Ph.D. THESIS

The Effects of Rehabilitation on Athletic Groin Pain:

Neuromuscular and Biomechanical Factors

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Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, that I have exercised reasonable care to ensure that the work is original, and does not to the best of my knowledge breach any law of copyright, and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: ID No: 16210704

Date: 10th December 2020

Acknowledgments

After climbing a great hill, one only finds that there are many more hills to climb – Nelson Mandela.

Completing a PhD certainly feels like climbing a great hill and there is no doubt that I will raise a glass or many with family and friends to toast the accomplishment of getting to the top, however, it has been the journey up the hill that I will savior the most. And for this I am deeply grateful to many people who have made my journey very enjoyable.

To my supervisor, Prof. Kieran Moran I would not have achieved this without your many hours of hard work and dedication. Coming into this process I was a green horn in the field of research and now with your mentorship, supervision and all the knowledge that you have passed on I am ready to tackle many more great hills in the future. I thoroughly enjoyed our meetings chatting about research, writing and life.

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I am grateful for the funding received from the 'Insight center of data analytics.

The journey up the hill and the many great friendships made along the way was the best part of the past five years. I will cherish these for life. I can safely say that I will enjoy many a beer and great laugh with all the following people. At Dublin City

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Finally, to my girlfriend Sara for being an absolute rock along the journey. You kept my eye on the bigger picture, stopped me being too grumpy and kept me laughing along the way. Without this it would not have been as enjoyable XOX.

Dedicated to Grandma – so she can add another graduation picture of the number one grandson to her fridge (one more that Matty and four more than Adsie).

Abstract

Name: Samuel Baida

Title: The Effects of Rehabilitation on Athletic Groin Pain: Neuromuscular and Biomechanical Factors

Introduction: Athletic groin pain (AGP) is an overuse musculoskeletal presentation accounting for approximately 7% of all football injuries, resulting in an average time-off period of 16 ± 23 days and with a re-injury rate of 11% (Werner *et al.*, 2019). During dynamic sporting actions (e.g. jumping, change-of-direction etc.) repetitive loading on the myotendinous and bony structures which stabilize and transfer force across the anterior pelvis may contribute to pain and injury if tissue tolerance levels are exceeded. The exact pathomechanics underlying AGP are poorly understood. Biomechanical analyses of joint loading, movement technique and muscle strength has previously been utilized to improve understanding of injury mechanisms in other overuse lower limb injuries. However, to date their remains a lack of biomechanical research investigating AGP. Therefore, the primary aim of this thesis was to examine movement patterns using three-dimensional biomechanical analysis to increase understanding of injury mechanisms.

Methods: This thesis incorporates the work from four research questions (Chapters 4, 5, 6, 7) and a systematic review on movement variability (Chapter 3). The analysis approach utilized combines both case-control and pre- to post-rehabilitation analyses for robust examination of factors deterministic of injury. Data collection included three-dimensional motion and force plate capture of jumping and hopping tasks, isometric hip strength, passive hip range-of-motion, lower limb reactive strength and patient reported outcome measures.

Results: Athletes with AGP demonstrated significant deficits in isometric hip strength and reduced lower limb reactive strength compared to uninjured control athletes. These deficits were no longer significant following successful rehabilitation. Furthermore, AGP athletes demonstrated significantly reduced landing impulse during a single leg countermovement jump and reduced peak force and longer ground contact times during a continuous hopping task in comparison to uninjured controls. Following successful rehabilitation, landing impulse further decreased in the AGP group and remained significantly less to the control group, while peak force and ground contacts improved and were no longer significantly different to the control group. The magnitude of movement variability and ground reaction force variability were not affected by AGP when compared to uninjured control athletes.

***Conclusion*:** This thesis adds important insights into potential biomechanical and strength factors that are affected by AGP and importantly which return to normal with successful rehabilitation. Targeting these factors may be used to enhance rehabilitation programs for AGP and may play a role in secondary injury prevention as athletes return-to-play.

List of Publications

Journal Articles

Baida, S., Gore, S., Franklyn-Miller, A., Moran, K., 2017. Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review. Scandinavian Journal of Medicine & Science in Sports.

Baida, S., King, E., Gore, S., Richter, C., Franklyn-Miller, A., Moran, K., 2021. Hip muscle strength explains only 11% of the improvement in HAGOS with an intersegmental approach to successful rehabilitation of athletic groin pain: Cohort intervention study with 6-month follow-up. American Journal of Sports Medicine.

Submitted journal articles

Baida, S., King, E., Gore, S., Richter, C., Franklyn-Miller, A., Moran, K., 2020. Athletic Groin Pain and Lower Limb Loading Patterns During a Countermovement Jump. Journal of Athletic Training. Resubmission.

Conference proceedings

Oral presentations

The role of biomechanics in the rehabilitation of athletic groin pain. Sports Surgery Clinic, return-to-play conference 2020, Dublin , Ireland.

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List of Abbreviations and Acronyms

AGP	Athletic Groin Pain
3D	Three dimensional
HAGOS	The Copenhagen Hip and Groin Outcome Score
HH	Hurdle hop
CHH	Continuous hurdle hop
CMJ	Countermovement jump
DL	Double leg
SL	Single leg
vGRF	Vertical ground reaction force
ES	Effect size
CI	Confidence interval
ACLR	Anterior cruciate ligament reconstruction
ROM	Range of motion
IR	Internal rotation
ER	External rotation
TROM	Total range of motion
ABD	Abduction

ADD	Adduction
EXT	Extension
FLEX	Flexion
ADD:ABD	Adduction to abduction strength ratio
EXT:FLEX	Flexion to extension strength ratio
ER:IR	External rotation to internal rotation strength ratio
RSI	Reactive strength index
RTP	Return to play

Thesis at a glance

Chapter	Question	Methods	Results	Conclusion
3	Does injury affect movement variability?	Systematic review	22 studies included with 73% finding a significant difference in at least one variable examined between injured and uninjured groups. There was a trend towards greater variability	Movement variability in those with lower limb musculoskeletal injuries was significantly different in 73% of studies compared to the injured population, with 64% reporting greater variability.
4	The effects on hip strength and power of segmentally focused rehabilitation in athletic groin pain	Case-control Intervention trial 42 AGP, 36 CON	86% AGP athletes RTP in 9.8 ± 3.0 weeks. Significant deficits in hip strength, reactive strength and HAGOS in AGP group pre-rehabilitation and all normalized post-rehabilitation in AGP the group. HAGOS maintain at 6-month post-RTP	Inter-segmentally focused rehabilitation is effective at improving local hip strength, lower limb reactive strength and HAGOS. The rehabilitation was effective over the first 6-month return to play period.
Appendix G	Intra-rater reliability using hand-held dynamometry to measure hip strength	Intra-tester, test-retest 15 healthy participants (8 male)	ICC's (2,1) ranged from 0.67 to 0.98. Standard error of measurement (SEM) ranged from 2 to 5%. Minimal detectable change from 9% to 18%.	Individual measures of hip strength using hand-held dynamometry demonstrated good to excellent test-retest reliability
6	Athletic groin pain and lower limb loading patterns during a double leg and single leg countermovement jump (CMJ)	Case-control Intervention trial 28 AGP, 28 CON	5 vertical ground reaction force variables, during the DL- and SL-CMJs, significantly differed between athletes with and without AGP pre-rehabilitation. 4 of the 5 variables significantly changed with successful rehabilitation the AGP group.	Lower limb loading patterns were affected by AGP and differed to uninjured athletes. In the AGP group these loading patterns change with successful rehabilitation and may provide important information for testing and targets for rehabilitation
6	Are ground reaction force (GRF) loading characteristics affected by AGP during a continuous hopping task?	Case-control Intervention trial 36 AGP, 36 CON	At baseline testing, 3 vertical GRF variables significantly differed between the AGP and uninjured athletes. These differences resolved with rehabilitation. No differences were found in variability of the GRF	Loading characteristics in the AGP group reflected strategies to reduce impact forces during continuous hopping. Post-rehabilitation, this loading strategy resolved indicating greater tolerance to higher loading parameters
7	Is movement technique and variability affected by AGP in a continuous hopping task?	Case-control Intervention trial 36 AGP, 36 CON	No differences were observed in any magnitude or variability kinematic or kinetic measure between AGP and uninjured athletes pre- or post-rehabilitation	Movement variability is not affected by AGP during a continuous lateral hurdle hop

Chapter 1

Introduction

Hip and groin injuries are among the most common injuries in many field-based sports. In men's professional soccer these account for 14% of all injuries at a rate of 1.0 / 1000 exposure hours (Werner *et al.*, 2019) with similar rates reported in Australian Rules football, Gaelic football and rugby league (O'Connor, 2004; Orchard, Seward and Orchard, 2013; Waldén, Hägglund and Ekstrand, 2015; Werner *et al.*, 2019; Murphy *et al.*, 2113). In addition, high reinjury rates are reported with one in five players suffering a reinjury within the same season (Werner *et al.*, 2019). Concerningly these rates have not changed over a fifteen year period in men's soccer (Werner *et al.*, 2019).

Chronic hip and groin pain of insidious onset can encompass a number of pathological structures including fascial and myotendinous tissues attaching to the pubic symphysis, the iliopsoas muscle and the hip joint and will collectively be referred to as athletic groin pain (AGP) throughout this thesis. It is common for athletes to present with co-existing pathologies which are through to arise from the large mechanical forces exerted on the anterior pelvis during repetitive jumping, change-of-direction, deceleration and acceleration actions during sporting activity (Meyers *et al.*, 2007; Edwards, Brooke and Cook, 2016; Franklyn-Miller *et al.*, 2017; Janse van Rensburg *et al.*, 2017; Gore *et al.*, 2020). If these actions are coupled with poorly controlled movement patterns excessive repetitive loading on structures common to AGP may eventually exceed tissue tolerance levels whereby normal mechanical forces result in pain and injury (Hreljac, 2005; Franklyn-Miller *et al.*, 2017). However, the precise pathomechanics remains unclear and there is a paucity of research which has biomechanically examined dynamic movement patterns in AGP. Three-dimensional (3D) biomechanics enables the detailed analysis of movement patterns and has been used extensively to successfully identify the pathomechanics in other lower limb injuries (e.g. anterior cruciate ligament rupture (Hewett *et al.*, 2005; Paterno *et al.*, 2010), ankle ligament instability (Dayakidis and Boudolos, 2006; Brown *et al.*, 2009). Biomechanical analysis can give insight in both technique and joint loading to improve our understanding of the pathomechanics related to AGP and is an essential step to improve management of the injury.

The management of hip and groin pain can be challenging due to the interconnected anatomy of the region (Falvey, Franklyn-Miller and McCrory, 2009; Schilders *et al.*, 2017), co-existing pathologies (Hölmich, 2007; Zoga, Mullens and Meyers, 2010; Falvey *et al.*, 2015) and limited evidence regarding risk factors (Ryan, DeBurca and Mc Creesh, 2014; Whittaker *et al.*, 2015). Evidence supports the non-surgical management of AGP and this has traditionally focused on strengthening a single muscle in a single plane of movement (Hölmich *et al.*, 1999; Weir *et al.*, 2010). A more recent rehabilitation approach has focused on intersegmental control during movement patterns to address the pathomechanics potentially related to the repetitive excessive loading of tissue structures common to AGP (King, Franklyn-Miller, *et al.*, 2018). However, the effect of rehabilitation on muscle strength or movement patterns in AGP remains very limited and increased knowledge is vital given the long-term injury trends and high reinjury rates in AGP. In addition, the long-term effectiveness of rehabilitation has not been assessed using a validated outcome measure.

To date, one of two approaches have been broadly employed in examining AGP, either a case-control or a pre- to post-rehabilitation analysis. A case-control analysis can provide information regarding important variables that are different between the case and control groups, however, one limitation to this approach is that these differences may not necessarily be related to the injury itself but rather a result of general deconditioning subsequent to the injury. Similarly, a pre- to post-rehabilitation analysis gives insight into variables that change following an intervention, however, one limitation is that these changes may not be important in the recovery of the specific injury but rather occur due to a broader reconditioning effect of the rehabilitation program. Within this thesis, I have simultaneously employed both the case-control and pre- to post-rehabilitation analysis, an approach which increases the likelihood of identifying factors more likely related to injury than when either approach is used in isolation. While this approach does not confer a true cause-effect relationship between an injury and biomechanical factors, which would require prospective research, it is referred to by Spirtes, Glymour and Scheines (2000) as ‘probabilistic causation’ because of the advantages inferred in combining both case-control and pre- to post-rehabilitation analyses.

The primary of this PhD was to examine biomechanical and strength factors related to AGP and how these factors change with rehabilitation. A second aim was to examine the long-term effectiveness of rehabilitation using a validate PRO.

1.1 Thesis structure and study aims

This thesis incorporates a review of literature (chapter 2), a published systematic review on movement variability (chapter 3) and the work from four research questions (chapters 4, 5, 6, 7). The following section outlines the aims and hypothesis for each study.

Chapter 3:

Study 1 - Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review.

Movement variability represents the natural variation in movement patterns across repetitions of a task when performed by an individual (Bernstein, 1967). Given that excessive repetitive tissue loading can contribute to injury, there has been increased interest in the functional role of movement variability in relation to overuse musculoskeletal injuries such as AGP (Edwards, Brooke and Cook, 2016; Nordin and Dufek, 2019). It has been suggested that too little variability can lead to repetitive loading on specific tissues resulting in injury (Harbourne and Stergiou, 2009). In direct contrast, others have proposed too much variability can result in poorly controlled movements leading to excessive tissue loading (Hamill, Palmer and Van Emmerik, 2012). The primary aim of this systematic review was to determine if the amount of movement variability in dynamic tasks differed between groups with lower limb musculoskeletal injury and uninjured controls.

The results from the systematic review have been published in the Scandinavian Journal of Medicine and Science in Sports: Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review (Baida *et al.*, 2018).

Chapter 4:

Study 2 - The effects on hip strength and power of segmentally focused rehabilitation in athletic groin pain. Cohort intervention study with 6-month follow-up.

Rehabilitation has traditionally focused on isolated muscle strength in single planes of motion, however, more recently a novel intervention program to treat AGP focused on segmental control through strength, linear running and change-of-direction movement (King, Franklyn-Miller, *et al.*, 2018). This approach demonstrated high success rates and fast recovery times. However, the influence of this approach on commonly reported strength risk factors for AGP strength and the long term-efficacy of the program remain unknown. In addition, lower limb reactive strength has not been examined in AGP and is considered important in relation to injury prevention and rehabilitation (Raschner *et al.*, 2012; Manske and Reiman, 2013). The primary aim of this study was to compare hip strength and lower limb reactive strength in athletes with

AGP before and after rehabilitation and compared to uninured controls. The secondary aim was to examine the efficacy of this program after return-to-play (RTP).

This study has been accepted for publication in the American Journal of Sports Medicine, March 2021. Hip muscle strength explains only 11% of the improvement in HAGOS with an intersegmental approach to successful rehabilitation of athletic groin pain: Cohort intervention study with 6-month follow-up (Baida *et al.* 2021).

Chapter 5:

Study 3 - Athletic groin pain and lower limb loading patterns during double leg and single leg countermovement jumps.

Altered lower limb loading patterns have been associated with overuse injuries (Worp, Vrielink and Bredeweg, 2016). Loading patterns can be examined via the vertical ground reaction force (vGRF) which can provide insight into the magnitude, rate and symmetry of loading on the body. Countermovement jumps have previously been used to identify compensation strategies in the loading patterns of those with knee injuries (Baumgart *et al.*, 2017; Baumgart, Hoppe and Freiwald, 2017). To date, however no study has examined the vGRF loading patterns in those with AGP. In addition, the effect of successful rehabilitation on the vGRF remains unknown. The aim of this exploratory study was to examine the magnitude, rate and symmetry of the vGRF during double and single leg countermovement jumps in those with AGP compared to uninjured controls and post-rehabilitation.

Chapter 6:

Study 4 - Ground reaction force loading characteristics affected by AGP during a continuous hopping task

Vertical ground reaction forces (GRF) have been frequently investigated as potential risk factors for overuse lower limb injuries using peak, rate of loading, impulse and variability measures (James, Dufek and Bates, 2000; Zadpoor and Nikooyan, 2011; Jordan, Aagaard and Herzog, 2015; Van Der Worp *et al.*, 2016). In relation to AGP, two studies have examined the GRF and conflicting findings were reported (Edwards, Brooke and Cook, 2016; Gore *et al.*, 2020). In these studies, Gore et al (2020) reported reduced vertical ground reaction force in the AGP group when compared to uninjured controls during a single lateral hurdle hop. In contrast, Edwards et al (2016) reported increased vertical GRF during a 110° running cut in the AGP group. With these conflicting findings there is a clear need for further research. In addition, the rate, impulse or variability of the GRF have not previously been examined in AGP and these measures may provide very important insight in the loading characteristics in AGP. In order to examine variability, a continuous movement task may better represent typical athletic events where individuals can adjust their movements from action to action in order to successful completed the movement. The aims of this study was to examine the magnitude and variability of the vertical GRF in those with AGP during a continuous lateral hurdle hop in comparison to uninjured controls and also following successful rehabilitation.

Chapter 7:

Study 5 – AGP does not affect the magnitude or variability of joint kinematics or kinetics during a continuous lateral hurdle hop when compared to uninjured athletes.

The findings from study 4 revealed reduced peak force, larger concentric impulse and longer ground contact times in the AGP group when compared to the uninjured control group pre-rehabilitation. Following rehabilitation, in the AGP group these variables improved towards the uninjured levels, although statistical equivalence was not shown. The GRF provides a summated measure of center of mass loading, however, it neglects the distribution of forces within joints and tissues. In an attempt to explain the GRF findings from study 4 and provide additional information insight into the underlying movement technique and/or joint loading strategies the aim of this research question was to examine the lower limb and trunk kinematics, kinetics and movement variability during the lateral hurdle hop task. In addition, to examine the effect of rehabilitation on movement technique and joint loading patterns.

Chapter 2

Review of Literature

2.1 Anatomy of Hip and Groin

Athletic groin pain (AGP) can affect a number of different tissue structures across the anterior pelvis and hip regions (Weir *et al.*, 2015). In part, this is due to the complex anatomy which includes multiple joints (i.e. pubic symphysis, hip joint, lumbosacral joints) and inter-related myotendinous attachments which are all located in close proximity on the anterior pelvis (Meyers *et al.*, 2007; Robinson *et al.*, 2007; Schilders *et al.*, 2017). To gain a better understanding of AGP, a detailed understanding of the structure and anatomy of the anterior pelvis is required and outlined below.

Pelvic Gridle

The pelvic girdle is a basin-shaped ring formed by the left and right innominate bones. It is connected anteriorly via the pubic symphysis joint and posteriorly via the sacroiliac joint. It is part of a complex movement system which articulates with the vertebral column superiorly and the two femurs, via the hip joints, inferiorly (Figure 2.1.A: A-B) (Glenister and Sharma, 2019). It has three primary functions with the first two of particular importance in relation to AGP: (1) provides attachment points for the myotendinous and aponeurotic structures of the powerful abdominal and adductor musculature, (2) controls the transfer of forces between the trunk and lower appendicular skeleton using the anterior sling of muscles (i.e. abdominals, hip flexors, adductors) (D’Antoni, 2016), and (3) maintains stability in upright postures against compressive and gravitational forces. The many multi-directional mobility and stability functions can make the pelvis and the structures which attach here susceptible to overload injury.

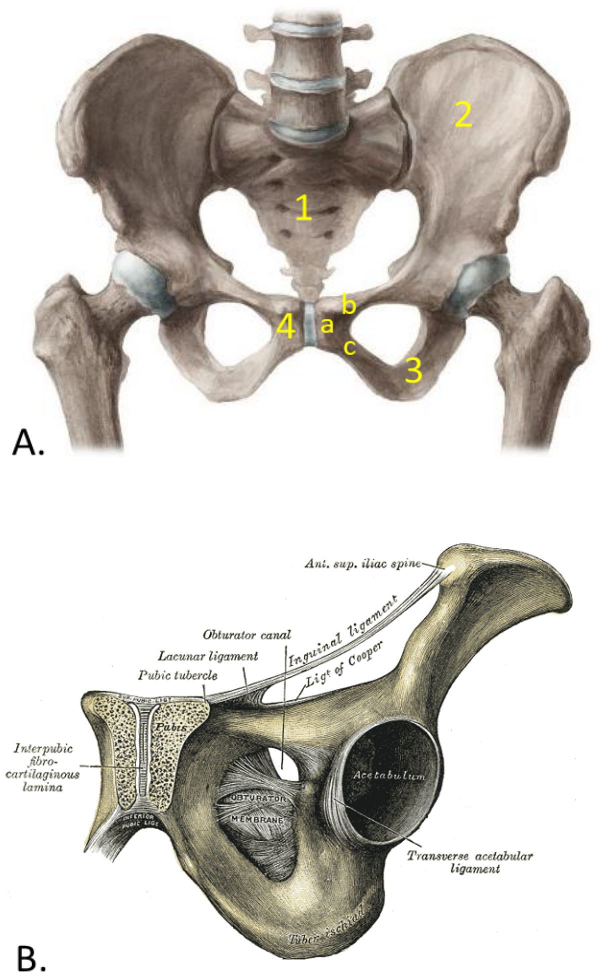


Figure 2.1.A (A) 1. Sacrum, 2. Ischium, 3. Ischium, 4. Pubic bone (a) Pubic body, (b) Ramus superior, (c) Ramus inferior (*Kenhub*, 2020)**. (B) The pubic symphysis separated with intra-pubic fibrocartilage disc and supported with the superior and inferior pubic ligaments** (Standring, Borley and Gray, 2008) **.**

The anterior pelvis is the key anatomical region pertinent to AGP. This is an anatomically crowded area which includes the left and right pubic bones, the pubic symphysis and numerous musculotendinous attachments which are commonly implicated in AGP (e.g. adductor longus, rectus abdominus) (Figure 2.1.B: A-B). Together, these structures act as a fulcrum to allow the transfer of large tensile, rotational and compressive forces across the front of the body (Meyers, Greenleaf and Saad, 2005). This is of particular importance in athletes where the anterior pelvis can take the brunt of the large forces generated during change-of-direction, rapid deceleration, jumping and hopping movements (Meyers *et al.*, 2007; Edwards, Brooke and Cook, 2016; Franklyn-Miller *et al.*, 2017; Janse van Rensburg *et al.*, 2017; Gore *et al.*, 2020). In order to help attenuate and transfer these forces, the anterior pelvis has both passive stability and dynamic control mechanisms, with the latter being most important in relation to AGP. Passive stability is provided via the pubic symphysis and it's supporting capsular and ligamentous structures (Walheim, Olerud and Ribbe, 1984). Dynamic control is provided by the inter-connected myotendinous structures that attach to the pubic symphysis from above, below and laterally (Meyers *et al.*, 2007).

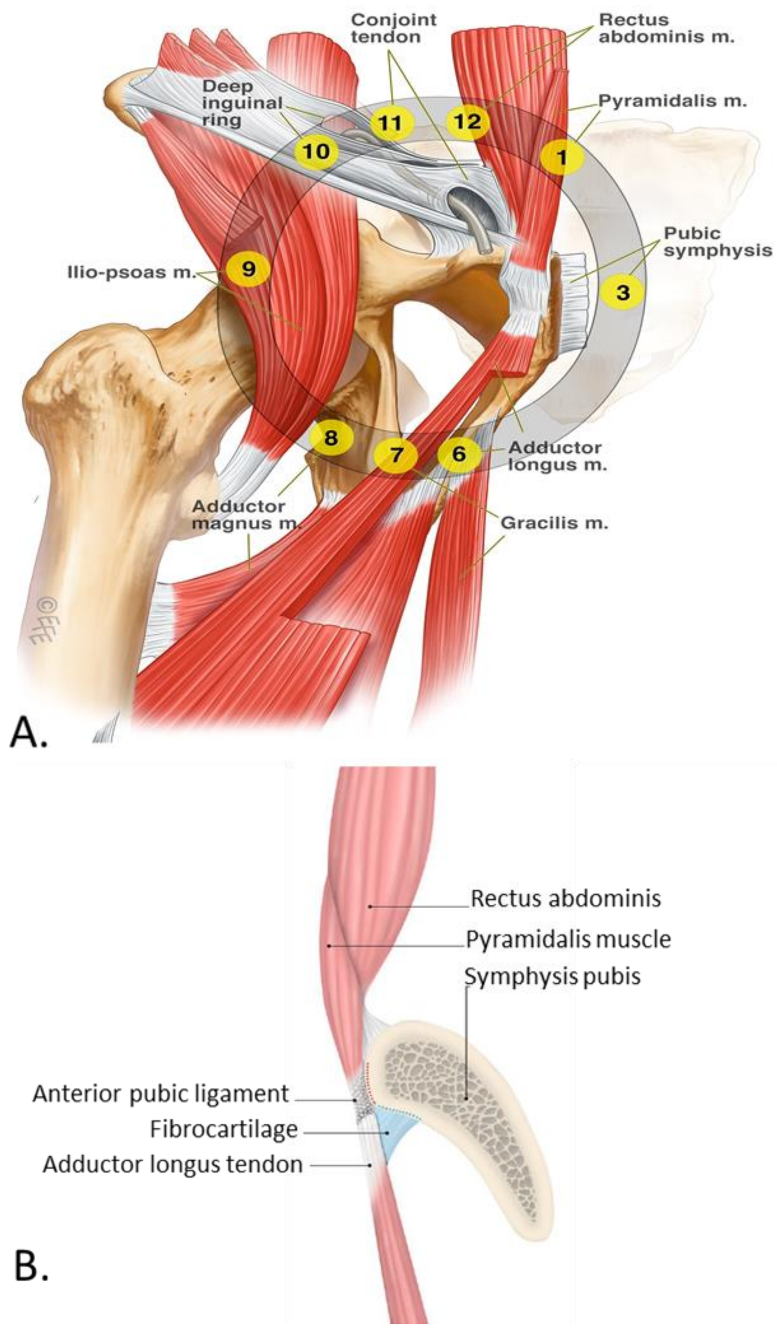


Figure 2.1.B (A) Pubic clock: schematic representation of the myotendinous attachments across the anterior pelvic region (Sports Surgery Clinic, unpublished). (B) Sagittal section through the pubic bone showing the pubic aponeurotic plate which is formed via the inter-connected rectus abdominis, adductor longus and anterior pubic ligament (Schilders *et al.*, 2017)

Superior support to the pubic symphysis is provided by the lower portion of the rectus abdominis and pyramidalis muscles. These muscles insert into the superior border and crest of the pubic bone with a continuation of internal fibers blending with the superior fibers of the symphyseal capsule, which in turn is connected to the fibrocartilaginous disc of the pubic symphysis (Robinson *et al.*, 2007). Inferiorly, the gracilis and adductor longus muscles insert into the pubic body with a continuation of fibers that converge with the rectus abdominis (Schilders *et al.*, 2017). This combination of rectus abdominis and adductor fibers, along with the superior pubic symphysis capsule forms the pre-pubic aponeurotic plate (Figure 2.1.B: A-B) (Zoga, Mullens and Meyers, 2010; Schilders *et al.*, 2017). Laterally, the lower fibers of the transverse abdominis and oblique musculature fuse to form the conjoint tendon which attaches on the pubic tubercle and crest (Robertson *et al.*, 2009). Additional support to the anterior pelvis is also provide by the iliopsoas tendon which acts as a stabilizing 'strap' as it crosses from the lumbar spine to the anterior hip joint (Meyers, Greenleaf and Saad, 2005). It is the intimate relationship of these myotendinous structures and shared action to transfer forces across the front of the body which can, in part, explain the coexisting pathologies and diffuse nature of symptoms commonly reported in AGP (Hölmich, 2007; Bradshaw, Bundy and Falvey, 2008; Falvey *et al.*, 2015). It is also for these reasons that AGP interventions which look to target a single pathological structure may be limited suggesting rehabilitation may be better to focus on whole-body movement patterns contributing to overload of the pathological structures.

The Hip Joint

The hip (femoro-acetabular) joint can also be considered as a source of groin pain (Falvey, Franklyn-Miller and McCrory, 2009). The hip joint is a synovial ball-and-socket joint created by the concave-shaped acetabulum which receives the ball-shaped head of femur (thigh bone) (Figure 2.1.C). The acetabulum labrum, a fibrocartilaginous lip, deepens the concave socket, extending from the acetabulum to cover approximately half of the femoral head to increase joint stability and loading capacity (Berendes *et al.*, 2018). Further stability is provided via the joint capsule and strong iliofemoral, pubofemoral and ischiofemoral ligaments (Navarro-Zarza *et al.*, 2012). The hip is part of a complex movement system together with the pelvis and lumbosacral spine. As a result, alterations in hip function or structure (e.g. capsular tightness or bony morphological changes to the neck of the femur) or changed lumbo-sacral orientation (e.g. excessive lumbar anterior tilt) may result in adverse loading across the pelvic and/or groin regions and manifest in anteromedial groin pain (Bedi *et al.*, 2011).

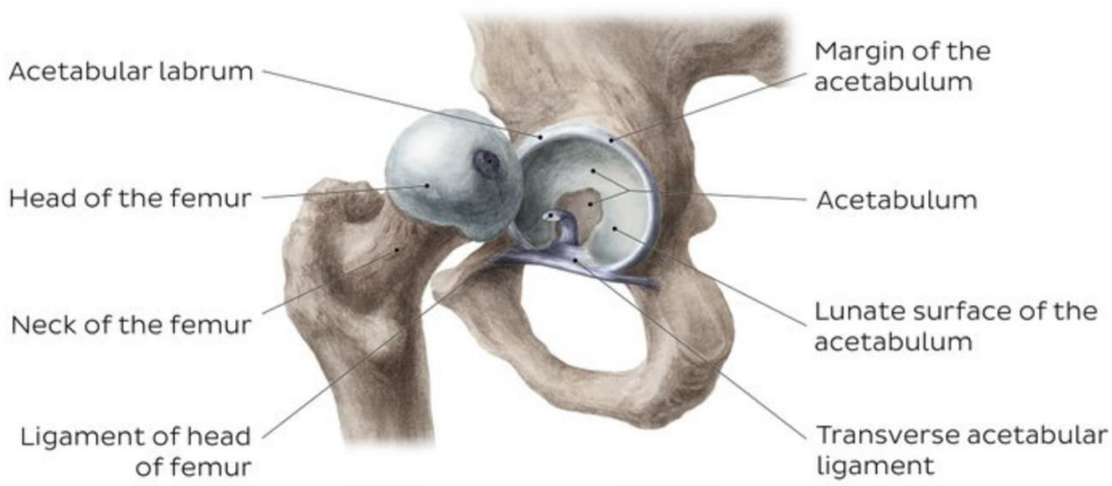


Figure 2.1.C Hip joint: A. ball-and-socket articulation with labral tissue to deepen acetabulum for increased stability (*Kenhub*, 2020)**.**

2.2 Terminology

Many different diagnostic labels have been used to describe groin pain in athletic populations that is of insidious onset. A recent systematic review reported thirty-three different names including Gilmore's groin, sport's man hernia, long-standing adductor pain and osteitis pubis (Serner *et al.*, 2015). Without a clear diagnosis, the subsequent management of groin pain is difficult and so in order to provide clarity Falvey et al. (2009) presented a systematic examination technique primarily based on palpation around a 'pubic clock' (Figure 2.1.B) to identify pathological structures. The different diagnoses and/or pathological structures are outlined below (Section 2.3) and are in line with a recent international consensus statement on terminology and definitions for groin pain in athletes (Weir *et al.*, 2015). These diagnoses fall under the umbrella term 'athletic groin pain' (AGP) which will be used throughout this thesis to describe all diagnoses concerning the pubic symphysis, hip, myotendinous and fascial structures which are overuse in nature and occur with sporting activity.

2.3 Clinical diagnoses in AGP

The following outlines the defined anatomical diagnoses for AGP based on clinical and radiological examination (Falvey *et al.*, 2015)**.**

Adductor injury: Palpation tenderness at the adductor tendon origin on the inferior aspect of pubic bone, pain on resisted adduction testing, Magnetic Resonance imaging (MRI) scan findings of high signal at, micro-tearing of or separation of the adductor from the pubic bone.

Hip flexor injury: Palpation pain over the iliopsoas muscle belly, pain of resisted hip flexion and/or passive hip extension in modified Thomas test position, stretching into hip extension.

Inguinal injury: Palpation tenderness over the inguinal canal, pain on resisted ipsilateral rotation of the trunk, or on Valsalva/cough/sneeze.

Pubic aponeurosis injury: Palpation pain over rectus abdominis insertion into the superomedial aspect of the pubic bone. Pain with squeeze test, cross-over test, resisted lower abdominal contraction. MRI scan findings of high signal at, micro-tearing of, or separation of the pubic aponeurosis from the pubic bone.

Hip injury: Signs of hip pathology (e.g. clicking, catching), limited hip passive hip range-of-motion (<30° with hip flexed to 90°), pain of combined movements of the hip joint (flexion-adduction-internal rotation, flexion-abduction-external rotation). MRI scan findings consistent with hip pathology – femoro-acetabular impingement, osteochondral or chondrolabral pathology.

Other non-musculoskeletal causes of groin pain can present and must be excluded for a diagnosis of AGP including nerve entrapments (i.e. ilioinguinal nerve, genitofemoral nerve), neurological conditions, rheumatological, urological, arterial endofibrosis, and visceral referred pain (Falvey, Franklyn-Miller and McCrory, 2009).

A clear diagnosis of AGP is an important consideration for management, however, it is typical for patients to present with coexisting pathologies. Holmich et al (2007) examined 207 patients with sports-related groin pain (duration > 8 week) and reported a secondary clinical diagnosis in 33% of patients, and a tertiary diagnosis in 10%. This implies that coexisting pathologies may result in pain at the same point in time and therefore can present difficulties in relation to treatment planning (Robertson *et al.*, 2009). Therefore, it has been suggested that interventions which focus on injury mechanics, rather than on a single pathological structure, may be more effective when treating AGP (King, Franklyn-Miller, *et al.*, 2018). The following section will review the injury mechanics related to AGP.

2.4 Epidemiology

Injury rates for AGP have been reported for male athletes in several sporting codes all involving repetitive jump/land and change-of-direction actions. Football has been the most frequently researched sport with a high-quality systematic review identifying twenty prospective studies examining the prevalence and rate of hip and groin injury in men's amateur football (Waldén, Hägglund and Ekstrand, 2015). In this review, Walden et al (2015) reported hip and groin injuries accounted for between 4% and 19% of all recorded time loss injuries per season with the rate of injury between 0.2 to 2.1/1000 exposure hours. These findings are consistent with Australian Rules football (8.8%, 2.7/1000hrs) (Orchard, Seward and Orchard, 2013), Gaelic football (9.4%, 5.8/1000hrs) (Murphy *et al.*, 2012), rugby league (6.7%, 2.3/1000hrs) (O'Connor, 2004) and professional football (14%, 1.0/1000hrs) (Werner *et al.*, 2019). However, athletes typically continue to play with AGP by modifying their training loads in order to prevent time-off, and therefore the recording of non-time loss injuries can better capture the true extent of the problem. Studies which have recorded all hip and groin 'complaints' have demonstrated a ten-fold increase in the weekly prevalence of groin problems (time-loss injury 1.3% versus non-time loss injury 10.4%) (Esteve *et al.*, 2020) and a seasonal prevalence ranging from 50-70% (Hanna *et al.*, 2010; Harøy *et al.*, 2017; Thorborg *et al.*, 2017).

A recent study examined the long-term trends in hip and groin injuries in men's professional football and concerningly there was very little improvement regarding overuse hip and groin injuries over a fifteen year period (2001/2002 to 2015/2016)

(Werner *et al.*, 2019). In their study, Werner et al (2019) reported that the annual average match injury rate had shown a 2.7% decrease per season, however, the training injury rate, the injury burden (16 days-off / 1000 exposure hours) and the reinjury rate (11%) had all remained constant (Werner *et al.*, 2019). The reinjury rate remains of particular concern given that reinjuries are known to cause longer lay-off times than the index injury (Werner *et al.*, 2009). These findings may suggest that there are limitations to the current management strategies and other factors may be required to enhance the effectiveness of rehabilitation programs. It is possible that athletes are returning to sport with ongoing movement impairments that are not detected in a basic clinical assessment (e.g. hip range of motion, single plane muscle strength test). Therefore, the addition of detailed biomechanical analysis may provide better insight into unresolved movement dysfunctions leading to reinjury.

2.5 Pathoetiology in AGP

The pathoetiology of AGP is complex owing to the overuse nature of the injury (Renstrom and Peterson, 1980; Fricker, 1997). There is no single inciting event that will precede the onset of pain and rather occurs after repetitive jump/land, change-of-direction, deceleration and acceleration actions (Robinson *et al.*, 2004; Orchard, 2015; Werner *et al.*, 2019). During such actions it is proposed the repetitive excessive forces exerted on the anterior pelvis, and to the supporting fascial, aponeurotic and myotendinous structures, can reduce tissue tolerance levels to a point where normal mechanical loads result in the gradual onset of pain and injury (Hreljac, 2005; Robinson *et al.*, 2007; Falvey, Franklyn-Miller and McCrory, 2009).

In addition to the various actions that can excessively load the anterior pelvis, how the forces are distributed through the pelvis is also an important consideration in AGP. The interdependent relationship between the stable pelvis and more flexible trunk and lower limb segments must be considered. Franklyn-Miller et al (2016) suggests that a loss of intersegmental coordination can alter how force is transmitted to the pubic symphysis and associated structures. In support of this, altered trunk (Edwards, Brooke and Cook, 2016; King, Franklyn-Miller, *et al.*, 2018; Rivadulla *et al.*, 2020) and ankle (Gore *et al.*, 2018, 2020; King, Franklyn-Miller, *et al.*, 2018) kinematics have been reported in AGP groups during dynamic movement tasks when compared to uninjured control groups. Also, a number of local movement impairments have been suggested to contribute to adverse loading on the pelvis including reduce hip mobility (Verrall, Slavotinek, Barnes, Esterman, *et al.*, 2005; Mosler *et al.*, 2015), reduced hip strength (Whittaker *et al.*, 2015), decreased hip muscle activation (Morrissey *et al.*, 2012) and muscular imbalances (Tyler *et al.*, 2001; Meyers *et al.*, 2007). Finally, pain is also known to affect movement patterns (Hodges and Tucker, 2011) and it is common for athletes with AGP to continue playing sport despite their pain (Waldén, Hägglund and Ekstrand, 2015). This fact may influence the force distribution across the anterior pelvis whereby compensated movement strategies to off-load the painful tissue structure(s) may increase the load on other tissue structures. For example, iliopsoas pain is a common clinical presentation in AGP and if this muscle is inhibited then increased adductor longus activation may be required to assist in flexing the hip near terminal stance of the gait cycle (Lenhart, Thelen and Heiderscheit, 2014) and thus leading to an overload on the adductor longus tendon.

Large mechanical forces exerted on the anterior pelvis appear to be a key factor in the development of AGP. Altered movement patterns, both locally at the pelvis and through the trunk and lower limb segments may contribute to the relative excessive loading on the anterior pelvis. Therefore, it is vitally important in the assessment and management of AGP that a whole-body analysis approach is considered. As such, the biomechanical evaluation of dynamic movements may provide additional insight into the movement patterns and joint loading which contribute to overload on the anterior pelvis. With very few studies investigating dynamic movements in AGP further research is required to increase our understanding of the pathoetiology.

2.6 Biomechanics and AGP

Within sports medicine biomechanical movement analysis has been utilized to identify potential risk factors for injury (Hewett *et al.*, 2005) and also to better understand the effect of injury on movement patterns in order to enhance rehabilitation programs (McIntosh, 2005; Franklyn-Miller *et al.*, 2017). Altered movement patterns can have direct consequences to how forces are applied on the body (Nigg, 1985). AGP is considered an overuse injury whereby repetitive forces on specific tissues structures over time may reduce tissue tolerance levels to a point where a normal mechanical load causes injury (Hreljac, 2005). It has been proposed that poorly controlled movement patterns during explosive sporting actions may result in excessive and repetitive forces on the specific tissues structures commonly implicated in the diagnosis of AGP (e.g. adductor tendon, pubic aponeurosis) (Edwards, Brooke and Cook, 2016; Franklyn-Miller *et al.*, 2017; King, Franklyn-Miller, *et al.*, 2018).

Unfortunately, there is very little research in this area with no published studies found prior to 2016.

Only seven studies were identified that biomechanically examined movement patterns in athletes with AGP and are summarized in Table 2.6.A. This included six retrospective case-control studies (Edwards, Brooke and Cook, 2016; Janse van Rensburg *et al.*, 2017; Severin, Mellifont and Sayers, 2017; Gore *et al.*, 2018, 2020; Rivadulla *et al.*, 2020) and one case series (King, Franklyn-Miller, *et al.*, 2018). Importantly, three of these studies investigated the effect of rehabilitation on movement patterns (Gore *et al.*, 2018, 2020; King, Franklyn-Miller, *et al.*, 2018), however, only two of these included a control group. The combination of analysis approaches (i.e. case-control and pre-to-post-rehabilitation) can provide additional insights into recovery that either approach in isolation cannot. Variables that differ between the injured and uninjured groups (case-control) and subsequently improve with successful rehabilitation (pre-to-post rehabilitation) are more likely associated with injury (Spirtes, Glymour and Scheines, 2000) and therefore provide important targets which may be used to enhance rehabilitation programs.

Four studies examined a single-leg deceleration movement task: drop land (DL) (Janse van Rensburg *et al.*, 2017), hurdle hop (HH) (Gore *et al.*, 2018, 2020), in-step soccer kick (Severin, Mellifont and Sayers, 2017), and three studies examined a running cut task. The single-leg deceleration tasks require greater control of vertical forces and eccentric loads and the cutting tasks require greater control in the frontal and transverse planes (Marshall *et al.*, 2015, 2016). As such the following section will review the biomechanical findings from these studies grouped by the type of task examined (single-leg deceleration; cutting).

Table 2.6.A. Summary of biomechanical studies examining AGP

Study	Design	Participants	Sport(s)	Clinical diagnosis	Task	Analysis (limb)	Variables
Gore *et al.*, 2020	Case control Pre- to post-rehabilitation	65 AGP M 24.6 ±4.8yrs. 55 CON M 23.9 ±3.4yrs	GAA, soccer, rugby	Current AGP > 4/52 PA (71%) Hip flexor (22%) Adductor (4%) Inguinal (2%)	Lateral hurdle hop	Continuous Stance phase (symptomatic)	Lower limb + trunk Kinematics Kinetics GRF (N/kg) x, y, z GCT
Gore *et al.*, 2018	Case control Pre- to post-rehabilitation	65 AGP M, 24.6 ±4.8yrs 65 CON M 23.9 ± 3.4yrs	GAA, soccer, rugby	Current AGP >4/52 PA (71%) Hip flexor (22%) Adductor (4%) Inguinal (2%)	Lateral hurdle hop	Continuous Stance phase (symptomatic)	Vertical stiffness Joint stiffness
Janse van Rensburg *et al.*, 2017	Case control	10 AGP M, 29.0 (22-48) 10 CON M 27.5 (19 - 54)	Rugby, runners, cyclists, soccer	Current AGP >3/12 Clinical entity NR	Single leg drop land	Discrete initial contact, lowest vertical Total ROM (symptomatic)	Pelvis + Hip Kinematics
Severin, Mellifont and Sayers, 2017	Case control	11 AGP, M 23yrs (17-28) 11 CON M, 24yrs (19-26)	Soccer	History of AGP Clinical entity NR	In-step kick 45°/ 60° approach angle	Discrete Total ROM Peak velocity (stance limb*)	Pelvis + Hip Kinematics Displacement

(Edwards, Brooke and Cook, 2016)	Case control	7 AGP M, 22.5 ±3.8 7 CON M 20.8 ±1.1	AR football	History of AGP Central pain (71%) Unilateral pain (29%) Clinical entity NR	45° unanticipated running cut	Discrete Peak zGRF at initial contact (Fmax) Minimum zGRF after Fmax (Fmin) Peak postGRF (Fpost) (right)	Lower limb + trunk Kinematics Kinetics GRF (N/kg): x, y, z Variability
(Rivadulla *et al.*, 2020)	Case control	20 AGP M, 24.8 ±4.9yrs. 21 CON M 25.0 ±4.9yrs	Field sport athletes	Current AGP > 4/52 PA (55%), Hip flexor (10%), Adductor (15%), Hip (10%)	110° anticipated running cut	Continuous Stance phase (symptomatic)	Lower limb + trunk Kinematics Kinetics
(King, Franklyn-Miller, *et al.*, 2018)	Case series Pre- to post-rehabilitation	AGP, M 112, 24.9 ±5.1	GAA, soccer, rugby, hockey	Current AGP >4/52 PA (64%) Adductor (17%) Hip (15%) Iliopsoas (4%)	110° anticipated running cut	Continuous Stance phase (symptomatic)	Lower limb + trunk Kinematics Kinetics Work GCT

*AGP – athletic groin pain, CON – uninjured control, M – male, yrs – years , AR – Australian rules, GAA – Gaelic football and hurling, PA – pubic aponeurosis, NR – not reported, ROM – range-of-motion, GRF – ground reaction force, x – medio-lateral, y – antero-posterior, z – vertical, post = posterior, GCT – ground contact time, * swing leg also examined in study but not reported here.*

Single leg deceleration tasks

Four studies examined single leg deceleration tasks (i.e. hurdle hop [HH], drop land [DL], stance leg during in-step soccer kick) with two of these studies examining whole-body kinematics and kinetics (Gore *et al.*, 2018, 2020) and two examining hip and pelvis segments only (Janse van Rensburg *et al.*, 2017; Severin, Mellifont and Sayers, 2017). Findings from these studies are summarized in Table 2.6.B. When comparing the AGP and uninjured control groups conflicting findings were reported at the pelvis and hip, while consistent findings were reported at the ankle. Following rehabilitation, hip and ankle variables were the factors most related to successful rehabilitation.

Table 2.6.B. Biomechanical findings from single leg loading tasks

Task	Variable	Summary of significant findings	ES
Drop Land [1]			**Diff. pre vs. post**
Hip	Abduction at initial contact	AGP > CON	d=1.12
	External rotation at initial	AGP > CON	d=0.61
	Total rotation external to internal	AGP > CON	d=0.52
Pelvis	Lateral tilt at initial contact	AGP > CON	d=0.75
	Internal rotation at lowest point	AGP > CON	d=0.62
	Downward lateral tilt at lowest point	AGP > CON	d=0.52
In-step kick (stance leg)[2]			
Hip	Flexion velocity (45°/65°)	AGP < CON	d=0.78/d=0.51
	Sagittal ROM (65°)	AGP < CON	d=0.57
	Transverse ROM (45°/65°)	AGP > CON	d=0.43/d=0.56
Pelvis	Sagittal ROM (45°)	AGP < CON	d=0.60
	Transverse ROM (45°/65°)	AGP < CON	d=0.46/d=0.61
	Peak posterior tilt velocity (45°/65°)	AGP < CON	d=0.87/d=0.62
	Peak rotation velocity (45°/65°)	AGP < CON	d=0.40/d=0.43
Hurdle hop			

Ankle	Plantar flexion moment 12-86% [4]	AGP pre < CON, AGP post < CON	d= -0.75
	Plantar flexion power 9-33%, 50-86% [4]	AGP pre < CON, AGP post < CON	d=-0.55,0.65
	Plantar flexion angle 26-75% [4]	AGP pre < CON, AGP post = CON*	d=0.46
	External rotation power 31-38% [4]	AGP pre < CON, AGP post = CON*	d=0.42
	Plantar flexor stiffness[3]	AGP pre < CON, AGP post < CON	d=0.55
Knee	Extensor moment 13-24% [4]	AGP pre > CON, AGP post = CON*	d=0.47
	Abductor moment 10-23% [4]	AGP pre > CON, AGP post > CON	d=0.42
	Extensor stiffness[3]	AGP pre < CON, AGP pre < CON	d=0.36
Hip	Abductor moment 16-22% [4]	AGP pre < CON, AGP pre > AGP post, AGP post = CON*	d= -0.47
	Extensor moment 44-51% [4]	AGP pre < CON, AGP pre > AGP post, AGP post = CON*	d= -0.43
	Flexor power absorption 38-43% [4]	AGP pre < CON, AGP post < CON	d=0.43
	Hip abductor stiffness[3]	AGP pre < CON, AGP pre > AGP post, AGP post = CON*	d=0.43
	Internal rotator power 75-80% [4]	AGP pre > CON, AGP pre < AGP post, AGP post = CON*	d= -0.39
	GRF vertical [4]	AGP pre < CON, AGP post < CON	d=-0.73
	GCT total [4]	AGP pre < CON, AGP post < CON	d=0.66
	GRF medio-lateral [4]	AGP pre < CON, AGP post < CON	d=-0.66
	CoM vertical power [4]	AGP pre < CON, AGP post < CON	d=0.52
	CoM power antero-posterior [4]	AGP < CON, AGP > AGP post, AGP = CON	d=-0.44
	GRF antero-posterior [4]	AGP pre < CON, AGP post < CON	d=0.43

CoM height [4]	AGP pre < CON, AGP pre > AGP post, AGP post = CON	d=-0.40
CoM power medio-lateral [4]	AGP pre < CON, AGP post < CON	d=0.29
Vertical stiffness[3]	AGP pre < CON, AGP post < CON	ADD

ROM – range-of-motion, GCT – ground contact time, GRF – ground reaction force, CoM – center of mass, 45°/65° in-step kick approach angle, Pre – pre-rehabilitation, post – post-rehabilitation, CON – uninjured control group, 1 Janse van Rensburg et al., (2017) , 2 Severin, Mellifont and Sayers, (2017), 3 Gore et al., (2020), 4 Gore et al., (2020).

Janse van Rensburg (2017) reported increased frontal and transverse plane hip (abduction *d*=1.12, external rotation *d*=0.61, total rotation *d*=0.52), and pelvis (lateral downward tilt *d*=0.52 *to* 0.75, internal rotation *d*=0.62) motion in the AGP group when compared to uninjured controls during a single-leg drop land. Severin et al (2017) also reported increased transverse plane hip motion (*d*=0.43 to 0.56) in the AGP group during an in-step soccer kick. These findings may reflect poor motor control in the frontal and transverse planes leading to abnormal loading on the hip and pelvis. In support of this, reduced strength of gluteal muscles has previously been reported in AGP (O'Connor, 2004; Morrissey *et al.*, 2012) which play a major role in controlling frontal and transverse hip and pelvic stability (Neumann, 2010). In contrast, Severin et al (2017) reported reduced pelvic motion in the sagittal (*d*=0.60) and transverse (*d*=0.62 to 0.87) planes and reduced sagittal plane hip motion (*d*=0.57) on the stance limb in the AGP group compared to uninjured controls during an in-step kick. In addition, reduced peak velocities of pelvis posterior tilt (*d*=0.46 to 0.87) and rotation (*d*=0.40 to 0.87) were also reported in the AGP group on the stance limb (Nb: Severin et al (2017) also examined the kicking limb in their study, however, as this did not involve a closed chain deceleration action as per Janse van Rensburg (2017), or Gore et al (2020), (2018) these findings were not synthesized in this review section). Their findings may reflect a compensated movement pattern during the kicking action whereby injured athletes limited movement and speed of movement to reduce loading on the anterior hip (Brophy *et al.*, 2007; Lees *et al.*, 2010). At the ankle, Gore et al (2020) reported decreased plantar flexion angle (*d*=0.46), power, (*d*=-0.55, 0.65), and moment (*d*=-0.75) in the AGP group when compared to uninjured controls during a lateral hurdle hop. Similarly, Gore et al (2018) also reported decreased plantar flexion stiffness (*d*=0.55) in the AGP group. The precise role ankle function has in relation to AGP is unclear, however it has been suggested that the reduced sagittal plane ankle function may adversely affect loading further up the kinetic chain by either altering the direction or increasing the magnitude of the GRF (Franklyn-Miller *et al.*, 2017).

Gore et al (2020, 2018) reported various hip and ankle variables which were significantly reduced in the AGP group when compared to the control group pre-rehabilitation during a HH task, which improved following successful rehabilitation, and were not significantly different post-rehabilitation when comparing the groups. These variables included reduced ankle plantar flexion (*d*=0.46), ankle external rotation power (*d*=0.42), hip abductor moment (*d*=-0.47), hip abductor stiffness (*d*=0.43), hip extensor moment (*d*=-0.43) and hip flexion power (*d*=0.43) (Gore *et al.*, 2018, 2020). These findings have a number of important implications for rehabilitation. Firstly, the increased sagittal and frontal plane hip function may reflect a reconditioning of the gluteal muscles via the targeted strength exercises as part of the rehabilitation program (Gore *et al.*, 2018, 2020; King, Franklyn-Miller, *et al.*, 2018). These gluteal muscles control femoro-pelvic motion (Neumann, 2010) and increased stability of this region may help to redistribute forces on the anterior pelvis and reduce loading on painful tissue structures. Previous research has also found frontal plane gluteal dysfunction in athletes with long-standing groin pain supporting the need to target these muscles for rehabilitation (Morrissey *et al.*, 2012). Secondly, ankle function appears to be an important factor in recover. The exact mechanism underpinning this remains unclear, although a possible explanation is improved ankle function can influence the magnitude of loading further up the kinetics chain (e.g. hip and pelvis). This has previously been demonstrated in healthy individuals during walking gait whereby increased ankle plantar flexion moment during the push-off action resulted in concurrent decreases in sagittal plane hip moments, peak powers and angular impulse (Lewis and Ferris, 2008). Lastly, hip stiffness also appears to be an important consideration for rehabilitation. The reduced stiffness observed in the AGP group may result in excessive joint motion contributing to excessive loading on the myotendinous structures which help to stabilize the region (Williams, McClay and Hamill, 2001; Butler, Crowell and Davis, 2003). Examination of joint stiffness requires 3D motion capture which is not readily accessible for the vast majority of rehabilitation clinics. Considering this, a recent study by Kipp et al (2018) examined the relationship of vertical limb stiffness to a number of biomechanical variables during a drop jump test, which is a commonly used clinical test in rehabilitation. A significant and positive correlation ($p<0.05$, $r=0.537$ to 7.54) was reported between vertical stiffness and the reactive strength index (RSI), the ratio of jump height to ground contact time. This is of importance from a clinical perspective where the RSI may be used as a pseudo measure of stiffness which may help guide assessment and rehabilitation; however, to date RSI has not been examined in AGP. Further review of reactive strength and AGP can be found in Section 2.7.3.

Running cut tasks

Three studies examined a running cut task including two case-control studies (Edwards, Brooke and Cook, 2016; Rivadulla *et al.*, 2020) and one case-series which examined changes in the AGP group pre- to post-rehabilitation (King, Franklyn-Miller, *et al.*, 2018). The findings from these studies are summarized in Table 2.6.C. When comparing the AGP and uninjured control groups significant differences were consistently reported at the trunk and the largest differences reported between groups were measures of trunk and hip movement variability. With regard to the effect of rehabilitation, the largest changes observed from pre to post-rehabilitation were at the trunk and ankle.

