dynamometer (HHD) for hip muscles Q-angle 	<ul style="list-style-type: none"> ➤ No significant deference was reported in this study
13	Noehren et al. (2013) 2 Years	400 female runners Age (18-45) years 34 injured	<ul style="list-style-type: none"> Kinematics (3D) during running over 25 m 3.7 (±5) speed HADD Hip internal rotation Rearfoot eversion 	<ul style="list-style-type: none"> ➤ Increase of HADD
14	Holden et al. (2015) 2 years	73 adolescent females Age (12.9 ±0.35) years 8 injured	<ul style="list-style-type: none"> Medial knee displacement (2D) during DVJ 	<ul style="list-style-type: none"> ➤ significantly increased in FPPA (mean difference = 7.79°; P = 0.002; partial eta squared = 0.07) ➤ 2D, 3D, DVJ Validity: (r = 0.946; r²= 0.894; P < 0.001)
15	Herbst et al. (2015) Basketball season	329 female adolescent basketball players Middle schools (255 complete) 38 injured	<ul style="list-style-type: none"> Isokinetic strength with dynamometer for knee flx/ext (con/con) from 90° sitting at 300°/s and hip abduction from standing 	<ul style="list-style-type: none"> ➤ Greater normalised hip strength

3.3.3. Participants

Numbers of participants

The total number of participants included in the 15 studies was 3,640, ranging between 62 and 1,319 per study, and the number of individuals who developed PFP was 381, ranging between 5 and 60. (Figure 3.2).

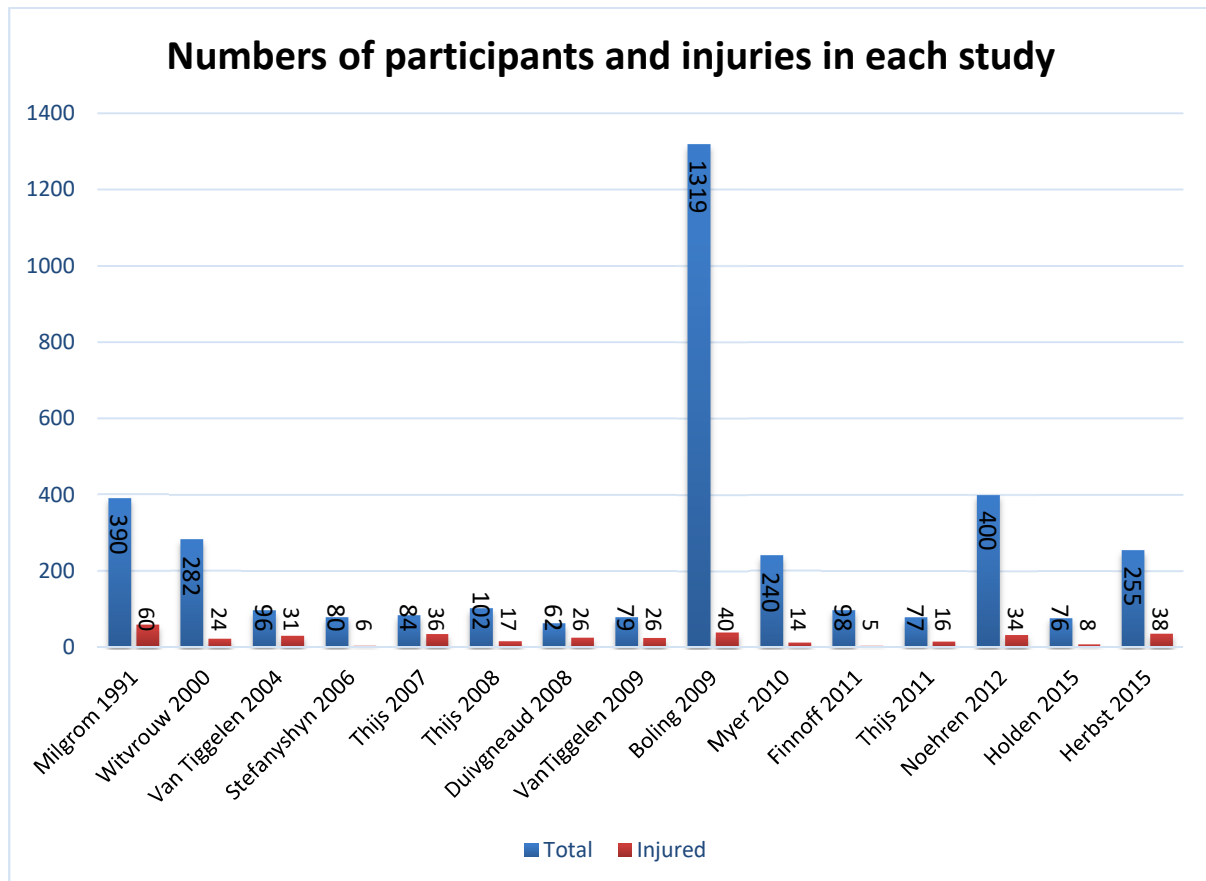


Figure 3.2 Numbers of participants and injuries

3.3.4. Follow-up periods

Follow-up periods of the included studies ranged between 6 weeks and 2.5 years (Figure 3.3).

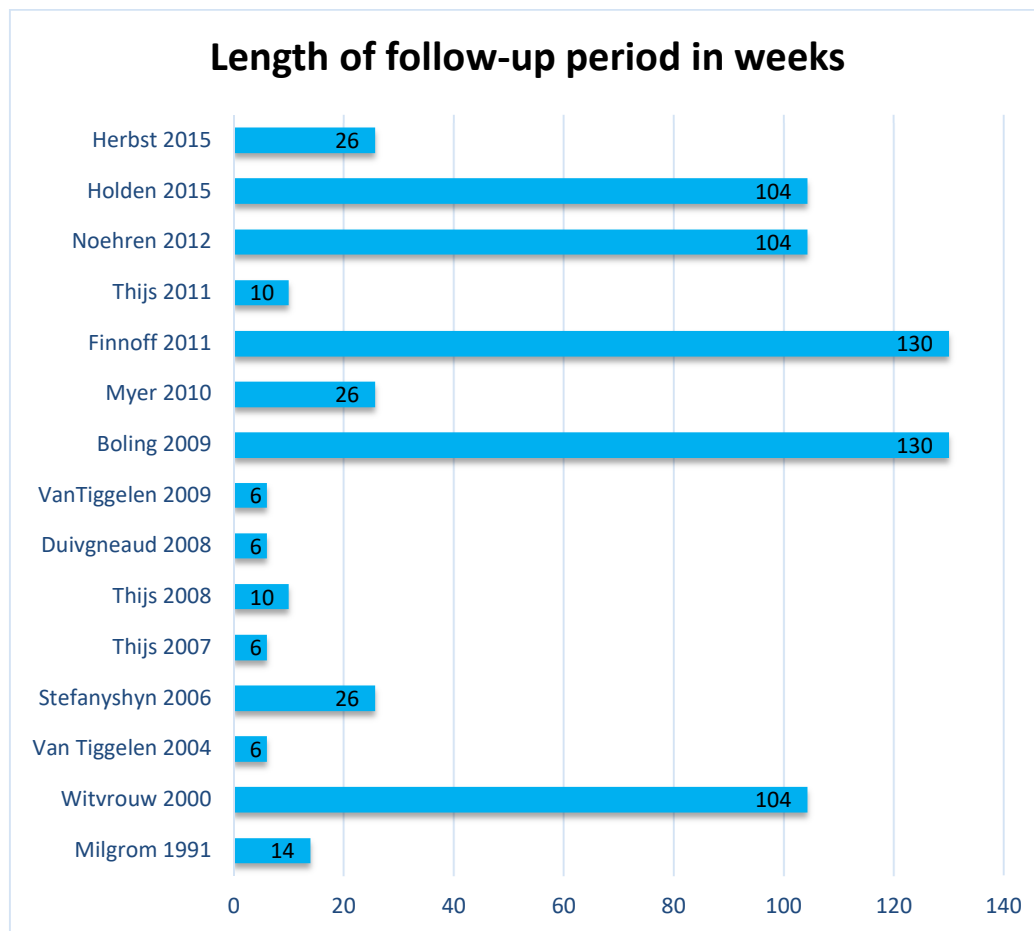


Figure 3.3 Length of the follow-up period in weeks

3.3.5. Types of population and participants

With regard to the participants in the selected studies, six studies included only females (Duvigneaud et al., 2008, Thijs et al., 2011, Noehren et al., 2013, Herbst et al., 2015, Holden et al., 2015, Myer et al., 2015), three studies included only males (Milgrom et al., 1991, Van Tiggelen et al., 2004, Van Tiggelen et al., 2009), and six studies included a mixture of males and females (Witvrouw et al., 2000, Stefanyshyn et al., 2006, Thijs et al., 2007, Thijs et al., 2008, Boling et al., 2009, Finnoff et al., 2011). From a total of 1,946 female participants, 594 were injured, while the number of injured male participants was 175 from a total of 1,694 (Figure 3.4).

The research population is divided into three main groups: military personnel, athletes >17, and students <17 (Figures 3.5 and 3.6). With regard to military personnel, 6 studies assessed 2,030 participants, 219 of whom were injured (Milgrom et al., 1991, Van Tiggelen et al., 2004,

Thijs et al., 2007d, Duvigneaud et al., 2008, Boling et al., 2009, Van Tiggelen et al., 2009); in the athletes' group, 5 studies assessed 941 participants, 98 of whom were injured (Witvrouw et al., 2000, Stefanyshyn et al., 2006, Thijs et al., 2008, Thijs et al., 2011, Noehren et al., 2013); and in the students' or <17 group, 4 studies assessed 666 participants, 65 of whom were injured (Finnoff et al., 2011, Herbst et al., 2015, Holden et al., 2015, Myer et al., 2015).

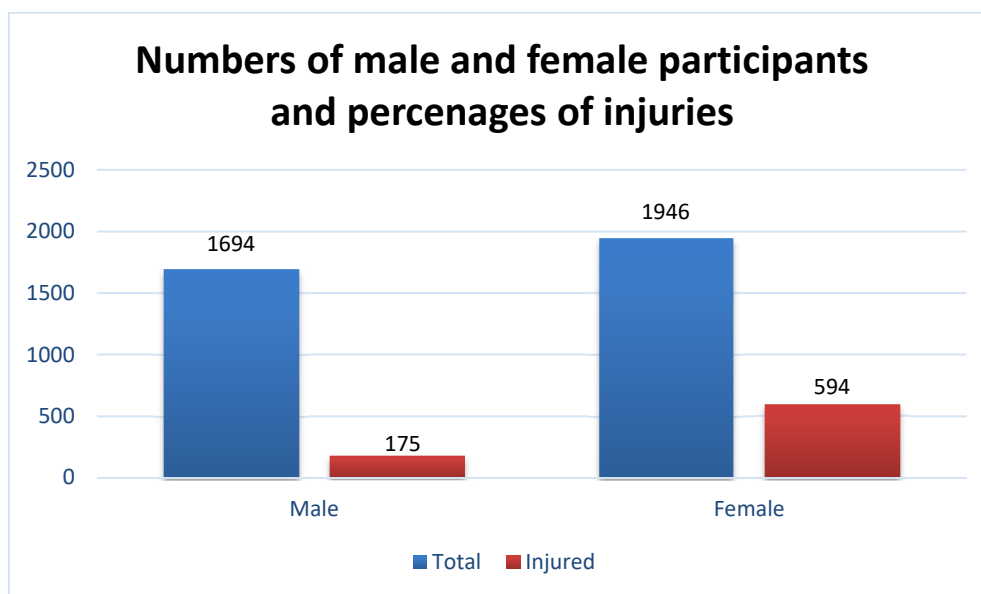


Figure 3.4 Male and female participants with percentage of injuries

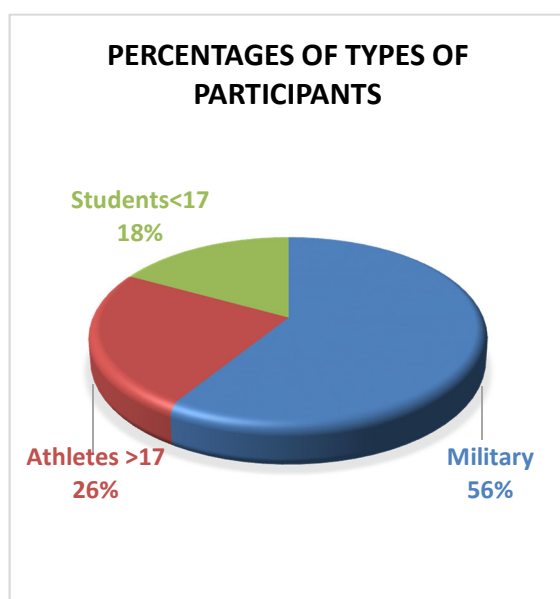


Figure 3.5 Percentages of types of participants

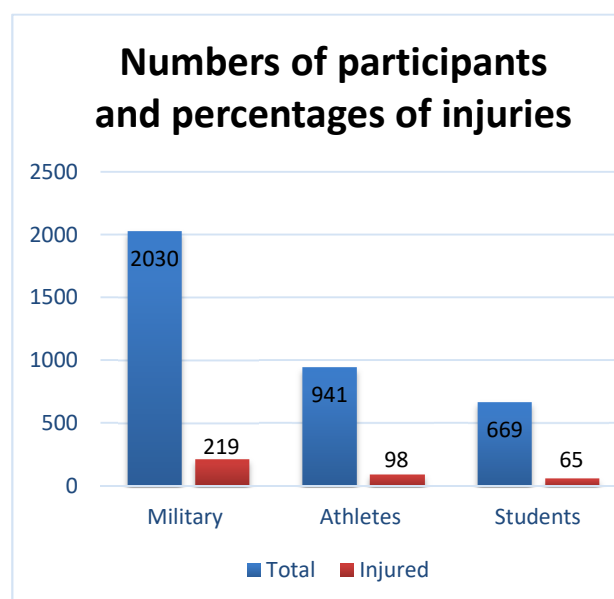
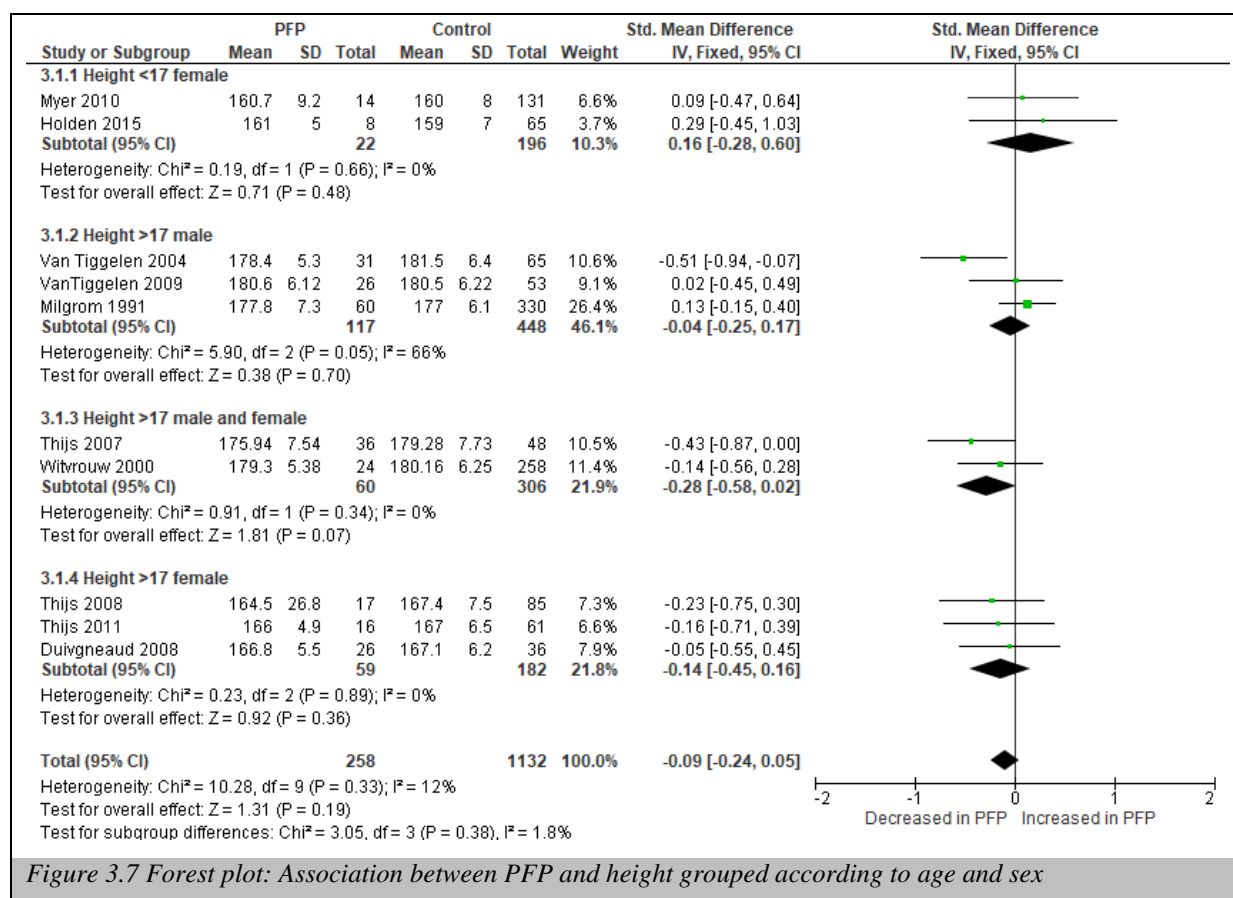


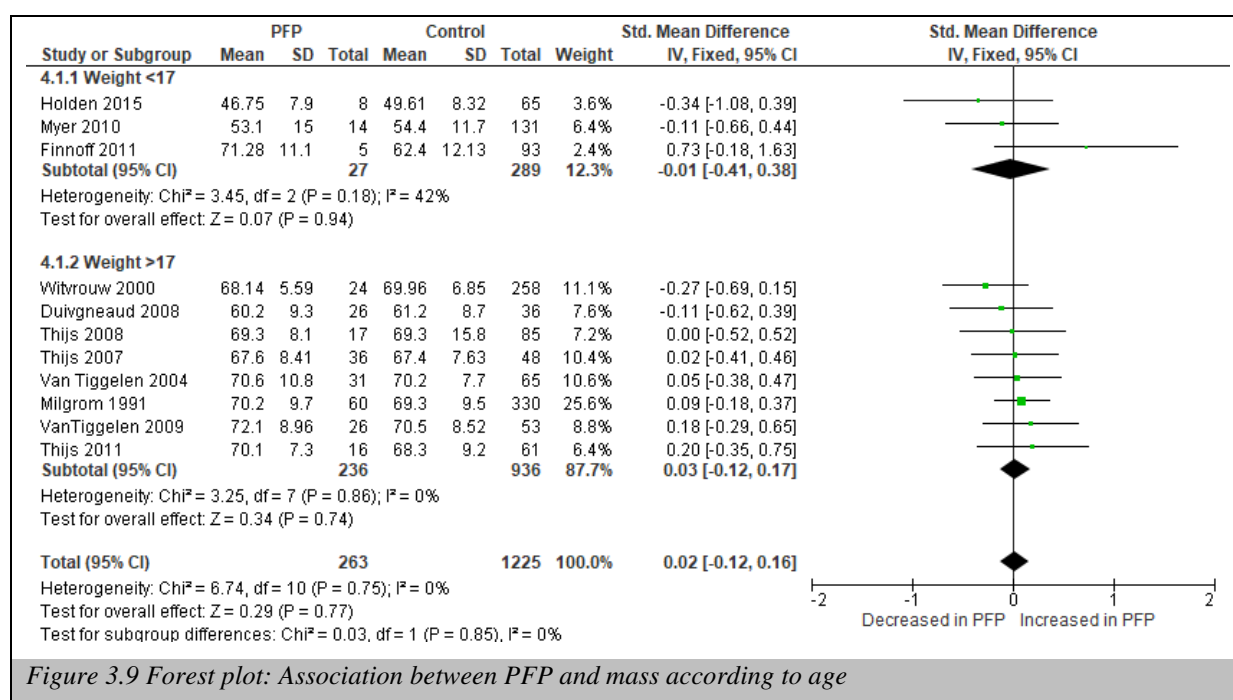
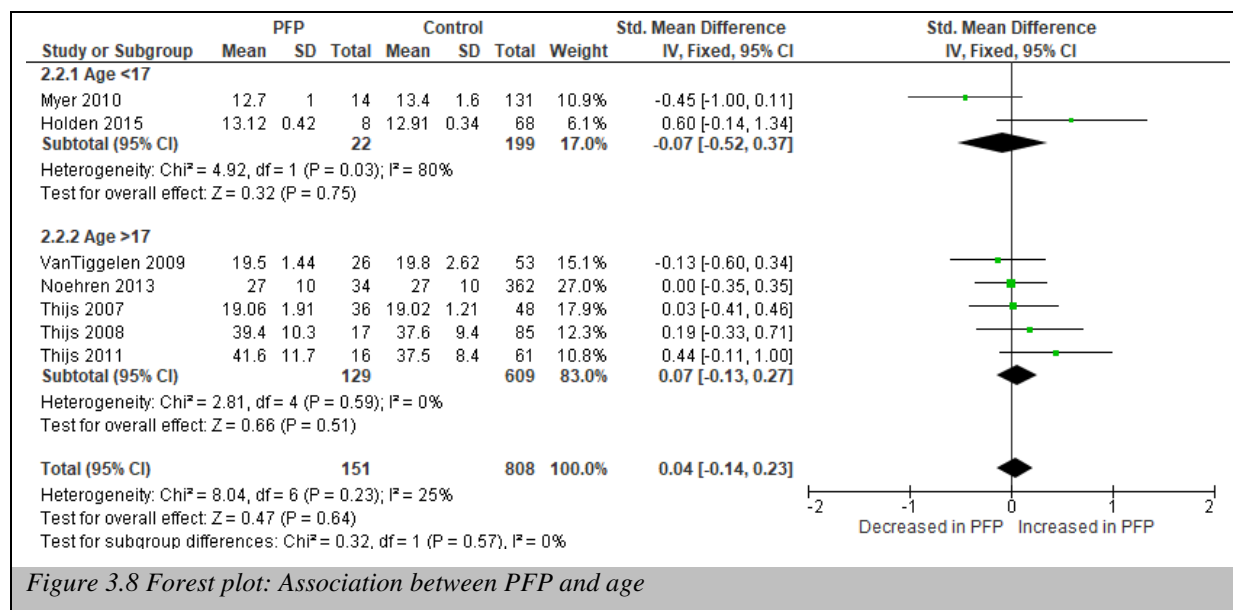
Figure 3.6 Number of participants and injuries in each type

3.3.6. Risk factors

3.3.6.1. Demographic characteristics

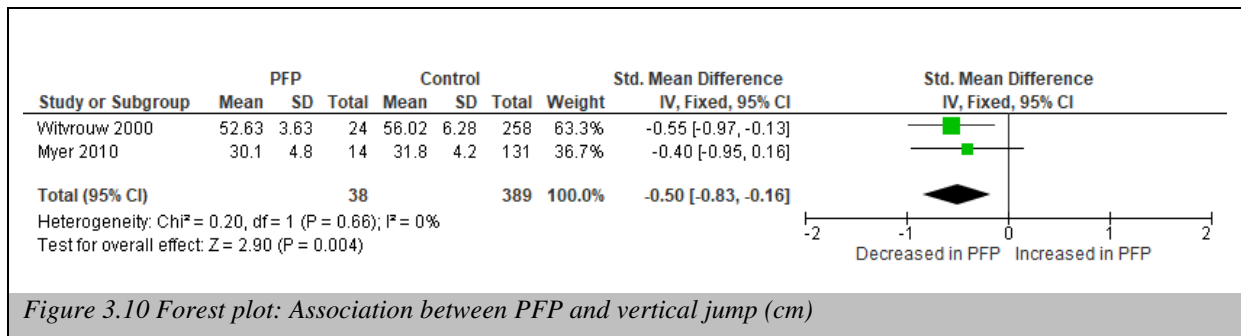
There is strong evidence from the pooled data from multiple studies, 5 HQ studies (Van Tiggelen et al., 2009; Duivgneaud et al., 2008; Thijs et al., 2007; Van Tiggelen et al., 2004; Milgrom et al., 1991) and 4 MQ studies (Holden et al., 2015; Thijs et al., 2011; Myer et al., 2010; Thijs et al., 2008) (indicated that there is no association between height and development of PFP, (Figure3.7). There is strong evidence from 3 HQ studies (Thijs et al., 2007; Van Tiggelen et al., 2009; Holden et al., 2015) and 4 MQ studies (Thijs et al., 2008; Myer et al., 2010; Thijs et al., 2011; Noehren et al., 2013), showing no association between PFP and age ($I^2 = 25\%$, SMD 0.4; 95% CI: -0.14 - 0.23) (Figure 3.8). There is strong evidence from 7 HQ studies (Milgrom et al., 1991; Witvrouw et al., 2000; Van Tiggelen, 2004; Thijs et al., 2007; Duivgneaud et al., 2008; Van Tiggelen et al., 2009; Holden et al., 2015) and four MQ studies (Thijs et al., 2008; Myer et al., 2010; Thijs et al., 2011; Finnoff et al., 2011), showing no association between PFP and mass ($I^2 = 0\%$, SMD 0.02; 95% CI: -0.12 to 0.16) (Figure 3.9). There is limited evidence from one HQ study (Boling et al., 2009) that females were at a higher risk of developing PFP.





3.3.6.2. Physical fitness

17 variables in four studies assessed the relationship between physical fitness parameters and PFP (Milgrom et al., 1991; Witvrouw et al., 2000; Duivigneaud et al., 2008; Myer et al., 2010). Pooling was possible for two variables. Pooled data showed that there is moderate evidence from one HQ study (Witvrouw et al., 2000) and one MQ study (Myer et al., 2010) of an association between PFP and decreased of height of vertical jump ($I^2 = 0\%$, SMD -0.50; 95% CI: -0.38 to 0.16) (Figure 3.10).



Additionally, limited evidence from one HQ study (Duivgneaud et al., 2008) identified that individuals who developed PFP were participated in sports fewer hours per week when compared with those who did not (SMD -0.73; 95% CI: -1.25 to -0.21).

3.3.6.3. Lower limb alignment and static measurement

Foot and ankle characteristics

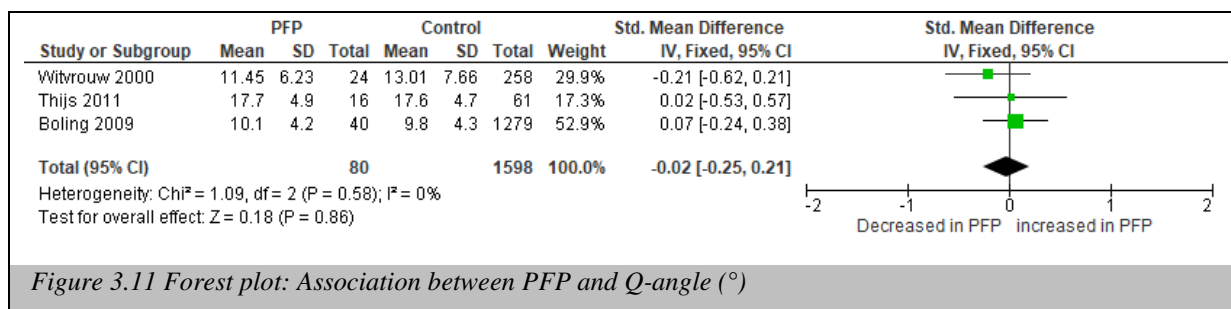
Static foot and ankle characteristics were assessed using 10 variables in four studies (Milgrom et al., 1991; Witvrouw et al., 2000; Thijs et al., 2008; Boling et al., 2009). Limited evidence from one HQ study (Boling et al., 2009) showed that individuals who developed PFP have a greater navicular drop when compared to control group (SMD, 0.33; 95% CI: 0.02 to 0.65)

Lower limb length difference and lower limb angles

Lower limb length difference was measured in two studies (Milgrom et al., 1991; Herbst et al., 2015), and no association was found between leg length and PFP. Knee valgus, was measured statically in a single study (Myer et al., 2010). In study of Myer et al., (2010) knee valgus was measured using 3D from standing position by measuring the knee angle of the lower limbs, and no association was found between knee valgus and PFP. Milgrom et al. (1991) used the medial tibial intercondylar distance in centimetres to assess lower limb alignment and found that larger medial tibial intercondylar distance was a predictor of the occurrence of PFP.

Q-angle

Three studies measured the difference between the Q-angle in individuals who developed PFP and in those who did not (Witvrouw et al., 2000; Boling et al., 2009; Thijs et al., 2011). Pooled data (Figure 3.11) showed strong evidence from two HQ studies (Witvrouw et al., 2000; Boling et al., 2009) and one MQ study (Thijs et al., 2011) showed no association between static Q-angle and development of PFP ($I^2 = 0\%$, SMD -0.02; 95% CI: -0.25 to 0.21) (Figure 3.11).

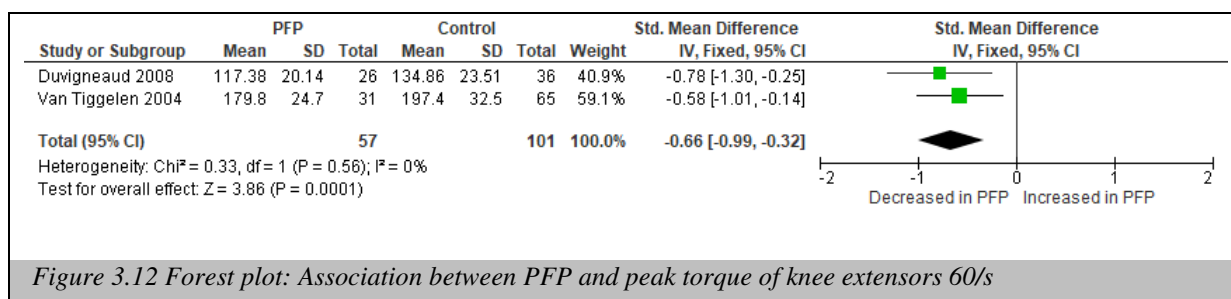


3.3.6.4. Muscle strength

Knee muscle strength

Peak torque of knee extensors

The peak torque of knee extensors was examined in 16 variables in four studies (Witvrouw et al., 2000; Van Tiggelen et al., 2004; Duvigneaud et al., 2008; Herbst et al., 2015). Pooling data was possible for 12 variables in two studies (Van Tiggelen et al., 2004; Duvigneaud et al., 2008). There is moderate evidence from two HQ studies (Van Tiggelen et al., 2004; Duvigneaud et al., 2008) showing that the concentric peak torque values for knee extensors at 60°/s and 240°/s, the concentric peak torque values for knee extensors at 60°/s and 240°/s normalised by body mass, and the concentric peak torque values for knee extensors at 60°/s and 240°/s normalised to body mass index BMI at 60°/s and 240°/s were significantly lower in individuals who developed PFP, compared to the control group ($I^2 = 0\%$, SMD -0.66; 95% CI: -0.99 to -0.32 and $I^2 = 17\%$, SMD -0.48; 95% CI: -0.81 to -0.15, respectively), ($I^2 = 0\%$, SMD -0.61; 95% CI: -0.95 to -0.28 and $I^2 = 0\%$, SMD -0.53; 95% CI: -0.87 to -0.20, respectively), and ($I^2 = 0\%$, SMD -0.69; 95% CI: -1.02 to -0.35 and $I^2 = 0\%$, SMD -0.51; 95% CI: -0.84 to -0.18, respectively) (Van Tiggelen et al., 2004; Duvigneaud et al., 2008) (Figure 3.12 – 3.17).



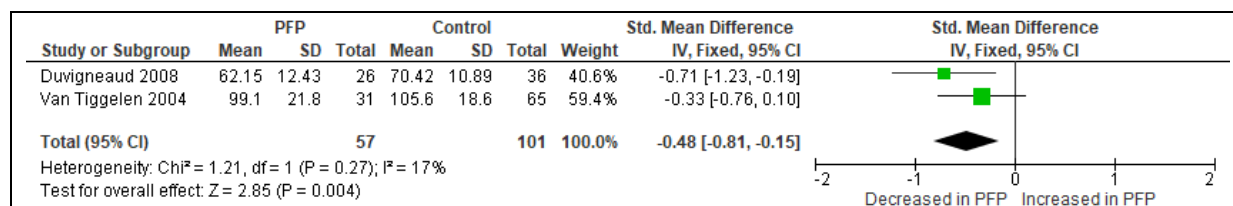


Figure 3.13 Forest plot: Association between PFP and peak torque of knee extensors 240/s

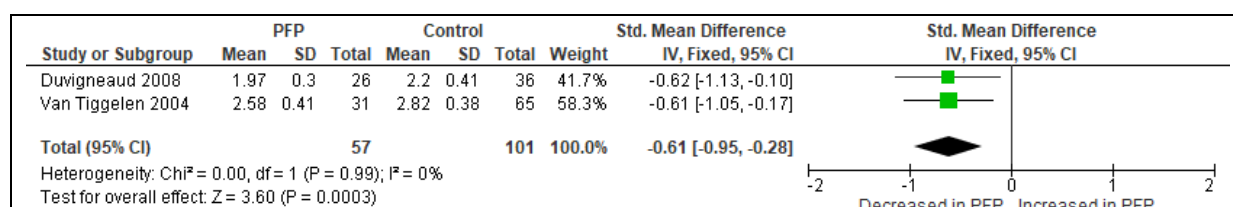


Figure 3.14 Forest plot: Association between PFP and peak torque of knee extensors 60/s %BW

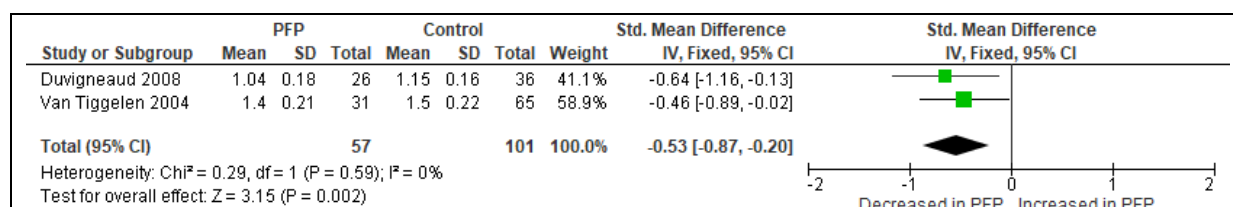


Figure 3.15 Forest plot: Association between PFP and peak torque of knee extensors 240/s %BW

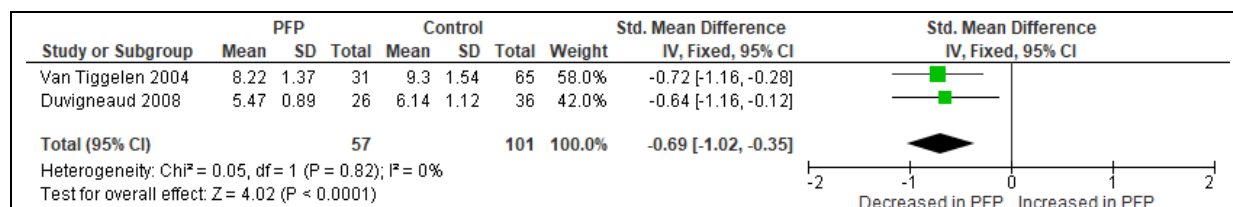


Figure 3.16 Forest plot: Association between PFP and peak torque of knee extensors 60/s %BMI

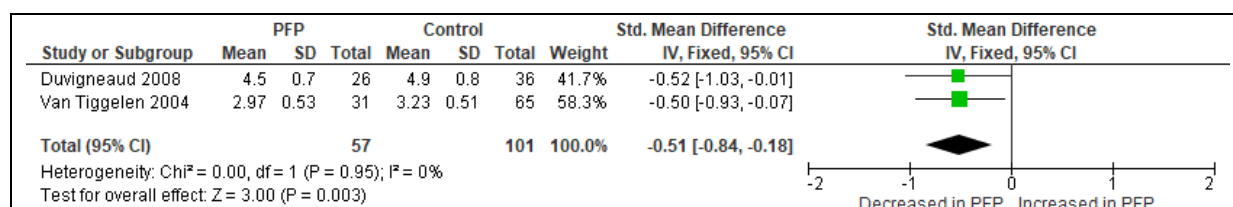
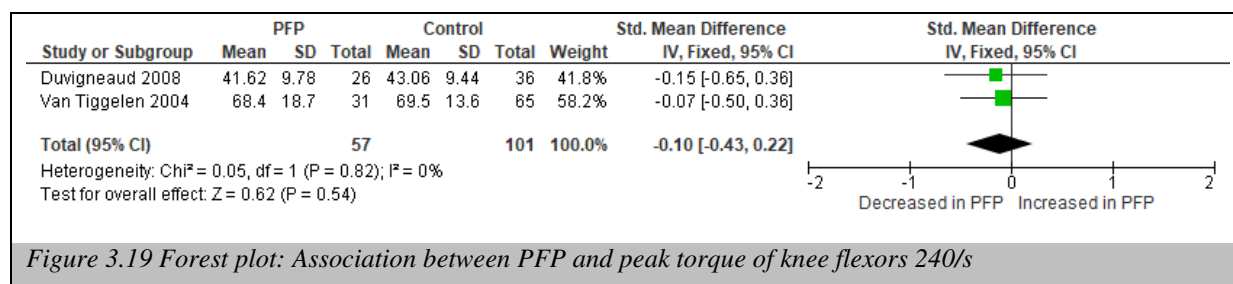
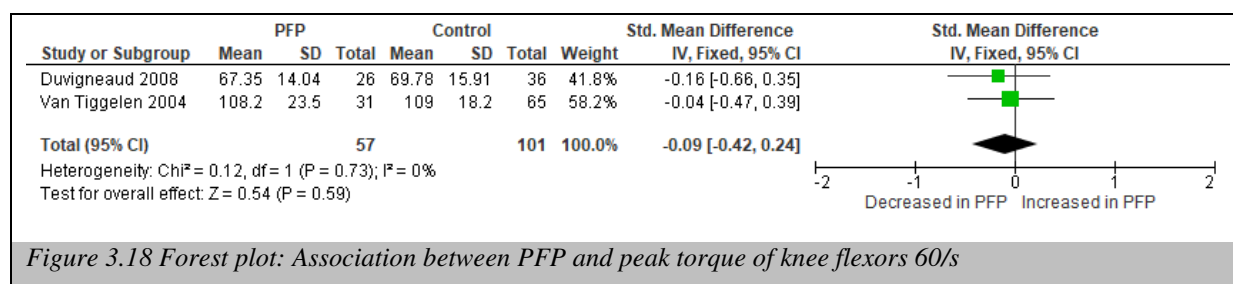


Figure 3.17 Forest plot: Association between PFP and peak torque of knee extensors 240/s %BMI

Peak torque of knee flexors

Four studies examined the peak torque of knee flexors of 11 variables (Witvrouw et al., 2000; Van Tiggelen et al., 2004; Duvigneaud et al., 2008; Herbst et al., 2015). Pooling was possible for two variables and showed that there is limited evidence in two HQ studies (Van Tiggelen et al., 2004; Duvigneaud et al., 2008) showing no association between the concentric peak torque of knee flexors measured at 60°/s and 240°/s and the development of PFP ($I^2 = 0\%$, SMD -0.09; 95% CI: -0.42 to -0.24 and $I^2 = 0\%$, SMD -0.10, -0.43 to -0.22, respectively) (Figure 3.18 – 3.19).

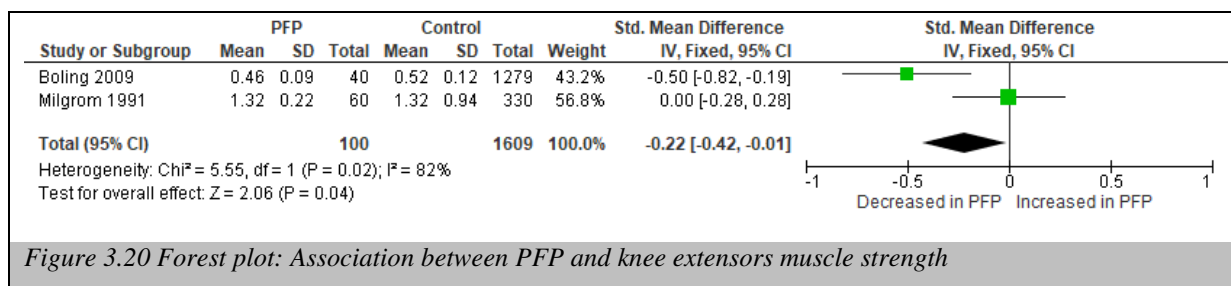


Peak torque ratio of knee flexors/extensors

Limited evidence from one HQ study (Duvigneaud et al., 2008) identified that the peak torque ratios of knee flexors/extensor at 60°/s and 240°/s were statistically significantly higher in individuals who developed PFP when compared to the healthy group (SMD 0.59; 95% CI: 0.08 to 1.11 and SMD 0.58; 95% CI: 0.07 to 1.10, respectively), and no association was found for eccentric peak torque of knee flexion and knee extension at 30°/s.

Knee extensors muscle strength

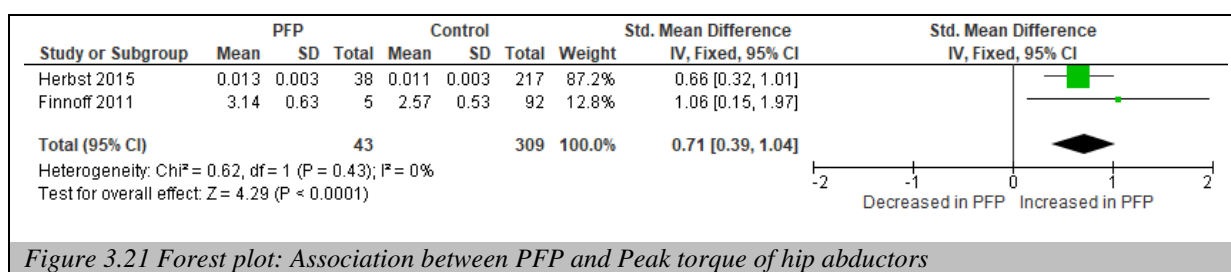
There is moderate pooled evidence from two HQ studies (Milgrom et al., 1991; Boling et al., 2009) showing relationship between decreased of quadriceps muscle strength and the development of PFP (SMD -0.22; 95% CI: -0.42 to -0.01) (Figure 3.20).



Hip muscle strength

Peak torque of hip abductors

A moderate evidence from two MQ studies (Finnoff et al., 2011; Herbst et al., 2015) was identified that individuals who developed PFP have a greater peak torque of hip abductors at 120°/s when compared to control (SMD 0.71; 95% CI: 0.39 to 1.04) (Figure 3.21).



Hip muscle strength

Two studies investigated the relationship between PFP and hip muscle strength by means of 19 variables (Boling et al., 2009; Thijs et al., 2011; Finnoff et al., 2015). Pooling of data was possible for eight variables (i.e. hip abductors, extensors, external rotators, and internal rotators) in two studies (Boling et al., 2009; Thijs et al., 2011). There is moderate pooled evidence from one HQ study (Boling et al., 2019) and one MQ study (Thijs et al., 2011) indicating that individuals who developed PFP have lower hip abductor muscle strength (in Newton, normalised to body mass) than the control group ($I^2 = 0\%$, SMD -0.29; 95% CI: -0.56 to -0.02) (Figure 3.22). In addition, moderate pooled data also shows that no significant association was found between hip extensor strength ($I^2 = 0\%$, SMD -0.21; 95% CI: -0.48 to -0.07), hip external rotator strength ($I^2 = 0\%$, SMD -0.23; 95% CI: -0.51 to 0.04), and hip internal rotator strength ($I^2 = 0\%$, SMD -0.19; 95% CI: -0.46 to 0.09) and the development of PFP, (Figure 3.23 – 3.25).

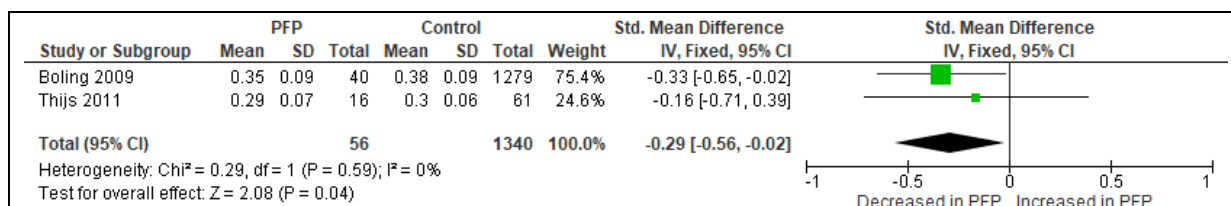


Figure 3.22 Forest plot: Association between PFP and hip abductor strength

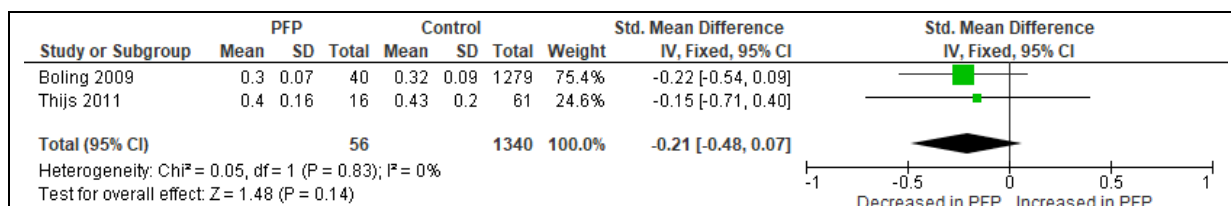


Figure 3.23 Forest plot: Association between PFP and hip extensor strength

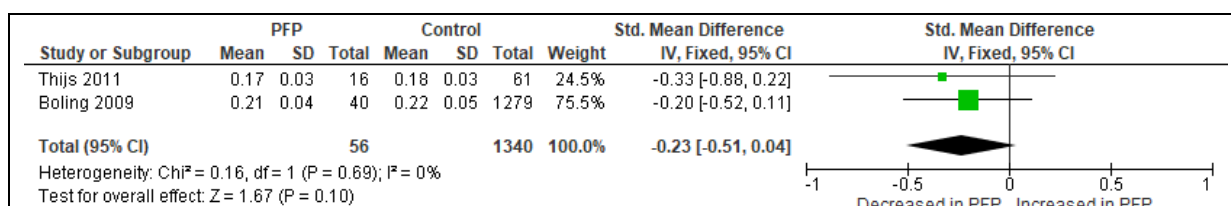


Figure 3.24 Forest plot: Association between PFP and hip external rotator strength

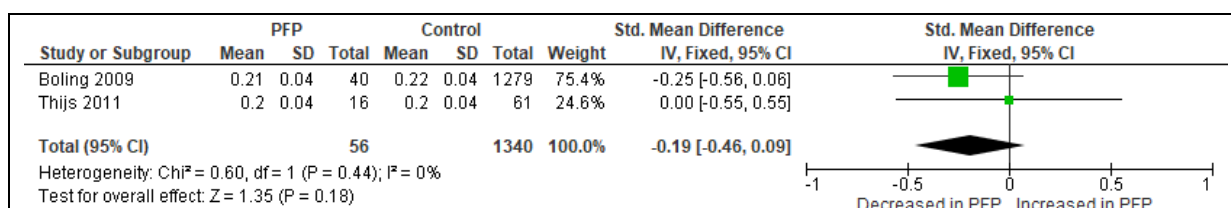


Figure 3.25 Forest plot: Association between PFP and hip internal rotation strength

3.3.6.5. Muscle timing

Electromyographic (EMG) onset timing between vastus medialis obliquus (VMO) and vastus lateralis (VL) muscles was assessed in two studies (Witvrouw et al., 2000; Van Tiggelen et al., 2009). Limited evidence from one HQ study (Van Tiggelen et al., 2009) indicated that individuals with PFP demonstrated a significant delay of onset of VMO regard to the onset of VL electromyographic activity compared to the healthy control. Limited evidence from one HQ study (Witvrouw et al., 2000) showed significant alterations of response time in VMO and

VLO in participants who developed PFP compared with those who did not (SMD -0.50; 95% CI: -0.92 to -0.08 and SMD -0.64; 95% CI: -1.06 to -0.22, respectively).

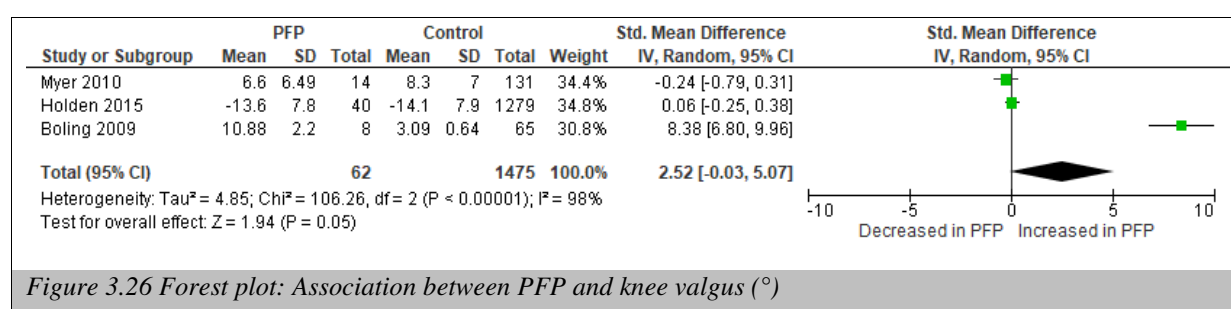
3.3.6.6. Kinematics

Hip kinematics

Five variables in two studies assessed the kinematic differences of the hip movement between the participants who developed PFP and those who did not (Boling et al., 2009; Noehren et al., 2013). Boling et al. (2009) measured hip flexion during drop vertical jump (DVJ) tests. No association was found between hip flexion and the development of PFP (Boling et al., 2009). Boling et al. (2009) reported an increase (not significant) in hip internal rotation in the PFP group, 7.6° (±8.9°) injured/7.2° (±8.4°) in uninjured group, and used a regression model that was able to significantly predict the development of PFP ($P = 0.04$) with this increase. HADD was assessed in two studies (Boling et al., 2009; Noehren et al., 2013), and very limited evidence from one MQ study (Noehren et al., 2013) identified an association between HADD and PFP using 3D analysis during running. Greater HADD angle during running was a significant predictor for the development of PFP (SMD 0.91; 95% CI: 0.55 to 1.27) (Noehren et al., 2013).