Table 2.6.C. Biomechanical findings from running cut tasks

Task	Variable	Summary of significant findings	ES
Run Cut			**Diff. pre vs.post**
Trunk	Ipsilateral side flexion (97-100%)[2]	AGP > CON	NR
	T12-L1 ipsilateral rotation (Fmax, Fmin)[1]	AGP > CON	*d*>0.80
	T12-L1 ipsilateral rotation variability (IC)[1]	AGP < CON	*d*=1.17
	T12-L1 ipsilateral rotation variability (Fmax)[1]	AGP > CON	*d*=0.99
	Contralateral side flexion 0-100%[3]	Post > Pre	d=-0.79
	Thorax on pelvis ipsilateral side flexion 16-100%[3]	Pre > Post	*d*=0.56
	Ipsilateral rotation 0-100%[3]	Post > Pre	*d*=-0.54
	Thorax on pelvis Ipsilateral rotation[3]	Post > Pre	*d*=-0.46

Pelvis	Contralateral rotation 0-100%[3]	Post > Pre	*d*=-0.76
	Contralateral side flexion 0-100%[3]	Post > Pre	*d*=-0.62
Hip	Flexion (27-41%)[2]	AGP > CON	NR
	Abduction (1-7%)[2]	AGP < CON	NR
	Internal rotation (Fmin)[1]	AGP < CON	*d*>0.80
	Internal rotation variability (Fmin)[1]	AGP > CON	*d*=0.94
	Flexion 0-100%[3]	Pre > Post	*d*= 0.51
	Abduction 67-100%[3]	Pre > Post	*d*=-0.36
	Sagittal concentric power 68-87%[3]	Pre > Post	*d*=0.43
	Sagittal extensor moment 50-89%[3]	Pre > Post	*d*= 0.41
	Frontal adduction moment 78-95%[3]	Pre > Post	*d*=-0.39
	Total work[3]	Pre > Post	*d*=0.48
	Sagitta workl[3]	Pre > Post	*d*=0.41
	Frontal work[3]	Pre > Post	*d*=0.24
	Transverse work[3]	Pre > Post	*d*=0.32
Knee	Internal rotation (Fmin)[1]	AGP > CON	*d*>0.80
	Internal rotation variability (Fmin)[1]	AGP < CON	*d*=0.95
	Flexion 57-100%[3]	Pre > Post	*d*= 0.33
	Total work[3]	Pre > Post	*d*=0.26
	Frontal work[3]	Pre > Post	*d*=0.36
	Sagittal concentric power 43-58%[3]	Post > Pre	*d*= −0.4
Ankle	External rotation (45-56%)[2]	AGP > CON	NR
	Dorsi-flexor moment (39-48%)[2]	AGP < CON	NR
	Sagittal work[3]	Post > Pre	*d*= -0.70
	Total work[3]	Post > Pre	*d*= -0.68
	Dorsiflexion 9-75%[3]	Post > Pre	*d*= −0.58
	Plantar flexion moment 6-71%[3]	Post > Pre	*d*= −0.48
	Sagittal eccentric power 1-24%[3]	Post > Post	*d*= 0.46
	Sagittal concentric power 57-83%[3]	Post > Pre	*d*= −0.46
	COM to COP anterior 4-41%[3]	Post > Pre	*d*=-0.36
	COM to COP contralateral 0-95%[3]	Post > Pre	*d*= 0.40
	GCT[3]	Pre > Post	*d*=0.30

Fmax – peak vertical force, Fmin – minimum force after peak vertical force, IC – initial contact, COM – centre of mass, COP – centre of pressure, GCT – ground contact time, [1]Edwards et al (2016), [2]Rivadulla et al (2020), [3] King et al (2018).

Edwards et al (2016) reported increased T12-L1 ipsilateral rotation (*d*>0.80) at peak vertical force and also at minimum force in the AGP group when compared to uninjured controls. Similarly, Rivadulla et al (2020) also reported increased ipsilateral trunk sway in the AGP group from 97-100% of the biomechanical waveform (Rivadulla *et al.*, 2020). When examining trunk motion from pre- to post-rehabilitation King et al (2018) reported a large increase in contralateral side flexion (*d*=-0.79). Together these findings suggest that increased trunk sway over the stance leg when cutting may be associated with AGP and rehabilitation improving the orientation of the trunk towards the direction of intended travel (away from the cutting leg) may contribute to recovery. In support of this, trunk position can increase activation of the adductor muscle (Prior *et al.*, 2014) and therefore increase or decrease the loading on the anterior pelvis depending on its orientation. Furthermore, the direct connections of the trunk musculature (e.g. rectus abdominis, external oblique) to the pelvis, inguinal and adductor regions may result in increased forces through the pelvis with poorly controlled or excessive trunk motion (Meyers *et al.*, 2007; Franklyn-Miller *et al.*, 2017).

The largest differences when comparing AGP and control athletes were reported for movement variability measures of trunk, hip and knee rotation (*d*=0.94 to 1.17) (Edwards, Brooke and Cook, 2016). Movement variability refers to the variability which occurs between repetitions of the same task (Bernstein, 1967). In relation to overuse injuries such as AGP, it has been proposed that movement variability may minimize the magnitude, direction and/or location of forces on the body in order to reduce the occurrence or severity of injury/re-injury caused by excessive repetitive loads (Hamill *et al.*, 1999; James, Dufek and Bates, 2000). However, when examining movement variability, Edwards et al (2016) reported mixed findings with both increased and decreased variability in different body segments (i.e. increased hip rotation variability and decreased knee rotation variability) and even within the same segment during different discrete points during a cutting task (i.e. decreased trunk rotation variability at initial contact and reduced trunk rotation variability at peak vertical force). Given the large differences observed between the AGP and control group and the mixed findings there is a clear need for further research examining the role of variability in relation to AGP and overuse injuries. A systematic review pertaining to movement variability and lower limb injury was conducted as part of this thesis (Baida *et al.*, 2018). This systematic review, '<u>Is Movement Variability Affected by Lower limb Injury'</u>, can be found in Chapter 3 of this thesis.

Ground Reaction Force

Examination of ground reaction forces (GRF) can provide insight into the loading forces applied to the body (Hreljac, 2004; Zadpoor and Nikooyan, 2011). This is an important biomechanical factor which has frequently been examined as a risk factor for overuse lower limb injures (Bredeweg, Buist and Kluitenberg, 2013; Van Der Worp, Vrielink and Bredeweg, 2016). In relation to AGP, only two studies have investigated the GRF and conflicting finding were reported. Gore et al. (2020) reported significantly reduced vertical (d=-0.73), anterior-posterior (d=-0.66) and medio-lateral (d=0.43) GRFs in the AGP group when compared to uninjured controls during a lateral hurdle. No difference in hop height or width was reported between the groups and therefore the AGP group may be utilizing a compensation strategy to reduce the magnitude of loading through the pelvis. In contrast, Edwards et al (2016) reported greater vertical (i.e. peak force at initial contact, and minimum force after weight acceptance) and posterior (*d*=0.50 to 0.82) GRFs during an unanticipated cutting task in the AGP group compared to the control group. This may represent a risk factor for injury and is in line with previous research which has reported increased GRF to be associated with lower limb overuse injuries (Hreljac, Marshall and Hume, 2000; Davis, Bowser and Mullineaux, 2016). With these contrast in findings and the limited number of studies there is a clear need for further research to examine GRF in AGP. In addition to the magnitude of the GRFs, the loading rate (Zadpoor and Nikooyan, 2011) and impulse (Jordan, Aagaard and Herzog, 2015) of the vertical GRF have previously been associated with lower limb injury, however, these have not been examined in AGP.

Summary

Within the literature very few studies have investigated 3D biomechanics and GRF in AGP. Further research is required to increase the understanding of how AGP affects movement patterns during dynamic tasks and also the effect of rehabilitation on these movement patterns. In this section of the literature review, the altered movement patterns identified in the AGP groups were discussed as both potential risk factors and compensation strategies, however, due to the retrospective design of the studies no causal relationship can be determined. In the absence of prospective research, the analysis approach utilized by Gore et al (2020) in which both case-control and pre- to post-rehabilitation analyses were employed invokes the concept of probabilistic causation whereby significant findings in both analyses are more likely related to the injury as compared to using either approach in isolation (Spirtes, Glymour and Scheines, 2000). This approach may help to identify biomechanical targets to enhance rehabilitation programs. In addition to the examination of joint kinematic and kinetic variables, movement variability and ground reaction forces warrant further investigation.

The heterogeneity of movement tasks examined makes comparing the biomechanical studies challenging. In an attempt to provide a clear summary of the findings, this current review section grouped the studies according to the type of task examined (i.e. single leg deceleration versus cutting task). Findings suggest that loading and movement control strategies may be task dependent. For example, during the cutting tasks consistent evidence was reported that altered trunk kinematics may be associated with AGP (Edwards, Brooke and Cook, 2016; King, Franklyn-Miller, *et al.*, 2018; Rivadulla *et al.*, 2020), whereas no alteration in trunk kinematics was reported during a lateral hurdle hop (Gore *et al.*, 2020). Likewise, during the single leg deceleration tasks, increased transverse plane hip motion was consistently reported in the AGP (Janse van Rensburg *et al.*, 2017; Severin, Mellifont and Sayers, 2017) and increased frontal and sagittal hip moments were reported after successful rehabilitation (Gore *et al.*, 2020), whereas during a cutting task Edwards et al (2016) reported decreased transverse plane hip motion (d>0.80) and King et al (2018) reported reduced work at the hip in the frontal and sagittal planes. Consistent to both tasks, sagittal plane ankle mechanics differed between the AGP and control group, of medium to large effect size (Gore *et al.*, 2018, 2020; Rivadulla *et al.*, 2020), and also improved with successful rehabilitation (King, Franklyn-Miller, *et al.*, 2018; Gore *et al.*, 2020). The examination of whole-body movement patterns is therefore very important when examining AGP. Movement tasks which place a large physical challenge on the ankle may provide additional insight into control and recovery of ankle function in AGP. A drop jump test would allow such examination, which could easily be examined in the vast majority of rehabilitation centers (in comparison to cutting and sprinting tasks).

2.7 Risk Factors

Understanding risk factors for injury is an important step to develop management strategies to help prevent injury and reinjury rates (Bahr and Holme, 2003). In relation to AGP, a high-quality systematic review by Whittaker et al (2015) examined risk factors from twenty-nine studies including two intervention studies (1 randomized controlled trial, 1 quasi-experimental), twenty-one cohort (19 prospective, 1 historical, 1 pilot), five case–control and one cross-sectional study (Whittaker *et al.*, 2015). Many modifiable and non-modifiable risk factors were examined and the only consistent risk factor reported was a previous hip or groin injury (Whittaker *et al.*, 2015). The two most commonly examined risk factors were hip strength and hip range-of-motion and as such these will be explored in detail in Section 2.7.1 and Section 2.7.4, respectively.

A past history of hip or groin injury was investigated in one randomized control trial and four prospective cohort studies with all five studies reporting this factor to be significantly associated with AGP (Whittaker *et al.*, 2015). It has been reported that football players with a history of AGP are at a seven times greater risk of sustaining another hip or groin injury compared to non-injured players (Arnason *et al.*, 2004). Importantly, it has been noted that inadequate or incomplete rehabilitation is the most likely mechanisms why a past injury is a risk factor (Emery and Meeuwisse, 2001; Arnason *et al.*, 2004; Hägglund, Waldén and Ekstrand, 2009). In support of this, previous research has demonstrated altered movement patterns are still evident in asymptomatic athletes with a past history of AGP that when compared to uninjured controls during dynamic sporting tasks despite returning to play (Edwards, Brooke and Cook, 2016; Severin, Mellifont and Sayers, 2017). To date, however, only three studies have investigated the effect of rehabilitation on movement patterns in AGP (Gore *et al.*, 2018, 2020; King, Franklyn-Miller, *et al.*, 2018). Increased research is vital to improve understanding of effective rehabilitation to help enhance injury management and potentially reduce re-injury.

Muscle Strength

Reduced strength of the hip musculature has been the most commonly examined modifiable risk factor associated for AGP (Ryan, DeBurca and Mc Creesh, 2014; Whittaker *et al.*, 2015). In fact, hip strength testing has been advocated as part of the minimum reporting standards in athletes with AGP (Delahunt *et al.*, 2015). However, Franklyn-Miller et al (2017) recently questioned the importance of isolated and single plane hip strength, suggesting that multi-planar movement control is more important (Franklyn-Miller *et al.*, 2017). Increased understanding of the role of hip strength in relation to AGP is therefore needed to help answer this question. In addition, it is common for only adductor muscle strength to be cited when discussing AGP, however, many different hip muscle groups (e.g. flexors, extensors, rotators) contribute to pelvis stability and movement and their role in relation to AGP remains unclear. The hip adductors and hip flexors are important as they include the adductor longus and iliopsoas muscles which are two of the most common pathological structures in AGP (Weir *et al.*, 2015; Werner *et al.*, 2019). Also, the hip abductors, extensors and rotators play important roles in stabilizing the femur, pelvis and trunk which may prevent excessive loading on structures across the pubic symphysis and hip joint (Reiman, Bolgla and Lorenz, 2009; Neumann, 2010; Powers, 2010; Morrissey *et al.*, 2012). In addition to the strength of individual muscle groups, the strength ratio between the hip adductors and abductor muscles has also been examined in those with AGP (Tyler *et al.*, 2002; Thorborg, Branci, Nielsen, *et al.*, 2014). It has been suggested that the balance between the agnostic and antagonist muscle groups may be important in optimizing muscle function and load distribution around the hip and pelvis (e.g. hip adductor strength to abductor strength). Traditionally, rehabilitation has primarily focussed on strengthening adductor and abdominal musculature with less attention given to the other hip muscle groups (e.g. hip extensors, abductors and flexors). Therefore, increased insight into the strength of all hip muscle groups may have implications from a rehabilitation perspective. The following section will review the literature on hip strength and AGP.

Eight studies were identified that objectively measured unilateral hip strength in populations with AGP. This included five prospective studies (Emery and Meeuwisse, 2001; Tyler *et al.*, 2001; O'Connor, 2004; Engebretsen *et al.*, 2010; Belhaj *et al.*, 2016), two case-control studies (Malliaras *et al.*, 2009; Thorborg, Branci, Stensbirk, *et al.*, 2014) and one case-series (Rafn *et al.*, 2016). Findings specific to each muscle group are reported below and have been summarized in Table 2.7.A. It was important to discern unilateral hip strength from bilateral hip strength in this section as a common approach to test hip adductor strength is also the bilateral adductor squeeze test (Malliaras *et al.*, 2009; Crow, Pearce, Veale, VanderWesthuizen, *et al.*, 2010; Esteve *et al.*, 2018). While the bilateral adductor strength test can provide important information, and is reviewed in Section 2.7.2, it fails to indicate which limb has the strength deficit and also it may involve increased force contribution from the hip internal rotators (Delahunt, Kennelly, *et al.*, 2011; Nevin and Delahunt, 2014).

Table 2.7.A Summary of findings from studies examining unilateral hip strength

Author	Subjects	Sport	Device Contraction (units)	Position	P-value INJ vs UNINJ	Uninjured Mean ± SD	Injured Mean ± SD	ES	Diff.
ADDUCTORS									
Prospective									
Tyler et al 2001	47 M, 23±4.3yrs, INJ=11	Ice Hockey Elite	HHD ECC (N/kg)	Side lie, long lever	p=0.021	Left 195 ±5, Right 200 ±5	S 160 ±10, NS 170 ±10	NR	18%
Engebresten et al 2010	508 M, age n/r, INJ=61	Soccer Div 1-3	HHD ISO	Supine, long lever	p>0.05	NR	NR	NR	NA
Emery & Meeuwisse 2001	1292 M, n/r, INJ=204	Ice Hockey Elite	HHD ISO (Nm)	Crook lie, short lever	P>0.05	203.26 ±4.05	NR	NR	NA
O'Connor 2004	100 M, 21yrs, INJ=21	Rugby League Amateur	IKD CON 30°, 120°, 210° (Nm)	side lie, short lever	p<0.05 (30°/s) D, ND p<0.05 (120°/s) D, ND p<0.05 (Rot 30°/s) D, ND p>0.05 (210°/s) D, ND	30° D: 168.1 ±72.2 ND: 163.7 ±61.5 120° D: 150.8 ±67.8, ND: 146.3 ±65.7 rot 30° D: 180.1 ±74.8, ND: 184.1 ±58.5 210 ° D: 90.8 ±57.3, ND: 88.2 ±54.2	30° DOM: inj 146.2 ±41.5, ND: 136.2 ±55.0 120° DOM: 118.6 ±39.6, ND 119.0 ±37.1 rot 30° DOM: 134.1 ±39.3, ND 151.9 ±45.8 210 ° D: 80.7 ±42.2, ND: 80.3 ±44.2	NR	14-18% 30° 21-24% 120° 15-29% rot 30°
Case control									
Thorborg et al 2014	21 M AGP, 24.5±2.5yrs , 16 M CON, 22.9±2.4yrs	Soccer Elite, sub-elite	HHD ECC , ISO (Nm/kg)	Side lie, long lever	p<0.001 D ECC p=0.001 ND ECC p=0.09 ISO	ECC D 3.12 ±0.43 ECC ND 3.17 ±0.45 ISO D 1.89 ±0.25	ECC D 2.47 ±0.49 ECC ND 2.54 ±0.51 ISO D 1.98 ±0.34	NR	23% ECC D limb 22% ECC ND limb
Case Series									
Rafn et al 2016	24 M AGP, 25.3yrs	Soccer Div 1-4	HHD ISO, ECC (Nm/kg)	Sidelie, long lever	p=0.895 ISO p=0.056 ECC	ISO 1.83 ±0.40 ECC 2.84 ±0.50	ISO 1.82 ±0.55 ECC 2.65 ±.62	NA	NA

ABDUCTORS									
Prospective									
Tyler et al 2001	47 M, 23±4.3yrs, INJ=11	Ice Hockey Elite	HHD ECC (N/kg)	Side lie, long lever	p>0.05	NR	NR	NR	NR
O'Connor 2004	100 M, 21yrs, INJ=21	Rugby League Ametuer	IKD CON 30°, 120°, 210 (Nm)°	side lie, short lever	p<0.05 peak (30°) D, ND p<0.05 peak (120°) ND p>0.05 peak (120°) D p>0.05 peak (210°) D, ND	30° D: 152.7 ±36.6, ND: 153.3 ±36.5 120° ND: 119.5 ±30.4 120° D: 114.3 ±34.7 210° D 65.0 ±33.4, ND: 56.5 ±27.7	30° D: 124.1 ±37.3, ND 115.1 ±30.2 120° ND: 97.1 ±32.9 120° D: 101.9 ±34.9 210° D 64.9 ±37.2, ND: 57.1 ±27.2	NR	21-28% 30° D, ND 21% 120° ND
Case control									
Thorborg et al 2014	21 M AGP, 24.5±2.5yrs 16 M CON, 22.9±2.4yrs	Soccer Elite, sub-elite	HHD ISO (Nm/kg)	Side lie, long lever	p=0.395 D p>0.05 ND	D: 1.89 ±0.25 ND: NR	D: 1.98 ±0.34 ND: NR	NR	0.09 (-0.12, 0.30)
Malliaras et al 2009	10 M AGP, 15-21yrs, 19 M CON, M, 15-21yrs	AR football Elite junior	HHD ISO (Nm)	Supine, short lever	p=0.84 left p=0.71 right	left: 13.5 ±2.4 right: 13.3 ±2.0	left: 13.2 ±2.3 right: 13.1 ±2.5	NR	NR
Case series									
Rafn et al 2016	24 M AGP, 25.3yrs	Soccer Div 1-4	HHD ISO (Nm/kg)	Side lie, long lever	p=0.225	ISO 1.98 ±0.28	ISO 1.93 ±0.30	NR	-0.05 (-0.14, 0.03)
FLEXORS									
Prospective									
Tyler et al 2001	47 M, 23±4.3yrs, INJ=11	Ice Hockey Elite	HHD ECC (N/kg)	sitting	p>0.05	NR	NR	NR	NR
Case control									
Thorborg et al 2014	21 M AGP, 24.5±2.5yrs 16 M CON, 22.9±2.4yrs	Soccer Elite, sub-elite	HHD ISO (Nm/kg)	supine, thomas test	p=0.737 D supine p=0.518 D thomas test	Supine 2.28 ±0.19 thomas test 1.98 ±0.20	Supine 2.32 ±0.33 thomas test 1.91 ±0.42	NR	0.03 (-0.15,0.21) -0.07 (-0.28,0.15)

Case series									
Rafn et al 2016	24 M AGP, 25.3yrs	Soccer Div 1-4	HHD ISO (Nm/kg)	supine, thomas test	p=0.970 p=0.335	Supine 2.35 ±0.28 thomas test 1.97 ±0.25	Supine 2.35 ±0.32 thomas test 1.91 ±0.43	NR	0.0001 (-0.7, 0.08) -0.06 (-0.18,0.06)
ROTATORS									
Case control									
Malliaras et al 2009	10 M AGP, 15-21yrs, 19 M CON, M, 15-21yrs	AR football Elite jnr	HHD ISO (Nm)	Supine, hip neutral, IR, ER	p>0.05 Left, Right IR p>0.05 Left Right ER	NR	NR	NR	NR
RATIOS									
Prospective									
Tyler et al 2001	47 M, 23±4.3yrs, INJ=11	Ice Hockey Elite	HHD ECC (N/kg) ADD:ABD	Side lie, long lever	p=0.038 INJ vs. UNINJ group p=0.011 INJ vs. UNINJ side	95% UNINJ group 86% UNINJ add side	78% INJ group 70% INJ add side	NR	
Belhaj et al 2016	9 M AGP 24.11 ±3.02yrs, 12 M CON, 23.17±3.88 yrs	Soccer Elite	IKD IKD (Nm) 60° ABD:ADD	Side lie, short lever	p=0.001 D 60° p=0.002 ND 60° p=0.008 I-side v NI-side	D 1.18 ±0.21 ND 1.22 ±0.33 1.53 ±0.49	D 3.04 ±2.57 ND 1.60 ±0.51 3.11 ±2.52	NR	NR
Case control									
Thorborg et al 2014	21 M AGP, 24.5±2.5yrs 16 M CON 22.9±2.4yrs	Soccer Elite, sub-elite	HHD ISO (Nm/kg) ADD:ABD	Side lie, long lever	p>0.353	D 0.92 ±0.23	D 0.99 ±0.18	NR	-0.07 (-0.21, 0.08)

M – males, yrs – years, Diff. – difference, INJ – injured, CON – control, AGP – athletic groin pain, AR – Australian football, div – division, HHD – hand-held dynamometry, IKD – isokinetic dynamometer, ECC – eccentric, ISO – isometric, Nm-newton-meters, D – dominant limb, ND – non-dominant limb, Rotn – rotation, S – symptomatic, NS – non-symptomatic, NR - not reported, ES – Cohen's d effect size, UNINJ – uninjured, wk – week, ADD:ABD – adductor-to-abductor strength ratio, add – adductor.

Hip adductor strength was examined in six studies including four prospective (Emery and Meeuwisse, 2001; Tyler *et al.*, 2001; O'Connor, 2004; Engebretsen *et al.*, 2010), one case control (Thorborg, Branci, Nielsen, *et al.*, 2014) and one case series (Rafn *et al.*, 2016) with mixed findings reported. Prospectively, Tyler et al (2001) reported an 18% reduction in eccentric adductor strength in ice hockey players who sustained a groin injury during the season (Tyler *et al.*, 2001). In contrast, Emery & Meeuwisse et al (2001) and Engebresten et al (2010) found no difference in adductor strength between football players who developed groin pain and those who did not (Emery and Meeuwisse, 2001; Engebretsen *et al.*, 2010). O'Connor et al (2004) reported mixed findings with a 14 to 29% deficit in peak concentric strength at 30° and 120°/second in athletes who sustained a groin injury, but no difference in strength measures at 210°/second (O'Connor, 2004).

Hip abduction strength was examined in five studies including two prospective (Tyler *et al.*, 2001; O'Connor, 2004), two case-control (Malliaras *et al.*, 2009; Thorborg, Branci, Nielsen, *et al.*, 2014) and one case-series (Rafn *et al.*, 2016) with mixed findings reported. Prospectively, one study reported both significantly reduced concentric abductor strength when tested at 30° and 120°/second ranging from 21-28%, while no difference in strength when tested at 210°/ second in athletes who developed AGP (O'Connor, 2004). Tyler et al (2001) found no significant difference in eccentric hip abductor strength when examined prospectively (Tyler *et al.*, 2001).

Isometric hip flexor strength was measure in three of the eight studies including one prospective (Tyler *et al.*, 2001), one case-control (Thorborg, Branci, Nielsen, *et al.*,

2014) and one case-series study (Rafn *et al.*, 2016) with no significant differences reported.

Isometric hip internal and external rotation strength were measured in one case-control study and no significant difference was found when comparing the AGP and uninjured control group (Malliaras *et al.*, 2009).

The strength ratio of the hip adductors relative to the abductors was examined in three studies including two prospective (Tyler *et al.*, 2001; Belhaj *et al.*, 2016) and one case-control (Thorborg, Branci, Nielsen, *et al.*, 2014). Prospectively, both studies reported significantly reduced ratios in athletes with AGP (Tyler *et al.*, 2001; Belhaj *et al.*, 2016) which were primarily due to reduced adductor strength. Tyler et al (2001) reported hip adductor strength 78% of abductor strength (p=0.038) on the injured limb (Tyler *et al.*, 2001) and similarly Belhaj et al (2016) reported hip adductor strength 49-68% of hip abductor strength (p<0.002) in the AGP group (Belhaj *et al.*, 2016). In contrast, Thorborg et al (2014) found no difference in adduction to abduction ratio in the AGP group when compared to uninjured controls. These authors reported that adductor strength was 99% of abductor strength (Thorborg, Branci, Nielsen, *et al.*, 2014).

Considering the measurement devices used, hand-held dynamometry (HHD) was the most frequently used in six of these studies (Emery and Meeuwisse, 2001; Tyler *et al.*, 2001; Malliaras *et al.*, 2009; Engebretsen *et al.*, 2010; Thorborg, Branci, Nielsen, *et al.*, 2014; Rafn *et al.*, 2016), followed by isokinetic dynamometry (IKD) in two studies (O’Connor, 2004; Belhaj *et al.*, 2016). While IKD is considered the gold standard of strength testing (Stark *et al.*, 2011), both devices were sensitive at detecting weakness where differences existed in athletes with AGP (Tyler *et al.*, 2001; O'Connor, 2004).

Therefore, considering the advantages of HHD (i.e. low cost, portable, ease of use and speed of use) in comparison to IKD, it may be considered the most suitable device for the clinical assessment of multiple hip muscle groups. Furthermore, HHD has demonstrated good-to-excellent validity ($ICC_{2,1}$ ≥0.75) of peak isometric hip strength (abduction, adduction, flexion and extension) when compared isokinetic dynamometry (IKD) strength testing (Mentiplay *et al.*, 2015). Also HHD hip strength testing has shown good to excellent inter-day intra-rater reliability ($ICC_{2,1}$ ≥ 0.75; hip abduction, adduction, flexion, extension, internal rotation and external rotation ranging) (Thorborg *et al.*, 2010).

The type of muscle contraction tested has been suggested to be of importance when examining hip strength, in particular hip adductor strength. Thorborg et al (2014) has suggested eccentric testing should be considered as it may produce larger mechanical stress to the muscle-tendon complex when compared to concentric or isometric testing (Thorborg, Branci, Nielsen, *et al.*, 2014). In the above studies, the most common type of muscle contraction examined was isometric (Emery and Meeuwisse, 2001; Malliaras *et al.*, 2009; Engebretsen *et al.*, 2010; Thorborg, Branci, Nielsen, *et al.*, 2014; Rafn *et al.*, 2016), followed by eccentric force (Tyler *et al.*, 2001; Thorborg, Branci, Nielsen, *et al.*, 2014; Rafn *et al.*, 2016) and concentric isokinetic force (O'Connor, 2004; Belhaj *et al.*, 2016). In this review no consistent trends were observed when comparing the different types of muscle contraction. However, in a recent systematic review investigating objective strength measures and hip-related pathologies it was recommended that isometric tests are preferable to eccentric test as they are more reliable, comfortable and have lower risk of post-testing soreness (Mayne *et al.*, 2017).

Summary

Overall, there is a paucity of literature on hip muscle strength and AGP. The hip adductors were the most frequently examined muscle group and this was only in a total of six studies. In addition, the hip rotators have only been examined in one study and no study has examined the hip extensors. This is surprising given the important role that the hip extensors and rotator muscle groups play in pelvis stability (Wilson and Ferris, 2005). Notably, significant reductions in strength were reported in the muscle groups directly affected by AGP (e.g. adductor muscles) and also in muscle groups important to pelvic stability (e.g. abductor muscles) and may help to reduce excessive loading across the pubic symphysis region (Neumann, 2010). It is therefore important to examine all hip muscle groups in athletes with AGP, however, no study has done so. Additionally, only strength ratios between the hip abductors and adductors have been examined in AGP (Tyler *et al.*, 2001; Thorborg, Branci, Nielsen, *et al.*, 2014; Belhaj *et al.*, 2016) and no study has examined hip extensor-to-flexor ratio or hip internal-to-external rotation ratios. A greater understanding of these ratios in populations with physical impairments of the hip and pelvis may help to develop targeted rehabilitation (Kemp *et al.*, 2013). In order to test multiple hip muscle groups, in a time efficient manner and to minimize potential post-testing soreness, an isometric testing protocol utilizing HHD can be considered a feasible option. Given the previous use of HHD in examination of hip strength and AGP, this can also aid in comparison of results with other studies.

Bilateral adductor strength tests

In additional to unilateral adductor strength, bilateral adductor strength has been commonly examined in AGP using a bilateral squeeze test (SQ) (Malliaras *et al.*, 2009; Hanna *et al.*, 2010; Esteve *et al.*, 2018; King, Franklyn-Miller, *et al.*, 2018; Mosler *et al.*, 2018). This test is becoming increasing popular when examining athletes with AGP due to its low cost, simplicity and good reliability (ICCs 0.89 to 0.95, standard error of measurement 3.2 to 5.3%) (Malliaras *et al.*, 2009; Delahunt, McEntee, *et al.*, 2011; Light and Thorborg, 2016). The SQ test is performed with the athlete supine and with a measuring device (i.e. sphygmomanometer cuff or hand-held dynamometer) placed between their knees or ankles as they forcefully adduct. The most common testing positions are with the hips in either 0° of flexion (SQ0) or in 45° flexion (SQ45), however, there is debate within the literature as to which position should be used in order to facilitate maximum force output (Delahunt, Kennelly, *et al.*, 2011; Light and Thorborg, 2016). This is important as the forces produced during the test must maximally stress the pubic region and surrounding myotendinous structures in order to detect subtle squeeze weakness in athletes with AGP (Light and Thorborg, 2016). The following section will review the studies which have utilized the SQ test in athletes with AGP.

In total nine studies were identified which examined the SQ45 including four prospective (Crow, Pearce, Veale, Westhuize, *et al.*, 2010; Delahunt, Fitzpatrick and

Blake, 2017; Mosler *et al.*, 2018; Moreno-Pérez *et al.*, 2019), three case-control (Jansen *et al.*, 2009; Malliaras *et al.*, 2009; Nevin and Delahunt, 2014), one cross-sectional (Esteve *et al.*, 2018) and one case series (King, Franklyn-Miller, *et al.*, 2018). Three studies concurrently examined the SQ0: one case control, one cross-sectional and one case series (Malliaras *et al.*, 2009; Esteve *et al.*, 2018; King, Franklyn-Miller, *et al.*, 2018) and no study was found to *only* examine the SQ0. The summary of findings from these studies are presented in Table 2.7.B. There was consistent evidence from three prospective studies that reduced strength in the SQ45 was associated with AGP (Crow, Pearce, Veale, VanderWesthuizen, *et al.*, 2010; Delahunt, Fitzpatrick and Blake, 2017; Moreno-Pérez *et al.*, 2017) of medium to very large effect size (d = 0.55 to 1.88). The mean deficits reported in the AGP groups ranged from 6% to 30%. In contrast, one prospective study found no significant difference in SQ45 strength scores in athletes who developed AGP compared to uninjured athletes (Mosler *et al.*, 2018).

Table 2.7.B. Bilateral squeeze tests in athletes with AGP

Author	Subjects	Sport	Device	P-value INJ vs UNINJ	Uninjured Mean ± SD	Injured Mean ± SD	ES	Diff.
SQ45								
Moreno-Perez et al (2019) Prospective	71 M, 22.0± 4.2, AGP 18 23.5 ± 3.7, CON 20.2 ± 4.7	Soccer elite	HHD	NR	564 ±58.7 N 7.71 ±0.89 N/kg	429.8 ±100 N 5.40 ±1.27 N/kg	N d=1.58 N/kg d=-1.88	N 23.8% N/kg 30.0%
Mosler et al (2018) Prospective	438 M, 26.0 ± 5yrs, AGP 97M	Soccer elite	HHD	p= 0.1 (N) p= 0.051 (N/kg)	242 ±63.0 N 3.4 ±0.8 N/kg	250 ±60.0 N 3.5 ±0.8 N/kg	NR	N 3.2% N/kg 2.8%
Delahunt et al (2017) Prospective	55M, 24.0±2.8yrs, AGP =10	GAA elite	Sphyg	p=0.01	260 ±40	210 ±55	*d*=0.74*	19%
Crow et al (2010) Prospective	86 M UNINJ, 16-18yrs, AGP n=9	ARF Elite Sub-elite	HHD	p<0.001 (wk of onset) p<0.004 (wk preceding onset)	330 ± 40	wk of injury 290 ± 35 wk preceding 315 ± 45	d=0.55 d=0.98	wk of 11.5% wk preceding 5.83%
Jansen et al (2009) Case control	53 M AGP, 26.5 ±8.6yrs CON M, 23.9±4.7yrs	Soccer (75%)	HHD	p=0.01 (INJ (left) v UNINJ) p>0.05 (INJ (right) v UNINJ)	355 ±45	left 290 ±60 right 340 ±80	NR	18.30%
Nevin & Delahunt (2014) Case control	18 M AGP, 23.89 ±3.18yrs CON M, 23.83 ±3.55yrs	GAA Elite	Sphyg	p<0.01	269.33 ±25.41	202.89 ±36.75	eta sq=0.54	24.70%
Malliaras et al (2009) Case control	10 M AGP-add, 15-21yrs, 19 CON M, 15-21yrs	ARF Elite junior	Sphyg	p=0.07	209.6 ±42.3	180.5 ±30.2	*d*=0.72*	13.90%

Esteve et al (2019) Cross-sectional	303 M, 23±4yrs, AGP=46, Past season AGP=123	Soccer	HHD	p>0.05 (current) p>0.05 (past season) p=0.002 (past Sx >6wks)	current: 1.814 ±0.4 past season: 1.818 ±0.3	current: 1.713 ±0.4 Past season: 1.77 ±0.4 past Sx >6wks: 1.580 ±0.4	d=0.22* d=0.13* d=0.58*	Current 2.6% Past season 5.6% past Sx >6wks 13%
King et al (2018) Case series	112 M AGP, 24.9 ±5.1yrs	GAA Amateur	Sphyg	p<0.05	P1 159 ±43 Max 223 ±41	Max 234 ±40	*d*=0.65	4.7%
SQ0								
Malliaras et al (2009) Case control	10 M AGP-add, 15-21yrs, 19 CON M, 15-21yrs	AR football Elite junior	Sphyg (short)	p =0.01	210.8 ±39.3	172.3 ±28.2	*d*=1.06*	18.30%
Esteve et al (2019) Cross-sectional	303 M, 23±4yrs, AGP=46, Past season AGP=123	Soccer	HHD (long)	Current p=0.01 past season p=0.013 past Sx >6wks p<0.001	current: 2.797 ±0.5 past season: 2.816 ±0.5	current: 2.515 ±0.6 Past season: 2.664 ±0.6 past Sx >6wks: 2.280 ±0.6	d=0.19* d=0.54* d=0.90*	Current 10.1% Past season 5.4% past Sx >6wks 19%
King et al (2018) Case series	112 M AGP, 24.9 ±5.1yrs	GAA	Sphyg (long)	p<0.05	P1 81 ±28 MAX 123 ±29	MAX 135 ±32	*d*=0.68	8.90%

*M – males, yrs – years, INJ – injured, Diff. difference, CON – control, AGP – athletic groin pain, ARF – Australian Rules football, GAA – Gaelic football HHD – hand-held dynamometry, Sphyg – sphygmomanometer, N – newtons Nm- newton-meters, ES – effect size, UNINJ – uninjured, wk – week, Sx – symptomatic, P1 – first onset of pain, MAX – maximum, * effect size not reported and calculated independently.*

When comparing the three studies that examined both SQ tests (Malliaras *et al.*, 2009; Esteve *et al.*, 2018; King, Franklyn-Miller, *et al.*, 2018) all three reported significantly reduced SQ0 values, ranging from small to large effect sizes (*d* = 0.19 to 1.06), and two of the studies reported significantly reduced SQ45 values of small to medium effect sizes (*d* = 0.13 to 7.2). The SQ0 demonstrated the largest differences between the AGP and control groups with deficits in the AGP group ranging from 5.4% to 19% when compared to the SQ45 with deficit ranging from 2.6% to 14%. Two studies reported greater force values during the SQ0 (Malliaras *et al.*, 2009; Esteve *et al.*, 2018) when compared to the SQ45. In similar findings, Light & Thorborg (2011) also reported greater torque values in the SQ0 compared to the SQ45 in elite football players (Light and Thorborg, 2016). In contrast, King et al (2018) reported increased force during the SQ45 when compared to the SQ0 in athletes with AGP (King, Franklyn-Miller, *et al.*, 2018). Similarly, Delahunt et al (2011b) reported the SQ45 produced greater levels of force production ($p<0.01$) and greater levels of adductor surface EMG muscle activity ($p<0.05$) when compared to the SQ0 (Delahunt, Kennelly, *et al.*, 2011). Both the SQ45 and SQ0 are sensitive at detecting differences in AGP athletes when compared to uninjured controls. With the contrast in findings regarding which position produced more force, and as the tests are quick and easy to administer, future research should include both positions.

Only one study examined SQ tests from pre- to post-rehabilitation in a cohort of athletes with AGP. The authors reported a significant increase in the SQ0 and SQ45 scores post-rehabilitation of medium effect sizes (*d* = 0.68 and 0.65, respectively). In addition, both tests were reported pain-free by all athletes following successful rehabilitation. Therefore, the SQ tests appears to be an important tool in examining the effectiveness of rehabilitation. In support of this, previous research has found that both reduced strength (mean difference in scores of 49 mmHg when examined with the sphygmomanometer or 53N with the hand-held dynamometer) and pain during the SQ45 test could differentiate athletes with AGP when compared to uninured controls.

In conclusion, the SQ test is sensitive at detecting strength deficits in athletes with AGP. There is consistent level I evidence for the SQ45 test and consistent level III and IV evidence for the SQ0 test. It remains unclear as to which position is most optimal for testing based on maximum force output and research should therefore include both test positions. In addition, the SQ test can be used to measure the effectiveness of rehabilitation and may potentially be used to aid in the comparison of different interventions.

Reactive strength

Isometric hip strength can provide important information regarding local muscle function; however, it does not adequately reflect the reactive strength quality characteristic to the performance of many sporting actions (e.g. change-of-direction, jumping). Reactive strength refers to the ability of an athlete to rapidly transfer from an eccentric to concentric muscle contraction utilizing the stretch-shorten-cycle (SSC) (Bobbert, Huijing and Schenau, 1987; Flanagan, Ebben and Jensen, 2008). This strength quality facilitates the rapid expression of muscular force and may be important from an injury and rehabilitation perspective (Markovic et al 2010). However, to date no study has examined reactive strength in this in relation to AGP.

Increased reactive strength may help shield against injury by providing dynamic stability to prevent excessive joint motion and potentially harmful loads (Chimera *et al.*, 2004; Hewett *et al.*, 2005). In addition, it has been reported that following injury reactive strength capacity is commonly lost and may have consequences for athletes safely returning to sports (Manske and Reiman, 2013). Deficits in reactive strength have been reported in other common lower limb pathologies including knee injuries (Angelozzi *et al.*, 2012; Nunes, Barton and Serrão, 2018), Achilles tendinopathy (Wang *et al.*, 2011), ankle (Doherty *et al.*, 2015) and hamstring strains (Opar *et al.*, 2013). Importantly, training programs utilizing plyometric exercises have been shown to improve reactive strength capacity (de Villarreal, Requena and Newton, 2010) and therefore rehabilitation programs which target reactive strength deficits may help play a role in preventing future injury as a means of tertiary prevention (Markovic & Mikulic, P., 2010; Maestroni *et al.*, 2020).

Reactive strength has been quantified using the reactive strength index (RSI) which, when used with a drop jump, is calculated by dividing jump height (meters) by the ground contact time (seconds) (Young, 1995). The RSI is most commonly assessed during a drop jump which is a quick and easy test that can be conducted in all rehabilitation settings. The drop jump generally examines the fast SSC with ground contact times ≤ 250-300ms (as opposed to the slow SSC with ground contact times >300ms) (Wilson and Flanagan, 2008) which is importance in AGP athletes as many actions that typically cause pain (e.g. change-of-direction, single leg hop) occur in times < 300ms (Marshall *et al.*, 2016).

The investigation of reactive strength in AGP athletes may provide important insights in neuromuscular function that is not adequality examined with the traditional local hip strength testing typically performed on athletes with AGP. In addition, examining the effect of rehabilitation on reactive strength may provide targets that can enhance management strategies, can be used in the return-to-play decision making process and are easily examined in rehabilitation settings.

Hip Joint Range-of-Motion

Clinical observation would suggest that reduced passive hip range-of-motion (ROM) is common in the presentation of athletes with AGP. It is hypothesized that reduced mobility may lead to overload on the hip joint, surrounding soft tissue structures and/or adjacent pubic region (Bedi *et al.*, 2011; Birmingham *et al.*, 2012). As such measurement of passive hip ROM is a common part of the clinical assessment for athletes' with AGP (Delahunt *et al.*, 2015). However, within the literature two high quality systematic reviews, Mosler *et al.*, (2015) and Tak *et al.*, (2017), have reported conflicting findings. Mosler et al (2015) included five case-control studies investigating passive hip ROM and reported strong evidence that reduced prone hip internal rotation range and also bent knee fall out range were associated with AGP. Furthermore, these authors reported moderate evidence that reduced supine hip internal rotation measured with the hip and knee at 90° flexion was also associated with AGP. In contrast, Tak et al (2017) synthesized the findings from seven prospective cohort and four case-control studies and reported strong evidence that reduced supine hip internal rotation range, hip abduction, and hip extension range were not associated in AGP.

Due to these conflicting findings further research is required to provide further insight into the importance of hip ROM and AGP. In our clinical practice, in the assessment of AGP patients we would commonly find reduced supine hip flexion internal rotation range and following successful rehabilitation ROM would be restored. Very few studies have examined hip ROM pre- to post-rehabilitation and this may provide important insight into this clinical observation. It has been well established that bony morphological changes to the femoral neck (cam morphology) can reduce hip ROM (Reichenbach *et al.*, 2010), however restoration of hip mobility following rehabilitation may suggest that other factors such as muscular imbalances or increased muscular spasm was the cause of reduced hip mobility (Ibrahim, Murrell and Knapman, 2007) and therefore provide important targets for rehabilitation.

2.8 AGP intervention programs

Exercise-based rehabilitation is commonly employed as the primary treatment for athletes with AGP (Jansen *et al.*, 2008). It has been demonstrated that return to play (RTP) times and rates are either superior or equivalent to surgical or passive (e.g. massage, electrotherapy, stretching) interventions (Hölmich *et al.*, 1999; Weir *et al.*, 2010; King *et al.*, 2015). However, a wide variety of exercised-based rehabilitation programs exist within the literature and the key components (e.g. hip strength, core strength, flexibility, running) underpinning successful rehabilitation remain unclear. In addition, it is important to examine how program success is defined in order to compare the effectiveness across intervention studies. Greater insight into the components of successful rehabilitation and how the effectiveness of intervention programs is evaluated may be used to enhance rehabilitation strategies. The following section will review the published intervention studies which have targeted AGP.

Overall twelve studies were identified including two randomized control trials (Hölmich *et al.*, 1999; Weir *et al.*, 2010), six case-series (Rodriguez C, Miguel A, Lima H, 2001; Wollin and Lovell, 2006; Verrall *et al.*, 2007; Yuill, Pajaczkowski and Howitt, 2012; King, Franklyn-Miller, *et al.*, 2018; Yousefzadeh *et al.*, 2018) and four case-reports (McCarthy and Vicenzino, 2003; Jarosz, 2011; Vijayakumar, Nagarajan and Ramli, 2012; McAleer *et al.*, 2015). Table 2.8.A presents an overview of the intervention studies and summary of the included rehabilitation components. Considering specific diagnoses, six studies investigated athletes with pubic-related AGP (Rodriguez C, Miguel A, Lima H, 2001; McCarthy and Vicenzino, 2003; Verrall, Slavotinek, Barnes and Fon, 2005; Wollin and Lovell, 2006; Jarosz, 2011; Vijayakumar, Nagarajan and Ramli, 2012) three with adductor-related AGP (Hölmich *et al.*, 1999; Weir *et al.*, 2010; McAleer *et al.*, 2015), one with inguinal-related AGP (Yuill, Pajaczkowski and Howitt, 2012) and one study which included all AGP diagnoses (King, Franklyn-Miller, *et al.*, 2018). It is common for athletes to present with multiple co-existing pathologies located on the anterior pelvis (Hölmich, 2007; Bradshaw, Bundy and Falvey, 2008; Falvey *et al.*, 2015) and limiting participants in a study based on having only a single diagnosis may be ineffective. Therefore, the inclusion of all clinical presentations of AGP, as per the intervention study by King et al (2018), may allow important insights in rehabilitation factors which can off-load the anterior pelvis and improve multiple structures concurrently.

Table 2.8.A. Summary of intervention studies

Characteristics			Intervention Summary		
Author **[study design]**	**Subjects** **(sport played)**	**Diagnosis** **[Sx duration weeks]**	**Rehabilitation components** **[co-intervention]**	**Supervised (S), Unsupervised (US), frequency/week, Duration**	**Strength component**
Holmich et al (1999) [RCT]	26 M AGP, range 18-50yrs 34 M CON, range 18-50yrs (soccer, other)	Adductor-related [39.6]	Strength hip (ADD, ABD), abdominal Balance [cycling]	S, US, 3/week minimum 8-12 weeks	ADD - ISO squeeze, slide board ADD/ABD- lying leg raises, stand pull Back extensors - prone lifts Abdominal - sit-ups Balance – SLS
Weir et al (2010) [RCT]	25 M AGP, 27.4 ±7.3yrs 29 M CON, 29.0 ±8.2yrs (FBS, running, speed skating)	Adductor-related [32 (IQR 17-81.2)]	Strength hip (ADD, ABD), abdominal Balance Running program [cycling]	US, 3/week minimum 8-12 weeks	ADD - ISO squeeze, slide board ADD/ABD- lying leg raises, stand pull Back extensors - prone lifts Abdominal - sit-ups Balance -SLS
Yousefzadeh et al (2018) [case-series]	15 M AGP, 26.13 ±4.48 SD) (Soccer, runner -Elite, sub-elite)	Adductor-related [90 ± 84]	Strength hip (ADD, ABD, EXT), abdominal Adductor stretch Balance Running program	S, 3/week minimum 10-12 weeks	ADD - ISO squeeze, slide board, copenhagen ADD/ABD - standing pull ABD - slide plank, EXT - SL bridge Back extensors - prone lifts Abdominal - V-holds, sit-ups, prone bridge Balance - SLS

King et al (2018) [case-series]	120 M AGP, 24.9yrs ± 5.1 (GAA, soccer, rugby, elite, sub-elite)	All entities PA 132 (64%) Iliopsoas 8 (4%) Adductor 35 (17%) Hip 30 (15%) [32 (IQR 20 - 52)]	Strength hip (ABD, FLEX, EXT, ER), abdominal. Compound strength. Plyometric Linear running. Change-of-direction running [nil]	S, US, 4/week Individual basis (pain, exercise competency)	ABD - band turn out, hip hitch ER - turn out Abdominals - banded pulls, pallof Compound - squat, deadlift, split squat Plyometric - skips, side shuffle COD - 180 cut
Verrall et al (2007) [case-series]	27 M AGP 23yrs ± 3.5 (AFL - elite)	Pubic-related bone stress injury (100%) [9 ± 36]	Rest period 3-month Core/pelvic stability program Linear run program [Swimming, upper body weights cycling, vera Climber]	U, NR Minimum 12	Core/pelvic stability
Rodriquez et al (2001) [case-series]	35 M AGP 18.97yrs ±2.89 (Soccer - elite)	Pubic-related Osteitis pubis (100%) [NR]	Strength (ABD, ADD), abdominal Flexibility adductors Running program Kicking exercises [Oral Ibuprofen, therapeutic modalities (cryomassage, laser, US or e-stim), cycling, swimming]	NR, NR Individual basis (pain)	ABD,ADD - elastic band
Wollin & Lovell (2006) [case-series]	4 M AGP 16.5yrs ± 0.58E (Soccer)	Pubic-related Osteitis pubis (100%) [22]	Strength hip (ADD, ABD, FLEX, EXT), abdominal Running program [ultrasound, compression shorts, cycling, upper body weights]	S, NR Individual basis (pain, exercise competency)	ADD - ISO, pulley ECC to CON loading, skating slide board FLEX/EXT/ABD - elastic bands Abdominal - pelvic floor and TrA
Yuill et al (2011) [case-series]	3 M AGP, 23.3yrs ±5.5 (Soccer – elite, reactional)	Inguinal-related (100%) [5.5]	Strength hip (ADD, ABD, EXT), abdominal. Balance. Plyometrics [Soft tissue therapy, laser therapy, microcurrent acupuncture , NSAIDs]	S, 3/wk 8 weeks	ADD – pulley. ABD - wall bangers, hip drops, side walking (resisted). EXT - glute bridge Compound - clock squats, lunge, step ups, single leg squat, sled pulls Balance-rocker, BOSU, Janda sandals Plyometric –hops, split squat, skipping,

					depth jumps, agility ladder, zig zag drills
McCarthy & Vincenzio (2003) [case report]	1 M AGP 20yrs (Gaelic – sub-elite)	Pubic-related [6]	Strength hip (ABD), abdominal Stretching (quadriceps, hip flexor, adductors). Movement pattern re-train [Massage]	S, 1-2/week 5 weeks	ABD - NR Abdominal - TrA, swiss ball
Jarosz (2011) [case report]	1 M AGP 20 (AFL – sub-elite)	Pubic-related [32]	Hip strength (ADD, ABD, EXT) Abdominal strength, running program, Kicking program [Spinal manipulative therapy Myofascial release PNF stretching Cycling]	S, 1/week Individual basis (pain)	ADD - ECC to CON slides ABD/EXT - glute bridge resisted abduction Abdominals - TrA, swiss ball rotation, side flex
Vijayakumar et al (2012) [case report]	1 M AGP 15yrs (Soccer – youth)	Pubic-related [24]	Strength hip (ADD, ABD, FLEX, EXT, IR, ER), abdominal Compound squat, lunge [Heat, PNF stretching, hydrotherapy, upper body weight]	S, 5/week Individual basis (pain)	ADD, ABD, FLEX, EXT - machine resistance ABD - side step in squat position resisted band. IR, ER - manual resistance Abdominal TrA, crunches Compound - squats (BW), lunge
McAleer et al (2015) [case report]	1 M AGP 23yrs (Soccer – elite)	Adductor-related [12]	Strength hip (ADD, ABD), abdominal, compound. Running program Pitched-based [Medication, soft tissue massage]	S, NR Individual basis (pain, exercise competency)	ADD - Copenhagen, cable resisted, side lunge. Abdominal - TrA, bent knee fall-outs, wood-chops Compound - squats, lunge, side lunge, split squat, step-ups

Sx – symptoms, RCT – randomised control trial, M – male, FBS – field -based sports, AFL – Australian rules football, PA – pubic aponeurosis, ADD – adductor, ABD – abductor, EXT – extensors , FLEX – flexors, IR – internal rotators, ER – external rotators, NR – not reported, ISO – isometric, CON – concentric, ECC – eccentric , CON – concentric, SL – single leg, SLS single leg squat, TrA – transverse abdominis , BW - body weight

Many different rehabilitation components were utilized in the intervention studies including strength (i.e. hip, core, compound, explosive), balance, movement technique training, running and kicking programs. The most utilized component of rehabilitation was the inclusion of strength-based exercises. Targeted hip strength exercises were included in all but one study (Verrall *et al.*, 2007) and the adductors were the most frequently targeted muscle group with all but two studies including adductor strength exercises (McCarthy and Vicenzino, 2003; King, Franklyn-Miller, *et al.*, 2018). In addition, four studies included general lower limb compound strength exercises (e.g. squat, lunge, deadlift) (McCarthy and Vicenzino, 2003; Vijayakumar, Nagarajan and Ramli, 2012; McAleer *et al.*, 2015; King, Franklyn-Miller, *et al.*, 2018) and two studies included explosive strength (e.g. plyometric) exercises (Yuill, Pajaczkowski and Howitt, 2012; King, Franklyn-Miller, *et al.*, 2018). Ten of the twelve studies utilized an external load (e.g. elastic bands, free-weights, body weight) to stimulate a strength adaptation to the hip muscles (Hölmich *et al.*, 1999; Rodriguez C, Miguel A, Lima H, 2001; Wollin and Lovell, 2006; Weir *et al.*, 2010; Jarosz, 2011; Vijayakumar, Nagarajan and Ramli, 2012; Yuill, Pajaczkowski and Howitt, 2012; McAleer *et al.*, 2015; King, Franklyn-Miller, *et al.*, 2018; Yousefzadeh *et al.*, 2018). However, despite the vast majority of studies employing a strength component of rehabilitation, only two studies objectively measured hip strength pre- to post-intervention: one case-series (Yousefzadeh *et al.*, 2018) and one case report (McAleer *et al.*, 2015). Both of these studies reported increased hip strength following rehabilitation; however, without a control group two issues arise. Firstly, it is unclear if the increase in strength was the result of the broad neuromuscular changes that can occur with rehabilitation programs or the resolution of a potential risk factor. Secondly, the strength increase cannot be compared to a 'normal' strength value as defined by a control group, and therefore the magnitude of any increase remains unclear. It is therefore of great clinical interest to better understand how AGP affects hip strength and subsequently how specific deficits are affected by rehabilitation.

Subjective and objective outcome measures were used to examine the effectiveness of intervention programs and are outlined in Table 2.8.B. Considering subjective measures, only one study used a validated and reliable patient reported outcome measure (King, Franklyn-Miller, *et al.*, 2018) and all other studies used the resolution of symptoms and/or pain to assess patient reported outcomes. Patient-reported outcomes (PROs) can provide greater insight into program effectiveness across a number of different areas (e.g. daily function, quality of life, sporting participation) and are therefore preferred over the assessment of pain and symptoms alone. The use of PROs in relation to AGP will be explored in detail in section 2.9.

Table 2.8.B. Summary on outcome measures used from intervention studies.

	Outcomes				Results				
Author	Subjective	RTP	O/E	Strength	End criteria [follow-up]	Subjective	RTP rate % RTP time [weeks]	O/E	Strength
Holmich et al (1999)	Pain-free palpation/RSC /sport activity, RTP Subjective global assessment	play = same level. Pain-free	ROM V02max	ADD (subjective)	Pain-free treatment and pain free jogging [No]	Much better category Passive 43% Exercise 76% p=0.006	Passive 14% Exercise 79% RTP p=0.001 [18.5]	ROM score NR Increased in both groups p=0.0004	ADD strength p=0.001
Weir et al (2010)	Pain-free palpation/RSC /sport activity, RTP	play = same level. Pain-free	ROM Flex IR/ER and total	No	pain free treatment and pain free jogging [No]	Excellent category Passive 27% Exercise 23% p=0.72	Passive 50% Exercise 55% p=0.78 [Passive 12.8 Exercise 17.4 p=0.043]	ROM baselines Flex IR 25 (11) Flex ER 39 (12) Total ROM 64 (17) ISQ both groups and between groups ROM p=0.45, p=0.65	No

Yousefzadeh et al (2018)	VAS pain, bilateral adductor squeeze and function	play = same level. Pain-free	ROM Ext IR, supine ABD T-test Edgren Side-step Test (ESST) Triple hop distance (THD)	ABD, ADD ISO, ECC Ratio ADD:ABD (HHD)	10 or 12 weeks [20-week, weekly]	VAS pain SQ p=0.0001 VAS function p=0.0001	86.60% [12.06 ± 3.4]	Hip ROM ABD p=0.0001 Hip ROM Flex IR p=0.006 t-test p=0.0001 ESST p=0.0001 THD p=0.0001	ADD ISO p=0.0001 ABD ISO p=0.0001 ADD ECC p=0.0001 ABD ECC p=0.0001 Ratio ADD:ABD ISO p=0.006 Ratio ADD:ABD ECC p=0.009
King et al (2018)	HAGOS	Play = unrestricted Completion of running program (linear, COD), pain-free SQ, symmetrical ROM	Squeeze test (0°, 45°, 90°)	No	Pain free squeeze, running, COD Symmetrical ROM [No]	HAGOS all scales p<0.05 ES 0.59-1.78	73% [9.9 ± 3.5]	Squeeze test p<0.05, ES 0.46-0.68 Joint kinetics Joint kinematic	no
Verrall et al (2007)	Subjective assessment of function (1) Playing (2) Without symptoms (3) Playing at	Play = pain-free training (30min)	Squeeze Test (0°, 45°)	No	Pain-free training (30min) [5,7,12,18, 24-month]	No	5mth 41% pain-free 63% symptoms 12mth 67% pain-free 24mth 81% pain-free	Positive Squeeze test (12week) in relation to pain during subsequent playing season p<0.01	nil

	a lower level competition						74% same level competition [NR]		
Rodriquez et al (2001)	Nil	NR	No	No	NR	No	NR [3.8-10]	No	No
Wollin & Lovell (2006)	Re-injury	Play = training Completion of running program (linear, COD, kicking), pain-free squeeze	Squeeze test (0°, 60°) 20m shuttle run 5m and 20m sprint test	No	Pain free training & palpation. Strong SQ (0, 60) [12-15-month]	Nil re-injuries	100% [10-16]	NR	No
Yuill et al 2011	VAS pain Re-injury	Play = unrestricted VAS score 0/10	NR	No	VAS score 0/10 [24-month]	Nil re-injuries	100% [8-9]	NR	NR
McCarthy & Vincenzio (2003)	Symptom-free running (2km)	Play = unrestricted	No	No	Symptom resolution running 2km [3-month]	pain-free running (2km)	100% [5]	No	No
Jarosz 2011	Pain reported during function	Play = full training	Squeeze test (unilateral and bilateral)	ADD, ABD abdominals (subjective)	Symptom resolution rehab	Nil re-injury	100% [4]	Squeeze test pain-free Hip ROM increased	No

			Hip ROM (Thomas test, abduction)		program, squeeze test [season]				
Vijayakumar et al. 2012	NR	Play = jogging/soft soccer skills	Hip ROM (Flex, Ext, IR, ER, add, abd)	ADD, ABD, FLEX, EXT, IR, ER (Subjective)	NR	No	100% [14]	NR	NR
McAleer et al. 2015	Pain during ADLs, function, squeeze test, linear running, COD	Play = match	Hip ROM Squeeze test (0°, 45°, 90°) Running speeds	ADD, ABD (HHD)	Symptoms resolution, pain-free squeeze, linear run, COD, training [No]	No	100% 12.5]	NR	NR

RSC – resisted static contraction, O/E – objective examination, RTP – return-to-play, VAS – visual analogue scale, HAGOS – hip and groin outcome score, COD – change-of-direction, ADL – activities of daily living, ROM – range-of-motion, ADD – adductor, ABD – abductor, EXT – extensors , FLEX – flexion, IR – internal rotation, ER – external rotation, NR – not reported, ECC – eccentric ISO – isometric, , ISQ – in status quo , SQ – squeeze test.

Objective outcome measured were utilized in all intervention studies, however, the reporting of results was poor making comparison between studies difficult. Hip range-of-motion (ROM) was the most commonly examined objective measure in six studies (Hölmich *et al.*, 1999; Weir *et al.*, 2010; Jarosz, 2011; Vijayakumar, Nagarajan and Ramli, 2012; McAleer *et al.*, 2015; Yousefzadeh *et al.*, 2018) but only two studies (Weir *et al.*, 2010; Yousefzadeh *et al.*, 2018) reported ROM values. Also, hip strength was examined in five studies (McAleer *et al.*, 2015; Yousefzadeh *et al.*, 2018) but only one study reported the strength values (Yousefzadeh *et al.*, 2018).

In addition to post-intervention measures, long term follow-up is also crucial when assessing the effectiveness of rehabilitation and this was only conducted in half of the intervention studies. Follow-up times ranged from 3 to 24 months and assessed symptoms (McCarthy and Vicenzino, 2003; Verrall *et al.*, 2007; Yousefzadeh *et al.*, 2018), level of competition (Verrall *et al.*, 2007) and injury recurrence (Wollin and Lovell, 2006; Jarosz, 2011; Yuill, Pajaczkowski and Howitt, 2012; Yousefzadeh *et al.*, 2018), however no study utilized a validated PRO. Assessing the long-term effectiveness of intervention programs is of particular importance in AGP as re-injury rates have been reported to range from 5-41% (Orchard *et al.*, 2001; Werner *et al.*, 2019).

Summary

Exercise-based rehabilitation for AGP is effective at returning athletes to sporting activity and strength-based rehabilitation is the most common approach. As hip strength is the main target for rehabilitation improved reporting on objective strength measures pre- to post-rehabilitation is required. Furthermore, the use of validated PROs is required to examine the effectiveness of intervention programs both on completion and long-term follow-up. PROs would also allow compassions between different intervention studies.

2.9 Patient Reported Outcome Measures

A patient reported outcome (PRO) is any measure of a patient's health status that comes directly from the patient (FDA, 2006). Most commonly in sport medicine, these are condition-specific questionnaires (e.g. groin pain, patellofemoral pain) which can assess a number of specific health-related constructs including pain, symptoms, disability, function and quality of life (QOL) (Mokkink *et al.*, 2010). PROs are of vital importance in assessing the effectiveness of an intervention from the patient's perspective (Patrick *et al.*, 2007; Lynch *et al.*, 2015), monitoring athletes once they have returned to sporting activities (Hinman *et al.*, 2014) and can be used to compare outcomes across different interventions and athletic groups (Mokkink *et al.*, 2010; Thorborg *et al.*, 2011). In relation to hip and groin research in athletic populations, the use of PRO questionnaires has recently been advocated as a minimum standard of data collection (Delahunt *et al.*, 2015).

AGP specific patient reported outcome measures

The Hip & Groin Outcome Score (HAGOS) is the only questionnaire that has been designed for use in both hip and groin conditions (Delahunt *et al.*, 2015). This is of key importance in AGP populations, where typically a patient's primary concern is groin-related pain (Weir *et al.*, 2015). HAGOS is a valid, reliable and responsive questionnaire (Thorborg *et al.*, 2015) that has been used in a number of athletic populations including: Gaelic football (Nevin and Delahunt, 2014), Australian Rules football (Drew *et al.*, 2017) and soccer (Thorborg, Branci, Stensbirk, *et al.*, 2014). It has demonstrated the ability to differentiate between those with and without groin pain (Mosler *et al.*, 2015). The questionnaire consists of six sperate subscales including: pain, symptoms, physical function in daily living, physical function in sports and recreation, participation in physical activities, and hip-related and/or groin-related quality of life. Subscales are scored separately with 0 indicating extreme hip/groin problems and 100 indicating no problems (Thorborg *et al.*, 2011). It is quick and easy to administer making it practicable for use in clinical and research settings.

HAGOS has previously been used to assess the effectiveness of an AGP rehabilitation program (King, Franklyn-Miller, *et al.*, 2018) and also to monitor hip and groin problems during a 22-week in-season period in youth soccer players (Wollin *et al.*, 2018). However, to date no study has utilized HAGOS to monitor long-term recovery in AGP following rehabilitation. Given the high reinjury rates reported in AGP (Orchard, 2015; Werner *et al.*, 2019) and susceptibility to re-injury during the early return-to-play period post-rehabilitation (Orchard and Best, 2002; Blanch and Gabbett, 2016) this may provide important insight into hip and groin function once returned to play and may help to enhance ongoing management strategies. Furthermore, it is unclear if the improvements observed in HAGOS following rehabilitation are related to objective measures of function (e.g. strength). Examining the relationship between the pre to post change in HAGOS and objective measures of function may help to better inform the return-to- play decision making process and provide useful targets to enhance rehabilitation programs.

Activity Level Questionnaires

In addition to condition-specific PRO, such as HAGOS, activity level questionnaires have been advocated to improve the generalizability of results across varied athletic populations (Marx *et al.*, 2001; Negahban *et al.*, 2011). Athletes returning to sport post-injury may do so at different times of the season (e.g. during season versus off-season) or with different training requirements (e.g. modified training versus unrestricted training) and therefore it is important to consider their level of disability and function in the context of sporting activities. The Marx scale is a commonly used activity rating instrument which is reliable, valid and responsive measure (Marx *et al.*, 2001; Negahban *et al.*, 2011). It is determined by measuring components of physical function (e.g. running and change-of-direction) that are common across most sporting activities and therefore can be used to compared athletes across different sporting codes and levels of competitions. The Marx scale contains four questions concerning the weekly frequency of common athletic tasks including: running, cutting, decelerating and pivoting, and is completed in less than two minutes using a Likert scale (0 = less than 1 per month, 1 = 1 x per month, 2 = 1 x per week, 3 = 2-3 x per week, 4 = 4 or greater per week, maximum 16 minimum 0). The Marx scale is important post-rehabilitation to assess if an athlete has returned to their pre-injury level of sporting activity (Irrgang, 2008).

2.10 Literature Review Summary

Athletic groin pain continues to be a challenging injury for many athletes playing multi-direction field sports (Orchard, 2015). The injury and reinjury rates have not changed over fifteen years of injury surveillance in men's professional football (Werner *et al.*, 2019). The high forces exerted on the anterior pelvis during repetitive jumping, change-of-direction, acceleration and deceleration actions common to many field sports may lead to excessive loading on multiple fascial and myotendinous structures common to AGP (Meyers *et al.*, 2007; Falvey *et al.*, 2015). Our understanding of the pathomechanics of AGP is very limited and has largely been confined to simple clinical measures such as hip strength or hip range-of-motion (Hölmich *et al.*, 1999; Tyler *et al.*, 2001; Tak *et al.*, 2017). More recently, research has investigated whole-body biomechanics during multi-planar tasks to better understand how AGP effects movement patterns (Edwards, Brooke and Cook, 2016; Janse van Rensburg *et al.*, 2017, Gore *et al.*, 2018, 2020; King *et al.*, 2018). Various aberrant movement patterns have been identified at the trunk, hip and ankle across of variety of tasks (e.g. hopping, change-of-direction cutting) in AGP groups when compared to healthy athletes (Janse van Rensburg *et al.*, 2017; Gore *et al.*, 2018, 2020; Rivadulla *et al.*, 2020). However, there is a significant paucity of research and findings are inconsistent suggesting the need for further examination of these tasks. In addition, given the task dependency of these findings it is of value to examine other movement tasks which have provided important insights into the injury mechanics of other lower limb injuries (e.g. countermovement jumps (Jordan, Aagaard and Herzog, 2015; Baumgart, Hoppe and

Freiwald, 2017)) or allows the examination of movement variability (e.g. continuous movement tasks (Harbourne and Stergiou, 2009)).

Our current understanding of the key rehabilitation factors for AGP is limited. This is evident by the fact that the only consistent risk factor for AGP is a previous history of hip or groin injury (Ryan, DeBurca and Mc Creesh, 2014; Whittaker *et al.*, 2015). The majority of published intervention programs have focussed on strengthening of the hip musculature, however, only one study has objectively examined the pre- to post-rehabilitation change in hip strength (Yousefzadeh *et al.*, 2018). In addition, very few studies have examined the change in whole-body movement patterns following rehabilitation (Gore *et al.*, 2018, 2020; King, Franklyn-Miller, *et al.*, 2018). This is vitally important given the suggested relationship between poorly controlled movement technique and repetitive excessive loading on the anterior pelvis (Franklyn-Miller *et al.*, 2017). Therefore, further research is required to better understand the effectiveness of rehabilitation programs on hip strength and whole-body movement patterns. Finally, no study has investigated the long-term effectiveness of rehabilitation in AGP using a validated PRO and this is of vital importance given the high re-injury rates reported.

To improve understanding of how biomechanical and strength factors are related to AGP many previous studies have solely utilized a case-control approach of comparing injured versus uninjured participants (Malliaras *et al.*, 2009; Morrissey *et al.*, 2012; Edwards, Brooke and Cook, 2016; Janse van Rensburg *et al.*, 2017). While providing useful information, one limitation is that findings may not be deterministic of injury but rather occur as a result of the injury itself. An alternative, but less utilized approach, involves additionally including an examination of an effective rehabilitation intervention to determine how the specific variables that differ between injured and uninjured groups are affected by an intervention. This invokes the concept of probabilistic causation whereby significant findings in both analyses (i.e. case-control and pre- to post-rehabilitation comparison) are more likely related to the injury as compared to using either approach in isolation and therefore provide important targets which may be used to enhance rehabilitation programs (Spirtes, Glymour and Scheines, 2000; Marshall and Moran, 2015; Gore *et al.*, 2018).

The overall primary aim of this PhD was to examine biomechanical and strength factors related to AGP and how these factors change with rehabilitation. A secondary aim was to examine the long-term effectiveness of rehabilitation using a validated PRO.

Chapter 3

Movement variability and lower limb injuries: A systematic review

This review has been published in full:

Samuel R. Baida, Shane J. Gore, Andrew D. Franklyn-Miller & Kieran A. Moran 2017. Does the amount of lower extremity movement variability differ between injured and uninjured populations? A systematic review. Scandinavian Journal of Medicine & Science in Sports.

It is presented in this chapter with only minor formatting changes to conform to this thesis.

3.1 Abstract

Movement variability during repetitive performance of a dynamic activity (e.g. running, jumping, kicking) is considered an integral characteristic of optimal movement execution, however, it's relationship with musculoskeletal injury is not known. The primary aim of this paper was to review published comparison trials to determine if movement variability differs between uninjured controls and subjects with a lower limb musculoskeletal injury.

A systematic search of online databases; Medline, Sports Discus, Scopus and Web of Science was conducted from July to November 2016. Studies were selected if they: (1) included participants with a lower limb injury, (2) compared injured participants to uninjured controls, (3) examined movement variability for at least one dependent variable, and (4) provided a statistical between-group comparison when comparing measures of movement variability. Studies were excluded if they: (1) investigated neurological disorders, (2) examined musculoskeletal injury in the upper extremity or spine, and (3) used non-linear measures to examine variability (i.e. complexity). A significant difference between injured and uninjured populations was reported in 73% of the included studies and of these, 64% reported greater movement variability in the injured group. This is the first systematic review with a best-evidence synthesis investigating the association between movement variability and musculoskeletal injury. Findings suggest that movement variability in those with a musculoskeletal injury differs from uninjured individuals. Interestingly, there was an overall trend towards greater

movement variability being associated with the injured groups; although it should be noted that this trend was not consistent across all sub-categories (e.g. injury type).

For a clearer insight into the clinical application of variability greater methodological homogeneity is required and prospective research is recommended.

3.2 Introduction

Variability in human movement can be defined as the natural variations in motor control strategies employed when performing multiple repetitions of the same task (Stergiou and Decker, 2011). This phenomenon was aptly described by Bernstein in 1967 as ‘repetition without repetition’ (Bernstein, 1967). Traditionally in biomechanical analysis variability has been treated as an error in movement, where the person attempts to reproduce the same exact movement but cannot, or noise arising from technical or measurement sources (Racic, Pavic and Brownjohn, 2009; Taylor *et al.*, 2015; Gore *et al.*, 2016). However, intra-individual variation in movement patterns between repetitive actions (e.g. stride cycle, hop task) is now considered an integral characteristic of any motor task (König *et al.*, 2016) allowing flexible adaptations to stresses placed on the human body (Stergiou, Harbourne and Cavanaugh, 2006). As such it is thought that movement variability has a functional role to play with respect to musculoskeletal injury (Bartlett, Wheat and Robins, 2007; Stergiou and Decker, 2011; Hamill, Palmer and Van Emmerik, 2012).

Movement variability can be assessed in terms of both the amount of variability and the structure of variability, which functionally represent different aspects of movement variability (Newell and Slifkin, 1998) and can vary independently of one another (Harbourne and Stergiou, 2009). To quantify the amount of movement variability linear statistical tools are utilized (e.g. standard deviation, coefficient of variation), whereas to quantify the structure of variability non-linear tools are utilized (e.g. sample entrophy, Lyapunov exponent) (Harbourne and Stergiou, 2009). While it would be of value to systematically review the literature on both forms of analysis, there are currently far fewer studies on the structure of variability, preventing robust conclusions from being drawn. Therefore, this review solely examines those articles investigating the difference in the amount of movement variability between injured and uninjured populations.

It has been postulated within the framework of dynamic systems theory (Hamill *et al.*, 1999), that reduced variability during movement might lead to repetitive loading on a specific tissue structure resulting in excessive stress and eventual injury (Harbourne and Stergiou, 2009). Several authors have provided further support for the association between injury and reduced variability in various injured groups including chronic ankle instability (Herb *et al.*, 2014) and patellar tendinopathy (Kulig, Joiner and Chang, 2015).

However, in direct contrast it has also been suggested that greater variability is associated with injury (Stergiou, Harbourne and Cavanaugh, 2006; Hamill, Palmer and Van Emmerik, 2012). In accordance with general motor program theory variations in movement may represent aberrant neuromuscular motor control (Schmidt, 2013) resulting in poorly controlled actions which may lead to excessive stress and injury (Hamill, Palmer and Van Emmerik, 2012). In support of this theory, numerous studies have found greater variability in a number of different injury groups including athletic groin pain(Edwards, Brooke and Cook, 2016), chronic ankle instability (Kipp and Palmieri-Smith, 2012) and iliotibial band syndrome(Miller *et al.*, 2008). With such contrasting evidence in the literature, there is a clear need for a systematic review investigating movement variability and its relationship with injury. To date this has not been conducted.

Both discrete (e.g. peak knee moment) and continuous measures (e.g. 0-100% of the knee moment waveform) have been examined when investigating inter-trial variability. Given that analysis of the whole continuous waveform has been shown to be more effective at detecting differences between groups (Richter, N. E. O'Connor, *et al.*, 2014; Marshall *et al.*, 2015) it would be useful to explore whether findings on movement variability is also affected by the type (discrete versus continuous) of analysis employed.

The primary aim of this systematic review is to investigate published comparison trials to determine if the amount of movement variability in dynamic tasks differs between groups with lower limb musculoskeletal injury and uninjured controls. In light of the diverse range of methods used, the secondary aim of this review is to provide methodological recommendations for future research.

3.3 Methodology

Protocol and Registration

This systematic review was registered (42016039113) with Prospero (Centre for Reviews and Dissemination), University of York, on 13/5/2016. The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement was used (Liberati *et al.*, 2009).

Search Strategy

A systematic search of the literature was undertaken independently by two authors (SB, SG) between June and September 2016 for clinical trials, case-comparison and cohort studies comparing movement variability between injured populations and uninjured controls. Databases, searched from inception until 01/09/16, included Medline, Sports Discus, Scopus and Web of Science. The terms applied in all database searches are presented in Table 3.3.A. These were combined using relevant Boolean terms and limits of English language and human population were placed on searches.

Table 3.3.A. Search terms

Population	injur* OR musculoskeletal
Outcome	Variability
Variables	Biomech* OR kinetic OR kinematic OR motor control OR coordination OR dynamic systems
NOT	upper* OR spine OR lumbar* OR arm OR back OR heart rate OR animal* OR Cadaver* OR rat* OR monkey OR frog OR robot* OR modelling OR pharma* OR mice OR cat* OR fish* OR DNA OR gene OR RNA

Selection Criteria

Three authors (SB, SG, KM) determined the selection criteria, as listed in Table 3.3.B, before commencing the search. This review only addresses measures that assess the amount of variability in movement, determined by linear analysis techniques applied to a time series (e.g. standard deviation, coefficient of variation, linear variation, range and circular variants of these metrics when examining coordination variability). This review does not examine non-linear analysis techniques (e.g. entropy measures and lyapunov exponent) that investigate the structure of variability throughout a time series.

Table 3.3.B. Selection criteria for literature search

Inclusion criteria	Exclusion criteria
Participants with a lower limb musculoskeletal injury Compared injured participants to uninjured controls Examined the amount of movement variability for at least one dependent variable Utilized linear tools to measure the amount of movement variability Provided a statistical between-group comparison when comparing linear measures of movement variability	Investigated neurological disorders Examined musculoskeletal injury in the upper extremity or spine Utilized non-linear measures to examine variability (i.e. complexity)

All studies investigating the amount of movement variability in lower extremity musculoskeletal injuries were included in this review. Musculoskeletal injury was defined as any acute or chronic injury episode that would have influenced both the peripheral (tissue damage) and central (spinal cord and brain) movement systems which may have led to altered movement patterns and variability of movement patterns. While it may be argued that patients who have undergone anterior cruciate ligament reconstruction (ACLR) are in fact recovered, we have included this population in this review. This is justified as potentially patho-mechanical movement strategies remain evident in this population 6 or more months following surgery (Gokeler *et al.*, 2010).

The two authors (SB, SG) independently applied the selection criteria when reviewing titles and abstracts and a full review of a manuscript was performed if selection was unclear. Disagreements were resolved by discussion or third-party consultation (KM). Reference lists of selected studies were examined in order to identify further relevant studies.

Data extraction and analysis

Data extraction was performed independently by the authors (SB, SG) using predefined data fields and then crossed-checked for accuracy. Data identified for qualitative analysis included type and location of musculoskeletal injuries, analysis techniques implemented, dependent variables utilized and physical tasks performed. The principle quantitative measure extracted for this review was the probability value used to identify significant between-group differences within a study. All of the variables examined within this review are listed within Appendix A along with the significant findings reported in the related studies. A meta-analysis of the studies was not possible due to the limited reporting of values and data for any one biomechanical measure. A qualitative analysis was therefore implemented to provide a best evidence synthesis and where possible a subgroup analysis between studies was performed (Yan *et al.*, no date; Pietrosimone *et al.*, 2008; Santamaria and Webster, 2010; Aderem and Louw, 2015; Undheim *et al.*, 2015). Where one study utilized various methodological approaches (tasks examined included both run and walk conditions, the dependent variables examined included both kinematic and spatiotemporal, or the analysis technique included both continuous point-by-point and discrete-point measures), both components were considered separately for analysis in the results section of this review.

Assessment for risk of bias

A modified version of the Downs and Black's checklist (Downs and Black, 1998) as proposed by Trac et al. 2016 (Trac *et al.*, 2016) was used to assess study quality (subscales include; reporting, external validity, internal validity, selection bias and power). This version changed the scoring of question 27 from 5 to 2, making 29 the total score of the 27 questions (Trac *et al.*, 2016). Studies were appraised independently (SB, SG).

3.4 Results

Overview of findings

The search method employed in this review identified 1053 studies. After titles and abstracts were reviewed 69 studies were retrieved; duplicates were then removed, leaving 37 studies for a full review. Of these 37 studies, 20 were excluded for the following reasons: (1) investigated variability using nonlinear approaches only (measures of complexity) (n=7), (2) provided no control group (n=5), (3) provided no inferential statistical comparison of movement variability (n=3), (4) did not measure variability (n=2), (5) were review papers (n=2), or (6) not relevant (n=1). This left 17 papers included for review from the database searches. *Pearling* of article bibliographies revealed an additional five studies adhering to the inclusion criteria. A final 22 papers were incorporated in this systematic review, which included the findings from 295 injured subjects and 319 uninjured controls. Figure 3.4.A presents a flow diagram of study inclusion.

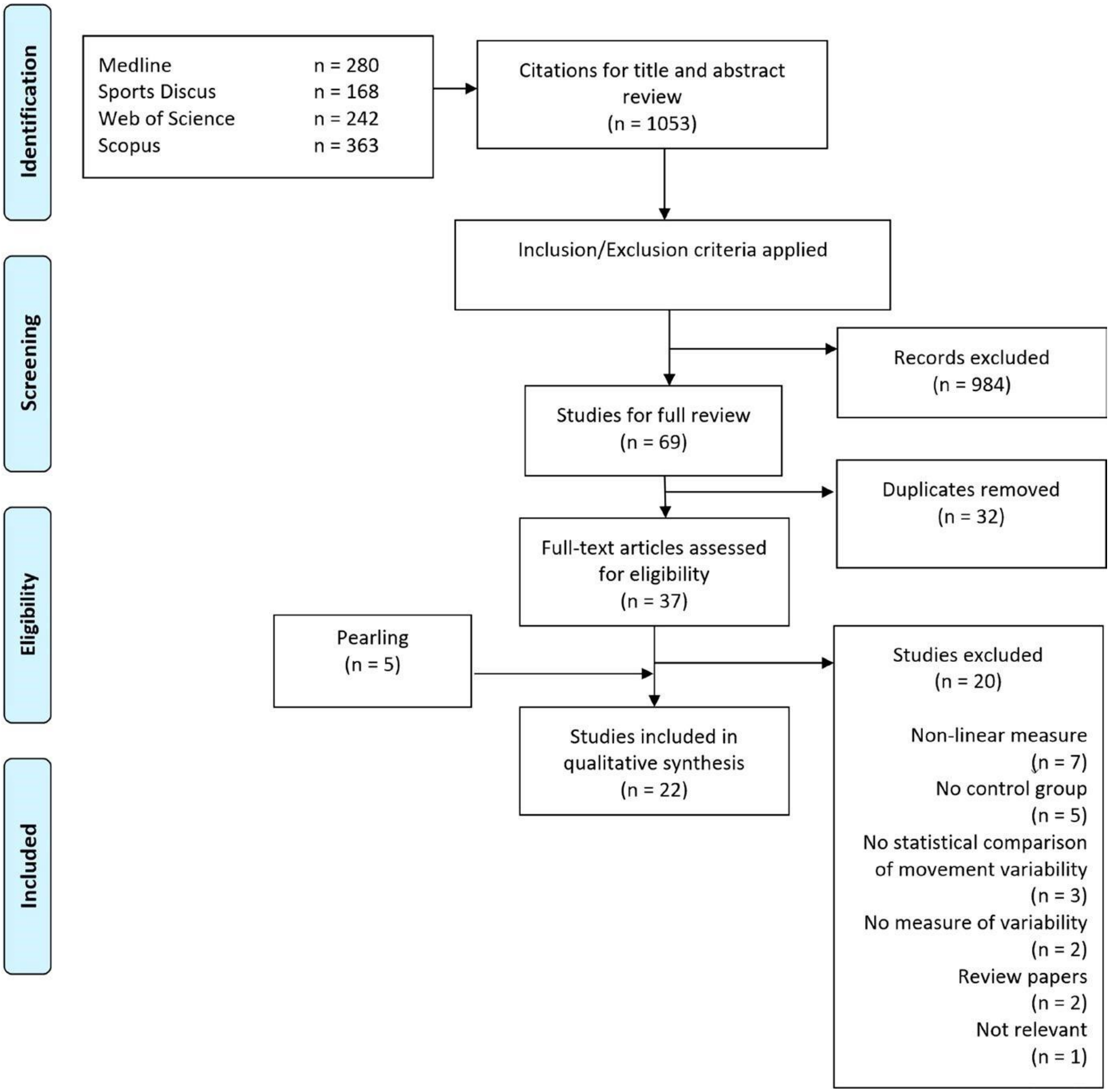


Figure 3.4.A. PRISMA flow diagram of search strategy

Quality appraisal scores using the modified Downs and Black's checklist (Trac *et al.*, 2016), presented in full in Appendix A2, ranged from 11 to 14 out of a possible 29 points with a median score of 12. No study received a point on the criterion scoring external validity (question 11, 12 and 13). Also criterion not fulfilled by any study included questions related to blinding, follow-up of patients' post-intervention and compliance with the intervention (questions 14, 15, 17, 19). Discrepancies in scores were based on points attained under the 'reporting' and 'power' sub-scales. Eighteen studies (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; Meardon, Hamill and Derrick, 2011; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2012; Hein *et al.*, 2012; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016) scored a point for clearly describing included subjects (criterion 3). Four studies (Heiderscheit, Hamill and Van Emmerik, 2002; Miller *et al.*, 2008; Cunningham *et al.*, 2014; Edwards, Brooke and Cook, 2016) scored a point for reporting adverse outcomes resulting from performance of the task (criterion 8). Eighteen studies (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Meardon, Hamill and Derrick, 2011; Brown, Bowser and Simpson, 2012; Hein *et al.*, 2012; Kipp and Palmieri-Smith, 2013; Cunningham *et al.*, 2014; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Pollard *et al.*, 2015; Cordeiro *et al.*, 2015; Paquette, Milner and Melcher, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016) scored a point by reporting actual probability values (criterion 10). Ten studies (Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Hein *et al.*, 2012; Cordeiro *et al.*, 2015; Mann *et al.*, 2015; Edwards, Brooke and Cook, 2016; Paquette, Milner and Melcher, 2016) scored a point for reporting calculation of sample size (criterion 27).

A summary of the main subject and analysis characteristics extracted for each study is presented in table 3.4.A. Overall findings revealed that 73% (n=16/22) of studies reported a statistically significant difference in at least one dependent variable used to examine movement variability between injured subjects and uninjured controls. Injured subject groups demonstrated greater variability in 64% (n=14/22) of the studies (James, Dufek and Bates, 2000; Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2013; Cunningham *et al.*, 2014; Pollard *et al.*, 2015; Cordeiro *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016), reduced variability in 27% (n=6/22) (James, Dufek and Bates, 2000; Miller *et al.*, 2008; Brown, Bowser and Simpson, 2012; Herb *et al.*, 2014; Kulig, Joiner and Chang, 2015; Timothy C. Gribbin *et al.*, 2016) and no difference between groups was evident in 27% (n=6/22) (Ferber *et al.*, 2005; Drewes *et al.*, 2009; Meardon, Hamill and Derrick, 2011; Hein *et al.*, 2012; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016). Table 3.4.B presents the percentage of studies reporting greater, less or no difference in variability when comparing injured subjects to uninjured controls.

Table 3.4.A. Summary of subject and analysis characteristics

Author	Subject characteristics						Analysis characteristics				Significant Finding
	Group	INJ	UNINJ	Impaired region	Variability Analysed	Pain Present	Task Performed	Number of Trials	Additional Technique	Variability Metric	
ACLR											
(van Uden *et al.*, 2003)	ACLR	13	7	knee	Knee- ankle	No	Single leg hopping	10 seconds	CRP	SD	**> Knee-Ankle**
(Cordeiro *et al.*, 2015)	ACLR	8	9	Knee	Knee	Yes	In-step soccer kick	3 kicks	-	SD	**> Knee**
(Pollard *et al.*, 2015)	ACLR	10	10	Knee	Hip-knee	NR	45° side-step cut	4 cut trials	VC	SD	**> Hip-Knee**
(Timothy C Gribbin *et al.*, 2016)	ACLR	22	15	Knee	Hip-knee	NR	Run/walk	10 strides	VC	VCV	**> Hip-Knee < Hip-Knee**
Ligamentous											
(Kipp and Palmieri-Smith, 2012)	CAI	11	11	Ankle	Ankle	Yes	Single leg land	5 trials	FPCA	SD	**> Ankle**
(Brown, Bowser and Simpson, 2012)	CAI	46	24	Ankle	Trunk, hip, knee, ankle	No	2 leg jump – single leg land (3 directions)	10 trials Each condition	-	CV	**> Trunk < Hip, Knee**
(Hamacher, Hollander and Zech, 2016)	CAI	12	12	Ankle	Ankle	NR	Run	40 strides	-	SD	**> Ankle**
(Drewes *et al.*, 2009)	CAI	7	7	Ankle	Shank, rearfoot	No	Run/Walk	21 run strides 14 walk strides	CRP	DP	**=**
(Herb *et al.*, 2014)	CAI	13	15	Ankle	Shank, rearfoot	NR	Run/Walk	3 strides	VC	VCV	**< Ankle**
Tendon											

(Kulig, Joiner and Chang, 2015)	PT	9	9	Knee	Hip, knee, ankle	No	Land (from jump spike)	3 -6 trials	-	CV	**< Ankle**
Overuse Injury											
(C. R. James, Dufek and Bates, 2000)	INJURY Prone	10	10	Lower limb	Hip, knee, ankle	No	Land	10 each condition	-	SD	**> Ankle < Ankle**
(Ferber *et al.*, 2005)	RRI	11	11	Lower limb	Tibia-rearfoot	No	Run	5 trials	VC	SD	**=**
(Mann *et al.*, 2015)	RRI	44	46	Lower limb	Spatiotemporal	No	Run	161 strides	-	CV	**=**
(Paquette, Milner and Melcher, 2016)	RRI	23	21	Lower limb	Ankle	No	Run	5 foot strikes @ 10 min intervals	-	SD	**=**
(MacLean, van Emmerik and Hamill, 2010)	RRI	9	9	Knee	Tibia-calcaneus, knee-rearfoot	No	Run	10 seconds In each condition	VC	SD	**> Tibia-calcaneus**
(Meardon, Hamill and Derrick, 2011)	RRI	9	9	Lower limb	Temporal	No	Run	661 strides	-	SD, CV	**=**
(Miller *et al.*, 2008)	ITBS	8	8	Knee	Thigh-tibia, thigh-foot, tibia-foot, knee-foot	No	Run	10 seconds @ 2min intervals	CRP	SD	**> Knee-Foot < Thigh-Foot, Tibia-Foot**
(Hein *et al.*, 2012)	ITBS	18	18	Knee	Hip-knee, knee-ankle,	Yes	Run	5 stance phases	CRP	SD	**=**
(Heiderscheit, Hamill and Van Emmerik, 2002)	PFPS	8	8	Knee	Thigh-leg, knee-ankle	Yes	Run	15 strides	VC	CV	**> stride length**

(Cunningham *et al.*, 2014)	PFPS	11	19	Knee	Knee-ankle	Yes	Run	5 strides	VC	Mean, SD	**> Knee-Ankle**
(Edwards, Brooke and Cook, 2016)	AGP	10	7	Hip	Ankle, knee, hip, trunk	No	Side-step cut	10 cut trials	-	CV	**> Trunk**
Osteoarthritis											
(Chiu, Lu and Chou, 2010)	THA	20	10	Hip	Hip-knee, knee-ankle	Yes	Walk	10 meters	CRP	SD	**> Hip-Knee, Knee-Ankle**
		Mean / Median						**Mean / Median**			
		15 /11	13 /10				**Strides**	85 / 14			
							Trials	6 / 5			

INJ – injured, UNINJ – uninjured, ACLR – anterior cruciate ligament reconstruction, CAI – chronic ankle instability, PT – patellar tendinopathy, RRI – running related injury, ITBS – iliotibial band syndrome, PFP – patellofemoral pain, AGP – athletic groin pain, THA – total hip arthroplasty. NR – not reported. CRP – continuous relative phase, VC – vector coding, VCV – vector coding variability, FPCA – functional principal component analysis, SD – standard deviation, CV coefficient of variation, DP – deviation phase.

Table 3.4.B. Percentage of studies that showed greater, less or no variability when comparing injured and uninjured controls[1]

Study category (n)	Greater variability % (n)	Less variability % (n)	No difference in variability % (n)
All Studies (22)	64(14)	27(6)	27(6)
Single specific injury types (16)	75 (12)	31 (5)	13 (2)
CAI (5) (Drewes *et al.*, 2009; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2012; Herb *et al.*, 2014; Hamacher, Hollander and Zech, 2016)	60 (3)	40 (2)	20 (1)
ACLR (4) (van Uden *et al.*, 2003; Cordeiro *et al.*, 2015; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016)	100(4)	25 (1)	0
PFPS (2) (Heiderscheit, Hamill and Van Emmerik, 2002; Cunningham *et al.*, 2014)	100 (2)	0	0
ITBS (2) (Miller *et al.*, 2008; Hein *et al.*, 2012)	50 (1)	50 (1)	50 (1)
AGP (Edwards, Brooke and Cook, 2016)	100 (1)	0	0
Hip OA (Chiu, Lu and Chou, 2010)	100(1)	0	0
Patellar Tendinopathy (Kulig, Joiner and Chang, 2015)	0	100 (1)	0
Various lower limb injury (6) (James, Dufek and Bates, 2000; Ferber *et al.*, 2005; MacLean, van Emmerik and Hamill, 2010; Meardon, Hamill and Derrick, 2011; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016)	33 (2)	17 (1)	67 (4)
Injury by region			
Hip (2) (Chiu, Lu and Chou, 2010; Edwards, Brooke and Cook, 2016)	100	0	0
Knee (10) (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Miller *et al.*, 2008; MacLean, van Emmerik and Hamill, 2010; Hein *et al.*, 2012; Cunningham *et al.*, 2014; Cordeiro *et al.*, 2015; Kulig, Joiner and Chang, 2015; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016)	80 (8)	30 (3)	10(1)
Ankle (5) (Drewes *et al.*, 2009; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2012; Herb *et al.*, 2014; Hamacher, Hollander and Zech, 2016)	60 (3)	40 (2)	20 (1)
Pain			

Pain (6) (Heiderscheit, Hamill and Van Emmerik, 2002; Chiu, Lu and Chou, 2010; Hein *et al.*, 2012; Kipp and Palmieri-Smith, 2012; Cunningham *et al.*, 2014; Cordeiro *et al.*, 2015)	83 (5)	0	17 (1)
Pain free (12)(James, Dufek and Bates, 2000; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; MacLean, van Emmerik and Hamill, 2010; Meardon, Hamill and Derrick, 2011; Brown, Bowser and Simpson, 2012; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016; Edwards, Brooke and Cook, 2016)	42 (5)	33 (4)	42 (5)
Analysis Types			
Continuous Measures (15) (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Hein *et al.*, 2012; Kipp and Palmieri-Smith, 2012; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016; Hamacher, Hollander and Zech, 2016)	67 (10)	20 (3)	27 (4)
Continuous Measure Types			
Vector Coding (7) (Heiderscheit, Hamill and Van Emmerik, 2002; Ferber *et al.*, 2005; MacLean, van Emmerik and Hamill, 2010; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016)	57 (4)	29 (2)	29 (2)
Continuous Relative Phase (5) (van Uden *et al.*, 2003; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; Hein *et al.*, 2012)	60 (3)	0	40 (2)
Discrete Measures (10) (James, Dufek and Bates, 2000; Heiderscheit, Hamill and Van Emmerik, 2002; Miller *et al.*, 2008; Meardon, Hamill and Derrick, 2011; Kipp and Palmieri-Smith, 2012; Cordeiro *et al.*, 2015; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Edwards, Brooke and Cook, 2016; Paquette, Milner and Melcher, 2016)	40 (4)	30 (3)	40 (4)
Task			
Cyclic (15) (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Meardon, Hamill and Derrick, 2011; Hein *et al.*, 2012; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016; Timothy C. Gribbin *et al.*, 2016; Hamacher, Hollander and Zech, 2016)	53 (8)	20 (3)	40 (6)
Non-cyclic (7) (James, Dufek and Bates, 2000; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2012; Cordeiro *et al.*, 2015; Kulig,	86 (6)	43 (3)	0

Variable			
Joiner and Chang, 2015; Pollard *et al.*, 2015; Edwards, Brooke and Cook, 2016)			
Kinematic (20) (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2012; Hein *et al.*, 2012; Herb *et al.*, 2014; Cunningham *et al.*, 2014; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Pollard *et al.*, 2015; Cordeiro *et al.*, 2015; Paquette, Milner and Melcher, 2016; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016)	60 (12)	25 (5)	30 (6)
Spatiotemporal (3) (Heiderscheit, Hamill and Van Emmerik, 2002; Meardon, Hamill and Derrick, 2011; Mann *et al.*, 2015)	33 (1)	0	67 (2)
Kinetic (3) (James, Dufek and Bates, 2000; Kipp and Palmieri-Smith, 2012; Edwards, Brooke and Cook, 2016)	33 (1)	33 (1)	67 (2)

[1]*Note: As some studies report significant findings of both lesser and greater variability or some studies utilized multiple methodological approaches (tasks, dependent variable types or analysis techniques) the total sum of percentages do not always equal 100% as one study may have been included for results under various subsections. CAI – chronic ankle instability, ACLR – anterior cruciate ligament reconstruction, PFPS – patellofemoral pain syndrome, ITBS – iliotibial band syndrome, AGP – athletic groin pain, OA – osteoarthritis.*

Subject Characteristics

Findings by Injury Type

A wide variety of different injury types were identified within the studies. Subject groups consisted of either individuals with a single specific injury or various lower limb injuries. In the studies investigating single specific injuries, 88% (n=14/16) reported significant between-group differences. Of these, greater variability was evident in 75% (n=12/16) of them (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003;

Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2013; Cunningham *et al.*, 2014; Cordeiro *et al.*, 2015; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016), reduced variability in 31% (n=5/16) (Miller *et al.*, 2008; Brown, Bowser and Simpson, 2012; Herb *et al.*, 2014; Kulig, Joiner and Chang, 2015; Timothy C. Gribbin *et al.*, 2016), while 13% (n=2/16) reported no significant differences between injured and uninjured groups (Drewes *et al.*, 2009; Hein *et al.*, 2012). Table 4 presents the breakdown of findings when specific injury types were group together.

Non-specific lower extremity injury types were reported in six studies and included running related injuries (n=5) (Ferber *et al.*, 2005; MacLean, van Emmerik and Hamill, 2010; Meardon, Hamill and Derrick, 2011; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016) and injury proneness (n=1) (James, Dufek and Bates, 2000). A significant between-group difference was reported in 33% (n=2/6) of these studies. When the injured group was compared to uninjured controls greater variability was evident in 33% (n=2/6) (James, Dufek and Bates, 2000; MacLean, van Emmerik and Hamill, 2010), reduced variability reported in 17% (n=1/6) (James, Dufek and Bates, 2000) and no difference in 67% (n=4/6) (Ferber *et al.*, 2005; Meardon, Hamill and Derrick, 2011; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016).

Findings by Region Location

Within the various subject groups, injury was spread across three lower limb regions (ankle, knee, hip). Injury at the knee joint was most commonly investigated. This was examined in 46% (n=10/22) of studies (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Miller *et al.*, 2008; MacLean, van Emmerik and Hamill, 2010; Hein *et al.*, 2012; Cunningham *et al.*, 2014; Cordeiro *et al.*, 2015; Kulig, Joiner and Chang, 2015; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016) with significant findings evident in 90% of these (n=9/10). In the injured group greater variability was evident in 80% (n=8/10) of the studies (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Miller *et al.*, 2008; MacLean, van Emmerik and Hamill, 2010; Cunningham *et al.*, 2014; Cordeiro *et al.*, 2015; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016), reduced variability reported in 30% (n=3/10) (Miller *et al.*, 2008; Kulig, Joiner and Chang, 2015; Timothy C. Gribbin *et al.*, 2016) and no between-group differences were found in 10% (n=1/10) (Hein *et al.*, 2012).

The ankle was the next most commonly examined injury location with 23% (n=5/22) of all studies (Drewes *et al.*, 2009; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2012; Herb *et al.*, 2014; Hamacher, Hollander and Zech, 2016). Significant between-group findings were evident in 80% of these (n=4/5) studies, with greater variability reported in the injured group in 60% (n=3/5) (Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2012; Hamacher, Hollander and Zech, 2016), reduced variability in 40% (n=2/5) (Brown, Bowser and Simpson, 2012; Herb *et al.*, 2014) and no difference in 20% (n=1/5) (Drewes *et al.*, 2009). Injury at the hip region was examined in only 9% (n=2/22) of all studies with both of these (100%) (n =2/2) reporting that injured subjects demonstrated greater variability when compared to controls (Chiu, Lu and Chou, 2010; Edwards, Brooke and Cook, 2016).

Groups consisting of injury across multiple lower limb regions (e.g. foot stress fracture, patellofemoral pain and hip pain) were examined in 23% (n=5/22) of studies and 80% reported no significant difference in variability between groups (Ferber *et al.*, 2005; Meardon, Hamill and Derrick, 2011; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016). One study reported mixed findings with the injured group demonstrating increased and reduced variability when compared to uninjured controls (James, Dufek and Bates, 2000).

Findings in Relation to Pain

Pain was reported in 27% (n=6/22) of the studies. Within these studies that reported pain, greater variability [83% (n=5/6)] was evident in the injured group compared to the uninjured group (Heiderscheit, Hamill and Van Emmerik, 2002; Chiu, Lu and Chou, 2010; Kipp and Palmieri-Smith, 2012; Cunningham *et al.*, 2014; Cordeiro *et al.*, 2015), while one study reported no between group differences (Hein *et al.*, 2012). Two of these studies assessed subjects' pain levels using a visual analogue scale during the task performed (Heiderscheit, Hamill and Van Emmerik, 2002; Cunningham *et al.*, 2014). Four studies reported pain, as assessed by orthopedic examination (Hein *et al.*, 2012) or a subjective questionnaire which included a subscale for pain (Chiu, Lu and Chou, 2010; Kipp and Palmieri-Smith, 2012; Cordeiro *et al.*, 2015) but did not assess pain rating/level during the task.

Injured subject groups were reported as pain free at the time of testing in 55% (n=12/22) of studies (James, Dufek and Bates, 2000; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; MacLean, van Emmerik and Hamill, 2010; Meardon, Hamill and Derrick, 2011; Brown, Bowser and Simpson, 2012; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016; Edwards, Brooke and Cook, 2016). Of these studies, significant findings were reported in 58% (n=7/12) of these studies. In the injured groups reporting no pain, greater movement variability in the injured group was evident in 42% (n=5/12) (James, Dufek and Bates, 2000; van Uden *et al.*, 2003; Miller *et al.*, 2008; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012), less variability in 33% (n=4/12) (James, Dufek and Bates, 2000; Miller *et al.*, 2008; Brown, Bowser and Simpson, 2012; Kulig, Joiner and Chang, 2015) and no between-group difference in 42% (n=5/12) (Ferber *et al.*, 2005; Drewes *et al.*, 2009; Meardon, Hamill and Derrick, 2011; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016).

Four papers did not report on pain levels as part of the selection criteria or during the performance of the task (Herb *et al.*, 2014; Pollard *et al.*, 2015; Hamacher, Hollander and Zech, 2016; Timothy C. Gribbin *et al.*, 2016).

Analysis Type

In the reviewed studies, movement variability was examined in both continuous and discrete measures. Continuous measures refer to analysis of the entire biomechanical waveform (0-100%), while discrete measures refer to individual points on the waveform (e.g. peak knee moment; knee angle at peak ground reaction force; time to peak hip angle). It should be noted, that in both cases the analysis could be of a single joint/segment measure (e.g. knee moment) or between two joints/segments (e.g. hip–

knee relative phase angle). Irrespective of whether a continuous or discrete measure was examined for variability, in line with the inclusion criteria of this review only studies employing linear statistical tools were utilized (e.g. standard deviation, coefficient of variation).

Continuous measures were examined for variability in 68% (n=15/22) of studies (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Hein *et al.*, 2012; Kipp and Palmieri-Smith, 2013; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016; Hamacher, Hollander and Zech, 2016). Significant findings were reported in 73% (n=11/15). Greater variability in the injured group was evident in 67% (n=10/15) of the studies (van Uden *et al.*, 2003; Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2013; Cunningham *et al.*, 2014; Pollard *et al.*, 2015; Hamacher, Hollander and Zech, 2016; Timothy C. Gribbin *et al.*, 2016), reduced variability in 20% (n=3/15) (Brown, Bowser and Simpson, 2012; Herb *et al.*, 2014; Timothy C. Gribbin *et al.*, 2016), and no difference observed between the two groups in 27% (n=4/15) (Heiderscheit, Hamill and Van Emmerik, 2002; Ferber *et al.*, 2005; Drewes *et al.*, 2009; Hein *et al.*, 2012).

Variability was examined in continuous waveforms using various continuous measurement types including: vector coding (n=7) (Heiderscheit, Hamill and Van Emmerik, 2002; Ferber *et al.*, 2005; MacLean, van Emmerik and Hamill, 2010;

Cunningham *et al.*, 2014; Herb *et al.*, 2014; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016), continuous relative phase (n=5) (van Uden *et al.*, 2003; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; Hein *et al.*, 2012), ensemble curves of individual joint/segmental angles at each percent of the task cycle (n=2) (Brown, Bowser and Simpson, 2012; Hamacher, Hollander and Zech, 2016), and principal component analysis of discrete variables over pre-determined continuous time periods (e.g. 300ms) (n=1) (Kipp and Palmieri-Smith, 2013). Table 4 presents the breakdown of findings when variability was examined in continuous and discrete measures, and a further breakdown of the different types of continuous measures employed (e.g. vector coding and continuous relative phase).

The second approach used to quantify movement variability involved discrete point analysis, which examined maximum, minimum metrics to represent the whole waveform. This technique was used in 45% (n=10/22) of studies (James, Dufek and Bates, 2000; Heiderscheit, Hamill and Van Emmerik, 2002; Miller *et al.*, 2008; Meardon, Hamill and Derrick, 2011; Kipp and Palmieri-Smith, 2013; Cordeiro *et al.*, 2015; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Edwards, Brooke and Cook, 2016; Paquette, Milner and Melcher, 2016) and significant findings were reported in 60% (n=6/10) of these studies. Greater variability was evident in 40% (n=4/10) (James, Dufek and Bates, 2000; Heiderscheit, Hamill and Van Emmerik, 2002; Cordeiro *et al.*, 2015; Edwards, Brooke and Cook, 2016), reduced variability in 30% (n=3/10) (James, Dufek and Bates, 2000; Miller *et al.*, 2008; Kulig, Joiner and Chang, 2015) and no difference reported in 40% (n=4/10) (Meardon, Hamill and Derrick, 2011; Kipp and Palmieri-Smith, 2013; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016).

Task

There were a wide variety of tasks used to examine movement variability including: running, walking, jumping, landing, side-step cutting and kicking a ball. To enable synthesis of findings the tasks were categorized into cyclic (end of one movement cycle is beginning of the next) or non-cyclic (distinct beginning and end) movements. Tasks that were cyclic in nature (running, walking or continuous single leg hopping) were utilized in 68% (n=15/22) of studies (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Meardon, Hamill and Derrick, 2011; Hein *et al.*, 2012; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016; Timothy C. Gribbin *et al.*, 2016; Hamacher, Hollander and Zech, 2016). Significant differences between the injured and uninjured groups were reported in 53% (n=9/15) of these studies. In the injured group greater variability was evident in 53% (n=8/15) (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Cunningham *et al.*, 2014; Hamacher, Hollander and Zech, 2016; Timothy C. Gribbin *et al.*, 2016), reduced variability in 20% (n=3/15) (Miller *et al.*, 2008; Herb *et al.*, 2014; Timothy C. Gribbin *et al.*, 2016) and no between-group difference reported in 40% (n=6/15) (Ferber *et al.*, 2005; Drewes *et al.*, 2009; Meardon, Hamill and Derrick, 2011; Hein *et al.*, 2012; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016). Movement variability was examined during a run condition in 87% (n=13/15) of these studies with 46% (n=6/13) reporting greater variability in the injured group when compared to controls (Heiderscheit, Hamill and Van Emmerik, 2002; Miller *et al.*, 2008; MacLean, van Emmerik and Hamill, 2010; Cunningham *et al.*, 2014; Hamacher, Hollander and Zech, 2016; Timothy C. Gribbin *et al.*, 2016), while 8% (n=1/13) reported reduced variability (Miller *et al.*, 2008), and 54% (n=7/13) found no difference between groups (Ferber *et al.*, 2005; Drewes *et al.*, 2009; Meardon, Hamill and Derrick, 2011; Hein *et al.*, 2012; Herb *et al.*, 2014; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016). Running was performed on a treadmill in 77% (n =10/13) of the studies (Heiderscheit, Hamill and Van Emmerik, 2002; Miller *et al.*, 2008; Drewes *et al.*, 2009; MacLean, van Emmerik and Hamill, 2010; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Mann *et al.*, 2015; Hamacher, Hollander and Zech, 2016; Paquette, Milner and Melcher, 2016; Timothy C. Gribbin *et al.*, 2016), a runway in 15% (n =2/13) (Ferber *et al.*, 2005; Hein *et al.*, 2012) and a 300-meter indoor track in 8% (n =1/13) (Meardon, Hamill and Derrick, 2011). Run conditions were either set at a fixed (n=7 (Heiderscheit, Hamill and Van Emmerik, 2002; Drewes *et al.*, 2009; MacLean, van Emmerik and Hamill, 2010; Hein *et al.*, 2012; Herb *et al.*, 2014; Hamacher, Hollander and Zech, 2016; Timothy C. Gribbin *et al.*, 2016) or self-selected speed (n=7 (Heiderscheit, Hamill and Van Emmerik, 2002; Ferber *et al.*, 2005; Miller *et al.*, 2008; Meardon, Hamill and Derrick, 2011; Cunningham *et al.*, 2014; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016). The average fixed speed was 10.4 km/h and the average self-selected speed for injured and uninjured control groups was 11.3 km/h. The length of the run condition ranged from 15 second trials to exhaustive 40-minute runs**.**

Non-cyclic tasks were utilized in 36% (n=7/22) of studies. A variety of different tasks were employed including a land (n=4/7) (James, Dufek and Bates, 2000; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2013; Kulig, Joiner and Chang,

2015) side-step cut (n=2) (Pollard *et al.*, 2015; Edwards, Brooke and Cook, 2016) and a soccer instep-kick (n=1) (Cordeiro *et al.*, 2015). Significant differences in movement variability between injured groups and uninjured controls were identified in 100% (n =7/7) of these studies. Greater variability was evident in the injured group in 86% (n=6/7) (James, Dufek and Bates, 2000; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2013; Cordeiro *et al.*, 2015; Pollard *et al.*, 2015; Edwards, Brooke and Cook, 2016) and reduced variability in 43% (n=3/7) (James, Dufek and Bates, 2000; Brown, Bowser and Simpson, 2012; Kulig, Joiner and Chang, 2015).