Knee kinematics

The relationship between dynamic knee angles (flexion, valgus, and internal rotation) and the incidence of PFP was assessed in three studies during jump-landing and DVJ involving eight variables (Boling et al., 2009; Myer et al., 2010; Holden et al., 2015), with pooling being possible for three variables. There is moderate evidence from two HQ studies (Boling et al., 2009; Holden et al., 2015) and one MQ study (Myer et al., 2010) indicating that individuals who developed PFP demonstrated greater knee valgus than those who did not ($I^2 = 98\%$, SMD 2.52; 95% CI: -0.03 to 5.07 (Figure 3.26).



Boling et al. (2009) evaluated dynamic knee flexion with 3D during a jump-landing task and reported significant decrease in knee flexion angle (c.4-5°) in participants with PFP.

Foot and ankle kinematics

The association between increase in dynamic rearfoot eversion and PFP has been investigated prospectively in a single study (Noehren et al., 2013). Noehren et al. (2013) assessed the rearfoot eversion angle in 400 female runners when running at a speed of 3.7 m.s⁻¹ (±5%) along a 25 m runway, using 3D motion analysis. No association was found between rearfoot eversion and PFP in this study.

3.3.6.7. Kinetics

Joint moments and vertical ground reaction force

Three studies investigated kinetic variables (Stefanyshyn et al., 2006; Boling et al., 2009; Myer et al., 2010). Knee valgus load was evaluated in two studies during running and landing tasks (Stefanyshyn et al., 2006; Myer et al., 2010). Very limited evidence from one MQ study (Myer et al., 2010) indicated that greater knee abduction moment at initial contact during landing was associated with the occurrence of PFP, (SMD 0.53; 95% CI:-0.02 to 1.09). Limited evidence from one HQ study (Stefanyshyn et al., 2006) showed that individuals who developed PFP had significantly (P = 0.042) higher knee abduction impulses during the stance phase of the baseline assessment than those who did not develop the injury (SMD 1.25; 95% CI: 0.34 to 2.17).

There is limited evidence from one HQ study (Boling et al., 2009) detected that individuals with PFP have a reduction in the vertical ground reaction force when compared to the control group (SMD -0.34; 95% CI: -0.65 to -0.02).

3.3.6.8. Plantar pressure

Foot plantar pressure was evaluated in two studies by means of 45 variables (Thijs et al., 2007b; Thijs et al., 2008). Limited evidence from one HQ study (Thijs et al., 2007), showed that individuals with PFP had shorter time to maximal pressure on the fourth metatarsal (small SMD -0.45, -0.85 to -0.06), increase in the lateral pressure distribution at initial contact of the foot (SMD -0.36; 95% CI: -0.75 to 0.04), and slower maximal velocity of the change in lateromedial direction of the centre of pressure during the forefoot contact phase (SMD -0.81; 95% CI: -1.22 to -0.41) during the baseline assessment of walking, and very limited evidence from one MQ study indicated that individuals with PFP had higher vertical peak force underneath the lateral heel (SMD -0.50; 95% CI: -0.02 to 1.02), metatarsal two (SMD 0.65; 95% CI: 0.12 to 1.17), and metatarsal three (SMD 0.60; 95% CI: 0.07 to 1.12) during running.

3.4. Discussion

This review examined the risk factors that have been reported to relate to the development of PFP. The results show that there is moderate evidence indicating that lower knee extensor strength, lower hip abductor strength and greater hip abductor torque (conflicted results), greater knee valgus, and decreased vertical jump are significantly associated with the occurrence of PFP. The pooled data for the Q-angle, hip flexor, extensors, external and internal rotation, and peak torque of knee flexors at 240°/s and 60°/s showed no difference between the individuals with PFP and healthy controls.

These findings are in accordance with two previous systematic reviews (Pappas & Wong-Tom, 2012; Lankhorst et al., 2012), in regard to decreased knee extensors muscle strength where both reviews included seven studies, which were slightly different, due to the variation in the data sources and inclusion and exclusion criteria of the search. Pappas & Wong-Tom, (2012) included (Boling et al., 2009; Milgrom et al., 1991; Thijs et al., 2007; Thijs et al., 2008; Van Tiggelen et al., 2009; Witvrouw et al., 2000; Myer et al., 2010) and Lankhorst and colleagues included (Boling et al., 2009; Milgrom et al., 1991; Thijs et al., 2007; Van Tiggelen et al., 2004; Van Tiggelen et al., 2009; Witvrouw et al., 2000; Duivigneaud et al., 2008). Because the two previous systematic reviews included only seven studies and the meta-analysis was based on pooled results from multiple studies, a limited number of variables were possible to be pooled and several risk factors were described individually, each in a single study.

In the pooled analysis of the Q-angle, three prospective studies were included, none of which detected a significant difference between the PFP group and the control group, whereas several retrospective studies reported a significantly larger Q-angle in PFP individuals when compared to the healthy control group (Aglietti et al., 1983; Messier et al., 1991; Haim et al., 2006; Emami et al., 2007). However, if the Q-angle is seen as a risk factor, then the position at which the measurements are taken needs to be appraised. In Witvrouw et al. (2000), the measurement was taken statically from a supine position, which did not reveal changes in the alignment of the lower extremities during weight bearing. In an earlier study, significant differences between the measurement of the Q-angle in standing and supine positions were found by Woodland and Francis (1992) and, consequently, the standing position was recommended. This could be due to the fact that the sample size was 77 female runners, which may be too small to elicit differences between the participants who developed injuries and those who did not, as in the study of Thijs et al. (2011). Another reason could be the proportion of participants who

developed PFP (only 3% out of 1,319) compared to the number of participants in the study, given the lack of information regarding medical records and the self-treatment of PFP, as stated in the study's limitations (Boling et al., 2009).

In addition to the significantly larger knee valgus of PFP individuals, the pooled data shows a large statistical heterogeneity between three studies, which may be a result of methodological differences in the studies, e.g. using 3D analysis in Myer et al. (2010) and Boling et al. (2009) while using 2D in Holden et al. (2015), or a lack of unanimity regarding the methods used to measure knee valgus. Such disparities may also due to the differentiation between the performance tasks or differences in the participants' ages. Contradictory findings were found in knee valgus measurements. Only one of the three pooled studies reported a significant knee valgus increase in the PFP group, relative to the control group (Holden et al., 2015). The other two studies, Boling et al. (2009) and Myer et al. (2010), found that the knee valgus of injured participants was smaller (not significant) when compared to non-injured participants. In Myer et al. (2010), there was a significant increase in the knee abduction moment of individuals who developed PFP, compared to the control group (Myer et al., 2010). Therefore, it is questionable how this increase in moment cannot create an increase in angle.

In the current review there is conflicting results from pooled data for muscle strength of hip abductors. Four studies investigated the relationship between the development of PFP and muscle strength of hip abductors (Boling et al., 2009; Thijs et al., 2011; Finnoff et al., 2011; Herbst et al., 2015). Two of these studies, one HQ study (Boling et al., 2009) and one MQ study (Thijs et al., 2011) assessed hip abductors muscle strength using HHD which being held by the assessor hand and normalized the results to body mass. Pooled data of the two studies indicated decreased of hip muscle strength in individuals how were developed PFP compared to healthy. The other two MQ studies (Finnoff et al., 2011; Herbst et al., 2015) investigated hip abductors muscle strength by torque using isokinetic dynamometer in Herbst and colleagues and HHD in Finnoff and colleagues. Both of the two studies report increase in hip abductors peak torque in participants with PFP and Pooled data of the two studies indicated same results that individuals with PFP had greater hip abductors muscle strength during the baseline assessment compared to control group. This result may be due to that in Herbest et al., (2015) assessed peak torque of hip abductors muscles with isokinetic dynamometer at 120 deg/s angular velocity which my higher than the normal velocity action of hip abductors and not revealed the real peak torque, or it may be due to that in Finnoff et al., (2011) assessed beak

torque of hip abductors isometrically using HHD which was held by the hand of assessor and the subjects were poorly stabilized in addition to that the dynamometer was placed proximal to the ankle joint while the appropriate position of the HHD for hip abductor assessment is proximal to the knee joint. Therefore, it may be needed further investigation to confirm the association between development of PFP and muscle strength of hip abductor.

The pooled data of two studies show that the muscle strength in hip extensors is lower in individuals with PFP, and although it is not significant, a positive trend towards lower muscle strength for hip extensors in individuals with PFP. However, due to the decrease in the pooled studies, hip extensors appear to be a risk factor for the development of PFP injury.

The author theorised, if we went back to the beginning and undertake the systematic review and meta-analysis based on only the included military studies in this review, there will only be six included studies (Milgrom et al., 1991, Van Tiggelen et al., 2004, Thijs et al., 2007, Duvigneaud et al., 2008, Boling et al., 2009, Van Tiggelen et al., 2009). The results of pooled data have shown that there is moderate evidence indicating that lower knee extensor muscle strength was a risk factor. The other risk factors could not be pooled due to the limited number of included studies.

From the current review, agreement in the prospective studies' findings could be influenced by several issues, such as the homogeneity of samples, the validity and reliability of the measurements, the variability of measurement methods, the period of data collection, and the length of follow-up time.

Although there is homogeneity with regard to participants' demographic characteristics and follow-up activity, there exists unknown data related to the activities undertaken by the participants for the rest of the day, e.g. in the studies based on athletes or runners. These unknown activities may be different in nature, load, and intensity, from one participant to another, which could affect the research findings. Recruits in basic military training at the beginning of military service are the most homogenised population for prospective studies, since all participants are undertaking almost exactly the same activities during the day. The second factor is the validity and reliability of the measurements. In this sense, the validity and reliability of the measurements for assessing muscle strength in some studies are questionable (Boling et al., 2009; Thijs et al., 2011; Finnoff et al., 2015), which could be due to errors resulting from the HHD used to measure muscle strength being held by the experimenter or not

being stabilised sufficiently to provide steadied resistance. The variability of measurement methods, e.g. measurement position, measurement tool, or screening tasks, between the studies is also an important factor that may cause a variety of findings.

In addition, the length of the data collection period and follow-up times are two additional factors. In this sense, the data collection is expected to take months, due to the time needed with each participant in some large studies (e.g. when using 3D analysis), leading to an increase in the time between the measurement of the first participants and the measurement of the last participants, which will cause differentiation between each participant's baseline test levels. Participants' levels of fitness at the baseline measurements could differ from one participant to another due to the type and amount of activities that were received during the time gap between them. Findings from some studies may be influenced by long follow-up times, due to other factors that could occur and affect the participants, such as changes in young participants' internal factors, since they are in the process of growing, or changes in any external factors.

3.5. Conclusion

Several issues were addressed in the literature review in chapter two and the systematic review in the current Chapter, that are considered as limitations of the previous prospective studies such as lack of validity and reliability, heterogeneity of sample, long duration of data collection, long follow-up time, and high cost of instruments. The meta-analysis shows that there are a limited number of pooled variables for each risk factor, and there was conflicting evidence in some cases or significant heterogeneity in others. However, it does show that there is moderate evidence indicating that lower knee extensor strength, lower hip abductor strength and greater hip abductor torque, greater knee valgus, and decreased vertical jump are significantly associated with the occurrence of PFP. The current systematic review divided the studies participants into three groups (military, athletes and students). It was focused for the first time on length of follow up period, duration of data collection, validity and reliability of measurement methods in addition to the biomechanical risk factors.

Therefore, there is a need for further investigation into a number of variables including hip abductor strength due to conflicting results, knee extensors that were confirmed only with isokinetic dynamometer, dynamic Q-angle due to negative findings with static Q-angle, dynamic knee valgus due to high heterogeneity in addition to others lower limb kinematic, to be undertaken in future studies in order to confirm if they are related to the risk of injury.

In this regard, we will employ for first time 2D for FPPA and HHD within the Saudi military population in order to screen for potential biomechanical PFJ injury risk. This aims to detect the biomechanical differences between the individuals with and without PFP, with low cost, portable, and easy to use tools in order to increase the ease and capacity of screening individuals who are at risk of PFP. Thus, before the use of these measurement tools, their reliability and validity against the gold standard (3D and isokinetic dynamometer) will be assessed in the following chapter.

CHAPTER 4

Validity and reliability of 2D analysis and HHD for kinematics and strength assessment of the lower limb

This chapter contains two separate, though related, studies. The first study is pilot work using data collected by Faisal Alenezi whilst undertaking his PhD, the author analysed the 2D data collected but not used in Alenezi's studies, to assess the reliability of 2D analysis for FPPA and HADD and its validity against the data from the 3D motion capture system using Qualysis Tracking Manager (QTM) which is 3D motion capture system and Visual3D which is biomotion modeling and analysis software. The analysis of the 3D data solely was published in Journal of Electromyography and Kinesiology in 2017 (Herrington et al., 2017) (Appendix B).

The second study, assessed the reliability of 2D analysis for lower limb kinematics, and its validity against 3D system using QTM only, and assessing the reliability of HHD measurement for knee extensors and hip abductors muscle strength and its validity against isokinetic dynamometry.

4.1. Study 1: The validity and reliability of the FPPA and HADD angle

4.1.1. Aims

The aims of this section are therefore to:

- a) Assess the reliability of 2D analysis for FPPA and HADD during RUN, SLS, and SLL to screen for PFP development injury occurrence in addition to the other lower limb injuries.
- b) Assess the relationship between 2D and 3D motion analysis for FPPA and HADD during RUN, SLS, and SLL to screen for PFP development injury occurrence in addition to the other lower limb injuries.

4.1.2. Introduction

Patellofemoral pain (PFP) is the most common cause of knee pain in orthopaedic outpatients. It is defined as the pain behind or around the patella that increases with weight-bearing activities, such as squatting, running, and stair ambulation (Crossly et al., 2016). It is the result of an imbalance in the forces controlling patella tracking during knee flexion and extension, particularly in regard to joint overloading. In sports medicine, PFP is diagnosed in about 25%

of all running injuries (Devereaux and Lachmann, 1984). Patellofemoral pain has been suggested as a multifactorial disorder that can result in the demonstration of dynamic knee valgus (Hewett et al., 2005; Willson & Davis, 2008; Boling et al., 2009; Souza and Powers, 2009). The identification of individuals who demonstrate excessive dynamic knee valgus during common athletic tasks may help to modify this pattern of movement or to reduce the risk of injury.

Motion analysis is commonly used in sports medicine research to investigate the risk of injury. Due to the high accuracy and reliability of 3D analysis in quantifying kinematic variables, it is extensively used in athletic tasks. This method is considered as a gold standard for this type of analysis. However, in injury prevention programmes, there is a need for large-scale screening within the field in order to identify high-risk athletes. 3D motion analysis has been widely used to evaluate kinetic and kinematic variables during lower limb movement. It has been considered as the gold standard for the assessment of individuals who are at a high risk of knee injury (McLean et al., 2005). Although 3D motion analysis is the gold standard for motion analysis, it is not used frequently in screening programmes, which may be due to the high cost of the equipment, the time required for processing and analysing the data collected and the training needed to use it effectively. As an alternative technique to 3D motion analysis, 2D analysis has been used to quantify hip and knee kinematics (Munro et al., 2012). However, 2D motion analysis has inherent limitations due to the perspective error that occurs when measuring kinematics not perpendicular to the camera. In this sense, 2D motion analysis is possibly not suitable for the assessment of any motion that is not purely uniplanar and has multiplane kinematics, such as dynamic knee valgus, which not only contains knee abduction and hip adduction in the frontal plane, but also tibial external rotation and hip internal rotation in the coronal plane (Malfait et al., 2014). A previous study by McLean et al. (2005) confirms this by noting that the 2D measurement of dynamic knee valgus angle was influenced by rotations in the hip and knee joints.

The level to which the non-uniplanar can be reflected in the uniplanar knee motion, measured with 2D motion, has only been investigated in a limited number of studies, which have investigated the relationship between the 2D and 3D motion of hip and knee kinematics (McLean et al., 2005; Willson & Davis, 2008; Norris & Olson, 2011; Olson et al., 2011; Munro et al., 2012; Sorenson et al. 2015). McLean et al. (2005) assessed the relationship between 2D and 3D motion analysis for frontal plane knee kinematics during side-jumping, side-stepping, and shuttle runs and found a strong correlation between 2D and 3D motion analysis at the peak

of the knee abduction angle during side-stepping ($r=0.76$) and side-jumping ($r=0.80$), whereas the correlation was low ($r=0.20$) during shuttle runs (McLean et al., 2005). Sorenson et al. (2015) investigated the relationship between 2D and 3D analysis in knee and hip kinematics during single leg drop landings, and they report that the 2D knee frontal plane projection angle had a moderate relationship with the 3D knee abduction angle ($R^2=0.72$), and the 2D hip adduction angle had a strong correlation with the 3D hip adduction angle ($R^2=0.52$). Gwynne & Curran (2014) report a strong correlation between FPPA and 3D knee abduction ($r=0.78$) during single leg squats, while Willson & Davis (2008) report that 2D FPPA reflected 23 – 30% of the variance of 3D kinematics during single leg squats. In addition, FPPA significantly correlated with the hip adduction angle ($r=0.32$). However, none of these studies examined the relationship between 2D FPPA and other lower limb kinematics in other planes.

A limited number of studies that investigated 2D FPPA reliability during SLS, SLL, and RUN were found in the literature (Munro et al., 2012; Gwynne & Curran, 2014). 2D analysis for FPPA measurements was found to have good to excellent between-day reliability (ICCs=0.72-0.91) and good within-day reliability (ICCs=0.59-0.88) during DJ, SLL, and SLS (Munro et al., 2012). Frontal plane projection angle has been assessed as a technique in the analysis of dynamic knee valgus to predict the risk of PFP injury (McLean et al., 2005; Willson & Davis, 2008; Norris & Olson, 2011; Olson et al., 2011; Munro et al., 2012). However, none of these studies have reported the reliability of 2D motion analysis for the measurement of hip adduction angle during SLS, SLL, and RUN tasks.

The purpose of this study was to assess the validity and reliability of 2D analysis for the kinematic assessment of the lower extremity; in particular, this study aims to assess the intra- and inter-tester, and within- and between-day reliability of the measurement of HADD and FPPA during SLS and SLL, in addition to assessing the validity of these measurements against 3D motion analysis.

4.1.3. Methods

4.1.3.1. Participants

Fifteen healthy and physically active individuals (six male and nine female) from the University of Salford's staff and students volunteered for the study. The participants had an average age of 25.86 years ($SD \pm 5.28$), an average mass of 66.27 kg ($SD \pm 10.25$), and an average height of 166.95 cm ($SD \pm 7.6$). All participants were accepted on the condition that

they participated in sports for at least three hours a week, had no history of knee complaints or surgery, and were in good physical condition.

Procedures

Data collection work in this study was collected as the following procedures.

4.1.3.2. Two-dimensional motion analysis procedure

2D Instrumentation

One commercial video camera (Casio Exilim F1), sampling at 30Hz, was placed on a levelled tripod 9 m in front of the centre of the capturing area, at a height of 60cm, and set at standard mode (30fps) to capture the markers of FPPA and HADD angle during kinematic movements. A Brower Timing Gate System (TC-Timing System, USA) was used to monitor the running speeds.

2D Calibration

The video camera was adjusted with a 10x optical zoom throughout each trial in order to standardise the position of camera to the participants, and it was calibrated with a 100cm square frame (Figure 4.1) using Quintic Biomechanics software package (Version 26) for digitising 2D.

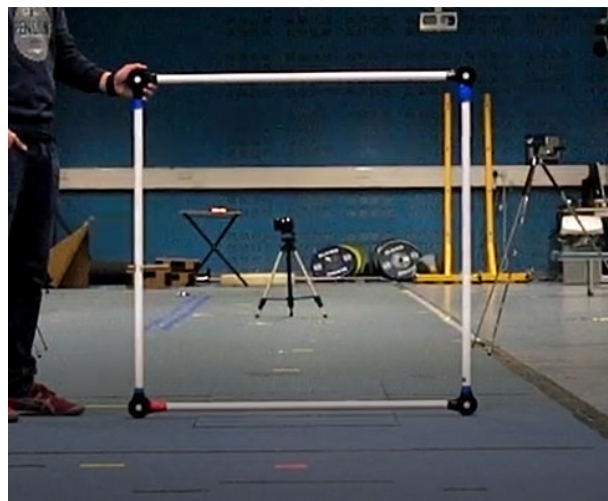


Figure 4.1 100cm square frame

2D Marker placement and preparation

For 2D analysis, five markers were placed on the FPPA anatomical references, which were employed by Willson et al. (2006). In this sense, markers were placed on the right lower limb at the midpoint of the ankle malleoli for the centre of the ankle joint, the midpoint of the femoral

condyles for the centre of the knee joint, the midpoint of the line from the anterior superior iliac spine to the knee marker at the proximal thigh, and two markers on both the right and left anterior superior iliac spine. The midpoints of the knee and ankle joints were determined manually using a standard tape measure. The method of placing markers to determine the centre of the joint has been shown to increase intra- and inter-rater reliability, in comparison to the approximation of joint centres with video digitisation (Bartlett et al., 2006). All markers were placed by the same examiner. The placement of the 2D markers is illustrated in Figure 4.2.

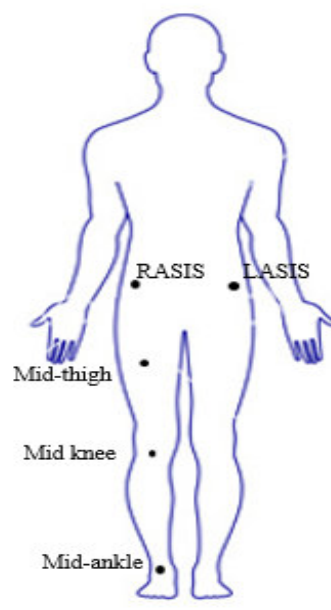


Figure 4.2 2D markers placement

4.1.3.3. Three-dimensional motion analysis procedure

3D Instrumentation

Ten infra-red (IR) cameras (Pro-Reflex, Qualisys), sampling at 240Hz frequency, passive retro-reflective markers, three force platforms (AMTI, USA), sampling at 1200Hz, and embedded into the running track, were used to collect the lower limb biomechanical data in 3D motion analysis during the different tasks. A Brower Timing Gate System (TC-Timing System, USA) was used to monitor the running speeds. A plan view of the procedure set up for 2D and 3D can be seen in Figure 4.3.

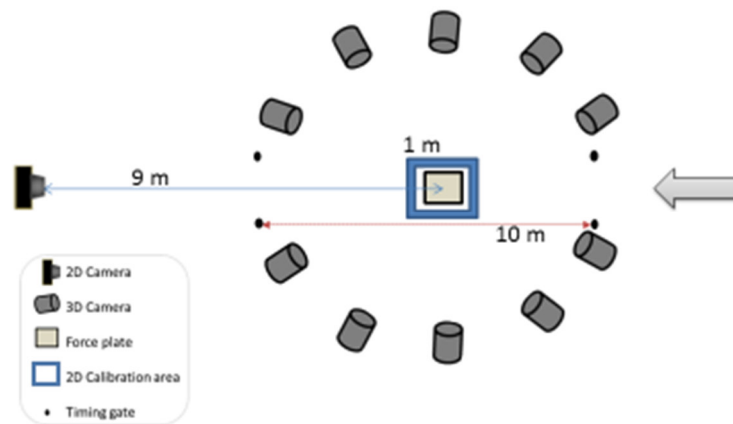


Figure 4.3 Overview of the procedure set up.

3D System calibration

Each individual infra-red camera gives 2D view and needs to be converted to 3D workplace to analyse of coordinate data. The process of system calibrations was performed in two phases (static and dynamic). The static calibration was performed using a right L-frame with four reflective markers to define the position of the orientation of the ten cameras in relation to the co-ordinate system of the laboratory (Figure 4.4). Dynamic calibration was then performed using T-shape handheld wand with fixed reflective markers at the two ends at a known distance (750.43mm) (Figure 4.4) in order to calibrate the volume that would be used during the dynamic trials. The captured time for dynamic calibration was 45 seconds to cover all calibration volume to be successfully calibrated and ready for data collection.



Figure 4.4 Calibration L-shaped frame (Left) and T-shaped handheld wand (right)

3D Marker placement and preparation

At the beginning of the procedure of data collection, twenty four reflective markers with 14.5 mm diameter were attached to pelvis and both lower limbs' anatomical landmarks, using double-sided tape. Pelvis markers were placed on the right and left anterior superior iliac spines(ASIS), right and left posterior superior iliac spines(PSIS), right and left iliac crest, lower limbs markers were placed on greater trochanters, lateral and medial femoral condyles, lateral and medial malleoli, posterior calcanei, and the head of the first, second, and fifth metatarsals of both limbs. Foot markers were placed on standard training shoes. Then, four cluster plates, each consisting of four reflective markers, were attached with adhesive tape to the antero-lateral aspect of the thigh and shank of both limbs and tightened with elastic bands. Previous work showed that using of clusters is the optimal configuration compared to separate markers attached to the skin (Manal et al., 2000). These markers were used to define the anatomical reference frame and the joints centres of rotation. In order to track the position of each segment in a three dimension space, three non-colinear markers supposed to be in view of at least two cameras during the capture time constantly (Cappozzo et al., 1996; Payton & Bartlett, 2008). The static trial markers, tracking markers and cluster plate are shown in Figures 4.5.



Figure 4.5 Static Trial Marker (Left) Tracking Markers (Right)

(Faisal Alenezi, 2015, PhD thesis)

Before the beginning of testing, participants wore standard shoes (New Balance, UK) and compression shorts. They started with a three-minute warm-up on a cycle ergometer at a low intensity level. Then, the participants practiced the testing procedure for each of the three screening tasks (RUN, SLS, and SLL), which will be explained next for familiarisation. After the participants felt comfortable with all the tasks, the principle researcher placed the 2D and 3D markers onto the participants' lower limbs, as previously explained.

Each participant was asked to stand with his/her lower limbs in natural alignment and weight distributed equally on the force plate in a stationary position for ten seconds, with their hands crossed over their chests to insure that the hands are clear of the markers and all were in view of the cameras, in order to undertake a static trial. After this, the anatomical markers were removed and keeping 28 markers (2 markers on the right and left ASIS, 2 markers on right and left PSIS, 8 markers on both shoes, and the 16 markers of the four clusters), as tracking markers, to start the screening tasks.

4.1.3.4. Screening Tasks

While both of 2D and 3D motion system were operating participants were asked to perform the following screening tasks:

Running

Subjects ran over a ten-metre runway at their perceived maximal velocity, with a ($\pm 5\%$) range between the trials. Running speed was monitored using the previously mentioned timing gates. An acceptable trial was one in which the participant contacted the force plate with the whole of the right foot. The brower timing gate system was set approximately at hip-height in order to ensure that only one part of the body would cross the beam (Yeadon et al., 1999). Then, the speed of the participants was calculated by dividing distance by time. Three successful trials were recorded for all subjects (Figure 4.6). To minimise the effect of fatigue, all participants were given one to one-and-a-half minutes in order to rest between the trials (Beaulieu et al., 2008; Cortes et al., 2010).



Figure 4.6 Running Task

Single leg squat

Subjects were asked to stand on their right limbs in the middle of the force plate while bending their left limbs, without any contact between the two legs, as a starting position. From this starting position, subjects were asked to squat down as far as possible but no further than the thigh being parallel to the ground, while maintaining the trunk as upright as possible (Figure 4.7), which is consistent with work of Zeller et al. (2003) and Dwyer et al. (2010). Each trial was conducted over a period of five seconds, using an electronic counter. The first count marked the initiate squat, the third count indicated the lowest point of the squat, and the fifth count indicates the end of the trial (Herrington, 2014). Before the trials, subjects were allowed

to practice SLS two to three times for familiarisation. This procedure was standardised for all subjects in the test, reducing the effects of velocity on the pattern of the knee joint movement.



Figure 4.7 Single Leg Squat Task

Single leg land

Subjects were asked to stand, with a single limb, on a 30cm-high step and to step down and land as vertically as possible onto the force plate with the contralateral limb. This height was previously used by Yeow et al. (2010), Hargrave et al. (2003), and McNair and Prapavessis (1999). Subjects were asked to put their arms across their chest during landing in addition to ensuring that the contralateral leg was not in contact with any objects or the ground during the trial (Pappas et al., 2007; Pflum et al., 2004; Decker et al., 2003) (Figure 4.8).

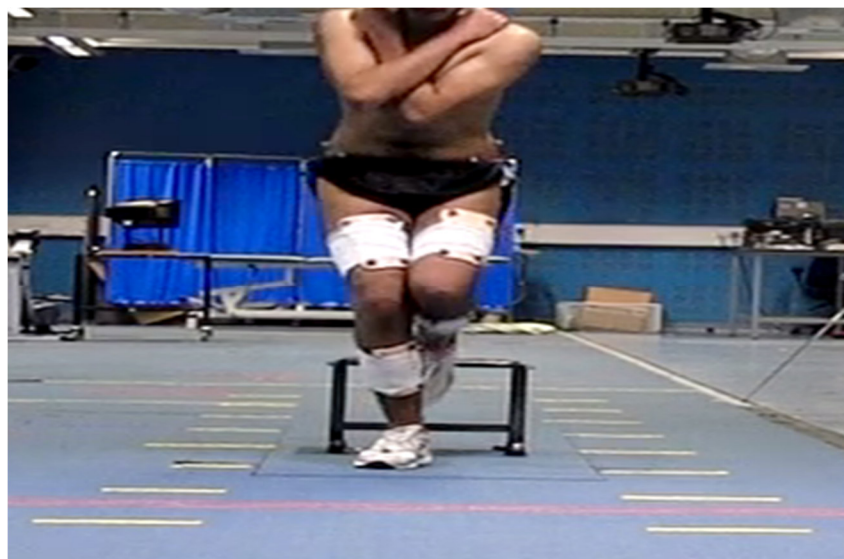


Figure 4.8 Single Leg Landing Task

4.1.3.5. Data processing

2D data processing

2D videos were analysed using the Quintec Biomechanics software package (Version 26), in order to measure the FPPA, and HADD during SLS, SLL, and RUN. The FPPA was calculated by quantifying the angle formed between the line from the marker of the knee joint to the marker of the ankle and the line from the marker of the proximal thigh to the marker of the midpoint of the knee joint. The HADD angle was calculated by measuring the angle formed between the line between the two ASIS and the line from the marker of the midpoint of the right knee joint. The FPPA and HADD were measured at the frame that corresponded to the maximum knee flexion angle (Willson et al., 2006; Willson et al., 2008).

3D data processing.

In this study, Visual3D motion analysis system (Version 4.21, C-Motion Inc. USA) was used to calculate biomechanical data of lower limbs. Motion and force plate data were filtered using a Butterworth 4th order bi-directional low-pass filter with cut-off frequencies of 12Hz for kinematic data and 25Hz for force plate data. The digital filters used to smooth the data help to minimise random noise, without any effect in the signal. The Butterworth filter is one of the common used filter in biomechanical research and it has been shown to be effective in removing random noise in kinetic and kinematic data (Winter et al., 1974). The selection of cut-off frequencies were based on the work of Yu et al. (1999). All lower limb segments were modelled as conical frustra, with inertial parameters estimated from anthropometric data (Dempster, 1959). An X-Y-Z Euler rotation sequence was used to calculate joint angles, where X stands for flexion-extension, Y stands for abduction-adduction, and Z stands for internal-external rotation (Figure 4.9) (Alenezi et al., 2014; Malfait et al., 2014). In each trial, joint angles of the lower extremity were calculated at sagittal, frontal, and transverse planes, at each peak of knee flexion corresponding frame.

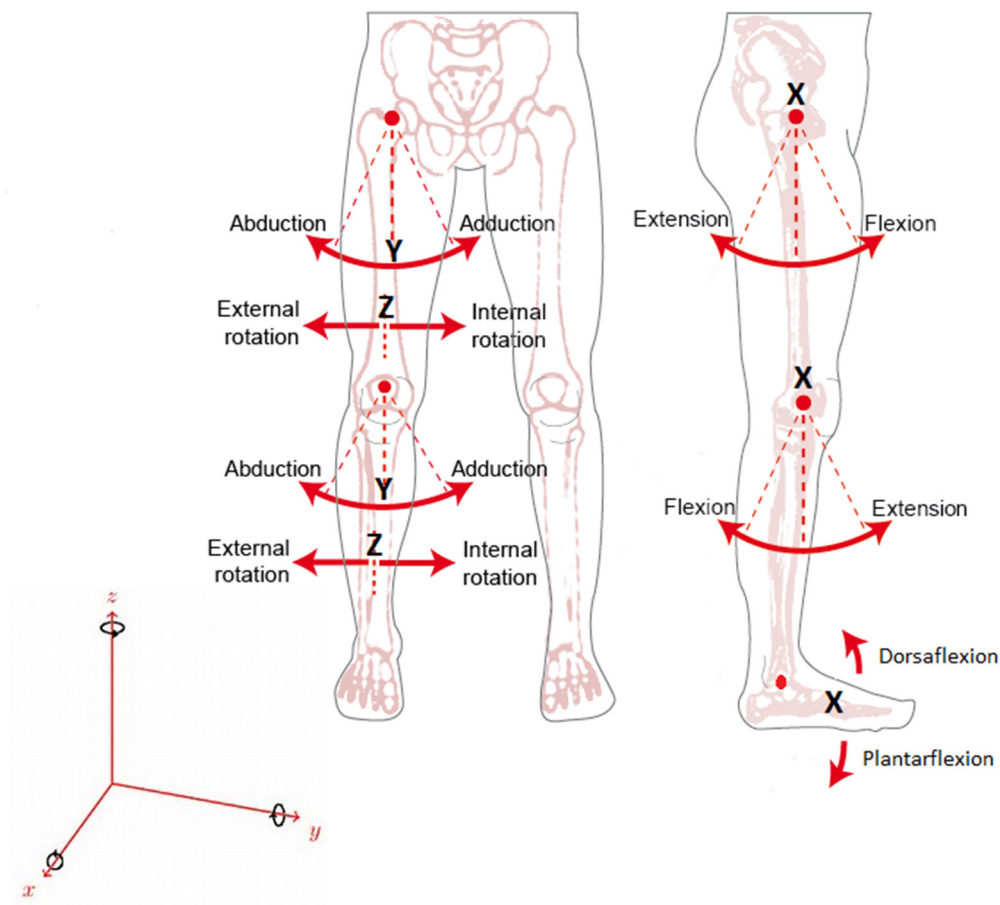


Figure 4.9 Lower limb segments and rotation according to the X-Y-Z Euler rotation sequence

The calibration anatomical systems technique (CAST) was used to define the 6 degrees of freedom in order to determine each segment of the lower limbs' movement during the trials (Cappozzo et al., 1995; Ford et al., 2007). The captured static trial of each participant that was collected with both of anatomical and tracking markers, acted as a baseline for the kinematic measurements of the lower limb during the movement trials using Qualysis Track Manager Software was used to create a kinematic model of the lower extremity with the Visual3D. This model was constructed with pelvis, thigh, shank, and foot. The anatomical markers provide a reference point for identification of bone movement using only tracking markers during movement trials.

4.1.3.6. Statistical analysis

All data was analysed statistically using SPSS v20. The test of normality was applied for each variable by means of the Kolmogorov-Smirnov test. In addition, means and standard deviations of all variables were calculated and are presented below.

Statistical analysis of reliability

Reliability of 2D analysis of FPPA and HADD during SLS, SLL, and RUN

The reliability test used the mean values from three trials and in FPPA and HADD during the screening tasks for all participants.

Within-day and between-session reliability

After analysing the 2D videos for each trial of all three sessions by the first experimenter (1st E), within-day reliability was assessed using session 1 (S1) and session 2 (S2) data, whereas data from S1 and session 3 (S3) was used to assess between-session reliability. Within- and between-session reliability was assessed with intra-class correlation (ICC) (Rankin and Stokes, 1998), from which 95% confidence intervals (CI) and standard error of measurement (SEM) estimates were used in order to determine the error of measurements, which were calculated by using the following formula: $SEM = SD(\text{pooled}) * \sqrt{(1-ICC)}$ (Harvill, 1991; Thomas et al., 2005). A lower SEM indicates better reliability (Baumgartner, 1989). ICC alone cannot provide a full picture of reliability because it does not indicate the amount of disagreement between the measurements. Therefore, SEM enables researchers to distinguish whether changes seen between tests are real or due to a potential error in measurement (Deneger and Ball, 1993). Additionally, minimal detectable differences (MDD) were calculated using the following formula: $MDD = 1.96 * \sqrt{2} * SEM$. MDD in order to determine the amount of change in the variable needed to reflect a true difference and to be considered clinically significant or meaningful (Kropmans et al., 1999).

Intra-tester reliability

Intra-tester reliability was assessed using S1 data from ten randomly selected participants by the 1st E. The same trials of the ten randomly selected participants were analysed twice by the same experimenter (1st E), with a minimum of one week in between. The ICC was used to assess intra-tester reliability, and SEM and MDD were calculated to determine the error of measurement.

Inter-tester reliability

The author was the first examiner (1st E (HA)) in this study, whereas the second examiner was PhD student Msaad Alzahrani (2nd E (MA)). The S1 data for all participants analysed by 1st E was then analysed by the second experimenter (2nd E (MA)) in order to assess inter-tester reliability. Written instructions for 2D analysis using Quintic software and the same methodology for calculating the variables used by the 1st E (HA) were given to the 2nd E (MA). In order to avoid potential bias, both testers were blinded to each other. The ICC was used to assess inter-tester reliability, and SEM and MDD were calculated to determine the error of measurement.

The ICC values across all reliability assessments were interpreted from the criteria in Table 4.1 (Coppeters et al., 2002).

Table 4.1 Classification of Intraclass Correlation Coefficient (ICC) values

ICC Value	Classification
< .40	Poor
.40 - .70	Fair
.70 - .90	Good
> .90	Excellent

Statistical analysis of the validity of 2D vs 3D

The validity of 2D analysis was assessed using S1 3D data collected during the same session for all participants and analysed with Visual 3D. Pearson's correlation coefficients (r) were used to assess the correlation between the 2D and 3D variables (kinematics of lower limbs during the three athletic tasks).

Alpha levels were set at $P < 0.05$, and grades of correlations ranged as in Table 4.2, as described by Hopkins et al. (2009).

Table 4.2 Grades of correlation ranges

Correlation range (r)	Grade
0 – 0.3	Small
0.3 – 0.5	Moderate
0.5 – 0.7	Large
0.7 – 1	Very large

4.1.4. Results

4.1.4.1. Reliability

Within-day reliability

Table 4.3 Within-Day Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN

Test	Variable	Session 1 Mean (SD)		Session 2 Mean (SD)		ICC	95% CI	SEM	MDD
SLS	FPPA(°)	11.25	(11.28)	9.22	(10.07)	.941	.805 - .982	2.42	6.72
	HADD(°)	19.4	(8.73)	18.25	(7.71)	.935	.786 - .980	1.99	5.52
SLL	FPPA(°)	11.22	(6.43)	11.75	(5.87)	.977	.925 - .993	0.89	2.48
	HADD(°)	11.23	(5.62)	9.76	(6.19)	.877	.597 – .962	2.06	5.72
RUN	FPPA(°)	-5.54	(8.84)	-6.14	(8.18)	.930	.781 - .977	2.23	6.20
	HADD(°)	13.52	(4.40)	12.73	(2.57)	.758	.246 - .922	1.48	4.12
SLS: Single Leg Land		SLL: Single Leg Land				RUN: Running			
FPPA: Frontal Plan Projection Angle						HADD: Hip Adduction Angle			

As shown in Table 4.3, the within-day reliability assessment of the 2D testing measure demonstrated excellent reliability for FPPA in the three athletic tasks: SLS (ICC=0.941, 95% CI=0.805 to 0.982), SLL (ICC=0.977, 95% CI=0.925 to 0.993) and RUN (ICC=0.930, 95% CI=0.781 to 0.977). The reliability for HADD was excellent in SLS (ICC=0.935, 95% CI=0.786 to 0.980) and good in SLL and RUN (ICC=0.877, 95% CI=0.597 to 0.962 and ICC=0.758, 95% CI=0.246 to 0.922, respectively). SEM ranged from 0.89° – 2.42° with MDD 2.48° – 6.72° for FPPA, and 1.48° – 2.06° with MDD 4.12° – 5.72° for HADD during the three tasks.

Between-sessions reliability

Table 4.4 Between-session Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN

Test	Variable	Session 1 Mean (SD)		Session 3 Mean (SD)		ICC	95% CI	SEM	MDD
SLS	FPPA(°)	11.25	(12.12)	11.61	(10.29)	.871	.576 - .961	3.79	10.53
	HADD(°)	19.4	(8.73)	19.50	(7.83)	.849	.504 - .954	3.11	8.63
SLL	FPPA(°)	11.22	(6.40)	10.77	(6.10)	.897	.661 - .968	2.01	5.59
	HADD(°)	11.23	(5.62)	8.76	(6.88)	.866	.559 - .959	2.24	6.22
RUN	FPPA(°)	-5.54	(8.84)	-5.81	(6.75)	.864	.576 - .956	2.71	7.51
	HADD(°)	13.52	(4.40)	11.78	(3.71)	.768	.310 - .922	1.93	5.36
<i>SLS: Single Leg Land</i>		<i>SLL: Single Leg Land</i>				<i>RUN: Running</i>			
<i>FPPA: Frontal Plan Projection Angle</i>						<i>HADD: Hip Adduction Angle</i>			

Referring to Table 4.4., between-session reliability for 2D measurements was good for both FPPA and HADD in the three tasks: SLS (ICC=0.871, 95% CI=0.576 to 0.961), (ICC=0.849, 95% CI=0.504 to 0.954), SLL (ICC=0.897, 95% CI=0.661 to 0.968), (ICC=0.866, 95% CI=0.559 to 0.959), and RUN (ICC=0.864, 95% CI=0.576 to 0.956), (ICC=0.768, 95% CI=0.310 to 0.922). SEM ranged from 2.01° – 3.79° with MDD 5.59° – 10.53° for FPPA and 1.93° – 3.11° with MDD 5.36° – 8.63° for HADD during the three tasks.

Intra-tester reliability

Table 4.5 Intra-tester Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN

Test	Variable	Test 1 Mean (SD)		Test 2 Mean (SD)		ICC	95% CI	SEM	MDD
SLS	FPPA(°)	16.06	(9.04)	12.39	(9.06)	.932	.700 – .985	2.35	6.52
	HADD(°)	22.27	(7.49)	20.49	(8.15)	.945	.757 - .988	1.82	5.05
SLL	FPPA(°)	10.31	(5.25)	11.88	(4.44)	.961	.825 – .991	0.79	2.20
	HADD(°)	10.83	(5.86)	9.22	(6.68)	.834	.263 - .962	2.54	7.04
RUN	FPPA(°)	-3.47	(7.07)	-3.92	(6.34)	.827	.306 - .957	2.76	7.66
	HADD(°)	15.01	(3.63)	12.89	(2.53)	.797	.182 - .950	1.30	3.60
<i>SLS: Single Leg Land</i>		<i>SLL: Single Leg Land</i>				<i>RUN: Running</i>			
<i>FPPA: Frontal Plan Projection Angle</i>						<i>HADD: Hip Adduction Angle</i>			

The results in Table 4.5 show excellent intra-tester reliability for FPPA and HADD in SLS (ICC=0.932, 95% CI=0.700 to 0.985), (ICC=0.945, 95% CI=0.757 to 0.988), SLL (ICC=0.961, 95% CI=0.825 to 0.991), (ICC=0.834, 95% CI=0.263 to 0.962), and RUN (ICC=0.827, 95% CI=0.306 to 0.957), (ICC=0.797, 95% CI=0.182 to 0.950). SEM ranged from 0.79° – 2.76° with MDD 2.20° – 7.66° for FPPA and 1.30° – 2.54° with MDD 3.60° – 7.04° for HADD during the three tasks.

Inter-tester reliability

Table 4.6 Inter-tester Intraclass Correlation Coefficients (ICC), 95% Confidence Intervals (CI), and SEM during SLS, SLL, and RUN

Test	Variable	Tester 1 Mean (SD)		Tester 2 Mean (SD)		ICC	95% CI	SEM	MDD
SLS	FPPA(°)	11.25	(12.12)	9.02	(10.45)	.985	.956 - .995	1.25	3.48
	HADD(°)	19.4	(8.73)	19.42	(8.67)	.980	.941 - .993	1.18	3.28
SLL	FPPA(°)	11.22	(6.40)	10.88	(6.35)	.994	.982 - .998	0.48	7.36
	HADD(°)	11.23	(5.62)	10.95	(5.21)	.991	.974 - .997	0.46	6.29
RUN	FPPA(°)	-5.54	(8.84)	-3.64	(7.64)	.971	.911 - .991	1.26	3.50
	HADD(°)	13.52	(4.40)	15.30	(3.95)	.914	.732 - .972	1.19	6.31
SLS: Single Leg Land		SLL: Single Leg Land				RUN: Running			
FPPA: Frontal Plan Projection Angle		HADD: Hip Adduction Angle							

As shown in Table 4.6, the 2D testing measurement demonstrated excellent inter-tester reliability for both FPPA and HADD in the three tasks: SLS (ICC=0.985, 95% CI=0.956 to 0.995), (ICC=0.980, 95% CI=0.941 to 0.993), SLL (ICC=0.994, 95% CI=0.982 to 0.998), (ICC=0.991, 95% CI=0.974 to 0.997), and RUN (ICC=0.971, 95% CI=0.911 to 0.991), (ICC=0.914, 95% CI=0.732 to 0.972). SEM ranged from 0.48° – 1.26° with MDD 3.48° – 7.36° for FPPA and 0.46° – 1.19° with MDD 3.28° – 6.31° for HADD during the three tasks.

4.1.4.2. 2D Validity

Table 4.7 2D FPPA and 3D variables correlations using Visual3D during SLS, SLL, and running.

3D	2D FPPA								
	SLS			SLL			RUN		
	Mean (SD)	<i>r</i>	<i>P</i>	Mean (SD)	<i>r</i>	<i>P</i>	Mean (SD)	<i>r</i>	<i>P</i>
2D FPPA	11.25 (11.27)	–	–	11.22 (6.43)	–	–	-5.54 (8.84)	–	–
2D HADD	19.4 (8.73)	.601*	.018	11.23 (5.62)	.556*	.031	13.52 (4.40)	.552*	.040
3D									
Hip_X_Angle	39.20 (16.22)	-.345	.208	38.12 (12.57)	-.125	.656	37.98 (6.62)	.168	.566
Hip_Y_Angle	7.62 (6.24)	-.566*	.028	-.14 (7.21)	.290	.294	15.65 (3.76)	.065	.824
Hip_Z_Angle	-3.70 (6.59)	-.005	.985	-5.60 (5.75)	-.446	.096	-10.47 (9.61)	.009	.976
Knee_X_Angle	51.71 (21.97)	-.308	.263	51.34 (13.91)	-.068	.810	55.29 (5.32)	.752**	.002
Knee_Y_Angle	5.61 (5.23)	.654**	.008	6.43 (5.02)	.146	.603	5.16 (6.41)	.354	.215
Knee_Z_Angle	-.56 (5.42)	-.182	.517	3.37 (5.26)	-.486	.066	1.65 (5.69)	-.562*	.036
Ankle_X_Angle	27.31 (10.31)	-.203	.469	18.66 (6.40)	.258	.353	30.04 (3.49)	.540*	.046
Ankle_Y_Angle	14.34 (7.16)	.173	.538	16.13 (6.76)	-.262	.346	12.06 (5.86)	-.253	.384

Nb. significant correlations are illustrated in bold

Table 4.8 2D HADD and 3D variables correlations using Visual3D during SLS, SLL, and running.

variable	HADD								
	SLS			SLL			RUN		
	Mean (SD)	<i>r</i>	<i>P</i>	Mean (SD)	<i>r</i>	<i>P</i>	Mean (SD)	<i>r</i>	<i>P</i>
2D FPPA	11.25(11.27)	.601*	.018	11.22 (6.43)	.556*	.031	-5.54 (8.84)	.552*	.040
2D HADD	70.59 (8.30)	–	–	78.76 (5.62)	–	–	76.47 (4.40)	–	–
3D									
Hip_X_Angle	39.20 (16.22)	-.148	.599	38.63 (12.57)	-.257	.356	37.98 (6.62)	-.116	.680
Hip_Y_Angle	7.62 (6.24)	.836*	<.001	-.14 (7.21)	.733*	.002	15.65 (3.76)	-.222	.427
Hip_Z_Angle	-3.70 (6.59)	-.033	.907	-5.60 (5.75)	-.362	.184	-10.47 (9.61)	.209	.455
Knee_X_Angle	51.71 (21.97)	-.028	.869	51.34 (13.91)	.046	.870	55.29 (5.32)	.559*	.030
Knee_Y_Angle	5.61 (5.23)	.179	.524	-6.43 (5.02)	.154	.584	5.16 (6.41)	.206	-.462
Knee_Z_Angle	-.56 (5.42)	-.506	.055	3.37 (5.26)	-.375	.169	1.65 (5.69)	-.333	.225
Ankle_X_Angle	27.31 (10.31)	.059	.834	18.66 (6.40)	.428	.111	30.04 (3.49)	.368	.178
Ankle_Y_Angle	14.34 (7.16)	.017	.951	16.13 (6.76)	-.419	.120	12.06 (5.86)	.202	.470

Nb. significant correlations are illustrated in bold

Validity of FPPA and HADD during SLS

The results of the 2D measurements during SLS show significant correlation between 2D FPPA and some 3D variables. A large correlation was found between 2D FPPA and knee abduction angle ($r=0.654$; $p=0.008$), HADD angle ($r= - 0.566$; $p=0.028$) using 3D measurements. No other significant correlations were found between 2D FPPA and the other 3D variables.