Variables

Three types of dependent variable were utilized to examine movement variability between injured and uninjured subjects: kinematic, spatiotemporal and kinetic. Kinematic variables were examined in 91% (n=20/22) of studies (Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Ferber *et al.*, 2005; Miller *et al.*, 2008; Drewes *et al.*, 2009; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Hein *et al.*, 2012; Kipp and Palmieri-Smith, 2013; Herb *et al.*, 2014; Cunningham *et al.*, 2014; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015; Pollard *et al.*, 2015; Cordeiro *et al.*, 2015; Paquette, Milner and Melcher, 2016; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016) and 70% (14/20) of these reported significant findings. Greater variability was evident in the injured group in 60% (n=12/20) of these studies (van Uden *et al.*, 2003; Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-

Smith, 2013; Cunningham *et al.*, 2014; Cordeiro *et al.*, 2015; Pollard *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016), reduced variability in 25% (n=5/20) (Miller *et al.*, 2008; Brown, Bowser and Simpson, 2012; Herb *et al.*, 2014; Kulig, Joiner and Chang, 2015; Timothy C. Gribbin *et al.*, 2016) and no between group differences was reported in 30% (n=6/20) (Heiderscheit, Hamill and Van Emmerik, 2002; Ferber *et al.*, 2005; Drewes *et al.*, 2009; Hein *et al.*, 2012; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2016).

Spatiotemporal variables (e.g. foot contact time, stride time, stride length, stride frequency and flight time) were used to examine movement variability in 14% (n=3/22) of the studies. Greater variability in the injured group was reported in 33% of the studies (n=1/3) (Heiderscheit, Hamill and Van Emmerik, 2002), and no between-group difference in 67% (n=2/3) (Meardon, Hamill and Derrick, 2011; Mann *et al.*, 2015).

Kinetic variables (e.g. ground reaction forces, impulses and joint moments) were examined in 14% (n=3/22) of studies. One study report both significantly increased and decreased measures of variability in the injured group when compared to controls (James, Dufek and Bates, 2000), while no significant between-group difference was evident in 67% (n=2/3) (Kipp and Palmieri-Smith, 2012; Edwards, Brooke and Cook, 2016).

3.5 Discussion

To date, this is the first systematic review to investigate if there is a difference in movement variability between populations with a lower limb musculoskeletal injury compared with uninjured controls. The overall findings suggest that injured populations tend to deviate from 'normal' ranges of movement variability (as quantified in the uninjured control groups). 73% of studies reported significant between group differences in at least one measure of variability assessed, when comparing injured subject groups to uninjured controls (James, Dufek and Bates, 2000; Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2013; Cunningham *et al.*, 2014; Herb *et al.*, 2014; Kulig, Joiner and Chang, 2015; Pollard *et al.*, 2015; Cordeiro *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016). The application of dynamic systems theory to help understand injury and movement variability has led to the hypothesis that an optimum range of variability exists for human movement, outside of which is associated with increased risk of injury (Stergiou, Harbourne and Cavanaugh, 2006; Hamill, Palmer and Van Emmerik, 2012). The focus in much of the literature has been that reduced variability has a greater association with injury (Hamill *et al.*, 1999; Davids *et al.*, 2003), however, in direct contrast to this hypothesis the findings from this systematic review found a trend towards increased variability in injured groups, as 64% of studies reported significantly greater variability in the injured group when compared to the uninjured controls(James, Dufek and Bates, 2000; Heiderscheit, Hamill and Van Emmerik, 2002; van Uden *et al.*, 2003; Miller *et al.*, 2008; Chiu, Lu and Chou, 2010; MacLean, van Emmerik and Hamill, 2010; Brown, Bowser and Simpson, 2012; Kipp and Palmieri-Smith, 2013; Cunningham *et al.*, 2014; Pollard *et al.*, 2015; Cordeiro *et al.*, 2015; Timothy C. Gribbin *et al.*, 2016; Edwards, Brooke and Cook, 2016; Hamacher, Hollander and Zech, 2016). This was compared to 27% that reported less variability in the injured group. The varied findings from this review may be explained by the 'optimal' theory proposed by Hamill et al. (Hamill, Palmer and Van Emmerik, 2012), where either too little or too much movement variability may be related to increased risk of injury. This however should not be confused with the inverted U theory presented by Stergiou et al. (Stergiou, Harbourne and Cavanaugh, 2006), which examines the temporal structure of movement signals. The theory proposed by Hamill et al. (Hamill, Palmer and Van Emmerik, 2012) presents the relationship between motor performance and variability as a "U" shaped association where either too little or too much is thought to have a detrimental impact on performance and may be associated with pathological populations. However, it is worth noting that to date no research has presented both significantly higher and lower variability in the injured group in comparison to the control group within the same variable.

There are a number of potential reasons why greater movement variability was identified in the injured groups. Firstly, as a causative risk factor for injury, it is possible that greater variability reflects a decrease in neuromuscular control leading to poorly controlled movement (Schmidt, 2013). This in turn may result in tissues (muscle, tendon, cartilage, bone) being subjected to unaccustomed strain and load, which if sustained overtime, or occurs at extremes in either force applied or the associated motion, may lead to injury (Stergiou, Harbourne and Cavanaugh, 2006; Hamill, Palmer and Van Emmerik, 2012). If greater movement variability does represent a risk factor for injury, then exercise interventions should focus on improving neuromuscular control.

However, the retrospective design of the studies in the present review does not allow this causative relationship between altered movement variability and injury to be concluded.

Secondly, with injury pain provides an organismic influence, and the greater movement variability evident in injured populations may reflect an unstable compensatory movement mechanism being utilized in order to reduce loading on the sensitized and painful tissues (Tsao, Galea and Hodges, 2008; Madeleine and Madsen, 2009; Hodges and Tucker, 2011). Pain causes changes in the body at both central (spinal cord and brain) (Kotler *et al.*, 1998; Hodges and Tucker, 2011) and peripheral levels (activation within and between muscles) (Hodges and Tucker, 2011) altering movement variability (Churchland, Afshar and Shenoy, 2006; Harbourne and Stergiou, 2009) and proprioceptive control of movement (Tsao, Galea and Hodges, 2008). This view is in line with dynamic systems theory, which suggests that movement patterns spontaneously arise through processes of self-organization as a result of several factors (e.g. task, environment, organismic) acting on the individual (Newell *et al.*, 1989; Davids *et al.*, 2003). While such a change in movement mechanics may achieve a short-term goal of protection from further pain and or injury, this may not be ideal as a long-term movement solution; therefore interventions would have to aim at decreasing variability to 'normal' levels seen in uninjured populations (Hodges and Tucker, 2011).

A third explanation is that once the tissue damage resulting from an injury has healed and the pain has resolved, variability may represent the exploration of movement solutions by the neuromuscular system to re-optimize movement in the presence of altered neuromuscular capacity (e.g. reduced muscular strength) and/or in the presence of pain induced changes to the body schema (the brain's representation of the body) (Schwoebel, 2001). In fact it has been previously observed that pain induced compensatory movement adaptions may even persist with recovery and the resolution of pain (Tsao, Galea and Hodges, 2008; Seay, Van Emmerik and Hamill, 2011). If this latter explanation is the case, then rehabilitation interventions should not aim to decrease movement variability, as indicated above, as it potentially represents the natural recovery process. To determine if variability should be targeted in rehabilitation there is a clear need for intervention studies investigating the efficacy of increased/decreased variability-targeted rehabilitation. Furthermore, prospective research is required to conclusively determine the relationship between variability and injury.

Throughout this review, several studies produced contrasting findings for the same injury. For example greater (Hamacher, Hollander and Zech, 2016), less variability (Herb *et al.*, 2014) and no difference in variability (Drewes *et al.*, 2009) was identified at the ankle joint when examining chronic ankle instability. It is hard to identify exactly why these inconsistencies are evident, however it may be related to the different tasks examined (e.g. jump land, running, walking) and/or different measurement types utilised (e.g. continuous relative phase and vector coding). In fact even within individual studies when examining the same group for the same task, two authors identified both greater and less variability when examined at multiple joints/segments (Miller *et al.*, 2008; Brown, Bowser and Simpson, 2012). This may reflect that in response to injury, the body reduces variability at certain joints to elicit a 'splinting effect' while increasing the variability at other joints to achieve the task outcome (Hodges and Tucker, 2011). These findings may indicate that the current application of dynamic systems theory to injuries requires revision.

Subject Characteristics

Examining movement variability in a single specific injury group (e.g. chronic ankle instability) or injury at a specific region (e.g. hip, knee, ankle) appeared to be more sensitive in detecting an influence on variability than if examined in a non-specified group (e.g. general lower extremity running related injury comprising multiple injury types and/or across multiple injury regions). Where 75% of studies examining a single specific injury identified significant between group differences only 33% using a non-specific injury group reported significant findings. Similarly, 89% of the studies that examined one injury location found a significant difference in variability between groups compared to just 20% of the studies that examined a subject population consisting of several injury locations.

This is perhaps not surprising as examining a heterogeneous group may mask findings between individuals within that group (Richter, N. E. O'Connor, *et al.*, 2014). For example, Ferber et al. (Ferber *et al.*, 2005) included subjects with a variety of running related injuries, including patellofemoral pain syndrome, and reported no significant between group difference; while Heiderscheit et al. (Heiderscheit, Hamill and Van Emmerik, 2002) and Cunningham et al. (Cunningham *et al.*, 2014) included only subjects with patellofemoral pain syndrome and both studies reported significant between-group differences.

Analysis Type

Findings from this review possibly favor examining variability in continuous measures, with 73% of studies examining a continuous waveform reporting significant differences between injured subjects and uninjured controls. This is in comparison to 60% of the studies examining discrete point data. In accordance with this finding, Kipp & Palmieri-Smith (Kipp and Palmieri-Smith, 2012) examined variability in both discrete and continuous measures and found that differences in variability between injured and uninjured groups was only detectable in continuous measures. Variability was examined in a number of continuous data analysis techniques within this review; these included the variation in continuous relative phase, vector coding and principle component analysis. With the variety of approaches utilized no trend was identified regarding their sensitivity. Further, no study directly compared different continuous analysis techniques.

Task

When tasks were categorized into cyclic or non-cyclic movements, the non-cyclic tasks appeared more sensitive at detecting differences in variability between injured and uninjured groups. All studies examining non-cyclic tasks reported significant between group differences. In comparison, only half of those that examined cyclic tasks reported significant between group differences. There are possibly three explanations for this finding. Firstly, this may simply represent a methodological/statistical phenomenon, in which the methods utilized are more suitable at detecting differences during non-cyclic tasks in comparison to cyclic tasks. Secondly, the greater detection of variability in non-cyclic tasks may be related, at least in part, to cyclic tasks, such as walking or running, being practiced more often (Stergiou and Decker, 2011). As such, at the time of testing subjects may have already explored alternative movement strategies for these cyclic tasks and have adopted a less variable movement solution. In contrast, non-cyclic tasks such as landings and cutting maneuverers are generally less practiced. This may result in alternative movement strategies still being explored at the time of testing resulting in greater variability (Bartlett, 2008). Finally, non-cyclic tasks (e.g. landing, change of direction) typically demonstrate greater ground reaction forces and loading than cyclic tasks (e.g. running, hopping). The greater detection of variability in non-cyclic tasks may therefore be reflective of greater compensation being utilized in comparison to cyclic tasks in order to offload the injured tissues.

It is worth noting, but probably unrelated to the previous point, that the median number of strides examined for cyclic tasks was 14 and the median number of trials for non-cyclic tasks was 5 with an interquartile range of 25.50 and 6.25 respectively. Within this review, no study provided justification for the number of trials examined. Previous research examined the number of trials required to reliably examine movement variability during walking (Sangeux *et al.*, 2016; Hafer and Boyer, 2017) and running (Hafer and Boyer, 2017) identifying that up to 20 trials are required for walking and 8 trials are required for running, similar to the median number of trials examined by studies in this review. However, caution should be applied here in adopting the findings of Sangeux et al. (Sangeux *et al.*, 2016) and Hafer and Boyer (Hafer and Boyer, 2017) as the number of trials required has been shown to be task dependent (Hafer and Boyer, 2017), and is likely specific to the population being examined, and these studies were examined in healthy participants. Future research should therefore look to investigate the number of trials needed to reliably examine movement variability during specific tasks and in specific populations. This should ideally be conducted not with just statistical reliability, as in Sangeux et al. (Sangeux *et al.*, 2016) and Hafer and Boyer (Hafer and Boyer, 2017) whereby the number of trials was determined based on the magnitude of variability staying within a given range (e.g. within 10% of a 15-stride mean or 10% relative precision) as the number of trials is increased. Rather the number of trials required should be determined with regard to how many trials are required to detect differences with an appropriately high effect-size in the amount of variability between subjects of interest (e*.g.* in injured subjects with chronic ankle instability vs. uninjured controls).

Variables

Within the reviewed studies, kinematic, kinetic and spatiotemporal measures were all utilized as dependent measures to compare movement variability between injured subjects and uninjured controls. Kinematic measures were the most commonly examined in 91% of studies and 70% of these reported a significant between group difference. In comparison, spatiotemporal and kinetic measures were each only examined in 14% of studies and 33% of these studies identified a significant difference between the two groups. When studies compared both kinetic and kinematic variables significant between-group differences were only evident in kinematic variables (Kipp and Palmieri-Smith, 2012; Edwards, Brooke and Cook, 2016). These findings at present would suggest that kinematic variability might be the most sensitive to differences between groups. This was somewhat surprising as kinetic measures reflect more closely the forces associated with injuries. This is difficult to explain as there is generally greater intra-subject variability in kinetic measures (Winter, 2009). Previous research has demonstrated that kinetic measures also have proportionally higher between-subject variability (Winter, 2009) which inhibits the ability to detect difference between groups. However, to date no research has examined the variability in kinetic variability measurements so it remains uncertain why kinematic variability might be the most sensitive to differences between groups.

These findings have numerous methodological implications. Firstly, when examining movement variability, it may be more appropriate for researchers to investigate a single specific injury type thus avoiding any possible masking of findings. Secondly, continuous analysis of data may be more sensitive than discrete-point analysis in detecting significant between-group differences. Finally, kinematic movement variability measured during non-cyclic tasks appeared to be most consistent in detecting significant between-group differences.

Limitations of Review

Given the large heterogeneity in study methodologies and metrics examined, this review was limited to a qualitative analysis of the literature. The qualitative approach adopted here results in papers being categorized as either finding greater variability or less variability if any *one* measure, of all the measures assessed, has greater or less variability, respectively. In contrast, for a paper to be categorized as having no effect on variability, *none* of the measures assessed must differ between the injured and uninjured controls. This introduces a bias in the reporting process that needs to be considered when interpreting the findings. For full report of findings please see Appendix A.

Another limitation to this review is the underlying assumption that a 'normal' magnitude of variability exists and is associated with healthy individuals. As with all cross-comparison studies it may be that the 'healthy' subjects also have an abnormal level of variability but have not been exposed to the volume or intensity required to develop an injury.

Secondary to the above point it is not possible to state an overall 'normal' range of variability within this qualitative review because of the wide variety of tasks, injury groups and analysis methods employed.

Finally, this review also only included linear magnitude-based representations of variability and excluded research investigating nonlinear measures of variability (e.g. entropy, Lyapunov exponent). Future systematic reviews should be conducted investigating the latter with respect to injury once a sufficient number of studies have been conducted in this area.

Limitations of Studies

Limitations of the studies reviewed include; poor control and/or reporting of possible confounding factors (including fatigue, gender, pain, running speed), biased examination of multiple comparisons without controlling for family wise errors and a lack of justification for the number of trials analysed when examining between trial variability. The later point is of importance as it is currently unknown how many trials are required to obtain reliable and meaningful measures. Other limitations include the use of the coefficient of variation metric in several studies (Heiderscheit, Hamill and Van Emmerik, 2002; Meardon, Hamill and Derrick, 2011; Brown, Bowser and Simpson, 2012; Kulig, Joiner and Chang, 2015; Mann *et al.*, 2015) which may result in findings of variability that are artificially inflated when the variable examined are of a small magnitude. Also the plethora of measurements types utilized within this review impedes the cross comparison and synthesis of findings between studies. A consensus should be reached for the standardization of analysis types. Finally, the lack of large normative databases currently limits the utility of variability as a clinical measure. To encourage the adoption of best research practice and allow the use of variability as a clinical measure, open access databases should be encouraged. This would not only enhance the transparency of research but also allow the investigation and direct comparison of these different methodologies.

Summary of systematic review

The overall findings from this review suggest that deviation from normal ranges of movement variability may be associated with injury. Interestingly, a trend was identified with injured populations exhibiting greater movement variability when compared to uninjured controls. This trend was evident in injured populations group reporting pain and ligamentous injury and as such future research should explore the association between pain and variability and sensorimotor control and variability. There is a clear need to repeat many of the studies within this review, using appropriate methodologies, to determine if there is a consistency in the findings of variability between those with and without injury. In order to enhance the sensitivity to detect between group differences in variability future research should consider examining variability using a subject group with a clearly defined injury type and/or injury location. Furthermore, it would appear advantageous to examine non-cyclic tasks utilizing continuous waveform methods of analysis, with a focus on kinematic measures. Finally, prospective research needs to be conducted to determine if alterations in movement variability precedes or follows an injury.

3.6 Implications of the systematic review for this thesis

Only one study in the systematic review investigated AGP which only included seven injured subjects (Edwards, Brooke and Cook, 2016). In this study by Edwards et al (2016), inconsistent findings were reported with both increased and decreased variability in different body segments (i.e. increased hip rotation variability and decreased knee rotation variability) and even within the same segment during different discrete points of a cutting task (i.e. decreased trunk rotation variability at initial contact and increased trunk rotation variability at peak vertical force) (Edwards, Brooke and Cook, 2016). Therefore, further research is vital to increase our understanding of the importance of movement variability in AGP. In line with the findings from the systematic review a continuous waveform approach will be utilized to analyze joint kinematics and kinetics. In addition, the variability of ground reaction force (GRF) measures will also be explored and may provide additional insight into whole-body loading strategies. In this thesis, variability of the GRF has been investigated in Chapter 6 and variability of joint kinematic and kinetic measures have been investigated in Chapter 7.

Chapter 4

The effects on hip strength and power of segmentally focused rehabilitation in athletic groin pain

This study was accepted by the American Journal of Sports Medicine in March 2021.

Samuel R. Baida, King Enda, Shane J. Gore, Richter Chris, Andrew D. Franklyn-Miller & Kieran A. Moran 2021. Hip muscle strength explains only 11% of the improvement in HAGOS with an intersegmental approach to successful rehabilitation of athletic groin pain: Cohort intervention study with 6-month follow-up

It is presented in this chapter with the addition of hip range-of-motion findings and with minor formatting changes to conform to this thesis.

4.1 Introduction

Athletic Groin Pain (AGP) is an overuse musculoskeletal presentation accounting for 9.4% of all injuries in male Gaelic football,(Murphy *et al.*, 2113) with similar percentages reported in soccer (Waldén, Hägglund and Ekstrand, 2015) and Australian Rules football (Orchard, Seward and Orchard, 2013). The diagnosis encompasses the clinical presentation of pain at musculotendinous or fascial attachments to the anterior pelvis (e.g. proximal adductor tendon, pubic aponeurosis, inguinal ligament, iliopsoas tendon) (Falvey *et al.*, 2015). It can result in reduced athletic performance, sporting participation and health-related quality of life (Nevin and Delahunt, 2014). Exercise-based rehabilitation is effective in treating athletes with AGP when compared to passive (Hölmich *et al.*, 1999) or surgical (King *et al.*, 2015) interventions.

Non-surgical rehabilitation of AGP has traditionally targeted the painful structures through targeted hip and trunk strengthening programs aiming to increase the target tissue's capacity to tolerate additional load (Hölmich *et al.*, 1999; Weir *et al.*, 2010). A potential limitation to this approach may arise when determining which structure to rehabilitate when multiple pathologies co-exist, as is commonly found clinically in athletes with AGP (Hölmich, 2007). In addition, this approach may not address overall movement control, which may have contributed to the initial injury (Franklyn-Miller *et al.*, 2017). More recent published research outlined an intervention program, inclusive of all AGP pathologies, which aimed to reduce overload on the injured structures/region by targeting intersegmental control of the trunk, pelvis and hip through strength, running and change of direction exercises (King, Franklyn-Miller, *et al.*, 2018). Intersegmental control describes the coordinated relationship between the trunk and lower limb segments (i.e. hip, knee and foot) in order to produce efficient multi-joint, multi-planar movements and which cannot be evaluated via the assessment of singular muscle groups. When this approach was utilized it was reported that the anatomical diagnosis of AGP did not influence the RTP times and also demonstrated quicker return-to-play times (RTP) when compared to studies using the traditional approach (mean RTP time: 9.9 vs. 12.8 to 18.5 weeks). It is important to note here, that other factors outside of the different intervention approaches utilized in these independent studies may also account for the difference in RTP times. These factors include: RTP definitions, inclusion of only adductor-related AGP vs. inclusion of all diagnosis of AGP, and program compliance. In addition, following intersegmental rehabilitation significant trunk and lower limb kinematic and kinetic changes were reported in change-of-direction technique which were associated with improved change-of-direction performance (King, Franklyn-Miller, *et al.*, 2018). Furthermore, significant improvements in self-reported pain and function (as measured by the Hip and Groin Outcome Score [HAGOS]) and pain provocation tests (bilateral squeeze test in 0°, 45° and 90° of hip flexion) were found (King, Franklyn-Miller, *et al.*, 2018). It has been proposed that isometric hip strength, strength ratios and hip range-of-motion (ROM) measures should be included in the assessment of AGP as they have been reported as risk factors for groin injury (Ryan, DeBurca and Mc Creesh, 2014; Delahunt *et al.*, 2015). However, these measures have not been assessed prior to or following an intersegmental rehabilitation approach.

In addition to isometric hip strength, lower limb reactive strength (Markovic & Mikulic, P., 2010) and inter-limb asymmetry (Impellizzeri *et al.*, 2007), have been associated with increased risk of lower limb injury and have not previously been examined in AGP athletes. Reactive strength reflects an athlete's explosive neuromuscular capacity utilizing the stretch-shorten cycle (i.e. rapid change from eccentric to concentric muscular contraction) and has been quantified using the reactive strength index (RSI) during a drop jump (Flanagan and Comyns, 2008). In athletes with AGP, longer ground contact times have been reported during plyometric actions when compared to uninjured controls (Gore *et al.*, 2020) suggesting reduced reactive strength capacity (Lockie *et al.*, 2012). Inter-limb asymmetry has been frequently used during rehabilitation to quantify the difference in strength or performance of one limb with respect to the other (Bishop *et al.*, 2018). Previous research has suggested that athletes with inter-limb asymmetries > 15% may have an increased risk of lower limb injury and thereby can provide important markers for rehabilitation and return-to-play status (Impellizzeri *et al.*, 2007). The importance of limb asymmetry in relation to AGP remains unknown. Further to the examination of strength measures (i.e. hip strength, reactive strength) the contribution of changes in strength to improvements in HAGOS scores are unknown. For clinicians rehabilitating athletes with AGP, a greater understanding of how strength is related to recovery of sporting function may help enhance rehabilitation programs.

The long-term efficacy of rehabilitation is extremely important due to the high reinjury rates reported in AGP (Werner *et al.*, 2019). When returning to sports post-rehabilitation, the initial six-month period is crucial, as the increasing physical demands placed on athletes during this period can increase susceptibility to re-injury of soft-tissue structures (Orchard and Best, 2002; Blanch and Gabbett, 2016). Assessment of HAGOS over this period can provide important insight into the efficacy of the intersegmental control after resuming full training and playing over a longer period of time.

The primary aim of this study is to examine isometric hip strength (peak torque and peak torque ratios), reactive strength, inter-limb asymmetry in isometric hip and reactive strength, hip ROM and patient reported outcomes (HAGOS questionnaire, Marx activity scale) in athletes with AGP from baseline (pre-rehabilitation) to return-to-play (post-rehabilitation) and in comparison to uninjured athletes (CON). A secondary aim is to examine the relationship between the pre- to post-rehabilitation change in strength measures and the pre- to post-rehabilitation change in HAGOS (sport and recreation function subscale). The tertiary aim is to examine the changes in HAGOS subscales at three and six months post-RTP after rehabilitation targeting intersegmental control.

It was hypothesized: (i) isometric hip strength, reactive strength and hip ROM would be lower and inter-limb asymmetries would be greater in AGP athletes compared to CON athletes at baseline testing, and would normalize to values observed in the CON athletes following rehabilitation, (ii) a positive association would exist between the increase in strength measures and the increase in HAGOS sport and recreation function score following rehabilitation, and (iii) HAGOS scores would improve in the AGP athletes at RTP and would be maintained at six-months follow-up.

4.2 Methods

This study was designed as a case-control study with pre- to post-intervention trial. The study was conducted in the department of Sports Medicine at Sports

Surgery Clinic, Dublin, Ireland. Enrolment started in December 2018 and ended in October 2019, with the last follow-up in April 2020. A power analysis was conducted based on previous HAGOS data (King, Franklyn-Miller, et al., 2018). King et al. (2018) reported medium to large effect size changes (d = 0.59 to 1.78) across all HAGOS subscales in a cohort of 150 athletes with AGP after successful completion of the intersegmental control rehabilitation program. Using the effect size of 0.59, with 80% power and alpha error probability 0.05, 36 participants were required a priori. To facilitate a potential dropout rate of 15% (King, Franklyn-Miller, et al., 2018), 42 participants were recruited.

Eligibility criteria

Clinical examination was completed by a Sports and Exercise Medicine Physician as previously described (Falvey *et al.*, 2015). Inclusion criteria included: (1) anatomical diagnosis falling under AGP (iliopsoas, adductor, pubic aponeurosis, inguinal and hip) (Falvey *et al.*, 2015), (2) male aged between 18-35 years involved in multi-directional field-based sports, (3) hip/groin symptoms during sporting activity with duration greater than four weeks, and (4) plan to return to same pre-injury sport and level of competition. Exclusion criteria included: (1) hip joint arthrosis (grade 3 or higher on MRI), (2) those with an underlying medical condition (e.g. inflammatory arthropathy or infection), and (3) past history of hip and/or groin surgery. Control participants were recruited via social media outlets and local sporting clubs, and were matched based on age, sports played and level of competition. Control participants were included if they had: (1) no previous groin or lower limb surgery, and (2) no lower limb injury within the previous three months. All participants provided informed consent. Ethical approval was granted by the Sports Surgery Clinic's Scientific Advisory and Research Ethics Boards (SAREB15/10/18SB/CB/G).

Protocol

Athletes attended the clinic for baseline testing (pre-rehabilitation) of hip range-of-motion and strength-related outcome measures. AGP athletes repeated all testing at return-to-play (RTP) following the rehabilitation program and completed the HAGOS and Marx questionnaires electronically at three and six-months post-RTP.

Clinical outcome measures

Return-to-play criteria have been defined previously (King, Franklyn-Miller, *et al.*, 2018) and include: symmetrical hip flexion/internal rotation range-of-motion, and pain-free: squeeze test in 45° (SQ45) and 0° (SQ0) of hip flexion (Delahunt, Kennelly, *et al.*, 2011), pubic stress test (Hogan, 2014), linear and multi-directional running (King, Franklyn-Miller, *et al.*, 2018). The RTP rate was calculated as (the number of athletes successfully achieving all RTP criterion)/(the total number of athletes enrolled in the study, n = 42)*100. The squeeze tests were recorded using a sphygmomanometer (Welch Allyn, USA), pre-inflated to 20 mmHg, with both a maximum value (MAX) and value at first onset of pain (P1) recorded (Hogan, 2010; Delahunt, Kennelly, *et al.*, 2011). Self-reported disability and function were assessed using the hip and groin outcome score (HAGOS) (scored 0 to 100 with 100 indicating nil problems) (Thorborg *et al.*, 2011) and the level of sporting activity was assessed with the Marx activity scale (Irrgang, 2008) (scored 0 to 16 with higher scores indicating increased frequency of high-demand sporting activity). Only athletes who successfully completed the rehabilitation program were followed-up for assessment with the HAGOS and the Marx activity scale at 3- and 6-months post-RTP. Therefore, analysis of HAGOS and Marx activity scale at 3- and 6-month does not include those athletes who could not be reached to complete the questionnaires or who developed symptoms post-RTP (Figure 4.2.5.A indicates the flow diagram of participants through the study).

Strength-related outcome measures

Hip strength was assessed with hand-held dynamometry (Commander J-tech, USA) as per a previously published protocol (Thorborg *et al.*, 2010). Intra-tester and inter-day reliability were examined and confirmed prior to commencing this study (Appendix C). In the current study, both limbs were tested for all athletes, with the order standardized to ensure systematic performance (flexion-supine [FLEX], extension-prone [EXT], abduction-side lie [ABD], adduction-side-lie [ADD], internal rotation-sitting [IR], external rotation-sitting [ER]). Strength ratios included ADD/ABD, EXT/FLEX and ER/IR. The length of the lever arm was measured (distance between approximate axis of rotation and the point of the application of force) and used to calculate torque (lever arm length [m] x force [newtons]) and values were normalized to body mass (Nm/kg) (Thorborg, Branci, Nielsen, *et al.*, 2014). The maximum value (from four trials) was used in the statistical analysis.

Lower limb reactive strength was assessed using a double-leg and single-leg drop jump (DLDJ / SLDJ). The protocol is outlined in Appendix F. Two 40cm x 60cm force plates (1000Hz; BP400600, AMTI, USA) were used to collect ground contact time (GCT). Jump height (JH) was calculated from flight time (Flanagan and

Comyns, 2008). Reactive strength index (RSI) was calculated by dividing JH (cm) by GCT (sec). The average of the three trials was used in the analysis.

Hip range-of-motion

Passive hip range of motion (ROM) was measured using a goniometer (Orthopaedic Equipment Co., Bourbon, USA) as per previously described methods (Malliaras *et al.*, 2009; Nussbaumer *et al.*, 2010). Two testers were used, with the primary tester passively moving the hip to an end of range position, defined as the first point at which resistance was felt and the seconder tester then placed the goniometer to assess the ROM. Both limbs were examined, and measures included supine hip internal and external rotation in 90° of hip flexion (flexion IR, ER), and prone hip internal and external rotation in hip neutral flexion and extension (extension IR, ER). The average of three trials was used for analysis.

Intervention

The content and criteria for progression through the intersegmental control programme have been published previously (King, Franklyn-Miller, *et al.*, 2018). The program was delivered by three experienced physiotherapists and based on the original intervention by our research group a number of exercise modifications were made to simplify coaching and for ease of implementation by athletes (Appendix D).

Data analysis

Data processing and descriptive statistics were carried out using MATLAB (version R2015a; The MathWorks Inc, Natick, MA). Isometric hip strength, reactive strength, bilateral squeeze test and inter-limb symmetry data are presented as mean

± standard deviation, normality was assessed (Sharpio-Wilk test) and parametric statistics were applied. When testing inter-limb symmetry, the asymmetry index was used (equation 1) (Robinson, Herzog and Nigg, 1987), where Sx is the symptomatic limb and Nx is the non-symptomatic limb.

$$Asymmetry\ Index\ =\ [(Sx - Nx)/((Sx + Nx/2))] * 100 \qquad (1)$$

The asymmetry index can provide both a magnitude (taking the absolute value of the inter-limb difference) and direction of symmetry (maintaining the positive or negative sign, with a negative sign indicating a greater value on the non-symptomatic limb). The magnitude of asymmetry was used to compared between AGP and CON athletes and the direction of asymmetry was used to compare AGP athletes pre- to post-rehabilitation.

To compare between AGP and CON athletes, symptomatic limbs were matched to CON athletes based on limb dominance (self-selected as an athlete's preferred kicking leg). To detect differences in AGP athletes from baseline to RTP (AGP Pre vs. Post) paired t-tests were used, and between AGP and CON athletes (AGP Pre vs. CON; AGP Post vs. CON) independent t-tests were used according to a per-protocol analysis. As the HAGOS data were not normally distributed, non-parametric statistics were applied. A Friedman analysis of variance (ANOVA) with repeated measures was used to examine the HAGOS subscale scores in the AGP athletes across all four time points (baseline, RTP, 3-month and 6-month post-RTP). Post-hoc analysis (Wilcoxon signed-rank test) was used to independently compare the HAGOS time-points pairwise. When examining HAGOS subscale scores between the AGP and CON athletes Mann-Whitney U tests were applied. Significance was set at $P < .05$. Effect sizes for parametric tests were calculated according to Cohen's *d*, with thresholds of trivial (< 0.20), small (< 0.50), medium (0.50 to 0.80) and large (>0.80) (Cohen, 1988). For non-parametric tests, effect sizes (*r)* were calculated by dividing the *z*-value by the $\sqrt{N}$ with thresholds of small (<0.1), medium (0.1 to 0.3) and large (>0.5) effect sizes (Pallant, 2011).

In order to more robustly examine the study aims and increase generalizability of our findings, a permutation technique (with replacement) was applied (Bruce, 2015). Briefly, 75% of AGP athletes were selected from the data and statistically compared to twenty-seven CON athletes who were randomly matched for leg dominance. This process was repeated 100 times, with all random data sets condensed to their average values (p-value and effect size) and the number of significant differences reported as a percent. Only when the consistency of significant differences was 85% or greater was the variable reported as significant in the results section.

Pearson's correlation coefficients were calculated to quantify the degree of relationship between self-reported sporting function (as measured by the pre- to post rehabilitation change in HAGOS Sport Rec score) and both hip strength and reactive strength (as measured by the pre- to post-rehabilitation changes in peak isometric hip torque, DL/SL DJ RSI, JH, GCT). Additionally, a linear regression analysis was applied with recursive feature elimination and a 5 x 3-fold nested cross-validation to examine the ability of the hip strength and RSI variables to predict the changes in the HAGOS Sport Rec score.

4.3 Results

The flow of athletes through the study is presented in Figure 4.3.A. Eighty-six athletes were referred for inclusion, forty-four athletes did not meet inclusion criteria, forty-two athletes enrolled in the study and six withdrew before achieving the RTP criteria. Two athletes RTP without completing the follow-up testing, two athletes withdrew due to other commitments, one athlete remained symptomatic and was referred back for review with the Sports and Exercise Medicine Physician and one athlete sustained a lower limb injury (work-related). Thirty-six athletes met the RTP criteria in an average of 9.8 ± 3.0 weeks and four athletes were lost to follow-up at 6-months post-RTP. Two of the four athletes suffered recurrent symptoms and were reviewed by the Sports and Exercise Medicine Physician and two were uncontactable. Athlete demographics are presented in Table 4.3.A. The most common anatomical diagnoses were pain or tenderness at the pubic aponeurosis (57%), followed by proximal adductor tendon insertion (19%), iliopsoas (14%), hip (8%) and inguinal (2%). A second anatomical diagnosis was reported in 60% of AGP athletes and a tertiary diagnosis reported in 17%. Each athlete attended the clinic an average of 4.7 ± 1.3 appointments.

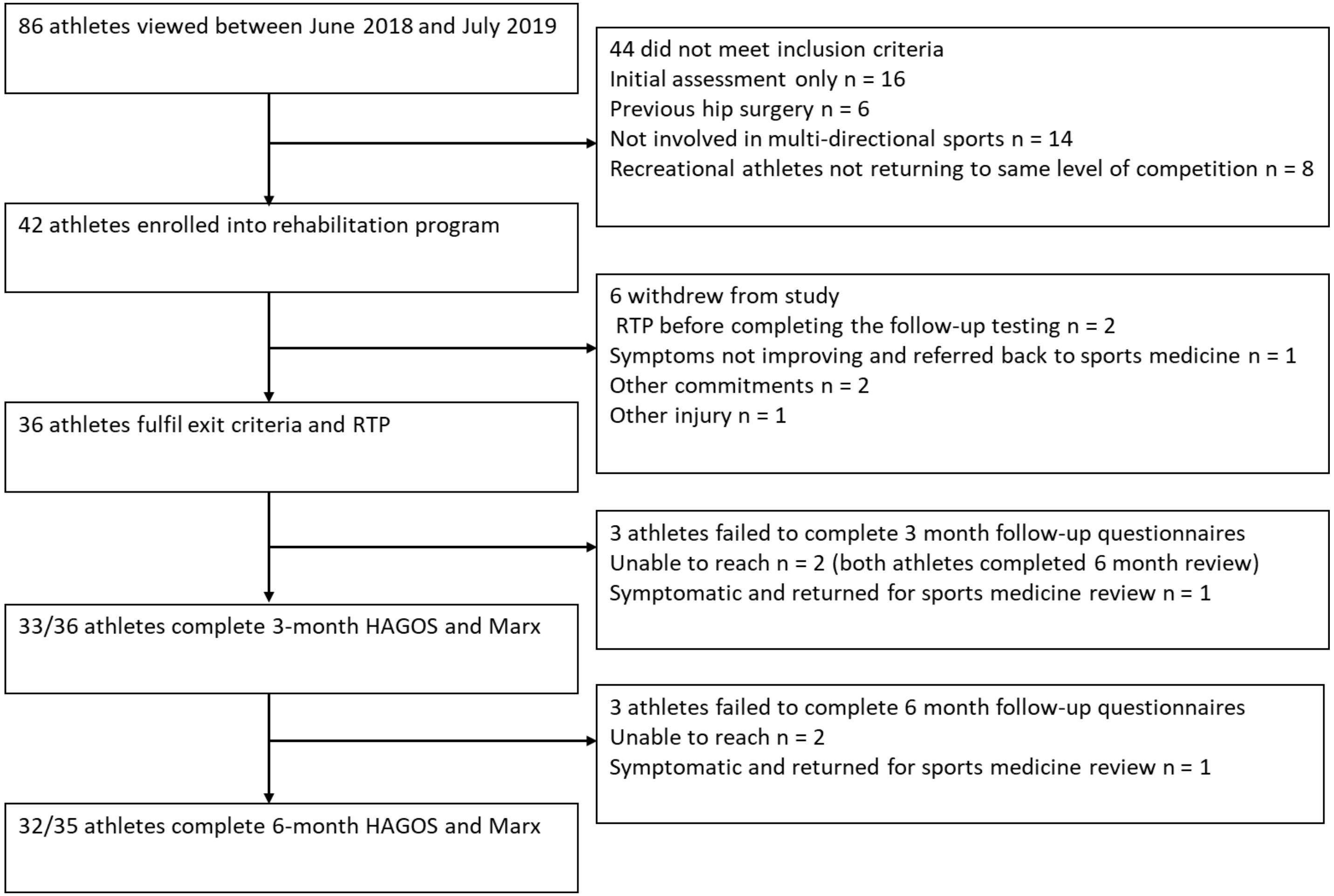


Figure 4.3.A Participant flow through the study

Table 4.3.A Athlete characteristics, sports played, clinical diagnoses and return-to-play times

Group	AGP n = 42	CON n = 36	
Age (yrs)	25.9 ± 4.9	24.1 ± 4.5	p = 0.169
Height (cm)	1797.1 ± 64.5	1809.5 ± 57.8	p = 0.408
Mass (kg)	80.3 ± 7.2	80.4 ± 8.2	p = 0.938
Sports Played (%)	GAA football (58%) soccer (25%) GAA hurling (14%) rugby union (3%)	GAA football (67%) soccer (17%) GAA hurling (6%) rugby union (8%) basketball (3%)	
Symptom Duration (weeks)	38.7 ±5.5	NA	
Primary diagnoses (%)	Pubic aponeurosis 57% (24/42) Adductor longus 19% (8/42) Psoas 14% (6/42) Hip 8% (3/42) Inguinal 2% (1/42)	NA	

Sx – symptom, PA – pubic aponeurosis, AL – adductor longus, inguinal, RTP – return to play, Level 1, 2, 3 of rehabilitation program, NA – not applicable

Clinical outcome measures: Baseline to RTP

Table 4.3.B presents all HAGOS findings and between group comparisons. All HAGOS subscale scores (p<0.001, *r* = -0.74 to -0.89) and the Marx score (p<0.001, *r* = -0.70) were significantly lower in AGP athletes compared to CON athletes at baseline testing with large effect sizes evident. Following rehabilitation, all HAGOS subscale scores (p<0.001, *r* = 0.50 to 0.60) and Marx score (p=0.002, *r* = -0.42) demonstrated significant improvements of large effect in the AGP athletes. At RTP, there was no difference in HAGOS Symptom score (p=0.112, *r* = -0.27) between the AGP and CON athletes, while all other HAGOS scores (p<0.02, *r* = -0.40 to – 0.77)

and Marx score (p=0.001, *r* = -0.61) remained significantly lower with medium to large effect size differences evident. When examining the squeeze tests in AGP athletes at baseline, 72% reported pain during the SQ45 and 61% during the SQ0, and at RTP no athletes reported pain during either test (Appendix C present the squeeze test values).

Table 4.3.B Comparison HAGOS subscales between AGP (all time points) and control athletes

	CON	AGP baseline	AGP RTP	AGP 3 month	AGP 6 month	AGP (baseline) vs. CON		AGP (baseline) vs. AGP (RTP)		AGP (RTP) vs. CON		AGP (RTP) vs. AGP (3 month)		AGP (3 month) vs. AGP (6 month)		AGP (6 month) vs. CON	
HAGOS	mean (IQR)	mean (IQR)	mean (IQR)	mean (IQR)	mean (IQR)	p	r	p	r	p	r	p	r	p	r	p	r
Symptom	89.3 (84.8 - 97.3)	60.2 (56.3 - 75.0)	83.9 (75.0 - 92.9)	89.3 (81.3 - 93.8)	85.7 (81.3 - 93.8)	<0.001	-0.74	<0.001	-0.58	0.112	-0.27	0.251	-0.14	0.84	-0.03	0.085	-0.21
Pain	97.5 (94.4 - 100)	76.3 (63.1 - 85.6)	92.5 (85.0 - 97.5)	96.3 (87.5 - 97.5)	96.3 (87.5 - 97.5)	<0.001	-0.76	<0.001	-0.53	0.020	-0.40	0.200	-0.16	0.35	-0.12	0.003	-0.36
ADL	100.0 (98.8 - 100)	75.0 (70.0 - 90.0)	95.0 (88.8 - 100)	100.0 (88.8 - 100)	95.0 (85.0 - 100)	<0.001	-0.76	<0.001	-0.50	0.014	-0.41	0.126	-0.19	0.24	-0.15	0.004	-0.35
Sport Rec	98.4 (93.9 - 100)	54.7 (39.9 - 67.2)	85.9 (80.5 - 93.8)	87.5 (78.1 - 96.9)	87.5 (77.4 - 94.5)	<0.001	-0.82	<0.001	-0.60	0.002	-0.48	0.613	-0.06	0.86	-0.02	<0.001	-0.48
PA	100.0 (100.0 - 100)	6.3 (0.0 - 37.5)	50.0 (21.9 - 75.0)	87.5 (75.0 - 100.0)	93.8 (75.0 - 100)	<0.001	-0.89	<0.001	-0.52	<0.001	-0.77	<0.001	-0.45	0.64	-0.06	0.002	-0.38
QOL	100.0 (90.0 - 100)	35.0 (30.0 - 45.0)	67.5 (45.0 - 80.0)	77.5 (67.5 - 90.3)	80.0 (68.8 - 95.0)	<0.001	-0.83	<0.001	-0.56	<0.001	-0.69	0.008	-0.32	0.52	-0.08	<0.001	-0.51
Marx	16.0 (13.8 - 16.0)	4.0 (0.0 - 8.3)	12.0 (9.0 - 12.0)	12.0 (11.8 - 16.0)	12.0 (8.7 - 12.3)	<0.001	-0.70	0.002	-0.42	<0.001	-0.61	0.099	-0.20	0.67	-0.05	<0.001	-0.48

ADL - activities of daily living, Sport Rec – sports and recreational activities, PA – participation in physical activity, QOL – quality of life, Marx – activity scale, IQR – inter-quartile range, r = effect size (small <0.1, medium 0.1 to 0.5, large >0.5)

HAGOS follow up at 3 and 6-months post RTP

The response rate for HAGOS and Marx questionnaires was 92% at 3-months and 91% at 6-months. From RTP to 3 months, HAGOS PA ($p<0.001$, $r = -0.45$) and QOL ($p=0.008$, $r = -0.32$) significantly increased with medium effect, while all other HAGOS subscale scores and Marx scores were maintained. From 3 to 6-month post-RTP, no significant changes were found in any HAGOS or Marx scores and at 6-month post-RTP, no difference in HAGOS Symptom score was evident between the AGP and CON athletes, while HAGOS Pain, ADL, Sport Rec, PA and QOL scores were significantly lower in the AGP athletes in comparison to CON athletes with differences of medium effect sizes evident ($p<0.003$, $r = -0.35$ to -0.51) (Figure 4.3.B).

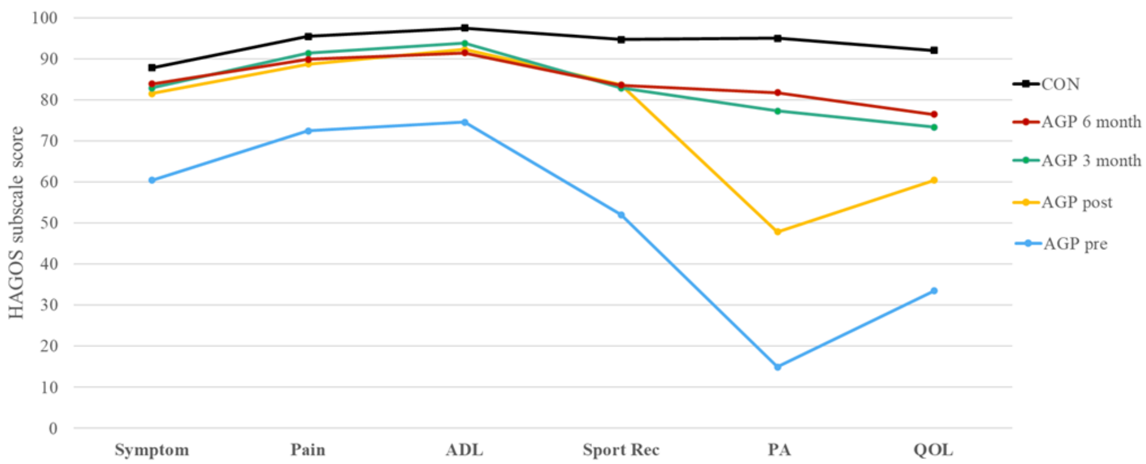
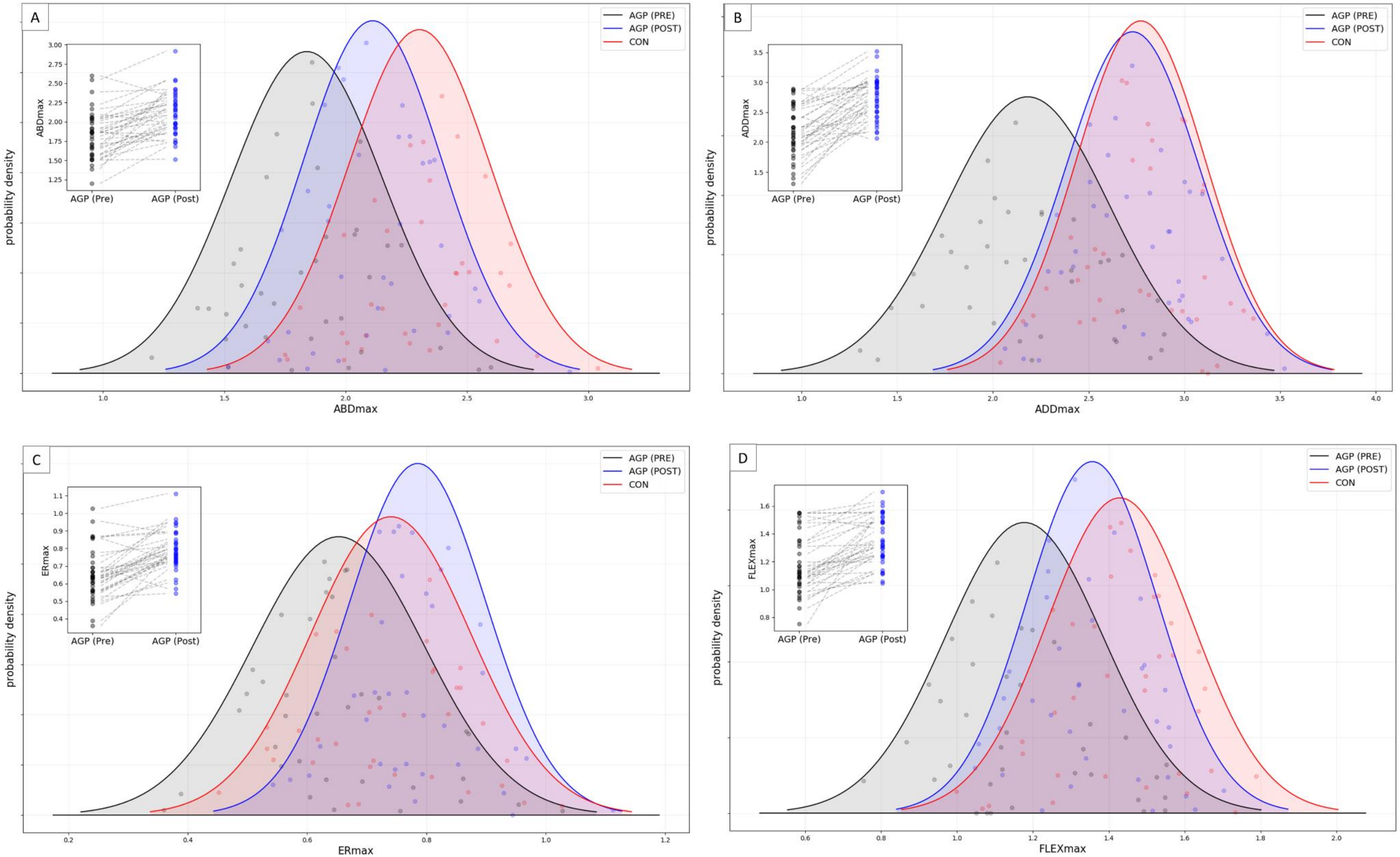


Figure 4.3.B HAGOS scores for control athletes and AGP athletes across all time points

Strength and hip ROM outcome measure: Baseline to RTP

Five out of the six peak hip torque measures (ABD p<0.001, *d* = -1.20; ADD p<0.001, *d* = -1.20; FLEX p<0.001, *d* = -1.07; EXT p=0.005, *d* = -0.83; ER p=0.03, *d* = -0.67) and SLDJ RSI (p=0.014, *d* = -0.73) were significantly lower in the AGP athletes compared to CON athletes at baseline testing with differences of medium to large effect sizes evident. No significant differences were found in any hip torque ratios (ADD/ABD, EXT/FLEX, ER/IR), DLDJ reactive strength (RSI, JH, GCT), hip ROM (flexion internal / external rotation, extension internal / external rotation) (Appendix B1) or asymmetry index measures (peak isometric hip torque, SLDJ: RSI, JH or CGT) (Appendix B2) at baseline testing. All five peak hip torque measures demonstrated significant increases in the AGP athletes following rehabilitation of large effect (p<0.03, *d* = -0.83 to -1.15), a small increase was evident in the SLDJ RSI (p=0.093, *d* = -0.30), and increased hip flexion internal rotation and total flexion rotation range-of-motion of medium effect size were demonstrated. At RTP testing, no significant differences were found in any of the peak hip torque measures (Figure 4.3.C: A-F), reactive strength, hip ROM, strength ratio or asymmetry measures when compared to the CON. Full results for all isometric hip strength, reactive strength, hip ROM and asymmetry variables are presented in Appendix B.


A
AGP (PRE)
AGP (POST)
CON
ABDmax
AGP (Pre)
AGP (Post)
probability density
ABDmax
B
AGP (PRE)
AGP (POST)
CON
ADDmax
AGP (Pre)
AGP (Post)
probability density
ADDmax
C
AGP (PRE)
AGP (POST)
CON
ERmax
AGP (Pre)
AGP (Post)
probability density
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CON
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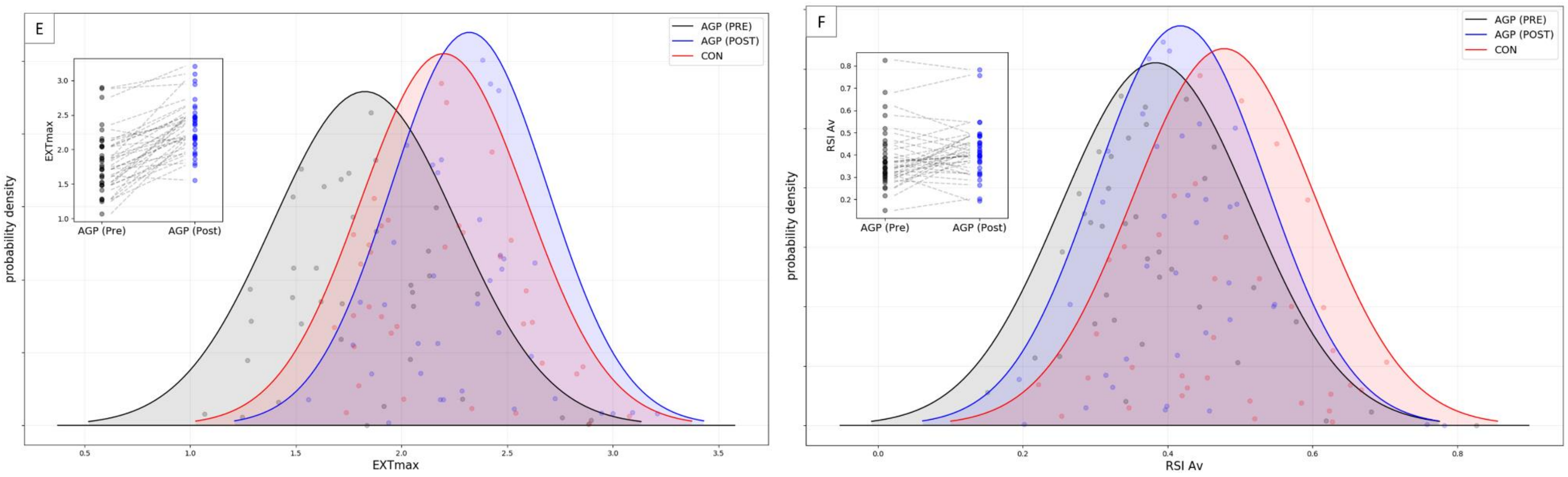


Figure 4.3.C Sample distributions for peak isometric hip strength (Nm/kg): (A) ABD max – peak hip abduction, (B) ADD max – peak hip adduction, (C) ER max – peak hip external rotation, (D) FLEX max – peak hip flexion, (E) EXT max – peak hip extension, (F) RSI - reactive strength index single leg drop jump. Black shaded - AGP group pre-rehabilitation (baseline), blue shaded - AGP post-rehabilitation (RTP), red shaded – uninjured control group. Inset box: individual changes in AGP athletes from pre-rehabilitation (black circles) to post-rehabilitation (blue circles) baseline to RTP testing.

Relationship between strength outcome measures and HAGOS sports and recreational function

No significant correlations were found between the pre- to post-rehabilitation change in HAGOS Sport Rec and the pre- to post-rehabilitation change in strength outcome measures (peak isometric hip torque: abduction: p=0.59, *r* = 0.32, flexion: p=0.104 *r* = 0.28, internal rotation: p=0.308 *r* = 0.18, extension p=0.625 *r* = 0.08, adduction: p=0.698 *r* = 0.07, ER: p=0.561 *r* = -0.10, DLDJ: GCT: p=0.90, r = 0.29, RSI: p=0.160 *r* = 0.24, JH: p=0.939 *r* =-0.01; SLDJ: JH: p=0.261 *r* = 0.21, RSI: p=0.429 *r* = 0.14, GCT: p=0.781, *r* = 0.05). The recursive feature elimination linear regression model selected two variables (pre- to post-rehabilitation change in isometric hip ABD and hip ER torque) which could explain 11% of the variance in the change in HAGOS Sport Rec.

4.4 Discussion

This study builds upon the previous research examining the efficacy of a rehabilitation programme targeting intersegmental control on athletes with AGP, with similar RTP times (mean ± SD: 9.8 ± 3.0), RTP rates (86%) and significant changes of *large* effect observed post-rehabilitation in HAGOS scores (King, Franklyn-Miller, *et al.*, 2018; Gore *et al.*, 2020). This is the first study to report HAGOS post-RTP and found athletes with AGP sustained or further improved HAGOS subscale scores over the six-months following RTP. In addition, the findings highlighted a number of strength variables in the AGP athletes, including hip adduction strength, that were weaker at baseline testing with *large* differences in comparison to CON athletes, and which resolved following the rehabilitation program despite no specifically directed adductor strengthening exercises. However, changes in hip and reactive strength only explained a small percentage of improvement in HAGOS Sport Rec (11%) suggesting other factors, such as intersegmental control, may hold greater importance in the rehabilitation of AGP.

The *large* improvements observed in all HAGOS subscale scores following AGP rehabilitation were larger than the smallest detectable change (SDC) values previously reported for each subscale (Thorborg *et al.*, 2011). The increase in HAGOS PA score from RTP to 3-month follow-up was also larger than the SDC. Notably, as the HAGOS PA score continued to improve over this period, indicating an increased level of physical activity, HAGOS symptoms, pain and sporting function subscale scores remained constant. This suggests improved capacity to tolerate the demands of sporting activities without reoccurrence of pain. Furthermore, from 3 to 6-month post-RTP, all HAGOS subscale scores and the Marx score remained constant in the AGP athletes indicating continued sporting participation did not negatively affect self-reported hip and/or groin function. At 6-month post-RTP, in AGP athletes all six HAGOS subscale scores had returned to the 95% reference range reported for hip and groin injury-free soccer players (Thorborg, Branci, Stensbirk, *et al.*, 2014). Although similar to other research, HAGOS scores remained lower when compared to the uninjured CON athletes with no history of hip and groin injury despite having made a pain free RTP (Thorborg, Branci, Stensbirk, *et al.*, 2014; Drew *et al.*, 2017). In the current study, the lower HAGOS scores may be explained by the long duration of pain reported by athletes in our study (mean of 39 weeks), as increased duration of pain duration (> 6 weeks) has been shown to negatively affect all HAGOS scores (Thorborg *et al.*, 2017).

At baseline testing, AGP athletes demonstrated *large* deficits in peak isometric hip torque in five out of six muscle groups (hip ABD, ADD, FLEX, ER and EXT torque) and *medium* deficits in SLDJ RSI when compared to CON athletes. Previous research has demonstrated comparable weakness of the hip ADD (Tyler *et al.*, 2001; O'Connor, 2004; Thorborg, Branci, Nielsen, *et al.*, 2014) and ABD (Robinson *et al.*, 2004) muscles in athletes with AGP when compared to uninjured controls, while no difference has been reported in hip FLEX (Tyler *et al.*, 2001; Thorborg, Branci, Nielsen, *et al.*, 2014; Rafn *et al.*, 2016), EXT (Mohammad *et al.*, 2014), IR (Malliaras *et al.*, 2009) or ER (Malliaras *et al.*, 2009) strength. Tri-planar hip strength, particularly the hip extensors, abductors and flexors, plays an important role in optimizing femoro-acetabular control during single-leg activities (Tyler *et al.*, 2006; Grimaldi *et al.*, 2009) during sports specific movements. Insufficient strength to control the large external forces during such activities has been suggested to adversely affect both movement technique (Janse van Rensburg *et al.*, 2017) and joint loading (Gore *et al.*, 2020), resulting in excessive loading across the pubic symphysis (Casartelli *et al.*, 2011). The lower SLDJ RSI observed in AGP athletes was primarily due to longer GCT. This may represent reduced capacity to utilize the stretch-shorten cycle (SSC) via a detraining mechanism (Mujika and Padilla, 2000) due to injury, as normal sporting activity (e.g. sprinting) can promote the SSC function (Markovic *et al.*, 2007). Alternatively, the longer GCT may be due to AGP athletes adopting a movement strategy to reduce the higher peak force and/or rate of loading that can occur with shorter ground contacts as per the impulse momentum relationship (Bressel and Cronin, 2005). The increase in SLDJ RSI observed in AGP athletes following rehabilitation resulted from a large effect size reduction in GCT. The shorter GCT may have been achieved through increased lower limb vertical stiffness (Gore *et al.*, 2018) and smaller angular displacements at the hip, knee and ankle, although further biomechanical analysis is required. In athletes with AGP, training methods (e.g. plyometrics) that utilize the stretch-shorten cycle and promote rapid expression of force in minimal times are of potential benefit during rehabilitation.

Following successful rehabilitation, *large* increases were evident in all isometric hip strength variables and a *medium* increase in SLDJ RSI in the AGP athletes. No significant differences were evident in any of these variables at RTP when compared to CON athletes. A major finding was that isometric adductor strength increased despite no specific adductor strength exercises being included in the intersegmental control program. Only one other AGP intervention study has objectively examined isometric hip strength (with hand-held dynamometry) pre- to post-rehabilitation (Yousefzadeh *et al.*, 2018). Yousefzadeh et al (2018) reported increased isometric hip adduction and abduction strength following rehabilitation, although the changes observed were larger than reported in the current study (Yousefzadeh *et al.*, 2018). This may be explained by the different intervention approaches employed, with Yousefzadeh et al (2018) utilizing exercises shown to induce high levels of adductor muscle activity (e.g. Copenhagen Adductor exercise) (Serner *et al.*, 2015). However, it is worth noting that the increase in hip adductor strength observed in our study was similar to the 35.7% increase in hip adductor strength that has been reported in uninjured soccer players after an 8-week program of targeted adductor muscle training (Ishoi *et al.*, 2016). Two possible mechanisms may explain the increased adductor strength found in our study. Firstly, reduced inhibition of the adductor muscle group as symptoms resolved with rehabilitation (Linthorne, 2001). Secondly, indirect muscle strengthening through the multi-planar action of the hip adductor musculature(Neumann, 2010) during the various levels of the rehabilitation program (e.g. compound strength, linear run / change-of-direction exercises). No other study has examined the changes in hip flexion, extension or external rotation strength following rehabilitation and our findings (AGP baseline vs. AGP RTP vs. CON) highlight the potential importance of rehabilitation targeting an increase in tri-planar hip strength in athletes with AGP. This is further supported by the findings that only 11% of the pre- to post-rehabilitation change in HAGOS Sport Rec could be explained by two of the isometric peak torque measures (hip abduction and hip external rotation). This may suggest that factors other than isometric hip strength, such as intersegmental control through dynamic sporting actions (e.g. running, change-of-direction), may play a more important role in explaining the improvements in HAGOS Sport and Rec score post-rehabilitation in AGP.

When examining muscle imbalances between AGP and CON athletes at baseline testing, no significant differences were evident in any of the hip muscle strength ratios (ADD/ABD, EXT/FLEX, ER/IR) or any measure of inter-limb asymmetry. This is consistent with the findings of Thorborg et al (2014) who also found no significant difference in hip ADD/ABD strength ratios when comparing soccer players with AGP to uninjured controls (Thorborg, Branci, Nielsen, *et al.*, 2014). Previous research has reported ADD/ABD strength ratio < 78% as a risk factor for groin injury (Tyler *et al.*,

2001) however, we found ADD/ABD strength ratios >100% in the injured AGP group, indicating stronger adductor muscles relative to abductor muscles in AGP athletes, at baseline testing. Thus, targeting the ADD/ABD strength ratio for AGP rehabilitation would not appear relevant in this cohort of athletes.

In relation to inter-limb symmetry, previous research has considered asymmetry indexes > 15% as abnormal and therefore targets for rehabilitation (Adams *et al.*, 2012). However, when examining AGP athletes at baseline testing in our study we found no asymmetry measures of isometric hip strength or reactive strength > 6% favouring a particular limb. These findings suggest a bilateral reduction in isometric hip strength and reactive strength (given that significantly reduced strength measures were observed on the symptomatic limb), and as such rehabilitation may be enhanced by targeting both limbs rather than specifically treating one side as symptomatic. Our hypothesis that there would be greater asymmetries in the injured population was rejected which was an unexpected finding given our clinical experience and asymmetries identified in lower limb injuries in other populations (Barber *et al.*, 1990; Impellizzeri *et al.*, 2007; Adams *et al.*, 2012; Jordan, Aagaard and Herzog, 2015). There are a number of potential explanations for these findings. Firstly, in our study 18% of AGP participants reported bilateral symptoms and therefore in these individuals there may be no preference to load or off-load a specific limb. Secondly, AGP participants may have strength and movement deficits on their non-symptomatic side which are driving or contributing to overload and pain on their symptomatic side. Lastly, when looking at the average asymmetry across a cohort, it may mask larger asymmetries in individual athletes. Given that there were strength deficits across all muscle groups at the hip, it is possible that some athletes had asymmetries in certain muscle groups but not in others which may give the appearance of the absence of asymmetry in the cohort. Future research may be directed further towards subgroup analysis of AGP participants which consistently off-load a particular limb.

In athletes with AGP no restrictions in any of the hip ROM measures were found pre-rehabilitation in comparison to CON athletes. These findings are in line with previous research (Verrall, Slavotinek, Barnes, Esterman, *et al.*, 2005; Malliaras *et al.*, 2009; Engebretsen *et al.*, 2010), whereas, in contrast others have reported significantly reduced hip ROM in athletes with AGP compared to uninjured control athletes (Ibrahim, Murrell and Knapman, 2007; Engebretsen *et al.*, 2010; Nevin and Delahunt, 2014). In the current study, following rehabilitation, hip flexion IR and total flexion IR/ER significantly increased in the AGP athletes. The implications of these finding remains unclear given that no deficits in hip ROM were evident between the AGP and CON groups pre-rehabilitation. It may be that increased ROM is of benefit for recovery given that previous research have reported increased loading of the pubic symphysis and surrounding soft tissue with restricted hip mobility (Verrall, Slavotinek, Barnes, Esterman, *et al.*, 2005; Birmingham *et al.*, 2012).

Limitations

CON athletes were only tested at baseline and therefore it was not possible to assess the change in clinical and strength measures that occurred in uninjured athletes as they continue to participate in regular sporting activities. Adherence to the intersegmental rehabilitation program was not collected and it is therefore not possible to examine if all athletes completed the same volume and intensity of exercises prescribed. Female athletes were not included and how our findings extrapolate to this athletic cohort remains unclear.

Conclusion

In a cohort of athletes with AGP, rehabilitation targeting intersegmental control reproduced rapid RTP times and confirmed significant improvements in all HAGOS subscale scores. HAGOS improvements were sustained and further improved in HAGOS PA and QOL scores up to three-month post-RTP and maintained across all of the HAGOS scores up to six months post RTP. The rehabilitation was effective at resolving the baseline deficits observed in isometric hip strength, including adductor strength despite the absence of targeted adductor strengthening, and single-leg reactive strength when compared to CON athletes. The strength measures had limited ability to explain the changes in HAGOS Sport and Rec scores, further supporting the suggestion that other factors, such as the targeting of intersegmental control during rehabilitation, are important considerations in the rehabilitation of AGP.

4.5 Relevance of this Chapter's findings to this thesis

The aim of this chapter was to investigate the effect of rehabilitation on isometric hip strength and reactive strength following rehabilitation which focused on intersegmental movement control. Furthermore, to examine the relationship between the pre- to post-rehabilitation change in strength variables and the pre- to post-rehabilitation change in HAGOS sport and recreational subscale score. Of particular interest for this thesis was that the significant increases found in multi-planar hip strength could only explain 11% of the change in HAGOS following successful rehabilitation. The implication from this finding is that factors other than isometric hip and reactive strength may be more important in successful rehabilitation. This subsequently led to the biomechanical analyses carried out in Chapter 5, 6 & 7 to improve our understanding of biomechanical factors related to AGP and also important for successful rehabilitation.

Chapter 5

Athletic groin pain and lower limb loading patterns during a countermovement jump

This study was submitted to the Journal of Athletic Training (May 2020) with revisions proposed by the journal (June 2020) in order to resubmit a revised manuscript.

Samuel R. Baida, Chris Richter, Enda King, Shane J. Gore, Andrew D. Franklyn-Miller & Kieran A. Moran. Athletic groin pain and lower limb loading patterns during a countermovement jump.

5.1 Introduction

Athletic groin pain (AGP) is a chronic musculoskeletal presentation predominantly affecting male athletes playing field-based sports (Orchard, 2015). In recreational male football, groin injury incidence ranges from 4 to 19% at a rate of 0.2-2.1/1000 hours (Waldén, Hägglund and Ekstrand, 2015). While the exact mechanisms causing AGP remain unclear, it is suggested that increased loading from repetitive mechanical forces (relative to tissue strength) affect the various musculotendinous insertions across the anterior pelvis of key muscular contributors to explosive sporting movements (e.g. jumping, change-of-direction) (Robinson *et al.*, 2004). During such movements optimal neuromuscular function (e.g. force development, power production) both attenuates and distributes mechanical forces experienced on the body to help reduce the risk of injury (Whiting, 2015). Deficits in neuromuscular function can remain post-injury despite rehabilitation and may in part explain why athletes with AGP have high seasonal carry-over rates (Thorborg *et al.*, 2017) and high injury reoccurrence rates (Orchard, Seward and Orchard, 2013).

Neuromuscular function can be quantified via analysis of vertical ground reaction forces (vGRF) which reflect the summated output of the lower limb neuromuscular system (Worp, Vrielink and Bredeweg, 2016). Research has shown altered vGRF loading rates, magnitudes (Bigouette *et al.*, 2016) and inter-limb symmetry (Jordan, Aagaard and Herzog, 2015) in groups with lower limb injuries when compared to uninjured controls. However, no previous research has examined vGRF in AGP and therefore it remains unclear if vGRF, magnitude, rate of loading and/or limb symmetry, is affected by the condition. To examine neuromuscular status in injured populations a countermovement jump (CMJ) has been used

(Baumgart, Hoppe and Freiwald, 2017), with previous research finding reduced peak force, peak power, impulse and force at the deepest point (during the jump phase) post anterior cruciate ligament repair (Baumgart, Hoppe and Freiwald, 2017; O'Malley *et al.*, 2018). The CMJ can be performed double-leg (DL) or single-leg (SL), with DL-CMJs providing insight into potential side-to-side compensatory mechanisms, whereas a SL-CMJs allow greater insight into a limb's neuromuscular capacity without compensation (Holsgaard-Larsen *et al.*, 2014). To date however, no research has investigated vGRF variables during a jump in athletes with AGP and this is the primary focus of our study.

Many previous studies examining the relationship between GRF and injury have solely utilized a case-control approach of comparing injured versus uninjured participants. While providing very useful information, one limitation is that findings may not be related to injury but rather occur as a result of deconditioning after an injury. An alternative but less utilized approach (Gore et al., 2018, 2020) involves additionally including an examination of an effective rehabilitation intervention to determine how the specific variables that differ between case and control are also affected by the intervention. This study simultaneously utilizes both a case-control and pre- to post-rehabilitation analysis, an approach which increases the likelihood of identifying factors more likely related to injury than when either approach is used in isolation. While this approach does not confer a true cause-effect relationship between an injury and biomechanical factors, which would require prospective research, it is referred to by Spirtes, Glymour and Scheines (2000) as 'probabilistic causation' because of the advantages inferred in combining both case-control and pre- to post-rehabilitation analyses.

Therefore, this study aims to determine: (1) if vGRF and inter-limb asymmetries during a DL-CMJ and SL-CMJ (jump and land phases) differ pre-rehabilitation in those with AGP compared to uninjured controls, and (2) the effect of rehabilitation on vGRF in those with AGP in comparison to an uninjured control group. Where differences in vGRF are evident, it is of value to clinicians and researchers to understand the underlying movement technique-based causes. Therefore, a tertiary aim is to identify the joint kinematics and kinetics that relate to key differences in vGRF.

In this exploratory study we hypothesize that vGRF, rate of force development, impulse, power and work metrics will be lower in the AGP group pre-rehabilitation compared to the uninjured controls, and post-rehabilitation will normalize to uninjured control values. Furthermore, we hypothesize that greater inter-limb asymmetry will be observed in the AGP group pre-rehabilitation and this will reduce post-rehabilitation.

5.2 Methods

Study design

A case-control and pre- to post-rehabilitation design was used to evaluate the between group differences in vGRF in those with AGP and uninjured control (CON) groups. Power was calculated using G*Power (3.1.9.2) for a large effect size (>0.80); 26 participants would be required to detect a significant between group difference (power = 80%, $p < 0.05$). Twenty-eight male AGP subjects attending the Sports Surgery Clinic, Dublin were recruited for the study and twenty-eight uninjured control subjects were matched based on age, sports played and competition level.

Participants

Participants diagnosed with AGP were eligible. A Sports and Exercise Medicine Physician made the diagnosis, based on clinical history, physical examination and interpretation of MRI (Falvey *et al.*, 2015). Inclusion criteria included: (1) anatomical diagnosis falling under AGP (iliopsoas, adductor, pubic aponeurosis and hip), (2) males aged between 18-35 years, (3) involved in multi-directional field-based sports, (4) hip/groin symptoms during sporting activity with duration greater than four weeks, and (5) plan to return to same pre-injury sport and level of competition. Exclusion criteria included: (1) hip joint arthrosis (grade 3 or higher on MRI), (2) those with an underlying medical condition (e.g. inflammatory arthropathy or infection), and (3) those who could not commit to completing the rehabilitation program due to time and/or location constraints. Uninjured controls were included if they had: (1) no previous groin pain/surgery, and (2) no lower limb injury within the previous three months. Participants were matched based on age, sports played and competition level. Study ethical approval was granted by the Sports Surgery Clinic's ethics committee (Ref 25EF011) and all participants signed informed consent.

Procedures

Participants received study information and consent forms following diagnosis with the Sports and Medicine Exercise Physician and were given the opportunity to read the study information at home. On follow-up appointment with the physiotherapist those who agreed to participate signed the consent form. The AGP group attended the biomechanics laboratory on two occasions; pre-rehabilitation and when cleared to return to play (symmetrical hip rotation and pain-free; bilateral squeeze test in 45° hip flexion, cross-over test, linear running program, change-of-direction drills) (King, Franklyn-Miller, *et al.*, 2018) and the control group attended once. Prior to each testing session a standardised dynamic warm-up was completed (Marshall *et al.*, 2015) before participants completed three maximal DL- and SL-CMJ with hands on iliac crests and starting from a stationary upright position. Instructions were given to jump as fast and as high as possible and no specific instructions were given for landing. If any of the jumps deviated from the required technique the trial was excluded and the jump was repeated. Jump variables were calculated as a mean of the three jumps.

Patient reported outcome measures

The AGP group independently completed the Copenhagen Hip and Groin Outcome Score (HAGOS) and Marx activity questionnaires on a tablet prior to their first and last laboratory testing session. HAGOS consists of six measurement dimensions: symptoms, pain, physical function in daily living, physical function in sport and recreational function, participation in physical activity and hip and/or groin related quality of life, and its use is advocated to establish levels of disability prior to rehabilitation and to assess the effectiveness of interventions post-rehabilitation (Thorborg *et al.*, 2011). The Marx activity questionnaire, which measures components of physical activity (e.g. running, cutting, pivoting) common to different sports, facilitates generalizability of results by reporting general activity levels as opposed to participation in specific sports (Marx *et al.*, 2001).

Intervention program

The rehabilitation program consisted of three levels, with each level designed to address specific components of recovery: control and strength, linear running mechanics, and multi-directional running mechanics (Figure 5.2.A). Progression through the levels is based on specific clinical criterion being achieved (e.g. pain-free cross-over test, completion of pain-free multi-directional drills). The program is described in detail in Appendix D (King, Franklyn-Miller, *et al.*, 2018).

Figure 5.2.A Criteria-based intervention program; specific levels of rehabilitation and the progression criterion (between levels or program exit)

Data capture and processing

The vertical ground reaction force (vGRF) was captured from two 40-by-60 cm force plates (1000Hz; BP400600, AMTI, USA), synchronized with 12 infrared cameras (200Hz; Vicon-Bonita B 10, UK) which collected lower extremity kinematic and kinetic data of the CMJs. Reflective markers (14 mm diameter) were placed at bony landmarks on the lower limb, pelvis and trunk (Vicon Plug-in Gait model, Vicon Motion Systems, UK). Force and motion data were filtered using a 4th order Butterworth filter with cut-off frequency of 15 Hz (Kristianslund, Krosshaug and Van Den Bogert, 2013). The data were exported to Matlab 2013b (Mathworks, USA) where the GRF was normalized to bodyweight, biomechanical variables calculated, and statistical analyses conducted.

Jump height was calculated from the centre of mass (CoM) vertical velocity at take-off. CMJ initiation was defined as the point the resultant vGRF fell below 99% of bodyweight, take-off and landing were defined as the first instants the resultant vGRF was <10N and >10N, respectively. Initiation of the eccentric phase of the CMJ was the point of minimum vGRF. The vertical CoM velocity was used to identify the start of the concentric phase (zero CoM velocity). The landing phase was defined as the time-interval from initial contact (resultant vGRF >10N) to zero vertical velocity of the body's CoM (Figure 5.2.B). In total 38 power, work and temporal variables were examined (Appendix G) in this exploratory study and was deemed necessary as no previous studies have examined vGRF in AGP. The vGRF variables were considered important if they were significantly different between groups pre-rehabilitation and subsequently normalize to values observed in the CON group post-rehabilitation. These variables are the focus of the results and discussion.

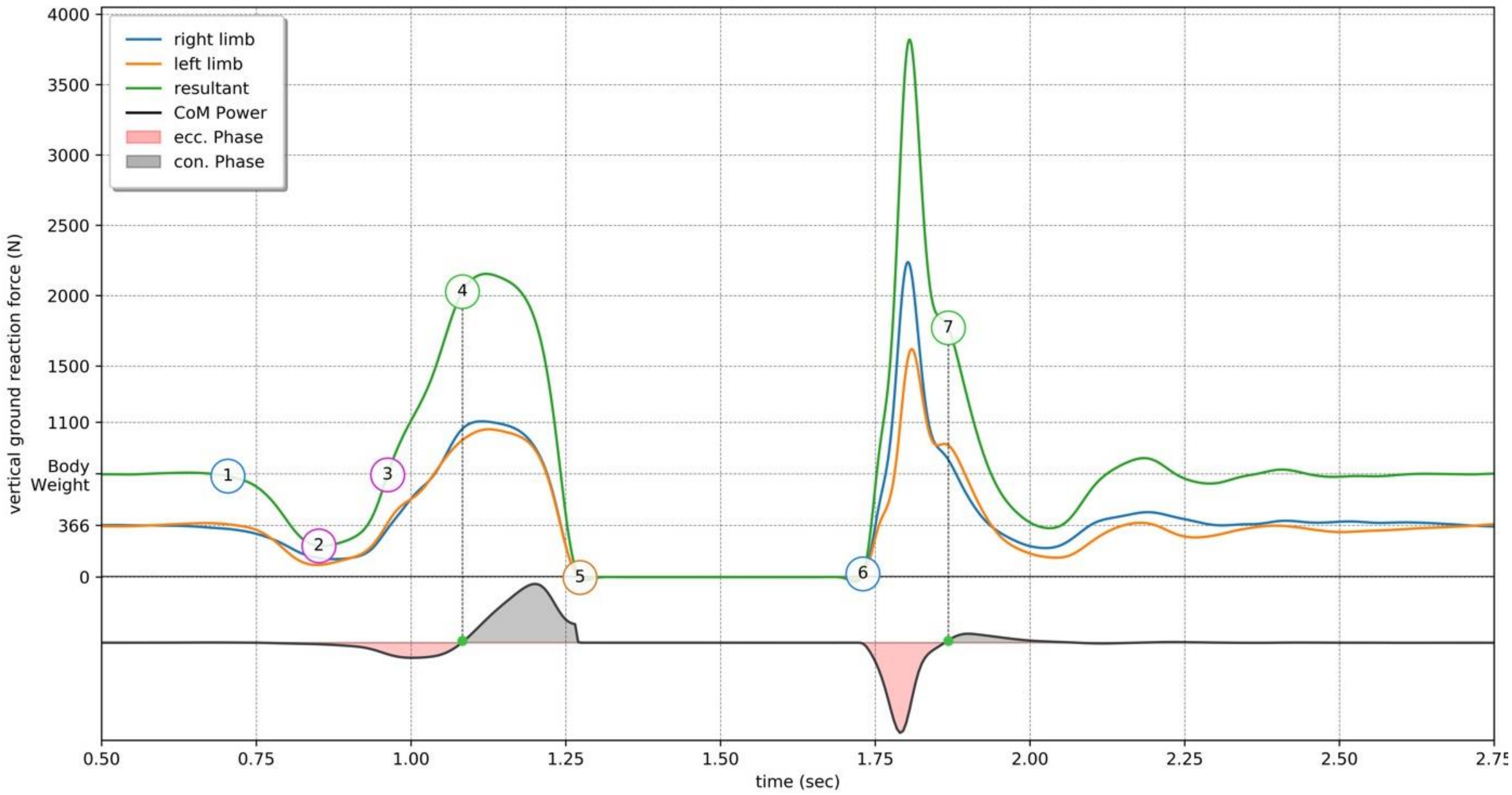


Figure 5.2.B Force-time curve of a DL-CMJ: 1 – beginning of jump, 2 – start of braking eccentric phase, 3 – start of eccentric deceleration phase, 4 – start of concentric phase, 5 – take-off, 6 – initial land impact, 7 – end of landing phase

To better understand how significant differences in vGRFs between the AGP and CON groups (pre-rehabilitation) were produced, sagittal plane joint kinematics and kinetics were explored (Appendix G1). This was deemed necessary as it is important to understand how movement technique relates to the key findings when examining vGRF.

Data analysis

Data were summarized with means ± standard deviations and assessed for normality using Shapiro-Wilks test. Both symptomatic and non-symptomatic limbs were analysed. The AGP symptomatic limb was determined by the side an athlete self-reported as painful; where pain was bilateral the most symptomatic side was selected. To allow for between-group comparisons, in the CON group symptomatic limbs were assigned based on the percent of AGP symptomatic dominant limbs (i.e. 53%). To avoid random sampling bias, a permutation analysis was utilized (100 shuffle-splits) (Richter *et al.*, 2019). During each shuffle-split a random side was chosen within the CON group that satisfied the constrain: 53% dominant and 47% non-dominant limbs. Independent t-tests were used to compare differences in vGRFs, kinematic and kinetic variables between the AGP and CON group pre- and post-rehabilitation. Paired t-tests were used to compare differences between the AGP pre- to post-rehabilitation. Non-parametric tests were used if normal distributions were not found. The p-value reported corresponds to the average p-value across the 100 splits.

To assess symmetry, absolute inter-limb asymmetry for vGRF variables was calculated (equation 1) (Impellizzeri *et al.*, 2007).

$$|\text{Absoulte interlimb asymmetry}| = \frac{non{-}symptomatic\ limb - symptomatic\ limb}{(symptomatic\ limb + non{-}symptomatic\ limb)/2} \quad (1)$$

Wilcoxon rank sum tests were used to examine differences in asymmetry between the AGP and CON groups, both pre- and post-rehabilitation. Where asymmetry was significant, the direction of asymmetry was assessed by examining the proportion of times that the magnitude was less on the symptomatic side.

The magnitude of differences was calculated with effect sizes according to Cohen's *d*, with thresholds of small (d<0.20), moderate (0.20>d>0.50) and large (d>0.80) (Cohen, 1988). For non-parametric tests, effect sizes (*r*) were calculated by dividing the *z*-value by the $\sqrt{N}$ with 0.1, 0.3 and 0.5 indicating small, medium and large effect sizes (Pallant, 2011).

5.3 Results

Patient demographics

Demographic characteristics of the AGP and CON groups are shown in Table 5.3.A with no significant differences in age, height or mass found. The AGP group had an average symptom duration of 32 weeks (interquartile range 16-42). In the AGP group 86% were right-leg dominant and 53% were most symptomatic on the right side. The most commonly identified anatomical diagnoses were pubic aponeurosis pain or tenderness at the pubic aponeurosis (61%), adductor tendon pain (18%), iliopsoas tendon pain (14%) and hip-related pain (7%).

Table 5.3.A Demographic characteristics and breakdown of primary sporting participation and clinical diagnosis

Group	Age (years)	Height (cm)	Mass (kg)	Sports Played (%)	Diagnosis n (%)
AGP (n=28)	25.0 ± 5.4	180.4 ± 5.6	81.7 ± 7.3	GAA football (57%), GAA hurling (18%), Soccer (14%), Rugby Union (7%), Basketball (4%)	PA 17 (61%), ADD 11 (18%), Iliopsoas 5 (14%), Hip 2 (7%)
CON (n=28)	27.9 ± 3.6	184.5 ± 6.9	82.9 ± 4.9	GAA football (54%), GAA hurling (29%), Soccer (14%), Rugby Union (4%)	

GAA - Gaelic Athletic Association, PA – pubic aponeurosis related symptoms, ADD – adductor-related symptoms, HIP – hip-related symptoms

Patient reported outcome measures

All HAGOS subscale scores and Marx activity questionnaire significantly improved post-rehabilitation (Table 5.3.B).

Table 5.3.B Patient reports outcome measure: Mean (standard deviation) Copenhagen Hip & Groin Outcome scores (HAGOS) and Marx activity pre- and post-rehabilitation

HAGOS	AGP-pre Mean (*SD*)	AGP-post Mean (*SD*)	p	*r*
Symptom	64.8 (13.3)	81.8 (12.0)	<0.001	0.58
Pain	73.8 (12.2)	91.0 (9.0)	<0.001	0.61
ADL	77.7 (11.4)	90.9 (11.0)	<0.001	0.58
Sport Rec	52.6 (18.5)	83.7 (14.3)	<0.001	0.60
Physic Act	14.7 (14.5)	67.0 (26.0)	<0.001	0.61
QOL	34.8 (16.2)	64.5 (20.8)	<0.001	0.60
Marx Act	5.9 (6.4)	11.9 (2.2)	<0.001	0.51

Pre – pre-rehabilitation, Post – post-rehabilitation, SD – standard deviation, , r = effect size (small <0.1, medium 0.1 to 0.5, large >0.5), ADL – activity daily living, SportRec – sports and recreational activity, Physic Act – physical activity, Marx Act – Marx activity score.

Double-leg countermovement jump

The following results reported are for the variables that were significantly different pre-rehabilitation between the AGP-pre and CON groups, the change in these variables pre- to post-rehabilitation in the AGP group and the post-rehabilitation comparison between the AGP-post- and CON groups.

Pre-rehabilitation, the AGP group had significantly greater maximum landing force on the symptomatic limb (p=0.037, *d*=0.59) and greater force at the start of the eccentric jump phase on the non-symptomatic limb (p=0.038, *d*=0.59) compared to the CON group (Table 5.3.C). After rehabilitation, the AGP group significantly increased maximum landing force on the symptomatic limb (p=0.032, *d=0.36)* and this remained significantly greater in comparison to the CON group (p=0.002, *d*=0.93) post-rehabilitation. On the non-symptomatic limb, force at the start of the eccentric phase significantly reduced in the AGP group after rehabilitation (p=0.002, *d*=0.56) and was no longer statistically different to the CON group post-rehabilitation. Appendix G2 & G3 provide the full results of the remaining 36 variables examined during the DL-CMJ.

Table 5.3.C DL-CMJ vGRF variables: group means (SD) and between group comparisons

Variables	AGP pre	AGP post	CON	AGP pre v CON		AGP pre v AGP post		AGP post v CON	
Symptomatic limb	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	p	*d*	p	*d*	p	*d*
Maximum landing force	27.6 (8.1)	29.7 (7.7)	23.5 (5.2)	0.037	-0.59	0.032	-0.36	0.002	-0.93
Non-symptomatic limb									
Force at start of eccentric phase (minimum vGRF)	2.3 (1.0)	1.7 (0.8)	1.7 (0.9)	0.038	-0.59	0.002	0.56	0.850	0.04

DL-CMJ - double leg countermovement jump, vGRF - vertical ground reaction force, PRE - pre-rehabilitation, POST - post-rehabilitation, d – Cohen's d effect size, force units – N/kg.

Single-leg countermovement jump

Pre-rehabilitation the AGP group had significantly less landing impulse in the first 40ms on both the symptomatic (p=0.046, *d*=0.63) and non-symptomatic (p=0.003, *d*=0.97) limbs and significantly less total landing impulse (p=0.006 *d*=0.89) on the non-symptomatic limb compared to the CON group (Table 5.3.D). After rehabilitation, the AGP group significantly decreased landing impulse 40ms on the symptomatic limb (p=0.020, d=0.39) and total landing impulse on the non-symptomatic limb (p=0.010, *d*=0.56) and all three variables remained significantly less when compared to the CON group post-rehabilitation. Appendix G4 & G5 provide the full results of the remaining 35 variables examined during the SL-CMJ.

Table 5.3.D SL-CMJ vGRF variables: group means (SD) and between group comparisons

Variables	AGP pre	AGP post	CON	AGP pre v CON		AGP pre v AGP post		AGP post v CON	
Symptomatic limb	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	p	*d*	p	*d*	p	*d*
Land Impulse First 40ms	-74.3 (7.2)	-71.5 (7.0)	-78.1 (4.6)	0.046	0.63	0.020	0.39	0.001	1.11
Non-symptomatic limb									
Land Impulse	-188.4 (31.5)	-169.3 (28.6)	-217.5 (34.0)	0.006	0.89	0.010	0.56	<0.001	1.53
Land Impulse First 40ms	- 71.8 (7.9)	-71.8 (6.1)	-78.1 (4.6)	0.003	0.97	0.975	0.00	<0.001	1.17

SL-CMJ - single leg countermovement jump, vGRF - vertical ground reaction force, PRE - pre-rehabilitation, POST - post-rehabilitation, d – Cohen's d effect size, impulse units – Ns/kg

Inter-limb asymmetries

Table 5.3.E presents the inter-limb asymmetry variables that were significantly different between the AGP and CON groups during the SL-CMJ pre-rehabilitation. No variables were found to be significantly different during the DL-CMJ pre-rehabilitation. During the SL-CMJ, minimum eccentric power (p=0.04, *d*=0.64), mean concentric force (p=0.038, *d*=0.62) and mean concentric power (p=0.015, *d*=0.74) asymmetries were significantly greater in the AGP group. Post-rehabilitation, these variables were no longer significantly different between the AGP and CON groups, however, no significant change was observed in the AGP group pre- to post-rehabilitation. In the AGP group, examining the direction of asymmetry, reduced minimum eccentric power was observed on the symptomatic limb in 36% of the comparisons to the non-symptomatic limb, and reduced mean concentric

force and mean concentric power was observed in 59% of comparisons to the non-symptomatic limb. Appendix G6 & G7 provide the full results for the remaining asymmetry variables examined during the DL- and SL-CMJs.

Table 5.3.E Inter-limb asymmetry: DL and SL-CMJ vertical GRF group means (SD), between group comparisons and limb loading frequency

Variables	AGP pre	AGP post	CON	AGP pre v CON			AGP pre v AGP post			AGP post v CON		
SL-CMJ	Mean (*SD*)	Mean (*SD*)	Mean (*SD*)	p	*d*	Sx <	p	*d*	Sx <	p	*d*	Sx <
Min ECC Power	0.17 (0.11)	0.15 (0.12)	0.11 (0.08)	0.040	0.64	36%	0.445	0.12	36%	0.42	0.41	64%
Mean CON Force	0.04 (0.02)	0.04 (0.03)	0.03 (0.02)	0.038	0.62	59%	0.833	0.09	59%	0.313	0.44	50%
Mean CON Power	0.08 (0.06)	0.06 (0.05)	0.05 (0.04)	0.015	0.74	59%	0.240	0.22	59%	0.360	0.34	68%

PRE - pre-rehabilitation, POST - post-rehabilitation, d – Cohen's d effect size, Sx < - proportion of times that magnitude of variable was less than on the symptomatic side compared to non-symptomatic side, power units – W/kg, force units – N/kg.

Examination of kinematic and kinetic factors explaining the changes in vGRF

The most consistent significant findings in vGRF variables were found during the landing phase of the DL- and SL-CMJ jumps and therefore the sagittal plane kinematics and kinetics were investigated. During the DL-CM, pre-rehabilitation the AGP group displayed significantly less change in sagittal plane range-of-motion at the ankle (symptomatic limb p=0.001, *d*=1.00, non-symptomatic limb p=0.006, *d*=0.82), knee (symptomatic limb p=0.005, *d*=0.82, non-symptomatic limb p=0.015, *d*=0.73) and hip (non-symptomatic limb p=0.044, *d*=0.61) during the first 40ms after impact, and significantly reduced change in hip moment (from hip extension towards flexion moment) during the first 40ms after impact (symptomatic limb p=0.049, *d*=0.60) when compared to the CON group (Appendix G8). During the SL-CMJ, pre-rehabilitation the AGP group displayed significantly greater ankle plantar flexion angle (symptom limb p=0.007, *d*=0.81, non-symptomatic limb p=0.006, *d*=0.82) and knee extension angle (non-symptomatic limb p=0.024, *d*=0.68) at impact, significantly less change in sagittal hip range-of-motion in the first 40ms after impact (symptomatic limb p=0.033, *d*=0.65), significantly reduced change in knee moment (from knee extension towards flexion moment) (symptomatic limb p=0.009, *d*=0.78) and significantly reduced change in hip moment (from hip extension towards flexion moment) (symptomatic limb p=0.030, *d*=0.66, non-symptomatic limb p=0.028, *d*=0.67) compared to the CON group (Appendix G9).

5.4 Discussion

Twenty-eight AGP participants successfully rehabilitated, returned to play in 12.2±6.3 weeks and demonstrated significant improvements across all HAGOS subscales. Pre-rehabilitation, five variables (DL-CMJ; symptomatic limb maximum landing force, non-symptomatic force at the start of the eccentric phase; SL-CMJ; symptomatic and non-symptomatic limbs landing impulse first 40ms, non-symptomatic limb total landing impulse) significantly differed between the AGP and CON groups.

Consistent with previous research in knee and ankle injuries (Baumgart, Hoppe and Freiwald, 2017; Powell *et al.*, 2018) the differences identified in vGRF variables occurred during the eccentric phases of movement. At the start of the eccentric phase (minimum vGRF) during the DL-CMJ, vGRF was greater in the AGP group (non-symptomatic limb $p<0.38$, d=0.59, symptomatic limb $p=0.061$, d=0.53), it significantly decreased with rehabilitation and was no longer significantly different to the CON group post-rehabilitation. This may reflect an increase in muscular control during the unweighting period prior to the start of the eccentric phase in which less force is then required to slow the downward center of mass (CoM) momentum, highlighting the potential importance of the eccentric periods where the jumper slows down and begin to reverse the downward acceleration of the CoM, in which greater leg muscle activation and increased joint stability are required for optimal force transfer (Linthorne, 2001). Our findings, in part, support our second hypothesis (variables which differentiated the AGP and CON groups pre-rehabilitation would normalize in the AGP group post-rehabilitation) which suggests that intervention programs may look to include exercises which focus on the eccentric phases of movement. In our study, many of the prescribed exercises focused on controlled eccentric movements (e.g. front squat, deadlift) potentially resulting in a re-conditioning of eccentric muscular control bilaterally.

In contrast to our secondary hypothesis, maximum landing force (DL-CMJ) and total landing impulse and landing impulse during the first 40ms (SL-CMJ), which were significantly different pre-rehabilitation between the AGP and CON groups, did not normalize post-rehabilitation, but in fact moved further away from the CON group's values. As such, post-rehabilitation maximum landing forces remained significantly greater and landing impulses remained significantly lower in the AGP group compared to the CON group and with greater effect sizes. In this study the AGP and CON groups dropped from similar jump heights and therefore the reduced landing impulse during the first 40ms may reflect a cushioning strategy utilized by the neuromuscular system to slow the rate of initial loading (Bressel and Cronin, 2005). This may in part be explained by the AGP group preparing with greater ankle plantar flexion and knee extension to reduce center of mass displacement (from the point of maximum jump height to impact) thus lowering the velocity of landing in order to reduce moments at the knee and hip (Appendix G). However, in order to retain overall performance associated with a subsequent push off action in normal sporting events (but not in the test action employed in the present study) it is important not to extend the duration of landing but instead to retain high overall eccentric loading to optimize the stretch shortening cycle (Ortega, Rodríguez Bíes and Berral de la Rosa, 2010). This could be made possible by increasing maximum force (as observed in our study) to offset the reduced initial loading.

It remains unclear as to whether the difference in landing impulse in the AGP group was an attempt to reduce loading as athletes continued to play sport (average duration of symptoms in the AGP group was 32 weeks) or through learned patterns during the rehabilitation process. While there is some debate within the literature as to whether the rate of loading (associated with the early impulse) or peak forces are more related to injury, in running at least, an activity that also requires similar rapid absorption of vGRF during initial impact, a recent systematic review found that higher loading rates at initial impact were related to lower limb injuries, while no differences were observed in the magnitude of the peak forces (Van Der Worp *et al.*, 2016).

It should be noted that in this exploratory study many more vGRF variables significantly changed in the AGP group from pre- to post-rehabilitation other than those discussed above. This suggests the rehabilitation program delivered broad neuromuscular adaptation. However, as these vGRF variables were not significantly different pre-rehabilitation between the AGP and CON group, they are deemed less likely to be of importance in relation to AGP.

Significantly greater inter-limb asymmetries were identified during the SL-CMJ (minimum eccentric power, mean concentric force and mean concentric power) when comparing the AGP and control groups pre-rehabilitation. Although, no consistent off-loading pattern was seen in any of these variables when analysing the direction of the asymmetry (determining the proportion of times that the magnitude of asymmetry was less on the symptomatic side). Three potential reasons may explain this inconsistency in off-loading patterns. Firstly, the pelvis is a central anatomical structure which serves as a common attachment point for many lower limb and trunk muscle groups (e.g. gluteals, adductors, abdominals) and as such the capacity to off-load forces away from a specific limb, in the same way one could off-load forces away from an injured knee, is somewhat negated. Secondly, in our study 18% of AGP participants reported bilateral symptoms and therefore in these individuals there may be no preference to preferentially load or off-load a specific limb. Lastly, AGP participants may have movement dysfunctions on their non-symptomatic side leading to overload and pain on their symptomatic side. Future research may be directed towards subgroup of AGP participants which consistently off-load a particular limb.

In this study, no significant differences were found between the AGP and CON groups pre-rehabilitation in any of the performance variables (i.e. jump height, jump duration or contraction time to jump height) and therefore vGRF variables are of more value when examining those with AGP in comparison to uninjured populations. In line with our findings, Gore et al (2020) found differences in vGRF during a lateral hurdle hop when comparing AGP and CON groups despite no differences in performance metrics (e.g. height or distance) (Gore *et al.*, 2020).

There were a number of limitations within this study. Firstly, given the exploratory nature of this study into vGRFs in AGP patients, it was deemed necessary to include a large number of dependent variables; the associated large number of comparisons can increase the likelihood of type I errors. However, this was partly controlled for with the permutation analysis approach used in this study. Secondly, a whole-group analysis approach was undertaken in this study. This has the potential to mask findings regarding movement strategies that may be present at a sub-group level (Richter, O′Connor, *et al.*, 2014). Lastly, the study focused AGP participants who successfully completed the intervention program and therefore, potentially important information regarding the neuromuscular outputs of those who fail to successfully rehabilitate has not been examined.

5.5 Perspectives

These findings support the future use of vGRF analysis in those with AGP using variables that differed between the AGP and CON groups of medium to large effect size despite no differences observed in outcome performance of the tasks. However, caution is required when interpreting these results given the large number of variables examined in this study. Given AGP is a common problem in athletes playing field sports, GRF during more explosive (e.g. drop jump) or multi-planar movements (e.g. lateral hop, change-of-direction cut) may be more appropriate to examine. The rehabilitation program used in this study was standardized for all AGP participants and therefore future rehabilitation strategies may benefit from the inclusion of movement patterns with particular focus on force absorption and landing strategies when abnormal vGRF loading patterns are identified. We consider our research as exploratory and therefore encourage replication of the study specifically examining the five variables we have identified as being most likely related to AGP injury. Future research should further explore AGP and GRFs to identify neuromuscular loading strategies which may contribute to injury and provide targets to optimize an individual athlete's rehabilitation. This may help reduce the high seasonal carry-over (Thorborg *et al.*, 2017) and reinjury rates (Orchard, Seward and Orchard, 2013) which are associated with AGP.

5.6 Reflection on return to play times

The different return-to-play times observed within this thesis (chapter 4: 9.8 ± 3.0 weeks versus chapter 5: 12.2 ± 6.3 weeks), when comparing two individual cohorts following the same intervention program, highlights the complex and challenging nature of defining RTP status. The longer RTP times reported in chapter 5 in this thesis may be explained by several different factors: (1) delayed time between when athletes completed the final ‘Run B’ program and when they could attend the Sports Surgery Clinic for their final 3D laboratory testing session which included their RTP assessment (i.e. hip range-of-motion, adductor squeeze test, pubic stress test) and (2) a low rate of adherence to the rehabilitation program. The different RTP times between the two individual cohorts reported in this thesis also highlights the potential difficulties when comparing RTP times between different studies which: (1) utilize different intervention programs, (2) set different RTP criterion, and (3) have different rates of program adherence. Defining return to play status can be challenging as the meaning of RTP can be different for the various stakeholders involved in the decision (e.g. player, coach, performance coach, physiotherapist) and complex as it involves multiple elements (e.g. psychological readiness, physical readiness, time of season etc) that require consideration (Ardern et al. 2016). Future research should look to employ standardised RTP criteria for athletes with AGP. The criteria should consider all factors (e.g. pain provocation tests, hip strength measures, lower limb power, running distances and running speeds, psychological readiness etc.) that can provide information on the various elements of RTP (i.e. return to train, return to play, return to performance).

5.7 Relevance of this chapter's findings to the thesis

In athletes with AGP, a cushioned landing strategy was identified during a single leg CMJ to reduce the initial landing impulse and potentially reduce loading on painful tissue structures at the pelvis. Following successful rehabilitation, this landing strategy was enhanced as the AGP group further decreased their initial landing impulse by increasing knee extension and ankle plantar flexion prior to the initial ground contact. These findings highlight movement strategies that may be targeted specifically for AGP rehabilitation programs to potentially enhance off-loading strategies to promote recovery and reduce reinjury. However, this was the first study to examine a vertical jump and land action in an AGP group and further research is needed to increase our understanding of movement patterns that require the rapid expression of vertical force and control of high eccentric loads in those with AGP. In this study, given the largest effect sizes were reported between the AGP and CON groups during a single leg CMJ, when compared to the double leg CMJ, single-leg actions (e.g. hopping) may be more sensitive to detect altered movement patterns in AGP groups. Considering this, Chapter 6 and 7 investigate the vertical GRF, joint kinematics and kinetics during a single leg hopping task.

Chapter 6

Ground reaction force loading characteristics affected by AGP during a continuous hopping task: a case-control study

6.1 Abstract

Background*:* Athletic Groin Pain (AGP) is a chronic overuse musculoskeletal injury common in sports which involve repetitive deceleration and jumping movements. One potential risk factor contributing to overload and injury in the region are the impact forces on the body which are quantified via the ground reaction force (GRF). Both the magnitude and variability of GRFs have been associated with various overuse injuries, however, their role in the development of AGP has not been explored.

Objective: To investigate the magnitude and variability of the vertical GRF in athletes with AGP during a continuous lateral hurdle hop task compared to uninjured controls. Secondly, to examine the changes in GRF magnitude and variability following successful rehabilitation in the AGP group.

Design: Case-control, intervention trial

Methods: Thirty-six male athletes diagnosed with AGP and 36 matched control athletes completed a continuous side-to-side hurdle hop at baseline testing, with the AGP group retested at return-to-play (RTP) after successfully completing rehabilitation. Primary outcome measures included the magnitude and variability of the GRF (concentric and eccentric phases: peak, impulse, rate-of-force development, ground contact time). Between-group comparisons were made using independent t-tests, and within-group comparisons with paired sampled t-tests.

Results: At baseline testing, the AGP group had significantly longer total (p=0.025, d=0.43) and concentric (p=0.020, d=0.50) ground contact times, larger

concentric impulse (p=0.028, d-0.52) and lower peak force (p=0.025, *d*=0.36) when compared to the CON group, while no differences in the variability of any measure was found at baseline. Following successful rehabilitation, in the AGP group these measures improved in the direction of the uninjured controls and were no longer statistically different between groups when compared at RTP.

Conclusion: The magnitude and not the variability of GRF measures were found to be significantly different in the AGP group in comparison to uninjured CON at baseline testing. The AGP displayed movement strategies to lessen the impact forces to potentially reduce excessive loading across the pubic region which may be related to injury. Following successful rehabilitation, these differences resolved which suggest an increased capacity to tolerate higher loading parameters as indicated by peak force and loading rates. These findings potentially highlight factors which can be used in the assessment of athletes with AGP and provide targets for rehabilitation.

6.2 Introduction

Athletic groin pain (AGP) is a common overuse injury prevalent in male athletes playing sports which involve jumping, change-of-direction, deceleration and acceleration movements (O'Connor, 2004; Murphy *et al.*, 2012; Orchard, 2015). In professional football, AGP accounts for 14% of all injuries at a rate of 1.0/1000 player exposure hours (Werner *et al.*, 2019). It is typical for athletes to present with co-existing pathologies to bony and myofascial structures at the anterior pelvis (Hölmich, 2007; Zoga, Mullens and Meyers, 2010). Athletes often report an insidious onset of pain that gradually worsens with continuous loading on the pelvis, occurring over several training sessions or within a single training session. It has been suggested that the large impact forces during repetitive deceleration and acceleration movements (e.g. hopping, running) contribute to excessive loading on the anterior pelvis leading to pain and injury (Janse van Rensburg *et al.*, 2017; Gore *et al.*, 2020), however, very few studies have examined the loading patterns in AGP compared to uninjured controls and following rehabilitation.

An important measure of loading on the body is the ground reaction force (GRF) which represents the summated measure of impact forces exerted on the body's center of mass. The vertical GRF has frequently been investigated as a potential risk factors for overuse lower limb injuries, using peak, rate of loading and impulse measures (Zadpoor and Nikooyan, 2011; Jordan, Aagaard and Herzog, 2015; Worp, Vrielink and Bredeweg, 2016). However, to date only two studies have examined the vertical GRF in AGP with conflicting findings reported (Edwards, Brooke and Cook, 2016; Gore *et al.*, 2020). Gore et al (2020) reported significantly reduced vertical GRF (d=0.73) in the AGP group compared to uninjured controls during a lateral hurdle hop. In contrast, Edwards et al (2016) reported greater peak vertical GRF in the AGP group when compared to the control group during the weight acceptance phase of an unanticipated cutting task. No study has examined the rate of loading or impulse of the GRF in AGP and it has been suggested these measure may be of greater importance then peak force measures as they provide insight into the levels of strain placed on tissues (Schaffler, Radin and Burr, 1989). In addition, no study has specifically examined the eccentric and concentric phases of the GRF in AGP and this may provide additional insight in braking and propulsive loading strategies when compared to only examining the entire stance phase (Jordan, Aagaard and Herzog, 2015).

Further to magnitude measures of the GRF, the variability of the GRF has also been suggested to be of importance in relation to overuse injuries such as AGP (C. R. James, Dufek and Bates, 2000). Variability refers to the individual variations in movement patterns across repetitions of the same task (Bernstein, 1967) and may play a functional role in tissue health by altering the magnitude, location and/or direction of loads placed on the body (Hamill *et al.*, 1999). In support of this, a recent systemic review found that deviations away from normal ranges of variability may be associated with lower limb overuse injury (Baida *et al.*, 2018). However, in their review only one study examined variability in AGP which included only seven injured subjects and reported both increased and decreased joint variability in the AGP group when compared to uninjured controls during a discrete running cut task, and no measure of GRF variability was examined (Edwards, Brooke and Cook, 2016). During field-based sports athletes rarely perform a single discrete movement but rather are heavily dependent on their ability to produce continuous movement for effective performance (Delahunt, RSI part II). Therefore, variability may be better examined during a continuous movement task (compared to a discrete task with pre-established initiation and termination points) as it promotes the natural variation in movement patterns as an individual continually adjusts their action between trials of the task (Hamill, Palmer and Van Emmerik, 2012).

Therefore, the aims of this study are to determine: (1) if AGP affects the magnitude or variability of the vertical GRF during a continuous side to side hurdle hop compared to uninjured controls, and (2) examine the changes in the vertical GRF measures in the AGP following rehabilitation and in comparison to uninjured controls at return to play.

We hypothesize that the AGP group will demonstrate reduced magnitude and increased variability of GRF variables compared to the CON group and following successful rehabilitation these differences will normalize in the AGP group.

6.3 Methods

Study Design and Setting

A case-control design was used including a pre-post rehabilitation analysis. The study was conducted in the department of Sports Medicine at the Sports Surgery Clinic (SSC), Dublin, Ireland. Enrolment started in December 2018 and ended in October 2019.

Participants

Thirty-six athletes with AGP (mean ± SD: age 25.9 ± 4.9 years, height 1797.1 ± 64.6 cm, mass 80.3 ± 7.2 kg) and 36 uninjured control athletes (mean ± SD: age 24.1 ± 4.5 years, 1809 ± 57.8 cm, mass 80.4 ± 8.2 kg) were included in this study. Clinical examination was completed by a Sports and Exercise Medicine Physician as previously described (Falvey *et al.*, 2015). Inclusion criteria included: (1) anatomical diagnosis falling under AGP (iliopsoas, adductor, pubic aponeurosis, inguinal and hip) (Falvey, Franklyn-Miller and McCrory, 2009), (2) male aged between 18-35 years involved in multi-directional field-based sports, (3) hip/groin symptoms during sporting activity with duration greater than four weeks, and (4) planned return to the same pre-injury sport and level of competition. Exclusion criteria included: (1) hip joint arthrosis (grade 3 or higher on MRI), (2) those with an underlying medical condition (e.g. inflammatory arthropathy or infection), and (3) past history of hip/groin surgery. Control participants were recruited via social media outlets and local sporting clubs and were matched based on age, sports played and level of competition. Control participants were included if they had: (1) no previous groin or lower limb surgery, and (2) no lower limb injury within the previous three months. All participants provided informed consent. Ethical approval was granted by the Sports Surgery Clinic's Scientific Advisory and Research Ethics Boards (SAREB15/10/18SB/CB/G).