The results of the 2D measurements during SLS show significant association between HADD and the hip adduction angle of the 3D variables. A very large correlation was found between the 2D and 3D measurements of the hip adduction angle ($r= 0.836$; $p< 0.001$). Other results of the 2D measures of HADD demonstrated a large correlation with tibia external rotation angle ($r= - 0.506$; $p=0.055$), with a statistically significant trend.

Interestingly, the results show that 2D FPPA during SLS was significantly correlated with some of the 3D variables during SLL and RUN. Correlations ranging from large to very large were found between 2D FPPA and the knee abduction angle ($r=0.656$; $p=0.008$) and tibial external rotation ($r= -0.547$; $p=0.035$) during SLL. Moreover, a large correlation was found between 2D FPPA during SLS and the hip adduction angle ($r= -0.383$; $p=0.023$), whereas this correlation was moderate and not statistically significant with the knee abduction angle ($r=0.393$; $p=0.148$) in 3D measurements during RUN.

Validity of FPPA and HADD during SLL

The results show that no significant correlations were found between 2D FPPA and 3D variables during SLL. However, a moderate association with a statistically significant trend was found between 2D FPPA and hip internal rotation ($r= -0.446$; $p=0.096$).

A very large and significant correlation was found between 2D HADD and the hip adduction angle using 3D measurements during SLL ($r=0.733$; $p=0.002$). A moderate association was found between 2D HADD and hip internal rotation ($r= -0.382$; $p=0.184$), knee abduction angle ($r= -0.313$; $p=0.255$), tibial external rotation ($r= -0.375$; $p=0.169$), ankle flexion angle ($r=0.428$; $p=0.111$), and ankle eversion angle ($r= -0.419$; $p=0.120$).

Validity of FPPA and HADD during RUN

The results of the 2D and 3D measurements during RUN show a significant correlation between 2D FPPA and knee flexion, tibial external rotation, and ankle dorsiflexion. A very large correlation was found between 2D FPPA and knee flexion ($r=0.752$; $p=0.002$). A large correlation was also found between 2D FPPA and 3D measurements in tibial external rotation ($r= -0.562$; $p=0.036$) and ankle dorsiflexion ($r=0.540$; $p=0.046$). Only knee flexion angle using 3D was associated with 2D HADD during RUN.

Main outcomes

Table 4.9 Validity and reliability of FPPA and HADD during SLS, SLL, and RUN

Variable	Validity		Reliability (ICC)			
	<i>r</i>	<i>P</i>	Within-day	Between-days	Intra-tester	Inter-tester
FPPA during SLS	0.654	0.008*	.941	.871	.932	.985
HADD during SLS	0.836	<0.001*	.935	.849	.945	.980
FPPA during SLL	0.146	0.603	.977	.897	.961	.994
HADD during SLL	0.733	0.002*	.877	.866	.834	.991
FPPA during RUN	0.354	0.215	.930	.864	.827	.971
HADD during RUN	0.222	0.427	.758	.768	.797	.914

4.1.5. Discussion

Previous researchers have suggested that an increase in FPPA and HADD during functional tasks may increase the load on the PFJ and contribute to the incidence of PFP (Huberti & Hayes, 1984; Dierks et al., 2008; Boling et al., 2009; Chen et al., 2010; Myer et al., 2010; Powers, 2010; Herrington, 2014; and Maykut et al., 2015). Objective clinical measurements are important in identifying individuals who demonstrate abnormal alignment of the lower extremity characterised by excessive knee valgus and hip adduction angle during athletic tasks. Such measurements can serve to recognise and subsequently develop an intervention programme aimed at reducing these abnormal movement patterns in the frontal plane (Noyes et al., 2005; Maykut et al., 2015). It has been assumed that 3D analysis has the ability to identify these kinematic abnormalities. However, it is not practical in large screening programmes due to the temporal cost, the space required, and extra time needed for marker placement.

A method is therefore needed that allows for the quick collection of data in a relatively small volume. In this sense, 2D motion analysis may provide an alternative solution to 3D analysis. However, the use of 2D as a clinical measurement depends on its validity and reliability in evaluating the kinematic variables.

The first aim of this study was to assess the validity of using 2D FPPA and HADD in the evolution of lower extremity movement patterns during SLS, SLL, and RUN. A large correlation was found in the current study between FPPA using 2D measurement and knee

abduction ($r=0.654$; $p=0.008$) and hip adduction angles ($r= -0.566$; $p=0.028$) with 3D measurements during SLS. Furthermore, there was a association with hip internal rotation with a trend to be statistically significant ($r=0.461$; $p=0.084$). All of these variables represent three of the most important components contributing to dynamic knee valgus. Additionally, across the three tasks, 2D HADD was found to range from a large to very large correlation with hip adduction angle in 3D measurements. Simultaneously, there was a large correlation with 2D FPPA during all of the tasks. Similar results were reported in Willson & Davis (2008), who found that HADD, one of the contributing factors to dynamic knee valgus, was significantly correlated with 2D FPPA.

The results of this study support the first hypothesis that, in SLS, 2D FPPA is significantly associated with the 3D dynamic components that contribute to dynamic knee valgus. 2D FPPA was consistent with knee abduction during SLS, and 2D HADD was consistent with hip adduction in 3D measurements during SLS and SLL. It accounts for 43% of the variance of knee valgus in 3D. 2D HADD accounts for 39% of the variance of hip adduction in 3D during SLS. The association between 2D FPPA and 3D kinematic was previously investigated by Willson & Davis (2008) and Gwynne & Curran (2014). In Willson & Davis (2008), FPPA during SLS reflected only 23% to 30% of the variance in 3D kinematic during SLS, RUN, and single leg jumps. The greatest results in SLS were reported by Gwynne & Curran (2014), who found significant associations between 2D FPPA and single leg stance ($r=0.64$, $p=0.002$) and single limb squats ($r=0.78$, $p<0.001$). The variation in the results may be related to the variation in knee flexion angles during knee abduction measurements. In the current study, 2D FPPA were obtained nearing 60° of knee flexion, while Willson & Davis (2008) neared 55° , Gwynne & Curran (2014) neared 60° , and McLean compared the measurements at the instance of peak KABD. However, most these studies report positive results for the correlation between 2D and 3D measurements in FPPA, particularly with regard to SLS.

Several studies have investigated the relationship between 2D and 3D FPPA during multiple functional tasks (McLean et al., 2005; Willson & Davis, 2008; Gwynne & Curran, 2014; Maykut et al., 2015; Sorenson et al., 2015). McLean et al. (2005) found that 2D FPPA reflected 58% to 64% of the variance in average peak 3D knee abduction angle in side-jump and side-step tasks (McLean et al., 2005). The significant correlation reported in the study of Mclean et al. (2005) may be related to the method of correlation between the two measurements. In this sense, Mclean et al. (2005) quantified 2D FPPA from initial contact to toe-off in both measurements, normalised the time to 100% of the stance phase, and resampled at 1%-time

increments through linear interpolation. However, although this method was the gold standard in the use of 2D for identifying the association with 3D, it is not practical for large-scale screening due to the time needed to analyse each trial. The benefit of the method of analysis in the current study is, therefore, the use of one video frame as a simple photo in order to measure the variable.

The current study unearthed interesting findings in the correlations between 2D FPPA and 3D measurements during RUN. The frontal plane projection angle was not associated with the 3D knee abduction angle, whereas it was significantly correlated with knee flexion, tibial external rotation, and ankle dorsiflexion. The hypothesis presented here is that these results may be due to an increase in the external rotation of the lower extremity during RUN, which moves the knee Y angle from the frontal plane externally and moves the knee and ankle X angles from the sagittal to the frontal plane. Therefore, knee X angle was read as knee Y angle with the 2D method, which is equal to FPPA. Maykut et al. (2015) investigated the association between 2D and 3D for FPPA and HADD during treadmill running. Despite the significant results reported between the two measurements in HADD for both limbs (right: $r=0.623$, $p=0.001$, left: $r=0.539$, $p=0.007$, and in left FPPA: $r=0.541$, $p=0.006$), it does not reflect the actual values of kinetic and kinematic measurements of running, as in running over ground. The great value of the correlation results reported in this study may therefore be due to a decrease in the rotation of the lower extremity, because the forces of running were not generated by the subject but by the treadmill. In addition, there were other differences in methodology. In the current study, FPPA and HADD were calculated in 3D at the frame of maximum knee flexion and in 2D at the deepest pelvic point, as the visual identification of maximum knee flexion during the stance phase for each subject. This was done for synchronisation between the 2D and 3D methods, since they were at the peak value of each variable during the stance phase, as in Maykut et al. (2015). Another previous study used a different approach, by calculating the correlation between variables during initial contact of the task (Sorenson et al., 2015), and reports that 2D knee frontal plane projection angles had a strong relationship with 3D frontal plane knee kinematics at initial contact ($r^2=0.72$) during single leg landings.

The current study investigated the association between 2D FPPA during SLS and 3D variables during SLL and RUN. There was a significant association between the value of 2D FPPA during SLS and the knee abduction angle and an inverse association with the hip adduction angle during RUN. Similar results were reported in a previous study by Willson & Davis

(2008), in which FPPA during SLS reflected only 23% to 30% of the variance in 3D kinematics during SLS, RUN, and single leg jumps.

It has been claimed that individuals who demonstrate great FPPA and HADD angles during SLS have almost the same angle during RUN or SLL. From this study's findings, the SLS task enabled the identification of the association between 2D and 3D for FPPA and HADD. In addition, 2D FPPA was associated with the kinematic variables of the lower extremity using 3D during RUN and SLL. Therefore, the 2D FPPA during tasks that contained a single leg stance may have the potential to identify individuals who are at risk of PFP, which was clearer during SLS.

This study indicates that the variation between the results of previous studies may be due to the type of task, whether it is single or double, the measuring time during the task or the degree of knee flexion angle during the task. Moreover, some studies only measured the peak of each variable, while others compared the two measurements' curves by normalising the time to 100% of the stance phase or by quantifying the changes in the angle over time. However, the type of task and the synchronisation between 2D and 3D during functional tasks are essential in the validation of 2D kinematic measurements. Some functional tasks contain rotation and high-speed movements in the lower extremity, which lead to moving the axis of motion outside of the frontal plane or affecting the accuracy of the measurement. This was an expected limitation in the use of 2D.

The second aim of this study was to assess the within- and between-session and intra- and inter-rater reliability of 2D. The results of the reliability assessment for 2D FPPA demonstrate excellent within-session reliability and good between-session reliability during all three tasks, confirming the results reported previously in SLS and SLL (Willson et al., 2006; Munro et al., 2012; Gwynne & Curran, 2014), with ICC values of 0.72 and 0.88 respectively. They also suggest that 2D analysis of FPPA is reliable both within- and between-session during SLS and SLL. Within- and between-session reliability of 2D FPPA during running over ground was not reported before this study. Within-session reliability assessment of 2D for HADD demonstrated excellent reliability during SLS and good reliability in SLL and RUN, and between-session assessment demonstrated good reliability during all three tasks. It was expected that within-session reliability would be greater than that for between-session reliability, likely due to factors such as a greater increase of marker placement error and the

greater possibility of within-subject performance variation in between-session assessment when compared to within-session assessment.

Intra- and inter-rater reliability leads to a better understanding of the source of measurement error and could be reduced by increasing the consistency of the experimenter's measurements. The ICC values for the intra- and inter-rater reliability assessment for 2D FPPA and HADD were excellent during all of the three tasks. Associated intra- and inter-rater SEM values ranged from 0.79 – 2.76 and 0.48 – 1.26, respectively, for FPPA and from 1.30 – 2.54 and 0.46 – 1.19, respectively, for HADD across the three tasks. The ICC value for the intra-rater reliability of FPPA (ICC=0.827) and HADD (ICC=0.797) using 2D during RUN was slightly lower the values reported previously by Maykut et al. (2015), 0.951 – 0.963 for HADD and 0.955 – 0.976 for KABD, on the treadmill, which may be the cause of the high ICCs. No previous studies have reported either intra- or inter-rater reliability of the 2D method during SLS and SLL, in addition to inter-rater reliability during RUN.

Future studies should investigate both limbs during functional tasks, increase the distance to the camera, and add some control for acceptable trials, such as limiting the range for the toe-out angle and the shin-to-ground angle, in addition to controlling the position of the swing limb.

In conclusion, the results of current study suggest that 2D is significantly correlated with the 3D method in FPPA and HADD during SLS, and demonstrates good to excellent within- and between-session and intra- and inter-session reliability across the tasks. Based on the previous results, 2D provides a reliable description of lower extremity movement patterns and offers similar potential as 3D in the screening of individuals who are at risk of PFP.

Therefore, according to the low association between 2D and 3D measurements for FPPA and HADD during SLL and RUN, this study presents the hypothesis that this may be due to the variation between the two systems using Visual3D software for 3D, which may be affected by joint definitions, particularly in determining the hip joint. Thus, in order to investigate this relationship in the second section, 3D markers for 2D marker placements are therefore employed in order to look at the same markers with the two systems simultaneously.

4.2. Study 2: Validity and reliability of 2D and HHD for kinematics and strength assessment of the lower limb

4.2.1. Aims

The aims of this part are therefore to:

- A) Assess the reliability of the 2D analysis of lower limb kinematics during SLS and SLL to screen for PFP development injury occurrence in addition to other lower limb injuries.
- B) Assess the relationship between 2D and 3D systems in lower limb kinematics during RUN, SLS, and SLL to screen for PFP development injury occurrence in addition to other lower limb injuries.
- C) Assess the reliability of HHD in strength measurements of knee extensors and hip abductors to screen for PFP development injury occurrence in addition to other lower limb injuries.
- D) Assess the relationship between HHD and isokinetic dynamometer systems in strength measurements for knee extensors and hip abductors to screen for PFP.

4.2.2. Introduction

Most lower extremities musculoskeletal injuries are associated with several disorders, such as abnormal movement patterns and muscle weakness (Zeller et al., 2003; Hewett et al., 2005; Willson et al., 2006; Willson & Davis, 2008; Myer et al., 2010). Patellofemoral pain is one of these injuries, and it has been suggested that its risk factors are characterised by the demonstration of dynamic knee valgus, which is a combination of the frontal and transverse planes in hip, knee, and ankle movement during functional movements and is also related to muscular dysfunction of hip and knee muscles (Hewett et al., 2005; Willson & Davis, 2008; Boling et al., 2009; Souza and Powers, 2009). The identification of individuals who demonstrate excessive dynamic knee valgus during common athletic tasks may help to modify this pattern of movement or to reduce the risk of injury.

Motion analysis and strengthening assessment techniques are widely used in sports medicine research in order to investigate the risk of injuries. Due to the high accuracy and reliability of 3D analysis in quantifying kinematic variables and of isokinetic dynamometers in muscle strength measurements, they are widely used in athletic tasks. As such, this method is considered as the gold standard for this type of analysis. However, in injury prevention

programmes, there is a need for large-scale screening within the field in order to identify high-risk athletes.

Therefore, while 3D analysis with isokinetic dynamometers should be used, they are not practical in large screening programmes due to the space and extra time needed for marker placement. A method is therefore required that allows for the quick collection of data in a relatively small volume; in this sense, 2D analysis with an HHD may provide an alternative solution to 3D analysis with isokinetic dynamometers (Martine et al., 2006; Munro et al., 2012; Kim et al., 2014).

The reliability of 2D FPPA analysis has been investigated in several studies. 2D FPPA measurements were found to have a good to excellent between-day reliability (ICCs=0.72-0.91) and good within-day reliability (ICCs=0.59-0.88) during DJ, SLL, and SLS (Munro et al., 2012). The frontal plane projection angle has been assessed as a technique in the analysis of dynamic knee valgus to predict the risk of PFP injury (McLean et al., 2005; Willson & Davis, 2008; Norris & Olson, 2011; Olson et al., 2011; Munro et al., 2012). Excellent intra-rater reliability was found in FPPA and HADD using 2D analysis during single-leg step-downs. Moderate to high intra-rater reliability was reported by Miller and Callister (2009) during functional tests. Recently, Maykut et al. (2015) report that 2D testing during running had excellent intra-rater reliability for peak HADD angle (ICC=0.951 – 0.963) and peak KABD (ICC=0.955 – 0.976).

Varied results were found regarding the validity of 2D analysis (Maykut et al., 2015). A moderate correlation was found for FPPA between 2D and 3D testing during side jump and side step tasks (McLean et al., 2005), while a poor correlation was reported for frontal knee plane kinematics during single-leg step-downs (Olson et al., 2011). During running, moderate correlations were found for the peak HADD on the left (0.539; $P=.007$) and the right (0.623; $p=.001$) and the peak KABD on the left (0.541; $p=.006$), which were only found in the lower extremity (Maykut et al., 2015). During SLS, 2D video analysis is significantly correlated with 3D motion analysis in measuring FPPA (Gwynne & Curran, 2014). In contrast, little connection was found in the utility of FPPA during SLS (Willson & Davis, 2008; Olson et al., 2011). It has been found that the 2D value reflects only 23 to 30% of the variance in the 3D value (Willson & Davis, 2008). Therefore, regarding the previous validity and reliability results for the 2D analysis of lower extremities during some athletic tasks, RUN, SLL, and SLS were selected as the functional tasks for the current study.

Running is the most frequently performed task used by researchers to evaluate the dynamic functioning of the lower limb. It has been suggested that examination into the biomechanics of running has the potential to identify individuals with risk factors related to running injuries (Schache et al., 1999). FPPA measured from PFP participants by Willson & Davis (2008), demonstrated a greater HADD angle compared with the healthy control group during running, jumping and squatting. Souza and Powers (2009) found greater peak hip internal rotation during running in individuals with PFP. Another study found that runners who developed PFP had greater HADD angles when compared with healthy individuals (Noehren and Davis, 2007). Individuals with PFP have also been reported to have greater knee abduction angular impulses during the stance phase of running, when compared with healthy individuals (Stefanyshyn et al., 2006).

The single leg landing is one of the most common tasks or techniques in sports, and it may be better than bilateral landing for assessing individuals who are at risk of knee injury (Faude et al., 2005). Studies have shown that during unilateral tasks, performers demonstrate an increase of knee valgus and HADD angle, compared to bilateral tasks (Myklebust et al., 1998; Evangelos Pappas et al., 2007). Single leg landing screening tasks appear to be more sensitive than DJ in identifying individuals who demonstrate dynamic knee valgus, due to the increased demand to decelerate the landing force.

The single leg squat is widely used to evaluate the dynamic function of the lower limb, particularly in screening for PFP. The SLS task has previously been used in the investigation of the correlations between 2D FPPA and 3D angles of the lower limb (Willson & Davis, 2008). Single leg squats have been used to distinguish between participants with and without PFP by demonstrating dynamic knee valgus (Willson & Davis, 2008; Whatman et al., 2011). The frontal plane projection angle of the PFP group during SLS was significantly greater than the FPPA of the healthy group ($P=.012$) (Willson & Davis, 2008). Furthermore, it has been suggested that this predicts the kinematics demonstrated during running or that it has similar mechanics to those of running during the stance phase.

Comparing to the gold standard in muscle strength measurement, the isokinetic dynamometer, several studies have investigated the validity of the HHD for lower extremity muscle strength. A number of studies report that the evaluation of lower extremity muscle strength for physically active individuals using the HHD has some limitations relating to the hand stabilisation of the instrument and the changing angle of the joint. This is especially the case if the subjects are

stronger than the examiner or in the case of large-scale screenings (Vasconcelos et al., 2009; Katoh et al., 2011). However, it has been found that the validity and reliability of isometric muscle strength increased when using an HHD with a stick, a steel support, and a belt (Brinkmann, 1994; Gagnon et al., 2005; Johansson et al., 2005; Kolber et al., 2007; Katoh et al., 2009; 2010; 2011; Vasconcelos et al., 2009). Katoh et al. (2009) assessed the reliability of isometric muscle strength using an HHD with a belt for lower limbs (i.e. abduction, adduction, flexion, extension, internal and external rotation of the hip, knee flexion and extension, and ankle dorsiflexion and planter flexion) and found ICC results ranging from 0.75 to 0.97 (Katoh et al., 2009). Inter-rater reliability using HHD with a belt was found to range from 0.97 to 0.99, whereas it ranged from 0.21 to 0.88 for measurements without a belt. When the belt was applied, the measurements were significantly higher with a paired t-test (Katoh et al., 2009). The reliability ICC of isometric muscle strength measurements of knee extensors for elderly people and hemiplegic patients using HHDs with a belt was 0.88 for women and 0.91 for men (Katoh et al., 2009). The inter-rater reliability for isometric measurements of knee extensors with fixed HHDs was excellent (0.952 – 0.984) (Kim et al., 2013).

Several studies have reported the validity of isometric muscle strength measurements obtained with HHDs for various muscles in the lower limbs, compared to the validity of those obtained with isokinetic dynamometers (Katoh et al., 2009). The isokinetic dynamometer and stabilised HHD with a belt were highly correlated for isometric muscle strength measurements for knee extensors from the sitting position ($r > .86$, $p < 0.001$) (Bohannon et al., 2011). Few studies were found in the literature assessing the validity and reliability of the isometric muscle strength of hip abductors with HHDs or HHDs with a belt (Kawaguchi and Babcock, 2010; Katoh et al., 2011). No significant correlation was obtained for hip abductors in a side-lying position between HHDs and isokinetic dynamometers (Katoh et al., 2011). The validity of hip abductor isometric strength measurements using fixed HHDs did not exist before this study. Therefore, it was planned to assess the validity of hip abductor isometric muscle strength with an HHD prior to using it in the current investigation.

However, Martins et al. (2017) recently observed a high correlation between stabilised HHDs with a belt and isokinetic dynamometers for knee extensors and hip abductors (r range=0.78 – 0.90). Conversely, despite the resistance provided by using an immovable belt for HHD, this validation still has some limitations and is not practical for large-scale screening. This is either due to the HHD not being stable or secure during maximal force tests, the procedure taking more time for adjusting the belt and the HHD position, which may limit the number of

participants in large-scale screenings, or depend on the isokinetic dynamometer chair and positions which will not be available in the field; for these reasons, further evaluation is needed to validate the suitable protocol for the current study.

Running, SLS, and SLL are three activities that require a single leg stance and weight bearing. During these types of activities, the mechanics are based on muscle function, and hip abductors play an important role in preventing pelvic drops and hip adduction (Hollman et al., 2009). During motion, hip abductors primarily stabilise the femur in the frontal plane (McLeish et al., 1970). It is therefore logical that the presence of an increased HADD angle is associated with the weakness of hip abductor muscles. Hip adductors have been found to be associated with PFP (Ireland et al., 2003). Furthermore, individuals with PFP demonstrate increases in the HADD angle and knee valgus (Willson & Davis, 2008; Powers, 2010). Recently, Stickler et al. (2014) investigated the relationship between hip strength (i.e. hip abductors, hip external rotators, hip extensors, and core musculature) and frontal plane alignment during SLS and report that hip abduction strength was the greatest predictor of the variation in FPPA, at $r^2=0.22$, $p=0.002$ with multiple regression analysis. Since weaknesses in hip abductors or hip abductor peak torque have been found to be correlated with knee valgus during SLS and landing, the author selected hip abductor and knee extensor isometric strengths to be assessed with a stabilised HHD as the methodology to screen for the development of PFP injury occurrence in addition to other lower limb injuries (Claiborne et al., 2006; Jacobs et al., 2007; Kagaya et al., 2013). The purpose of this study was to assess the validity and reliability of using 2D testing for lower extremity kinematics and of using a stabilised HHD for knee extensor and hip abductor strengths, in comparison to the gold standard of 3D analysis and isokinetic dynamometers.

4.2.3. Methods

4.2.3.1. Participants

Eight healthy and physically active male students from the University of Salford volunteered for the study. The participants had an average age of 28.62 years ($SD \pm 4.06$), an average mass of 69.27kg ($SD \pm 6.44$), and an average height of 171.25cm ($SD \pm 4.89$). All participants were accepted on the condition that they participated in sports for at least three hours weekly, had no history of knee complaints or surgery, and were in good physical condition.

4.2.3.2. 3D procedure

3D Instrumentation

Full details for 3D instrumentation were described previously in section 4.1.3.3.

3D System calibration

Full details for 3D system calibration were described previously in section 4.1.3.3.

4.2.3.3. 2D Procedure

2D instrumentation

Four commercial video cameras (Casio Exilim F1), sampling at 30Hz, were located at a suitable position and distance for filming. The first camera was placed, on a tripod, 10m in front of the centre and set in standard mode (30fps), at a height of 50cm, in order to capture the markers and determine the Q-angle, FPPA, and HADD angles during kinematic movements. The second and third cameras were placed on tripods, 3m to the left and right of the centre of the capturing area, at a height of 50cm, and set on high speed mode (100fps) in order to film the lower limb sagittal plane movement (maximum knee flexion and dorsiflexion) during screening tasks. The fourth camera was placed on a tripod, 10m behind the centre of the capturing area, at a height of 50cm, in order to film the rearfoot eversion during tasks. A Brower Timing Gate System (TC-Timing System, USA) was used to monitor the running speeds.

Kinematic outcome measures

The following kinematics outcome measures were measured with 2D and 3D systems during SLS, SLL, and RUN for reliability and validity assessment:

1. Frontal plane projection angle (FPPA)
2. Hip adduction (HADD)
3. Q-angle (QA)
4. Knee Flexion (KFLX)
5. Ankle dorsiflexion (DFLX)
6. Rearfoot angle (RFA)

2D Calibration

The four cameras were levelled using a fixed level on each tripod and calibrated with 100cm square frames using Quintic software for digitising 2D. To minimise the occurrence of perspective and parallax error, all cameras were placed as far as possible from and

perpendicular to the plane of motion and were synchronised with a flashlight at the beginning of each trial. Overview of the procedure set-up Figure 4.10.

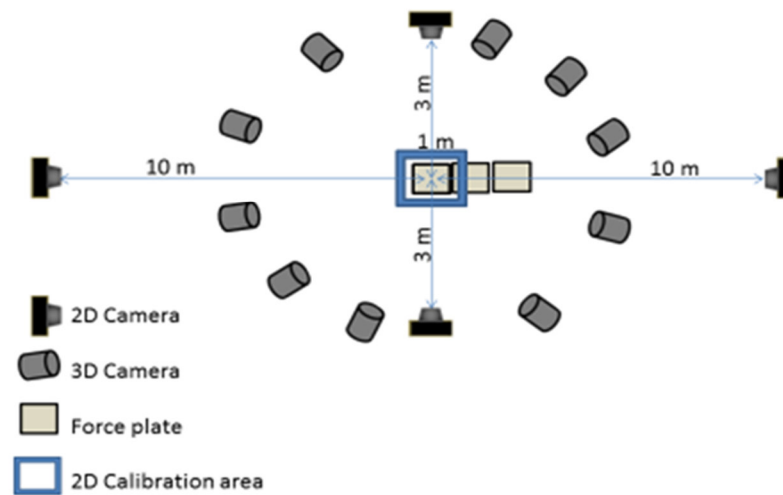


Figure 4.10 Overview of the procedure set-up

4.2.3.4. 2D and 3D Marker placement

26 3D reflective markers were used in both the 3D and 2D systems' marker placements. The 3D marker placements were similar to the 2D marker placements, which enabled each marker to be viewed simultaneously by both systems. The markers were placed on the anatomical landmarks of FPPA, HADD, Q-angle, knee flexion angle, ankle dorsiflexion angle, and rearfoot angle, as described below.

Marker placement and measurement of Q-angle

At the beginning of the procedure, three markers were placed on the anatomical landmarks of each participant's Q-angle and on both legs, i.e. the anterior superior iliac supine (ASIS), the mid-point of the patella, and the tibial tubercle, in order to define the anatomical references of the Q-angle. The Q-angle is the angle formed between the line connecting the ASIS to the centre of the patella and the line connecting the tibial tuberosity to the centre of the patella (Caylor, Fites and Worrell, 1993).

Marker placement and measurement of FPPA

Three markers were placed on the FPPA anatomical references employed by Willson et al. (2006). In this sense, markers were placed on the midpoint of the ankle malleoli for the centre of the ankle joint, the midpoint of the femoral condyles for the centre of the knee joint, and the

midpoint of the line from the anterior superior iliac spine to the knee marker at the proximal thigh. Midpoints of the knee and ankle joints were determined manually using a standard tape measure. Manual methods of midpoint approximation with a tape measure have been shown to increase intra- and inter-rater reliability, in comparison to approximations with video digitisation (Bartlett et al., 2006). The frontal plane projection angle was calculated by measuring the angle between the line from the marker of the proximal thigh to the marker of the midpoint of the knee joint and the line from the marker of the knee joint to the marker of the ankle. The frontal plane projection angle was measured at the frame corresponding to the maximum knee flexion angle (Willson, Ireland and Davis, 2006; Willson, Binder-Macleod and Davis, 2008).

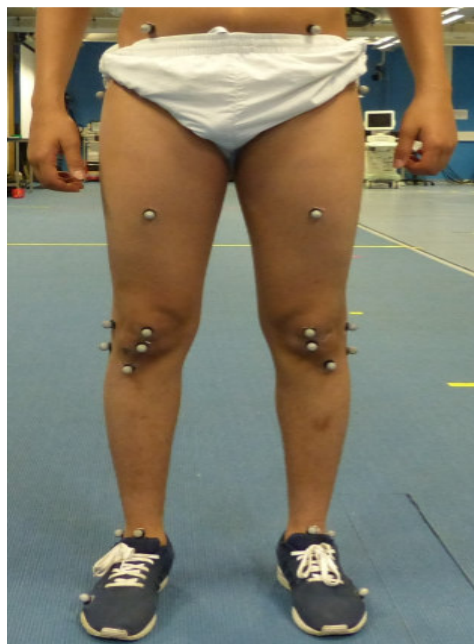


Figure 4.11 Marker placement for FPPA, Q-angle, and HADD

Marker placement and measurement of knee flexion

After determining the knee flexion landmarks, three markers were placed on the greater trochanter, lateral epicondyle, and lateral malleolus. The knee flexion angle is the angle formed between the line from the greater trochanter to the lateral epicondyle and the line from the lateral malleolus to the lateral epicondyle (Norris & Olson, 2011; Mann et al., 2013).

Marker placement and measurement of ankle dorsiflexion

Dorsiflexion markers were placed on the head of the fibula, the lateral malleolus, and the head of the fifth metatarsal, which was approximated inside standard shoes. The dorsiflexion angle was represented by the angle formed between the lines from the two peripheral markers to the central marker placed on the lateral malleolus (Fong et al., 2011).



Figure 4.12 Marker placement for KFA and DFA

Marker placement and measurement of rearfoot eversion

Four markers were placed, in descending order, on the midpoint of the calf muscle, the top of the Achilles tendon, the top of the heel, and the bottom of the heel, on standard training shoes. The rearfoot angle was represented by the conjunction formed between the line of the upper two markers and the lower two markers (Powers, 2010).



Figure 4.13 Marker placement for RFA

Participants were allowed to practice two or three times before each test, until they felt familiarised and comfortable with the trials. Subsequently, three acceptable trials from each participant and for both legs were selected and analysed for all tasks.

4.2.3.5. Screening tasks

SLS, SLL, and RUN were used as screening tasks for the baseline assessment of kinematic variables. Subjects ran over a ten-meter runway at a velocity of approximately 3m/s, with a ($\pm 5\%$) range between the trials. Running speed was monitored using the previously mentioned timing gates. A Brower Timing Gate System was set at approximately hip-height for all participants to make sure that only one part of the body crossed the beam (Yeadon et al., 1999). Then, the speed of participants was calculated by dividing distance by time. To minimise the effect of fatigue, about one to one-and-a-half minutes were given to all participants between the trials (Beaulieu et al., 2008; Cortes et al., 2010).

Participants were allowed to practice each task two or three times until they felt familiarised and comfortable with the trials. Three acceptable trials from each participant for both legs were selected and analysed for all tasks (these screening tasks were previously described in Section 4.1.3.3).

4.2.3.6. Data processing

2D data processing

The videos collected at the baseline of kinematic assessment were analysed using the Quintic Biomechanics software package (Version, 26). Each variable was measured in the corresponding frame of maximum knee flexion, which was detected visually. An average of three trials for each variable and for both limbs were recorded for all participants during the three tasks.

3D data processing with QTM analysis

Post-processing calculations of the 3D kinematic time series data were conducted using QTM software. All 3D markers were labelled with their anatomical names in the QTM. Markers that formed angles of each variable, as previously described in section 4.2.3.4, were selected manually and analysed using QTM for measuring the angles on the three X-Y-Z axes in order to track changes in the values of the measured angles over the duration of the tasks. The process started with the selection of the labelled markers of the target angles from the QTM screen. Then, 'analyse' was chosen from the drop-down list and the 'angle' option was selected from the calculation box with category of components. This was followed by ordering the markers of the measured angles in the same box and running the analysis. From the analysis screen, the value of the component of the angular movement in the YZ plane is the adduction-abduction angle, and in the XZ plane it is the flexion-extension angle in the joints of the lower extremity

(Figure 4.14). In the final stage, the analysis results were exported to an Excel spreadsheet and all the measured variables were calculated at the frame that corresponded with the greater knee flexion in the task.

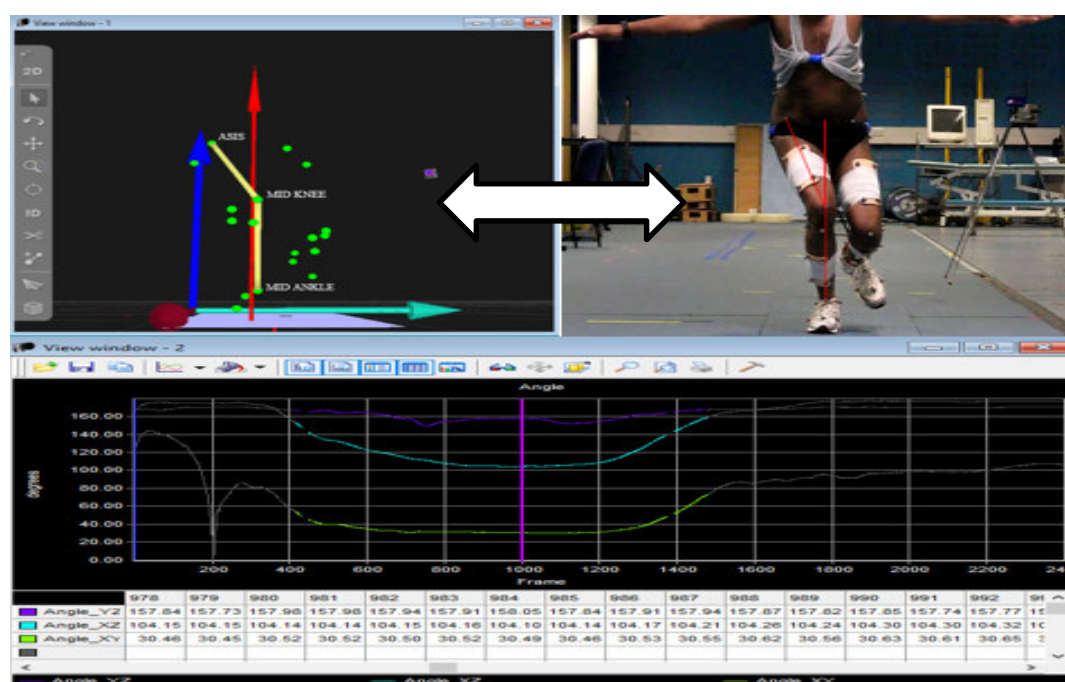


Figure 4.14 Process of 3D measurements using QTM

Strength outcome measures:

The following strength outcome measures were measured with HHD to assess their reliability and their validity against isokinetic dynamometer:

- 1- Isometric strength of knee extensors.
- 2- Isometric strength of hip abductors.

4.2.3.7. Isometric strength assessment for hip abductors and knee extensors

Handheld dynamometer procedure

Knee extensors

The HHD (MicroFet F1) was stabilised on a horizontal stake, at 20cm in height, using a 12cm wooden frame with a circular opening fitted to the back of the HHD with adhesive tape, in order to improve stability during the test (Figure 4.15). The HHD was attached to the wooden frame and then securely attached to the horsetail stake with adhesive tape. The subjects were asked to sit on the edge of the treatment bed, with 90° flexion in the knee and with both feet off the ground (Figure 4.16). The height of the treatment bed was adjusted in order to place the HHD 5cm proximal to the ankle joint at the front aspect. The subjects were then asked to apply maximum force to extend the knee joint against the fixed device for five seconds and to repeat

this four times, with a 30 second rest in between. The last three trials were recorded, while the first trial was used as practice for familiarisation (Bolgla et al., 2008). The maximum force, in newton (N), of the knee extensors in each trial was recorded and the average was multiplied by lower leg length in meter (m) (the distance from the head of the fibula to the lateral malleolus) to calculate the isometric peak torque of knee extensors in (Nm) then normalized to body mass.

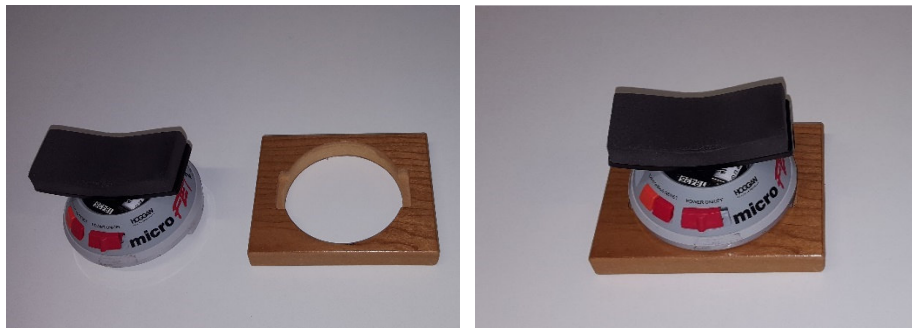


Figure 4.15 The wooden frame of HHD



Figure 4.16 Isometric strength assessment of knee extensors with HHD

Hip abductors

The HHD was stabilised on the wall just above the treatment bed using the 12cm square wooden frame and adhesive tape. The hip abductors were assessed from a supine position, with the knee flexed at 90° on the edge of the bed. This position was chosen because it is potentially easier and more applicable than the side-lying position in large-scale screenings, as it avoids the use of a belt, which is movable and less secure than a stabilised HHD. Additionally, it is quick and easy to undertake directly following on from the position of the knee extensor strength assessment, and therefore it is less time consuming with regard to changing positions. However, in this position the HHD was placed laterally, 5cm proximal to the knee joint.

Subjects were asked to lie down on their backs, with knees flexed at 90° on the edge of the bed and beside the stabilised HHD, and to apply maximum force in abducting the hip joint against the fixed HHD for five seconds and to repeat this four times, with a 30 second rest in between (Figure 4.17). The last three trials were recorded, while the first trial was used as practice for familiarisation (Bolgla et al., 2008). The maximum force, in (N), of hip abductors in each trial was recorded and the average was multiplied by length of femur in (m) (the distance from greater trochanter to the lateral epicondyle) to calculate the isometric peak torque of hip abductors in (Nm) then normalized to body mass.



Figure 4.17 Isometric strength assessment of hip abductors with HHD

Isokinetic dynamometer procedure

Knee extensors

For the isokinetic dynamometer (Biodex System 3; Biodex Medical Systems, New York, NY, USA) procedure, subjects were seated on the dynamometer chair, with knees and hip joints at 90°, in order to perform the isometric knee extensor test. The lateral femoral condyle of the knee was aligned with the rotating axis of the Biodex. The lever arm was adjusted 5cm proximal to the ankle joint at the front aspect, opposite to the direction of the action of the knee extensors (Figure 4.18). Subjects were instructed to apply maximal effort against the dynamometer for five seconds of contraction time in order to extend the knee joint, and then to repeat this four times, with a 30 second rest between the trials. The last three trials were recorded, while the first trial was used as practice for familiarisation (Bolgla et al., 2008). Isometric peak torque (Nm) of the knee extensors in each trial was recorded.

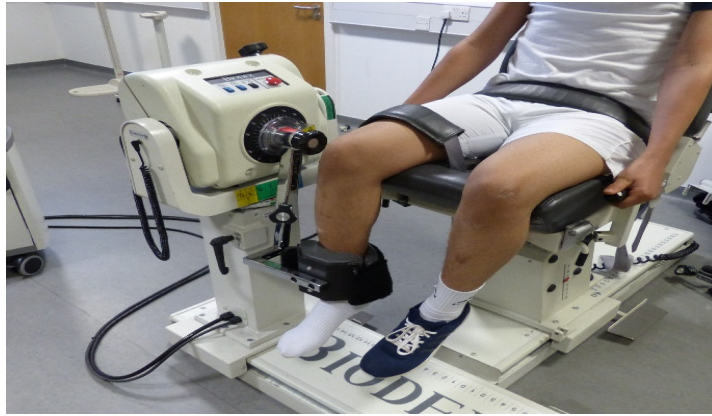


Figure 4.18 Isometric strength assessment of knee extensors with Biodex

Hip abductors

The side-lying position was applied for the hip abductor isometric test with the Biodex. This position has been chosen because it was found to be the most valid for isometric hip abductor strength, compared to standing and supine positions, with 0.9 ICC for test-retest reliability (Widler et al., 2009). After reclining on the backrest of the dynamometer chair, subjects were instructed to lie in the side-lying position, with the test leg on top of the non-test leg, and then to bend the non-test leg for stabilisation in addition to using leg and trunk straps. The lever of the arm was adjusted to apply resistance onto the test leg, 5cm proximal to the knee joint at the lateral aspect of the thigh (Figure 4.19). The rotating axis of the lever arm was aligned medial to the ASIS at the level of the greater trochanter of the test leg. Subjects were instructed to apply maximal effort against the dynamometer for five seconds of contraction time in order to abduct the hip joint, and then to repeat this four times, with a 30 second rest time between the trials. The last three trials were recorded, while the first trial was used as practice for familiarisation (Bolgla et al., 2008). Isometric peak torque (Nm) of the hip abductors for each trial was recorded.



Figure 4.19 Isometric strength assessment of hip abductors with Biodex

4.2.3.8. Statistical analysis

Reliability

The reliability test used the mean value from three trials with regard to strength and kinematic variables during screening tasks for all participants. Between-session reliability of the isometric strength assessment of hip abductors and knee extensors with HHD and lower limb 2D kinematic measurements were assessed with ICC (Rankin and Stokes, 1998), from which 95% CI was obtained; in addition, SEM and MDD were calculated to determine the error of measurement. For more details, see Chapter 4, Section 4.1.3.5.

Validity

Pearson's correlation coefficients were used to assess the correlations between lower limb strength and 2D kinematic measurements with the HHD against the gold standard of 3D analysis with an isokinetic dynamometer. One sample t-test was performed for the differences between values of the two instruments in order to test the applicability of bland Altman to assess the agreement between them. For more details, see Chapter 4, Section 4.1.3.5.

4.2.4. Results

Between-session reliability of kinematic variables

Table 4.10 Between-session intraclass correlation coefficients (ICC) for lower limb kinematics using 2D analysis during SLS

Variable	Test 1	Test 2	ICC 95% CI	SEM	MDD
	Mean (°) (SD)	Mean (°) (SD)			
R FPPA	12.82 (7.35)	12.66 (7.75)	.976 (.878 - .995)	1.163	3.22
L FPPA	12.31 (8.06)	13.12 (8.87)	.953 (.765 - .991)	1.795	4.97
R HADD	15.99 (7.82)	15.88 (7.18)	.968 (.841 - .994)	1.300	3.59
L HADD	15.94 (6.82)	13.10 (7.72)	.905 (.525 - .981)	2.200	6.10
R QA	14.94 (8.76)	15.79 (9.86)	.953 (.767 - .991)	1.935	5.36
L QA	15.93 (9.77)	15.17 (9.51)	.986 (.930 - .997)	1.138	3.15
R KFLX	102.13 (4.63)	100.94 (5.21)	.903 (.513 - .980)	1.510	4.18
L KFLX	106.27 (6.57)	103.23 (9.03)	.877 (.385 - .975)	2.481	6.88
R DFLX	80.45 (4.52)	80.57 (3.18)	.925 (.625 - .985)	0.828	1.99
L DFLX	81.81 (5.34)	82.78 (5.56)	.866 (.328 - .973)	1.995	5.53
R RFA	10.39 (3.16)	10.43 (2.92)	.961 (.805 - .992)	0.598	1.65
L RFA	11.26 (3.81)	11.68(3.49)	.967 (.837 - .993)	0.641	1.78
<i>R FPPA: Right frontal plane projection angle L FPPA: Left frontal plane projection angle</i> <i>R HADD: Right hip Adduction Angle L HADD: Left hip adduction angle</i> <i>R QA: Right Q-angle L QA: Left Q-angle</i> <i>R KFLX: Right knee flexion angle L KFLX: Left knee flexion angle</i> <i>R DFLX: Right dorsiflexion angle L DFLX: Left dorsiflexion angle</i> <i>R RFA: Right rearfoot angle L RFA: Left rearfoot angle</i>					

Table 4.11 Between-session intraclass correlation coefficients (ICC) for lower limb kinematics using 2D analysis during SLL

Variable	Test 1 Mean (°) (SD)	Test 2 Mean (°) (SD)	ICC 95% CI	SEM	MDD
R FPPA	13.86 (6.99)	12.43 (6.46)	.955 (.774 - .991)	1.406	3.90
L FPPA	7.51 (6.88)	8.46 (7.60)	.990 (.951 - .998)	0.624	1.73
R HADD	10.86 (5.54)	10.65 (4.05)	.886 (.429 - .977)	1.457	4.03
L HADD	6.13 (5.99)	5.21 (6.07)	.925 (.624 - .985)	1.654	4.58
R QA	16.00 (11.33)	16.35 (9.65)	.982 (.911 - .996)	1.124	3.11
L QA	10.68 (9.39)	11.01 (11.03)	.977 (.887 - .995)	1.303	3.61
R KFLX	115.73 (10.71)	116.88 (9.66)	.974 (.868 - .995)	1.570	4.35
L KFLX	123.71 (7.57)	122.42 (7.53)	.962 (.808 - .992)	1.479	4.10
R DFLX	93.47 (4.50)	92.92 (4.72)	.845 (.223 - .969)	1.815	5.03
L DFLX	96.38 (5.47)	97.38 (5.77)	.891 (.458 - .978)	1.847	5.12
R RFA	11.94 (2.89)	11.10 (3.19)	.900 (.500 - .980)	0.952	2.64
L RFA	12.90 (3.29)	12.20(4.38)	.892 (.460 - .978)	1.149	3.18
<i>R FPPA: Right frontal plane projection angle L FPPA: Left frontal plane projection angle</i> <i>R HADD: Right hip Adduction Angle L HADD: Left hip adduction angle</i> <i>R QA: Right Q-angle L QA: Left Q-angle</i> <i>R KFLX: Right knee flexion angle L KFLX: Left knee flexion angle</i> <i>R DFLX: Right dorsiflexion angle L DFLX: Left dorsiflexion angle</i> <i>R RFA: Right rearfoot angle L RFA: Left rearfoot angle</i>					

Table 4.12 Between-session intraclass correlation coefficients (ICC) for lower limb kinematics using 2D analysis during RUN

Variable	Test 1 Mean (°) (SD)	Test 2 Mean (°) (SD)	ICC 95% CI	SEM	MDD
R FPPA	-1.52 (4.43)	-0.70 (3.56)	.945 (.726 - .989)	0.834	2.31
L FPPA	-1.76 (3.72)	-1.13 (5.40)	.887 (.435 - .977)	1.306	3.62
R HADD	11.17 (3.76)	10.75 (3.21)	.959 (.797 - .992)	0.651	1.80
L HADD	11.20 (2.39)	11.37 (4.22)	.817 (.086 - .963)	1.126	3.12
R QA	6.43 (7.85)	6.47 (6.49)	.897 (.488 - .979)	2.205	6.11
L QA	8.11 (5.41)	8.18 (7.94)	.908 (.543 - .982)	1.605	4.45
R KFLX	132.82 (5.05)	132.05 (4.92)	.924 (.621 - .985)	1.372	3.80
L KFLX	132.61 (5.22)	130.16 (5.43)	.904 (.521 - .981)	1.647	4.56
R DFLX	91.18 (7.99)	89.62 (7.99)	.957 (.783 - .991)	1.665	4.61
L DFLX	91.15 (5.94)	91.07 (5.77)	.939 (.693 - .988)	1.449	4.01
R RFA	10.90 (4.55)	11.23 (4.50)	.926 (.630 - .985)	1.230	3.41
L RFA	11.98 (4.08)	11.51 (4.49)	.903 (.518 - .981)	1.316	3.64
<i>R FPPA: Right frontal plane projection angle L FPPA: Left frontal plane projection angle</i> <i>R HADD: Right hip Adduction Angle L HADD: Left hip adduction angle</i> <i>R QA: Right Q-angle L QA: Left Q-angle</i> <i>R KFLX: Right knee flexion angle L KFLX: Left knee flexion angle</i> <i>R DFLX: Right dorsiflexion angle L DFLX: Left dorsiflexion angle</i> <i>R RFA: Right rearfoot angle L RFA: Left rearfoot angle</i>					

Referring to Table 4.10, between-session reliability of the kinematic variables with 2D measurement during SLS ranged from good to excellent (0.866 – 0.986) with SEM (0.598° - 2.481°) and MDD (1.65° – 6.88°). Only two variables were good, left knee flexion (ICC = 0.877), and left dorsiflexion, and other variables were excellent. In SLL task, ICCs values of the between-session reliability of the kinematic variables with 2D measurement during SLL, in Table 4.11, ranged from good to excellent (0.845 – 0.990) with SEM (0.624° - 1.845°) and MDD (1.73° – 5.12°). The lowest ICC value was for right dorsiflexion (ICC = 0.845). Three variables during running task out of the 12 variables were non-normally distributed. Between-session reliability of the kinematic variables with 2D measurement during RUN ranged from good to excellent (0.817 – 0.959) with SEM (0.651° - 2.205°) and MDD (1.80° – 6.11°) (Table 4.12).