Intervention

A rehabilitation program focusing on intersegmental control through strength, linear running and change of direction mechanics was employed (Appendix D). The content and criteria for progression through the program have been published previously (King, Franklyn-Miller, *et al.*, 2018). In brief, the program consists of three levels, with each level designed to address a specific component of recovery (i.e. strength, linear running, change-of-direction). Progression between the three levels of rehabilitation is individualized based on the achievement of clinical criterion. These clinical milestones must be achieved before an athlete is cleared to return-to-play and include symmetrical hip flexion and internal rotation range-of-motion, pain-free squeeze test, Thomas test and running programs.

Procedure

AGP and CON groups attended the clinic for baseline testing (pre-rehabilitation) and the AGP group repeated the testing at return-to-play (RTP) after successfully completing the rehabilitation program. All athletes undertook a standardized warm-up prior to their biomechanical test session (Marshall and Moran, 2015). The continuous side-to-side hurdle hop (CHH) test involved athletes performing ten continuous side-to-side hops over a 15-cm hurdle and back. From a stationary start, athletes were instructed to perform the hops as quickly as possible, with hands unrestricted. The non-symptomatic (AGP) or dominant (CON) limb was tested first and the initiating hop was in a lateral direction followed by a medial hop and so forth until completion. Each athlete performed one warm-up trial before the maximum effort trial was undertaken. If an athlete failed to complete the 10 continuous hops (e.g. stumbled, fell, double hop, etc.) a second trial was performed. If after the second trial, an athlete was still unable to complete ten continuous hops the trial with the highest number of continuous hops was included for analysis. A two-minute rest period was given between each trial.

Self-reported disability and function were assessed pre- and post-rehabilitation using the hip and groin outcome score (HAGOS) (scored 0 to 100 with 100 indicating nil problems) (Thorborg *et al.*, 2011) and the level of sporting activity was assessed with the Marx activity scale (Irrgang, 2008) (scored 0 to 16 with higher scores indicating increased frequency of high-demand sporting activity) (Appendix E).

Data processing

Ground reaction force data was captured using two 40 x 60 cm force plates (1000Hz; BP400600, AMTI, USA). Data were captured at a sampling frequency of 1000 Hz and filtered using a fourth order Butterworth filter with cut-off frequency of 15 Hz (Kristianslund, Krosshaug and Van Den Bogert, 2013). The vertical GRF was normalized to body mass and the following variables were calculated: Total, eccentric and concentric ground contact time (GCT), peak force and impulse and eccentric rate of force development (ECC RFD). The eccentric phase was defined from initial ground contact to zero center of mass power and the concentric phase from zero center of mass power to the toe-off.

Data was screened for outlier trials for each of the subjects. Firstly, using contact time, outliers were identified and removed using Dixon's Q test (Dean and Dixon, 1951). Secondly, the GRF waveforms and motion capture data were manually screened to identify adverse events (e.g. a stumble). Where an adverse event was identified, this hop and the subsequent hop were excluded from the biomechanical analysis, thereby ensuring only representative continuous hops were statistically examined. Following the screening process six medial hops and six lateral hops from each trial for all athletes were included for analysis as this number represents the number of trials required to provide a representative mean during a hurdle hop movement (Gore *et al.*, 2016).

Statistical analysis

The magnitude and variability of the GRF, for both medial and lateral hops, are reported as mean ± standard deviation. Normality was assessed (Sharpio-Wilk test) and parametric statistics were applied to the GRF variables. Variability was calculated for each participant as the SD across each trial hop. Paired sample t-tests were used to assess differences in the AGP group from baseline to RTP, and independent t-tests were used to assess differences between the AGP and CON groups at both baseline and RTP. In addition, the similarity between the AGP and CON groups at RTP was assessed using one-sided equivalence tests with a

Cohen's *d* effect size of 0.3 chosen as the lower bounds to indicate group similarity (Lakens, 2017). Alpha level for all test was set at 0.05. Effect sizes are reported with Cohen's *d* as small (0.2 – 0.5), medium (0.5 – 0.8) and large (> 0.8) (Cohen, 1988).

In order to improve the generalizability of this study's findings a permutation analysis was applied (Bruce, 2015). Thirty subjects from the CON and AGP groups were randomly selected from the data. This number was chosen to ensure that the central limit theorem could be assumed (i.e. $n \geq 30$). The CON group was then randomly matched with the AGP group for leg dominance and statistically compared to the AGP group, both at baseline and RTP. This randomization process was completed 100 times, findings were aggregated to their mean values (p-value, effect size, equivalence value) and only statistically significant findings that were identified in ≥ 85% of the random samples were considered as true differences. All data analyses were conducted in MATLAB R2018a, while data visualization was conducted using R statistical software (V.3.6.2).

6.4 Results

Participant demographics are presented in Table 6.4.A. In the AGP group the most common anatomical diagnoses were pain or tenderness at the pubic aponeurosis (61%), followed by proximal adductor tendon insertion (17%), iliopsoas (14%), hip (6%) and inguinal (3%). The average RTP time was 9.8 ± 3.0 weeks and at RTP all HAGOS subscale scores ($p<0.001$, r = 0.50 to 0.60) and Marx score ($p=0.002$, r = -0.42) demonstrated significant improvements of large effect in the AGP group.

Table 6.4.A Participant demographics, sports played and clinical diagnoses

AGP (n=36)	Characteristics	Sports played (%)	Primary diagnosis (%)	
Age (years)	25.9 ± 4.9	GAA football (58%)	PA	61% (22/36)
Height (cm)	179.7 ± 6.5	Soccer (25%)	AL	19% (6/36)
Mass (kg)	80.3 ± 7.2	GAA hurling (14%)	Psoas	14% (5/36)
Symptoms duration (weeks)	38.7 ± 5.5	Rugby (3%)	Hip	6% (2/36)
			Inguinal	3% (1/36)
CON (n=36)				
Age (years)	24.1 ± 4.5	GAA football (67%)		
Height (cm)	181.0 ± 5.8	Soccer (17%)		
Mass (kg)	80.4 ± 8.2	GAA hurling (6%)	NA	
		Rugby (8%)		
		Basketball (3%)		

Sx – symptom, PA – pubic aponeurosis, AL – adductor longus, PS – pubic symphysis, ING – inguinal, RTP – return to play, Level 1, 2, 3 of rehabilitation program, NR – not relevant.

Magnitude measures of the GRF

At baseline testing, during the lateral hops longer total GCT (p = 0.025, *d* = 0.43), concentric GCT (p = 0.020, *d* = 0.50), and larger concentric impulse (p = 0.028, *d* = 0.52), of small to medium effect size, were shown in the AGP group compared with the CON group, while lower peak GRF (p = 0.025, *d* = 0.36) of small effect size was also shown in the AGP group (Figure 6.4.A). Following rehabilitation, small decreases were evident it total GCT (p = 0.169, *d* = 0.39), concentric GCT (p = 0.190, *d* = 0.37), concentric impulse (p = 0.317, *d* = 0.29) in the AGP group and also a medium increase in peak force (p = 0.098, *d* = 0.47). At RTP testing, all four variables were not significantly different (total GCT: p = 0.755, *d* = 0.08, concentric

GCT: p = 0.702, *d* = 0.11, peak force: p = 0.589, *d* = 0.15, concentric impulse: p = 0.478, *d* = 0.20), and not statistically equivalent (total GCT: p = 0.128, concentric GCT: p = 0.091, concentric impulse: p = 0.056, peak force: p = 0.275) when comparing the AGP and CON groups. During the medial hops, no significant differences were found for any magnitude measure of the GRF ay baseline between the AGP and CON groups. Table 6.4.B presents the full results for the magnitude measures of the vertical GRF during both the lateral and medial hop and also the between group comparisons.

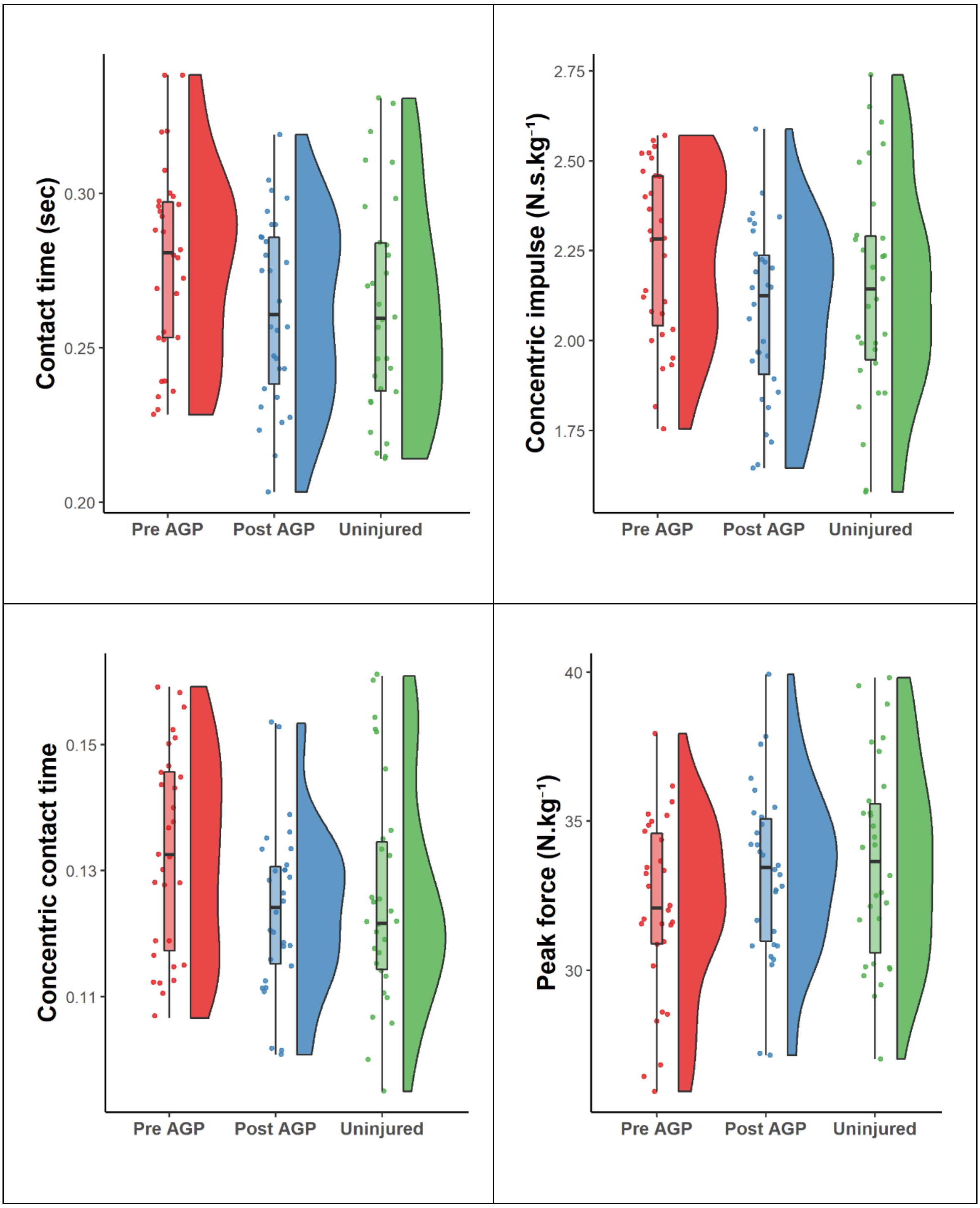


Figure 6.4.A Box plots with violin charts of the vertical GRF variables that were significantly different in comparison of AGP and CON groups at baseline testing. Pre – pre-rehabilitation, post – post-rehabilitation, uninjured – controls. Note these figures represent one of the random sample sets taken during the permutation analysis.

Variability measures of the GRF

No significant differences were found in the variability of GRF measures during either the lateral or medial hops when comparing the AGP and CON at any time point or in the AGP group from baseline to RTP. Table 6.4.C presents the full results for the variability measures of the vertical GRF during both the lateral and medial hop and also the between group comparisons.

Table 6.4.B. Magnitudes of vertical GRF during lateral and medial repeated side hurdle hop

		AGP baseline	AGP RTP	CON	Baseline AGP vs. CON			AGP baseline vs. AGP RTP			RTP AGP vs. CON				
Lateral hop	**Variable**	**mean ± SD**	**mean ± SD**	**mean ± SD**	**p**	***d***	**cons. sig (%)**	**p**	***d***	**cons. sig (%)**	**p**	***d***	**EQ**	**cons. sig (%)**	**cons. EQ (%)**
Contact time	Total	0.276 ± 0.03	0.263 ± 0.03	0.264 ± 0.03	**0.025***	**0.43**	**89**	0.169	0.39	13	0.755	0.08	0.120	0	17
(sec)	ECC	0.144 ± 0.02	0.138 ± 0.02	0.138 ± 0.02	0.064	0.32	53	0.225	0.34	6	0.770	0.08	0.141	0	9
	CON	0.132 ± 0.02	0.125 ± 0.01	0.126 ± 0.02	**0.020***	**0.50**	**97**	0.190	0.37	9	0.702	0.11	0.089	0	25
Force (N/kg)	Peak	32.13 ± 2.88	33.19 ± 3.01	33.61 ± 3.42	**0.025***	**0.36**	**88**	0.098	0.47	31	0.589	0.15	0.275	0	2
	ECC peak	32.09 ± 2.90	33.14 ± 3.04	33.58 ± 3.43	0.029	0.35	82	0.096	0.47	32	0.580	0.15	0.282	0	1
	CON peak	30.51 ± 2.67	31.28 ± 2.96	31.56 ± 2.71	0.054	0.27	52	0.163	0.39	11	0.663	0.12	0.236	0	2
Impulse	Total	5.01 ± 0.45	4.83 ± 0.55	4.94 ± 0.52	0.061	0.36	59	0.530	0.18	1	0.488	0.19	0.095	0	67
(N.s/kg)	ECC	2.79 ± 0.24	2.74 ± 0.32	2.79 ± 0.29	0.277	0.18	1	0.735	0.09	0	0.554	0.16	0.240	0	13
	CON	2.22 ± 0.25	2.09 ± 0.25	2.14 ± 0.29	**0.028***	**0.52**	**86**	0.317	0.29	4	0.478	0.20	0.056	0	73
RFD (N.kg/sec)	ECC	283.84 ± 65.30	309.30 ± 82.85	315.03 ± 87.27	0.049	0.34	65	0.158	0.40	17	0.705	0.10	0.205	0	2

Medial hop	Variable														
Contact time	Total	0.268 ± 0.03	0.261 ± 0.03	0.256 ± 0.04	0.203	0.21	5	0.234	0.33	5	0.614	0.14	0.269	0	0
(sec)	ECC	0.141 ± 0.02	0.139 ± 0.02	0.135 ± 0.02	0.463	0.12	1	0.268	0.31	2	0.519	0.18	0.329	0	0
	CON	0.126 ± 0.01	0.122 ± 0.02	0.121 ± 0.02	0.079	0.32	37	0.270	0.32	8	0.754	0.08	0.177	0	4
Force (N/kg)	Peak	33.75 ± 3.19	34.06 ± 3.44	35.35 ± 3.95	0.594	0.10	0	0.127	0.44	25	0.228	0.35	0.567	7	0
(N/kg)	ECC peak	33.71 ± 3.21	34.01 ± 3.47	35.32 ± 3.97	0.605	0.10	0	0.127	0.44	24	0.223	0.35	0.571	8	0
	CON peak	32.63± 2.67	32.74 ± 3.07	33.88 ± 3.59	0.714	0.06	0	0.177	0.39	14	0.235	0.34	0.557	5	0
Impulse	Total	5.08 ± 0.46	4.93 ± 0.58	4.97 ± 0.60	0.114	0.28	20	0.448	0.21	1	0.731	0.09	0.115	0	17
(Ns/kg)	ECC	2.88 ± 0.25	2.85 ± 0.31	2.87 ± 0.32	0.477	0.13	0	0.736	0.09	0	0.702	0.11	0.185	0	7
	CON	2.19 ± 0.26	2.09 ± 0.30	2.09 ± 0.33	0.038	0.39	74	0.232	0.34	9	0.754	0.08	0.120	0	13
RFD (N.kg/sec)	ECC	283.80 ± 67.02	292.97 ± 78.57	318.07 ± 76.79	0.465	0.13	1	0.107	0.47	40	0.267	0.32	0.532	6	0

*AGP – Athletic Groin Pain, CON – control, baseline – pre-rehabilitation, RTP – return-to-play (post-rehabilitation), ECC – eccentric, CON – concentric, GRF – ground reaction force, RFD – rate of force development, cons. sig / EQ (%) – consistency of p<0.05, EQ – equivalence p value, * significant difference AGP group versus CON group with p<0.05 & cons. p >85*

Table 6.4.C. Variability of vertical GRF during lateral and medial repeated side hurdle hop

		AGP baseline	AGP RTP	CON	AGP baseline vs. CON			AGP baseline vs. AGP RTP			RTP AGP vs. CON				
Lateral hop	**Variable**	**mean ± SD**	**mean ± SD**	**mean ± SD**	**p**	**d**	**cons. sig (%)**	**p**	**d**	**cons. sig (%)**	**p**	**d**	**EQ**	**cons. sig (%)**	**cons. EQ (%)**
Contact time	Total	0.018 ± 0.01	0.016 ± 0.01	0.015 ± 0.01	0.521	0.17	0	0.358	0.28	9	0.589	0.16	0.278	0	3
(sec)	ECC	0.010 ± 0.00	0.009 ± 0.01	0.009 ± 0.00	0.392	0.23	0	0.323	0.28	3	0.692	0.11	0.195	0	9
	CON	0.011 ± 0.01	0.011 ± 0.01	0.010 ± 0.01	0.729	0.09	0	0.271	0.35	19	0.349	0.28	0.471	10	0
Force (N/kg)	Peak	2.410 ± 1.20	2.136 ± 0.99	2.340 ± 1.16	0.391	0.25	2	0.653	0.12	0	0.494	0.20	0.199	0	37
	ECC peak	2.450 ± 1.22	2.180 ± 0.99	2.362 ± 1.17	0.406	0.24	1	0.635	0.13	0	0.529	0.18	0.187	0	36
	CON peak	1.850 ± 0.84	1.791 ± 0.90	1.768 ± 0.93	0.707	0.09	0	0.601	0.14	0	0.685	0.11	0.218	0	3
Impulse	Total	0.258 ± 0.11	0.234 ± 0.11	0.247 ± 0.16	0.397	0.22	1	0.589	0.16	0	0.620	0.14	0.218	0	10
(Ns/kg)	ECC	0.147 ± 0.06	0.131 ± 0.06	0.133 ± 0.08	0.363	0.26	0	0.464	0.22	6	0.651	0.12	0.191	0	16
	CON	0.202 ± 0.07	0.202 ± 0.09	0.188 ± 0.09	0.762	0.08	0	0.500	0.20	2	0.539	0.18	0.332	2	0
RFD (N.kg/sec)	ECC	63.52 ± 26.43	59.37 ± 34.24	55.31 ± 31.79	0.463	0.13	0	0.364	0.29	13	0.578	0.18	0.295	3	3

Medial hop	**Variable**														
Contact time	Total	0.018 ± 0.01	0.018 ± 0.01	0.016 ± 0.01	0.776	0.07	0	0.426	0.23	3	0.460	0.21	0.379	1	0
(sec)	ECC	0.011 ± 0.00	0.012 ± 0.01	0.009 ± 0.00	0.681	0.12	1	0.092	0.50	43	0.064	0.53	0.794	60	0
	CON	0.010 ± 0.00	0.009 ± 0.00	0.010 ± 0.01	0.667	0.09	0	0.674	0.11	0	0.639	0.13	0.239	0	4
Force (N/kg)	Peak	2.561 ± 1.12	2.628 ± 1.46	2.387 ± 1.05	0.746	0.08	0	0.546	0.17	0	0.503	0.19	0.345	0	3
(N/kg)	ECC peak	2.597 ± 1.13	2.665 ± 1.48	2.399 ± 1.05	0.746	0.08	0	0.508	0.19	1	0.468	0.21	0.370	0	2
	CON peak	2.100 ± 0.95	2.220 ± 1.43	2.057 ± 0.91	0.627	0.10	0	0.648	0.13	0	0.576	0.16	0.284	0	3
Impulse	Total	0.262 ± 0.16	0.258 ± 0.12	0.229 ± 0.11	0.718	0.10	0	0.412	0.24	2	0.409	0.25	0.426	6	1
(Ns/kg)	ECC	0.167 ± 0.09	0.156 ± 0.07	0.135 ± 0.06	0.563	0.16	0	0.159	0.43	30	0.284	0.34	0.542	16	0
	CON	0.173 ± 0.08	0.173 ± 0.08	0.172 ± 0.08	0.770	0.07	0	0.718	0.10	0	0.694	0.11	0.214	0	5
RFD (N.kg/sec)	ECC	62.73 ± 28.64	53.01 ± 24.4	59.05 ± 27.17	0.538	0.14	0	0.228	0.36	18	0.406	0.25	0.415	2	2

AGP – Athletic Groin Pain, CON – control, pre – pre-rehabilitation, post – post-rehabilitation, ECC – eccentric, CON – concentric, GRF – ground reaction force, cons. sig/EQ – consistency of p<0.05, EQ – equivalence p value

6.5 Discussion

The purpose of this study was to investigate the magnitude and variability of the vertical GRF in athletes with AGP during a continuous side-to-side hurdle hop task. We found significant less peak force, of small effect size, and increased concentric impulse and GCT, of small to medium effect size, in the AGP group compared to the CON group at baseline testing. Importantly, following successful rehabilitation these variables all moved towards values observed in the CON group this making these variables potential targets to enhance rehabilitation. In contrast to our hypothesis, no differences were found in the variability of the vertical GRF measures between the AGP and CON group at baseline or RTP and also when comparing the AGP group from baseline to RTP.

The major findings from this study was that GRF measures were able to detect differences between the AGP and CON groups and crucially these measures improved with successful rehabilitation. As such they may provide important targets for rehabilitation. Of particular interest, one of the largest effect sizes for between group differences were the longer GCT in the AGP group. This may provide clinicians with a simple measure which can reflect improvements in the loading patterns of the GRF, namely reduced concentric impulse and increased peak force. In support of our findings, Gore et al (2020) also reported significantly longer ground contact times in AGP during a single hurdle hop when compared to uninjured controls (Gore *et al.*, 2020). In our study, there are three likely explanations for the longer ground contact times and altered GRF loading characteristics observed in the AGP group. Firstly, it may reflect a reduction in performance as athletes were instructed to perform the continuous hops as quickly as possible. More specifically, the longer GCT may represent a reduced ability to effectively utilize the elastic storage energy from the rapid eccentric loading on myotendinous structures (i.e. the stretch-shorten cycle) to enhance the concentric propulsive forces (Flanagan and Comyns, 2008). In line with this, the AGP group demonstrated reduced eccentric RFD, of medium effect size, and subsequently demonstrated reduced peak concentric force and longer concentric GCT when compared to the CON group. Secondly, the longer GCT found in the AGP group may represent a compensatory strategy to reduce the peak loading force on the painful structures. This can be explained by the impulse-momentum relationship where the AGP group applied a smaller force over a longer time period to control their momentum (Bressel and Cronin, 2005). Similar compensatory strategies have also previously been reported in athletes with AGP (Gore *et al.*, 2020) and anterior knee pain (Duffey *et al.*, 2000). Thirdly, it is possibly that that the longer GCT represents a risk factor for AGP potentially leading to greater joint range of motion (Bobbert, Huijing and Schenau, 1987; Smith *et al.*, 2011). While longer ground contacts generally reduce peak GRF, the increased joint range of motion may increase localized loading on the soft tissues structures which play a role in joint stability (Powers, 2010). In support of this, previous research has shown increased pelvis range-of-motion in AGP participants during a single-leg drop-land task in comparison to uninjured participants (Janse van Rensburg *et al.*, 2017).

At RTP, no significant differences were found between the AGP and CON groups in the magnitude measures of GRF that differentiated the groups at baseline testing (peak force, concentric impulse and GCT). These measures did not fully return to normal values as observed in the CON group (within the lower equivalence bounds of *d* = 0.30) and may indicate the need for specific elements of the rehabilitation program to be continue post-RTP in individual athletes. The rehabilitation program included plyometric exercises which likely led to enhanced SSC capabilities in order to minimize the GCT (Markovic *et al.*, 2007). It has been suggested the speed of the eccentric action can increase the potentiation effect of the SSC and thus reduce the amount of transition time between the eccentric and concentric phases. In support of this, is was found in the AGP group that through rehabilitation eccentric RFD increased and subsequently increased concentric force and shorter concentric GCT. In addition, decreased GCT has been strongly correlated to increased limb stiffness (Arampatzis *et al.*, 2001). Stiffness is proposed to play an integral role in the braking phase of fast SSC movements (i.e. < 250ms). Therefore, mechanism underpinning leg stiffness are likely responsible for the reduced GCTs seen in the AGP group. While stiffness was not examined in this study, Gore et al. (2018) has previously found significantly lower limb and joint stiffness in AGP athletes compared to healthy subjects and which improved post-rehabilitation.

Variability, describing the intra-individual variation in motor performance across repetitions of a task, has been suggested to play a functional role in relation to overuse injuries by altering the load magnitude, rate or timing to potentially reduce the accumulation of stress on tissue structures (C. R. James, Dufek and Bates, 2000) However, we found no difference in any measure of GRF variability (GCT, peak, impulse, RFD) between the AGP and CON groups at baseline or RTP testing. While our findings are in contrast to Edwards et al (2016) who reported substantially reduced

GRF variability in athletes with a history of AGP when compared to uninjured controls, their study only included seven subjects in the injured group and assessment was based on magnitude based inference (Hopkins *et al.*, 2009) rather than null hypothesis testing (Edwards *et al.*, 2017). Our findings suggest that examining the variability of the GRF in AGP provides no additional insight into motor control strategies that could enhance assessment or rehabilitation programs.

6.6 Limitations

A number of limitations were present in this study. The CON group were only tested at baseline and therefore it was not possible to assess the change in the magnitude and variability of the GRF that may have occurred with continued sporting activity. In addition, the lack of significant findings in variability may result from the whole-body, discrete GRF measures examined in this study. Further research may consider examining joint level variability over the entire biomechanical waveform.

6.7 Conclusion

Altered loading patterns were identified in the vertical GRF in AGP compared to the uninjured control group; no differences were identified in GRF variability. The altered GRF variables improved with rehabilitation and were no longer significantly different between groups at RTP. Specifically, ground contact times, peak force and concentric impulse measures may provide targets for rehabilitation. We would suggest that plyometric type exercises are likely beneficial when rehabilitating athletes with AGP.

6.8 Link between Chapter 6 and 7

Variability of the vertical GRF was not significantly different when comparing AGP and CON groups. However, examination of the vertical GRF provides a whole-body summated measure and does not fully account for potential variability of individual joints. Previous research has reported significant differences in movement variability at an individual joint level and which have been in different directions (e.g. increased hip joint variability and reduced knee joint variability) in AGP patients when compared to healthy individuals (Edwards, Brooke and Cook, 2016). Therefore, it would be of value to examine the variability of the kinetics and kinematics during the continuous hurdle hop. Further analysis is undertaken in Chapter 7.

Chapter 7

Movement technique and variability not affected by AGP in a continuous lateral hurdle hop: A case-control study

7.1 Introduction

Athletic groin pain is a chronic overuse injury common to sports which involve repetitive jumping and change of direction actions (Orchard, 2015). Diagnosis typically encompasses co-existing pathologies involving fascial and myotendinous structures attaching to the pubic symphysis (Hölmich, 2007; Bradshaw, Bundy and Falvey, 2008). It has been suggested that a loss of segmental movement control can affect the distribution of mechanical forces on these tissue structures resulting in excessive loading and the propagation of AGP (Franklyn-Miller *et al.*, 2017). To gain a better understanding of how segmental control may contribute to AGP, a number of recent studies have examined the joint kinematics, kinetics and movement variability during jumping and change-of-direction tasks. These studies have identified altered ankle, knee, hip, pelvis and trunk segmental control in AGP groups when compared to uninjured control groups (Edwards, Brooke and Cook, 2016; Gore *et al.*, 2018, 2020; Rivadulla *et al.*, 2020). Furthermore, altered movement patterns have demonstrated a return to normal (as indicated by the uninjured control group) following successful rehabilitation in the AGP group (Gore *et al.*, 2018, 2020). Research in this thesis has reported altered loading patterns in the ground reaction force (GRF) (i.e. greater concentric impulse and reduced peak force) during a continuous hurdle hop (HH) task in the AGP group when compared to the control group, and no differences were reported in the variability of the GRF variables (Chapter 6). However, joint kinematics and kinetics and the variability of the kinematics and kinetics during the continuous HH were not examined. This additional analysis may provide greater insight into the local movement techniques (e.g. at the pelvis, trunk, ankle, etc.) that can explain the altered loading patterns previously identified in the GRF.

Given the association between repetitive loading and overuse injuries (Baida *et al.*, 2018), further examination of the functional role of movement variability with respect to AGP is warranted. Movement variability has been described as the natural variations across multiple repetitions of the same task (Bernstein, 1967) and is theorized to reduce repetitive loading on specific tissues thus minimizing injury risk (Harbourne and Stergiou, 2009). Baida et al (2018) reported in a recent systematic review that deviations away from normal ranges of variability may be associated with lower limb overuse injury, however only one study was identified in their review which examined movement variability in relation to AGP (Baida *et al.*, 2018). In this study by Edwards et al (2016) only seven subjects with a past-history of AGP and nine control subjects were examined and the authors reported both increased and decreased joint motion variability in the AGP group at discrete time points (e.g. initial contact) during a running cut task (Edwards, Brooke and Cook, 2016). The low number of subjects and inconsistent findings suggest the need for further examination of movement variability. In addition, analysis of entire biomechanical waveforms, as opposed to discrete variables or time points (e.g. initial contact), may provide greater insight into movement variability across the duration of a task (Kipp and Palmieri-Smith, 2013; Richter, N. O'Connor, *et al.*, 2014).

The primary aim of this study was to determine if AGP affects the magnitude and variability of lower limb and trunk kinematics and kinetics during a continuous lateral hurdle hop in comparison to uninjured control athletes (CON). A secondary aim was to examine the changes in kinematics and kinetics in the AGP group following successful rehabilitation. It was hypothesized that reduced ankle and hip moments (Gore *et al.*, 2020) and greater hip, pelvic and trunk motion (Franklyn-Miller *et al.*, 2017; Janse van Rensburg *et al.*, 2017) and movement variability (Baida *et al.*, 2018) would be observed in the AGP group in comparison to uninjured controls and these variables would normalize following rehabilitation.

7.2 Methods

Study design

A case-control design was used including a pre-post rehabilitation analysis.

Participants

Thirty-six athletes with AGP (mean ± SD: age 25.9 ± 4.9 years, height 1797.1 ± 64.6 cm, mass 80.3 ± 7.2 kg) and 36 uninjured control athletes (mean ± SD: age 24.1 ± 4.5 years, 1809 ± 57.8 cm, mass 80.4 ± 8.2 kg) were included in this study. In the AGP group the most common anatomical diagnoses were pain or tenderness at the pubic aponeurosis (61%), followed by proximal adductor tendon insertion (17%), iliopsoas (14%), hip (6%) and inguinal (3%). Clinical examination was completed by a Sports and Exercise Medicine Physician as previously described (Falvey *et al.*, 2015). Inclusion criteria included: (1) anatomical diagnosis falling under AGP (iliopsoas, adductor, pubic aponeurosis, inguinal and hip) (Falvey, Franklyn-Miller and McCrory, 2009), (2) male aged between 18-35 years involved in multi-directional field-based sports, (3) hip/groin symptoms during sporting activity with duration greater than four weeks, and (4) planned return to the same pre-injury sport and level of competition. Exclusion criteria included: (1) hip joint arthrosis (grade 3 or higher on MRI), (2) those with an underlying medical condition (e.g. inflammatory arthropathy or infection), and (3) past history of hip/groin surgery. Control participants were recruited via social media outlets and local sporting clubs and were matched based on age, sports played and level of competition. Control participants were included if they had: (1) no previous groin or lower limb surgery, and (2) no lower limb injury within the previous three months. All participants provided informed consent.

Intervention

A rehabilitation program focusing on intersegmental control through strength, linear running and change of direction mechanics was employed (Appendix D). The content and criteria for progression through the program have been published previously (King, Franklyn-Miller, *et al.*, 2018).

Procedure

AGP and CON groups attended the clinic for baseline testing (pre-rehabilitation) and the AGP group repeated the testing at return-to-play (RTP) after successfully completing the rehabilitation program. All athletes undertook a standardized warm-up prior to their biomechanical test session (Marshall and Moran, 2015). The continuous side-to-side hurdle hop (CHH) test involved athletes performing ten continuous side-to-side hops over a 15-cm hurdle and back. From a stationary start, athletes were instructed to perform the hops as quickly as possible, with hands unrestricted. The non-symptomatic (AGP) or dominant (CON) limb was tested first and the initiating hop was in a lateral direction followed by a medial hop and so forth until completion. Each athlete performed one warm-up trial before the maximum effort trial was undertaken. If an athlete failed to complete the 10 continuous hops (e.g. stumbled, fell, double hop, etc.) a second trial was performed. If after the second trial, an athlete was still unable to complete ten continuous hops the trial with the highest number of continuous hops was included for analysis. A two-minute rest period was given between each trial.

Self-reported disability and function were assessed pre- and post-rehabilitation using the hip and groin outcome score (HAGOS) (scored 0 to 100 with 100 indicating nil problems) (Thorborg *et al.*, 2011) and the level of sporting activity was assessed with the Marx activity scale (Irrgang, 2008) (scored 0 to 16 with higher scores indicating increased frequency of high-demand sporting activity) (Appendix E).

Data processing

Reflective markers (14mm diameter) were placed on bony landmarks on the lower limbs, pelvis and trunk as per the Vicon Plug in Gait (PiG) model (Vicon Motion Systems, Oxford, UK), synchronised with two 40 x 60 cm force platforms (AMTI – BP400600, USA) collecting ground reaction force data. Motion and force data were captured at a sampling frequency of 200 Hz and 1000 Hz, respectively. Both marker and force data were filtered using a fourth order Butterworth filter with a cut-off frequency of 15 Hz (Kristianslund, Krosshaug and Van Den Bogert, 2013). Kinematic and kinetic calculations were performed in Nexus software (Vicon Motion Systems, Oxford, UK) with the variables defined as per the standard Vicon PiG model. Thereafter, the magnitude of movement variability of the kinematics and kinetics was determined using the standard deviation. Each subject was screened for outliers two-fold. Firstly, using ground contact time (i.e. too long or too short) and were identified and removed using Dixon's Q test (Dean and Dixon, 1951). Secondly, all biomechanical waveforms were manually screened with trials removed when adverse events were identified (e.g. double hop). Following the screening process six lateral hops from each trial for all athletes were included for analysis (Gore *et al.*, 2016). All data were exported to MATLAB for statistical analysis.

Statistical analysis:

Data processing and descriptive statistics were carried out using MATLAB (version R2015a; The MathWorks Inc, Natick, MA). Analysis of Characterising Phases (ACP) (Richter, N. O'Connor, *et al.*, 2014) was conducted on the kinematic and kinetic waveforms to generate subjects' scores that capture the behaviour of each subject. This utilised VARIMAX rotated principle components that retained more than 99% of the variance to identify phases of interest (Richter, N. O'Connor, *et al.*, 2014). Subject scores were generated within these phases (magnitude domain) and planned t-tests were conducted to test for significant differences (unpaired t-test: AGP baseline vs. CON, AGP RTP vs. CON; paired t-test: pre- vs. post-rehabilitation). Where a significant difference existed, the key phase was extended to either side separately and re-tested for significance (Richter, N. O'Connor, *et al.*, 2014). This was repeated to identify the full phase of the difference, terminating when a data point was not statistically significantly different. Cohen's effect size was reported as small (<0.5), medium (0.5–0.8), and large (>0.8).

7.3 Results

Following rehabilitation, the AGP group returned-to-play pain-free in a mean time of 9.8 ± 3.0 weeks. In addition all HAGOS subscale scores (symptoms effect size *r* = -0.58, pain *r* = -0.53, activities of daily living *r* = -0.50, sports and recreational activity *r* = -0.60, participation in physical activity *r* = -0.52, and quality of life *r* = -0.56) and Marx activity scale (*r* = -0.42) significantly improved with large effect sizes (Table 7.3.A).

Table 7.3.A Results from pre- to post-rehabilitation HAGOS and Marx scores

	AGP pre-rehabilitation	AGP post-rehabilitation	AGP (pre) vs. AGP (post)	
HAGOS	**mean (IQR)**	**mean (IQR)**	**p**	**r**
Symptom	60.2 (56.3 - 75.0)	83.9 (75.0 - 92.9)	<0.001	-0.58
Pain	76.3 (63.1 - 85.6)	92.5 (85.0 - 97.5)	<0.001	-0.53
ADL	75.0 (70.0 - 90.0)	95.0 (88.8 - 100.0)	<0.001	-0.50
Sport Rec	54.7 (39.9 - 67.2)	85.9 (80.5 - 93.8)	<0.001	-0.60
PA	6.3 (0.0 - 37.5)	50.0 (21.9 - 75.0)	<0.001	-0.52
QOL	35.0 (30.0 - 45.0)	67.5 (45.0 - 80.0)	<0.001	-0.56
MARX	4.0 (0.0 - 8.3)	12.0 (9.0 - 12.0)	0.002	-0.42

ADL – activities of daily living, Sport Rec – sports and recreational activities, PA – participation in physical activity, QOL – quality of life, MARX – activity rating scale, IQR – inter-quartile range

Differences in 3D biomechanical measures between AGP and CON groups

There were no significant differences when comparing the AGP and uninjured CON groups in any kinematic (3D trunk, pelvis, hip, knee and ankle angles), kinetic (3D hip, knee, ankle moments or powers), or movement variability of the joint kinematics or kinetics either pre- or post-rehabilitation. Full kinematic and kinetic waveforms are presented below as mean ± standard errors for the ankle (Figure 7.3.A), knee (Figure 7.3.B), hip (Figure 7.3.C), trunk and pelvis (Figure 7.3.D).

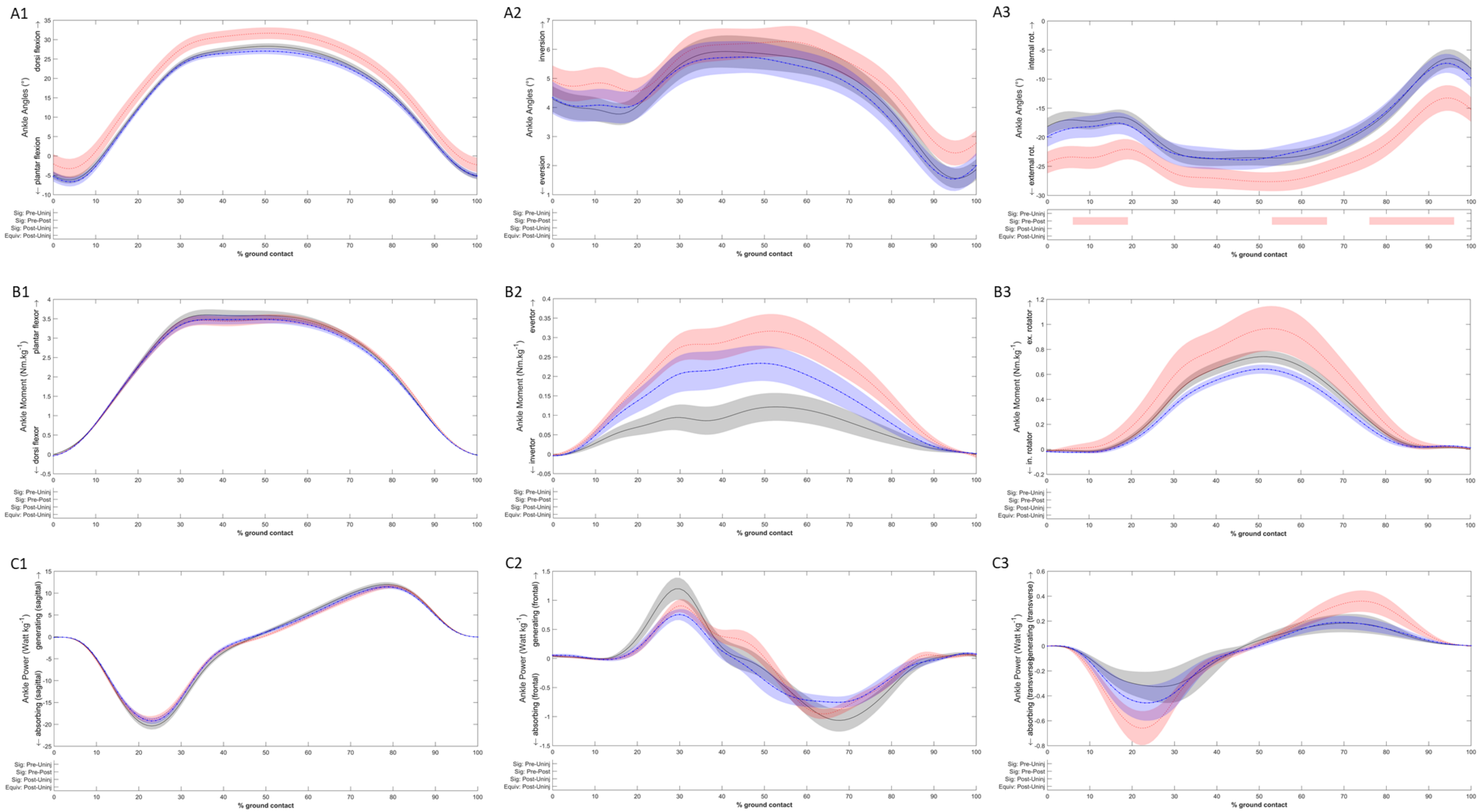


Figure 7.3.A Ankle kinetics and kinematics. Row A, B, C refers to joint angle, moment and power, respectively. Column 1, 2 & 3 refers to sagittal plane, frontal plane and transverse plane, respectively. Red --- = AGP pre-rehabilitation, blue --- = AGP post-rehabilitation, black --- = Uninjured. Sub-graph bar indicates phases of significant difference (Pre AGP vs. uninjured controls, pre AGP vs. post AGP, post AGP vs. uninjured controls) and of equivalence (Post AGP vs. uninjured controls)

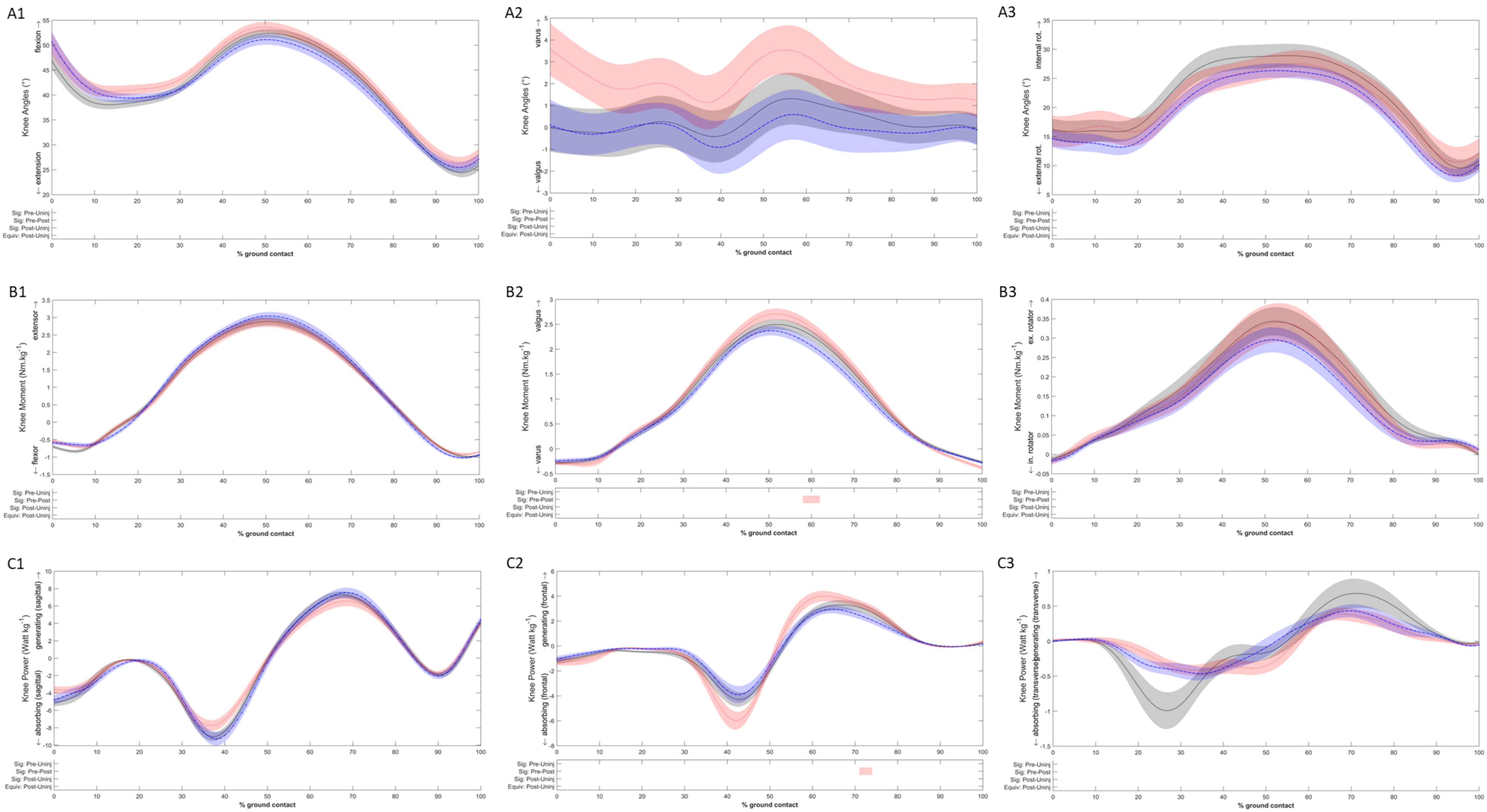


Figure 7.3.B Knee kinetics and kinematics. Row A, B, C refers to joint angle, moment and power, respectively. Column 1, 2 & 3 refers to sagittal plane, frontal plane and transverse plane, respectively. Red --- = AGP pre-rehabilitation, blue --- = AGP post-rehabilitation, black --- = Uninjured. Sub-graph bar indicates phases of significant difference (Pre AGP vs. uninjured controls, pre AGP vs. post AGP, post AGP vs. uninjured controls) and of equivalence (Post AGP vs. uninjured controls)

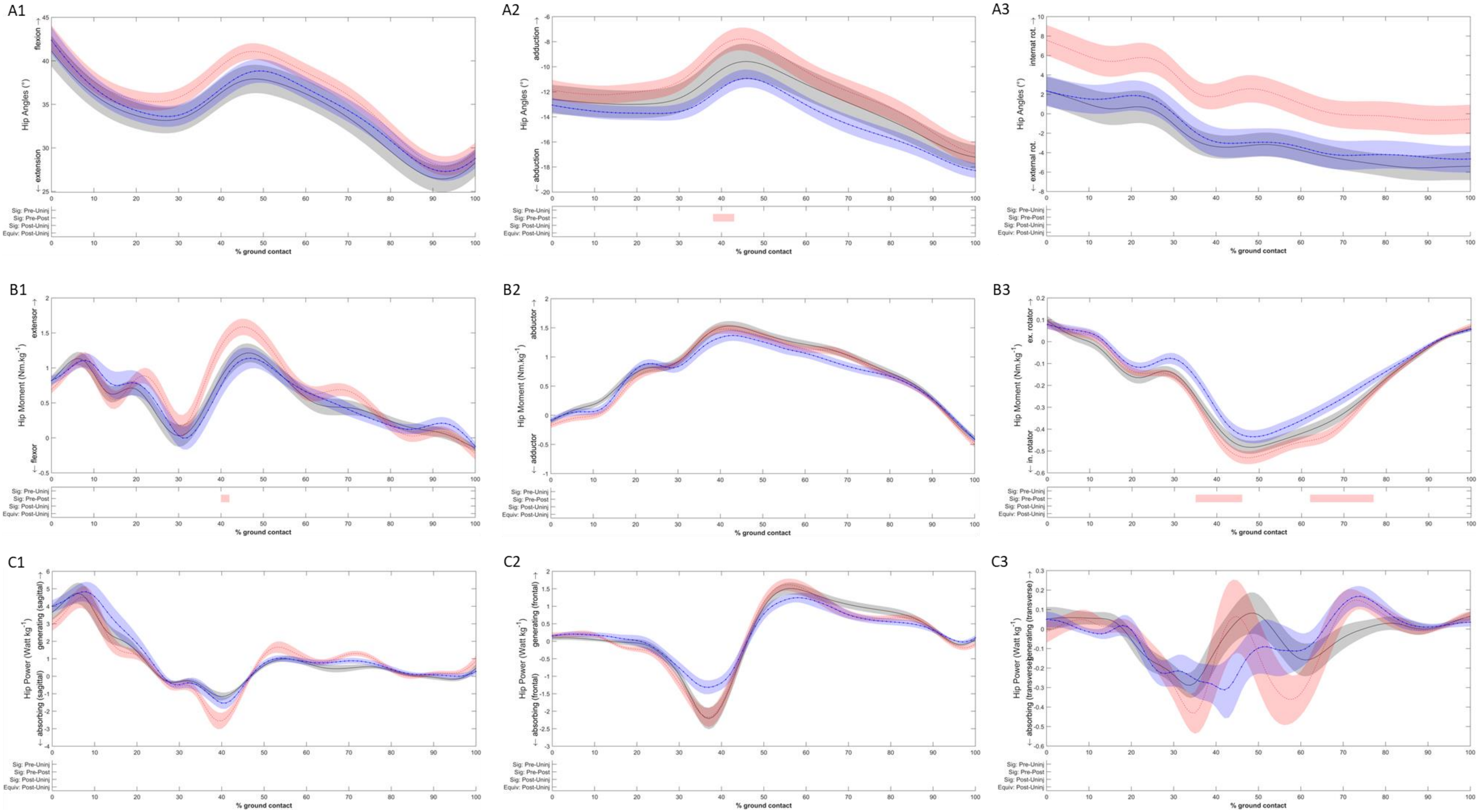


Figure 7.3.C Hip kinetics and kinematics. Row A, B, C refers to joint angle, moment and power, respectively Column 1, 2 & 3 refers to sagittal plane, frontal plane and transverse plane, respectively. Red --- = AGP pre-rehabilitation, blue --- = AGP post-rehabilitation, black --- = Uninjured. Sub-graph bar indicates phases of significant difference (Pre AGP vs. uninjured controls, pre AGP vs. post AGP, post AGP vs. uninjured controls) and of equivalence (Post AGP vs. uninjured controls)

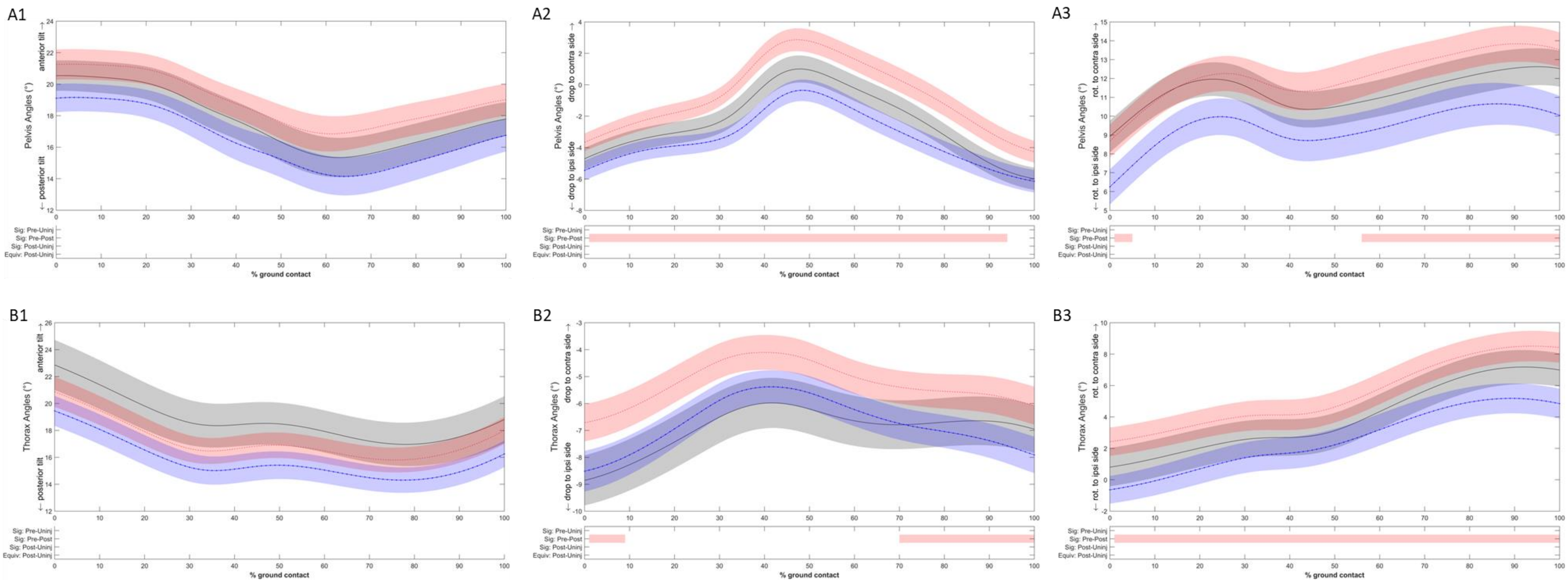


Figure 7.3.D Pelvis and trunk kinematics. Row A refers to pelvis angle. Row B refers to trunk angle. Column 1, 2 & 3 refers to sagittal plane, frontal plane and transverse plane, respectively. Red --- = AGP pre-rehabilitation, blue --- = AGP post-rehabilitation, black --- = Uninjured. Sub-graph bar indicates phases of significant difference (Pre AGP vs. uninjured controls, pre AGP vs. post AGP, post AGP vs. uninjured controls) and of equivalence (Post AGP vs. uninjured controls)

Changes in 3D biomechanical analysis of continuous HH

In the AGP group, significant changes were observed in the kinematics and kinetics following rehabilitation (pre- versus post-rehabilitation) (Table 7.3.B). Kinematically, the largest changes were of medium effect size with increased thorax ipsilateral abduction at the start and end of the hop (*d* = -0.55, -0.46, respectively), decreased pelvic contralateral drop during the entire stance phase of the hop (*d* = -0.53), decreased pelvic rotation at the start and end of the hop (*d* = -0.45, -0.27, respectively) and decreased ankle external rotation throughout the stance phase (*d* = 0.39 to 0.58). There were small effect sizes for increased hip abduction mid-stance phase of the hop (*d* = -0.27) and decreased thorax contralateral rotation during the entire stance phase of the hop (*d* = -0.25). Kinetic analysis demonstrated medium effect sizes for reduced hip extension (*d* = -0.42) and hip internal rotation (*d* = 0.34 to 0.41) during the propulsive phase of the hop, and small effect size for reduced knee valgus moments (*d* = -0.18) and knee abduction power (*d* = 0.11) during the during the propulsive phase of the hop

Table 7.3.B Kinematic and Kinetic changes in the continuous lateral hurdle hop following rehabilitation

Variable	Plane	ES	Phase	Direction of change
Kinematic				
Ankle external rotation	Transverse	0.58, 0.39, 0.52	6-19%, 53-66%, 76-96%	↓ Pre to Post
Thorax ipsilateral abduction	Frontal	-0.55, -0.46	1-9%, 70-100%	↑ Pre to Post
Pelvis abduction	Frontal	-0.53	1-94%	↓ Pre to Post
Pelvis contralateral rotation	Transverse	-0.045, -0.27	1-5%, 56-100%	↓ Pre to Post
Hip abduction	Frontal	-0.27	38-43%	↑ Pre to Post
Thorax contralateral rotation	Transverse	-0.25	1-101%	↓ Pre to Post
Kinetics				
Hip internal rotation moment	Transverse	0.41, 0.34	35-46%, 62-77%	↓ Pre to Post
Knee valgus moment	Frontal	-0.18	58-62%	↓ Pre to Post
Knee abduction power	Frontal	-0.11	71-74%	↓ Pre to Post

ES – effect size Cohen's d, ↓ - decreased post-rehabilitation, ↑ - increased post-rehabilitation, phase – %

7.4 Discussion

This is the first study to examine the effect of AGP on joint kinematics, kinetics and movement variability during a continuous HH tasks in comparison to uninjured controls and following successful rehabilitation. Following successful rehabilitation, the AGP group returned to play in an average of 9.8 ± 3.0 weeks with large improvements in all HAGOS scores and Marx score, and changes of small to medium effect sizes were demonstrated in trunk, pelvis and hip kinematics, and hip and knee kinetics. When the AGP and control groups were compared to each other pre- and post-rehabilitation, no significant differences were demonstrated in any kinematic, kinetic or variability measure. Also, no significant changes were observed in movement variability from pre- to post-rehabilitation in the AGP.

Joint kinematics and kinetics

The lack of significant differences in the kinematics and kinetics between the AGP and uninjured group is in contrast with previous research (Edwards, Brooke and Cook, 2016; Janse van Rensburg *et al.*, 2017; Gore *et al.*, 2018, 2020; Rivadulla *et al.*, 2020). In a similar action to the one examined in the current study, Gore et al (2020) investigated a <u>single</u> hurdle hop task and reported significantly less ankle planter flexion range-of-motion, reduced ankle plantar flexion moment, reduced hip extension and abduction moments, reduced hip extensor power, and significantly greater knee extension and abduction moments in the AGP group when compared to the uninjured control group. Furthermore, these authors reported significant improvements in a number of these variables in the AGP group following successful rehabilitation (when employing the same intersegmental control program used in this study). There are two possible explanations for the lack of findings in our study. Firstly, in direct comparison to the Gore et al (2020) study we excluded the initial hop from the stationary start position (as it represented a different movement to all subsequent hops which come directly from a rebound action), whereas Gore et al (2020) examined the initial hop from the stationary start position. Secondly, the continuous HH task may allow a measured and controlled action in which forces can be easily modulated and thus avoiding excessive strain on the body resulting in the loss of segmental control. In support of this, altered kinematics have been reported during discrete movement tasks: a running cut (Edwards, Brooke and Cook, 2016) and a single leg drop land (Janse van Rensburg *et al.*, 2017) in AGP groups when compared to uninjured control groups. Marshall et al (2015) examined all three of these movement tasks in uninjured athletes (i.e. hurdle hop, running cut, single leg drop land) and found greater vertical ground reaction force during the initial eccentric phase (approximately 0-10% of the movement cycle) in the drop land and running cut task when compared to the hurdle hop (Marshall *et al.*, 2015). During these tasks, which require periods of higher loading, greater compensatory movement patterns may be used by injured populations to reduce the stress placed on the myotendinous structures and joints (LaStayo *et al.*, 2003). Therefore, when examining athletes with AGP, stressing the eccentric capabilities of the neuromuscular system may better expose differences between injured and uninjured groups.

A number of kinematic variables demonstrated change of medium effect sizes from pre- to post-rehabilitation in the AGP group. As there were no significant differences found in these variables' pre-rehabilitation between the AGP and CON groups their importance for successful rehabilitation remain unclear. However, only three previous studies have examined the effect of rehabilitation on the movement patterns in AGP groups (Gore *et al.*, 2018, 2020; King, Franklyn-Miller, *et al.*, 2018) and therefore analysis of these variables is provide here. Of potential importance for rehabilitation, we found that pelvis contralateral drop reduced following rehabilitation. In line with this, previous research has identified reduced muscle activation (Morrissey *et al.*, 2012) and strength (O'Connor, 2004) in the hip abductors in AGP patients. Furthermore, Gore et al (2020) reported an increase in hip abductor moment following successful rehabilitation in AGP patients during a single hurdle hop task (Gore *et al.*, 2020). As the hip abductors play an important role in coronal plane stability of the pelvis and help to prevent contralateral pelvis drop the role of the hip abductors may require further considerations as targets to enhance rehabilitation. Other kinematic changes following rehabilitation included reduced ankle external rotation and increased ipsilateral trunk side flexion. Previous research has also demonstrated altered ankle (Gore *et al.*, 2020) and trunk (King, Franklyn-Miller, *et al.*, 2018) kinematics post-rehabilitation, although the findings are in contrast to the current study. Gore et al (2020) reported *increased* ankle plantar flexion during a single HH task, and King et al (2018) reported *reduced* ipsilateral trunk side flexion during a running cut task. Despite the conflicting findings, it appears that ankle and trunk kinematics are prone to change in AGP patients following successful rehabilitation. It is possible that altered mechanics at these distal or proximal segments may influence the distribution of loading on the pelvis (Franklyn-Miller *et al.*, 2017) and thus provide potential targets to enhance rehabilitation in AGP.

Variability of the joint kinematics and kinetics

Movement variability has been theorized to play a functional role in relation to overload injuries by allowing flexible adaptations to repetitive tissue loading (Hamill *et al.*, 1999; Stergiou, Harbourne and Cavanaugh, 2006). However, we found no differences in movement variability (i.e. kinematic and kinetic variability of the trunk or lower limbs) when comparing the AGP and CON groups pre- or post-rehabilitation, or in the AGP following successful rehabilitation. In conflicting findings, Edwards et al (2016) reported significantly less movement variability at the ankle, knee and T12-L1 joints and increased movement variability at the L5-S1 joint in the AGP group when compared to the uninjured control group during a running cut task (Edwards, Brooke and Cook, 2016). However, their study only included seven AGP participants who had a past history of groin pain and were currently asymptomatic and this may limit the generalizability of their findings. Furthermore, these authors examined the magnitude of movement variability using the coefficient of variation which can inflate values when means are close to zero (Brown, Bowser and Simpson, 2012). For example, in their study the within-subject coefficient of variation percentage for trunk rotation (T12-L1) for the control group was 589%. In addition, the conflicting findings may be explained by the familiarity of the tasks examined. A running cut task would typically be a more practiced movement pattern in field sport athletes as compared to a continuous lateral hurdle hop and therefore a more stable pattern has potentially been learnt by individuals through practice, as in line with the Dynamic System Theory of motor learning (Davids *et al.*, 2003; Bartlett, 2008). Therefore, it is possible that the continuous HH task may have resulted in increased movement variability in both the AGP and CON groups thereby preventing any between-group differences being observed. Overall, our findings would question the importance of movement variability in relation to AGP.

Limitations

One potential limitation is that only the magnitude of movement variability was examined and therefore it remains unclear if the structure of movement variability was affected. Non-linear statistics (e.g. sample entropy) are required to examine the structure of movement variability which have been shown to vary independently of magnitude measures (Harbourne and Stergiou, 2009). Previous research has reported that the structure of movement variability (i.e. complexity) was associated with AGP (Gore *et al.*, 2017) and may be considered in future research in AGP.

7.5 Conclusion:

In this cohort of athletes, AGP does not affect trunk and lower limb kinematic or kinetic movement patterns during a continuous hurdle hop in comparison to uninjured controls. In addition, no differences in the movement variability of these measures were found and therefore our findings do not support the proposed association between altered variability and overuse injury. It is possible that movement tasks that are well practiced and require high eccentric loading may better expose any potentially differences in movement patterns and movement variability between AGP and uninjured groups. This should be taken into consideration for future research.

Chapter 8

Thesis Summary

The aims of this thesis were to examine biomechanical and strength factors related to AGP and how these changed with rehabilitation. A secondary aim was to examine the long-term effectiveness of rehabilitation using a validated patient reported outcome measure. These were addressed in four research questions (Chapters 4, 5, 6, 7) and a systematic review on movement variability (Chapter 3). The analysis approach employed by the studies in this thesis was to combine both case-control and pre- to post-rehabilitation comparisons, whereby significant findings in both (i.e. case-control and pre- to post-rehabilitation comparison) are more likely associated with the injury as compared to using either approach in isolation (Spirtes, Glymour and Scheines, 2000; Marshall and Moran, 2015; Gore *et al.*, 2018). A number of important strength and biomechanical factors were identified that can provide important targets following injury to enhance rehabilitation programs and which may help to reduce the risk of reinjury.

Several strength variables were affected by AGP and resolved following successful rehabilitation, which focused on intersegmental control through strength, linear running and change-of-direction movements. Significant deficits in isometric hip strength in all three-planes of motion (i.e. hip abductors, adductors, flexors, extensors, external rotators) and single leg reactive strength were reported in the AGP group compared to the control group pre-rehabilitation. Of considerable interest from a rehabilitation perspective was that adductor muscle strength increased following successful rehabilitation despite no targeted adductor strength exercises. Two possible explanations are likely. Firstly, reduced inhibition of the adductor muscle group as pain resolved with rehabilitation (Linthorne, 2001). Secondly, indirect muscle strengthening through the multi-planar action of the hip adductor musculature (Neumann, 2010). This finding cast doubts over the need for intervention programs which only focus on adductor strength and which do not consider tri-planar hip strength or the pathomechanics potentially contributing to the onset of pain and pathology. Hip strength, in particular the hip abductors and extensors, plays a vital role in stabilizing the pelvis during multi-planar actions (e.g. hopping and change-of-direction) (Neumann, 2010). Increased strength and stability may help to reduce loading or redistribute forces on the pubic symphysis and associated fascial and myotendinous structures common to AGP. In support of this, reduced capacity of the hip abductors (i.e. strength [O'Connor, 2004], activation [Morrissey *et al.*, 2012], joint moment [Gore *et al.*, 2020], joint stiffness [Gore *et al.*, 2018]) and hip extensors (i.e. joint moment [Gore *et al.*, 2020]) have previously been reported in AGP patients. Furthermore, increased hip abductor and extensor moments and hip abductor stiffness were reported in AGP patients following successful rehabilitation (Gore *et al.*, 2018, 2020). Reactive strength has not previously been examined in relation to AGP and the findings from this thesis suggest it may be an important factor in recovery. Following successful rehabilitation, improved reactive strength in the AGP group resulted from the ability to produce shorter ground contact times measured during a drop jump. The shorter ground contacts likely reflect increased joint stiffness (i.e. difference in joint range of motion and angular velocity under a given force) which may prevent excessive joint motion and overload on the pelvis and supporting tissue structures (Butler, Crowell and Davis, 2003; Chimera *et al.*, 2004; Flanagan, Galvin and Harrison, 2008). In support, Gore et al (2018) reported reduced hip stiffness in AGP athletes when compared to uninjured controls and, following successful rehabilitation hip stiffness was no longer significantly different (Gore *et al.*, 2018). To enhance rehabilitation programs and potentially minimize reinjury risk, clinicians may consider plyometric drills to improve single-leg reactive strength with the goal to shorten ground contact times and also the inclusion of targeted exercises for the hip abductor and extensor musculature. However, while strength is considered an important factor in recovery, the change in strength variables from pre- to post-rehabilitation could only explain 11% of the change in HAGOS Sport Rec score suggesting the importance of joint loading and movement technique in the recovery of AGP.

A number of important joint loading and movement technique factors associated with AGP were identified in this thesis. Altered loading patterns of the vertical ground reaction force (GRF) were reported in the AGP group during a countermovement jump (CMJ) (Chapter 5) and a continuous hurdle hop (HH) task (Chapter 6) when compared to uninjured control groups pre-rehabilitation. These altered patterns likely represent cushioning strategies to decrease loading on painful tissue structures by reducing the magnitude and/or loading rate of the GRF. During the single leg CMJ, the cushioning strategy was reflected by reduced landing impulse in the first 40ms in the AGP group. Following successful rehabilitation, the AGP group demonstrated a further decrease in the landing impulse in the first 40ms. In order to reduce landing impulse, the AGP group increased knee extension and ankle plantar flexion prior to landing to decrease their initial impact velocity (i.e. reduced the height of falling) and in doing so decrease their initial rate of loading. In line with this, Rowley et al (2015) has demonstrated that increased ankle plantar flexion angle during landing reduces the loading rate of the vertical ground reaction force and also the hip's contribution to the support moment in healthy individuals (Rowley and Richards, 2015). Similarly, during a continuous HH task, the AGP group employed a cushioning strategy whereby longer ground contact times were used to spread the force over an extended period to reduce peak force and eccentric rate of loading when compared to the control group. In similar findings, Gore et al (2020) also reported reduced vertical GRF and longer ground contact times in AGP patients during a single hurdle hop compared to uninjured controls. In this thesis, following successful rehabilitation, the AGP demonstrated shorter ground contact times and increased peak force and eccentric loading rates. These findings suggest an increased tolerance to higher loading levels likely related to the resolution of symptoms, and a reconditioning of reactive strength capacity with rehabilitation (which included plyometric exercises drills to improve the utilization of the stretch-shorten cycle). These altered GRF loading patterns found in this thesis are novel for AGP but in line with previous research which has reported increased peak force (Grimston *et al.*, 1991; Hreljac, Marshall and Hume, 2000; Zifchock, Davis and Hamill, 2006) and increased loading rates (Ribeiro *et al.*, 2015; Bigouette *et al.*, 2016; Davis, Bowser and

Mullineaux, 2016) are associated with other pathological conditions at the knee, shank and ankle. Importantly, from a rehabilitation perspective the intervention strategies utilized in this thesis influenced the cushioning strategies identified in the vertical GRF. During the single leg CMJ the strategy was enhanced (i.e. reduced landing impulse), while during the continuous HH task the strategy was resolved (i.e. increase peak force and loading rate). Therefore, rehabilitation programs may focus on techniques to soften single leg landing patterns utilizing increased ankle plantar flexion strategies and also which aim to reduce ground contact times and promote higher peak forces and loading rates during single leg hopping actions.

In addition to peak kinematic and kinetic measures, variability has also been suggested to play an important role in relation to overuse injuries (Hamill *et al.*, 1999; James, Dufek and Bates, 2000; Davids *et al.*, 2003). The magnitude of variability in the ground reaction force (GRF), joint kinematics and joint kinetics was examined during a continuous hopping task (Chapter 6, 7) and no significant differences were identified in the AGP group when compared to uninjured controls pre- or post-rehabilitation, or in the AGP group following successful rehabilitation. These findings are in contrast to the systematic review undertaken as part of this thesis which found lower limb pathology affected movement variability (Baida *et al.*, 2018). The lack of findings in this thesis may be explained by the novel nature of the continuous HH task which may have resulted in increased movement variability in both the AGP and CON group thereby preventing any between group differences being observed (Bartlett, 2008). Overall, these findings question the importance of movement variability in relation to AGP.

Finally, this thesis is the only study to examine the long-term efficacy of rehabilitation using a validated patient reported outcome measure (HAGOS) (Study 4). The initial 6-month period post return-to-play (RTP) was deemed the most important as this is when athletes are most susceptible to re-injury as training loads and intensity increase (Orchard, Best and Verrall, 2005; Blanch and Gabbett, 2016). Importantly, over this period HAGOS scores for participation in physical activity and quality of life increased from RTP to 3-month follow-up. Furthermore, from 3 to 6-month post-RTP, all HAGOS subscale scores and the Marx score remained constant in the AGP athletes. These findings indicate that with increased and maintained sporting participation HAGOS was not negatively affected, suggesting the efficacy of the intersegmental rehabilitation program over 6-months without the reoccurrence of pain and symptoms (as indicated by HAGOS).

8.1 Future Research

The results of this thesis have a number of important implications. Firstly, rehabilitation focused on intersegmental control improves not only local hip strength but also reactive strength and can alter movement technique and loading patterns in AGP athletes. As such, future research should directly compare the intersegmental rehabilitation approach to the traditional rehabilitation approaches which primarily focusses on local hip strength. In order to compare these different rehabilitation approaches a multi-center, randomized control trial, with sites in Dublin (Sports Surgery Clinic), Oslo (Oslo Sports Trauma Research Center) and Copenhagen (Hvidovre Hospital, Denmark), has been proposed. This study has been planned as an assessor blinded, superiority trial with two parallel groups to compare return-to-play rates and times between the different rehabilitation approaches. Outcomes will also include short, mid- and long-term follow-up of HAGOS and pain provocation tests. Both rehabilitation programs will be delivered at each site and by physiotherapists who have received extensive training in the standardized delivery of each program. Additionally, as a secondary embedded study and the Dublin site, objective strength data (e.g. hip strength, reactive strength index), running metrics (e.g. total distances, maximum velocity) and detailed episodes of re-injury post-rehabilitation over the 0-12 month post-RTP period. This period is when athletes are susceptible to re-injury as training and match loads increase and also when athletes can be expected to begin to return to full athletic performance (Ardern et al. 2016). Tracking strength measures and running metrics post-RTP may give valuable insight into potential factors that result in athletes suffering recurrent injury or being unable to achieve a return-to-full performance. It is possible that when athletes RTP they neglect their rehabilitation/strength program and/or rapidly increase their training loads too quickly thus making them more susceptible to issues of tissue fatigue, reduced strength, mechanical overload and ultimately re-injury. This additional strength information could be used in subsequent rehabilitation protocols to set specific strength values that need to be achieved for successful RTP clearance and which should be maintained post-RTP. The running metrics information be subsequently used to provide a range of targets (e.g. total volume, high speed running meters, accelerations and deceleration etc.) that need to be reached on a weekly basis in order to safely progress from RTP clearance to full performance, or to be limited to so as to decrease the likelihood of excessive overload.

The detailed reporting of re-injuries post-RTP can give additional and valuable insight into factors that may have been associated with re-injury (e.g. training/match loads, repeated high-intensity acceleration etc.) that cannot be accurately captured in patient-reported outcomes measures. In order to gain greater insight into re-injuries post-RTP, studies would need to consider very large sample sizes given that reinjures affect approximately one out of five athletes (Werner et al., 2019).

A second important implication from this thesis was that rehabilitation could influence lower loading patterns that were affected by AGP. As such, future studies should consider interventions that directly target the loading strategies identified in this thesis. Broadly, these strategies would be categorized as force production (e.g. development of peak forces via shorter ground contact times during lateral plyometric movements) or force absorption (e.g. landing techniques aimed to reduce the rate of initial loading on landing). Given the high incidence of AGP in sports which require rapid deceleration and acceleration movements, improvements in these physical capacities driven via rehabilitation programs may help to optimize loading strategies in athletes with AGP.

A third important finding from this thesis was that single leg reactive strength exercises should be incorporated into rehabilitation programs for AGP. Further research should explore lower limb kinematics and kinetics during a drop jump task to identify the joint strategies underpinning increases in reactive strength. This may help to enhance rehabilitation programs as specific exercises can be prescribed to target different joint loading strategies (e.g. ankle versus hip dominant strategies). In line with this, Gore et al (2018) examined joint stiffness in athletes with AGP and reported significantly reduced ankle and hip stiffness when compared to uninjured control athletes and that post-rehabilitation in the AGP athletes hip stiffness significantly increased while ankle stiffness remained less.

A fourth important implication was the different return-to-play times observed within this thesis (chapter 4 - 9.8 ± 3.0 weeks versus chapter 5 - 12.2 ± 6.3 weeks) when comparing two individual cohorts who both successfully completed the same intervention program. This highlights the complex and challenging nature of defining RTP status and also the potential difficulties when comparing RTP times between individual studies which utilize different intervention programs, set different RTP criterion and have different rates of program adherence. In this thesis, the longer RTP times reported in chapter 5 are most likely explained by the timing of RTP clearance and a delay in 3D biomechanical testing. At the Sports Surgery Clinic, demand for 3D laboratory testing appointments is extremely high (with thousands of athletes tested every year) and this can result in an approximate 3-4 week wait for laboratory testing appointments. Athletes are only given RTP clearance following the follow-up 3D laboratory testing (when all criteria can be assessed: bilateral squeeze test, pubic stress test and hip range-of-motion) and therefore this likely contributed to the longer RTP times reported in chapter 5. When conducting the intervention study in chapter 4, priority 3D laboratory appointments were held, which meant as soon as an athlete had completed their final RTP criteria (completion of Run B program) they could attend the clinic the following day for assessment (and clearance to RTP if all criteria were successfully achieved). Future research should look to employ a standardized set of

RTP criterion to ensure consistency in comparing outcomes. These measures should be based on a number of factors (e.g. pain provocation tests, strength, power, running speed and volume etc.) and that can be compared across a number for different field-based sports. In addition, RTP criterion should involve tiered progressions to help ensure a safe return-to-train, followed by a return-to-play and finally a return-to-performance. These tiered progressions should be used to ensure that specific strength, running or training/match minutes are achieved each week as athletes gradually build their weekly loads until full performance is successfully met.

Lastly, regarding important implications from this thesis, movement variability was not found to be affected by AGP. However, the lack of a significant effect may have been due to the novel task that was employed in this thesis when examining movement variability and thus further investigations should utilize actions that are more familiar to individuals, such as running and acceleration tasks commonly repeated during training and matches. Furthermore, in line with the 'optimal' variability theory (Hamill, Palmer and Van Emmerik, 2012), research should investigate the normal amount of variability in a given group for a given movement action in order to better detect deviations outside this 'normal' or 'optimal' range.

Appendix

Appendix A: Supplementary information for 'A systematic review on movement variability and lower limb injuries'.

Appendix A1: Variables measured and significant findings

Author	Variables Examined	Significant Finding
(van Uden *et al.*, 2003) ACLR	knee and ankle sagittal plane angular displacements	> operated limb, sagittal plane, ankle-knee coupling (p=0.001)
(Cordeiro *et al.*, 2015) ACLR	Knee sagittal plane kinematics: ROM, angular velocity, angular acceleration, angular position at maximum velocity. Temporal: duration time to peak velocity and to peak acceleration, time of max angular velocity, duration time to contact.	> operated limb, maximum extension angle (p < 0.012) > peak velocity (p > 0.033)
(Pollard *et al.*, 2015) ACLR	Intra-limb coupling angles; hip rotation – knee abd/add hip flex/ext – knee abd/add, hip rotation – ankle IN/EV, knee abd/add – knee flex/ext knee abd/add – ankle IN/EV, knee abd/add – knee rotation, knee flex/ext – knee rotation	> hip rotation – knee abd-add (p=0.04) > hip flex/ext – knee abd-add (p=0.05) > knee abd/add – knee flex/ext (p < 0.01) > knee abd/add – knee rotn (p=0.03)

(Timothy C Gribbin *et al.*, 2016) ACLR	Intra-limb joint couples; hip frontal knee frontal, hip frontal-knee sagittal, hip frontal-knee transverse, hip sagittal-knee frontal, hip sagittal-knee transverse, hip transverse-knee frontal	WALK > hip frontal – knee frontal 24-32% gait cycle (midstance) (cohen's d 11.7) > hip frontal – knee frontal 49-53% gait cycle (late stance) (cohen's d 4.5) > hip frontal – knee transverse 51-58% gait cycle (late stance) (cohen's d 7.3) > hip sagittal – knee transverse 53-55% gait cycle (late stance) (cohen's d 7.69) > hip sagittal – knee transverse 67-69% gait cycle (swing) (cohen's d 35.85) > hip transverse – knee frontal 27-29% gait cycle (midstance) (cohen's d 14.9) > hip transverse – knee frontal 45-47% gait cycle (late stance) (cohen's d 12.0) < hip sagittal – knee frontal 25-31% gait cycle (midstance) (cohen's d -2.3) < hip sagittal – knee transverse 25-30% gait cycle (midstance) (cohen's d -2.69) RUN > hip sagittal – knee transverse swing (not reported)
(Kipp and Palmieri-Smith, 2012) CAI	Ankle sagittal and frontal plane; touchdown, maximum, minimum angle. Ankle sagittal and frontal peak moment. Sagittal and frontal principal components kinematic & kinetic time-series data	= touchdown angle, max/min angle sagittal/frontal plane = peak moments, kinetic PC scores > kinematic sagittal PC 3 (100ms pretouchdown) > kinematic frontal PC 1 (through entire 300ms)

(Brown, Bowser and Simpson, 2012) CAI	3D kinematics ankle, knee, hip, trunk	PRE-INITIAL > (FAI) trunk LF (p=0.006) < (FAI) knee IR/ER (p=0.007) < (coper) knee IR/ER (p=0.001) < (MAI) hip flex (p=0.006) < (FAI) hip flex (p=0.001) < (coper) (p=0.006) < coper anterior (p=0.007) STANCE < FAI knee IR/ER (p=0.003) < MAI hip flex (p=0.003) < FAI hip flex (p<0.001) < Coper hip flex (p=0.001) < MAI hip abd/add (p=0.003) <FAI lateral (p=0.003) < MAI anterior (p=0.006) < FAI anterior (p=0.005)
(Hamacher, Hollander and Zech, 2016) CAI	Ankle sagittal and frontal plane angles	> injured ankle frontal plane 11-24% stance (p < 0.001) > injured ankle frontal plane 77-83% swing (p=0.005) > injured ankle frontal plane 92-97% swing (p=0.007) > unaffected ankle frontal plane 66-69% swing (p=0.023)
(Drewes *et al.*, 2009) CAI	Rear-foot inversion-eversion, shank rotation. Coupling shank rotation rear-foot inversion-eversion	= No significant differences in DP measures between groups during walking or jogging (p > 0.05)
(Herb *et al.*, 2014) CAI	Joint coupling rear-foot and shank	WALK < injured ankle rear-foot-shank late stance, toe off, early swing (not reported)

(Kulig, Joiner and Chang, 2015) Patellar tendon	Lower extremity contact angle, sagittal plane hip, knee and ankle	< injured limb ankle DF initial contact (p=0.01)
(C. R. James, Dufek and Bates, 2000) Injury prone	Hip, knee, ankle; peak joint moments, time to peak moment values, impact impulse	> injured limb 100% jump height peak AJM ($p < 0.05$) < injured limb 50% jump height time to peak AJM ($p < 0.05$)
(Ferber *et al.*, 2005) RRI	Intra-limb couple; rear-foot eversion/inversion - tibial internal/external rotation	= No significant differences in variability in joint coupling between groups
(Mann *et al.*, 2015) RRI	Strike Index, contact time, stride time, flight time, duty factor, stride length, stride frequency	= No significant differences in variability found between groups
(Paquette, Milner and Melcher, 2016) RRI	Sagittal plane foot contact ankle	= No significant differences in variability of sagittal plane foot contact ankle between groups
(MacLean, van Emmerik and Hamill, 2010) RRI	Intra-limb couples; tibia transverse – calcaneus frontal, knee sagittal – rearfoot frontal, knee frontal – rear-foot frontal, knee transverse – rear-foot frontal	> Injured limb tibial transverse-calcaneus frontal early stance (p=0.004; ES=0.30)
(Meardon, Hamill and Derrick, 2011) RRI	Stride time	= No significant differences in variability of stride time between groups at the beginning of the run

(Miller *et al.*, 2008) ITBS	Intra-limb couples; thigh frontal (Abd/Add) – tibia transverse (IR/ER), thigh frontal – foot transverse (IN/EV), tibia transverse – foot transverse (IN/EV), knee sagittal (Flex/Ext) – foot frontal (Abd/Add), knee frontal (Abd/Add) – foot transverse	> knee flex/ext – foot abd/add complete stride (p=0.02) > knee flex/ext – foot abd/add swing (p=0.04) > knee flex/ext – foot abd/add stance (p=0.02) < tibial IR/ER – foot IN/EV heel strike (p=0.04) ^ discrete measure
(Hein *et al.*, 2012) ITBS	Intra-limb coupling; hip sagittal – knee sagittal, hip frontal – knee sagittal, knee sagittal-ankle sagittal, knee sagittal-ankle sagittal	= No significant differences in variability of dependent measures found between groups during stance phase, intervals of stance phase or continuously during
(Heiderscheit, Hamill and Van Emmerik, 2002) PFP	Stride duration and length. Within limb coupling; thigh transverse – leg transverse, thigh sagittal – leg sagittal, knee transverse – ankle transverse (IN), Knee sagittal – ankle transverse (IN), knee sagittal – ankle sagittal	> stride length preferred running speed (p=0.03, ES 0.30)
(Cunningham *et al.*, 2014) PFP	Coupling angle variability; knee valgus/varus (KV) – ankle inversion/eversion (AI), knee valgus/varus – ankle plantar/dorsi flexion (AF), knee flexion/extension (KF) – ankle inversion/eversion, knee flexion/extension – ankle plantar/dorsi flexion, knee internal/external rotation (KR), knee internal/external – ankle plantar/dorsi flexion	> KF-AF Q1 (p=0.020; cohen's d 0.97) > KR-AI Q2 (p=0.049; 0.80) > KR-AF Q2 (p=0.038; 0.85) > KV-AF Q4 (p=0.010; 1.09) > KV-AF Q5 (p=0.008: 1.12) > KV-AF stance (p=0.008: 1.21) > KV-AI stride (p=0.031; 0.89)
(Edwards, Brooke and Cook, 2016) AGP	3D kinematics ankle, knee, hip, L5-S1 and T12-L1. Peak net internal ankle, knee and hip joint moments. Peak ground reaction force (vertical, minima, posterior)	> T12-L1 right-left rotation (p < 0.05)

(Chiu, Lu and Chou, 2010) THA	Inter-joint coordination variability; hip -knee, knee -ankle	> surgical limb hip-knee sagittal plane pre-surgery (p=0.019) > surgical limb knee-ankle sagittal plane pre-surgery (p=0.008) > surgical limb knee-ankle sagittal plane 6 weeks post-op (p=0.036)

ACLR – anterior cruciate ligament reconstruction, CAI – chronic ankle instability, RRI – running related injury, ITBS – iliotibial band syndrome, PFP – patellofemoral pain, AGP – athletic groin pain, THA – total hip arthroplasty, > greater than, < less than, = no between group difference, ROM – range of motion, abd – abduction, add – adduction, flex – flexion, ext – extension, IN – inversion, EV – eversion, rotn – rotation, PC – principal component, max – maximum, min – minimum, FAI – functional ankle instability, MAI – mechanical ankle instability, IR – internal rotation, ER – external rotation, LF – lateral flexion, DP – deviation phase, DF – dorsi-flexion, AJM – ankle joint moment, ES – effect size, T12 – thoracic vertebrae 12, L1 – lumbar vertebrae 1.

Appendix A2: Quality appraisal checklist (Downs and Black, 1998)

AUTHOR	REPORTING											EXTERNAL				INTERNAL BIAS								CONFOUNDING							POWER	
	Q1	2	3	4	5	6	7	8	9	10		11	12	13		14	15	16	17	18	19	20		21	22	23	24	25	26		27	TOTAL
(van Uden et al. 2003)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
(Cordeiro et al. 2015)	1	1	0	1	1	1	1	0	1	1	8	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	12
(Pollard et al. 2015)	1	1	0	1	1	1	1	0	1	1	8	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	11
(Gribbin et al. 2016)	1	1	1	1	1	1	1	0	1	0	8	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	11
(Herb et al 2014)	1	1	1	1	1	1	1	0	1	0	8	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	11
(Kipp and Palmieri-Smith 2013)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
(Brown, Bowser, and Simpson 2012)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
(Hamacher, Hollander, and Zech 2016)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
(Drewes et al. 2009)	1	1	1	1	1	1	1	0	1	0	8	0	0	0	0	0	0	1	0		0	1	2	0	0	0	0	0	0	0	1	11
(Kulig, Joiner, and Chang 2015)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
(James, Dufek, and Bates 2000)	1	1	0	1	1	1	1	0	1	0	7	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	10
(Ferber, Davis, and	1	1	1	1	1	1	1	0	1	1	9	0	1	0	1	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	14

Williams 2005)																																
(Mann et al. 2015)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
(Paquette, Milner, and Melcher 2016)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
(Maclean, Emmerik, and Hamill 2010)	1	1	0	1	1	1	1	0	1	1	8	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	12
(Meardon, Hamill, and Derrick 2011)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
(Miller et al. 2008)	1	1	1	1	1	1	1	1	1	1	10	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	14
(Hein et al. 2012)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	13
(Heiderscheit, Hamill & Emmerik 2002)	1	1	1	1	1	1	1	1	1	1	10	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	13
(Cunningham et al. 2014)	1	1	1	1	1	1	1	1	1	1	10	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	13
(Edwards et al. 2016)	1	1	1	1	1	1	1	1	1	1	10	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	1	14
(Chiu, Lu, and Chou 2010)	1	1	1	1	1	1	1	0	1	1	9	0	0	0	0	0	0	1	0	1	0	1	3	0	0	0	0	0	0	0	0	12
										Mean	9				0								3							0		12
										Median	9				0								3							0		12

Appendix B: Supplementary information for ‘The effects on hip strength and power of segmentally focused rehabilitation in athletic groin pain’.

Appendix B1: Outcome measures: Peak isometric hip torque, hip torque ratios, double-leg and single-leg reactive strength, bilateral adductor squeeze test and hip ROM

	AGP pre	AGP post	CON	AGP pre vs. CON				AGP pre vs. AGP post				AGP post vs. CON			
Peak torque (Nm/kg)	**Mean ±SD**	**Mean ±SD**	**Mean ±SD**	**p**	***d***	**% Diff**	**Cons (%)**	**p**	***d***	**% Δ**	**Cons (%)**	**p**	***d***	**% Diff**	**Cons (%)**
ABD	1.84 ± 0.31	2.11 ± 0.38	2.28 ± 0.27	0.000*	-1.20	24%	100	0.000*	-0.83	15%	100	0.066	-0.58	8%	60
ADD	2.18 ± 0.43	2.73 ± 0.35	2.81 ± 0.39	0.000*	-1.20	29%	100	0.000*	-1.15	25%	100	0.505	-0.20	3%	3
FLEX	1.18 ± 0.21	1.36 ± 0.17	1.43 ± 0.19	0.000*	-1.07	22%	100	0.000*	-0.86	15%	100	0.212	-0.40	6%	19
EXT	1.83 ± 0.43	2.33 ± 0.37	2.20 ± 0.39	0.005*	-0.83	21%	100	0.000*	-1.05	27%	100	0.303	0.32	-5%	4
ER	0.65 ± 0.14	0.78 ± 0.11	0.75 ± 0.14	0.030*	-0.67	15%	85	0.000*	-0.92	20%	100	0.394	0.26	-4%	4
IR	0.91 ± 0.18	1.06 ± 0.16	0.95 ± 0.18	0.439	-0.23	5%	1	0.000*	-0.84	17%	100	0.035	0.64	-11%	73
Torque ratio															
ADD/ABD	1.21 ± 0.26	1.31 ± 0.21	1.25 ± 0.21	0.556	-0.16	3%	0	0.041	-0.43	9%	75	0.328	0.31	-5%	10
EXT/FLEX	1.57 ± 0.30	1.73 ± 0.24	1.55 ± 0.22	0.638	0.07	-1%	0	0.009*	-0.55	10%	99	0.018*	0.71	-10%	90
ER/IR	0.72 ± 0.14	0.76 ± 0.13	0.80 ± 0.13	0.061	-0.58	11%	60	0.222	-0.25	5%	8	0.254	-0.37	6%	14
Reactive strength															
DLDJ GCT (sec)	0.30 ± 0.08	0.26 ± 0.06	0.26 ± 0.09	0.158	0.42	-12%	15	0.010*	0.54	-13%	100	0.726	-0.03	1%	0
DLDJ JH (cm)	30.49 ± 5.30	29.70 ± 5.12	30.59 ± 3.93	0.672	-0.03	0%	0	0.373	0.15	-2%	2	0.507	-0.20	2%	0
DLDJ RSI	1.09 ± 0.33	1.19 ± 0.30	1.29 ± 0.40	0.082	-0.53	18%	49	0.086	-0.32	9%	41	0.366	-0.27	8%	2
SLDJ GCT (sec)	0.37 ± 0.07	0.32 ± 0.04	0.33 ± 0.06	0.050	0.58	-11%	64	0.001*	0.76	-14%	100	0.555	-0.17	3%	0
SLDJ JH (cm)	13.42 ± 3.08	13.15 ± 3.18	15.21 ± 2.45	0.050	-0.61	13%	68	0.542	0.09	-2%	0	0.029	-0.68	16%	83
SLDJ RSI	0.38 ± 0.13	0.42 ± 0.12	0.48 ± 0.12	0.014*	-0.73	26%	97	0.093	-0.30	9%	45	0.099	-0.51	15%	43

Squeeze test (mm Hg)																
SQ0 Max	151 ± 24	170 ± 28	171 ± 32	0.024*	-0.66	13%	86	0.008*	-0.66	12%	100	0.662	-0.05	1%	0
SQ0 P1	126 ± 17	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SQ45 Max	257 ± 38	276 ± 27	273 ± 39	0.177	-0.41	6%	19	0.006*	-0.57	8%	100	0.627	0.09	-1%	0
SQ45 P1	128 ± 36	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hip ROM															
Ext ER	31.17 ±6.18	30.04 ±6.46	30.89 ±6.41	0.666	0.06	-1%	0	0.465	0.18	-4%	3	0.629	-0.11	3%	0
Ext IR	32.35 ±7.89	31.62 ±6.47	26.98 ±7.58	0.034	0.64	-17%	20	0.553	0.10	-2%	1	0.066	0.61	-15%	17
Flex ER	28.09 ±6.69	28.91 ±6.32	29.55 ±7.01	0.484	-0.22	5%	1	0.552	-0.12	3%	1	0.632	-0.10	2%	0
Flex IR	19.83 ±8.45	24.33 ±6.76	19.66 ±6.96	0.597	-0.01	-1%	0	0.000	-0.57	23%	100	0.051	0.62	-19%	17
TROM Ext IR/ER	63.52 ±9.30	61.66 ±8.12	56.27 ±13.53	0.048	0.59	-11%	66	0.419	0.21	-3%	6	0.126	0.46	-9%	25
TROM Flex IR/ER	47.92 ±10.96	53.24 ±8.19	47.77 ±12.58	0.664	0.00	0%	0	0.010	-0.53	11%	100	0.107	0.49	-10%	35

*ABD – abduction, ADD – adduction, FLEX – flexion, EXT – extension, ER – external rotation, IR –internal rotation, % Diff – percent mean difference, % Δ - percent change in mean score, cons – consistency of p<0.05, DL – double leg, GCT – ground contact time, JH – jump height, RSI – reactive strength index, SL – single leg, *significant difference (p < 0.05, freq > 85%), SQ45/0 – bilateral squeeze test in 45°/0° hip flexion, MAX – maximum value, P1 – value recorded at onset of pain occurred, N/A – not applicable (no squeeze pain reported in AGP post or CON group)*

Appendix B2: Asymmetry index of peak isometric hip torque and single-leg reactive strength

	AGP pre		AGP post		CON	AGP pre V CON Absolute			AGP pre V AGP post Directional			AGP post V CON Absolute		
	Absolute	Directional	Absolute	Directional	Absolute									
Peak torque (Nm/kg)	mean ±SD	mean ±SD	mean ±SD	mean ±SD	mean ±SD	p	*d*	Cons (%)	p	*d*	Cons (%)	p	*d*	Cons (%)
ABD	8.62 ± 7.69	-0.15 ± 11.50	7.05 ± 5.67	1.48 ± 8.89	8.56 ± 5.13	0.239	0.01	6	0.400	-0.16	1	0.133	-0.27	20
ADD	9.94 ± 8.86	-4.21 ± 12.58	6.23 ± 4.78	0.77 ± 7.80	7.91 ± 5.39	0.328	0.27	0	0.115	-0.46	30	0.148	-0.33	16
ER	12.42 ± 9.07	-3.22 ± 15.01	10.52 ± 6.10	-1.03 ± 12.06	7.90 ± 5.67	0.049	0.57	64	0.450	-0.16	0	0.076	0.43	42
EXT	12.31 ± 8.96	-0.31 ± 15.17	8.54 ±5 .65	3.64 ± 9.54	11.29 ± 8.04	0.338	0.12	0	0.171	-0.31	22	0.180	-0.39	10
FLEX	9.32 ± 6.65	-3.02 ± 11.01	5.61 ± 4.86	-1.77 ± 7.18	6.18 ± 4.22	0.059	0.54	55	0.565	-0.13	1	0.269	-0.13	2
IR	13.00 ± 8.89	-3.3 ± 15.33	11.02 ± 9.46	-3.52 ± 14.05	9.85 ± 6.74	0.142	0.39	14	0.727	0.01	0	0.330	0.14	1
Reactive strength														
SLDJ CT	9.47 ±7.50	2.50 ±11.77	6.79 ±5.88	2.59 ±8.58	5.98 ±5.13	0.057	0.52	61	0.698	-0.01	0	0.297	0.15	0
SLDJ JH	10.77 ±9.61	-3.55 ±13.93	14.85 ±16.28	-3.05 ±21.69	10.57 ±7.89	0.273	0.02	5	0.687	-0.02	0	0.278	0.32	3
SLDJ RSI	15.18 ±14.38	-5.49 ±20.11	15.42 ±14.96	-5.39 ±20.66	11.64 ±10.00	0.257	0.28	4	0.695	-0.01	0	0.212	0.29	4

ABD – abduction, ADD – adduction, FLEX – flexion, EXT – extension, ER – external rotation, IR –internal rotation, SL – single leg, GCT – ground contact time (sec), JH – jump height (cm) , RSI – reactive strength index, cons – consistency of p<0.05. Nb: a negative sign in the directional asymmetry value indicates a greater value on the non-symptomatic limb

Appendix C: Assessment of hip muscle strength using a hand-held dynamometer: A inter- and intra-rater reliability study.

Introduction

Following injury or the onset of pain, strength deficits in the hip musculature have been reported in populations with AGP (Esteve *et al.*, 2015; Rafn *et al.*, 2016; Delahunt, Fitzpatrick and Blake, 2017). The hip musculature plays a vital role in maintaining dynamic pelvic stability in multiple planes of movement (Neumann, 2010) and may help to reduce excessive loading on the anterior pelvis and myotendinous structures common to AGP. As such, the restoration of hip muscle strength is the primary focus of intervention programs targeting AGP (Charlton *et al.*, 2017) and is important for both sporting performance and to minimize the potential risk of re-injury when returning to play. Hip strength is commonly assessed with hand-held dynamometry, a portable measurement device, which has demonstrated good validity when compared to the gold standard isokinetic testing (Stark *et al.*, 2011). Thorborg et al (2010) provided a standardized assessment protocol for hip muscle strength which showed good-to-excellent intra-tester reliability and standard measurement error (SEM) ranging between 3 and 12%. It is important to establish this for every tester to establish reliability and precision of the testing protocol and importantly to be confident in interpreting the results as real change and not measurement error. Therefore, in order to utilize this protocol for the intervention study in Chapter 4 of this thesis is was important to establish the reliability, SEM and minimal detectable change (MDC) for the clinician performing the hip strength testing. Furthermore, the inter-rater reliability of this strength testing protocol has not previously been examined.

The aims of this study were to examine the intra- and inter-rater reliability, SEM and MDC of a standardized HHD hip strength protocol.

Methods

Participants: 15 healthy participants with no previous history of AGP (8M/7F, age 23.6 ± 4.5years, height 1792 ± 53.4 cm, weight 76.1 ± 8.3 kg, Marx activity score 13.6 ± 2.5) were tested in May 2018.

Protocol: Isometric hip strength was assessed with hand-held dynamometry (Commander J-tech) as per a published protocol by Thorborg et al (2010). Each participant was tested by assessor 1 and assessor 2 during two sperate testing sessions which were seven days apart. On each testing day assessor 1 would test participants in the morning session and assessor 2 would test participants in the afternoon session. Prior to the testing session each participant performed a standardized warm-up including a five-min stationary bike (light resistance, 90RPM) and ten body weight squats. Isometric hip strength was examined in the following order for all participants and included six pairs: (1) left flexion / right flexion (supine), (2) left abduction/ right adduction (side-lie), (3) right abduction / left adduction (side-lie), (4) left extension / right extension (prone), (5) right internal rotation / left external rotation (seated) and (6) left internal rotation / right external rotation (seated). For each muscle tested, two sub-maximal warm-up trials were conducted for familiarization, followed by four maximum effort trials. Each trial consisted of a five second isometric maximum voluntary contraction (MVC) against the dynamometer and examiner with the verbal instructions given to push as fast and hard as possible against the dynamometer, followed by push, push, push, relax. To avoid fatigue, a rest period of 20-seconds was given between each trial and a two-minute rest between muscle pairs. Force measures were converted to peak by multiplying the length of the lever arm. Lever length was measured in standing and included: (1) anterior thigh - ASIS to 5cm above superior border of patella, (2) posterior thigh - PSIS to posterior thigh mark 5cm above posterior knee joint line, (3) leg lateral - ASIS to 5cm proximal to the most prominent point lateral malleoli, and (4) leg medial - ASIS to 5cm proximal to the most prominent point medial malleoli, (5) shank lateral – lateral joint line knee to 5cm proximal to the most prominent point lateral malleoli, and (6) medial shank – medial joint line knee to 5cm proximal to the most prominent point medial malleoli. Strength measures reported included mean (highest three values from the four trials) and peak values.

Test positions: Hip Abduction (side lie) - subject lying on side with both hips in neutral flexion-extension position, lower hand under head and upper hand holding table to stabilize. Subject is assisted in bringing tested leg in neutral hip adduction-abduction position. Examiner stands at bottom end of plinth, leaning over lower leg and provides a fixed resistance with both hands and the force transducer on the subject's leg 5cm above the lateral malleoli. Hip Adduction (side lie) - subject lying on side with bottom leg in hip neutral flexion-extension and top leg in 70-90 hip flexion and resting on foam roller. Examiner stands at bottom end of plinth, leaning over lower leg and provides a fixed resistance with both hands and the force transducer on the subject's leg 5cm above the medial malleoli. Towel required at site of force transducer. Flexion (supine) - subject lying supine with tested leg in 90 hip flexion and both hands holding the edge of the plinth for stabilization. The examiner stands at top end of table, facing caudally, and provides a fixed resistance with both hands and the force transducer on the subject's thigh 5 cm proximal to the superior pole of the patella. Extension (prone)- subject lying prone with tested leg in 70-90 of knee flexion and both hands holding the top of the plinth for stabilization. The examiner stands in middle of plinth leaning over thigh and provides a fixed resistance with both hands and the force transducer on the subject's thigh 5 cm proximal to the knee joint line. Internal rotation (sitting) - Subject sitting upright with thigh fully supported on plinth, knee at 90 flexion and both hands holding edged of plinth for stabilization. The examiner kneels on the outside of subject's tested leg and provides a fixed resistance with both hands and the force transducer on the subject's leg 5cm proximal to the lateral malleoli. Towel required at site of force transducer. External rotation (sitting) - Subject sitting upright with thigh fully supported on plinth, knee at 90 flexion and both hands holding edged of plinth for stabilization. The examiner kneels on the of subject's tested leg and provides a fixed resistance with both hands and the force transducer on the subject's leg 5cm proximal to the medial malleoli. Towel required at site of force transducer.

Statistics Analysis

Strength values are presented as mean ± standard deviation. Data were normally distributed (Sharpio-Wilk test) and parametric tests used. Intra-rater reliability was assessed using intra-class correlation coefficient (ICC) 2,1 (two-way mixed model, consistency definition) and inter-rater reliability assessed using ICC 3,1 (two-way mixed model, absolute agreement) and the corresponding 95% confidence intervals were calculated in SPSS statistical package version 25 (SPSS Inc. Chicago, IL). To assess and measurement precision was assessment standard error of measurement (SEM) and minimal detectable change (MDC) (Hopkins, 2000; Portney and Watkins, 2009; Beninato and Portney, 2011; Furlan and Sterr, 2018). The SEM was calculated by the *root mean square* average of the standard deviations (Baker, 2016). The MDC was calculated from the SEM with a 95% degree of confidence (MDC_{95}) and is the minimum amount of change that needs to be observed, at either group or individual level, that can be considered above measurement error (Beninato and Portney, 2011). MDC_{95} was calculated by:

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

Where SEM is the standard error of measurement, z represents the 95% degree of confidence for the estimate of the MDC (z = 1.96), and $\sqrt{2}$ is applied to the formula as a correction factor to account for the uncertainty introduced by taking measurement at different points of time (Beninato and Portney, 2011).

Results

The intra-rater reliability hip for strength measures are presented in Table C1 and inter-rater reliability hip for strength measures are presented in Table C2. Intra-rater reliability for peak strength measures the standard error of measurement (SEM) ranged from 2.1 to 5.1%, the minimal detectable change (MDC_{95}) from 9% to 18% and intra-class correlation coefficient (ICC 2,1) ranged from 0.67 to 0.98. For average strength measures the standard error of measurement (SEM) ranged from 2.6 to 4.5%, the MDC_{95} from 11% to 18% and intra-class correlation coefficient (ICC 2,1) ranged from 0.78 to 0.99. Inter-rater reliability for peak strength measures the SEM ranged from 3.9 to 12.5%, the MDC from 16 to 50% and ICC 3,1 ranged from 0.37 to 0.96. For average strength measures the SEM ranged from 4.2 to 15%, the MDC from 17 to 58% and ICC 3,1 ranged from 0.50 to 0.96.

Table C1: Intra-rater reliability: Maximum and average torque (Nm.kg)

		Test		**Retest**		**Diff test-retest**		**ICC (CI 95%)**	**SEM**	**% SEM**	**MDC_{95}**	**% MDC**
		Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**					
MAX												
ABD	DOM	1.93	0.28	2.02	0.27	0.09	0.14	0.93 (0.76-0.98)	0.11	3.61	0.29	14.89
	NDOM	1.90	0.21	1.92	0.29	0.03	0.16	0.88 (0.64-0.93)	0.11	3.83	0.30	15.87
ADD	DOM	2.14	0.26	2.21	0.29	0.07	0.14	0.86 (0.55-0.95)	0.10	3.01	0.27	12.46
	NDOM	2.04	0.28	2.21	0.35	0.17	0.15	0.87 (0.58-0.96)	0.13	4.26	0.37	17.50
FLEX	DOM	1.21	0.21	1.26	0.20	0.05	0.04	0.98 (0.94-0.99)	0.04	2.08	0.11	8.60
	NDOM	1.23	0.24	1.29	0.24	0.06	0.06	0.97 (0.91-0.99)	0.05	2.80	0.15	11.53
EXT	DOM	1.70	0.47	1.77	0.47	0.07	0.09	0.98 (0.96-0.99)	0.07	2.65	0.19	10.93
	NDOM	1.68	0.46	1.81	0.48	0.13	0.08	0.99 (0.98-1.0)	0.09	3.60	0.26	14.79
IR	DOM	0.81	0.14	0.84	0.14	0.03	0.08	0.79 (0.35-0.93)	0.05	4.25	0.14	17.57
	NDOM	0.75	0.14	0.79	0.15	0.03	0.05	0.92 (0.75-0.97)	0.04	3.45	0.11	14.26
ER	DOM	0.63	0.11	0.63	0.17	0.00	0.06	0.67 (0.035-0.89)	0.04	4.27	0.11	17.75
	NDOM	0.61	0.07	0.64	0.10	0.03	0.07	0.82 (0.45-0.94)	0.05	5.13	0.13	21.16
AVGERAGE												
ABD	DOM	1.85	0.30	1.94	0.29	0.09	0.14	0.92 (0.76-0.98)	0.11	3.76	0.29	15.52

	NDOM	1.80	0.22	1.87	0.25	0.07	0.13	0.89 (0.65-0.96)	0.10	3.55	0.27	14.67
ADD	DOM	2.03	0.27	2.14	0.27	0.11	0.16	0.85 (0.53-0.95)	0.12	3.87	0.33	15.96
	NDOM	1.95	0.29	2.10	0.34	0.15	0.16	0.85 (0.53-0.95)	0.13	4.47	0.37	18.35
FLEX	DOM	1.16	0.22	1.22	0.20	0.07	0.04	0.99 (0.96-0.99)	0.05	2.60	0.13	10.71
	NDOM	1.17	0.24	1.25	0.22	0.08	0.06	0.97 (0.91-0.99)	0.06	3.35	0.17	13.79
EXT	DOM	1.62	0.42	1.72	0.46	0.09	0.09	0.98 (0.93-0.99)	0.08	3.32	0.23	13.69
	NDOM	1.60	0.42	1.74	0.49	0.14	0.07	0.99 (0.97-1.0)	0.09	3.81	0.26	15.61
IR	DOM	0.77	0.12	0.79	0.13	0.03	0.07	0.78 (0.33-0.93)	0.05	4.14	0.13	17.10
	NDOM	0.71	0.14	0.74	0.14	0.03	0.04	0.95 (0.83-0.98)	0.03	3.08	0.09	12.69
ER	DOM	0.59	0.09	0.60	0.14	0.00	0.05	0.76 (0.24-0.92)	0.03	3.86	0.10	16.04

ABD – abduction, ADD – adduction, FLEX – flexion, EXT -extension, IR – internal rotation, ER – external rotation, DOM – dominant limb, NDOM – non-dominant limb, SEM – standard error of measurement, MDC – minimal detectable change

Table C2 : Inter-rater: Maximum and average torque (Nm.kg)

		Assessor 1		Assessor 2		Diff. 1 vs. 2		ICC (CI 95%)	SEM	% SEM	MDC_{95}	% MDC
		Mean	SD	Mean	SD	Mean	SD					
MAX												
HABD	DOM	1.93	0.29	1.92	0.34	0.01	0.23	0.86 (0.58 - 0.95)	0.16	5.39	0.43	22.42
	NDOM	1.90	0.23	1.93	0.29	0.03	0.17	0.90 (0.70 - 0.97)	0.11	3.91	0.31	16.22
ADD	DOM	2.14	0.26	2.41	0.48	0.27	0.31	0.68 (-0.01 - 0.81)	0.30	8.84	0.82	36.05
	NDOM	2.41	0.33	2.32	0.52	0.28	0.31	0.64 (0.01 - 0.88)	0.29	8.92	0.79	36.29
FLEX	DOM	1.21	0.21	1.24	0.22	0.03	0.11	0.91 (0.75 - 0.97)	0.08	4.64	0.24	19.22
	NDOM	1.23	0.23	1.19	0.23	-0.04	0.08	0.96 (0.88 - 0.99)	0.06	3.47	0.18	14.51
EXT	DOM	1.70	0.46	1.80	0.51	0.10	0.22	0.94 (0.81 - 0.98)	0.17	6.60	0.48	27.19
	NDOM	1.68	0.45	1.74	0.46	0.06	0.20	0.95 (0.86 - 0.98)	0.14	5.43	0.38	22.46
IR	DOM	0.81	0.14	0.98	0.15	0.17	0.17	0.37 (-0.29 - 0.75)	0.16	12.50	0.45	50.38
	NDOM	0.75	0.14	0.93	0.21	0.18	0.13	0.64 (-0.24 - 0.90)	0.15	12.40	0.42	49.72
ER	DOM	0.63	0.10	0.66	0.12	0.03	0.04	0.904 (0.68 - 0.97)	0.04	4.45	0.12	18.33
	NDOM	0.61	0.08	0.66	0.12	0.05	0.08	0.77 (0.32 - 0.92)	0.07	7.26	0.19	29.79
AVERAGE												
HABD	DOM	1.85	0.30	1.82	0.34	-0.03	0.22	0.88 (0.65 - 0.96)	0.15	5.40	0.41	22.50
	NDOM	1.80	0.22	1.87	0.29	0.07	0.18	0.85 (0.58 - 0.95)	0.13	4.78	0.36	19.76
ADD	DOM	2.03	0.28	2.31	0.46	0.28	0.28	0.74 (-0.04 - 0.92)	0.27	8.58	0.76	34.91
	NDOM	1.95	0.30	2.23	0.47	0.28	0.31	0.74 (0.01 - 0.92)	0.28	9.14	0.78	37.17
FLEX	DOM	1.16	0.22	1.19	0.22	0.04	0.11	0.92 (0.78 - 0.97)	0.08	4.70	0.23	19.45
	NDOM	1.17	0.23	1.14	0.25	-0.02	0.11	0.95 (0.86 - 0.98)	0.07	4.19	0.20	17.49
EXT	DOM	1.62	0.43	1.69	0.46	0.07	0.18	0.96 (0.87 - 0.99)	0.14	5.51	0.38	22.74
	NDOM	1.60	0.44	1.66	0.43	0.06	0.17	0.96 (0.88 - 0.99)	0.12	5.02	0.34	20.75

IR	DOM	0.77	0.13	0.91	0.15	0.15	0.15	0.50 (-0.25 - 0.82)	0.14	11.58	0.39	46.78
	NDOM	0.71	0.14	0.91	0.19	0.20	0.14	0.55 (-0.26 - 0.86)	0.17	14.46	0.47	57.69
ER	DOM	0.59	0.09	0.63	0.11	0.04	0.04	0.89 (0.56 - 0.97)	0.04	4.85	0.12	19.94
	NDOM	0.58	0.08	0.63	0.12	0.05	0.06	0.85 (0.43 - 0.96)	0.05	6.07	0.15	24.91

ABD – abduction, ADD – adduction, FLEX – flexion, EXT -extension, IR – internal rotation, ER – external rotation, DOM – dominant limb, NDOM – non-dominant limb, SEM – standard error of measurement, MDC – minimal detectable change

Discussion

Good to excellent intra-rater reliability of hip ABD, ADD, FLEX, EXT, IR and ER strength utilizing a standardized hand-held dynamometry testing protocol was demonstrated for both peak and average measures. These findings are similar to Thorborg et al (2010) who utilized the same testing protocol. Importantly, in the current study the MDC ranged from 9-18% and this allows clinicians to interpret differences in test-retest findings as a real change in muscle strength and not a result of measurement error (Ries *et al.*, 2009). Inter-rater reliability ranged from poor to excellent for hip ABD, ADD, FLEX, EXT, IR and ER strength. The MDC values where larger than those reported for intra-rater reliability and therefore greater individual change in strength values are required to be considered true change. The largest MDC value for the inter-rater reliability was reported for hip IR at 58% and it is unknown whether changes of this magnitude are possible with regards to hip IR strength. A possible reason for the differences between intra-rater and inter-rater reliability may be due to the strength of ach tester in HDD affecting inter-rater reliability (Kelln *et al.*, 2008).