Validity of 2D

Table 4.13 2D and 3D correlation using QTM during SLS

Variable	2D Mean (SD)	3D Mean (SD)	<i>r</i>	<i>P</i>
R FPPA	12.82 (7.35)	13.50 (7.44)	.962**	<.001
L FPPA	12.31 (8.06)	13.56 (9.27)	.957**	<.001
R HADD	15.99 (7.82)	16.02 (7.45)	.993**	< .001
L HADD	15.94 (6.82)	16.45 (7.63)	.989**	< .001
R QA	14.94 (8.76)	16.42 (9.03)	.984**	< .001
L QA	15.93 (9.77)	15.89 (11.18)	.959**	<.001
R KFLX	102.13 (4.63)	102.64 (4.78)	.974**	< .001
L KFLX	106.27 (6.57)	106.64 (7.07)	.988**	< .001
R DFLX	80.45 (4.52)	79.33 (5.42)	.943**	< .001
L DFLX	81.81 (5.34)	80.78 (6.02)	.838**	.009
R RFA	10.39 (3.16)	9.62 (2.75)	.891**	.003
L RFA	11.26 (3.81)	11.34 (3.31)	.819*	.013
<i>R FPPA: Right frontal plane projection angle L FPPA: Left frontal plane projection angle</i> <i>R HADD: Right hip Adduction Angle L HADD: Left hip adduction angle</i> <i>R QA: Right Q-angle L QA: Left Q-angle</i> <i>R KFLX: Right knee flexion angle L KFLX: Left knee flexion angle</i> <i>R DFLX: Right dorsiflexion angle L DFLX: Left dorsiflexion angle</i> <i>R RFA: Right rearfoot angle L RFA: Left rearfoot angle</i>				

Table 4.14 2D and 3D correlation using QTM during SLL

Variable	2D Mean (SD)	3D Mean (SD)	<i>r</i>	<i>P</i>
R FPPA	13.86 (6.99)	16.10 (5.90)	.876**	.004
L FPPA	7.51 (6.88)	8.59 (7.13)	.964**	<.000
R HADD	10.86 (5.54)	10.33 (5.55)	.973**	< .001
L HADD	6.13 (5.99)	6.24 (5.90)	.916**	<.001
R QA	16.00 (11.33)	19.47 (9.72)	.872**	.005
L QA	10.68 (9.39)	12.85 (11.77)	.983**	< .001
R KFLX	115.73 (10.71)	116.50 (10.23)	.988**	< .001
L KFLX	123.71 (7.57)	124.35 (7.04)	.994**	< .001
R DFLX	93.47 (4.50)	92.88 (5.71)	.982**	< .001
L DFLX	96.38 (5.47)	96.00 (5.29)	.992**	< .001
R RFA	11.94 (2.89)	11.94 (3.38)	.834**	.001
L RFA	12.90 (3.29)	12.53 (3.43)	.821*	.012
<i>R FPPA: Right frontal plane projection angle L FPPA: Left frontal plane projection angle</i> <i>R HADD: Right hip Adduction Angle L HADD: Left hip adduction angle</i> <i>R QA: Right Q-angle L QA: Left Q-angle</i> <i>R KFLX: Right knee flexion angle L KFLX: Left knee flexion angle</i> <i>R DFLX: Right dorsiflexion angle L DFLX: Left dorsiflexion angle</i> <i>R RFA: Right rearfoot angle L RFA: Left rearfoot angle</i>				

Table 4.15 2D and 3D correlation using QTM during RUN

Variable	2D Mean (SD)	3D Mean (SD)	<i>r</i>	<i>P</i>
R FPPA	-1.52 (4.43)	-1.71 (4.39)	.967**	<.000
L FPPA	-1.76 (3.72)	-2.21 (3.88)	.982**	< .001
R HADD	11.17 (3.76)	11.06 (4.65)	.912**	.002
L HADD	11.20 (2.39)	10.70 (3.48)	.895**	.003
R QA	6.43 (7.85)	6.88 (6.64)	.982**	< .001
L QA	8.11 (5.41)	8.77 (4.46)	.925**	.001
R KFLX	132.82 (5.05)	134.13 (5.33)	.968**	< .001
L KFLX	132.61 (5.22)	132.66 (5.93)	.942**	<.001
R DFLX	91.18 (7.99)	90.73 (9.15)	.984**	< .001
L DFLX	91.15 (5.94)	89.30 (6.28)	.972**	<.001
R RFA	10.90 (4.55)	10.57 (4.22)	.861**	.006
L RFA	11.98 (4.08)	11.01 (3.37)	.827*	.011
<i>R FPPA: Right frontal plane projection angle L FPPA: Left frontal plane projection angle</i> <i>R HADD: Right hip Adduction Angle L HADD: Left hip adduction angle</i> <i>R QA: Right Q-angle L QA: Left Q-angle</i> <i>R KFLX: Right knee flexion angle L KFLX: Left knee flexion angle</i> <i>R DFLX: Right dorsiflexion angle L DFLX: Left dorsiflexion angle</i> <i>R RFA: Right rearfoot angle L RFA: Left rearfoot angle</i>				

The results show a very significant correlation between 2D and 3D analysis in all of the kinematic variables, ranging from 0.832 – 0.994 across all the three tasks (Tables 4.13, 4.14, and 4.15).

Between-session reliability of muscle strength

Table 4.16 Between-session intraclass correlation coefficients (ICC) for HHD

Muscle	Test 1		Test 2		ICC	95% CI	SEM	MDD
	Mean (N.m)	(SD)	Mean (N.m)	(SD)				
KEXT	138.02	(41.65)	136.54	(43.64)	.980	.900 - .996	5.96	16.53
HABD	88.00	(22.17)	92.16	(21.71)	.983	.915 - .997	2.85	7.90
<i>KEXT: knee extensors</i>					<i>HABD: Hip Abductors</i>			

As shown in Table 4.16, the between-session reliability assessment of isometric muscle strength testing with the HHD demonstrated excellent reliability for quadriceps (ICC=0.997, 95% CI=0.968 to 0.999) and hip abductor (ICC=0.993, 95% CI=0.917 to 0.997) muscle strength.

Validity of HHD

Table 4.17 HHD and Biodex correlation for isometric strength assessment of knee extensors and hip abductors

Muscle	HHD		Biodex		t-test of difference	<i>r</i>
	Mean (N.m)	(SD)	Mean (N.m)	(SD)		
KEXT	138.02	(41.65)	181.61	(52.15)	0.003	0.969*
HABD	88.00	(22.17)	100.96	(29.01)	0.029	0.900*
<i>KEXT: knee extensors</i>			<i>HABD: Hip Abductors</i>			

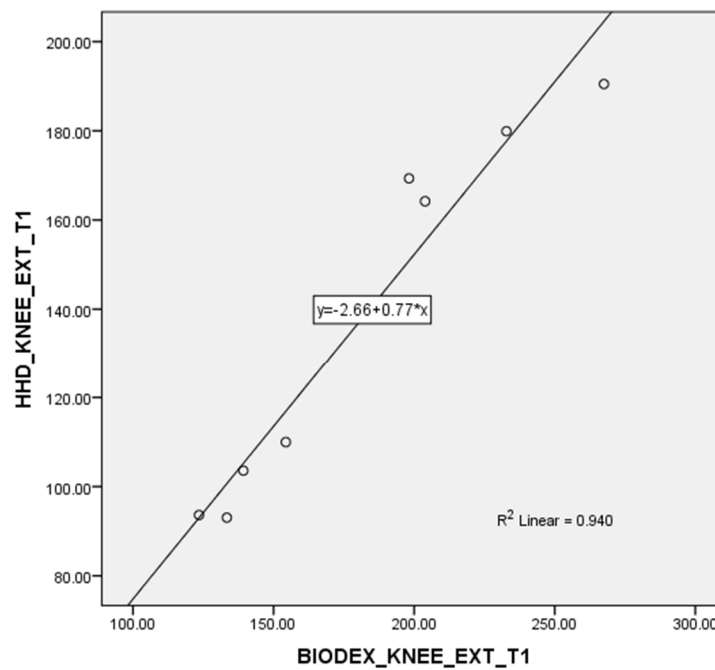


Figure 4. 20 Scatterplot illustrating the linear relationship, with (r^2) value, between the HHD procedure and the isokinetic dynamometer procedure for knee extensors

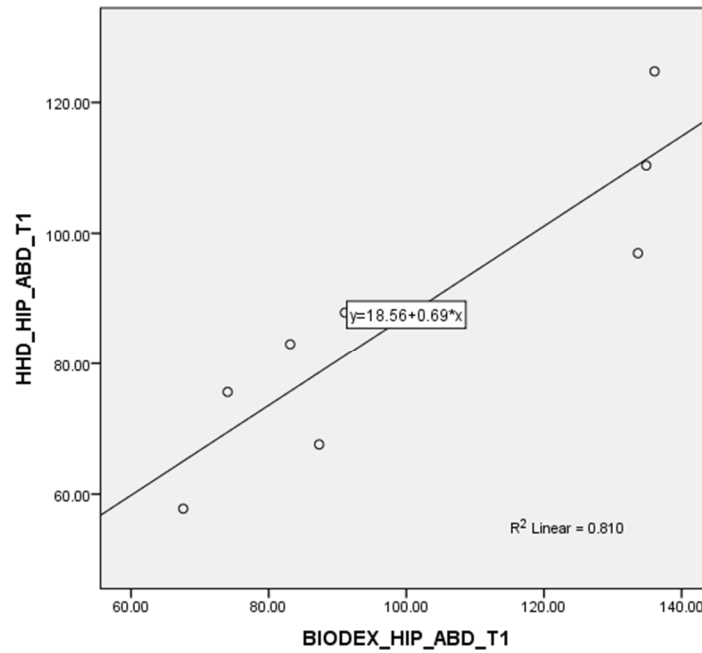


Figure 4. 21 Scatterplot illustrating the linear relationship, with (r^2) value, between the HHD procedure and the isokinetic dynamometer procedure for hip abductors

The results show that the value obtained with the isokinetic dynamometer are significantly higher than the value obtained with the HHD, and the bland Altman test was not applicable due to significant difference between the two instruments with t-test. However, at the same time of this difference, there is very large correlation between the two instruments in quadriceps ($r=0.969$) and hip abductor ($r=0.900$) isometric muscle strength. The scatterplot illustrates a positive linear relationship between the HHD procedure and isokinetic dynamometer procedure for knee extensors was ($r^2=0.940$) and hip abductors was ($r^2=0.810$), (Table 4.17) (Figure 4.21).

4.2.5. Discussion

One of the aims of this study is to assess the relationship between 2D and 3D systems with regard to the kinematics of the lower limb during SLS, SLL and RUN. In this section, 3D reflective markers for motion analysis were employed on the 2D landmarks for FPPA and other lower limb kinematic variables in order to view the two systems simultaneously during each athletic task. The results of the correlation assessment were surprising, showing that 2D analysis has a very large correlation with 3D analysis, with excellent between-day reliability in the majority of the kinematic variables. Most previous studies, as well as the study in study (1) in chapter 4, used Visual3D for 3D measurements in order to assess this relationship with the 2D measurements. In the current study, efforts have been made to avoid the differences that may exist due to the use of Visual3D through utilising QTM only with 3D markers for 2D

marker placements. In this method, no model was created, and the 3D measurements for kinematic variables in the frontal and sagittal planes were performed manually based on the 2D method of measurement. By so doing, the agreement between 2D and 3D measurements in tracking the same point at the same time was improved. However, this method only supports the accuracy of the use of 2D measurements in the frontal and sagittal planes separately. In this sense, it does not reflect the actual movement in the joint that could be measured with the use of Visual3D. For more details regarding similar studies, see chapter 4, Section 4.1.5.

Several studies have assessed the repeatability and validity of the HHD with regard to its population, and the significant advantages of its use as an alternative tool to the isokinetic dynamometer with regard to its low cost and portability. Most of these studies report conflicting results in assessments with the HHD (Martin et al., 2006), which may be due to the position of testing or the poor stabilisation of participants or the HHD, which is especially apparent when testing powerful muscle groups, such as quadriceps (Agre et al., 1987; Bohannon, 1990; Hayes and Falconer, 1992; Martin et al., 2006). Other studies have used a belt to stabilise the HHD in order to provide more support and stability for the instrument and to assess its validity and reliability (Katoh et al., 2011, Kim et al., 2014). This seems to be more practical than being stabilised by the examiner's hand, but, in fact, this method is less secure due to the movability of the HHD, particularly with a long belt.

In the present study, we addressed the issues behind the conflicting results of using an HHD. Therefore, the HHD was stabilised on the wall using wooden frame in the current study. In addition, a sitting position was selected for knee extensors and a supine position was selected for hip abductors. The results of the isometric strength assessment with the HHD show excellent between-day repeatability for knee extensors and hip abductors with a fixed HHD. Similar results were reported in a number of previous studies that assessed the reliability of the isometric strength of hip abductors and knee extensors using an HHD (Katoh et al., 2011; Kim et al., 2014).

The current study's results regarding HHD validation compared to the gold standard of an isokinetic dynamometer system show that the results obtained with the isokinetic dynamometer are significantly higher than the results obtained with the HHD. However, there is very significant correlation between the two systems in the muscles tested, $r=0.969$ for knee extensors and $r=0.900$ for hip abductors. Martin et al. (2006), Bohannon et al. (2011) and Kim et al. (2014) investigated the validity of HHD measurements for knee extensors, and similar

results are reported in all of these studies. Martin et al. (2006) assessed the validity of HHD measurements for knee extensors from a supine position, while Kim et al. (2014) did so from supine and sitting positions; Bohannon et al. (2011) assessed the same muscle group from a sitting position, which is similar to the current study. All of these studies report a correlation between the isokinetic dynamometer and the HHD, but the values obtained with the isokinetic dynamometer were greater than those obtained with the HHD. The lowest variation between the two measurements was found, by Kim et al. (2014), in supine position with a 35° flexion in the knee joint: the isokinetic dynamometer compared to the HHD was 69.63Nm and 66.03Nm, respectively, with a large correlation ($r=.806^*$). In the same study, Kim et al. (2014) report that the value obtained with the HHD from a supine position with 35° flexion in knee joint was 10.23% greater than a sitting position with 90° in knee flexion. They claim that this difference may have been due to the optimal muscle length at the moment of the peak muscle force, in addition to the muscle length, which changes according to the angle of the knee and the hip joints (Visser et al., 1990; Kim et al., 2014). We are uncertain why there was a variation of values between the two procedures in the current study and in that of Bohannon et al. (2011), but it might be due to the extra comfort and stability offered by the isokinetic dynamometer and the absence of trunk support with the HHD procedure (Hart et al., 1984; Bohannon et al., 2011).

The current study's results that were obtained with the isokinetic dynamometer for hip abductors are significantly higher than the results obtained with the HHD. However, there is a very large correlation ($r=0.903$) between the two systems in the muscles tested. Few studies were found in the literature that assessed the validity and reliability of the isometric muscle strength of hip abductors with an HHD or an HHD with a belt (Kawaguchi and Babcock, 2010; Katoh et al., 2011). Katoh et al. (2011) assessed the association between the HHD and isokinetic dynamometer for hip abductors from a side-lying position, and no significant correlation between the two instruments was obtained for hip abductors (Katoh et al., 2011). The validity of hip isometric strength measurements using the HHD did not exist before conducting the current study. Recently, Martins et al. (2017) observed a high correlation between an HHD stabilised with a belt and an isokinetic dynamometer for knee extensors and hip abductors (r range=0.78 – 0.90). However, Martin et al.'s (2017) study supports the findings of the current study. The linear relationships between the two procedures for knee extensors and hip abductors ($r^2=0.940$ and $r^2=0.810$, respectively: Figure 4.20) provide evidence that the same underlying constructs were being measured, i.e. hip abductors and knee extensors.

Measurements of hip abductors and knee extensors obtained with an HHD are significantly lower than, but at the same time highly correlated with, those obtained with an isokinetic dynamometer. As the HHD is less expensive, requires less space, and is more portable than the isokinetic dynamometer system, and as limitations due to examiner strength do not appear to apply, the use of an HHD is suitable for measuring hip abductor and knee extensor strength in large-scale screenings of healthy individuals.

In conclusion:

Based on these results, it could be proven that the 2D motion analysis and HHD are valid and reliable in measurement of all outcome measures which will be tested in the next chapter:

1. Frontal plane projection angle (FPPA) during SLS, SLL, and RUN
2. Hip adduction (HADD) during SLS, SLL, and RUN
3. Q-angle (QA) during SLS, SLL, and RUN
4. Knee Flexion (KFLX) during RUN
5. Ankle dorsiflexion (DFLX) during RUN
6. Rearfoot angle (RFA) during RUN
7. Isometric muscle strength of knee extensors
8. Isometric muscle strength of hip abductors

CHAPTER 5

Prospective Investigation of Biomechanical Risk Factors in the Initiation of PFP in Basic Military Training

5.1. Introduction

Military physical training has the potential risk of injury, which increases as the intensity of training exercises increases. Occurrence of injury causes temporary or long-term disability for recruits, resulting in a loss of training time as well as treatment and rehabilitation (Powell & Barber-Foss, 2000; Agel et al., 2007; Hootman et al., 2007; and Rauh & Wiksten, 2007). Basic military training is considered to be the most physically demanding training course for new recruits across many military institutions in the world (Wilkinson et al., 2008), which, in order to reach the maximum level of physical readiness, mainly consists of running, battle training, resistance training, and loaded marches to improve muscle strength, endurance, and aerobic fitness (Greeves et al., 2001; Blacker et al., 2008). The volume and physical load for many recruits is higher than they have previously experienced (Cowan et al., 1996; Almeida, 1999). It has been claimed that the risk of musculoskeletal injury is increased due to a failure to adapt to the significant increase in physical load (Popovich et al., 2000; Sharma, 2007; Knapik et al., 2011).

Incidence of musculoskeletal injuries within military populations has been reported in many studies, ranging from 20 to 59% during basic military training (Linenger & West, 1992; Franklyn et al., 2011; and Knapik et al., 2013). The medical discharge rate at the Infantry Training Centre in Catterick in the UK is over 8%, primarily due to musculoskeletal injuries (Blacker et al., 2008). The rate for knee injury was about 203 per 1,000 trainees, and lower limb injuries comprised 72% of all injuries. It has been suggested that PFP is a high-rate musculoskeletal injury, associated with an increase in the volume of exercise or physical load, such as in sports or basic military training (Cowan et al., 1996; Almeida, 1999).

Patellofemoral pain is one of the main sources of chronic knee pain in young athletes (Brody & Thein, 1998; Piva et al., 2006), accounting for 25 to 40% of all knee joint problems examined in sports medicine clinics (Rubin & Collins, 1980; Chesworth et al., 1989; Bizzini et al., 2003). Patellofemoral pain is a major problem among physically active populations, such as adolescents, young adults, and military recruits (Messier et al., 1991; Cutbill et al., 1997; Duffey et al., 2000; Witvrouw et al., 2000; Laprade et al., 2003; Powers et al., 2003; Thijs et al., 2007).

Various methods and instruments have been used by researchers to investigate the source of this condition. There is evidence from retrospective studies that the condition may be related to biomechanical factors, such as an increase of hip adduction and internal rotation angles, an increase of knee valgus, an increase of Q-angle, an increase of rearfoot eversion angle, a decrease of knee extensors strength, and a decrease of hip abductor and external rotator strength (Aglieetti et al., 1983; Al-Rawi & Nessian, 1997; Aliberti et al., 2010; Anderson & Herrington, 2003; Baker et al., 2002; Barton et al., 2010; Barton et al., 2009; Besier et al., 2008; Callaghan & Oldham, 2004; Cowan et al., 2002; Cowan et al., 2001; Crossley et al., 2004; Dierks et al., 2008; Dorotka et al., 2002; Draper et al., 2009). However, with a retrospective design, it is difficult to determine if the risk factor is the cause or the consequence of the condition. Therefore, to progress within this field, further prospective studies are needed in order to improve our understanding of the biomechanical risk factors of PFP and to develop its treatment and prevention. Previously documented prospective studies, of which there are a limited number, have made progress within this field and have reported various risk factors related to the injury. From the fifteen prospective studies, six were found in the literature that investigated the biomechanical risk factors of PFP in military populations (Milgrom et al., 1991; Van Tiggelen et al., 2004; Hetsroni et al., 2006; Thijs et al., 2007; Duivigneaud et al., 2008; VanTiggelen et al., 2009; Boling et al., 2009). However, despite the benefit of choosing a military population during basic military training, as it is a homogenous group in terms of age, physical fitness, activity, and amount of daily training, there are some limitations that need to be addressed. The most important limitations are the time taken for collecting data and a dependency on the use of advanced technology, which is expensive and not applicable to large-scale screening (such as isokinetic dynamometers for strength and 3D systems for kinematic and kinetic measurements). Therefore, the most important factors in screening large populations are speed, simplicity, and portability, which are crucial in future injury prevention programmes. It has been noted from reviewing the previous prospective studies that none report on their reliability, and there is a lack of validation regarding the measurement tools; in addition, no study used 2D measurements for FPPA and other lower limb kinematics in military populations and no study used a stabilised HHD for the isometric muscle strength assessment of hip abductors and knee flexors.

In Chapter 4, it was recognised that 2D and HHD measurements are significantly correlated with 3D and isokinetic dynamometer measurements in lower limb kinematics during SLS, SLL, and RUN, as well as for isometric muscle strength assessment of hip abductors and knee

extensors. These results support studies that found similar results for 2D measurement of lower limb kinematics and isometric muscle strength assessment using an HHD, in addition to the conclusion that an HHD and 2D analysis may have the potential to identify individuals who are at high risk of PFP (McLean et al., 2005; Willson & Davis, 2008; Katoh & Yamasaki, 2009; Bohannon et al., 2011; Gwynne & Curran, 2014; Maykut et al., 2015; Sorenson et al., 2015).

In the Saudi military population, it is notable that there is a high incidence rate for knee injuries during the first three months of military training and that it is one of the most common causes of discharge or referral to hospital. In order to further advance the current state of research and gain a better understanding of the risk factors that contribute to the occurrence of PFP, the purpose of this study is to employ 2D motion analysis and HHD for FPPA and other lower limb kinematics and strength within the military population in order to be the first study to investigate the risk factors of PFP and other lower limb injuries among Saudi recruits.

5.2. Aims

The aims of this study are therefore to prospectively examine:

- a) The use of 2D analysis in FPPA, HADD, dynamic Q-angle, knee flexion, dorsiflexion, and rearfoot eversion during running, SLS, and SLL to screen for PFP development injury occurrence in addition to other lower limb injuries.
- b) The use of an HHD in isometric strength testing of hip abductors and knee extensors to screen for PFP development injury occurrence in addition to other lower limb injuries.
- c) Identify the risk factors that can be measured and have a clear relationship to the incidence of PFP, more than other risk factors.

Objective:

The objective of this study is to screen a large military population with 2D video and an HHD in order to investigate the biomechanical risk factors associated with patellofemoral pain and other lower limb injuries.

Hypotheses

Therefore, the following null hypotheses will be tested within the study:

1. H₀₁: There will be no significant difference between the kinematics of individuals who sustain patellofemoral pain and any other lower limb injuries, and those who do not.
2. H₀₂: There will be no significant difference in muscle strength between individuals who sustain patellofemoral pain and any other lower limb injuries and those who do not.

3. H0₃: There will be no risk factor that can be measured and has a clear relationship to the incidence of PFP, more than other risk factors.

5.3. Methods

5.3.1. Instruments

Four video cameras (Casio Exilim F1) and Quantic motion analysis software were used to assess lower extremity kinematics during the sport screening tasks. Two HHD (MicroFet F1) were used for lower limb strength assessments in order to collect peak values of the isometric strength of knee extensors and hip abductors. Each participant's height and mass were measured using the (Seca) Height and Weight Measure (OCZ-M1007). A Brower Timing Gate System (TC-Timing System, USA) was used to monitor running speeds.

5.3.2. Participants

All cadets and recruits from Royal Saudi Land Forces who had joined the 12-week basic military training course were invited to participate in this study. Enrolled study participants were spread among three cities in Saudi Arabia (King Abdul-Aziz Military Academy (KAMA) in Riyadh: 04 Oct – 27 Dec 2015; Military Maintenance Institute (MI) in Taif: 08 Nov 2015 – 31 Jan 2016; Military Artillery Institute (AI) in Khamees Mshait: 20 Dec 2015 – 13 Mar 2016). Before the enrolment, all of the new cadets and recruits had passed the standard health evaluation of joining the Royal Saudi Armed Forces and the standard Physical Testing of Saudi Military Academies and institutes, which included the following: a one mile run in less than 8.04 min, 20 push-ups, 29 sit-ups, from the Military Acceptance Committee, before the enrolment.

The invitation for participation in the study came via a verbal announcement with some information about the study and demonstration of the screening tasks by the researcher, during assembly on the first day. The individuals were asked to read the information sheet and were given 24 hours to decide whether they were happy to participate. Once the individuals were happy to participate, they signed an informed consent form. It was required that all participants were free from any recent lower limb injury or lower back pain (Van Tiggelen et al., 2009). Additionally, the individuals were clinically screened by the principal investigator in regard to the inclusion criteria before the period of basic military training and for signs of meniscal abnormalities, ligamentous instability, effusion, and tenderness. Any individuals with such injuries were referred to the Academy's physician and were excluded from the study.

5.3.3. Basic military training

During the 12 weeks of basic military training, approximately 12-15 hours of daily training programmes are performed, similar to basic military training in most nations such as UK and USA army and consisting mainly of extensive physical training, marching with backpacks, military tactical exercises, and shooting, in addition to theoretical classes starting in the second week (five hours daily). At the end of the 12 weeks, the recruits undertake a 60km hike with backpack within a strict time schedule. Since all the participants benefited from the same training programme, environmental conditions, equipment, food, and daily schedules, this study departs from the assertion that extrinsic contributing factors which may affect PFP incidence were mostly under control within the current study (Roos et al., 1998; Parkkari et al., 2001).

5.3.4. Camera setup

The camera setup was previously described in detail in Chapter 4, Section (4.2.3.3).

Before participation, each cadet signed a consent form that was approved by the ethical committee of the University of Salford and also by the relevant authority in the Saudi Armed Forces. All cadets were fitted with the standard training shoes for basic military training (Nike Air Max 95), and they wore white shorts as well as coloured and numbered training shirts for identification. The data collection procedure was spread into three stations, which are described below.

First station

The first station was a clinical screening by the main investigator to confirm that there were no recent injuries to the lower limb or back. Mass, height, shoe size, and dominant leg (referred to as the one which they would kick a ball with) were recorded in the first phase. Participants were asked to fill out the Arabic version of the Knee injury and Osteoarthritis Outcome Score (KOOS) questionnaire instead of Anterior Knee Pain Scale (AKPS) questionnaire which is the common one used for PFP, because the Arabic version was not exist. KOOS is a widely used as subjective knee measurement tools; it is a 42-item self-report questionnaire categorised into five subscales: Pain (P), Symptoms (S), Activity of Daily Living (ADL), Sport (SP), and Knee function related to Quality of Life (Q). A scale relating to associated pain or disorder ranging from 0 (no problem) to 4 (extreme problems) was used to score each item. Subscale scores were then individually transformed into a 0 to 100 scale (0=extreme knee problem, 100=no knee problem) (Roos et al., 1998) The test-retest reliability of the Arabic version of KOOS was

found to be between 0.875 and 0.957 across all subscales and to have a high correlation with the Arabic version of the RAND-36 questionnaire items, which ranged from 0.659 to 0.810 (Almangoush et al., 2013). Additionally, an information questionnaire about sports, weekly hours in sports, previous lower limb injuries, and previous knee injuries was supplied, followed by marker placements for the anatomical landmarks of the variables.

Three markers were placed on anatomical landmarks for the measurement of the Q-angle, on both lower limbs of each participant. These markers were placed on the ASIS, the mid-point of the patella, and the tibial tubercle to define the anatomical references of the Q-angle in both limbs. For the FPPA, three markers were placed on FPPA anatomical references of each participant, on both lower limbs. The three markers were placed on the midpoint of the ankle malleoli for the centre of the ankle joint, the midpoint of the femoral condyles for the centre of the knee joint, and on the midpoint of the line from the anterior superior iliac spine to the knee marker at the proximal thigh. Markers of knee flexion angle were placed on the greater trochanter, lateral epicondyle, and lateral malleolus. Three markers were placed on the head of the fibula, the lateral malleolus, and the head of the fifth metatarsal, which was approximated inside standard shoes in order to determine the anatomical landmarks of the dorsiflexion angle. Finally, for the rearfoot eversion angle, four markers were placed, in descending order, on the midpoint of the calf muscle, the top of the Achilles tendon, the top of the heel, and the bottom of the heel. The lower two markers were placed on standard training shoes (Figure 5.1). For more details, see Chapter 4, Section 4.2.3.4. The cadets subsequently moved onto the second phase.

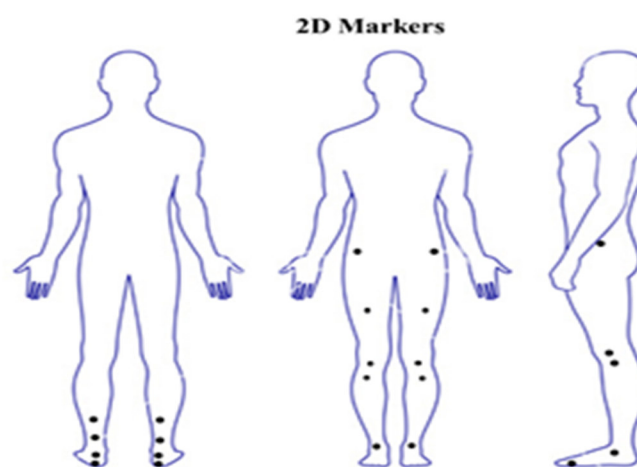


Figure 5.1 Marker placement

Second station

5.3.5. Baseline for kinematic assessments using 2D analysis

Screening tasks

SLS, SLL, and RUN were used as screening tasks for the baseline assessment of kinematic variables. Participants were allowed to practice each task twice or three times until they felt familiarised and comfortable with the trials. Three acceptable trials from each participant for both legs were then selected and analysed for all tasks. These screening tasks were previously described in more detail in chapter 4, Section 4.1.3.4. After this, the participants then moved onto the third phase.

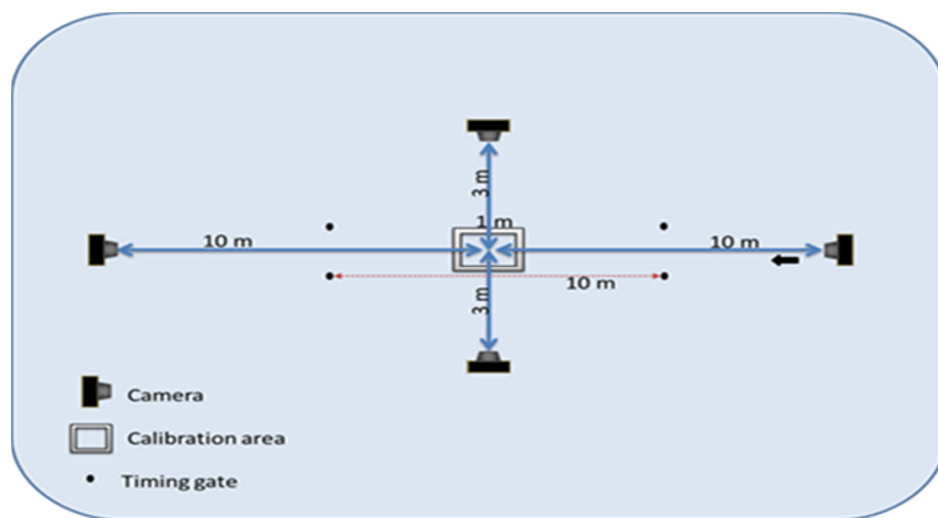


Figure 5.2 Overview of the 2D procedure set-up

Third station

5.3.6. Baseline for strengthening assessments using HHD

5.3.6.1. Knee extensors

The HHD (MicroFet F1) was stabilised on a horizontal stake at a height of 20cm. The subjects were asked to sit on the edge of the treatment bed, with a 90° flexion at the knee and both feet off the ground. The height of the treatment bed was adjusted to place the HHD 5cm proximal to the ankle joint at the front aspect. The subjects were then asked to apply maximum force to extend the knee joint against the fixed device for five seconds and to repeat this four times, with a 30 second rest in between. The last three trials were recorded, while the first trial was

used as practice for familiarisation (Bolgla et al., 2008). The maximum force, in (N), of the knee extensors for each trial was recorded for both sides and the average multiplied by lower leg length in meter (m) (the distance from the head of the fibula to the lateral malleolus) to calculate the isometric peak torque of knee extensors in (Nm). For more details, see Section 4.2.3.7.

5.3.6.2. *Hip abductors*

The HHD was stabilised on the wall, and subjects were asked to lie down on their backs with their knees flexed at 90° on the edge of the bed, beside the stabilised HHD, to apply maximum force in abducting the hip joint against the fixed HHD for five seconds, and to repeat this four times, with a 30 second rest in between. The last three trials were recorded, while the first was used as practice for familiarisation (Bolgla et al., 2008). The maximum force, in (N), of the hip abductors for each trial was recorded for both sides and the average multiplied by length of femur in (m) (the distance from greater trochanter to the lateral epicondyle) to calculate the isometric peak torque of hip abductors in (Nm). For more details, see Section 4.2.3.7.

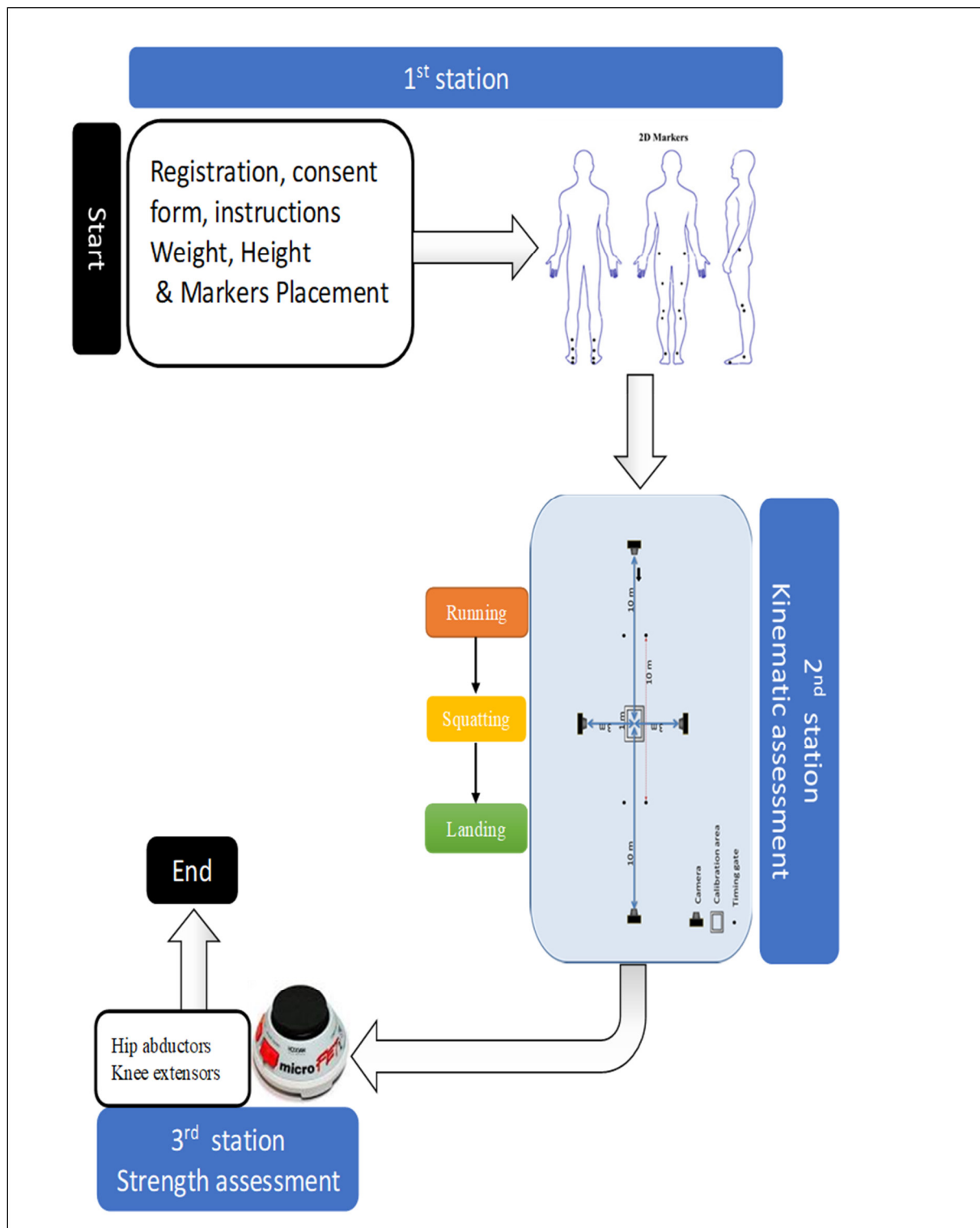


Figure 5.3 Diagram of data collection procedure

All data was collected in the first five days of basic military training and it was anonymous and remained confidential, additionally all videos were stored in a password protected file on a personal computer with the main researcher.

5.3.7. Data processing

The videos collected at the baseline of kinematic assessment were analysed using a Quintic Biomechanics software package (Version 26) to measure the FPPA, Q-angle, HADD, knee flexion angle, dorsiflexion angle, and rearfoot angle, as in the following table:

Table 5.1 Measurements of the kinematic variables for the lower limb

Variable	Method of measurements
FPPA	The FPPA was calculated by quantifying the angle formed between the line from the marker of the proximal thigh to the marker of the midpoint of the knee joint and the line from the marker of the knee joint to the marker of the ankle.
Q-angle	The Q-angle was measured by quantifying the angle formed between the line connecting the ASIS to the centre of the patella and the line connecting the tibial tuberosity to the centre of the patella.
HADD	The HADD angle was calculated by measuring the angle formed between the line between the two ASIS and the line from the marker of the midpoint of the knee joint in the tested limb.
Knee flexion	The knee flexion angle was calculated by quantifying the angle formed between line from the marker of the greater trochanter to the marker of the lateral epicondyle and the second line from the marker of the lateral malleolus to the marker of lateral epicondyle.
Dorsiflexion	The dorsiflexion angle was represented by the angle formed between the lines from the two peripheral markers to the central marker placed on the lateral malleolus.
Rearfoot eversion	The angle formed by conjunction between the line from the marker of the midpoint of the calf muscle and the marker of the top of the Achilles tendon and the line from the marker of the bottom of the heel to the marker of the top of the heel.

An average of three trials for each variable in both limbs were recorded for all participants during the three tasks. For more details, see Chapter 4, Section 4.1.3.4.

5.3.8. Assessment and registration of injuries

Participants' medical records were followed up to record the occurrence of PFP and other lower limb injuries during the 12 weeks of basic military training. During the basic military training, any cadet presenting with a suspected injury was reported to the training camp medical unit's physician for assessment and diagnosis. The inclusion criteria described by Van Tiggelen et al. (2009) was used to assign participants to the PFP group. These are:

- Exhibit retropatellar pain during at least two of the following activities: jumping/hopping, squatting, stairs, and running (Arroll et al., 1997; Cowan et al., 2002).
- Exhibit two of the following clinical criteria in the clinical assessment (with minimal values along a scale of 3/10) (Witvrouw et al., 1996; Powers et al., 1998):
 - Pain during direct compression of the patella against the femoral condyle while knee is in full extension.
 - Tenderness on palpation of the posterior surface of the patella.
 - Pain on resisted knee extension from 90° of flexion to the full extension.
 - Pain during isometric contraction of the quadriceps against resistance on the suprapatellar resistance with 15° of knee flexion.

Additionally, negative findings (i.e. no symptoms) in the examination of knee ligaments, bursae, menisci, synovial plicae, iliotibial band, Hoffa's fat pad, and the hamstring, quadriceps, and patellar tendons and their insertions were essential for being included in the PFP group. Each clinic in the three military units was provided with a copy of the instructions for PFP inclusion criteria.

PFP and other lower limb injuries were registered by means of the clinic's medical registration form. Any participants with knee pain were examined firstly by the clinic's physician and were then referred to the physiotherapist for more investigation and assessment of the PFP inclusion criteria. Definition of injury was based on time loss of training, therefore participant who presented with positive findings, according to the above criteria, and received medical recommendation to reduce activities for three days were assigned to the injured group. Each injured participant diagnosed with PFP was also provided with a copy of the KOOS questionnaire (Roos et al., 1998; Almangoush et al., 2013). A meeting was held between the main investigator and the physiotherapist and other medical staff in each unit to explain the purpose of the study, the inclusion criteria of PFP, and the duration of follow-up, in addition to methods of communication and how to send the information weekly.

5.3.9. Statistical analysis

All statistical analysis (Figure 5.4) was obtained using IBM SPSS statistical software (Version 23). Means and standard deviations for all measured variables were obtained. All measured variables were analysed in order to check the normality of distribution using a Shapiro-Wilk test. In comparing the injured and non-injured groups, independent t-tests were used for normally distributed variables and Mann-Whitney *U* tests for non-normally distributed

variables. Effect sizes were calculated to assess the importance of significant differences found between injured and non-injured groups for each variable. Effect sizes were determined using Cohen δ , which was categorised into three levels: 0.2 represented a small effect size, 0.5 a medium effect size, and 0.8 a large effect size (Thomas et al., 2005). Binary logistic regression analysis was performed for each variable in order to identify the predictive variables on the development of PFP. Forward stepwise logistic regression analysis was applied to create a predictive model in order to determine the predicted variable with regards to interaction with other variables. Only the variables that were significantly different between the injured and non-injured groups were included in multivariate logistic regression and creating the model. Before developing a multivariate logistic regression model, multicollinearity between variables was evaluated; if a correlation between two variables was ≥ 0.8 , only one of the variables was chosen for the multivariate analyses. Each task was calculated separately for regression model and results were expressed in odds ratios (ORs). Number of variables that could be interred in each model complied with the one-in-ten rule (one variable for each ten injuries), based on previous work was done by Peduzzi et al., (1996). The A receiver operating characteristic (ROC) curve, with a value of area under the curve and sensitivity and specificity values, was performed in order to identify the discriminatory capability of each variable. The cut-off point on the ROC curve was chosen with maximised sensitivity and specificity values. Statistical significance was accepted at $\alpha = 0.05$ level. Risk Ratio was performed to compare the risks for the injured and non-injured groups according to the predicted risk factor. It was calculated by dividing the cumulative incidence in PFP group by the cumulative incidence in the healthy group. Rate Ratio also was calculated by dividing the incidence rate of injured group on incidence rate of non-injured group. Finally, causality relationship between FPPA and development of PFP was assessed using widely accepted epidemiologic criteria for causality, known as the Bradford Hill criteria which consists of nine elements (strength, consistency, specificity, temporality, biological gradient, coherence and biological plausibility, experiment, and analogy)

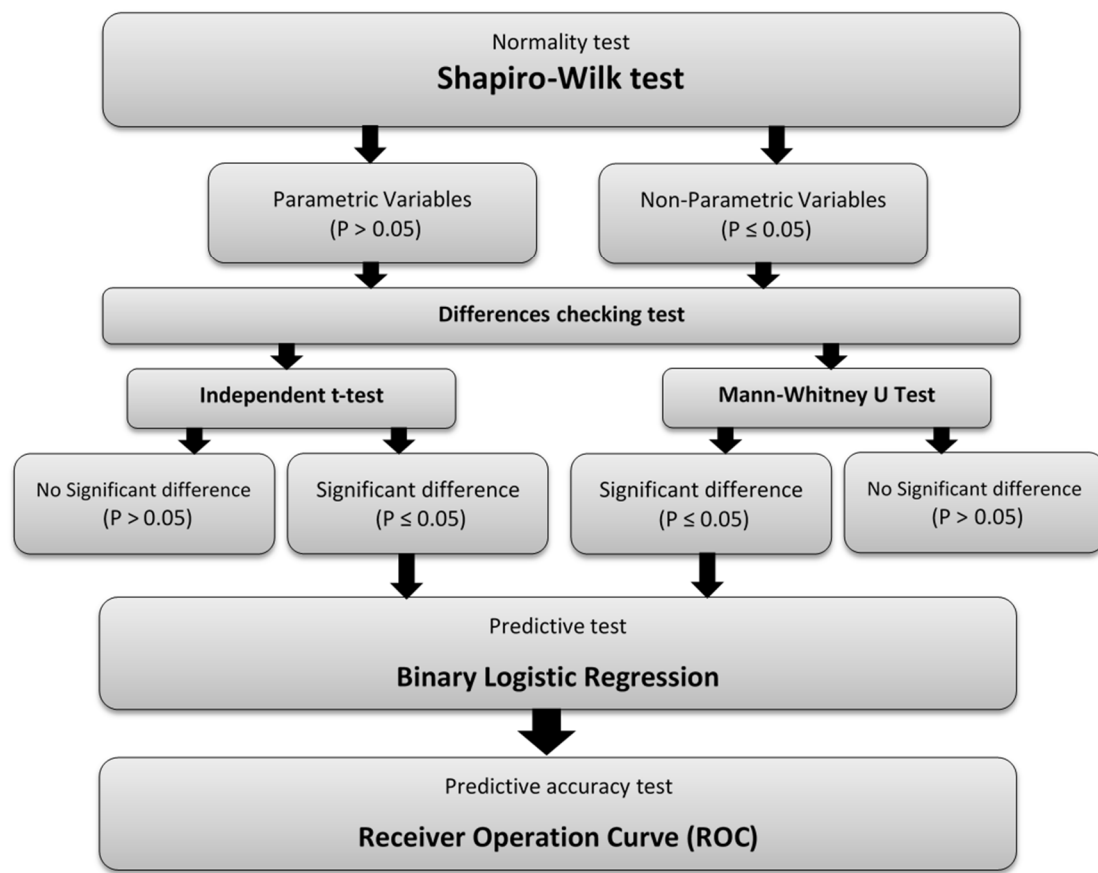


Figure 5.4 Statistical analysis diagram

5.4. Results

338 out of 475 cadets and recruits from Royal Saudi Land Forces who joined the basic 12 weeks military training participated in this study (Figure 5.5). The participants were from three cities in Saudi Arabia. 213 cadets came from King Abdul-Aziz Military Academy (KAMA) in Riyadh. A total of 6 cadets of the 213 did not meet the inclusion criteria during the baseline assessments, 2 cadets did not complete the training programme due to another health condition, and 2 cadets withdrew from the training programme. 52 recruits from military maintenance institute (MI) in Taif. A total of 7 recruits of the 52 did not meet the inclusion criteria during the baseline assessments, one recruit did not complete the training programme due to another health condition, and one recruit withdrew from the training programme. 73 recruits from military Artillery institute (AI) in Khamees msheet. A total of 3 recruits of the 73 did not meet the inclusion criteria during the baseline assessments, and one recruit did not complete the training programme due to another health condition.

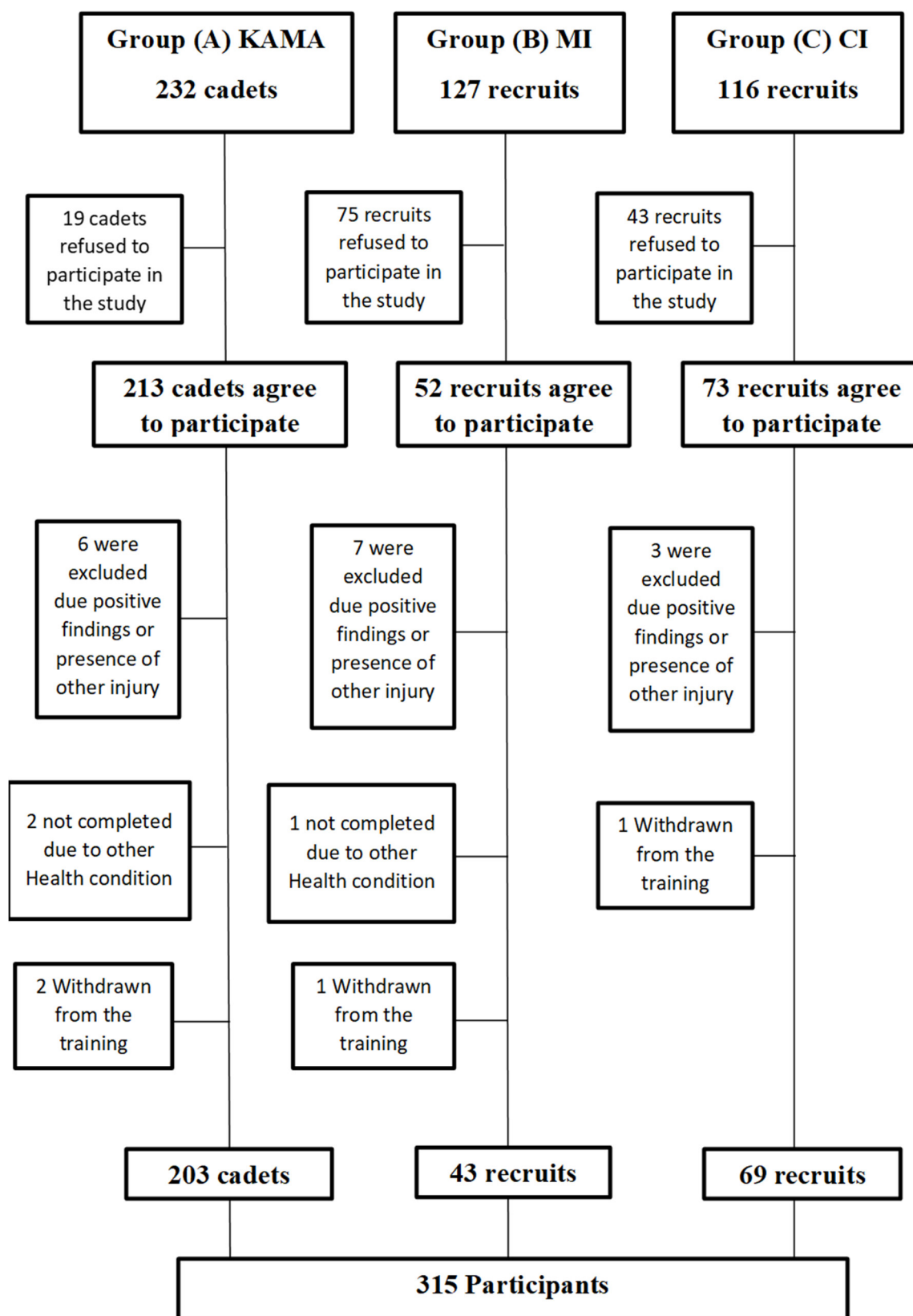


Figure 5.5 Number of participants of the three groups

At the baseline assessment 16 participants were excluded due to presence of knee pain or other lower limb injuries. 4 participants were withdrawn from the training during the first two weeks and 3 not completed the training programme due to other health condition and they were excluded. 315 participants were completed the basic military training. During the weekly follow-up 68 participants developed 85 lower limb injuries (48 knee pain and 37 other lower limb injuries) were recorded in the clinic of the unit. 37 were confirmed via the assessment of inclusion criteria that mentioned previously in section 5.3.9 as PFP and 11 were excluded from PFP injury group because they were not submitted the inclusion criteria and were considered as other sources of knee pain to be added to the group of other lower limb injury to be 48 lower limb injuries (Figure 5.6).

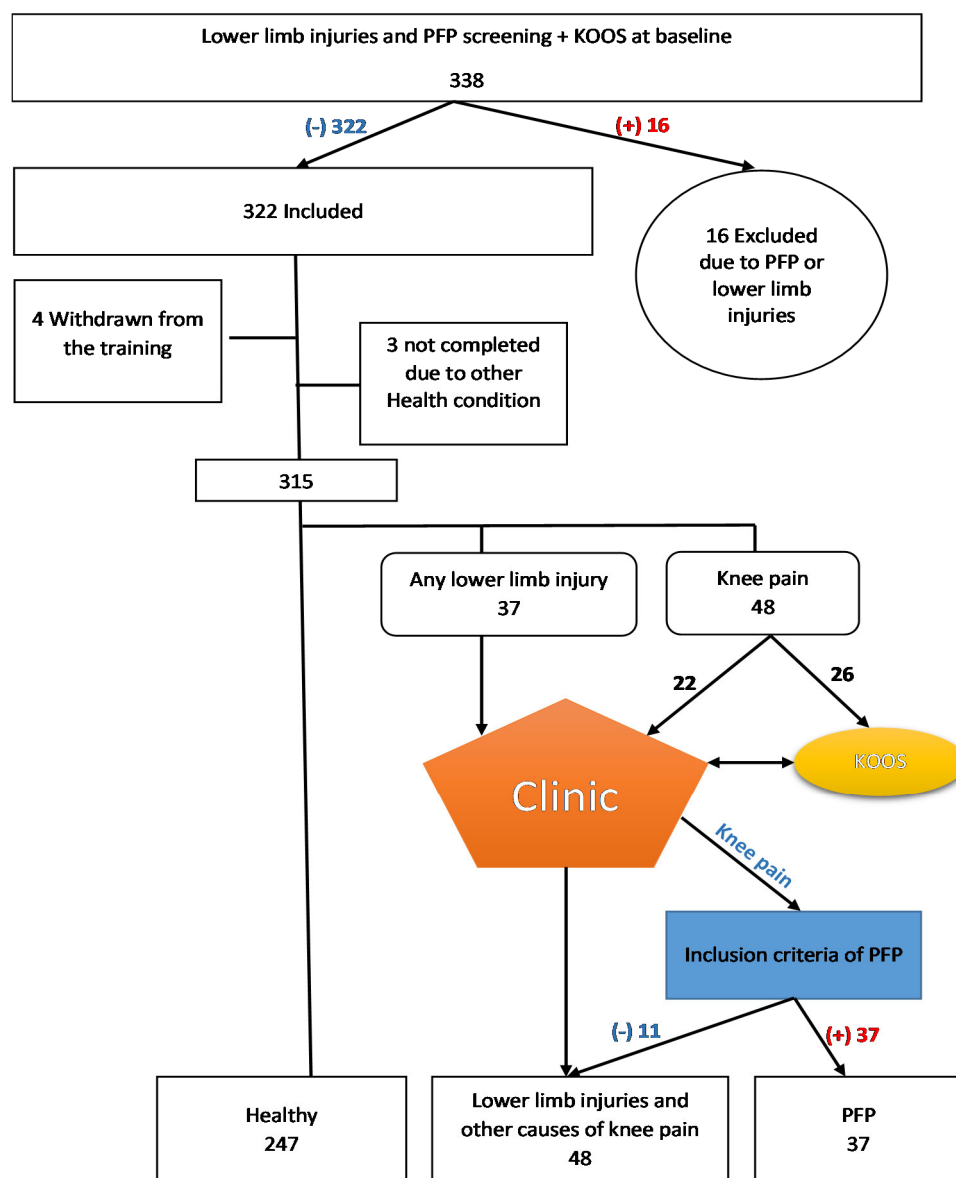


Figure 5.6 Flow chart of groups' identification

5.4.1. Results (A) all participants of the three groups (315 subjects)

During the twelve weeks of basic military training, 68 of the 315 participants (21.58%) were diagnosed with 85 lower limb musculoskeletal injuries in 112 (17.78%) of 630 tested limbs: 37 (11.75%) PFP, 11 (3.49%) other sources of knee pain (KP), 8 (2.54%) medial tibial stress (MTS), 7 (2.22%) planter fasciitis (PF), 7 (2.22%) ankle pain (AP), 4 (1.27%) foot pain (FP), 3 (0.95%) tibia stress fracture (TSF), 3 (0.95%) ankle sprain (AS), 3 (0.95%) iliotibial band (ITB), and 2 (0.63%) hip joint pain (HP) (Table 5.3 and Figures 5.7 – 5.9).

Table 5.2 Demographic characteristics of the participants

Age (y)	Height (m)	Mass (Kg)	BMI (kg/m ²)
19.83±2.86	1.72±0.06	66.43±12.73	22.39 ±3.88

Table 5.3 Numbers and percentages of injured participants and injured limbs in each injury

Injury	Right limb	Left limb	Both limb	Number of injured Participants	Number of injured limbs	Injury incidence (%)	Injury rate per 1000
PFP	20	8	9	37	46	11.75%	0.44
KP	6	5	-	11	11	3.49%	0.13
MTS	-	-	8	8	16	2.54%	0.10
PF	-	-	7	7	14	2.22%	0.08
AP	3	4	-	7	7	2.22%	0.08
FP	2	-	2	4	6	1.27%	0.05
TSF	3	-	-	3	3	0.95%	0.04
AS	2	1	-	3	3	0.95%	0.04
ITB	1	1	1	3	4	0.95%	0.04
HP	-	2	-	2	2	0.63%	0.02
Total	37	21	27	85	112	26.98%	1.01

PFP: Patellofemoral pain

AP: Ankle pain

AS: Ankle sprain

KP: Knee pain

FP: Foot Pain

ITB: Iliotibial band

MTS: Medial tibial stress

TST: Tibial stress fracture

HP: Hip pain

PF: Planter fasciitis

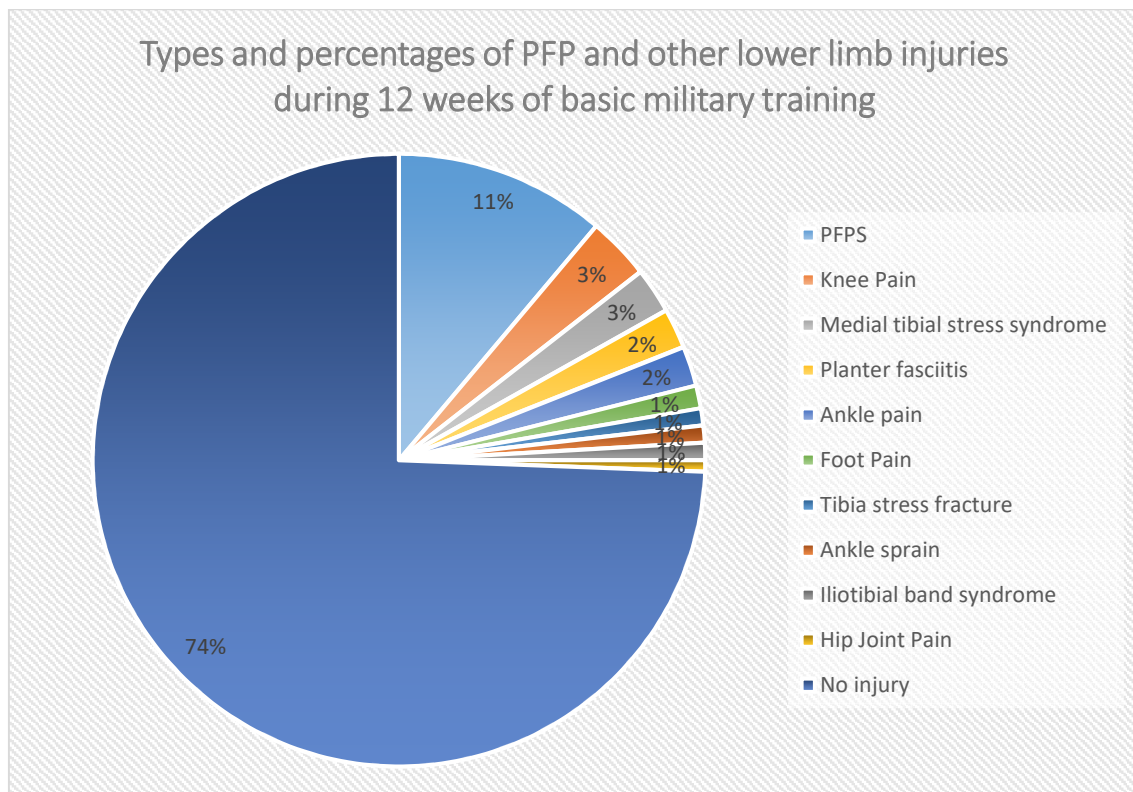


Figure 5.7 Types and percentages of PFP and other lower limb injuries during the 12 weeks of basic military training

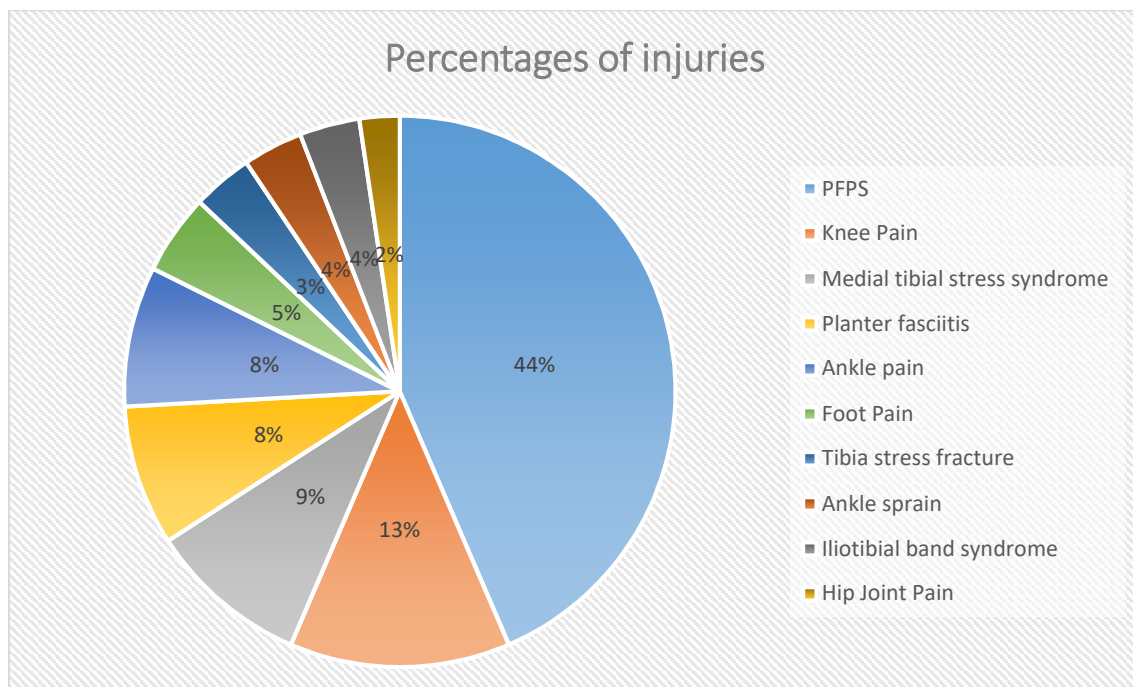


Figure 5.8 Percentages of injuries

As illustrated in Figure 5.9, after the end of the first training week with no recorded injuries, there was a high incidence of injuries in the second week (34: 40%), which decreased gradually

in the following three weeks and was then distributed equally over the rest of the training period.

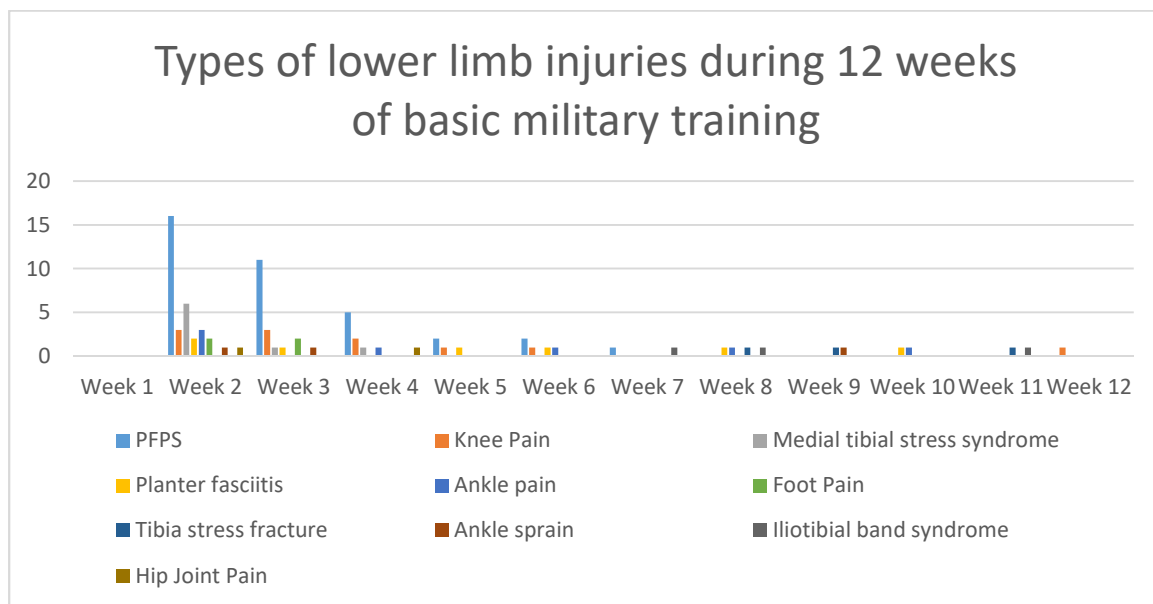


Figure 5.9 Types and numbers of lower limb injuries during the 12 weeks of basic military training

All lower limbs injuries

68 subjects developed at least one lower limbs musculoskeletal injury; it accounted for approximately (21.6%) of all participants (Figure 5.7). Most of injuries occurred during the first three weeks. Participants who developed the injuries were significantly heavier than the healthy group ($P=0.000$), with a higher BMI ($P=0.001$) and normalised body mass ($P=0.000$). Effect sizes were small for body mass-related variables (mass 0.31; BMI 0.27; mass normalised to height 0.30). With regard to strength variables, the injured group had significantly lower muscle strength during the baseline assessment in knee extensors ($P=0.006$), hip abductors ($P=0.003$), and the summation of knee extensors and hip abductors ($P=0.003$), when compared to the non-injured group. Small effect sizes were found for the strength variables: 0.27 for knee extensors, 0.32 for hip abductors, and 0.31 for the summation of knee extensors and hip abductors. The FPPA of injured participants was significantly greater than those without during the SLL screening task: $P=0.033$. Participants who developed lower limb musculoskeletal injuries had a significantly greater HADD angle ($P=0.048$) in SLS and in SLL ($P=0.016$) during the baseline assessment. KFA during RUN screening tasks of injured participants was significantly greater than those without: $P=0.041$. No significant differences were detected between the two groups in any of the other kinematic variables or in sports participation. Effect

sizes were moderate for FPPA during SLL (0.03) and running (0.24) and were small for the other kinematic variables that had significant differences (Table 5.4 – 5.6).

Table 5.4 .Mean, standard deviation, 95% confidence interval (CI), and P value of the demographic characteristics of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
Age	Non-Injured	247	19.95	2.16	19.68	20.22	0.118	0.17
	Injured	68	19.42	1.77	19.00	19.85		
Height	Non-Injured	247	1.72	0.06	1.71	1.72	0.133	0.30
	Injured	68	1.74	0.06	1.73	1.76		
Mass	Non-Injured	247	64.41	10.92	63.04	65.78	0.000*	0.49
	Injured	68	73.66	15.82	69.86	77.46		
BMI	Non-Injured	247	21.88	3.45	21.45	22.31	0.001	0.40
	Injured	68	24.20	4.74	23.06	25.34		
Mass norm to Height	Non-Injured	247	367.96	58.67	360.59	375.33	0.000*	0.46
	Injured	68	413.84	83.48	393.79	433.90		

Table 5.5 Mean, standard deviation, 95% confidence interval (CI), and P value of the strength variables of injured and non-injured groups

Variable	Group	Number	Mean	SD	95 % CI		p	Effect size
					Lower	Upper		
KEXT (%BW*TL)	Non-Injured	247	139.53	46.48	133.70	145.37	0.006*	0.25
	Injured	68	122.43	45.58	111.48	133.38		
HABD (%BW*FL)	Non-Injured	247	75.95	21.19	73.29	78.61	0.003*	0.28
	Injured	68	67.23	19.63	62.52	71.95		
KEXT + HABD	Non-Injured	247	215.49	61.71	207.74	223.24	0.003*	0.28
	Injured	68	189.66	59.52	175.36	203.96		
<i>KEXT: Knee extensors</i>		<i>HABD: Hip abductors</i>		<i>KEXT+HABD: Knee extensors + hip abductors</i>				

Table 5.6 Mean, standard deviation, 95% confidence intervals (CI), and P value of kinematic variables and sports participation of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		P	Effect size
					Lower	Upper		
FPPA in SLS (°)	Non-Injured	241	3.79	9.08	2.63	4.94	0.146*	0.14
	Injured	66	5.71	9.57	3.36	8.07		
HADD in SLS (°)	Non-Injured	241	9.45	4.67	8.86	10.05	0.048*	0.20
	Injured	66	10.89	5.26	9.59	12.18		
QA in SLS (°)	Non-Injured	241	10.65	8.57	9.56	11.74	0.094*	0.16
	Injured	66	12.75	8.84	10.58	14.92		
FPPA in SLL (°)	Non-Injured	244	2.51	7.77	1.53	3.49	0.033*	0.20
	Injured	68	4.92	8.61	2.84	7.00		
HADD in SLL (°)	Non-Injured	245	3.85	4.87	3.24	4.46	0.016*	0.24
	Injured	68	5.69	5.60	4.34	7.05		
QA in SLL (°)	Non-Injured	245	10.16	7.95	9.16	11.16	0.021*	0.21
	Injured	68	12.77	8.38	10.74	14.80		
FPPA in RUN (°)	Non-Injured	240	-2.98	5.32	-3.66	-2.30	0.394*	0.05
	Injured	65	-2.58	5.70	-3.99	-1.17		
HADD in RUN (°)	Non-Injured	240	8.87	3.90	8.37	9.37	0.937	0.03
	Injured	65	8.69	3.75	7.76	9.62		
QA in RUN (°)	Non-Injured	240	6.13	5.89	5.39	6.88	0.742*	0.04
	Injured	65	6.45	5.66	5.05	7.85		
KFA in RUN (°)	Non-Injured	176	46.34	4.23	45.71	46.97	0.041	0.24
	Injured	48	44.89	3.61	43.85	45.94		
DFA in RUN (°)	Non-Injured	176	81.77	4.69	81.08	82.47	0.307	0.11
	Injured	48	82.55	4.92	81.12	83.98		
RFA in RUN (°)	Non-Injured	178	14.50	4.41	13.85	15.15	0.385	0.11
	Injured	48	15.27	4.79	13.88	16.66		
Participating in sport	Non-Injured	247	6.05	1.54	5.86	6.25	0.321	0.10
	Injured	68	5.81	1.53	5.44	6.18		
FPPA: Frontal plane projection angle			HADD: Hip adduction			QA: Q-angle		
SLS: Single leg squat			SLL: Single leg land			RUN: Running		
KFA: Knee flexion angle			DFA: Dorsiflexion angle			RFA: Rearfoot angle		

5.4.1.1. Predicted risk factors of lower limbs injuries.

Results of the binary logistic regression for each individual variable are presented in Table 5.7. The results show that mass, BMI, mass norm to height, KEXT, HABD, KEXT & HABD, FPPA during SLL, HADD during SLS and SLL, QA during SLL and KFA during RUN are significantly predicted lower limbs injuries. The odds ratio of each variable are ranged between 0.912 for KFA during running and 1.168 for BMI.

Table 5.7 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable

	OR	P	95% CI for OR	
			Lower	Upper
Mass	1.058	.000	1.035	1.082
BMI	1.168	.000	1.088	1.255
Mass norm to Height	1.010	.000	1.006	1.014
KEXT MS (%BW*TL)	.991	.008	.985	.998
HABD MS (%BW*FL)	.978	.003	.964	.992
KNEE + HIP MS	.993	.003	.988	.997
HADD in SLS (°)	1.063	.035	1.004	1.124
FPPA in SLL (°)	1.039	.030	1.004	1.076
HADD in SLL (°)	1.076	.009	1.019	1.136
QA in SLL (°)	1.043	.020	1.007	1.080
KFA in RUN (°)	.912	.033	.838	.993

One multivariate logistic regression model was created for each task to analyse. The variables included in the three models were: (BMI, hip abductor and knee extensor strength, in addition to HADD during SLS, FPPA and HADD during SLL, and knee flexion angle during running). The most predictive created model is presented in Table 5.8. The results show that BMI significantly predicted PFP ($P < 0.001$). The odds ratio shows that the risk of lower limb musculoskeletal injuries in subjects who had greater BMI during the baseline assessment was 1.175 times higher than in the healthy group.

Table 5.8 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for regression model

	OR	P	95% CI for OR	
			Lower	Upper
BMI	.000	1.175	1.088	1.268
KNEE + HIP MS	.032	.994	.989	1.000
FPPA in SLL	.007	1.089	1.024	1.158
Constant	.000	.009		

Patellofemoral pain

37 subjects (11.75%) developed PFP in 46 (7.30%) knees; as the highest recorded injury, it accounted for approximately half (44%) of all recorded lower limb musculoskeletal injuries (Figure 5.7). 40% of PFP injuries occurred during the second week. Participants who developed PFP were significantly heavier than the healthy group ($P=0.039$), with a higher BMI ($P=0.048$) and normalised body mass ($P=0.027$). Effect sizes were small for body mass-related variables (mass 0.26; BMI 0.22; mass normalised to height 0.25). With regard to strength variables, the injured group had significantly lower muscle strength during the baseline assessment in knee extensors ($P=0.046$), hip abductors ($P=0.050$), and the summation of knee extensors and hip abductors ($P=0.038$), when compared to the non-injured group. Small effect sizes were found for the strength variables: 0.23 for knee extensors, 0.22 for hip abductors, and 0.25 for the summation of knee extensors and hip abductors. The FPPA and Q-angle of participants with PFP were significantly greater than those without during the three screening tasks: $P=0.003$ and $P=0.016$ during SLS, $P<0.001$ and $P=0.001$ during SLL, and $P=0.001$ and $P=0.025$ during RUN. Participants who developed PFP had a significantly greater HADD angle ($P=0.003$) in SLS and in SLL ($P<0.001$) during the baseline assessment. No significant differences were detected between the two groups in any of the other kinematic variables or in sports participation. Effect sizes were moderate only for FPPA during SLL (0.50) and were small for the other kinematic variables that had significant differences (Table 5.9 – 5.11).

Table 5.9 Mean, standard deviation, 95% confidence interval (CI), and P value of the demographic characteristics of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
Age	Non-Injured	278	19.84	2.11	19.59	20.09	0.954	0.02
	Injured	37	19.78	1.89	19.15	20.41		
Height	Non-Injured	278	1.72	0.06	1.71	1.73	0.133	0.22
	Injured	37	1.74	0.06	1.72	1.76		
Mass	Non-Injured	278	65.82	12.23	64.38	67.27	0.039*	0.26
	Injured	37	71.05	15.38	65.92	76.18		
BMI	Non-Injured	278	22.23	3.73	21.80	22.67	0.048*	0.22
	Injured	37	23.56	4.80	21.96	25.16		
Mass norm to Height	Non-Injured	278	374.95	64.77	367.31	382.60	0.027*	0.25
	Injured	37	400.98	82.75	373.39	428.57		

Table 5.10 Mean, standard deviation, 95% confidence interval (CI), and P value of the strength variables of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
KEXT (%BW*TL)	Non-Injured	278	137.62	47.02	132.07	143.17	0.046*	0.23
	Injured	37	122.02	42.81	107.75	136.29		
HABD (%BW*FL)	Non-Injured	278	74.86	21.10	72.37	77.35	0.050*	0.22
	Injured	37	67.92	20.71	61.02	74.83		
KEXT + HABD	Non-Injured	278	212.48	62.17	205.13	219.82	0.038*	0.25
	Injured	37	189.94	58.32	170.50	209.39		
<i>KEXT: Knee extensors</i>		<i>HABD: Hip abductors</i>		<i>KEXT+HABD: Knee extensors + hip abductors</i>				

Table 5.11 Mean, standard deviation, 95% confidence intervals (CI), and P value of kinematic variables and sports participation of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
FPPA in SLS (°)	Non-Injured	271	3.78	9.20	2.68	4.88	0.003*	0.26
	Injured	36	7.36	8.78	4.39	10.33		
HADD in SLS (°)	Non-Injured	271	9.58	4.75	9.01	10.14	0.003*	0.21
	Injured	36	11.16	5.27	9.37	12.94		
QA in SLS (°)	Non-Injured	271	10.75	8.65	9.71	11.78	0.016*	0.24
	Injured	36	13.77	8.34	10.95	16.59		
FPPA in SLL (°)	Non-Injured	276	2.46	7.81	1.53	3.39	0.000*	0.50
	Injured	36	7.48	8.20	4.71	10.26		
HADD in SLL (°)	Non-Injured	277	3.93	5.00	3.34	4.52	0.000*	0.37
	Injured	36	6.74	5.11	5.01	8.47		
QA in SLL (°)	Non-Injured	277	10.23	7.97	9.29	11.17	0.001*	0.36
	Injured	36	14.56	8.16	11.80	17.33		
FPPA in RUN (°)	Non-Injured	270	-3.22	5.41	-3.86	-2.57	0.001*	0.36
	Injured	35	-0.41	4.64	-2.01	1.18		
HADD in RUN (°)	Non-Injured	270	8.76	3.96	8.28	9.23	0.258	0.12
	Injured	35	9.41	2.95	8.40	10.42		
QA in RUN (°)	Non-Injured	270	6.00	5.82	5.31	6.70	0.025*	0.20
	Injured	35	7.73	5.77	5.75	9.71		
KFA in RUN (°)	Non-Injured	195	46.12	4.24	45.52	46.72	0.148	0.12
	Injured	29	45.41	3.33	44.15	46.68		
DFA in RUN (°)	Non-Injured	195	81.82	4.69	81.16	82.48	0.121	0.13
	Injured	29	82.73	5.06	80.81	84.65		
RFA in RUN (°)	Non-Injured	197	14.82	4.46	14.19	15.45	0.156	0.18
	Injured	29	13.61	4.64	11.84	15.37		
Participating in sport	Non-Injured	278	6.04	1.55	5.85	6.22	0.321	0.14
	Injured	37	5.73	1.39	5.27	6.19		
FPPA: Frontal plane projection angle			HADD: Hip adduction		QA: Q-angle			
SLS: Single leg squat			SLL: Single leg land		RUN: Running			
KFA: Knee flexion angle			DFA: Dorsiflexion angle		RFA: Rearfoot angle			

Table 5.12 Mean, standard deviation, and P value of KOOS for PFP

KOOS at Baseline		KOOS at Diagnosis		P value
Mean	SD	Mean	SD	
100	<0.01	70.749	24.14	<0.01

The results show that mean and standard deviation of KOOS scores of the 37 participants who developed PFP were 72.07 (24.84) at the diagnosis time with significant decrease ($p<0.01$) comparing to the baseline scores (Table 5.12).

5.4.1.2. Predicted risk factors of PFP

Results of the binary logistic regression for each individual variable are presented in Table 5.13. The results show that mass, mass norm to height, KEXT & HADD, FPPA during SLS, SLL, and RUN, HADD and QA during SLL are significantly predicted PFP. The odds ratio of each variable are ranged between 0.994 for KNEE + HIP MS and 1.120 for FPPA during SLL.

Table 5.13 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable

	OR	P	95% CI for OR	
			Lower	Upper
Mass	1.031	.021	1.005	1.058
BMI	1.090	.054	.999	1.189
Mass norm to Height	1.006	.029	1.001	1.010
KEXT MS (%BW*TL)	.992	.057	.984	1.000
HADD MS (%BW*FL)	.983	.061	.965	1.001
KNEE + HIP MS	.994	.039	.988	1.000
FPPA in SLS (°)	1.045	.030	1.004	1.088
HADD in SLS (°)	1.067	.067	.995	1.145
QA in SLS (°)	1.044	.051	1.000	1.091
FPPA in SLL (°)	1.120	.001	1.037	1.140
HADD in SLL (°)	1.087	.002	1.042	1.204
QA in SLL (°)	1.075	.003	1.025	1.128
FPPA in RUN (°)	1.110	.004	1.034	1.191
QA in RUN (°)	1.056	.100	.990	1.127

One multivariate logistic regression model was created for each task to analyse. Maximum three variables were entered in each model. The variables included in the three models were: (normalised mass to height, hip abductor and knee extensor strength, in addition to FPPA during each task). The most predictive created model is presented in Table 5.14. The results show that FPPA during SLL significantly predicted PFP ($P=0.001$). The odds ratio shows that the risk of PFP in subjects who had demonstrated greater FPPA in SLL during the baseline assessment was 1.133 times higher than in the healthy group.

Table 5.14 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for regression model

	OR	P	95% CI for OR	
			Lower	Upper
Mass norm to Height	1.008	.002	1.003	1.014
FPPA in SLL	1.133	.001	1.051	1.222
Constant	.006	.000		

5.4.1.3. Receiver Operation Curve (ROC)

Receiver Operation Curve (ROC) analysis demonstrated that weight normalized to height and FPPA during SLL and RUN in addition to HADD and Q-angle during SLL, were significant predictors for PFP. FPPA during SLL tasks was the highest predictor for PFP (Area=0.70; $P<0.001$). $FPPA \geq 5.2^\circ$ during SLL predicted PFP with a sensitivity of 70% and a specificity of 70%. The associated positive likelihood ratio (sensitivity/1-specificity) was 2.3.

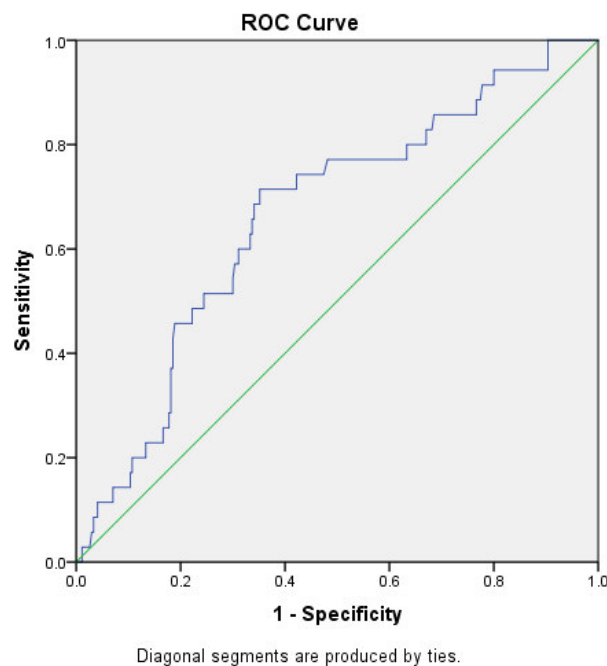


Figure 5.10 Receiver Operation Curve (ROC) of FPPA during SLL

Risk ratio

Participants with FPPA during SLL $\geq 5.20^\circ$ had 2.2 times risk of development of PFP compared who were with FPPA during $< 5.20^\circ$.

Rate Ratio

Individuals with PFP incidence was 0.13 times the rate of healthy group.

Causality relationship between FPPA and development of PFP

Eight criteria of the nine criteria (strength, consistency, biological gradient, Temporality, coherence and biological plausibility, experiment, and analogy) of Bradford Hill criteria are supported the association between FPPA and development of PFP. The causality assessment results of Bradford Hill criteria showed that there is causality relationship between FPPA and development of PFP. Risk of developing PFP is higher in individuals who demonstrated greater FPPA.

Due to the presence of significant differences in mass-related demographic characteristics (i.e. mass, mass normalised to height, and BMI) between injured and non-injured groups, we assessed the differences of all variables and the predicted risk factors between the compared groups, and categorised their results into three sets: all 315 participants from the three units in results (A), the 203 cadets of KAMA in results (B), and all the participants excluding those with a BMI of greater than 27% in results (C). This was done in order to investigate the effect of excluding the overweight participants from the results and to focus on the KAMA group (infantry cadets) separately due to the fact that they are a highly homogenised group.

5.4.2. Results (B): First group (203 cadets from KAMA).

During the twelve weeks of basic military training, 39 of the 203 participants (19.21%) were diagnosed with 64 lower limb musculoskeletal injuries in 79 (19.46%) out of 406 tested limbs: 26 (12.8%) with PFP, 10 (4.92%) with other sources of knee pain, 5 (2.46%) with medial tibial stress, 5 (2.46%) with planter fasciitis, 3 (1.48%) with ankle pain, 4 (1.97%) with foot pain, 3 (1.48%) with a tibia stress fracture, 2 (0.98%) with an ankle sprain, 3 (1.48%) with an iliotibial band, and 2 (0.98%) with hip joint pain (Table 5.15 and Figures 5.11 – 5.13).

Table 5.15 Numbers and percentages of injured participants and injured limbs in each injury

Injury	Right limb	Left limb	Both limb	Number of injured Participants	Number of injured limbs	Injury incidence (%)	Injury rate per 1000
PFP	16	7	3	26	29	12.8%	0.31
KP	5	5	-	10	10	4.92%	0.12
MTS	-	-	5	5	10	2.46%	0.06
AP	2	3	-	5	5	2.46%	0.06
PF	-	-	4	4	8	1.97%	0.05
FP	2	-	2	4	6	1.97%	0.05
TST	3	-	-	3	3	1.48%	0.04
ITB	1	1	1	3	4	1.48%	0.04
AS	1	1	-	2	2	0.98%	0.02
HP	-	2	-	2	2	0.98%	0.02
Total	30	19	15	64	79	19.56%	0.76
<p><i>PFP: Patellofemoral pain AP: Ankle pain AS: Ankle sprain</i> <i>KP: Knee pain FP: Foot Pain ITB: Iliotibial band</i> <i>MTS: Medial tibial stress TST: Tibial stress fracture HP: Hip pain</i> <i>PF: Planter fasciitis</i></p>							

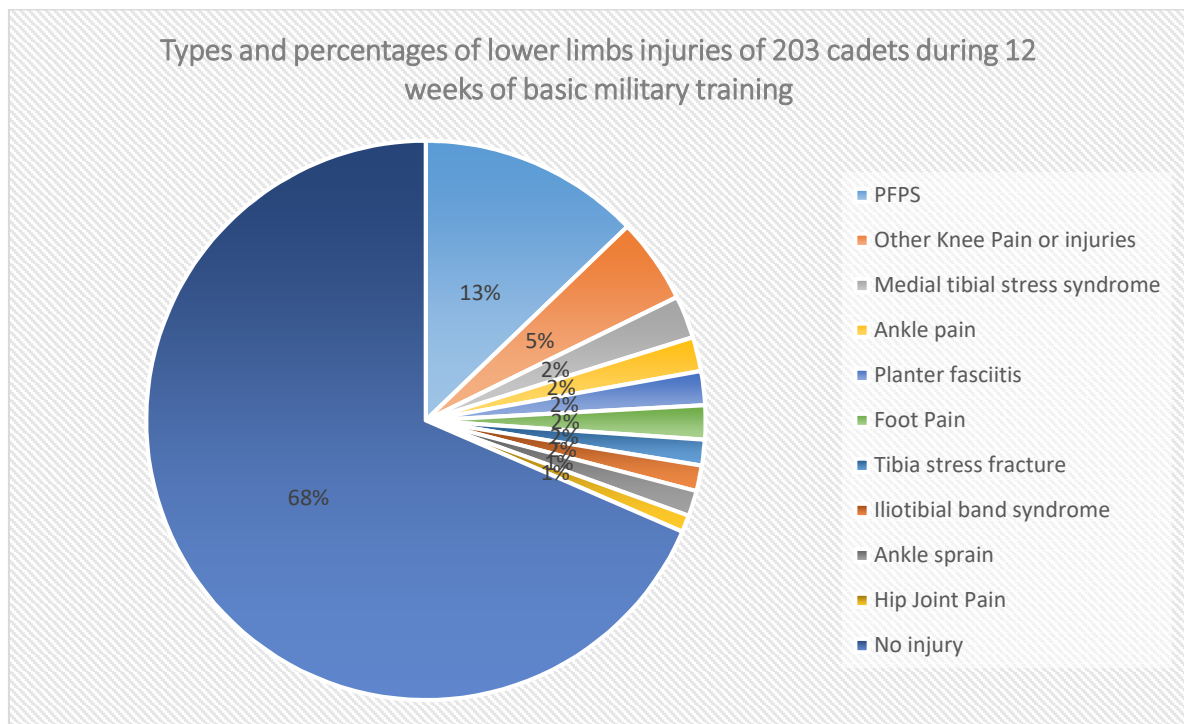


Figure 5.11 Types and percentages of PFP and other lower limb injuries during the 12 weeks of basic military training

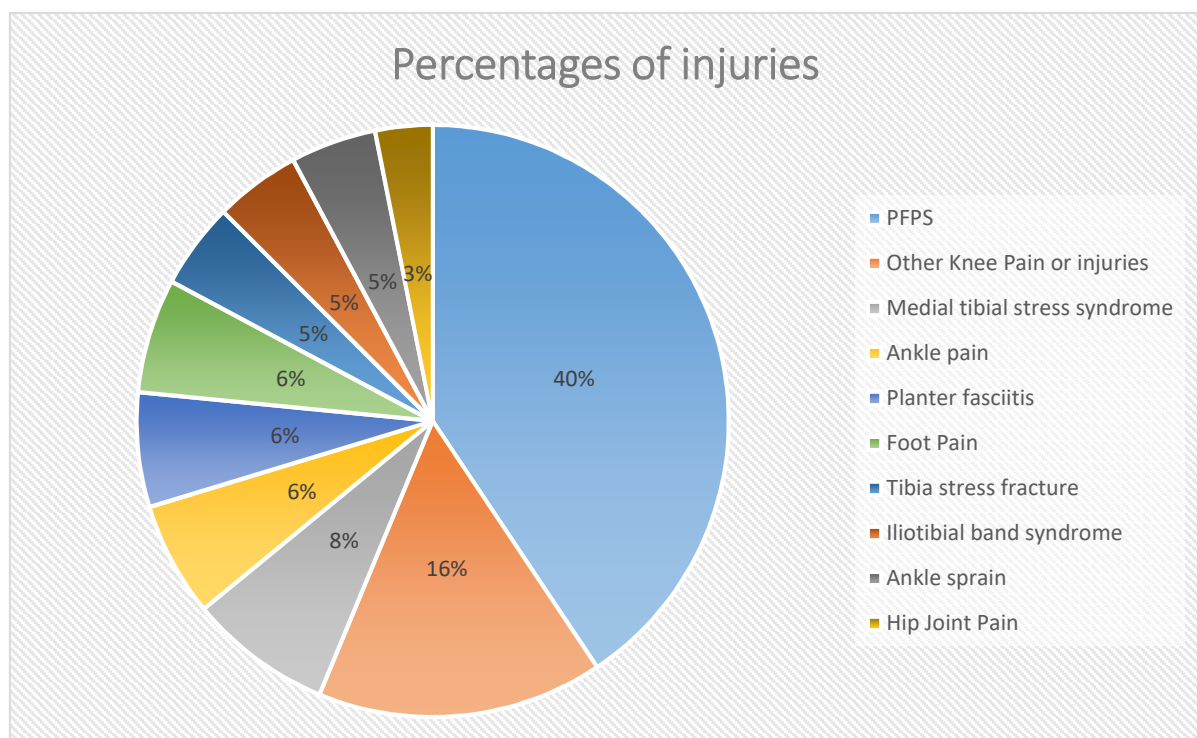


Figure 5.12 Percentages of injuries

As illustrated in Figure 5.13, after the end of the first training week with no recorded injuries, there was a high incidence of injuries in the second week (25: 39%), which decreased gradually in the following three weeks and then was distributed equally over the rest of the training period.

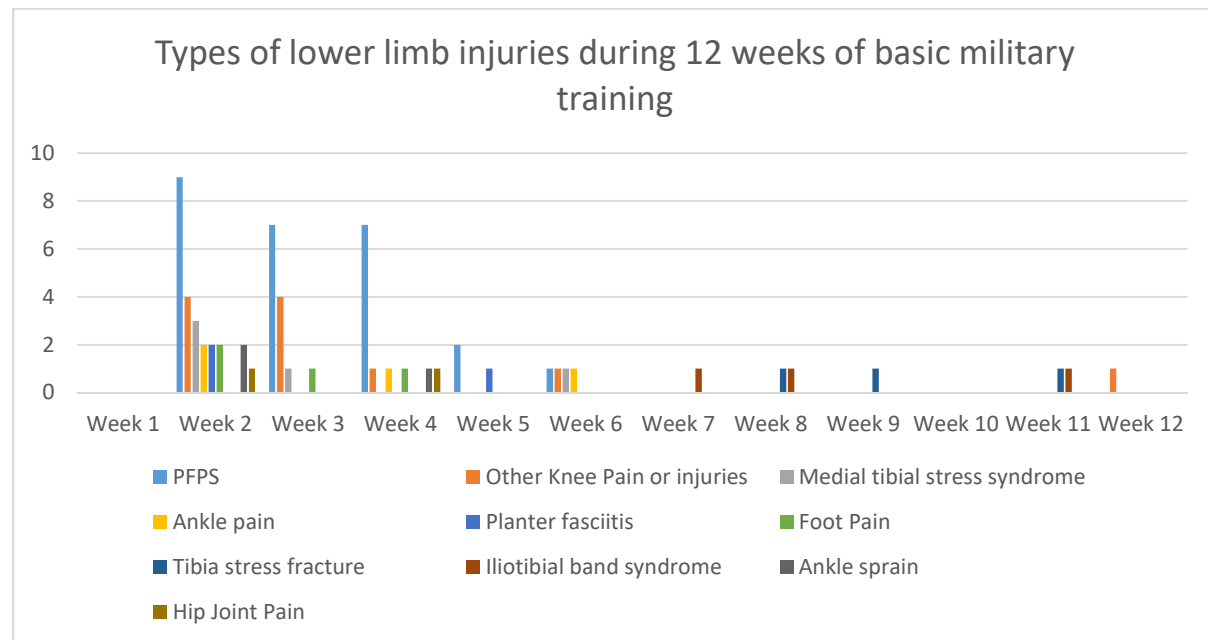


Figure 5.13 Types and numbers of lower limb injuries during the 12 weeks of basic military training

26 subjects (12.8%) developed PFP in 29 (7.14%) knees; as the highest recorded injury, it accounted for approximately 41% of all recorded lower limb musculoskeletal injuries. 35% of PFP occurred during the second week. No significant differences were found in the demographic characteristics and muscle strength variables between participants who developed the injury and the healthy control. The FPPA and Q-angle of participants with PFP were significantly greater than those without PFP during the three screening tasks: $P=0.014$ and $P=0.012$ during SLS, $P=0.001$ and $P=0.006$ during SLL, and $P=0.009$ and $P=0.028$ during RUN. Participants who developed PFP during the baseline assessment had a significantly greater HADD ($P=0.027$) in SLS and in SLL ($P=0.001$). Effect sizes were small for all kinematic variables that had significant differences. No significant differences were detected between the two groups in any of the other kinematic variables or when participating in sports (Table 5.16 – 5.18).

Table 5.16 Mean, standard deviation, 95% confidence intervals (CI), and P value of the demographic characteristics of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
Age	Non-Injured	177	18.54	0.59	18.48	18.60	0.083	0.25
	Injured	26	18.79	0.82	18.48	19.10		
Height	Non-Injured	177	1.74	0.05	1.74	1.75	0.121	0.29
	Injured	26	1.76	0.04	1.74	1.78		
Mass	Non-Injured	177	68.23	12.42	66.98	69.49	0.096	0.26
	Injured	26	73.68	16.66	67.34	80.02		
BMI	Non-Injured	177	22.40	3.84	22.01	22.79	0.160	0.22
	Injured	26	23.76	4.92	21.89	25.63		
Mass norm to Height	Non-Injured	177	383.31	66.97	376.53	390.09	0.115	0.24
	Injured	26	410.21	88.09	376.70	443.72		

Table 5.17 Mean, standard deviation, 95% confidence intervals (CI), and P value of the strength variables of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
KEXT MS (%BW*TL)	Non-Injured	177	144.08	50.48	136.59	151.57	0.379	0.17
	Injured	26	131.93	40.68	115.49	148.36		
HABD MS (%BW*FL)	Non-Injured	177	76.46	22.15	73.17	79.75	0.312	0.14
	Injured	26	72.13	19.78	64.15	80.12		
KNEE + HIP MS	Non-Injured	177	220.54	65.20	210.87	230.21	0.371	0.18
	Injured	26	204.06	54.04	182.23	225.89		
<i>KEXT: Knee extensors</i>		<i>HABD: Hip abductors</i>		<i>KEXT+HABD: Knee extensors + hip abductors</i>				

Table 5.18 Mean, standard deviation, 95% confidence intervals (CI), and P value of the kinematic variables and sports participation of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
FPPA in SLS (°)	Non-Injured	170	3.38	9.54	1.94	4.83	0.014*	0.35
	Injured	25	8.26	8.65	4.69	11.83		
HADD in SLS (°)	Non-Injured	170	9.28	4.81	8.55	10.01	0.027*	0.31
	Injured	25	11.61	5.45	9.36	13.87		
QA in SLS (°)	Non-Injured	170	10.17	8.42	8.89	11.44	0.012*	0.36
	Injured	25	14.71	8.26	11.30	18.12		
FPPA in SLL (°)	Non-Injured	176	2.29	7.51	1.17	3.41	0.001*	0.48
	Injured	25	7.88	8.52	4.37	11.40		
HADD in SLL (°)	Non-Injured	176	3.44	4.85	2.72	4.16	0.001*	0.47
	Injured	25	7.03	5.48	4.77	9.29		
QA in SLL (°)	Non-Injured	176	9.89	7.00	8.85	10.93	0.006*	0.47
	Injured	25	15.04	7.97	11.75	18.33		
FPPA in RUN (°)	Non-Injured	169	-3.26	5.07	-4.02	-2.49	0.009*	0.39
	Injured	24	-0.38	4.52	-2.29	1.53		
HADD in RUN (°)	Non-Injured	169	8.80	4.07	8.19	9.42	0.384	0.13
	Injured	24	9.56	3.30	8.17	10.95		
QA in RUN (°)	Non-Injured	169	6.04	4.83	5.30	6.77	0.028*	0.33
	Injured	24	8.39	4.49	6.49	10.28		
KFA in RUN (°)	Non-Injured	96	46.25	4.28	45.38	47.12	0.220	0.22
	Injured	18	44.93	3.34	43.27	46.60		
DFA in RUN (°)	Non-Injured	96	82.29	4.86	81.31	83.28	0.548	0.10
	Injured	18	83.06	5.40	80.38	85.75		
RFA in RUN (°)	Non-Injured	96	16.95	4.35	16.07	17.83	0.073	0.30
	Injured	18	14.88	5.05	12.37	17.38		
Participating in sport	Non-Injured	177	6.16	1.63	5.92	6.41	0.335	0.15
	Injured	26	5.81	1.47	5.21	6.40		
FPPA: Frontal plane projection angle			HADD: Hip adduction			QA: Q-angle		
SLS: Single leg squat			SLL: Single leg land			RUN: Running		
KFA: Knee flexion angle			DFA: Dorsiflexion angle			RFA: Rearfoot angle		

The primary results of the FPPA comparison between participants who developed FPF and who did not in this section were presented in the 5th international patellofemoral pain research retreat as a conference paper (Appendix B).

The results show that mean and standard deviation of KOOS scores of the 26 participants who developed PFP were 64.25 (24.38) at the diagnosis time with significant decrease ($p < 0.01$) comparing to the baseline scores (Table 5.19).

Table 5.19 Mean, standard deviation, and P value of KOOS

KOOS at Baseline		KOOS at Diagnosis		P value
Mean	SD	Mean	SD	
100	<0.01	64.25	24.38	<0.01

5.4.2.1. Predicted risk factors of PFP

Results of the binary logistic regression for each individual variable are presented in Table 5.20. The results show that FPPA and Q-angle during SLS, SLL and RUN, HADD during SLS and SLL are significantly predicted PFP. The odds ratio of each variable are ranged between 1.067 for Q-angle during SLS and 1.235 for FPPA during SLL.

Table 5.20 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable

	OR	<i>p</i>	95% CI for OR	
			Lower	Upper
FPPA in SLS (°)	1.070	.013	1.014	1.128
HADD in SLS (°)	1.126	.011	1.027	1.234
QA in SLS (°)	1.067	.037	1.004	1.134
FPPA in SLL (°)	1.235	.000	1.107	1.378
HADD in SLL (°)	1.124	.001	1.049	1.204
QA in SLL (°)	1.121	.003	1.040	1.210
FPPA in RUN (°)	1.156	.008	1.039	1.286
QA in RUN (°)	1.140	.024	1.017	1.279

Only single variable, FPPA during each task could be entered in regression model. So, there is no logistic regression model.

5.4.2.2. Receiver Operation Curve (ROC)

Receiver Operation Curve (ROC) analysis demonstrated that FPPA during SLL was the highest predictor for PFP (Area=0.74; $P=0.002$). $FPPA \geq 5.40^\circ$ during SLL predicted PFP with a sensitivity of 70% and a specificity of 70%. The associated positive likelihood ratio (sensitivity/1-specificity) was 2.33.

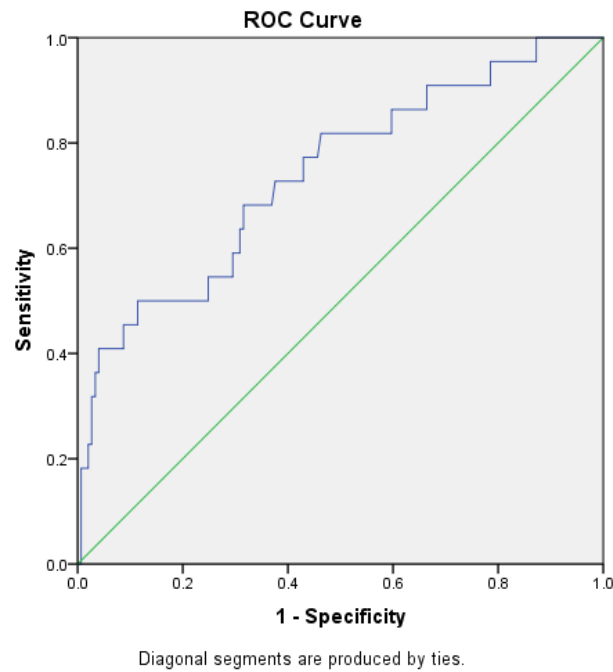


Figure 5.14 Receiver Operation Curve (ROC) of FPPA during SLL

5.4.3. Results (C): All of the three groups without overweight participants

During the twelve weeks of basic military training, 45 of the 271 participants (16.60%) were diagnosed with 53 lower limb musculoskeletal injuries in 67 (12.36%) out of 542 tested limbs: 26 (9.59%) with PFP, 9 (3.32%) with other sources of knee pain, 6 (2.21%) with medial tibial stress, 3 (1.11%) with planter fasciitis, 2 (0.74%) with ankle pain, 2 (0.74%) with foot pain, 1 (0.37%) with a tibia stress fracture, 2 (0.74%) with an ankle sprain, 1 (0.37%) with an iliotibial band, and 1 (0.37%) with hip joint pain (Table 5.21 and Figures 5.15 – 5.17).

Table 5.21 Numbers and percentages of injured participants and injured limbs in each injury

Injury	Right limb	Left limb	Both limb	Number of injured Participants	Number of injured limbs	Injury incidence (%)	Injury rate per 1000
PFP	16	7	3	26	29	9.59%	0.31
KP	5	4	-	9	9	3.32%	0.11
MTS	-	-	6	6	12	2.21%	0.07
PF	-	-	3	3	6	1.11%	0.04
AP	1	1	-	2	2	0.74%	0.02
FP	1	-	1	2	3	0.74%	0.02
TSF	1	-	-	1	1	0.37%	0.01
AS	1	1	-	2	2	0.74%	0.02
ITB	-	-	1	1	2	0.37%	0.01
HP	-	1	-	1	1	0.37%	0.01
Total	25	14	14	53	67	19.56%	0.63
PFP: Patellofemoral pain			AP: Ankle pain			AS: Ankle sprain	
KP: Knee pain			FP: Foot Pain			ITB: Iliotibial band	
MTS: Medial tibial stress			TST: Tibial stress fracture			HP: Hip pain	
PF: Planter fasciitis							

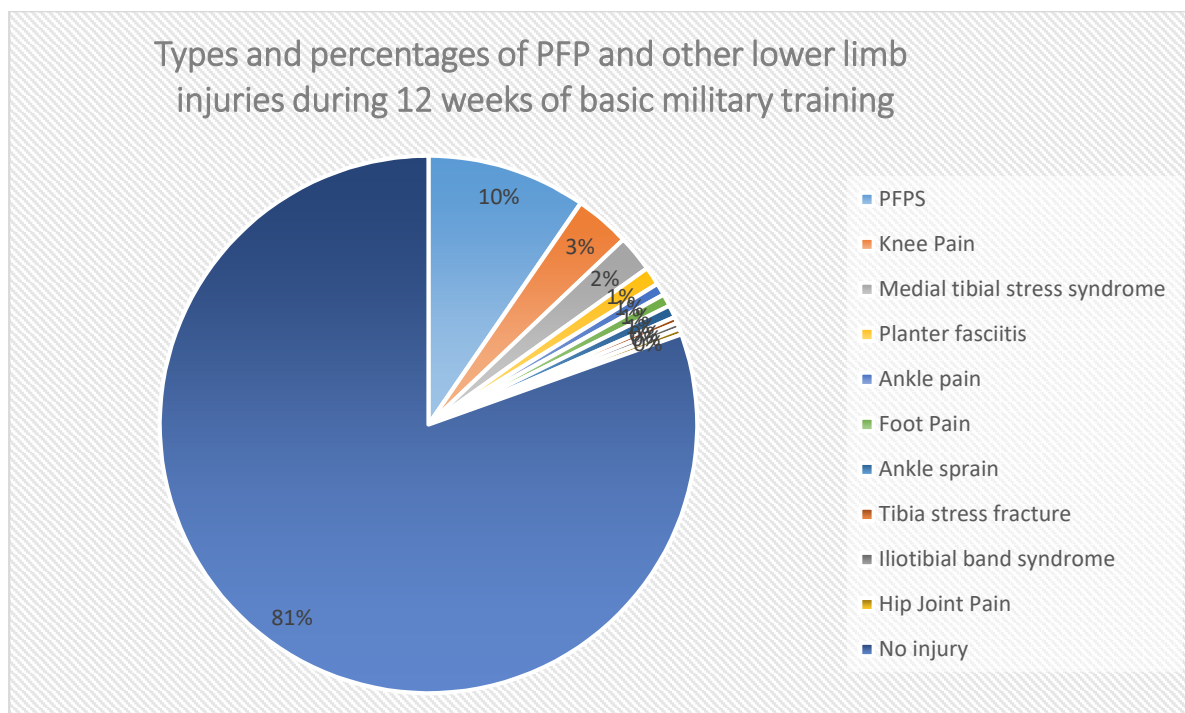


Figure 5.15 and percentages of PFP and other lower limb injuries during the 12 weeks of basic military training

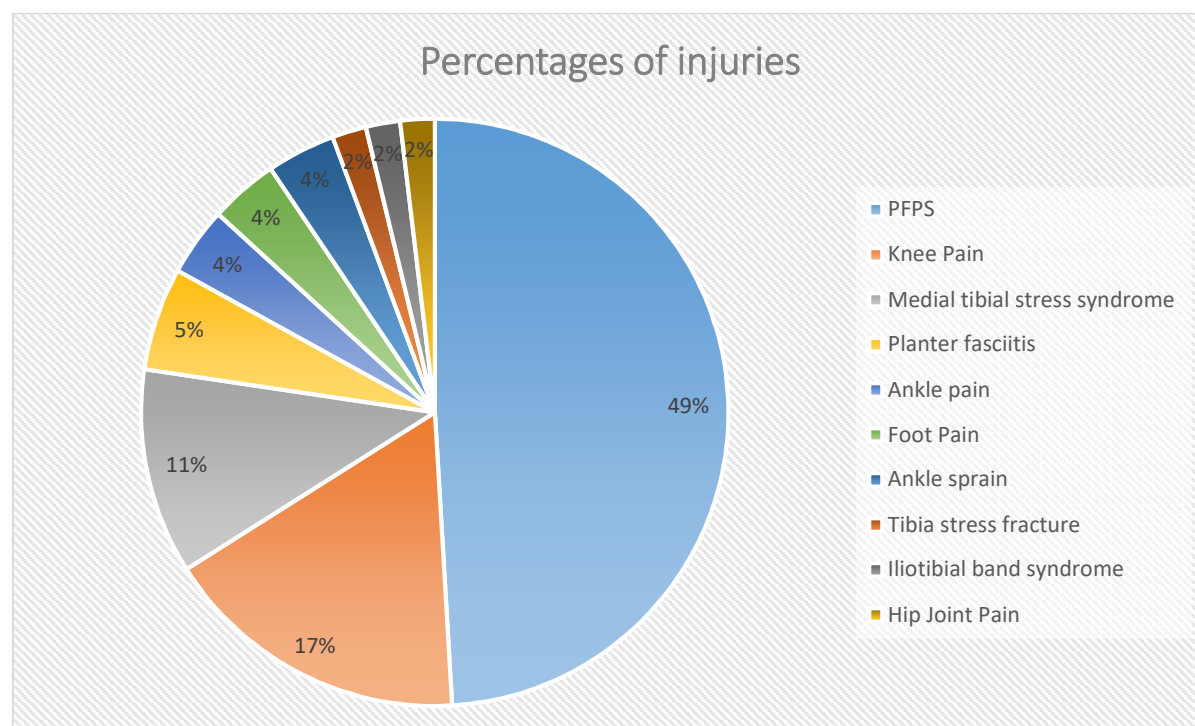


Figure 5.16 Percentages of injuries

As illustrated in Figure 5.17, after the end of the first training week with no recorded injuries, there was a high incidence of injuries in the second week (22: 41.5%), which decreased gradually in the following three weeks and then distributed equally over the rest of the training period.

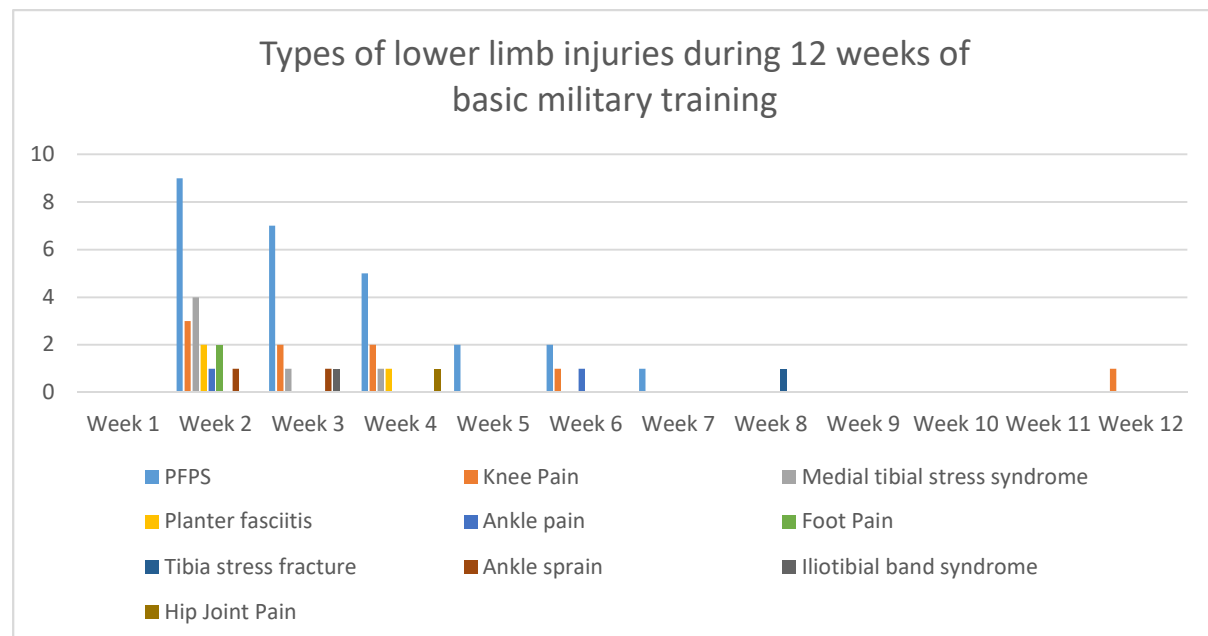


Figure 5.17 Types and numbers of lower limb injuries during the 12 weeks of basic military training

26 subjects (9.59%) developed PFP in 29 (5.35%) knees; as the highest recorded injury, it accounted for approximately half (49%) of all recorded lower limb musculoskeletal injuries. 35% of PFP occurred during the second week. No significant differences were found in the demographic characteristics and muscle strength variables between participants who developed the injury and the healthy control. The FPPA and Q-angle of participants with PFP were significantly greater than for those without PFP during SLL and RUN screening tasks: $P=0.013$ and $P=0.030$ during SLL and $P=0.015$ and $P=0.041$ during RUN. Participants who developed PFP during the baseline assessment had a significantly greater HADD ($P<0.008$) in SLL. Effect sizes were small for the kinematic variables that had significant differences, ranging from 0.03 to 0.40. No significant differences were detected between the two groups in any of the other kinematic variables or in sports participation (Tables 5.22 – 5.24).

Table 5.22 Mean, standard deviation, 95% confidence intervals (CI), and P value of the demographic characteristics of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
Age	Non-Injured	245	19.88	2.11	19.62	20.15	0.757	0.11
	Injured	26	19.54	1.70	18.85	20.23		
Height	Non-Injured	245	1.72	0.06	1.71	1.73	0.678	0.24
	Injured	26	1.74	0.05	1.72	1.75		
Mass	Non-Injured	245	63.02	9.62	61.81	64.23	0.211	0.08
	Injured	26	64.28	11.68	59.56	69.00		
BMI	Non-Injured	245	21.34	2.97	20.97	21.72	0.982	0.00
	Injured	26	21.36	3.78	19.83	22.88		
Mass norm to Height	Non-Injured	245	359.47	50.87	353.07	365.88	0.781	0.05
	Injured	26	363.27	64.16	337.35	389.18		

Table 5.23 Mean, standard deviation, 95% confidence intervals (CI), and P value of the strength variables of injured and non-injured groups

Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
KEXT MS (%BW*TL)	Non-Injured	245	140.28	47.01	134.37	146.20	0.97	0.10
	Injured	26	133.74	41.19	117.10	150.37		
HABD MS (%BW*FL)	Non-Injured	245	75.95	20.98	73.31	78.59	0.404	0.12
	Injured	26	72.26	21.24	63.68	80.84		
KNEE + HIP MS	Non-Injured	245	216.23	61.70	208.47	223.99	0.636	0.11
	Injured	26	206.00	56.86	183.03	228.96		
<i>KEXT: Knee extensors</i>		<i>HABD: Hip abductors</i>		<i>KEXT+HABD: Knee extensors + hip abductors</i>				

Table 5.24 Mean, standard deviation, 95% confidence intervals (CI), and P value of the kinematic variables and participation in sports of injured and non-injured groups

Knee pain in athletes participating in sports of injured and non-injured groups								
Variable	Group	Number	Mean	SD	95% CI		p	Effect size
					Lower	Upper		
FPPA in SLS (°)	Non-Injured	238	3.91	9.22	2.73	5.09	0.097*	0.23
	Injured	26	7.00	8.69	3.49	10.51		
HADD in SLS (°)	Non-Injured	238	9.71	4.79	9.10	10.33	0.087*	0.26
	Injured	26	11.68	5.43	9.48	13.87		
QA in SLS (°)	Non-Injured	238	10.74	8.70	9.63	11.85	0.167*	0.19
	Injured	26	13.25	8.43	9.84	16.65		
FPPA in SLL (°)	Non-Injured	244	2.60	7.80	1.61	3.58	0.013*	0.38
	Injured	26	7.26	8.66	3.77	10.76		
HADD in SLL (°)	Non-Injured	245	3.97	4.88	3.36	4.59	0.008*	0.40
	Injured	26	6.91	5.08	4.86	8.96		
QA in SLL (°)	Non-Injured	245	10.37	8.07	9.35	11.38	0.030	0.32
	Injured	26	14.47	9.40	10.68	18.27		
FPPA in RUN (°)	Non-Injured	238	-3.04	5.30	-3.72	-2.36	0.015*	0.33
	Injured	24	-0.55	4.43	-2.42	1.32		
HADD in RUN (°)	Non-Injured	238	9.04	3.98	8.53	9.55	0.056	0.23
	Injured	24	10.30	2.84	9.10	11.50		
QA in RUN (°)	Non-Injured	238	6.19	5.82	5.44	6.93	0.041*	0.26
	Injured	24	8.44	5.57	6.09	10.79		
KFA in RUN (°)	Non-Injured	174	46.19	4.20	45.56	46.81	0.340	0.16
	Injured	21	45.23	3.35	43.70	46.75		
DFA in RUN (°)	Non-Injured	174	81.86	4.68	81.16	82.56	0.757	0.03
	Injured	21	82.05	4.60	79.96	84.15		
RFA in RUN (°)	Non-Injured	176	14.71	4.37	14.06	15.36	0.210	0.12
	Injured	21	13.88	5.19	11.52	16.24		
Participating in sport	Non-Injured	245	6.17	1.56	5.97	6.36	0.724	0.07
	Injured	26	6.00	1.36	5.45	6.55		
FPPA: Frontal plane projection angle			HADD: Hip adduction		QA: Q-angle			
SLS: Single leg squat			SLL: Single leg land		RUN: Running			
KFA: Knee flexion angle			DFA: Dorsiflexion angle		RFA: Rearfoot angle			

The results show that mean and standard deviation of KOOS scores of the 26 participants who developed PFP were 72.780 (22.180) at the diagnosis time with significant decrease ($p<0.01$) comparing to the baseline scores (Table 5.25).

Table 5.25 Mean, standard deviation, and P value of KOOS

KOOS at Baseline		KOOS at Diagnosis		P value
Mean	SD	Mean	SD	
100	<0.01	72.780	22.180	<0.01

5.4.3.1. Predicted risk factors of PFP

Results of the binary logistic regression for each individual variable are presented in Table 5.26. The results show that FPPA during SLS, SLL and RUN, and HADD during SLS and SLL, and Q-angle during SLL and RUN are significantly predicted PFP. The odds ratio of each variable are ranged between 1.082 for Q-angle during SLL and 1.165 for FPPA during SLL.

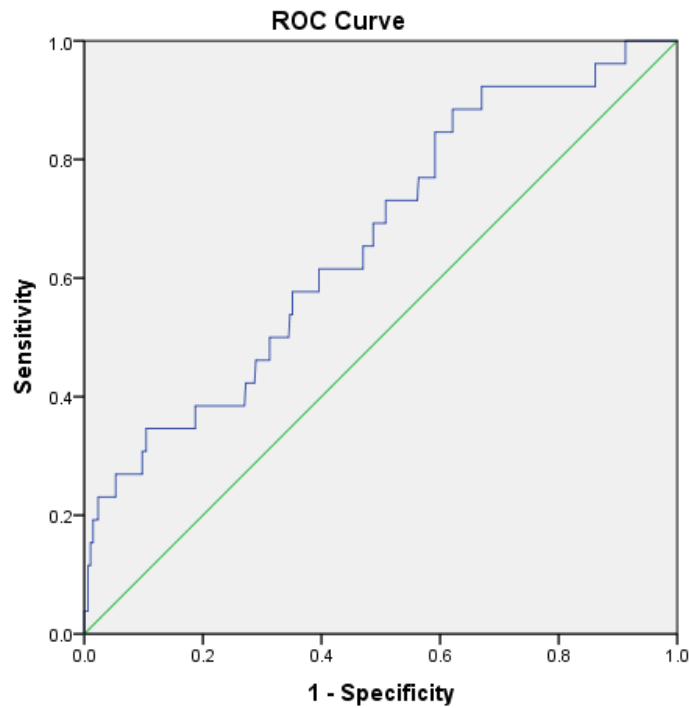
Table 5.26 Odds ratio with P value and 95% confidence intervals (CI) of odds ratio for each variable

	OR	P	95% CI for OR	
			Lower	Upper
FPPA in SLS (°)	1.056	.039	1.003	1.111
HADD in SLS (°)	1.123	.009	1.029	1.226
FPPA in SLL (°)	1.165	.002	1.060	1.280
HADD in SLL (°)	1.093	.002	1.033	1.158
QA in SLL (°)	1.082	.007	1.021	1.146
FPPA in RUN (°)	1.116	.018	1.019	1.221
HADD in RUN	1.077	.133	.978	1.186
QA in RUN	1.105	.026	1.012	1.206

Only single variable, FPPA during each task could be entered in regression model. So, there is no logistic regression model.

5.4.3.2. Receiver Operation Curve (ROC)

Receiver Operation Curve (ROC) analysis demonstrated that FPPA during SLL was significant and the highest predictor for PFP (Area=0.68; $P<0.005$). $FPPA \geq 5.50^\circ$ during SLL predicted PFP with a sensitivity of 62% and a specificity of 60%. The associated positive likelihood ratio (sensitivity/1-specificity) was 1.55.



Diagonal segments are produced by ties.

Figure 5.18 Receiver Operation Curve (ROC) of FPPA during SLL

5.5. Discussion

This study provides one of the first descriptions of basic military physical training injuries in the Saudi military population. The first aim of this study was to quantify the incidence of PFP and any other lower limb injuries during basic military training in the Saudi military population. The results show that the lower limb musculoskeletal injury rate was 26.98 per 100 and PFP made up about 44 per 100 of all injuries. Many studies have reported incidences of physical training injuries during basic military training (Linenger and West, 1992; Blacker et al., 2008; Franklyn et al., 2011; Knapik et al., 2013; Sharma et al., 2015). Most of these studies found that the majority of the injuries were in the lower extremities, particularly in the knee joint (James et al., 1978).

68 subjects developed lower limbs musculoskeletal injury; it accounted for approximately (21.59%) of all participants. Most of injuries occurred during the first three weeks. This may be due to that the first two weeks of training are contains mainly extensive physical training and the classes start by the third week. In addition, some participants might not be custom to the load of early training which means that there is significant difference between acute chronic workload ratio of the initial weeks of basic military training and the previous acute chronic workload ratio history of some participants, or it seems that workload was poorly managed during this period of training. 37 participants developed PFP during the 12 weeks of basic military training, thus reflecting the highest injury rate of 11.75 per 100. This result is within the injury rate range of previous prospective studies (2.5 – 43 per 100) and similar to that of Holden et al. (2015) 11 per 100. However, it is lower than most of the PFP injury rates from similar prospective studies that investigated the incidence rate during basic military training. Only Boling et al. (2009) report a lower injury rate than the one recorded in the current study.

Surprisingly, there are significant differences in mass-related demographic characteristics (i.e. mass, mass normalised to height, and BMI) between injured and non-injured groups. For this reason, we assessed the differences in all variables and the predicted risk factors between the comparison groups, and we grouped the results into three sets: all 315 participants from the three units in results (A), the 203 cadets of KAMA in results (B), and all participants excluding those with a BMI greater than 27% in results (C).

The first aim of this study was to investigate the differences in the kinematics of the lower limb joints between individuals who developed PFP and any other lower limb injuries and those who did not by using 2D analysis for running, SLS, and SLL. The present study is the first to

investigate the development of PFP using 2D measurement for FPPA and also for other lower limb kinematics in the Saudi military population. The results of kinematic differences show that the FPPA, Q-angle, and HADD of participants who developed PFP were significantly greater than the FPPA, Q-angle, and HADD of those who did not develop the injury during the three screening tasks, except for HADD during running.

Dynamic knee valgus has been cited as a predictor of PFP (Prins and Wurff, 2009; Souza and Powers, 2009). A significantly high correlation was found between dynamic knee valgus and FPPA during SLS and SLL tasks in Chapter 4, which has also been previously reported in similar tasks and side-jump task (McClean et al., 2005; Willson & Davis 2008; Sorenson et al., 2015; Herrington et al., 2017). Thus, an increase in FPPA will lead to an increase in dynamic knee valgus, which will increase the potential risk of PFP development. The present results show that 2D FPPA in participants with PFP was significantly greater than in those without PFP during the three screening tasks. The results of the current study support those of Holden et al. (2015), who investigated the development of PFP prospectively in 76 adolescent female athletes using 2D measurements for knee valgus displacement during drop vertical jump tasks. Eight participants developed the injury, and knee valgus displacement increased in the PFP group ($10.88 \pm 2.2^\circ$) in comparison to the control group ($3.09 \pm 0.64^\circ$). However, we have to understand that the sex and age of the participants are not similar (i.e. in the current study, young adult males were examined), in addition to there being variations in the screening tasks.

Knee valgus or medial knee displacement was assessed in several previous prospective studies using 3D measurement. None of these studies reported any significant difference between the injured and non-injured groups. The author suggests that this may be due to the screening tasks, which were bilateral screening tasks, as in DVJ (Myer et al., 2010) and jump-landing (Boling et al., 2009), a lack of information in the medical records, or self-treatment for PFP, as stated in the limitations of Boling et al. (2009). Additionally, it is questionable how, in Myer et al. (2010), the injured group had a significantly greater knee abduction moment during the baseline assessment but it was not combined with a significant increase in knee valgus.

An increased HADD angle is one of the elements of dynamic knee valgus, and it has been associated with the development of PFP (Willson & Davis, 2008; Powers, 2010). Increased HADD has been shown to decrease the PFJ contact area and concentrate the articular stress on the lateral part on the patella (Huberti and Hayes, 1984). Individuals with PFP were found to have greater articular stress on the patella (Farrokhi et al., 2011). The finding of a significantly greater HADD in the PFP group further supports the findings of Neohren et al. (2012). HADD

angle in the current results was significantly greater during SLS and SLL, with a trend to be significant in running. While the results of Neohren et al. (2012) are based on 3D measurement, this may be due to the limitations of 2D during filming high-speed movement.

This is the first prospective study to investigate the association between dynamic Q-angle and the development of PFP. The validity and reliability of dynamic Q-angle using 2D analysis were assessed in Chapter 4. In this sense, 2D measurement was shown to be a valid and reliable tool for measuring dynamic Q-angle, with a very large correlation with 3D analysis, excellent ICCs, and a small SEM across the three screening tasks. Participants who developed PFP demonstrated a greater dynamic Q-angle in all of the screening tasks.

The significant decrease of isometric quadricep muscle strength is consistent with the findings of Van Tiggelen et al. (2004), Duivigneaud et al. (2008), and Boling et al. (2009), while contradicting those of Milgrom et al., (1991). In spite of the differences in testing procedures, it seems as if there is general agreement about the weakness of quadriceps. Milgrom et al. (1991) and Boling et al. (2009) assessed quadricep muscle strength isometrically, while Witvrouw et al. (2000), Van Tiggelen et al. (2004), Duivigneaud et al. (2008), and Herbest et al. (2015) assessed quadricep muscle torque in different angular velocities. Witvrouw et al. (2000) and Herbest et al. (2015) report no significant differences between the injured and control groups. Only Milgrom et al. (1991) found that the isometric muscle strength of quadriceps was greater in participants who developed PFP, the reason for which may be due to not normalising the isometric strength of quadriceps to body mass.

The findings of the current study indicate that the isometric hip abductor muscle strength of participants with PFP was significantly lower than for participant without PFP, which is in contrast to the results of Finnoff et al. (2011) and Herbest et al. (2015). Finnoff et al. (2011) measured hip abductors with an HHD stabilised by the examiner's hand (i.e. not fixed or stabilised with a belt), whereas Herbest et al. (2015) assessed hip isokinetic muscle strength from a standing position with a fixed dynamometer, which may have been affected by the influence of the contralateral limb (Widler et al., 2009). Two other previous prospective studies assessed isometric hip abductor muscle strength with an HHD, and both of them did not find any significant differences between the injured and non-injured groups.

Additionally, in the current study, we calculated the summation of hip abductor and knee extensor muscle strength as an indicator for total lower limb muscle strength and investigated the differences of the results between the participants who developed PFP and those who did

not. The group who developed PFP had a significantly lower summed hip abductor and knee extensor muscle strength during the baseline assessment.

It is important to note that this study was able to detect significant differences between the injured and non-injured groups with regard to kinematic variables (FPPA, HADD, and Q-angle during the three tasks, except HADD during running), strength variables (knee extensors, hip abductors, and the summation of knee extensors and hip abductors), at the same time as there being a difference between mass-related variables (i.e. mass, BMI, and mass normalised to height). These findings will help to identify the individuals who are at risk of PFP development with simple, portable, and low-cost measurement tools, leading to the development of injury prevention and intervention programmes.

In this study, in addition to the recording of PFP, we include the recording of other lower limb musculoskeletal injuries. This helps us to eliminate the individuals who were affected with these injuries from logistic regression in order to avoid their effects on the results of predicted risk factors, not only for PFP but also for all other lower limbs musculoskeletal injuries. Thus, after excluding other lower limb injuries, all variables showing a P value of <0.05 in the comparison analysis between the injured and non-injured groups were entered together into the forward logistic regression. Variables were entered together to understand how all of the risk factors may interact with each other and lead to the development of PFP. The results of the forward logistic regression revealed that mass, hip abductor muscle strength, Q-angle during SLS and SLL, and FPPA during SLL all significantly predict PFP. The highest predictor variable was FPPA during SLL (OR=1.133, P=0.01).

Greater FPPA during SLL with 2D analysis significantly predicted the development of PFP. This result supports the similar findings of Holden et al. (2015), who used 2D measurement to investigate knee valgus displacement during drop vertical jump tasks in 76 adolescent females, wherein eight developed PFP. In this sense, greater knee valgus displacement was associated with the development of PFP. In the current study, we used, for the first time, single leg screening tasks, such as SLS and SLL, in addition to running. The author hypothesised that single leg tasks would be better than bilateral leg tasks in investigating the injuries related with dynamic leg valgus because most lower limb musculoskeletal injuries, such as ACL and ankle sprain, occur during single leg landings.

Three previous prospective studies reported the OR within the results (Loedke et al., 2016; Finnoff et al., 2011; Rauh et al., 2010). The ORs that were reported in the previous studies

were based on outcome measure in each study. Only one previous study reported OR of the association between hip muscle strength and development of knee pain (Finnoff et al., 2011). They found higher baseline hip abduction normalized torque percent (odds ratio = 5.35, 95% CI = 1.46, 19.53; $P < .01$) and it was higher than the OR of the current study. Rauh et al., (2010) reported OR for several anatomic static measures in relationship with development of lower limb overused injury, and there was no specific data for PFP injury. In another study Loedke et al., (2016) reported OR for step rate in different speed and relationship with development of shin injury and AKP. No significant relationships were found between step rate and AKP at either speed. Some other studies reported either relative risk or only P value from logistic regression (Thijs et al., 2007; Witfrouw et al., 2000; Milgrom et al., 1991). No previous prospective study reported the OR of the relationship between strength or kinematic variables and development of PFP.

Receiver operating characteristic (ROC) analysis curve was performed in the current study to verify the discriminatory capability of each variable. The FPPA during the SLL task was the highest significant predictor for PFP (Area=0.70; $P < 0.001$). A $FPPA \geq 5.2^\circ$ during SLL predicted PFP with a sensitivity of 70% and a specificity of 70%. Holden et al. (2015) previously performed ROC and found that knee valgus displacement was a significant predictor of PFP (Area= 0.77; $P = 0.002$). Knee valgus displacement $\geq 10.6^\circ$ predicted PFP with a sensitivity of 75% and specificity of 85% (Holden et al., 2015). Despite the difference in values of angles of cut-off point between Holden et al., (2015) and the current study, there is agreement between the two studies with regard to understanding that FPPA and medial knee displacement are not same and there are variations in the screening tasks. In addition, the participants' sex and age are dissimilar, in that the current study examined young adult males while Holden et al. (2015) examined adolescent females.

In results (B), no significant differences in the demographic characteristics were found between the two compared groups. The results of the comparison between the PFP group and the healthy group with regard to the kinematic variables were typically similar to those in results (A). The FPPA and Q-angle of participants with PFP were significantly greater than for those without PFP during the three screening tasks: $P = 0.014$ and $P = 0.012$ during SLS, $P = 0.001$ and $P = 0.006$ during SLL, and $P = 0.009$ and $P = 0.028$ during RUN. Participants who developed PFP had a significantly greater HADD angle ($P = 0.027$) in SLS and in SLL ($P = 0.001$) during the baseline assessment. No significant differences in muscle strength variables were found between the two compared groups. Binary logistic regression revealed that FPPA during SLL was the most

predicted variable of the development of PFP similar to result (A). Due to absence of strength and mass related variables which were not significant difference there was no regression model created. Receiver operating characteristic (ROC) analysis is similar to that found in results (A): FPPA during SLL was a significant predictor for PFP (Area=0.74; $P<0.001$). $FPPA \geq 5.40^\circ$ during SLL predicted PFP with a sensitivity of 70% and a specificity of 70%.

In results (C), no significant differences in the demographic characteristics were found between the two compared groups. The results between the two compared groups, the PFP group and the healthy group, with regard to kinematic variables were slightly similar to the results in (A). The FPPA, HADD, and Q-angle of the PFP group during SLS task were not significantly greater than the healthy group as in results (A) and (B), but there was a trend for FPPA and HADD to be significant. The FPPA and Q-angle of participants with PFP were significantly greater than for those without PFP during SLL and RUN tasks in the baseline assessment: $P=0.013$ and $P=0.030$ during SLL, and $P=0.015$ and $P=0.041$ during RUN. No significant differences in muscle strength variables were found between the two compared groups. Binary logistic regression revealed that the FPPA during SLL was the most predicted variable of the development of PFP, which supports the results (A) and (B) regarding the FPPA during SLL. Additionally, ROC analysis shows similar results to those found in results (A) and (B): FPPA during SLL was a significant predictor for PFP (Area=0.68; $P<0.005$). $FPPA \geq 5.50^\circ$ during SLL predicted PFP with a sensitivity of 62% and a specificity of 60%.

After excluding the participants who were over 27% in BMI, in order to predict PFP development, the FPPA in SLL was greater than the angles found in results (A). This means that the risk of injury was decreased for the same values in results (A). So, the FPPA during SLL needs to be greater in order to significantly predict the development of PFP, and mass plays an important role in increasing the risk of injury in landing tasks.

From the previous findings of this investigation, several factors contribute to increasing the risk of PFP injury development: mass, the FPPA during SLL, hip abductor muscle strength, the Q-angle during SLL, and the Q-angle during SLS. In all three results sets, one variable was found to be the greatest predictor for the occurrence of injury: the FPPA during SLL. This finding, as previously stated, supports the findings of Holden et al. (2015).

It has been argued that PFP is a multifactorial injury, and the findings of the current study support this theory. Therefore, in injury prevention or mitigation programmes, we should consider each factor individually and subgroup individuals according to the findings in order

to ensure a targeted intervention approach. The method of subgrouping the individuals with PFP according to the findings has been used before in Selfe et al., (2015) study. They subgrouped PFP individuals to three subgroups (strong, weak and tighter, and weak and pronated feet) according to the findings of seven clinical tests based on measurements of range of motion, flexibility, strength, and FPI (Selfe et al., 2015). There was no kinematic screening or in particular FPPA screening in Selfe and colleagues study. FPPA is one of the main outcome measures in the current study and was able to identify the individuals who are at risk of PFP development and demonstrate greater dynamic knee valgus during movement, which is a result of contribution several factors have been discussed in chapter 2.

However, the recommendation of the current study is in agreement with Selfe et al., (2015) study and the participants should be divided according to the findings into three groups such as: overweight, weak hip abductors, and high knee valgus deducted using the FPPA during SLL. Therefore, the results (A) include all three groups of participants (i.e. overweight, weak hip abductors, and high knee valgus), the results (B) and (C) only include the high knee valgus group, which was identified using the FPPA during SLL and was also found in all the three result sets, with no inclusion for overweight or muscle weakness groups.

Therefore, according to the findings of the current study, future military strategy, with regard to injury prevention or mitigation programmes, should start earlier than basic military training with a preparation programme that includes general screening and, in particular, muscle strength and FPPA during SLL assessment; doing so would help to identify individuals who are at high risk of PFP development and to subgroup them into an injury prevention strategy. The preparation programme should contain, for instance, a weight loss programme for overweight participants, muscle strengthening for weaker participants, and education or feedback for individuals with high FPPA. This programme will help to reduce the risk of injury and increase the capability of participants to deal with the high loads of basic military training.

This study has a number of limitations. A main limitation of this investigation is that the cohort population does not represent the general population and the results are not generalisable. In this sense, the results are only applicable to young active males. Another limitation is the small number of injured participants relative to the average number of previous studies. This could be due to several factors, the first of which relates to the mindset of injured participants; in this sense, injury or tolerance of injury is seen as part of basic military training and participants may try to avoid raising a complaint or visiting the clinic because it may affect their military

service profiles. Another reason may be that injury registration is potentially not of the same quality in the three cohorts but as this was controlled by the principal investigator, it is difficult to determine how this could be improved.

5.6. Conclusion

In conclusion, PFP results from the contribution of several risk factors. In this sense, the risk of injury increases with the presence of an increased number of risk factors. However, some of these risk factors are modifiable and can be managed. In injury prevention programmes, there is a need within large-scale screening to identify individuals who are at high risk of PFP development. In the current investigation, we observed that participants who developed PFP had a greater mass, BMI, mass normalised to height, FPPA, and dynamic Q-angle during all three tasks, as well as a greater HADD during SLS and SLL and lower hip abductor and knee extensor muscle strength during baseline measurements. We also observed that the baseline measures of knee valgus displacement, $\geq 5.2^\circ$, as measured by 2D FPPA analysis during SLL tasks, were predictive of PFP. Therefore, these findings may provide injury prevention programmes with a simple and evidence-based test to identify individuals who are at risk of PFP development in young adult males.

CHAPTER 6

Overall discussion, conclusion, and suggestions for future work

6.1. Overall discussion

Patellofemoral pain is one of the most common sources of chronic knee pain in young athletes (Brody and Thein, 1998; Piva et al., 2006), accounting for 25 to 40% of all the knee joint problems that have been investigated in sports medicine clinics (Rubin and Collins, 1980; Chesworth et al., 1989; Bizzini et al., 2003). Patellofemoral pain is a major problem among physically active populations, such as adolescents, young adults, and military recruits (Messier et al., 1991; Cutbill et al., 1997; Duffey et al., 2000; Witvrouw et al., 2000; Laprade et al., 2003; Powers et al., 2003; Thijs et al., 2007). There is evidence from retrospective studies that the condition may be related to biomechanical factors, such as kinematic, kinetic, and strengthening abnormalities. However, with a retrospective design, it is difficult to determine whether the risk factors are the cause or the consequence of the condition. To progress further in this field, prospective studies are therefore needed in order to gain a better understanding of the biomechanical risk factors of PFP and to develop future treatment and prevention.

Motion analysis and strengthening assessment techniques are widely used in sports medicine research in order to investigate the risk of injuries. Due to the high accuracy and reliability of 3D analysis in quantifying kinematic variables and of isokinetic dynamometers for muscle strength measurements, they are widely used in athletic tasks. In fact, this method is considered as the gold standard for this type of analysis. However, in injury prevention programmes, there is a need for large-scale screening within the field in order to identify high-risk athletes.

Therefore, while 3D analysis and isokinetic dynamometers should ideally be used, they are not practical for use in large-screening programmes due to the required space and extra time needed for marker placement. A method is therefore needed that allows for the quick collection of data in a relatively small volume; in this regard, 2D analysis and HHDs may provide an alternative solution to 3D measurement and isokinetic dynamometers (Martine et al., 2006; Munro et al 2012; Kim et al., 2014).

This thesis has offered a novel insight into the use of 2D analysis and a stabilised HHD in the kinematic and isometric muscle strength assessment of lower limbs in order to provide clinicians and researchers with alternative tools to 3D analysis and isokinetic dynamometers, which are portable, cheaper, and easy to use in large-scale screening programmes for

prospectively examining individuals for PFP development in addition to the other lower limb injuries. In order to effectively investigate this issue, three main aspects were explored in this thesis. The first aspect was identifying the limitations and the gaps in the literature relating to the biomechanical risk factors of PFP and measurement tools (Chapters 2 and 3). The second aspect was assessing the reliability and validity of 2D analysis and the HHD in kinematic and isometric muscle strength measurements against the gold standard of 3D measurement using Visual3D or QTM and isokinetic dynamometers (Chapters 4). Finally, the third aspect related to the prospective investigation of the biomechanical risk factors of PFP and other lower limb injuries during basic military training (Chapter 5).

This thesis reviewed prospective studies associated with the risk factors of PFP and ran a meta-analysis as a part of the investigation to detect the gaps in the literature (Chapters 2 and 3). Several issues were addressed from reviewing the literature. In this sense, some of the studies are based on the use of advanced technology, so they are not practical for large-scale screening (Stefanyshyn et al., 2006; Boling et al., 2009; Myer et al., 2010). Further, the results of some studies were not generalisable (Myer et al., 2010) because they were based on static measurements (Witvrouw et al., 2000; Thijs et al., 2011) or were only focused on a single factor or only observed a single task (Van Tiggelen et al., 2009; Thijs et al., 2011). None of the previous prospective studies reported on their reliability, and there is a lack of validation for the measurement tools (Boling et al., 2009; Thijs et al., 2011), as well as a low incidence rate of PFP in some of the studies (Boling et al., 2009). Only one recent study used 2D analysis in knee valgus displacement during DVJ landing in adolescent females.

The results of the meta-analysis show that weaker hip abductor and knee extensor strength appear to be risk factors for PFP, which support the results of two similar studies (Lankhorst et al., 2012; Pappas & Wong-Tom, 2012), who concluded that low knee extensor muscle strength may be a risk factor for developing PFP. Both of these studies reviewed a limited number of studies. Although there were a significant number of prospective studies included in the systematic review and meta-analysis, there was a limited number of pooled variables for each risk factor, with conflicting evidence in some cases or significant heterogeneity in others. As a result of the review, 2D analysis with a stabilised HHD was chosen to assess the isometric muscle strength and kinematics of the lower limbs during SLS, SLL, and running as unilateral limb screening tasks. However, the reliability and validity of measurements using 2D and an HHD were assessed in Chapters 4 before starting the measurements of the prospective study.

Within-day, between-day, intra-tester, and, for the first time, inter-rater reliabilities of 2D FPPA were assessed in Chapter 4. The results of the reliability assessment for 2D FPPA demonstrated excellent within-session reliability and good between-session reliability during all three tasks, supporting the results previously reported for SLS and SLL (Willson et al., 2006; Munro et al., 2012; Gwynne & Curran, 2014), with ICC values of 0.72 and 0.88 respectively. The within- and between-session reliability of 2D FPPA during running over ground was not reported before this study. It was expected that the within-session reliability would be greater than that of between-session reliability, likely due to factors such as a greater increase of marker placement error and the greater possibility of within-subject performance variation in between-session when compared to within-session.

Intra- and inter-rater reliability leads to a better understanding of the source of measurement error and could be reduced by increasing the constancy of the experimenter's measurements. The ICC values for the intra- and inter-rater reliability assessment of 2D FPPA were excellent during all of the three tasks. Associated SEM values for intra- and inter-rater reliability ranged from 0.79 – 2.76 and 0.48 – 1.26, respectively, across the three tasks. This low SEM value indicates that the experimenter's measurement error contributed minimally to the overall measurement error. This study has been published in the *Journal of Electromyography and Kinesiology*, April 2017.

This thesis examined the validity of FPPA and HADD using 2D analysis and compared it to the gold standard of a 3D motion-capture QTM system for lower limb kinematic variables using Visual3D (Chapter 4). The validity results show a large correlation between FPPA using 2D measurement and knee abduction ($r=0.654$; $p=0.008$) and a very large correlation between HADD using 2D measurement and hip adduction angle with 3D measurement ($r=0.836$; $p<0.001$) during SLS. A very significant correlation was found between 2D HADD and hip adduction angle using 3D measurements during SLL ($r=0.733$; $p=0.002$). Despite the variation between the tasks in this study and some of the previous studies, there is agreement between this study and other previous studies. The association between 2D analysis for FPPA and 3D knee abduction angle in these studies ranged from moderate to large, and the correlation between 2D analysis for HADD and 3D hip adduction angle ranged from large to very large (McLean et al., 2005; Willson & Davis, 2008; Gwynne & Curran, 2014; Sorenson et al., 2015).

Due to the low association between 2D and 3D measurements for FPPA during SLL and RUN, this study presents the hypothesis that this may be due to the variation between the two systems using Visual 3D software for 3D, which may be affected with joints definition, particularly in determining hip joint. In order to investigate this relationship in the second section, 3D markers for 2D marker placements were therefore employed in order to look at the same markers simultaneously with the two systems.

Several previous studies have investigated the relationship between 2D and 3D FPPA during multiple functional tasks (McLean et al., 2005; Willson & Davis, 2008; Gwynne & Curran, 2014; Maykut et al., 2015; Sorenson et al., 2015).

In this thesis, the validity and reliability of 2D analysis, compared to the gold standard of 3D, without using Visual3D for lower limb kinematics, and stabilised HHD, compared to the gold standard of isokinetic dynamometers for knee extensor and hip abductor muscle strength, were tested in Chapter 4 before use for large-scale screening. In the validity assessment of this study, we looked at both 2D and 3D systems with the same markers and at the same time and avoided the use of Visual3D. This method was based on, for the first time, the use of 3D retro-reflective markers for 3D and 2D marker placements. Surprisingly, a very significant correlation was found between the 2D and 3D systems in all the kinematic variables during tasks. The results suggest that 2D measurements for the frontal and sagittal plane are highly correlated with the gold standard of 3D capture. However, despite significant results regarding the validity of 2D measurements, it is not reflective of the actual motion of a moving limb due to absence of measurement in the transverse plane.

This thesis attempted to employ, for first time, 2D analysis for quantifying FPPA and other lower limb kinematics, in addition to a stabilised HHD for muscle strength assessment, in large-scale screening for PFP development, instead of using 3D measurements and an isokinetic dynamometer. This was the main study in Chapter 5. The incidence of PFP in this study is nearly identical to that (12%) reported in a study of younger female (12.9±0.34 years) adolescent athletes (Holden et al., 2015). However, the population for the current study was young adult male cadets and recruits in basic military training, and the PFP incidence was less than that of the majority of previous studies in the military population (Milgrom et al., 1991; Van Tiggelen, 2004; Thijs et al., 2007; Duvigneaud et al., 2008; Van Tiggelen et al., 2009). This may be due to the below diagnosis that may affect the number of diagnosed injuries.

In the current investigation, we firstly analysed all of the three investigated groups together and observed that, in the baseline measurements, the injured group had significantly greater FPPA, Q-angle, and HADD during the three screening tasks, with the exception of HADD during running. Knee extensor and hip abductor muscle strengths were significantly lower in the injured individuals in the baseline assessments. Additionally, there were significant differences in mass-related variables between individuals who developed PFP and those who did not. In addition, mass, BMI, and mass normalised to height were significantly greater in the PFP group when compared to non-injured group.

In the current thesis, we employed, for the first time, 2D FPPA and other lower limb kinematics during single leg tasks for large-scale screening in order to investigate the development of PFP during basic military training. FPPA was significantly greater in the PFP group during the three tasks, which means an increase of knee valgus. Increases of FPPA, and HADD are two of the risk factors that contribute to an increase in dynamic knee valgus, which, in previous research, has been associated with the development of PFP (Powers, 2010; Willson & Davis, 2008). A $FPPA \geq 5.2$ degrees during SLL predicted the development of PFP.

The results of the current study are in agreement with those of Holden et al. (2015), whose research established a relationship between knee valgus displacement and the development of PFP in adolescent females. In their cohort study, they found that $\geq 10.6^\circ$ of knee valgus displacement during DVJ is associated with the risk of PFP development. Myer et al. (2010) conducted a similar study to Holden et al. (2015), using 3D capture. Participants who developed PFP had a significantly greater knee abduction moment. In this sense, a knee abduction moment ≥ 15.4 Nm was associated with the risk of PFP development. The author theorised that this increase in knee abduction moment may be associated with an increase in knee abduction angle. However, both studies used bilateral DVJ tasks in adolescent females, which may not have the same level of muscle activation as unilateral tasks. In addition, Myer et al. (2010) used 3D capture, which may not provide a practical method for large-scale screening.

The results of this study support the finding of previous studies that PFP is a multifactorial condition that cannot be predicted by a single risk factor. This statement is also supported by result sets (A), (B), and (C) in Chapter 5, Section 5.4. The increase of dynamic knee valgus reported in the current study supports the results of Holden et al. (2015), which is the only other study to have used 2D capture in the investigation of knee valgus during DVJ (Holden et al.,

2015). Individuals who have greater dynamic knee valgus may be at a higher risk of developing PFP, and this risk may increase with an increase of BMI or lower limb muscle strength.

The current study lends support to the body of evidence that the development of PFP is multifactorial and may involve a variety of biomechanical factors. The evidence indicates that the occurrence of PFP is higher in participants who demonstrated greater FPPA and that there is some indication that the relationship may be causal.

6.2. Conclusion

PFP is a multifactorial condition that affects a significant number of young adults and athletes and which may lead to serious complications and chronic diseases, such as osteoarthritis. Therefore, there is a need to identify the individuals who are at high risk of this condition in order to prevent injury and develop treatment programmes. The current research was able to detect differences between the injured and non-injured groups in kinematic variables and muscle strength variables, at the same time as noting differences between mass-related variables. We found that participants who developed PFP had a greater mass, BMI, mass normalised to height, FPPA, and dynamic Q-angle during the three tasks, as well as greater HADD during SLS and SLL and lower hip abductor and knee extensor muscle strength during baseline measurements. We also found that the baseline measures of knee valgus displacement $\geq 5.3^\circ$, as measured by 2D FPPA analysis during SLL tasks, were predictive of PFP. These findings will help to identify those who are at risk of PFP development with simple, portable, and low-cost measurement tools, leading to the development of injury prevention programmes.

Contribution to literature

- **This research has offered the first epidemiological study in musculoskeletal lower limb injuries among the Saudi military population during basic military training. This will help as a reference for future strategy plans in injury treatment and prevention within the Saudi military population.**
- **This research has provided the researchers with a simple, cheap, and portable, evidence based as a valid and reliable assessment tools (2D and HHD) for kinematic and strength measurements. As alternative tools in the absence of 3D and isokinetic dynamometer and for large scale screening.**
- **This research has also offered 2D FPPA during SLL as a simple measurement approach that may help health practitioners and coaches to identify the individuals who are at risk of developing PFP, and could be used in large scale screening.**
- **An additional fruitful advantage is that it provided off-the-shelf norms for several elements in the Saudi young male population in some lower limb kinematics that measured with 2D during SLS, SLL, and RUN, and isometric muscle strength of hip abductors and knee extensors that measured with HHD.**
- **These norms can be highly beneficial for health practitioners and coaches in injury prevention or mitigating programmes**
- **Finally, the screening protocol of this study will be implemented into Saudi Army as standard practice.**

Suggestions for future work

The findings of this thesis bring about several recommendations for future research. Firstly, from the results of the reliability and validity study in chapter 4, it is recommended that 2D capture and HHD are appropriate instruments for large-scale screening programmes and for investigating the predisposed risk factors associated with dynamic knee valgus that cause the development of PFP.

The FPPA, HADD, and dynamic Q-angle during SLS, SLL, and RUN and hip abductor and knee extensor muscle strength assessments were able to distinguish between the subjects who developed PFP and those who did not. An increase in knee valgus was identified with quantifying FPPA during SLL tasks as the greatest predictor for PFP development. Therefore, it is recommended that these measures should be used for future studies in conditions related to an increase of dynamic knee valgus.

The results in chapter 5 show that PFP is a multifactorial condition resulting from the contribution of several factors, such as mass-related factors, muscle weakness of knee extensors and hip abductors, and the increase of dynamic knee valgus. Therefore, it is recommended that future studies should be based on randomised control trial design with several military units over Saudi Arabia and screen the participants with 2D FPPA during SLL and HHD for hip abductors and knee extensors muscle strength and categorise subjects according to the findings in baseline assessments. Intervention programmes should be based on the findings of baseline assessments, which should be grouped according to subjects with muscle weakness and those with greater knee valgus. Interventions should be as pre-training programme aim to increase muscle strength for the group with muscle weakness and decrease knee valgus in the group with greater valgus. Such interventions should evaluate whether interventions aiming to increase hip abductor and knee extensor muscle strength and decrease dynamic knee valgus could prevent or mitigate the development of PFP in basic military training. Additionally, it is recommended that to divide the participants to two homogenous groups: intervention group, with intervention programme before the start of the training and control group, without intervention programme with consideration to reassess the target variables of the intervention during the follow up or at least at the end of the prospective studies.

References

- Agel, J., Evans, T. A., Dick, R., Putukian, M., & Marshall, S. W. (2007). Descriptive epidemiology of collegiate men's soccer injuries: National Collegiate Athletic Association Injury Surveillance System, 1988–1989 through 2002–2003. *J Athl Train*, 42(2), 270.
- Aglietti, P., Insall, J. N., & Cerulli, G. (1983). Patellar pain and incongruence. I: Measurements of incongruence. *Clin Orthop Relat Res*(176), 217-224.
- Agre, J., Magness, J., Hull, S., Wright, K., Baxter, T., Patterson, R., & Stradel, L. (1987). Strength testing with a portable dynamometer: reliability for upper and lower extremities. *Arch Phys Med Rehabil*, 68(7), 454-457.
- Al-Rawi, Z., & Nessim, A. (1997). Joint hypermobility in patients with chondromalacia patellae. *Rheumatology*, 36(12), 1324-1327.
- Alenezi, F., Herrington, L., Jones, P., & Jones, R. (2014). The reliability of biomechanical variables collected during single leg squat and landing tasks. *Journal of Electromyography and Kinesiology*, 24(5), 718-721.
- Aliberti, S., Costa, M. S. X., Passaro, A. C., Arnese, A. C., & Sacco, I. C. N. (2010). Medial contact and smaller plantar loads characterize individuals with Patellofemoral Pain Syndrome during stair descent. *Physical Therapy In Sport: Official Journal Of The Association Of Chartered Physiotherapists In Sports Medicine*, 11(1), 30-34. doi:10.1016/j.ptsp.2009.11.001
- Almeida, S. A., Trone, D. W., Leone, D. M., Shaffer, R. A., Patheal, S. L., & Long, K. (1999). Gender differences in musculoskeletal injury rates: A function of symptom reporting? *Med Sci Sports Exerc*, 31(12), 1807-1812.
- Altman, A. R., & Davis, I. S. (2016). Prospective comparison of running injuries between shod and barefoot runners. *British Journal of Sports Medicine*, 50(8), 476-U451. doi:10.1136/bjsports-2014-094482
- Aminaka, N., & Gribble, P. A. (2008). Patellar taping, patellofemoral pain syndrome, lower extremity kinematics, and dynamic postural control. *J Athl Train*, 43(1), 21-28.
- Anderson, G., & Herrington, L. (2003). A comparison of eccentric isokinetic torque production and velocity of knee flexion angle during step down in patellofemoral pain syndrome patients and unaffected subjects. *Clin Biomech (Bristol, Avon)*, 18(6), 500-504.
- Anh-Dung, N., Boling, M. C., Slye, C. A., Hartley, E. M., & Parisi, G. L. (2013). Various Methods for Assessing Static Lower Extremity Alignment: Implications for Prospective Risk-Factor Screenings. *Journal of Athletic Training*, 48(2), 248-257. doi:10.4085/1062-6050-48.2.08
- Arroll, B., Ellis-Pegler, E., Edwards, A., & Sutcliffe, G. (1997). Patellofemoral pain syndrome: a critical review of the clinical trials on nonoperative therapy. *Am J Sports Med*, 25(2), 207-212.
- Åström, M., & Arvidson, T. (1995). Alignment and joint motion in the normal foot. *Journal of Orthopaedic & Sports Physical Therapy*, 22(5), 216-222.
- Atkin, K., Herrington, L., Alenezi, F., Jones, P., & Jones, R. (2014). The relationship between 2d knee valgus angle during single leg squat (sls), single leg landing (sll), and forward running. *Br J Sports Med*, 48(7), 563-563.

- Attal, N., Masselin-Dubois, A., Martinez, V., Jayr, C., Albi, A., Fermanian, J., . . . Baudic, S. (2014). Does cognitive functioning predict chronic pain? Results from a prospective surgical cohort. *Brain*, 137(Pt 3), 904-917. doi:10.1093/brain/awt354
- Baker, V., Bennell, K., Stillman, B., Cowan, S., & Crossley, K. (2002). Abnormal knee joint position sense in individuals with patellofemoral pain syndrome. *Journal of Orthopaedic Research*, 20(2), 208-214.
- Bartlett, R., Bussey, M., & Flyger, N. (2006). Movement variability cannot be determined reliably from no-marker conditions. *J Biomech*, 39(16), 3076-3079.
- Barton, C. J., Bonanno, D., Levinger, P., & Menz, H. B. (2010). Foot and ankle characteristics in patellofemoral pain syndrome: a case control and reliability study. *J Orthop Sports Phys Ther*, 40(5), 286-296. doi:10.2519/jospt.2010.3227
- Barton, C. J., Levinger, P., Crossley, K. M., Webster, K. E., & Menz, H. B. (2012). The relationship between rearfoot, tibial and hip kinematics in individuals with patellofemoral pain syndrome. *Clinical Biomechanics*, 27(7), 702-705. doi:10.1016/j.clinbiomech.2012.02.007
- Barton, C. J., Levinger, P., Crossley, K. M., Webster, K. E., & Menz, H. B. (2012). The relationship between rearfoot, tibial and hip kinematics in individuals with patellofemoral pain syndrome. *Clin Biomech (Bristol, Avon)*, 27(7), 702-705. doi:10.1016/j.clinbiomech.2012.02.007
- Barton, C. J., Levinger, P., Menz, H. B., & Webster, K. E. (2009). Kinematic gait characteristics associated with patellofemoral pain syndrome: A systematic review. *Gait Posture*, 30(4), 405-416. doi:10.1016/j.gaitpost.2009.07.109
- Barton, C. J., Levinger, P., Menz, H. B., & Webster, K. E. (2009). Kinematic gait characteristics associated with patellofemoral pain syndrome: a systematic review. *Gait Posture*, 30(4), 405-416. doi:10.1016/j.gaitpost.2009.07.109
- Bassey, E., & Harries, U. (1993). Normal values for handgrip strength in 920 men and women aged over 65 years, and longitudinal changes over 4 years in 620 survivors. *Clinical science*, 84(3), 331-337.
- Baumgartner, T. A. (1989). Norm-referenced measurement: reliability. *Measurement concepts in physical education and exercise science*, 20, 45-47.
- Beaulieu, F. G., Pelland, L., & Robertson, D. G. E. (2008). Kinetic analysis of forwards and backwards stair descent. *Gait Posture*, 27(4), 564-571.
- Berry, P. A., Hanna, F. S., Teichtahl, A. J., Wluka, A. E., Urquhart, D. M., Bell, R. J., . . . Cicuttini, F. M. (2008). Vastus medialis cross-sectional area is associated with patella cartilage defects and bone volume in healthy women. *Osteoarthritis Cartilage*, 16(8), 956-960. doi:10.1016/j.joca.2007.11.011
- Besier, T. F., Fredericson, M., Gold, G. E., Beaupré, G. S., & Delp, S. L. (2009). Knee muscle forces during walking and running in patellofemoral pain patients and pain-free controls. *J Biomech*, 42(7), 898-905.
- Besier, T. F., Gold, G. E., Delp, S. L., Fredericson, M., & Beaupré, G. S. (2008). The influence of femoral internal and external rotation on cartilage stresses within the patellofemoral joint. *Journal of Orthopaedic Research*, 26(12), 1627-1635.

- Bizzini, M., Childs, J. D., Piva, S. R., & Delitto, A. (2003). Systematic review of the quality of randomized controlled trials for patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, 33(1), 4-20.
- Blacker, S. D., Wilkinson, D. M., Bilzon, J. L., & Rayson, M. P. (2008). Risk factors for training injuries among British Army recruits. *Mil Med*, 173(3), 278-286.
- Bolgia, L. A., & Boling, M. C. (2011). An update for the conservative management of patellofemoral pain syndrome: a systematic review of the literature from 2000 to 2010. *Int J Sports Phys Ther*, 6(2).
- Bolgia, L. A., Malone, T. R., Umberger, B. R., & Uhl, T. L. (2008). Hip strength and hip and knee kinematics during stair descent in females with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther*, 38(1), 12-18. doi:10.2519/jospt.2008.2462
- Boling, M. C., Padua, D. A., Marshall, S. W., Guskiewicz, K., Pyne, S., & Beutler, A. (2009a). A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *Am J Sports Med*, 37(11), 2108-2116. doi:10.1177/0363546509337934
- Boling, M. C., Padua, D. A., Marshall, S. W., Guskiewicz, K., Pyne, S., & Beutler, A. (2009). A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *Am J Sports Med*, 37(11), 2108-2116. doi:10.1177/0363546509337934
- Boling, M. C., Padua, D. A., Marshall, S. W., Guskiewicz, K., Pyne, S., & Beutler, A. (2009b). A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *American Journal of Sports Medicine*, 37(11), 2108-2116. doi:10.1177/0363546509337934
- Bout-Tabaku, S., Shults, J., Zemel, B. S., Leonard, M. B., Berkowitz, R. I., Stettler, N., & Burnham, J. M. (2015). Obesity is associated with greater valgus knee alignment in pubertal children, and higher body mass index is associated with greater variability in knee alignment in girls. *J Rheumatol*, 42(1), 126-133. doi:10.3899/jrheum.131349
- Brennan, S. L., Cicuttini, F. M., Shortreed, S., Forbes, A., Jones, G., Stuckey, S. L., & Wluka, A. E. (2010). Women lose patella cartilage at a faster rate than men: a 4.5-year cohort study of subjects with knee OA. *Maturitas*, 67(3), 270-274. doi:10.1016/j.maturitas.2010.07.008
- Brindle, T. J., Mattacola, C., & McCrory, J. (2003). Electromyographic changes in the gluteus medius during stair ascent and descent in subjects with anterior knee pain. *Knee Surgery, Sports Traumatology, Arthroscopy*, 11(4), 244-251.
- Brinkmann, J. R. (1994). Comparison of a hand-held and fixed dynamometer in measuring strength of patients with neuromuscular disease. *Journal of Orthopaedic & Sports Physical Therapy*, 19(2), 100-104.
- Brody, L. T., & Thein, J. M. (1998). Nonoperative treatment for patellofemoral pain. *J Orthop Sports Phys Ther*, 28(5), 336-344. doi:10.2519/jospt.1998.28.5.336
- Brody, L. T., & Thein, J. M. (1998). Nonoperative treatment for patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy*, 28(5), 336-344.
- Brukner, P. (2012). *Brukner & Khan's clinical sports medicine*: McGraw-Hill North Ryde.

- Buchbinder, M., Napora, N., & Biggs, E. (1979). The relationship of abnormal pronation to chondromalacia of the patella in distance runners. *Journal of the American Podiatry Association*, 69(2), 159.
- Callaghan, M., & Baltzopoulos, V. (1994). Gait analysis in patients with anterior knee pain. *Clin Biomech (Bristol, Avon)*, 9(2), 79-84.
- Callaghan, M., & Oldham, J. (2004). Quadriceps atrophy: to what extent does it exist in patellofemoral pain syndrome? *Br J Sports Med*, 38(3), 295-299.
- Callaghan, M. J., & Baltzopoulos, V. (1994). Gait analysis in patients with anterior knee pain. *Clin Biomech (Bristol, Avon)*, 9(2), 79-84. doi:10.1016/0268-0033(94)90028-0
- Callaghan, M. J., & Selfe, J. (2007). Has the incidence or prevalence of patellofemoral pain in the general population in the United Kingdom been properly evaluated? *Physical Therapy in Sport*, 8(1), 37-43.
- Cameron, K. L., & Owens, B. D. (2016). *Musculoskeletal Injuries in the Military*: Springer.
- Cappozzo, A., Catani, F., Della Croce, U., & Leardini, A. (1995). Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin Biomech (Bristol, Avon)*, 10(4), 171-178.
- Carey, D. L., Blanch, P., Ong, K.-L., Crossley, K. M., Crow, J., & Morris, M. E. (2016). Training loads and injury risk in Australian football—differing acute: chronic workload ratios influence match injury risk. *Br J Sports Med*, bjsports-2016-096309.
- Caylor, D., Fites, R., & Worrell, T. W. (1993). The relationship between quadriceps angle and anterior knee pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, 17(1), 11-16.
- Cervellin, M., de Girolamo, L., Bait, C., Denti, M., & Volpi, P. (2012). Autologous platelet-rich plasma gel to reduce donor-site morbidity after patellar tendon graft harvesting for anterior cruciate ligament reconstruction: a randomized, controlled clinical study. *Knee Surgery, Sports Traumatology, Arthroscopy: Official Journal Of The ESSKA*, 20(1), 114-120. doi:10.1007/s00167-011-1570-5
- Chen, Y.-J., & Powers, C. M. (2010). The dynamic quadriceps angle: A comparison of persons with and without patellofemoral pain. *J Orthop Sports Phys Ther*, 40, A24-A25.
- Chesworth, B. M., Culham, E., Tata, G. E., & Peat, M. (1989). Validation of outcome measures in patients with patellofemoral syndrome. *J Orthop Sports Phys Ther*, 10(8), 302-308.
- Christian, S. R., Anderson, M. B., Workman, R., Conway, W. F., & Pope, T. L. (2006). Imaging of anterior knee pain. *Clin Sports Med*, 25(4), 681-702.
- Claiborne, T. L., Armstrong, C. W., Gandhi, V., & Pincivero, D. M. (2006). Relationship between hip and knee strength and knee valgus during a single leg squat. *J Appl Biomech*, 22(1), 41-50.
- Collins, N. J., Bierma-Zeinstra, S. M., Crossley, K. M., van Linschoten, R. L., Vicenzino, B., & van Middelkoop, M. (2013). Prognostic factors for patellofemoral pain: a multicentre observational analysis. *British Journal of Sports Medicine*, 47(4), 227-233. doi:10.1136/bjsports-2012-091696
- Coppieters, M., Stappaerts, K., Janssens, K., & Jull, G. (2002). Reliability of detecting 'onset of pain' and 'submaximal pain' during neural provocation testing of the upper quadrant. *Physiotherapy Research International*, 7(3), 146-156.

- Cowan, D. N., Jones, B. H., Frykman, P. N., Polly Jr, D. W., Harman, E. A., Rosenstein, R. M., & Rosenstein, M. T. (1996). Lower limb morphology and risk of overuse injury among male infantry trainees. *Med Sci Sports Exerc*, 28(8), 945-952.
- Cowan, S. M., Bennell, K. L., Crossley, K. M., Hodges, P. W., & McConnell, J. (2002). Physical therapy alters recruitment of the vasti in patellofemoral pain syndrome. *Med Sci Sports Exerc*, 34(12), 1879-1885. doi:10.1249/01.MSS.0000038893.30443.CE
- Cowan, S. M., Bennell, K. L., Hodges, P. W., Crossley, K. M., & McConnell, J. (2001). Delayed onset of electromyographic activity of vastus medialis obliquus relative to vastus lateralis in subjects with patellofemoral pain syndrome. *Arch Phys Med Rehabil*, 82(2), 183-189.
- Crossley, K., Bennell, K., Green, S., Cowan, S., & McConnell, J. (2002). Physical therapy for patellofemoral pain A randomized, double-blinded, placebo-controlled trial. *Am J Sports Med*, 30(6), 857-865.
- Crossley, K., Bennell, K., Green, S., Cowan, S., & McConnell, J. (2002). Physical therapy for patellofemoral pain: a randomized, double-blinded, placebo-controlled trial. *Am J Sports Med*, 30(6), 857-865.
- Crossley, K., Bennell, K., Green, S., & McConnell, J. (2001). A systematic review of physical interventions for patellofemoral pain syndrome. *Clinical Journal of Sport Medicine*, 11(2), 103-110.
- Crossley, K. M., Cowan, S. M., Bennell, K. L., & McConnell, J. (2004). Knee flexion during stair ambulation is altered in individuals with patellofemoral pain. *Journal of Orthopaedic Research*, 22(2), 267-274.
- Crossley, K. M., van Middelkoop, M., Callaghan, M. J., Collins, N. J., Rathleff, M. S., & Barton, C. J. (2016). 2016 Patellofemoral pain consensus statement from the 4th International Patellofemoral Pain Research Retreat, Manchester. Part 2: recommended physical interventions (exercise, taping, bracing, foot orthoses and combined interventions). *Br J Sports Med*, 50(14), 844-852.
- Cumps, E., Verhagen, E., & Meeusen, R. (2007). Prospective epidemiological study of basketball injuries during one competitive season: ankle sprains and overuse knee injuries. *J Sports Sci Med*, 6(2), 204-211.
- Davies, A. P., Costa, M. L., Donnell, S. T., Glasgow, M. M., & Shepstone, L. (2000a). The sulcus angle and malalignment of the extensor mechanism of the knee. *Journal of Bone & Joint Surgery, British Volume*, 82(8), 1162-1166.
- Davies, A. P., Costa, M. L., Donnell, S. T., Glasgow, M. M., & Shepstone, L. (2000b). The sulcus angle and malalignment of the extensor mechanism of the knee. *Bone & Joint Journal*, 82(8), 1162-1166.
- Davis, I. S. (2007). Running: A threshold for injury. *Faseb Journal*, 21(5), A83-A83.
- Davis, I. S., Bowser, B. J., & Mullineaux, D. R. (2016). Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation. *British Journal of Sports Medicine*, 50(14), 887-U129. doi:10.1136/bjsports-2015-094579
- Davis, I. S., & Powers, C. (2010). Patellofemoral Pain Syndrome: Proximal, Distal, and Local Factors—International Research Retreat, April 30–May 2, 2009, Baltimore, Maryland. *Journal of Orthopaedic & Sports Physical Therapy*, 40(3), A1-A48.

- de Oliveira Silva, D., Briani, R. V., Pazzinatto, M. F., Gonçalves, A. V., Ferrari, D., Aragão, F. A., & de Azevedo, F. M. (2015). Q-angle static or dynamic measurements, which is the best choice for patellofemoral pain? *Clin Biomech (Bristol, Avon)*, 30(10), 1083-1087.
- Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clin Biomech (Bristol, Avon)*, 18(7), 662-669.
- DeHaven, K. E., & Lintner, D. M. (1986). Athletic injuries: comparison by age, sport, and gender. *Am J Sports Med*, 14(3), 218-224.
- Dempster, W. T., Gabel, W. C., & Felts, W. J. (1959). The anthropometry of the manual work space for the seated subject. *American journal of physical anthropology*, 17(4), 289-317.
- Denegar, C. R., & Ball, D. W. (1993). Assessing reliability and precision of measurement: an introduction to intraclass correlation and standard error of measurement. *J Sport Rehabil*, 2(1), 35-42.
- Devereaux, M., & Lachmann, S. (1984). Patello-femoral arthralgia in athletes attending a Sports Injury Clinic. *Br J Sports Med*, 18(1), 18-21.
- Devereaux, M. D., & Lachmann, S. M. (1984). Patello-femoral arthralgia in athletes attending a Sports Injury Clinic. *Br J Sports Med*, 18(1), 18-21.
- Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. S. (2008). Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther*, 38(8), 448-456. doi:10.2519/jospt.2008.2490
- Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. S. (2008). Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *Journal of Orthopaedic & Sports Physical Therapy*, 38(8), 448-456.
- Dileep, K., Harish, K., & Mohammed, R. P. (2017). Correlation of rearfoot angle to Q-angle in patellofemoral pain syndrome: a prospective study. *International Journal of Research in Orthopaedics*, 3(4), 688-691.
- Dingenen, B., Malfait, B., Nijs, S., Peers, K. H. E., Vereecken, S., Verschueren, S. M. P., & Staes, F. F. (2015). Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study. *Clinical Biomechanics*, 30(8), 781-787. doi:10.1016/j.clinbiomech.2015.06.013
- Dorotka, R., Boj, E. J., Kypta, A., & Kollar, B. (2002). [Patellofemoral pain syndrome in young men compared to a normal population exposed to the same physical strain]. *Z Orthop Ihre Grenzgeb*, 140(1), 48-51. doi:10.1055/s-2002-22091
- Dowling, G. J., Murley, G. S., Munteanu, S. E., Smith, M. M. F., Neal, B. S., Griffiths, I. B., . . . Collins, N. J. (2014). Dynamic foot function as a risk factor for lower limb overuse injury: a systematic review. *J Foot Ankle Res*, 7(1), 53-53. doi:10.1186/s13047-014-0053-6
- Draper, C. E., Besier, T. F., Santos, J. M., Jennings, F., Fredericson, M., Gold, G. E., . . . Delp, S. L. (2009). Using real-time MRI to quantify altered joint kinematics in subjects with patellofemoral pain and to evaluate the effects of a patellar brace or sleeve on joint motion. *Journal of Orthopaedic Research*, 27(5), 571-577.

- Drouin, J. M., Valovich-mcLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European journal of applied physiology*, 91(1), 22-29.
- Duffey, M. J., Martin, D. F., Cannon, D. W., Craven, T., & Messier, S. P. (2000a). Etiologic factors associated with anterior knee pain in distance runners. *Med Sci Sports Exerc*, 32(11), 1825-1832.
- Duffey, M. J., Martin, D. F., Cannon, D. W., Craven, T., & Messier, S. P. (2000b). Etiologic factors associated with anterior knee pain in distance runners. *Medicine & Science in Sports & Exercise*, 32(11), 1825-1832.
- Duvigneaud, N., Bernard, E., Stevens, V., Witvrouw, E., & Van Tiggelen, D. (2008a). Isokinetic assessment of patellofemoral pain syndrome: a prospective study in female recruits. *Isokinetics & Exercise Science*, 16(4), 213-219.
- Duvigneaud, N., Bernard, E., Stevens, V., Witvrouw, E., & Van Tiggelen, D. (2008b). Isokinetic assessment of patellofemoral pain syndrome: A prospective study in female recruits. *Isokinetics and Exercise Science*, 16(4), 213-219.
- Dwyer, M. K., Boudreau, S. N., Mattacola, C. G., Uhl, T. L., & Lattermann, C. (2010). Comparison of lower extremity kinematics and hip muscle activation during rehabilitation tasks between sexes. *J Athl Train*, 45(2), 181-190.
- Earl, J. E., Hertel, J. N., & Denegar, C. R. (2010). Patterns of dynamic malalignment, muscle activation, joint motion, and patellofemoral-pain syndrome. *JSR*, 14(3).
- Echegoyen, S., Acuna, E., & Rodriguez, C. (2010). Injuries in students of three different dance techniques. *Med Probl Perform Art*, 25(2), 72-74.
- Edwards, R., & McDonnell, M. (1974). Hand-held dynamometer for evaluating voluntary-muscle function. *The Lancet*, 304(7883), 757-758.
- Elias, D., & White, L. (2004). Imaging of patellofemoral disorders. *Clinical radiology*, 59(7), 543-557.
- Emami, M.-J., Ghahramani, M.-H., Abdinejad, F., & Namazi, H. (2007). Q-angle: an invaluable parameter for evaluation of anterior knee pain. *Arch Iran Med*, 10(1), 24-26.
- Eng, J. J., & Pierrynowski, M. R. (1993). Evaluation of soft foot orthotics in the treatment of patellofemoral pain syndrome. *Phys Ther*, 73(2), 62-68; discussion 68-70.
- Farrokhi, S., Keyak, J., & Powers, C. (2011). Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: a finite element analysis study. *Osteoarthritis and Cartilage*, 19(3), 287-294.
- Faude, O., Junge, A., Kindermann, W., & Dvorak, J. (2005). Injuries in female soccer players a prospective study in the german national league. *Am J Sports Med*, 33(11), 1694-1700.
- Finnoff, J. T., Hall, M. M., Kyle, K., Krause, D. A., Lai, J., & Smith, J. (2011). Hip strength and knee pain in high school runners: a prospective study. *PM & R: The Journal Of Injury, Function, And Rehabilitation*, 3(9), 792-801. doi:10.1016/j.pmrj.2011.04.007
- Finnoff, J. T., Hall, M. M., Kyle, K., Krause, D. A., Lai, J., & Smith, J. (2011). Hip strength and knee pain in high school runners: a prospective study. *PM&R*, 3(9), 792-801.
- Fong, C.-M., Blackburn, J. T., Norcross, M. F., McGrath, M., & Padua, D. A. (2011). Ankle-dorsiflexion range of motion and landing biomechanics. *J Athl Train*, 46(1), 5-10.

- Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*, 35(10), 1745-1750. doi:10.1249/01.MSS.0000089346.85744.D9
- Ford, K. R., Myer, G. D., & Hewett, T. E. (2007). Reliability of landing 3D motion analysis: implications for longitudinal analyses. *Medicine & Science in Sports & Exercise*, 39(11), 2021-2028.
- Frese, E., Brown, M., & Norton, B. J. (1987). Clinical reliability of manual muscle testing: middle trapezius and gluteus medius muscles. *Phys Ther*, 67(7), 1072-1076.
- Fulkerson, J., & Shea, K. (1990a). Disorders of patellofemoral alignment. *JBJS*, 72(9), 1424-1429.
- Fulkerson, J., & Shea, K. (1990b). Disorders of patellofemoral alignment. *The Journal of Bone & Joint Surgery*, 72(9), 1424-1429.
- Fulkerson, J. P. (1983). The etiology of patellofemoral pain in young, active patients: a prospective study. *Clin Orthop Relat Res*, 179, 129-133.
- Fulkerson, J. P. (2002). Diagnosis and treatment of patients with patellofemoral pain. *Am J Sports Med*, 30(3), 447-456.
- Fulkerson, J. P., & Arendt, E. A. (2000). Anterior knee pain in females. *Clin Orthop Relat Res*, 372, 69-73.
- Fulkerson, J. P., Buuck, D. A., & Post, W. R. (2004). *Disorders of the patellofemoral joint*: Lippincott Williams & Wilkins Philadelphia.
- Gabbett, T. J. (2016). The training-injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med*, bjsports-2015-095788.
- Gagnon, D., Nadeau, S., Gravel, D., Robert, J., Bélanger, D., & Hilsenrath, M. (2005). Reliability and validity of static knee strength measurements obtained with a chair-fixed dynamometer in subjects with hip or knee arthroplasty. *Arch Phys Med Rehabil*, 86(10), 1998-2008.
- Graci, V., & Salsich, G. B. (2015). Trunk and lower extremity segment kinematics and their relationship to pain following movement instruction during a single-leg squat in females with dynamic knee valgus and patellofemoral pain. *Journal of Science and Medicine in Sport*, 18(3), 343-347.
- Greeves, J. (2001). Physical training of women in the military. *J Defence Science*, 6, 228-238.
- Gross, M. T., & Foxworth, J. L. (2003). The role of foot orthoses as an intervention for patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), 661-670.
- Gwynne, C. R., & Curran, S. A. (2014). QUANTIFYING FRONTAL PLANE KNEE MOTION DURING SINGLE LIMB SQUATS: RELIABILITY AND VALIDITY OF 2-DIMENSIONAL MEASURES. *Int J Sports Phys Ther*, 9(7), 898.
- Haim, A., Yaniv, M., Dekel, S., & Amir, H. (2006). Patellofemoral pain syndrome: validity of clinical and radiological features. *Clin Orthop Relat Res*, 451, 223-228. doi:10.1097/01.blo.0000229284.45485.6c
- Hamill, J., Bates, B. T., & Holt, K. G. (1992). Timing of lower extremity joint actions during treadmill running. *Med Sci Sports Exerc*, 24(7), 807-813.

- Hanna, F. S., Bell, R. J., Davis, S. R., Wluka, A. E., Teichtahl, A. J., O'Sullivan, R., & Cicuttini, F. M. (2007). Factors affecting patella cartilage and bone in middle-aged women. *Arthritis Rheum*, 57(2), 272-278. doi:10.1002/art.22535
- Hansen, E. M., McCartney, C. N., Sweeney, R. S., Palimenio, M. R., & Grindstaff, T. L. (2015). Hand-held Dynamometer Positioning Impacts Discomfort During Quadriceps Strength Testing: A Validity and Reliability Study. *Int J Sports Phys Ther*, 10(1), 62.
- Hargrave, M. D., Carcia, C. R., Gansneder, B. M., & Shultz, S. J. (2003). Subtalar pronation does not influence impact forces or rate of loading during a single-leg landing. *J Athl Train*, 38(1), 18.
- Harilainen, A., Lindroos, M., Sandelin, J., Tallroth, K., & Kujala, U. (2005). Patellofemoral relationships and cartilage breakdown. *Knee Surgery, Sports Traumatology, Arthroscopy*, 13(2), 142-144.
- Harvill, L. M. (1991). Standard error of measurement. *Educational Measurement: issues and practice*, 10(2), 33-41.
- Hayes, K. W., & Falconer, J. (1992). Reliability of hand-held dynamometry and its relationship with manual muscle testing in patients with osteoarthritis in the knee. *Journal of Orthopaedic & Sports Physical Therapy*, 16(3), 145-149.
- Herbst, K. A., Barber Foss, K. D., Fader, L., Hewett, T. E., Witvrouw, E., Stanfield, D., & Myer, G. D. (2015). Hip Strength Is Greater in Athletes Who Subsequently Develop Patellofemoral Pain. *Am J Sports Med*, 43(11), 2747-2752. doi:10.1177/0363546515599628
- Herrington, L. (2014). Knee valgus angle during single leg squat and landing in patellofemoral pain patients and controls. *Knee*, 21(2), 514-517.
- Herrington, L., Alenezi, F., Alzhrani, M., Alrayani, H., & Jones, R. (2017). The reliability and criterion validity of 2D video assessment of single leg squat and hop landing. *Journal of Electromyography and Kinesiology*, 34, 80-85.
- Herrington, L., Hatcher, J., Hatcher, A., & McNicholas, M. (2009). A comparison of Star Excursion Balance Test reach distances between ACL deficient patients and asymptomatic controls. *Knee*, 16(2), 149-152. doi:10.1016/j.knee.2008.10.004
- Herrington, L., Munro, A., & Comfort, P. (2015). A preliminary study into the effect of jumping–landing training and strength training on frontal plane projection angle. *Man Ther*, 20(5), 680-685.
- Hetsroni, I., Finestone, A., Milgrom, C., Ben Sira, D., Nyska, M., Radeva-Petrova, D., & Ayalon, M. (2006). Prospective biomechanical study of the association between foot pronation and the incidence of anterior knee pain among military recruits. *Journal of Bone and Joint Surgery-British Volume*, 88B(7), 905-908. doi:10.1302/0301-620x.88b7.17826
- Hetsroni, I., Finestone, A., Milgrom, C., Sira, D. B., Nyska, M., Radeva-Petrova, D., & Ayalon, M. (2006). A prospective biomechanical study of the association between foot pronation and the incidence of anterior knee pain among military recruits. *Bone & Joint Journal*, 88(7), 905-908.
- Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., McLean, S. G., . . . Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus

- loading of the knee predict anterior cruciate ligament injury risk in female athletes. *Am J Sports Med*, 33(4), 492-501.
- Higgins, J. P., Thompson, S. G., Deeks, J. J., & Altman, D. G. (2003). Measuring inconsistency in meta-analyses. *BMJ: British Medical Journal*, 327(7414), 557.
- Holden, S., Boreham, C., Doherty, C., & Delahunt, E. (2015). Two-dimensional knee valgus displacement as a predictor of patellofemoral pain in adolescent females. *Scand J Med Sci Sports*. doi:10.1111/sms.12633
- Hollman, J. H., Ginos, B. E., Kozuchowski, J., Vaughn, A. S., Krause, D. A., & Youdas, J. W. (2009). Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *J Sport Rehabil*, 18(1), 104-117.
- Holmbäck, A. M., Porter, M., Downham, D., & Lexell, J. (1999). Reliability of isokinetic ankle dorsiflexor strength measurements in healthy young men and women. *Scand J Rehabil Med*, 31(4), 229-239.
- Holmbäck, A. M., Porter, M. M., Downham, D., & Lexell, J. (1999). Reliability of isokinetic ankle dorsiflexor strength measurements in healthy young men and women. *Scand J Rehabil Med*, 31(4), 229-239.
- Hopkins, W., Marshall, S., Batterham, A., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine+ Science in Sports+ Exercise*, 41(1), 3.
- Hsiang-Ling, T., Macleod, T. D., Link, T. M., Majumdar, S., & Souza, R. B. (2015). Higher Knee Flexion Moment During the Second Half of the Stance Phase of Gait Is Associated With the Progression of Osteoarthritis of the Patellofemoral Joint on Magnetic Resonance Imaging. *Journal of Orthopaedic & Sports Physical Therapy*, 45(9), 656-664. doi:10.2519/jospt.2015.5859
- Huang, B. Y., Shih, Y. F., Chen, W. Y., & Ma, H. L. (2015). Predictors for identifying patients with patellofemoral pain syndrome responding to femoral nerve mobilization. *Arch Phys Med Rehabil*, 96(5), 920-927. doi:10.1016/j.apmr.2015.01.001
- Huberti, H., & Hayes, W. (1984). Patellofemoral contact pressures. The influence of q-angle and tendofemoral contact. *JBJS*, 66(5), 715-724.
- Hulin, B. T., Gabbett, T. J., Lawson, D. W., Caputi, P., & Sampson, J. A. (2016). The acute: chronic workload ratio predicts injury: high chronic workload may decrease injury risk in elite rugby league players. *Br J Sports Med*, 50(4), 231-236.
- Hume, P., Hopkins, W., Rome, K., Maulder, P., Coyle, G., & Nigg, B. (2008). Effectiveness of foot orthoses for treatment and prevention of lower limb injuries. *Sports Med*, 38(9), 759-779.
- Ieiri, A., Tushima, E., Ishida, K., Inoue, M., Kanno, T., & Masuda, T. (2015). Reliability of measurements of hip abduction strength obtained with a hand-held dynamometer. *Physiother Theory Pract*, 31(2), 146-152.
- Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther*, 33(11), 671-676. doi:10.2519/jospt.2003.33.11.671
- Jacobs, C. A., Uhl, T. L., Mattacola, C. G., Shapiro, R., & Rayens, W. S. (2007). Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train*, 42(1), 76.

- James, S., Bates, B., & Osternig, L. (1978). Injuries to runners. *American Journal of Sports Medicine*, 6(2), 40-50.
- Johansson, K. M., & Adolfsson, L. E. (2005). Intraobserver and interobserver reliability for the strength test in the Constant-Murley shoulder assessment. *Journal of shoulder and elbow surgery*, 14(3), 273-278.
- Kagaya, Y., Fujii, Y., & Nishizono, H. (2013). Association between hip abductor function, rear-foot dynamic alignment, and dynamic knee valgus during single-leg squats and drop landings. *Journal of Sport and Health Science*.
- Kastelein, M., Luijsterburg, P. A. J., Heintjes, E. M., van Middelkoop, M., Verhaar, J. A. N., Koes, B. W., & Bierma-Zeinstra, S. M. A. (2015). The 6-year trajectory of non-traumatic knee symptoms (including patellofemoral pain) in adolescents and young adults in general practice: a study of clinical predictors. *British Journal of Sports Medicine*, 49(6), 400-405. doi:10.1136/bjsports-2014-093557
- Katoh, M. (2015). Test-retest reliability of isometric shoulder muscle strength measurement with a handheld dynamometer and belt. *J Phys Ther Sci*, 27(6), 1719-1722.
- Katoh, M., Hiragi, Y., & Uchida, M. (2011). Validity of isometric muscle strength measurements of the lower limbs using a hand-held dynamometer and belt: a comparison with an isokinetic dynamometer. *J Phys Ther Sci*, 23(4), 553-557.
- Katoh, M., & Yamasaki, H. (2009a). Comparison of reliability of isometric leg muscle strength measurements made using a hand-held dynamometer with and without a restraining belt. *J Phys Ther Sci*, 21(1), 37-42.
- Katoh, M., & Yamasaki, H. (2009b). Test-retest reliability of isometric leg muscle strength measurements made using a hand-held dynamometer restrained by a belt: comparisons during and between sessions. *J Phys Ther Sci*, 21(3), 239-243.
- Kawaguchi, J., & Babcock, G. (2010). Validity and reliability of handheld dynamometric strength assessment of hip extensor and abductor muscles. *Athl Training & Sports Health Care*, 2, 11-17.
- Kawaguchi, J. K., & Babcock, G. (2010). Validity and reliability of handheld dynamometric strength assessment of hip extensor and abductor muscles. *Athletic Training and Sports Health Care*, 2(1), 11-17.
- Kirtley, C. (2006). *Clinical gait analysis: theory and practice*: Elsevier Health Sciences.
- Knapik, J. J., Steelman, R., Grier, T., Graham, B., Hoedebecke, K., Rankin, S., . . . Jones, B. H. (2011). Military parachuting injuries, associated events, and injury risk factors. *Aviation, space, and environmental medicine*, 82(8), 797-804.
- Kramer, J. F., Vaz, M. D., & Vandervoort, A. A. (1991). Reliability of isometric hip abductor torques during examiner-and belt-resisted tests. *Journal of gerontology*, 46(2), M47-M51.
- Krebs, D. E., Edelstein, J. E., & Fishman, S. (1985). Reliability of observational kinematic gait analysis. *Phys Ther*, 65(7), 1027-1033.
- Kropmans, T. J., Dijkstra, P., Stegenga, B., Stewart, R., & De Bont, L. (1999). Smallest detectable difference in outcome variables related to painful restriction of the temporomandibular joint. *Journal of dental research*, 78(3), 784-789.

- Kuh, D., Bassey, J., Hardy, R., Aihie Sayer, A., Wadsworth, M., & Cooper, C. (2002). Birth weight, childhood size, and muscle strength in adult life: evidence from a birth cohort study. *American Journal of Epidemiology*, 156(7), 627-633.
- Kuhman, D. J., Paquette, M. R., Peel, S. A., & Melcher, D. A. (2016). Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners. *Human Movement Science*, 47, 9-15. doi:10.1016/j.humov.2016.01.013
- Lankhorst, N. E., Bierma-Zeinstra, S. M. A., & van Middelkoop, M. (2012). Risk factors for patellofemoral pain syndrome: a systematic review. *J Orthop Sports Phys Ther*, 42(2), 81-94. doi:10.2519/jospt.2012.3803
- Lankhorst, N. E., Bierma-Zeinstra, S. M. A., & Van Middelkoop, M. (2012). Risk factors for patellofemoral pain syndrome: A systematic review. *Journal of Orthopaedic and Sports Physical Therapy*, 42(2), 81-A12.
- Laprade, J., & Culham, E. (2003). Radiographic measures in subjects who are asymptomatic and subjects with patellofemoral pain syndrome. *Clin Orthop Relat Res*, 414, 172-182.
- Lee, T. Q., Morris, G., & Csintalan, R. P. (2003). The influence of tibial and femoral rotation on patellofemoral contact area and pressure. *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), 686-693.
- Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core stability measures as risk factors for lower extremity injury in athletes. *Medicine and Science in Sports and Exercise*, 36(6), 926-934. doi:10.1249/01.mss.0000128145.75199.c3
- Lehr, M. E., Plisky, P. J., Butler, R. J., Fink, M. L., Kiesel, K. B., & Underwood, F. B. (2013). Field-expedient screening and injury risk algorithm categories as predictors of noncontact lower extremity injury. *Scand J Med Sci Sports*, 23(4), e225-e232. doi:10.1111/sms.12062
- Lephart, S. M., Ferris, C. M., Riemann, B. L., Myers, J. B., & Fu, F. H. (2002). Gender differences in strength and lower extremity kinematics during landing. *Clin Orthop Relat Res*, 401, 162-169.
- Levine, J. (1979). Chondromalacia patellae. *Phys Sportsmed*, 7, 41-49.
- Levinger, P., & Gilleard, W. (2004). An evaluation of the rearfoot posture in individuals with patellofemoral pain syndrome. *J Sports Sci Med*, 3(YISI 1), 8-14.
- Levinger, P., & Gilleard, W. (2007). Tibia and rearfoot motion and ground reaction forces in subjects with patellofemoral pain syndrome during walking. *Gait Posture*, 25(1), 2-8. doi:10.1016/j.gaitpost.2005.12.015
- Li, G., DeFrate, L., Zayontz, S., Park, S., & Gill, T. (2004). The effect of tibiofemoral joint kinematics on patellofemoral contact pressures under simulated muscle loads. *Journal of Orthopaedic Research*, 22(4), 801-806.
- Linenger, J., & West, L. (1992). Epidemiology of soft-tissue/musculoskeletal injury among US Marine recruits undergoing basic training. *Mil Med*, 157(9), 491-493.
- Livingston, L. A. (1998). The quadriceps angle: a review of the literature. *Journal of Orthopaedic & Sports Physical Therapy*, 28(2), 105-109.
- Loudon, J. K., Gajewski, B., Goist-Foley, H. L., & Loudon, K. L. (2004). The effectiveness of exercise in treating patellofemoral-pain syndrome. *J Sport Rehabil*, 13(4), 323-342.

- Luedke, L. E., Heiderscheit, B. C., Williams, D., & Rauh, M. J. (2016). Influence of Step Rate on Shin Injury and Anterior Knee Pain in High School Runners. *Med Sci Sports Exerc*, 48(7), 1244-1250.
- Luedke, L. E., Heiderscheit, B. C., Williams, D. S., & Rauh, M. J. (2016). Influence of Step Rate on Shin Injury and Anterior Knee Pain in High School Runners. *Med Sci Sports Exerc*, 48(7), 1244-1250. doi:10.1249/mss.0000000000000890
- Lun, V., Meeuwisse, W. H., Stergiou, P., & Stefanyshyn, D. (2004). Relation between running injury and static lower limb alignment in recreational runners. *Br J Sports Med*, 38(5), 576-580.
- Magalhães, E., Fukuda, T. Y., Sacramento, S. N., Forgas, A., Cohen, M., & Abdalla, R. J. (2010). A comparison of hip strength between sedentary females with and without patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, 40(10), 641-647.
- Malfait, B., Sankey, S., Azidin, R. F. R., Deschamps, K., Vanrenterghem, J., Robinson, M. A., . . . Verschueren, S. (2014). How reliable are lower-limb kinematics and kinetics during a drop vertical jump. *Med Sci Sports Exerc*, 46(4), 678-685.
- Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clin Biomech (Bristol, Avon)*, 16(5), 438-445.
- Malone, S., Owen, A., Newton, M., Mendes, B., Collins, K. D., & Gabbett, T. J. (2017). The acute: chronic workload ratio in relation to injury risk in professional soccer. *Journal of Science and Medicine in Sport*, 20(6), 561-565.
- Mann, K., Edwards, S., Drinkwater, E. J., & Bird, S. (2013). A lower limb assessment tool for athletes at risk of developing patellar tendinopathy.
- Manske, R. C., & Davies, G. J. (2016). Examination of the patellofemoral joint. *Int J Sports Phys Ther*, 11(6), 831.
- Martin, H. J., Yule, V., Syddall, H. E., Dennison, E. M., Cooper, C., & Aihie Sayer, A. (2006). Is hand-held dynamometry useful for the measurement of quadriceps strength in older people? A comparison with the gold standard Bodex dynamometry. *Gerontology*, 52(3), 154-159. doi:10.1159/000091824
- Martins, J., da Silva, J. R., da Silva, M. R. B., & Bevilacqua-Grossi, D. (2017). Reliability and Validity of the Belt-Stabilized Handheld Dynamometer in Hip-and Knee-Strength Tests. *J Athl Train*, 52(9), 809-819.
- Massada, M., Aido, R., Magalhães, C., & Puga, N. (2011). Dynamic quadriceps angle: a comparison of female elite volleyball players with and without patellofemoral pain syndrome. *Br J Sports Med*, 45(6), 537-537.
- Maykut, J. N., Taylor-Haas, J. A., Paterno, M. V., DiCesare, C. A., & Ford, K. R. (2015). CONCURRENT VALIDITY AND RELIABILITY OF 2D KINEMATIC ANALYSIS OF FRONTAL PLANE MOTION DURING RUNNING. *Int J Sports Phys Ther*, 10(2), 136.
- McClay, I., & Manal, K. (1998). A comparison of three-dimensional lower extremity kinematics during running between excessive pronators and normals. *Clin Biomech (Bristol, Avon)*, 13(3), 195-203.

- McClinton, S., Donatell, G., Weir, J., & Heiderscheit, B. (2007). Influence of step height on quadriceps onset timing and activation during stair ascent in individuals with patellofemoral pain syndrome. *Journal of Orthopaedic & Sports Physical Therapy*, 37(5), 239-244.
- McConnell, J. (1986). The management of chondromalacia patellae: a long term solution. *Australian journal of physiotherapy*, 32(4), 215-223.
- McConnell, J. (1996). Management of patellofemoral problems. *Man Ther*, 1(2), 60-66.
- McLean, S. G., Walker, K., Ford, K. R., Myer, G. D., Hewett, T. E., & van den Bogert, A. J. (2005). Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *Br J Sports Med*, 39(6), 355-362. doi:10.1136/bjsm.2005.018598
- McLeish, R., & Charnley, J. (1970). Abduction forces in the one-legged stance. *J Biomech*, 3(2), 191IN7195-7194IN9209.
- McNair, P. J., & Prapavessis, H. (1999). Normative data of vertical ground reaction forces during landing from a jump. *Journal of Science and Medicine in Sport*, 2(1), 86-88.
- Melicharek, A., Miller, M. K., & Hazzard, J. (2011). *A COMPARISON OF THE BILATERAL, DYNAMIC Q-ANGLE IN FEMALES*. Paper presented at the ISBS-Conference Proceedings Archive.
- Messier, S. P., Davis, S. E., Curl, W. W., Lowery, R. B., & Pack, R. J. (1991). Etiologic factors associated with patellofemoral pain in runners. *Med Sci Sports Exerc*, 23(9), 1008-1015.
- Milgrom, C., Finestone, A., Eldad, A., & Shlamkovitch, N. (1991a). Patellofemoral pain caused by overactivity. A prospective study of risk factors in infantry recruits. *J Bone Joint Surg Am*, 73(7), 1041-1043.
- Milgrom, C., Finestone, A., Eldad, A., & Shlamkovitch, N. (1991b). Patellofemoral pain caused by overactivity. A prospective study of risk factors in infantry recruits. *J Bone Joint Surg Am*, 73(7), 1041-1043.
- Milgrom, C., Kerem, E., Finestone, A., Eldad, A., & Shlamkovitch, N. (1991). Patellofemoral pain caused by overactivity. A prospective study of risk factors in infantry recruits. *Journal of Bone and Joint Surgery - Series A*, 73(7), 1041-1043.
- Mizuno, Y., Kumagai, M., Mattessich, S. M., Elias, J. J., Ramrattan, N., Cosgarea, A. J., & Chao, E. (2001). Q-angle influences tibiofemoral and patellofemoral kinematics. *Journal of Orthopaedic Research*, 19(5), 834-840.
- Mohtadi, N. (2001). Risk factors for patellofemoral pain syndrome in athletic young adults...Witvrouw E, Lysens R, Bellemans J, et al. Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. *Am J Sports Med* 2000;28:480-489. *Clinical Journal of Sport Medicine*, 11(2), 127-127.
- Molloy, J. M. (2016). Factors Influencing Running-Related Musculoskeletal Injury Risk Among US Military Recruits. *Mil Med*, 181(6), 512-523. doi:10.7205/milmed-d-15-00143
- Mucha, M. D., Caldwell, W., Schlueter, E. L., Walters, C., & Hassen, A. (2017). Hip abductor strength and lower extremity running related injury in distance runners: A systematic review. *Journal of Science and Medicine in Sport*, 20(4), 349-355.

- Munro, A., Herrington, L., & Carolan, M. (2012). Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *J Sport Rehabil*, 21(1), 7-11.
- Myer, G. D., Ford, K. R., Barber Foss, K. D., Goodman, A., Ceasar, A., Rauh, M. J., . . . Hewett, T. E. (2010). The incidence and potential pathomechanics of patellofemoral pain in female athletes. *Clinical Biomechanics (Bristol, Avon)*, 25(7), 700-707. doi:10.1016/j.clinbiomech.2010.04.001
- Myer, G. D., Ford, K. R., Barber Foss, K. D., Goodman, A., Ceasar, A., Rauh, M. J., . . . Hewett, T. E. (2010). The incidence and potential pathomechanics of patellofemoral pain in female athletes. *Clin Biomech (Bristol, Avon)*, 25(7), 700-707. doi:10.1016/j.clinbiomech.2010.04.001
- Myer, G. D., Ford, K. R., Di Stasi, S. L., Foss, K. D., Micheli, L. J., & Hewett, T. E. (2015). High knee abduction moments are common risk factors for patellofemoral pain (PFP) and anterior cruciate ligament (ACL) injury in girls: is PFP itself a predictor for subsequent ACL injury? *Br J Sports Med*, 49(2), 118-122. doi:10.1136/bjsports-2013-092536
- Myer, G. D., Ford, K. R., Foss, K. D., Rauh, M. J., Paterno, M. V., & Hewett, T. E. (2014). A predictive model to estimate knee-abduction moment: implications for development of a clinically applicable patellofemoral pain screening tool in female athletes. *J Athl Train*, 49(3), 389-398. doi:10.4085/1062-6050-49.2.17
- Myklebust, G., Maehlum, S., Holm, I., & Bahr, R. (1998). A prospective cohort study of anterior cruciate ligament injuries in elite Norwegian team handball. *Scand J Med Sci Sports*, 8(3), 149-153.
- Nakagawa, T., Serrão, F., Maciel, C., & Powers, C. (2013). Hip and knee kinematics are associated with pain and self-reported functional status in males and females with patellofemoral pain. *Int J Sports Med*, 34(11), 997-1002.
- Nakagawa, T. H., Maciel, C. D., & Serrão, F. V. (2015). Trunk biomechanics and its association with hip and knee kinematics in patients with and without patellofemoral pain. *Man Ther*, 20(1), 189-193.
- Natri, A., Kannus, P., & Järvinen, M. (1998). Which factors predict the long-term outcome in chronic patellofemoral pain syndrome? A 7-yr prospective follow-up study. *Medicine & Science in Sports & Exercise*.
- Nawoczenski, D. A., Saltzman, C. L., & Cook, T. M. (1998). The effect of foot structure on the three-dimensional kinematic coupling behavior of the leg and rear foot. *Phys Ther*, 78(4), 404-416.
- Neal, B. S., Barton, C. J., Gallie, R., O'Halloran, P., & Morrissey, D. (2016). Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: a systematic review and meta-analysis. *Gait Posture*, 45, 69-82.
- Neal, B. S., Griffiths, I. B., Dowling, G. J., Murley, G. S., Munteanu, S. E., Franettovich Smith, M. M., . . . Barton, C. J. (2014). Foot posture as a risk factor for lower limb overuse injury: a systematic review and meta-analysis. *J Foot Ankle Res*, 7(1), 55. doi:10.1186/s13047-014-0055-4
- Neumann, D. A. (2013). *Kinesiology of the Musculoskeletal System-E-Book: Foundations for Rehabilitation*: Elsevier Health Sciences.

- Nielsen, R. O., Parner, E. T., Nohr, E. A., Sorensen, H., Lind, M., & Rasmussen, S. (2014). Excessive progression in weekly running distance and risk of running-related injuries: an association which varies according to type of injury. *J Orthop Sports Phys Ther*, 44(10), 739-747. doi:10.2519/jospt.2014.5164
- Noehren, B., & Davis, I. (2007). *Prospective study of the biomechanical factors associated with patellofemoral pain syndrome*. Paper presented at the American Society of Biomechanics Annual Meeting. Palo Alto, CA.
- Noehren, B., Hamill, J., & Davis, I. (2013). Prospective evidence for a hip etiology in patellofemoral pain. *Med Sci Sports Exerc*, 45(6), 1120-1124. doi:10.1249/MSS.0b013e31828249d2
- Noehren, B., Hamill, J., & Davis, I. (2013). Prospective Evidence for a Hip Etiology in Patellofemoral Pain. *Medicine and Science in Sports and Exercise*, 45(6), 1120-1124. doi:10.1249/MSS.0b013e31828249d2
- Norris, B. S., & Olson, S. L. (2011). Concurrent validity and reliability of two-dimensional video analysis of hip and knee joint motion during mechanical lifting. *Physiother Theory Pract*, 27(7), 521-530.
- Noyes, F. R., Barber-Westin, S. D., Fleckenstein, C., Walsh, C., & West, J. (2005). The drop-jump screening test. *Am J Sports Med*, 33(2), 197-207.
- Nunes, G. S., Stapait, E. L., Kirsten, M. H., de Noronha, M., & Santos, G. M. (2013). Clinical test for diagnosis of patellofemoral pain syndrome: Systematic review with meta-analysis. *Physical Therapy in Sport*, 14(1), 54-59.
- Olson, T. J., Chebny, C., Willson, J. D., Kernozek, T. W., & Straker, J. S. (2011). Comparison of 2D and 3D kinematic changes during a single leg step down following neuromuscular training. *Physical Therapy in Sport*, 12(2), 93-99.
- Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. (2007). Biomechanical differences between unilateral and bilateral landings from a jump: gender differences. *Clinical Journal of Sport Medicine*, 17(4), 263-268.
- Pappas, E., & Wong-Tom, W. M. (2012). Prospective Predictors of Patellofemoral Pain Syndrome: A Systematic Review With Meta-analysis. *Sports Health*, 4(2), 115-120. doi:10.1177/1941738111432097
- Peat, G., Duncan, R. C., Wood, L. R., Thomas, E., & Muller, S. (2012). Clinical features of symptomatic patellofemoral joint osteoarthritis. *Arthritis Res Ther*, 14(2), R63. doi:10.1186/ar3779
- Pengel, L. H., Herbert, R. D., Maher, C. G., & Refshauge, K. M. (2003). Acute low back pain: systematic review of its prognosis. *BMJ*, 327(7410), 323.
- Peterson-Kendall, F., Kendall-McCreary, E., Geise-Provance, P., McIntyre-Rodgers, M., & Romani, W. (2005). *Muscles testing and function with posture and pain*: Philadelphia: Lippincott Williams & Wilkins.
- Piva, S. R., Fitzgerald, K., Irrgang, J. J., Jones, S., Hando, B. R., Browder, D. A., & Childs, J. D. (2006). Reliability of measures of impairments associated with patellofemoral pain syndrome. *BMC Musculoskelet Disord*, 7, 33. doi:10.1186/1471-2474-7-33
- Piva, S. R., Fitzgerald, K., Irrgang, J. J., Jones, S., Hando, B. R., Browder, D. A., & Childs, J. D. (2006). Reliability of measures of impairments associated with patellofemoral pain syndrome. *BMC Musculoskelet Disord*, 7(1), 33.

- Piva, S. R., Goodnite, E. A., & Childs, J. D. (2005). Strength around the hip and flexibility of soft tissues in individuals with and without patellofemoral pain syndrome. *J Orthop Sports Phys Ther*, 35(12), 793-801. doi:10.2519/jospt.2005.35.12.793
- Pollard, C. D., Sigward, S. M., Ota, S., Langford, K., & Powers, C. M. (2006). The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clinical Journal of Sport Medicine*, 16(3), 223-227.
- Popovich, S. R. (2000). Adaptive control system with efficiently constrained adaptation: Google Patents.
- Post, W. R. (1999). Current concepts clinical evaluation of patients with patellofemoral disorders. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 15(8), 841-851.
- Powell, J. W., & Barber-Foss, K. D. (2000). Sex-related injury patterns among selected high school sports. *Am J Sports Med*, 28(3), 385-391.
- Powers, C. M. (1998). Rehabilitation of patellofemoral joint disorders: a critical review. *J Orthop Sports Phys Ther*, 28(5), 345-354. doi:10.2519/jospt.1998.28.5.345
- Powers, C. M. (2003). The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), 639-646.
- Powers, C. M. (2010). The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), 42-51.
- Powers, C. M. (2010). The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*, 40(2), 42-51. doi:10.2519/jospt.2010.3337
- Powers, C. M., Chen, P.-Y., Reischl, S. F., & Perry, J. (2002). Comparison of foot pronation and lower extremity rotation in persons with and without patellofemoral pain. *Foot Ankle Int*, 23(7), 634-640.
- Powers, C. M., Maffucci, R., & Hampton, S. (1995). Rearfoot posture in subjects with patellofemoral pain. *J Orthop Sports Phys Ther*, 22(4), 155-160. doi:10.2519/jospt.1995.22.4.155
- Powers, C. M., Ward, S. R., Fredericson, M., Guillet, M., & Shellock, F. G. (2003). Patellofemoral kinematics during weight-bearing and non-weight-bearing knee extension in persons with lateral subluxation of the patella: a preliminary study. *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), 677-685.
- Ramsgov, D., Barton, C., Nielsen, R. O., & Rasmussen, S. (2015). High Eccentric Hip Abduction Strength Reduces the Risk of Developing Patellofemoral Pain Among Novice Runners Initiating a Self-Structured Running Program: A 1-Year Observational Study. *Journal of Orthopaedic & Sports Physical Therapy*, 45(3), 153-161. doi:10.2519/jospt.2015.5091
- Rankin, G., & Stokes, M. (1998). Reliability of assessment tools in rehabilitation: an illustration of appropriate statistical analyses. *Clin Rehabil*, 12(3), 187-199.
- Rathleff, C. R., Olesen, J. L., Roos, E. M., Rasmussen, S., & Rathleff, M. S. (2013). Half of 12-15-year-olds with knee pain still have pain after one year. *Danish Medical Journal*, 60(11).

- Rathleff, M. S., Rathleff, C. R., Crossley, K. M., & Barton, C. J. (2014). Is hip strength a risk factor for patellofemoral pain? A systematic review and meta-analysis. *Br J Sports Med*, 48(14), 1088-1088. doi:10.1136/bjsports-2013-093305
- Rauh, M. J., Koepsell, T. D., Rivara, F. P., Rice, S. G., & Margherita, A. J. (2007). Quadriceps angle and risk of injury among high school cross-country runners. *Journal of Orthopaedic & Sports Physical Therapy*, 37(12), 725-733. doi:10.2519/jospt.2007.2453
- Rauh, M. J., Macera, C. A., Ji, M., & Wiksten, D. L. (2007). Subsequent injury patterns in girls' high school sports. *J Athl Train*, 42(4), 486.
- Rauh, M. J., Macera, C. A., Trone, D. W., Reis, J. P., & Shaffer, R. A. (2010). Selected static anatomic measures predict overuse injuries in female recruits. *Mil Med*, 175(5), 329-335.
- Reid, A., Birmingham, T. B., Stratford, P. W., Alcock, G. K., & Giffin, J. R. (2007). Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther*, 87(3), 337-349.
- Robinson, R. L., & Nee, R. J. (2007). Analysis of hip strength in females seeking physical therapy treatment for unilateral patellofemoral pain syndrome. *J Orthop Sports Phys Ther*, 37(5), 232-238. doi:10.2519/jospt.2007.2439
- Rubin, B., & Collins, R. (1980). Runner's knee. *Phys Sportsmed*, 8, 49-58.
- Rubin, B. D., & Collins, H. R. (1980). Runner's knee. *Phys Sportsmed*, 8(6), 47-58.
- Salsich, G. B., & Perman, W. H. (2007). Patellofemoral joint contact area is influenced by tibiofemoral rotation alignment in individuals who have patellofemoral pain. *J Orthop Sports Phys Ther*, 37(9), 521-528. doi:10.2519/jospt.2007.37.9.521
- Schache, A. G., Bennell, K. L., Blanch, P. D., & Wrigley, T. V. (1999). The coordinated movement of the lumbo-pelvic-hip complex during running: a literature review. *Gait Posture*, 10(1), 30-47.
- Sigward, S. M., Ota, S., & Powers, C. M. (2008). Predictors of frontal plane knee excursion during a drop land in young female soccer players. *Journal of Orthopaedic & Sports Physical Therapy*, 38(11), 661-667.
- Smidt, G. L., & Rogers, M. W. (1982). Factors contributing to the regulation and clinical assessment of muscular strength. *Phys Ther*, 62(9), 1283-1290.
- Smith, B. E., Selfe, J., Thacker, D., Hendrick, P., Bateman, M., Moffatt, F., . . . Logan, P. (2018). Incidence and prevalence of patellofemoral pain: A systematic review and meta-analysis. *PLoS One*, 13(1), e0190892.
- Smith, T. O., Hunt, N. J., & Donell, S. T. (2008). The reliability and validity of the Q-angle: a systematic review. *Knee Surgery, Sports Traumatology, Arthroscopy*, 16(12), 1068-1079.
- Soligard, T., Schwellnus, M., Alonso, J.-M., Bahr, R., Clarsen, B., Dijkstra, H. P., . . . Hutchinson, M. R. (2016). How much is too much?(Part 1) International Olympic Committee consensus statement on load in sport and risk of injury. *Br J Sports Med*, 50(17), 1030-1041.
- Song, C. Y., Lin, J. J., Jan, M. H., & Lin, Y. F. (2011). The role of patellar alignment and tracking in vivo: the potential mechanism of patellofemoral pain syndrome. *Phys Ther Sport*, 12(3), 140-147. doi:10.1016/j.ptsp.2011.04.004

10.1016/j.ptsp.2011.02.008

- Sorenson, B., Kernozek, T. W., Willson, J. D., Ragan, R., & Hove, J. (2015). Two-and three-dimensional relationships between knee and hip kinematic motion analysis: Single-leg drop-jump landings. *J Sport Rehabil*, 24(4), 363-372.
- Souza, R. B., & Powers, C. M. (2009a). Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *Journal of Orthopaedic & Sports Physical Therapy*, 39(1), 12-19.
- Souza, R. B., & Powers, C. M. (2009b). Predictors of hip internal rotation during running an Evaluation of hip strength and femoral structure in women with and without patellofemoral pain. *Am J Sports Med*, 37(3), 579-587.
- Stefanik, J. J., Zumwalt, A. C., Segal, N. A., Lynch, J. A., & Powers, C. M. (2013). Association between measures of patella height, morphologic features of the trochlea, and patellofemoral joint alignment: the MOST study. *Clinical Orthopaedics & Related Research*, 471(8), 2641-2648. doi:10.1007/s11999-013-2942-6
- Stefanyshyn, D. J., Stergiou, P., Lun, V. M., Meeuwisse, W. H., & Worobets, J. T. (2006). Knee angular impulse as a predictor of patellofemoral pain in runners. *Am J Sports Med*, 34(11), 1844-1851. doi:10.1177/0363546506288753
- Stefanyshyn, D. J., Stergiou, P., Lun, V. M. Y., Meeuwisse, W. H., & Worobets, J. T. (2006). Knee angular impulse as a predictor of patellofemoral pain in runners. *Am J Sports Med*, 34(11), 1844-1851.
- Stickler, L., Finley, M., & Gulgin, H. (2015). Relationship between hip and core strength and frontal plane alignment during a single leg squat. *Physical Therapy in Sport*, 16(1), 66-71.
- Symons, T. B., Vandervoort, A. A., Rice, C. L., Overend, T. J., & Marsh, G. D. (2005). Reliability of a single-session isokinetic and isometric strength measurement protocol in older men. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, 60(1), 114-119.
- Tenforde, A. S., Sayres, L. C., McCurdy, M. L., Collado, H., Sainani, K. L., & Fredericson, M. (2011). Overuse injuries in high school runners: lifetime prevalence and prevention strategies. *PM & R: The Journal Of Injury, Function, And Rehabilitation*, 3(2), 125-131. doi:10.1016/j.pmrj.2010.09.009
- Thijs, Y., De Clercq, D., Roosen, P., & Witvrouw, E. (2008a). Gait-related intrinsic risk factors for patellofemoral pain in novice recreational runners. *Br J Sports Med*, 42(6), 466-471. doi:10.1136/bjsm.2008.046649
- Thijs, Y., De Clercq, D., Roosen, P., & Witvrouw, E. (2008b). Gait-related intrinsic risk factors for patellofemoral pain in novice recreational runners. *British Journal of Sports Medicine*, 42(6), 466-471.
- Thijs, Y., Pattyn, E., Van Tiggelen, D., Rombaut, L., & Witvrouw, E. (2011a). Is Hip Muscle Weakness a Predisposing Factor for Patellofemoral Pain in Female Novice Runners? A Prospective Study. *American Journal of Sports Medicine*, 39(9), 1877-1882. doi:10.1177/0363546511407617
- Thijs, Y., Pattyn, E., Van Tiggelen, D., Rombaut, L., & Witvrouw, E. (2011). Is hip muscle weakness a predisposing factor for patellofemoral pain in female novice runners? A

- prospective study. *Am J Sports Med*, 39(9), 1877-1882. doi:10.1177/0363546511407617
- Thijs, Y., Pattyn, E., Van Tiggelen, D., Rombaut, L., & Witvrouw, E. (2011b). Is Hip Muscle Weakness a Predisposing Factor for Patellofemoral Pain in Female Novice Runners? A Prospective Study. *Am J Sports Med*, 39(9), 1877-1882. doi:10.1177/0363546511407617
- Thijs, Y., Tiggelen, D. V., Roosen, P., Clercq, D. D., & Witvrouw, E. (2007). A prospective study on gait-related intrinsic risk factors for patellofemoral pain. *Clinical Journal of Sport Medicine*, 17(6), 437-445. doi:10.1097/JSM.0b013e31815ac44f
- Thijs, Y., Van Tiggelen, D., Roosen, P., De Clercq, D., & Witvrouw, E. (2007a). A prospective study on gait-related intrinsic risk factors for patellofemoral pain. *Clinical Journal of Sport Medicine*, 17(6), 437-445.
- Thijs, Y., Van Tiggelen, D., Roosen, P., De Clercq, D., & Witvrouw, E. (2007b). A prospective study on gait-related intrinsic risk factors for patellofemoral pain. *Clin J Sport Med*, 17(6), 437-445. doi:10.1097/JSM.0b013e31815ac44f
- Thijs, Y., Van Tiggelen, D., Roosen, P., De Clercq, D., & Witvrouw, E. (2007). A prospective study on gait-related intrinsic risk factors for patellofemoral pain. *Clinical Journal Of Sport Medicine: Official Journal Of The Canadian Academy Of Sport Medicine*, 17(6), 437-445.
- Thomeé, R., Augustsson, J., & Karlsson, J. (1999). Patellofemoral pain syndrome: a review of current issues. *Sports Med*, 28(4), 245-262.
- Thorborg, K., Bandholm, T., & Hölmich, P. (2013). Hip-and knee-strength assessments using a hand-held dynamometer with external belt-fixation are inter-tester reliable. *Knee Surgery, Sports Traumatology, Arthroscopy*, 21(3), 550-555.
- Tiberio, D. (1987). The effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. *Journal of Orthopaedic & Sports Physical Therapy*, 9(4), 160-165.
- Utting, M. R., Davies, G., & Newman, J. H. (2005). Is anterior knee pain a predisposing factor to patellofemoral osteoarthritis? *Knee*, 12(5), 362-365. doi:10.1016/j.knee.2004.12.006
- Van Tiggelen, D., Cowan, S., Coorevits, P., Duvigneaud, N., & Witvrouw, E. (2009a). Delayed vastus medialis obliquus to vastus lateralis onset timing contributes to the development of patellofemoral pain in previously healthy men: a prospective study. *American Journal of Sports Medicine*, 37(6), 1099-1105. doi:10.1177/0363546508331135
- Van Tiggelen, D., Cowan, S., Coorevits, P., Duvigneaud, N., & Witvrouw, E. (2009). Delayed vastus medialis obliquus to vastus lateralis onset timing contributes to the development of patellofemoral pain in previously healthy men: a prospective study. *Am J Sports Med*, 37(6), 1099-1105. doi:10.1177/0363546508331135
- Van Tiggelen, D., Cowan, S., Coorevits, P., Duvigneaud, N., & Witvrouw, E. (2009b). Delayed vastus medialis obliquus to vastus lateralis onset timing contributes to the development of patellofemoral pain in previously healthy men: a prospective study. *Am J Sports Med*, 37(6), 1099-1105. doi:10.1177/0363546508331135
- Van Tiggelen, D., Witvrouw, E., Coorevits, P., Croisier, J., & Roget, P. (2004a). Analysis of isokinetic parameters in the development of anterior knee pain syndrome: a prospective study in a military setting. *Isokinetics & Exercise Science*, 12(4), 223-228.

- Van Tiggelen, D., Witvrouw, E., Coorevits, P., Croisier, J. L., & Roget, P. (2004b). Analysis of isokinetic parameters in the development of anterior knee pain syndrome: A prospective study in a military setting. *Isokinetics and Exercise Science*, 12(4), 223-228.
- Van Tulder, M., Furlan, A., Bombardier, C., Bouter, L., & Group, E. B. o. t. C. C. B. R. (2003). Updated method guidelines for systematic reviews in the cochrane collaboration back review group. *Spine*, 28(12), 1290-1299.
- Vasconcelos, R. A. d., Bevilaqua-Grossi, D., Shimano, A. C., Paccola, C. J., Salvini, T. F., Prado, C. L., . . . Wilson, A. (2009). Reliability and validity of a modified isometric dynamometer in the assessment of muscular performance in individuals with anterior cruciate ligament reconstruction. *Revista Brasileira de Ortopedia*, 44(3), 214-224.
- Wadsworth, C. T., Krishnan, R., Sear, M., Harrold, J., & Nielsen, D. H. (1987). Intrarater reliability of manual muscle testing and hand-held dynametric muscle testing. *Phys Ther*, 67(9), 1342-1347.
- Wagemakers, H. P. A., Luijsterburg, P. A. J., Heintjes, E. M., Berger, M. Y., Verhaar, J. A. N., Koes, B. W., & Bierma-Zeinstra, S. M. A. (2012). Predictors of persistent complaints after a knee injury in primary care. *British Journal of General Practice*, 62(601). doi:10.3399/bjgp12X653615
- Waryasz, G. R., & McDermott, A. Y. (2008). Patellofemoral pain syndrome (PFPS): a systematic review of anatomy and potential risk factors. *Dyn Med*, 7, 9. doi:10.1186/1476-5918-7-9
- Weiss, K., & Whatman, C. (2015). Biomechanics Associated with Patellofemoral Pain and ACL Injuries in Sports. *Sports Medicine*, 45(9), 1325-1337. doi:10.1007/s40279-015-0353-4
- Whatman, C., Hing, W., & Hume, P. (2011). Kinematics during lower extremity functional screening tests—Are they reliable and related to jogging? *Physical Therapy in Sport*, 12(1), 22-29.
- Widler, K. S., Glatthorn, J. F., Bizzini, M., Impellizzeri, F. M., Munzinger, U., Leunig, M., & Maffiuletti, N. A. (2009). Assessment of hip abductor muscle strength. A validity and reliability study. *JBJS*, 91(11), 2666-2672.
- Wikholm, J. B., & Bohannon, R. W. (1991). Hand-held dynamometer measurements: tester strength makes a difference. *Journal of Orthopaedic & Sports Physical Therapy*, 13(4), 191-198.
- Wilkinson, D. M., Rayson, M. P., & Bilzon, J. L. (2008). A physical demands analysis of the 24-week British Army Parachute Regiment recruit training syllabus. *Ergonomics*, 51(5), 649-662.
- Willson, J. D., Binder-Macleod, S., & Davis, I. S. (2008). Lower extremity jumping mechanics of female athletes with and without patellofemoral pain before and after exertion. *Am J Sports Med*, 36(8), 1587-1596. doi:10.1177/0363546508315592
- Willson, J. D., & Davis, I. S. (2008). Utility of the frontal plane projection angle in females with patellofemoral pain. *J Orthop Sports Phys Ther*, 38(10), 606-615. doi:10.2519/jospt.2008.2706

- Willson, J. D., Ireland, M. L., & Davis, I. (2006). Core strength and lower extremity alignment during single leg squats. *Med Sci Sports Exerc*, 38(5), 945-952. doi:10.1249/01.mss.0000218140.05074.fa
- Wilson, N. A., Press, J. M., Koh, J. L., Hendrix, R. W., & Zhang, L. Q. (2009). In vivo noninvasive evaluation of abnormal patellar tracking during squatting in patients with patellofemoral pain. *J Bone Joint Surg Am*, 91(3), 558-566. doi:10.2106/jbjs.g.00572
- Winter, D. A., Sidwall, H. G., & Hobson, D. A. (1974). Measurement and reduction of noise in kinematics of locomotion. *J Biomech*, 7(2), 157-159.
- Witvrouw, E., Callaghan, M. J., Stefanik, J. J., Noehren, B., Bazett-Jones, D. M., Willson, J. D., . . . McConnell, J. (2014). Patellofemoral pain: consensus statement from the 3rd International Patellofemoral Pain Research Retreat held in Vancouver, September 2013. *Br J Sports Med*, 48(6), 411-414.
- Witvrouw, E., Lysens, R., Bellemans, J., Cambier, D., & Vanderstraeten, G. (2000a). Intrinsic risk factors for the development of anterior knee pain in an athletic population - A two-year prospective study. *American Journal of Sports Medicine*, 28(4), 480-489.
- Witvrouw, E., Lysens, R., Bellemans, J., Cambier, D., & Vanderstraeten, G. (2000b). Intrinsic risk factors for the development of anterior knee pain in an athletic population. A two-year prospective study. *Am J Sports Med*, 28(4), 480-489.
- Woodland, L. H., & Francis, R. S. (1992). Parameters and comparisons of the quadriceps angle of college-aged men and women in the supine and standing positions. *Am J Sports Med*, 20(2), 208-211.
- Yeadon, M., Kato, T., & Kerwin, D. (1999). Measuring running speed using photocells. *J Sports Sci*, 17(3), 249-257.
- Yeow, C., Lee, P., & Goh, J. (2010). Sagittal knee joint kinematics and energetics in response to different landing heights and techniques. *Knee*, 17(2), 127-131.
- Yu, B., Gabriel, D., Noble, L., & An, K.-N. (1999). Estimate of the optimum cutoff frequency for the Butterworth low-pass digital filter. *J Appl Biomech*, 15(3), 318-329.
- Zazulak, B. T., Hewett, T. E., Reeves, N. P., Goldberg, B., & Cholewicki, J. (2007). Deficits in neuromuscular control of the trunk predict knee injury risk: a prospective biomechanical-epidemiologic study. *Am J Sports Med*, 35(7), 1123-1130. doi:10.1177/0363546507301585
- Zeller, B. L., McCrory, J. L., Ben Kibler, W., & Uhl, T. L. (2003). Differences in kinematics and electromyographic activity between men and women during the single-legged squat. *Am J Sports Med*, 31(3), 449-456.

Appendices

Appendix A

Additional Materials



Research, Innovation and Academic
Engagement Ethical Approval Panel

College of Health & Social Care
AD 101 Allerton Building
University of Salford
M6 6PU

T +44(0)161 295 2280
HSresearch@salford.ac.uk

www.salford.ac.uk/

10 August 2015

Dear Hasan,

RE: ETHICS APPLICATION HSCR15/40 – Within-day and between-days reliability and agreement of kinematic and isometric measurements using two different measurement techniques during athletic tasks

Based on the information you provided, I am pleased to inform you that application HSCR15/40 has been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible by contacting HSresearch@salford.ac.uk

Yours sincerely,

A handwritten signature in black ink, appearing to read 'Sue McAndrew'.

Sue McAndrew
Chair of the Research Ethics Panel

15 October 2015

Dear Hasan,

**RE: ETHICS APPLICATION HSCR 15-78 –Prospective Investigation of Biomechanical Risk Factors in
The Initiation of Patellofemoral Pain Syndrome**

Based on the information you provided, I am pleased to inform you that application HSCR15-78 has been approved.

If there are any changes to the project and/ or its methodology, please inform the Panel as soon as possible by contacting Health-ResearchEthics@salford.ac.uk

Yours sincerely,



Sue McAndrew
Chair of the Research Ethics Panel

NEWCASTLE - OTTAWA QUALITY ASSESSMENT SCALE COHORT STUDIES

Note: A study can be awarded a maximum of one star for each numbered item within the Selection and Outcome categories. A maximum of two stars can be given for Comparability

Selection

- 1) Representativeness of the exposed cohort
 - a) Truly representative of the average _____ (describe) in the community *
 - b) Somewhat representative of the average _____ in the community *
 - c) Selected group of users eg nurses, volunteers
 - d) No description of the derivation of the cohort
- 2) Selection of the non-exposed cohort
 - a) Drawn from the same community as the exposed cohort *
 - b) Drawn from a different source
 - c) No description of the derivation of the non-exposed cohort
- 3) Ascertainment of exposure
 - a) Secure record (eg surgical records) *
 - b) Structured interview *
 - c) Written self-report
 - d) No description
- 4) Demonstration that outcome of interest was not present at start of study
 - a) Yes *
 - b) No

Comparability

- 1) Comparability of cohorts on the basis of the design or analysis
 - a) Study controls for _____ (select the most important factor) *
 - b) Study controls for any additional factor * (This criteria could be modified to indicate specific control for a second important factor.)

Outcome

- 1) Assessment of outcome
 - a) Independent blind assessment *
 - b) Record linkage *
 - c) Self-report
 - d) No description
- 2) Was follow-up long enough for outcomes to occur
 - a) Yes (select an adequate follow up period for outcome of interest) *
 - b) No
- 3) Adequacy of follow up of cohorts
 - a) Complete follow up - all subjects accounted for *
 - b) Subjects lost to follow up unlikely to introduce bias - small number lost - > ____ % (select an Adequate %) follow up, or description provided of those lost) *
 - c) Follow up rate < ____ % (select an adequate %) and no description of those lost
 - d) No statement

Newcastle-Ottawa Quality Assessment List

Note: A study can be awarded a maximum of one star for each numbered item within the Selection and Outcome categories. A maximum of two stars can be given for Comparability

<u>Selection</u>	
1) Representativeness of the exposed cohort	a) truly representative of the average PFP population in the community ★ b) somewhat representative of the average PFP population in the community ★ c) selected group of users eg nurses, volunteers d) no description of the derivation of the cohort
2) Selection of the non-exposed cohort	a) drawn from the same community as the exposed cohort ★ b) drawn from a different source c) no description of the derivation of the non-exposed cohort
3) Ascertainment of exposure	a) secure record (eg surgical records) ★ b) structured interview ★ c) written self-report d) no description
4) Demonstration that outcome of interest was not present at start of study	a) yes ★ b) no
<u>Comparability</u>	
1) Comparability of cohorts on the basis of the design or analysis	a) study controls for anthropometric characteristics ★ b) Study controls for extrinsic factors ★
<u>Outcome</u>	
1) Assessment of outcome	a) independent blind assessment ★ b) record linkage ★ c) self-report d) no description
2) Was follow-up long enough for outcomes to occur	a) yes (select an adequate follow up period for outcome of interest) ★ b) no
3) Adequacy of follow up of cohorts	a) complete follow up - all subjects accounted for ★ b) $\geq 80\%$ of subjects complete the follow up or description provided of those lost ★ c) follow up rate $< 80\%$ and no description of those lost d) no statement

List of injured participants

Number	CODE	Injury 1	Injury 2	Injury 3	Injury 4
1	1	BITS			
2	10	R Foot Pain			
3	13	L PFP			
4	16	R PFP	SF		
5	21	R PFP			
6	24	B Foot Pain			
7	28	L PFP			
8	30	Planter F			
9	34	L PFP			
10	35	L Ankle S			
11	45	L PFP			
12	46	R KNEE PAIN	Planter F		
13	47	L KNEE PAIN	L Hip		
14	52	B PFP			
15	53	R Foot Pain			
16	60	R PFP			
17	63	R KNEE PAIN			
18	64	R ankle Pain			
19	65	Planter F	L Ankle P	MTS	RITS
20	79	B Foot Pain	SF	MTS	
21	81	R Ankle pain			
22	90	R PFP			
23	91	L PFP			
24	93	R ankle S			
25	95	R PFP			
26	96	L PFP			
27	99	L Hip			
28	111	L KNEE PAIN			
29	118	R PFP	L Ankle P		
30	119	L KNEE PAIN			
31	121	B PFP			
32	126	R PFP			
33	130	L PFP	MTS	S F	
34	131	B PFP			
35	135	R PFP			
36	136	L ITB			
37	138	R PFP			
38	145	R KNEE PAIN			
39	149	MTS			
40	153	L Ankle Pain			
41	159	R PFP			
42	165	R KNEE PAIN			
43	166	L KNEE PAIN			

44	168	R PFP			
45	173	R PFP			
46	174	R KNEE PAIN			
47	175	R PFP			
48	178	L KNEE PAIN			
49	184	R PFP			
50	188	MTS			
51	190	R PFP			
52	194	R PFP			
53	213	MTS	R Ankle pain		
54	219	PF			
55	225	R PFP	L Ankle pain		
56	229	B PFP			
57	230	B PFP			
58	232	R Ankle S			
59	256	R PFP			
60	261	B PFP			
61	268	B PFP	Planter F		
62	272	R KNEE PAIN	MTS		
63	273	PF			
64	285	B PFP	MTS		
65	292	L PFP			
66	319	R PFP			
67	323	R PFP			
68	330	B PFP			

إستبيان لتقييم الحالة الصحية للركبة

تاريخ اليوم :/...../..... تاريخ الميلاد :/...../.....

الاسم :

هذه المعلومات سوف تساعدنا لمعرفة كيف تشعر بركبتك وكذلك كيف ستكون قادراً على إنجاز نشاطاتك الاعتيادية .
أجب عن كل سؤال بوضع علامة () واحدة على الإجابة المناسبة أمام كل سؤال , وإذا كنت غير متأكد من الإجابة
الرجاء اختيار أقرب أجابة ممكنة .

أعراض المرض

ينبغي الإجابة بهذه الأسئلة المتعلقة بالأعراض المصاحبة لركبتك خلال الأسبوع الماضي.

- S1** صعوبة فرد الركبة عند إستيقاظك في الصباح ؟ ماهي شدة ذلك؟
- | | | | | |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| لا يوجد | خفيف | معتدل | شديد | شديد جداً |
| <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
- S2** ماهي شدة صعوبة فرد الركبة بعد وضع الجلوس , التمدد أو الإسترخاء في وقت لاحق في من نفس اليوم؟
- | | | | | |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| لا يوجد | خفيف | معتدل | شديد | شديد جداً |
| <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
- S3** هل يوجد تورم في ركبتيك ؟
- | | | | | |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| لا يوجد | نادراً | أحياناً | غالباً | دائماً |
| <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
- S4** هل تشعر بأي خشخشة أو سماع طقطقة , أو أي نوع آخر من الأصوات عندما تحرك ركبتيك ؟
- | | | | | |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| لا يوجد | نادراً | أحياناً | غالباً | دائماً |
| <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |
- S5** هل ركبتيك تتصلب فجأة عندما تقوم بالحركة ؟
- | | | | | |
|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| لا يوجد | نادراً | أحياناً | غالباً | دائماً |
| <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> | <input type="checkbox"/> |

التيبس

الأسئلة التالية تتعلق بدرجة تيبس (تصلب) مفصل الركبة الذي أحسست به خلال الأسبوع الماضي . التيبس هو بالتقيد أو صعوبة حركة مفصل الركبة .

S6 هل تستطيع الفرد الكامل للركبة ؟

دائماً	غالباً	أحياناً	نادراً	أبداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

S7 هل تستطيع ثني الركبة بشكل كامل ؟

دائماً	غالباً	أحياناً	نادراً	أبداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

الألم

P1 كم مرة تشعر فيها بالألم الركبة عادةً

لا يوجد ☐ كل شهر ☐ كل أسبوع ☐ كل يوم ☐ دوماً ☐

ماهي شدة الألم التي قد تكون شعرت بها الأسبوع الماضي خلال أدائك للنشاطات التالية ؟

P2 الدوران مع الارتكاز على الركبة المصابة

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

P3 فرد الركبة كاملاً

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

P4 ثني الركبة كاملاً (مثلاً عند وضع الجاوس في الصلاة)

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

P5 المشي على الأرض المستوية

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

P6 عند طلوع أو نزول الدرج

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

P7 أثناء وجودك في السرير ليلاً عند النوم

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

P8 وضع الجلوس أو وضع الإستلقاء

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

P9 عند الوقوف معتدلاً

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

أنشطة الحياة اليومية

ما الصعوبات التي قابلتها في الركبة الأسبوع الماضي ؟

A1 عند نزول الدرج

لا شيء ☐ خفيف ☐ معتدل ☐ شديد ☐ شديد جداً ☐

A2 عند طلوع الدرج				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A3 القيام من وضع الجلوس				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A4 الوقوف				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A5 إنحناء الجسم أو النزول لالتقاط الأشياء من الأرض				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A6 المشي على أرض مستوية				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A7 الصعود أو النزول من السيارة				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A8 الذهاب للتسوق				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A9 لبس الشراريب القصيرة أو الطويلة				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A10 القيام أو النهوض من السرير				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A11 خلع الشراريب القصيرة أو الطويلة				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A12 النوم في السرير (التقلب على أحد الجانبين أو الحفاظ على وضع ثابت للركبة)				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A13 عند الإستحمام				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A14 وضع الجلوس				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

A15 عند قضاء الحاجة (أياً كان نوع المرحاض)				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A16 الأعمال المنزلية المجهدة (مثل تحريك ونقل الأثاث والصناديق.....)				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
A17 الأعمال المنزلية الخفيفة مثل التنظيف وأعمال المطبخ.....				
لا شيء	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

النشاط الرياضي والمهارات اللازمة لممارسة الهوايات

ما الصعوبات التي قابلتها في الركبة الأسبوع الماضي وذلك عند

SP1 ثني الركبة من وضع الوقوف				
لا يوجد	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
SP2 الجري				
لا يوجد	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
SP3 القفز				
لا يوجد	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
SP4 الدوران مع الإرتكاز على الركبة المصابة				
لا يوجد	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
SP5 النزول والإرتكاز على الركبتين (كالنزول للسجود في الصلاة مثلاً....)				
لا يوجد	خفيف	معتدل	شديد	شديد جداً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

الركبة المصابة وعلاقتها بنمط الحياة

Q1 إلى أي مدى تشغلك مشاكل ركبتك أو تمثل مساحة من ذهنك أو تفكيرك ؟				
أبداً	شهرياً	أسبوعياً	يوميّاً	دائماً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Q2 هل قمت بتعديل أسلوب حياتك لتجنب الأنشطة التي قد تسبب تلفاً في ركبتك؟				
أبداً	قليلاً	باعتدال	غالباً	كلياً
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Q3 ما مدى قلقك من عدم ثقتك بكفاءة أداء ركبتك؟

بأفراط	بشدة	نوعاً ما	قليلاً	لا شيء	Q4
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
بشكل عام, ما مدى الصعوبات التي تقابلها عند ممارسة حياتك الطبيعية بسبب مشاكل ركبتك؟					
شديدة جداً	شديدة	متوسطة	خفيف	لا شيء	
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	

شكراً جزيلاً لإجابتك على كل الأسئلة في هذا الاستبيان

بيانات تسجيل المشاركين

التاريخ / /

[illegible]

إستمارة بيانات مشارك

التاريخ / /

رقم التسلسل : اللون : الرقم :
 العمر : الطول : الوزن :
☐ أيمن ☐ أيسر مقاس الحذاء :

طول الساق		طول الفخذ	
الساق الأيمن :	الساق الأيسر :	الفخذ الأيمن :	الفخذ الأيسر :

قوة دفع الساق اليمنى	قوة دفع الساق اليسرى	قوة دفع الفخذ اليمنى للجانب	قوة دفع الفخذ اليسرى للجانب
.1	.1	.1	.1
.2	.2	.2	.2
.3	.3	.3	.3
المتوسط :	المتوسط :	المتوسط :	المتوسط :

معلومات الانشطه البدنية

العمر:

الوزن:

الطول:

في الشهر الاخير السابق للإنضمام للخدمة العسكرية هل مارست اي من ماييلي:

النشاط	عدد الساعات في الاسبوع
المشي	
الجري	
ركوب الدراجة	
السباحة	
تمارين رفع الاثقال	
حلقات التدريب	
فنون الدفاع عن النفس	
الرياضات الجماعية مثل(كرة القدم, كرة اليد, كرة السلة)	

لا

نعم

هل لديك إصابه سابقة بالركبة

لا

نعم

هل لديك إصابه سابقة بالطرف السفلي

Appendix B

Publications and Participation Activities

Journal of Electromyography and Kinesiology 34 (2017) 80–85



Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin



The reliability and criterion validity of 2D video assessment of single leg squat and hop landing



Lee Herrington^{a,*}, Faisal Alenezi^a, Msaad Alzhrani^b, Hasan Alrayani^a, Richard Jones^a

^a Centre for Health, Sport and Rehabilitation Sciences, University of Salford, United Kingdom

^b Physiotherapy Department, Majmaah University, Saudi Arabia

ARTICLE INFO

Article history:

Received 6 November 2016

Received in revised form 6 April 2017

Accepted 7 April 2017

Keywords:

Biomechanics

Landing

Assessment

ABSTRACT

The objective was to assess the intra-tester, within and between day reliability of measurement of hip adduction (HADD) and frontal plane projection angles (FPPA) during single leg squat (SLS) and single leg landing (SLJ) using 2D video and the validity of these measurements against those found during 3D motion capture. 15 healthy subjects had their SLS and SLJ assessed using 3D motion capture and video analysis. Intra-tester reliability for both SLS and SLJ when measuring FPPA and HADD show excellent correlations ($ICC_{3,1}$ 0.97–0.99). Within and between day assessment of SLS and SLJ showed good to excellent correlations for both variables ($ICC_{3,1}$ 0.72–0.91). 2D FPPA measures were found to have good correlation with knee abduction angle in 3-D ($r = 0.79$, $p = 0.008$) during SLS, and also to knee abduction moment ($r = 0.65$, $p = 0.009$). 2D HADD showed very good correlation with 3D HADD during SLS ($r = 0.81$, $p = 0.001$), and a good correlation during SLJ ($r = 0.62$, $p = 0.013$). All other associations were weak ($r < 0.4$). This study suggests that 2D video kinematics have a reasonable association to what is being measured with 3D motion capture.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Three dimensional (3D) motion analysis has been used extensively to assess kinematic and kinetic variables during lower limb motion. It has been regarded as the 'gold standard' for the assessment of potentially high risk manoeuvres related to a variety of knee injuries (McLean et al., 2005). Although 3D motion capture is considered the gold standard for kinematic and kinetic analysis, it is frequently not used in the clinical environment or for pre-participation screening, possibly due to the time required to acquire and analyse the data, large cost of equipment, and the training needed to effectively use it. In the place of 3D motion capture, 2-dimensional (2D) video motion analysis has been used to quantify hip and knee kinematics (Marras et al., 2012). 2D motion capture though has an inherent limitation as it cannot measure kinematics that occurs in planes not perpendicular to the camera without potential for perspective error. As such, 2D motion capture may not be suitable for performance assessment of any motion that is not purely uniplanar such as the knee valgus motion at

the knee, which in reality is a movement not only comprising of knee abduction and hip adduction in the frontal plane but also hip internal rotation and tibial external rotation in the coronal plane (Maffei et al., 2014). The work of McLean et al. (2005) confirmed this noting that 2D knee valgus angles were inherently influenced by hip and knee joint rotations.

The extent to which non-uniplanar motions can be reflected in the uniplanar knee motion, measured with 2D video, has only been investigated in a limited number of studies. These studies have tested for a relationship between 2D measures of knee and hip motion and 3D hip and knee kinematics. For example, McLean et al. (2005) reported the relationship between 2D and 3D motion capture in assessing frontal-plane knee kinematics during side-stepping, side-jumping, and shuttle run. They reported strong correlations of $r = 0.76$ and 0.80 between peak knee abduction angles during 2D and 3D motion capture for side-stepping and side-jumping, respectively; however, the shuttle run yielded a much lower relationship of just $r = 0.20$. Sorensen et al. (2015) found a strong relationship between 2D frontal plane projection angle (knee abduction angle) and 3D knee abduction angle ($R^2 = 0.72$), and between 2D hip adduction and 3D hip adduction ($R^2 = 0.52$) during single leg hop landings. Gwynne and Curran (2014) found FPPA to correlate strongly with 3D knee abduction angle during single leg squat ($r = 0.78$). The study of Wilson and Davis (2008)

* Corresponding author at: Directorate of Sport, Exercise and Physiotherapy, Allerton Building, University of Salford, Manchester M6 6PU, United Kingdom.

E-mail addresses: l.herrington@salford.ac.uk (L. Herrington), f.alenezi@salford.ac.uk (F. Alenezi), m.alzhrani@salford.ac.uk (M. Alzhrani), h.alrayani@salford.ac.uk (H. Alrayani), r.jones@salford.ac.uk (R. Jones).

<http://dx.doi.org/10.1016/j.jelekin.2017.04.004>
1050-6411/© 2017 Elsevier Ltd. All rights reserved.

Patellofemoral pain in Saudi military training and associated risk factors evaluated by two-dimensional motion analysis

Hasan H. Alrayani^{1,2}, Lee Herrington¹, Richard K. Jones¹,

¹ University of Salford, Manchester, UK; ² Ministry of Defence, Riyadh, Saudi Arabia

Email for correspondence: h.h.a.alrayani@edu.salford.ac.uk

Introduction

Military training is an intensive task where individuals suffer lower limb injuries (1). Previous studies have shown that Patellofemoral Pain to be one of the greatest (2). However, there is currently no literature on the incidence of Patellofemoral Pain (PFP) in Saudi Arabian cadets during training. Previous literature has identified that simple 2-dimensional (2D) analysis utilising the Frontal Plane Projection Angle (FPPA) can identify individuals at risk of PFP (3). The purpose of this study was to prospectively assess individuals with 2D FPPA for PFP development, in addition to the other lower limb injuries in Saudi Arabian Military Cadets.

Methods

203 healthy male infantry cadets (age 18.56 ±0.61 years, mass 68.62±12.84 kg, height 175±0.05 cm, and BMI 22.5±3.94 kg/m²) from King Abdul-Aziz Military Academy in Riyadh, Saudi Arabia participated in this study. All individuals were screened during single leg squatting (SLS), single leg landing (SLL) and running (RUN) in the first week of the basic military training to assess FPPA. Three markers were placed on the midpoint of the ankle, the centre of the knee joint and the proximal thigh of both lower limbs of all participants, to define the anatomical landmarks of FPPA. The maximum FPPA was recorded during stance phase as an average of three trials. All of the screened participants were followed up over the twelve weeks of basic military training. The individuals who developed PFP and other lower limb injuries were recorded and compared.

Results

During the twelve weeks of follow up, 64 participants out of 203 were diagnosed with a lower limb musculoskeletal injury. The recorded lower limb injuries are illustrated in figure 1:

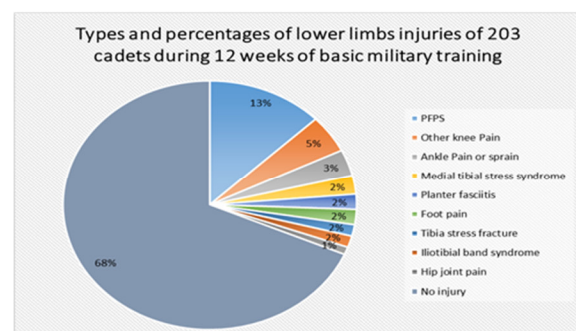


Figure 1: Distribution of injuries during recruit training

26 subjects (12.8%) developed PFP. Means and standard deviation of the FPPA of the injured and non-

injured subjects during the three tasks are in the following table:

Table 1: Mean and standard deviation (SD) with P-value of FPPA for injured and non injured participants.

Test	injured	non injured	P
	Mean (SD)	Mean (SD)	
SLS (°)	8.26 (8.65)	3.32 (9.51)	.015
SLL (°)	7.88 (8.51)	2.25 (7.59)	.001
RUN (°)	-0.38 (4.52)	-3.26 (5.06)	.009

Participants who developed PFP had a statistically significant increased FPPA during all of the three screening tasks with the difference greater in the SLL and SLS tasks.

Discussion

This is the first study to show injuries sustained in military training in Saudi Arabia. Approximately a quarter of participants experienced at least one lower limb injury over the twelve weeks of the basic military training. PFP was the most common injury, accounting for 40.6% of lower limb injuries. Individuals who developed PFP demonstrated greater FPPA in the three screening tests at pre-screening. FPPA appears a useful simple measure to use in large-scale screening for individuals who are at risk of PFP development. Therefore, reducing FPPA, during early training may play a role in reducing the PFP development but further prospective studies are needed to determine the effectiveness. A larger sample is being assessed along with other factors to determine multi-factorial risk factors in this population.

Acknowledgements

Funding of this study was received from University of Salford in the United Kingdom and Ministry of defence of Saudi Arabia.

References

- Sharma J et al (2015). *BMC Musculoskelet Disord*, 16: 106.
- Cutbill JW et al (1997). *CJSM Clinical Journal of Sport Medicine*, 7: 40-45.
- Willson JD et al (2006). *MSS Med Sci Sports Exerc*, 38:945-952.