Conclusion

Hip strength testing with HHD is reliable and may be used to asses strength changes over time. Intra-rater testing was more reliable when compared to inter-rater reliability. MDC values presented here can be used to determine the minimal amount of change that each strength measurement must show to be certain that it is a true change (i.e. beyond variability and measurement error).

Appendix D: Intersegmental control rehabilitation program.

The rehabilitation program was designed to address trunk, pelvis and lower limb intersegmental control through strengthening, linear running and change-of-direction mechanics (King et al., 2018). Intersegmental control describes the relationship between the trunk, pelvis, hip, knee and ankle during dynamic movements and a loss of control has been suggested to play a role in the propagation of athletic groin pain. (Franklyn-Miller et al., 2017). Figure D1 provides a brief overview of the rehabilitation program.

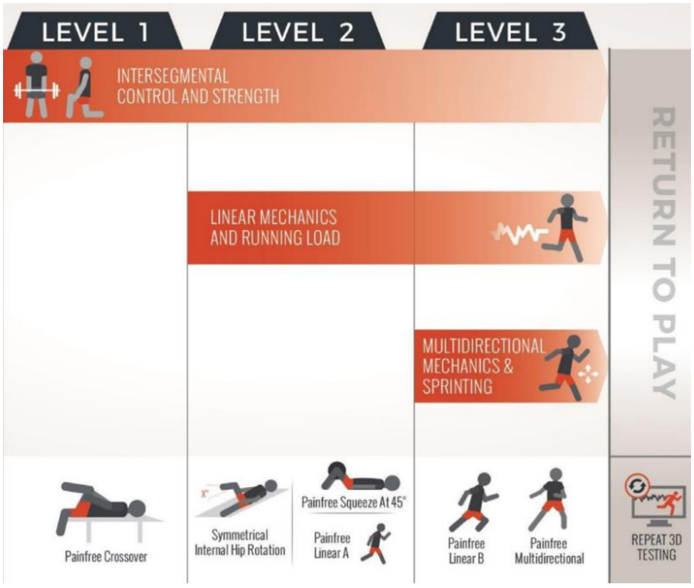


Figure D.1 Intersegmental rehabilitation program levels, components and progression criteria

The intersegmental control rehabilitation program consists of three levels, with each level designed to address specific components of recovery. Level 1 focuses on intersegmental control through strengthening exercises, level 2 focuses on intersegmental control through linear running technique and progression of running load tolerance, and level 3 focuses on intersegmental control through change-of-direction technique and progression back to high speed running. Progression from level 1 to level 2 is achieved with a pain-free cross-over test (in the modified Thomas test position), progression from level 2 to 3 occurs with pain-free squeeze test (in 45° hip flexion), pain-free completion of linear ‘Run A’ program and symmetrical hip range-of-motion (flexion 90° internal rotation mobility). Finally, progression from level 3 to return-to-play is achieved with pain-free completion of ‘Run B’ program and multi-directional drills. Table D1 outlines the exercise streams for each level of the program and Table D2 outlines the exercise progressions for each of the exercise streams.

Once athletes are cleared to return-to-play, they are advised to complete one full strength session per week (i.e. level 1 control, strength and power exercises), three sessions of the level 1 intersegmental control exercises (e.g. as part of an athlete’s pre-pitch/gym preparation) and are to perform the linear and multi-directional technique drills prior to their sporting activity.

Table D1: Outline of exercise streams prescribed during each level of the intersegmental rehabilitation program

LEVEL 1	***Stream***	***Segment***	***Target***	***set***	***reps***
Control	Hip flexor holds	Pelvis on femur	Isometric inner range hip flexion	3	8
	Palloff press*	Thorax on pelvis/pelvis on femur	Unilateral obliques	3	8
	Deadbugs	Thorax on pelvis/pelvis on femur	Bilateral obliques	3	8
	Hip hitch	Pelvis on femur	Inner range hip abduction	3	8
	Banded turn outs	Pelvis on femur	Hip external rotation / abduction	3	8
Strength	Single leg hip thrust*	Thorax on pelvis/pelvis on femur	Single leg hip extension	3	8
	Front squat	Multi-segmental	Front squat	3	8
	Deadlift	Multi-segmental	Deadlift	3	8
	Split squat	Multi-segmental	Split Squat	3	8
Power	Ankling	Multi-segmental	Reactive strength	4	10
Progression criteria - pain-free crossover test					
LEVEL 2	***Completed prior to Run A and B***				
	Switch step	Multi-segmental	Lateral hip RFD	3	3
	Vertical skips	Multi-segmental	Vertical plyometric	4	20
	Resisted box lunge *	Multi-segmental	Horizontal RFD	3	3
Progression criteria - symmetrical hip flexion (90°)/ IR range, pain-free squeeze (45° hip flexion) and completion Run A program					
LEVEL 3	***Completed prior to Run B***				
	Lateral jump/land*	Multi-segmental	Lateral deceleration RFD	3	3
	Side shuffle cut	Multi-segmental	Lateral reactive strength	3	3
	180° cut	Multi-segmental	RFD + deceleration/reacceleration	3	3
RTP Criteria – pain-free completion Run B program and multi-directional drills					

** Exercise additions to the rehabilitation program from King et al. (2018), RFD – rate of force development, IR – internal rotation, RTP – return to play.*

Table D2: Progressions for each exercise stream during each level of the intersegmental rehabilitation program: 1 – basic level, 2 – intermediate (entry) level, 3 – advanced level

LEVEL 1	***Stream***	***1***	***2***	***3***
Control	Hip flexor holds	Supine	Supported stand	Unsupported stand
	Palloff press	Half kneel	Stand	Stand + rotation
	Deadbugs	Crook lie leg lifts	Crook lie alternate leg lowers	Crook lie bilateral leg lowers
	Hip hitch	Supported stand	Unsupported stand	Low box step-up
	Banded turn outs	Light resistance	Moderate resistance	Heavy resistance
Strength	Single leg hip thrust	Supported	Unsupported	Loaded
	Front squat	High box (60cm)	Low box (45cm) (20% BW)	Low box loaded
	Deadlift	Hip hinge	Rack deadlift loaded (40% BW)	Rack deadlift loaded
	Split squat	Supported	Bodyweight	Loaded
Power	Ankling	Supported single taps	Unsupported single tap	Unsupported double taps
LEVEL 2				
	Switch step	March step	Switch step with 5kg plate	Overhead press 5kg plate
	Vertical skips	Overhead march	Vertical skip 50% intensity	Build intensity +/- load
	Resisted box lunge ⱡ	Unresisted lunge	Resisted lunge single band	Resisted lunge double band
LEVEL 3				
	Lateral jump/land ⱡ	0.5-meter jump/land	1-meter jump/land	1-meter + 5kg medball
	Side shuffle cut	50% intensity	Build intensity	Shadow opponent
	180° cut	50% intensity	Build intensity	5kg medball

ⱡ Exercise modifications to the rehabilitation program from King et al. (2018), BW – bodyweight

Equipment: The equipment required includes a squat rack, barbell, weights, box/chair (60cm, 45cm), resistance bands and 5kg medicine ball.

Rehabilitation sessions: Rehabilitation sessions were taken by one of three physiotherapists who were trained in the delivery of the intersegmental control rehabilitation program. All physiotherapists had five or more years clinical experience.

Athletes started their rehabilitation on the same day as their initial testing session. Each rehabilitation session was one-to-one and approximately 1 hour in length. Athletes are taken through the various exercises depending on which rehabilitation level they are in (Table D1) with the difficulty of the exercise selected, progressed or regressed depending on the participants ability to execute with appropriate technique (good form and no reproduction of symptoms) (Table D2). These sessions took place every 14-21 days depending on athlete availability.

In between supervised rehabilitation sessions, athletes were instructed to perform the rehabilitation program at their own training base. Each subject was given a printed handout of all the exercises with the main coaching cues for each), in addition to each exercise being captured on video using Dartfish™ software and the videos hosted online for the athlete to review between sessions. Athletes were instructed to complete a weekly exercise diary to help ensure compliance. Athletes were advised that should any exercise reproduce their symptoms, they should review their videos and amend their technique to resolve and if unable to do so these exercises should be discontinued and their physiotherapist will review during the next rehabilitation session.

Level 1: Level 1 exercises focus on both the control between two segments across one joint (e.g. hip flexor holds) and also multi-segmental movements (e.g. deadlift). For the loaded exercises, the deadlift weight started at approximately 40% bodyweight, front squat 20% bodyweight and split squat bodyweight only. The weight was gradually increased as athletes could reach the appropriate number of repetitions in each set with good control and no symptoms. The importance of correct technique was repeatedly emphasized. Athletes are instructed that no exercises should result in onset or increase in their symptoms. Level 1 exercises were included throughout the duration of the rehabilitation program and instructions/coaching on each exercise can be found below:

Hip flexor holds: In supine, pull hip into inner range flexion, hold steady while providing gentle downward force to front of thigh (i.e. direction of pushing knee away from body). Should feel muscle working deep in front of hip joint.

Palloff press: In standing, exhale and pull lower ribs towards spine, maintain tension in upper abdominal muscles and push out both arms fully straight while holding resistance band (with resistance perpendicular to fully extended arms from left or right side). Should feel upper abdominal muscles working predominately on the side the resistance band is coming from.

Deadbugs: In supine, exhale and pull lower ribs towards spine, with straight arms directly above head, pull resistance on band until feel increased tension in the upper abdominal region, hold and lift/lower legs without losing tension (with resistance coming from behind head i.e. pulling band towards feet). Should feel upper abdominal muscles working equally on left and right sides.

Hip hitch: Standing on one leg with other supported on box (so that supported hip and knee are at 90° flexion), keep standing leg straight, maintain a neutral pelvis and squeeze in gluteal muscles on standing leg to lift (hitch) hip/pelvic on opposite side. Should feel gluteal muscle working directly on the lateral side of hip.

Banded turn outs: In squat position (thighs parallel to ground), resistance band placed above knees, keep feet flat on ground and knees pointed over toes, slowly take knees apart and control back to start position. Should feel gluteal muscles working in 'back pocket' region.

Single leg hip thrust: With upper-back rested on bench, hips below the trunk near the ground, knees at 90° flexion and feet flat on ground, start movement with a posterior pelvic tilt and then continue to curl hips up towards trunk to ensure hip extension.

Front squat / Deadlift / Split squat: Athletes' cue to maintain lumbo-pelvic neutral through all lifts.

Ankling: Holding onto support in front of body, skip from one foot to the other while maximizing movement at the foot and ankle and minimizing movement at the knees.

Level 2: The focus of the level 2 exercise streams (Table D1) is to improve intersegmental control during linear running with exercise drills designed to address commonly observed technical faults (e.g. poor lumbopelvic control at toe-off, poor swing leg recovery) or reduced neuromuscular capacity (e.g. contralateral hip drop during the stance phase of the running gait). Once athletes complete the linear running drills, they carry out the Run A program (Table D3). This was developed for field-sport athletes to gradually build tolerance to running loads and intensity while assessing the athletes' tolerance and suitability for progression. It starts with low volume and low intensity, both of which increase at different points through the program. Athletes are instructed to progress, or regress based on a traffic-light system. Green light means no pain during or the following day and athletes can progress to the next running session. Red light means increased pain during or the following day and athletes are instructed to repeat the same session or drop back a session when scheduled until they can tolerate it and then progress to the next session (by obtaining a green light).

Level 3: The focus of the level 3 exercise streams is to improve intersegmental control during multidirectional movements, lateral rate of force development and agility prior to returning to sports (Table D1). Athletes also progress from Run A to Run B program which increases exposure to high-speed running. Once athletes complete the multidirectional drills (and linear run drills) they carry out the Run B program. The drills are executed at as high an intensity as possible without reproduction of symptoms.

Weekly frequency: Level 1 of the rehabilitation program is prescribed on a 3-day cycle: day 1 all exercises (control, strength and power), day 2 control exercises only and day 3 rest. Level 2 and 3 is prescribed on a 4-day cycle: day 1 all exercises (control, strength and power), day 2 Run A or B (depending on which level an athlete is at), day 3 control exercises only, day 4 rest.

Table D3: Run A and B programs included in Level 2and 3 of the intersegmental control rehabilitation and comparison to King et al (2018).

Baida et al (2020)

Run A (Level 2)		*Dist. (m)*	*Time (sec)*	*Speed (km/h)*	*sets*	*reps*	*Work: Rest*	*Speed Dist.*	*Total Dist.*
Warm-up		400		50%	1	2	1:1	0	800
Linear exercise drills									
session 1	Intervals	20/80/20	24	12	2	8	1:2	1920	2720
session 2		20/80/20	24	12	2	10	1:2	2400	3200
session 3		20/80/20	21	14	2	10	1:2	2400	3200
session 4		20/80/20	21	14	3	8	1:2	2800	3400
session 5		20/80/20	19	16	3	8	1:2	2880	3480
session 6		20/80/20	17	18	3	8	1:2	2880	3480
Run B (Level 3)									
Warm-up		400		50%	1	2	1:1	0	800
Linear + multi-directional exercise drills									
session 1	Sprints (rolling start)	30	7	18	3	2	1:10	180	
	Intervals	80	25-22	14-16	6	3	1:1	1440	2420
session 2	Sprints (rolling start)	30	6	20-22	3	2	1:10	180	
	Intervals	80	25-22	14-16	6	3	1:1	1440	2420
session 3	Sprints (rolling start)	30	6	20-22	5	2	1:10	300	
	Intervals	80	25-22	14-16	6	3	1:1	1440	2540
session 4	Sprints (standing start)	30	6	20-22	5	2	1:10	300	
	Intervals	80	25-22	14-16	6	4	1:1	1920	3020
session 5	Sprints (rolling start)	30	5	24-26	5	2	1:10	300	
	Intervals	80	25-22	14-16	6	4	1:1	1920	3020
session 6	Sprints (standing start)	30	5	24-26	5	2	1:10	300	
	Intervals	80	25-22	14-16	6	4	1:1	1920	3020

King et al (2018)

Run A (Level 2)		*Dist.(m)*	*Speed*	*set*	*rep*	*Rest (rep)*	*Dist.*	*Total Dist.*
Linear exercise drills								
session 1	Intervals	400	50%	1	6	60sec	2400	2400
session 2		400	50%	1	8	60sec	3200	3200
session 3		400	50%	1	10	60sec	4000	4000
session 4		400	70%	1	10	60sec	4000	4000
session 5		400	85%	1	10	60sec	4000	4000
session 6		400	100%	1	10	60sec	4000	4000
RUN B (Level 3)								
Warm-up		400	70%	1	4	60sec	1600	
Linear + multi-directional exercise drills								
session 1	Sprints (rolling start)	100	70%	1	10	60sec	1000	2600
session 2	Sprints (rolling start)	100	85%	1	10	30sec	1000	2600
session 3	Sprints (rolling start)	100	100%	1	10	30sec	1000	2600
session 4	Sprints (rolling start)	100	100%	1	5	30sec	500	
	Sprints (standing start)	50	70%	1	5	30sec	250	2350
session 5	Sprints (rolling start)	100	100%	1	5	30sec	500	
	Sprints (standing start)	50	85%	1	5	30sec	250	2350
session 6	Sprints (rolling start)	100	100%	1	5	30sec	500	
	Sprints (standing start)	50	100%	1	5	30sec	250	2350
session 7	Sprints (rolling start)	100	100%	1	5	30sec	500	
	Sprints (standing start)	50	100%	1	10	30sec	500	2600

Appendix E: Patient reported outcome measures

The following appendix outlines the patient reported outcome measures used in this thesis. The questionnaires were independently completed by all athletes prior to the initial testing session and the AGP athletes completed both questionnaires after completing the rehabilitation program and at 3- and 6-month time points post-RTP.

Appendix E1: Hip and Groin Outcome Score (HAGOS)

HAGOS is a valid and reliable questionnaire evaluating hip and/or groin disability and consists of six subscales (Symptom, Pain, Activities of Daily Living [ADL], Sports and Recreation [Sport Rec], Participation in Physical Activities [PA], and Quality of Life [QOL]). Each subscale ranges from 0 to 100 with 100 indicating no problems (Thorborg *et al.*, 2011).

Instructions: This questionnaire asks for your view about your hip and/or groin problem. The questions should be answered considering your hip and/or groin function during the past week. This information will help us keep track of how you feel, and how well you are able to do your usual activities.

Answer every question by ticking the appropriate box. Tick only one box for each question. If a question does not pertain to you or you have not experienced, it in the past week please make your “best guess” as to which response would be the most accurate.

Symptoms

These questions should be answered considering your hip and/or groin symptoms and difficulties during the past week. (Nb: all answers are under each question in the questionnaire but for the purpose of this appendix they are only under the first question for each subscale)

S1 Do you feel discomfort in your hip and/or groin?

Never Rarely Sometimes Often All the time

S2 Do you hear clicking or any other type of noise from your hip and/or groin?

S3 Do you have difficulties stretching your legs far out to the side?

S4 Do you have difficulties taking full strides when you walk?

S5 Do you experience sudden twinging/stabbing sensations in your hip / groin?

Stiffness

The following questions concern the amount of stiffness you have experienced during the past week in your hip and/or groin. Stiffness is a sensation of restriction or slowness in the ease with which you move your hip and/or groin.

S6 How severe is your hip / groin stiffness after first awakening in the morning?

Never Rarely Sometimes Often All the time

S7 How severe is your hip / groin stiffness after sitting, lying or resting later in the day?

Pain

P1 How often is your hip and/or groin painful?

Never Rarely Sometimes Often All the time

P2 How often do you have pain in areas other than your hip and/or groin that you think may be related to your hip and/or groin problem?

The following questions concern the amount of pain you have experienced during the past week in your hip and/or groin. What amount of hip and/or groin pain have you experienced during the following activities?

P3 Straightening your hip fully

None Mild Moderate Severe Extreme

P4 Bending your hip fully

P5 Walking up or down stairs

P6 At night while in bed (pain that disturbs your sleep

P7 Sitting or lying

The following questions concern the amount of pain you have experienced during the past week in your hip and/or groin. What amount of hip and/or groin pain have you experienced during the following activities?

P8 Standing upright

None Mild Moderate Severe Extreme

P9 Walking on a hard surface (asphalt, concrete, etc.)

P10 Walking on an uneven surface

Physical function, daily living

The following questions concern your physical function. For each of the following activities please indicate the degree of difficulty you have experienced in the past week due to your hip and/or groin problem.

A1 Walking up stairs

None Mild Moderate Severe Extreme

A2 Bending down, e.g. to pick something up from the floor

A3 Getting in/out of car

A4 Lying in bed (turning over or maintaining the same hip position for a long time)

A5 Heavy domestic duties (scrubbing floors, vacuuming, moving heavy boxes etc)

Function, sports and recreational activities

The following questions concern your physical function when participating in higher-level activities. Answer every question by ticking the appropriate box. If a question does not pertain to you or you have not experienced it in the past week please make your "best guess" as to which response would be the most accurate. The questions should be answered considering what degree of difficulty you have experienced during the following activities in the past week due to problems with your hip and/or groin.

SP1 Squatting

None Mild Moderate Severe Extreme

SP2 Running

SP3 Twisting/pivoting on a weight bearing leg

SP4 Walking on an uneven surface

SP5 Running as fast as you can

SP6 Bringing the leg forcefully forward and/or out to the side, such as in kicking, skating etc.

SP7 Sudden explosive movements that involve quick footwork, such as accelerations, decelerations, change of directions etc.

SP8 Situations where the leg is stretched into an outer position (such as when the leg is placed as far away from the body as possible).

Participation in physical activities

The following questions are about your ability to participate in your preferred physical activities. Physical activities include sporting activities as well as all other forms of activity where you become slightly out of breath. When you answer these questions consider to what degree your ability to participate in physical activities during the past week has been affected by your hip and/or groin problem.

PA1 Are you able to participate in your preferred physical activities for as long as you would like?

Always Often Sometimes Rarely Never

PA2 Are you able to participate in your preferred physical activities at your normal performance level?

Quality of Life

Q1 How often are you aware of your hip and/or groin problem?

Never Monthly Weekly Daily Constantly

Q2 Have you modified your life-style to avoid activities potentially damaging to your hip and/or groin?

Not at all Mildly Moderately Severely Totally

Q3 In general, how much difficulty do you have with your hip and/or groin?

None Mild Moderate Severe Extreme

Q4 Does your hip and/or groin problem affect your mood in a negative way?

Not at all Rarely Sometimes Often All the time

Q5 Do you feel restricted due to your hip and/or groin problem?

Not at all Rarely Sometimes Often All the time

Thank you very much for completing all the questions in this questionnaire.

Appendix E2: Marx Activity Scale (Marx)

The Marx activity scale is a valid and reliable questionnaire containing four questions concerning the weekly frequency of common athletic tasks (i.e. running, cutting, decelerating and pivoting) and is completed using a 0-4 Likert scale (0 = less than 1 per month, 1 = 1 x per month, 2 = 1 x per week, 3 = 2-3 x per week, 4 = 4 or greater per week, maximum 16, minimum 0). The Marx scale increases the generalizability of results across different athletic populations and is important to assess post-rehabilitation and during RTP to assess if an athlete has returned to their pre-injury level of sporting activity (Irrgang, 2008).

Please indicate how often you performed each activity in your healthiest and most active state, **in the past year.**

	Less than one time in a month	**One time in a month**	**One time in a week**	**2 or 3 times in a week**	**4 or more times in a week**
Running: running while playing a sport or jogging					
Cutting: changing directions while running					
Decelerating: coming to a quick stop while running					
Pivoting: turning your body with your foot planted while playing a sport; For example: skiing, skating, kicking, throwing, hitting a ball (golf, tennis, squash), etc.					

Appendix F: Screening test utilized in thesis

Appendix F1: Drop jump

The drop jump is commonly utilized to examine lower limb reactive strength (Flanagan and Comyns, 2008). Reactive strength refers to the ability of an individual to quickly move from an eccentric to a concentric muscle contraction (Young, 1995). The reactive strength index (RSI) has widely been used to measure reactive strength during drop jump performance (Lephart *et al.*, 2005; Flanagan, Galvin and Harrison, 2008; Lockie *et al.*, 2011). The RSI assesses an individual's ability to produce force rapidly under high eccentric load. Reactive strength ability may be important for injury prevent and in the recovery from injury (Gore *et al.*, 2018; King, Richter, *et al.*, 2018) and has not been previously examined in relation to AGP. To perform the drop jump participants stepped off a 30cm box for the double-leg drop jump (DLDJ) and a 20cm box for the single leg drop jump (SLDJ). They were instructed to keep their hands-on hips, spend minimal time on the ground and jump vertically as high as possible. Three practice and three maximum effort trials were performed. Jumps were separated by a 30-second rest period and two-minute rest between double and single leg conditions.

Appendix F2: Countermovement jump

A common test performed on force platforms is the countermovement jump (CMJ). The CMJ has been established as a valid and reliable means to assess lower-limb neuromuscular capacity (Markovic *et al.*, 2004; Impellizzeri *et al.*, 2007; Cormack *et al.*, 2008). This has previous been used in the assessment of injured population (Jordan, Aagaard and Herzog, 2015; Baumgart *et al.*, 2017; Moreno-Pérez *et al.*,

2017) and also as part of athletic testing batteries (Suchomel *et al.*, 2015; Claudino *et al.*, 2017). In a CMJ the jumper starts from an upright standing position, makes a preliminary downward movement by flexing at the knees and hips (countermovement), then immediately and vigorously extends the knees and hips to jump vertically up off the ground (Figure F1).

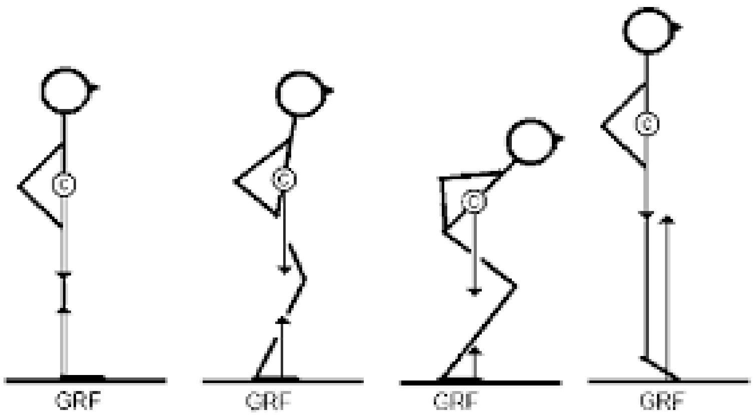


Figure F1: Countermovement jump action. Ground Reaction Force (GRF) indicated with bottom arrow during the eccentric and concentric phase of take-off (Linthorne, 2001)

The characteristics of the CMJ (explosive closed-chain vertical movement and fast muscle actions involving the stretch-shorten cycle) are similar to many sporting tasks (Linthorne, 2001; Impellizzeri *et al.*, 2007). This makes the CMJ a useful test to monitor athletics performance (Claudino *et al.*, 2017), injury status (Jordan, Aagaard and Herzog, 2015) and as part of athletic return-to-play testing (Manske and Reiman, 2013; Herbst *et al.*, 2015). Furthermore, the CMJ allows comprehensive insight into an athlete's neuromuscular function through detailed analysis of the force-time curve throughout specific phases or the entire CMJ (Cormie, McBride and McCaulley, 2009; Bates *et al.*, 2013; Mcerlain-naylor *et al.*, 2014; Sole *et al.*, 2017). Figure F2 displays the different phases of the countermovement jump. The CMJ can be performed double-leg (DL) or single-leg (SL). In relation to injury, DL jumps may provide insight into any potential side-to-side compensatory mechanisms employed to off-load a particular limb, whereas a SL jump allows greater insight into a limb's capacity without potential compensation from the uninjured limb (Holsgaard-Larsen *et al.*, 2014). The CMJ is an appealing test because it is quick to perform, non-fatiguing, and a relatively easy movement pattern to execute with little familiarization. Also, from a rehabilitation perspective it provides a safe action with very little risk of re-injury. It can be assessed easily in clinical setting with little space required and with relatively inexpensive equipment (Benjanuvatra *et al.*, 2013; McMahon *et al.*, 2018). The CMJ has not previously been examined in relation to AGP and may provide a useful screening tool.

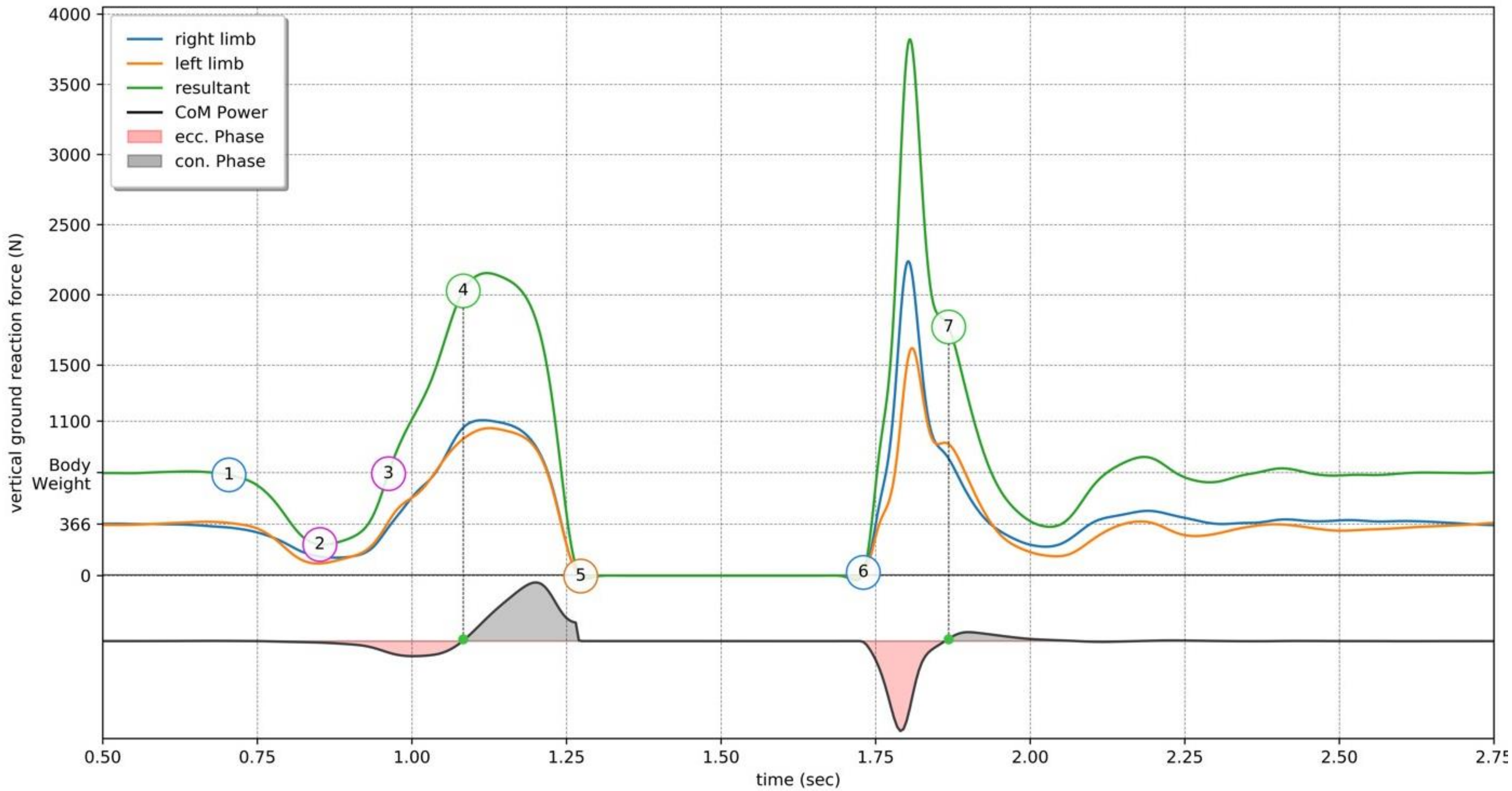


Figure 2F: Force-time curve of a DL-CMJ: 1 – beginning of jump, 2 – start of braking eccentric phase, 3 – start of eccentric deceleration phase, 4 – start of concentric phase, 5 – take-off, 6 – initial land impact, 7 – end of landing phase

Appendix F3: Continuous lateral hurdle hop

The lateral hurdle hop has been commonly employed to examine individuals with AGP in comparison to uninjured individuals and also following rehabilitation programs (Gore *et al.*, 2018, 2020). The lateral hop test aims to stress frontal plane control patterns and rate of force development similar to common sporting actions (e.g. running cut) (Marshall *et al.*, 2015, 2016) which are thought to propagate AGP. A continuous lateral hurdle hop has not previous been examined but given that AGP is common to field-based sports which required rapid and continuous change-of-direction it may be an appropriate screening tool for this injury.

The participant starts standing on one leg with opposite leg flexed with the hip at 90° and arms unrestricted for balance. From a stationary start, the participant then hops laterally over a 15cm hurdle and immediately back and continues this action until ten lateral hops are completed (Figure F3). Instructions are given to perform the hops as quickly as possible.

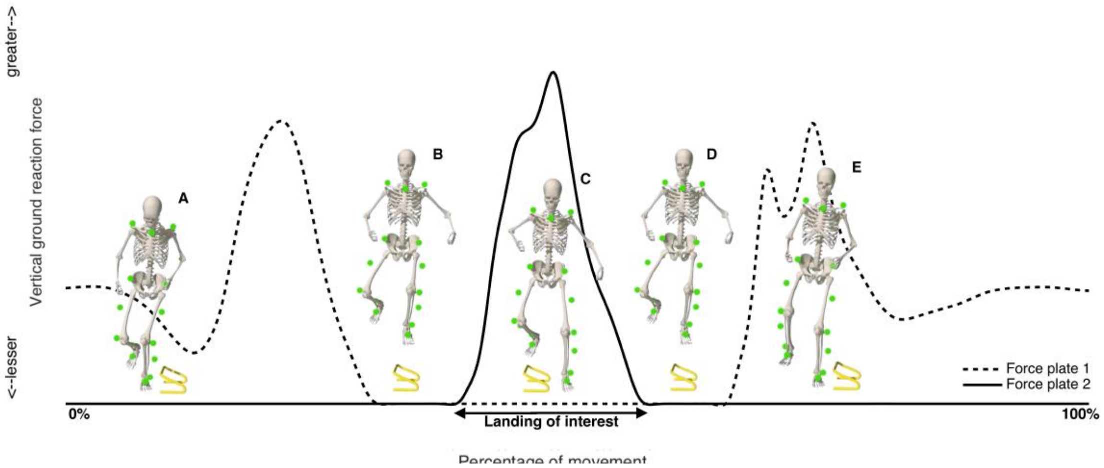
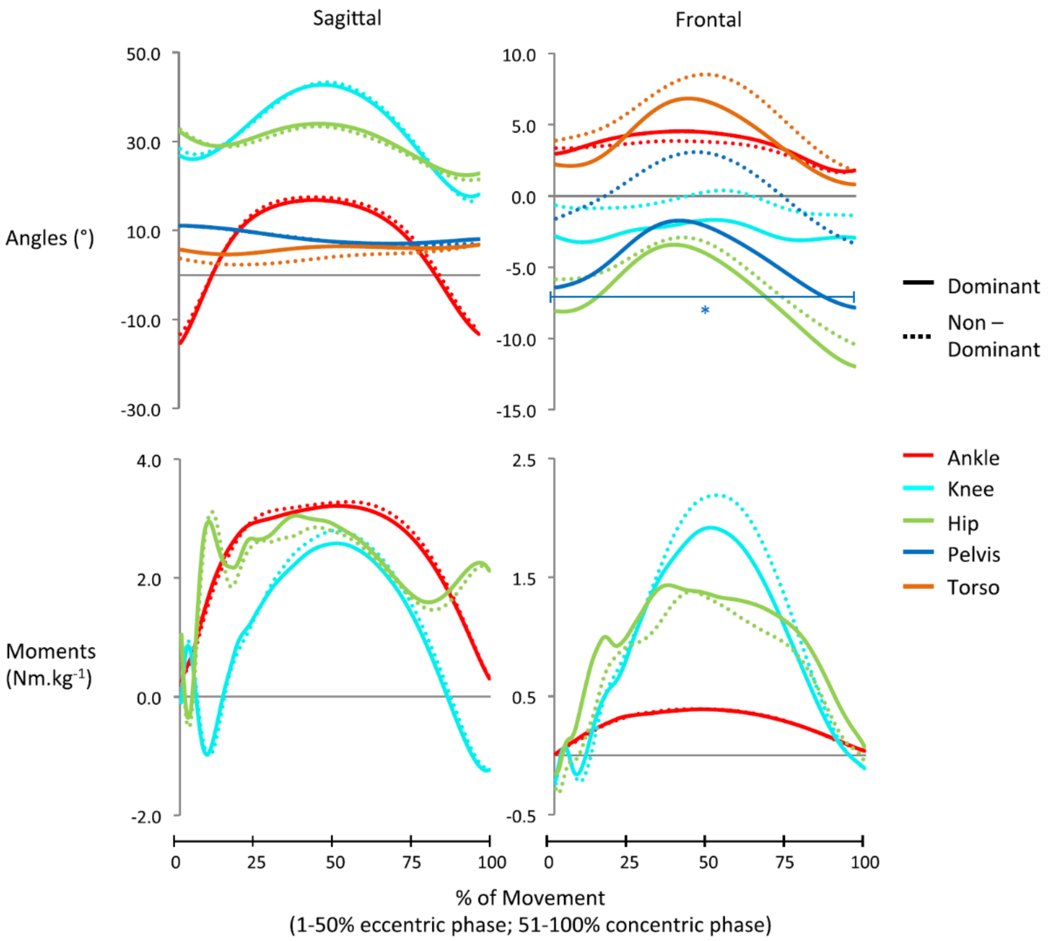


Figure F3. The continuous hurdle hop test: (A) Starting position on force plate, (B) Initial hop over hurdle, (C) Lateral stance phase which is biomechanically examined on force plate, (D) Return hop back over the hurdle, (E) Medial stance phase before hopping back over hurdle (Gore *et al.*, 2020)**.**

During each stance phase of the hopping action the hip moves through a small range of motion in an extension, flexion, extension pattern to resist eccentric loading and help generate greater forces during the subsequent push off. The knee and ankle follow similar movement patterns with a small amount of flexion on landing during the first half of the stance phases and followed by extension movements (Figure F4).



* Significant difference between pelvis angles on the dominant and non-dominant sides, between 1-100% of the movement.

Figure F4. Wave-forms for kinetic and kinematic variables in the single hurdle hop. Sagittal angles: ankle dorsiflexion (+)/plantarflexion (−); knee flexion (+)/extension (−); hip flexion (+)/extension (−); pelvis anterior tilt (+)/posterior tilt(−); thorax flexion (+)/thorax extension (−). Frontal angles: ankle eversion (+)/inversion (−); knee varus (+)/valgus (−); hip adduction (+)/abduction (−); pelvis contralateral drop (+)/contralateral lift (−); thorax lateral flexion (+)/ medial flexion (−) Sagittal moments: ankle plantarflexion (+)/dorsiflexion (−); knee extension (+)/flexion (−); hip extension (+)/flexion (−). Frontal moments: ankle eversion (+)/inversion (−); knee valgus (+)/varus (−); hip abduction (+)/ adduction (−) (Marshall *et al.*, 2015)

Appendix G: Supplementary information for ‘Athletic Groin Pain and Lower Limb Loading Patterns During a Countermovement Jump: A case-control study’.

Appendix G1: All vGRF phase and variable and definitions

Eccentric phase duration	Minimum vGRF to zero CoM velocity
Eccentric braking duration phase	Minimum vGRF to force minimum CoM velocity
Eccentric deceleration phase duration	Minimum CoM velocity to zero CoM velocity
Concentric phase duration	Zero CoM velocity to take-off (resultant vGRF < 10N)
Land Phase Duration	Initial contact (resultant vGRF > 10N) to zero CoM velocity (end of eccentric phase)
Mean ECC force (N/kg)	Average vGRF over the duration from minimum vGRF to zero CoM velocity
Max ECC force (N/kg)	Peak vGRF magnitude over the duration of minimum vGRF to zero CoM velocity
Force at start of jump (N/kg)	Force standing prior to starting jump
Force at discrete point during ECC phase:	Start of ECC phase (minimum vGRF) Force at Minimum CoM velocity (start of eccentric deceleration phase) Eccentric minimum power Zero CoM velocity (end of the eccentric phase)
RoFD eccentric deceleration (N.s/kg)	Slope of force magnitude between minimum CoM velocity and zero CoM velocity
RoFD eccentric braking (N.s/kg)	Slope of force magnitude between minimum vGRF and force minimum CoM velocity
Eccentric Impulse (N.s/kg)	Area under the curve from minimum vGRF to zero CoM velocity
Eccentric Deceleration Impulse (N.s/kg)	Area under the curve from minimum CoM velocity to zero CoM velocity
Mean Eccentric Power (W/kg)	Average power over the duration from minimum vGRF to zero CoM velocity
Minimum Eccentric Power (W/kg)	Smallest power magnitude from minimum vGRF to zero CoM velocity
RoPD Eccentric (W.s/kg)	Slope of power magnitude between minimum vGRF to zero CoM velocity
Average RoPD Eccentric (W.s/kg)	Average slope of power magnitude between minimum vGRF to zero CoM velocity

Work Done Eccentric Phase (J/kg)	Work done from minimum vGRF to zero CoM velocity
Mean CON force (N/kg)	Average vGRF over duration from zero CoM velocity to take-off (resultant vGRF < 10N)
Max CON force (N/kg)	Peak vGRF magnitude over duration from zero CoM velocity to take-off (resultant vGRF < 10N)
Force at discrete point during CON phase:	Force at peak power
RoFD Concentric Acceleration (N.s/kg)	Slope of force magnitude between zero CoM velocity (start of concentric phase) to maximum power
Concentric Impulse (N.s/kg)	Area under the curve from zero CoM velocity to take-off (resultant vGRF < 10N)
Concentric acceleration impulse	Area under curve from zero CoM velocity (start of concentric phase) to maximum power
Mean Concentric Power (W/kg)	Average power over the duration from zero CoM velocity to take-off (resultant vGRF < 10N)
Maximum Concentric Power(W/kg)	Largest power magnitude from zero CoM velocity to take-off (resultant vGRF < 10N)
Average RoPD Concentric (W.s/kg)	Average slope of power magnitude between zero CoM velocity to take-off (resultant vGRF < 10N)
Work Done Concentric (J/kg)	Work done from zero CoM velocity to take-off (resultant vGRF > 10N)
Maximum Landing Force (N/kg)	Peak vGRF magnitude from initial contact (resultant vGRF > 10N) to zero CoM velocity (end of eccentric phase)
Land Impulse (N.s/kg)	Area under curve from initial contact (resultant vGRF > 10N) to zero CoM velocity (end of eccentric phase)
Land Impulse First 40ms (N.s/kg)	Area under curve from initial contact (resultant vGRF > 10N) to 40ms after initial contact
Work Done Landing (J/kg)	Work done from initial contact (resultant vGRF > 10N) to zero CoM velocity (end of eccentric phase)
Duration Falling (s)	Time period from initial downward movement (resultant vGRF < 10N) to minimum vGRF
Duration Eccentric Phase (s)	Time period from minimum vGRF to zero CoM velocity
Duration Concentric Phase (s)	Time period from zero CoM velocity to take-off (resultant vGRF < 10N)
Duration Jump (s)	Time period from minimum vGRF to zero CoM velocity to take-off (resultant vGRF < 10N)
Time Impact to Peak Land Force (s)	Time period from initial contact (resultant vGRF > 10N) to the largest force magnitude
Time Impact to Negative Peak Power (s)	Time period from initial contact (resultant vGRF > 10N) to the largest negative power magnitude
Jump Height (m)	Vertical velocity of the center of mass (CoM) at take-off as derived from the concentric impulse-momentum
Contraction Time to Jump Height (m/s)	Ratio of time period from minimum vGRF to zero CoM velocity to take-off (resultant vertical GRF < 10N) and jump height

vGRF – vertical ground reaction force, CoM – center of mass velocity, ECC - eccentric, CON – concentric, RoFD - rate of force development, RoPD - rate of power development.

Appendix G2: All vGRF variables for DL-CMJ

	AGP PRE				AGP POST				CON			
	Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb	
Variables	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Force At Start Of Jump	4.9	0.3	4.7	0.3	4.9	0.3	4.7	0.3	4.8	0.3	4.8	0.3
Eccentric Jump Phase												
Mean ECC Force (N/kg)	5.7	0.5	5.5	0.6	5.9	0.5	5.9	0.6	5.7	0.6	5.7	0.6
Max ECC Force (N/kg)	10.6	1.5	10.5	1.9	11.5	1.5	11.3	1.6	10.7	1.6	10.7	1.6
Force At Zero Velocity (N/kg)	10.6	1.5	10.5	1.9	11.5	1.5	11.3	1.5	10.7	1.6	10.7	1.6
Force At ECC Min Power (N/kg)	7.3	1.2	7.0	1.3	7.7	1.2	7.8	1.3	7.3	1.4	7.4	1.4
Force At ECC Min CoM velocity (N/kg)	5.1	0.6	4.8	0.6	5.0	0.5	4.9	0.5	4.9	0.6	4.9	0.6
Force At Start of ECC Phase (N/kg)	2.2	1.0	2.3	1.0	1.7	0.9	1.7	0.9	1.7	0.8	1.7	0.8
RoFD Eccentric Deceleration (N.s/kg)	22.7	11.9	21.6	12.8	32.5	15.9	33.8	19.3	25.3	11.1	27.3	11.1
RoFD Eccentric Breaking (N.s/kg)	31.7	15.9	32.9	17.2	41.5	17.2	40.7	16.5	31.1	12.1	31.4	12.4
Eccentric Impulse (N.s/kg)	-144.2	38.3	-137.2	34.2	-131.1	38.4	-131.8	33.7	-144.3	27.9	-144.3	27.9
Eccentric Deceleration Impulse (N.s/kg)	-109.7	32.4	-104.4	28.3	-99.5	29.3	-100.7	27.8	-107.2	20.4	-107.2	20.4
Mean Eccentric Power (W/kg)	-4.0	1.0	-3.8	1.1	-4.4	1.0	-4.4	1.0	-4.4	1.0	-4.4	1.0
Minimum Eccentric Power (W/kg)	-6.6	2.4	-6.3	2.3	-7.7	2.4	-7.8	2.7	-7.4	2.3	-7.5	2.4
RoPD Eccentric (W.s/kg)	-25.7	13.7	-24.4	13.3	-36.5	18.9	-35.2	16.9	-31.1	14.2	-32.6	14.2
Average RoPD Eccentric (W.s/kg)	-24.7	14.5	-23.7	14.1	-35.8	18.9	-34.4	17.7	-29.2	14.1	-31.0	14.1

Work Done Eccentric Phase (J/kg)	-1489.9	381.2	-1421.6	348.0	-1392.8	368.9	-1375.5	341.0	-1518.5	277.0	-1518.5	277.0
Concentric Jump Phase												
Mean Concentric Force	9.6	0.8	9.5	0.9	10.0	1.0	10.0	0.9	9.5	0.8	9.5	0.8
Maximum Concentric Force	11.6	1.2	11.5	1.1	12.3	1.5	12.2	1.5	11.6	1.3	11.6	1.1
Force At Peak Power	10.2	0.7	10.2	0.6	10.5	1.0	10.5	0.9	10.2	0.7	10.2	0.7
RoFD Concentric Acceleration (N.s/kg)	-2.4	7.1	-2.0	8.6	-5.6	8.0	-4.6	7.5	-2.9	8.1	-2.8	8.1
Concentric Impulse (N.s/kg)	206.3	37.5	203.7	34.6	198.8	36.0	197.3	38.1	210.8	25.0	210.8	25.0
Concentric Acceleration Impulse (N.s/kg)	128.7	32.1	128.6	32.3	120.6	33.5	118.3	31.6	127.3	19.6	127.3	19.6
Mean Concentric Power (W/kg)	13.2	2.0	13.2	1.9	14.1	2.1	14.0	2.0	13.2	1.8	13.2	1.8
Maximum Concentric Power(W/kg)	24.4	3.1	24.5	2.8	25.2	3.5	25.2	3.2	24.5	3.0	24.5	3.0
Average RoPD Concentric (W.s/kg)	116.4	25.9	116.3	25.2	138.0	40.9	137.6	39.9	120.2	27.6	121.3	27.3
Work Done Concentric (J/kg)	3618.8	615.8	3606.1	580.9	3582.9	570.8	3572.7	584.7	3622.2	359.5	3622.2	359.5
Landing Phase												
Maximum Landing Force (N/kg)	27.6	8.1	27.0	7.5	29.7	7.7	29.5	6.6	23.5	5.2	23.5	5.2
Land Impulse (N.s/kg)	-110.2	32.6	-112.5	37.1	-96.0	23.3	-103.9	26.4	-128.9	37.6	-128.9	38.0
Land Impulse First 40ms (N.s/kg)	-49.1	11.0	-51.4	11.4	-46.7	8.9	-52.7	10.1	-52.5	11.4	-52.5	11.4
Work Done Landing (J/kg)	-2649.8	645.8	-2633.6	624.2	-2526.6	505.3	-2631.4	569.5	-2742.9	518.2	-2742.9	518.2
Temporal												
Duration Falling (s)	0.18	0.03	0.18	0.03	0.19	0.05	0.19	0.05	0.18	0.04	0.18	0.04
Duration Eccentric Phase (s)	0.39	0.10	0.39	0.10	0.32	0.08	0.32	0.08	0.36	0.06	0.36	0.06
Duration Concentric Phase (s)	0.28	0.04	0.28	0.04	0.26	0.04	0.26	0.04	0.28	0.03	0.28	0.03
Duration Jump (s)	0.85	0.15	0.85	0.15	0.77	0.13	0.77	0.13	0.81	0.10	0.81	0.10
Time Impact to Peak Land Force (s)	0.07	0.02	0.07	0.02	0.06	0.02	0.06	0.02	0.07	0.02	0.07	0.02

Time Impact to Negative Peak Power (s)	0.06	0.01	0.06	0.01	0.06	0.02	0.06	0.02	0.06	0.01	0.06	0.01
Performance												
Jump Height (m)	0.32	0.06	0.32	0.06	0.33	0.06	0.33	0.06	0.32	0.05	0.32	0.05
Contraction Time to Jump Height (m/s)	2.71	0.67	2.71	0.67	2.70	0.55	2.64	0.55	2.70	0.55	2.64	0.55

DL-CMJ – double-leg countermovement jump, vGRF – vertical ground reaction force, AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, SD - standard deviation, ECC - eccentric, RoFD - rate of force development, RoPD - rate of power development, CoM – centre of mass

Appendix G3: DL-CMJ vGRF variables: group comparisons (mean difference, p-values and effect sizes)

Variables	AGP PRE v CON						AGP PRE v AGP POST						AGP POST v CON					
	Sx Limb			Non-Sx Limb			Sx Limb			Non-Sx Limb			Sx Limb			Non-Sx Limb		
Eccentric Jump Phase	*Mean Diff*	*p*	*ES*	*Mean Diff*	*p*	*ES*	*Mean Diff*	*p*	*ES*	*Mean Diff*	*p*	*ES*	*Mean Diff*	*p*	*ES*	*Mean Diff*	*p*	*ES*
Mean ECC Force (N/kg)	-0.04	0.650	0.07	-0.22	0.235	0.35	-0.20	0.028	-0.41	-0.35	0.004	-0.54	0.15	0.352	-0.28	0.12	0.483	-0.20
Max ECC Force (N/kg)	-0.11	0.739	0.08	-0.24	0.616	0.14	-0.88	0.007	-0.58	-0.82	0.023	-0.46	0.76	0.081	-0.50	0.60	0.174	-0.39
Force At Zero Velocity (N/kg)	-0.10	0.745	0.07	-0.25	0.615	0.14	-0.88	0.007	-0.58	-0.80	0.027	-0.45	0.77	0.076	-0.51	0.58	0.183	-0.38
Force At ECC Min Power (N/kg)	-0.07	0.769	0.05	-0.39	0.331	0.28	-0.41	0.105	-0.34	-0.82	0.003	-0.59	0.33	0.377	-0.25	0.43	0.282	-0.30
Force At ECC Min CoM velocity (N/kg)	0.17	0.361	-0.28	-0.13	0.467	0.22	0.09	0.275	0.16	-0.11	0.188	-0.19	0.07	0.565	-0.14	-0.02	0.617	0.04
RoFD Eccentric Deceleration (N.s/kg)	-2.56	0.427	0.22	-3.69	0.271	0.31	-9.76	0.004	-0.66	-12.24	0.002	-0.71	5.18	0.225	-0.33	6.13	0.196	-0.38
RoFD Eccentric Breaking (N.s/kg)	0.61	0.859	-0.04	1.60	0.693	-0.11	-9.77	0.013	-0.57	-7.84	0.043	-0.46	8.33	0.070	-0.50	9.07	0.032	-0.63
Eccentric Impulse (N.s/kg)	0.16	0.835	0.00	7.10	0.422	-0.23	-11.41	0.133	-0.30	-6.99	0.350	-0.21	13.21	0.170	-0.39	13.02	0.143	-0.41
Eccentric Deceleration Impulse (N.s/kg)	-2.44	0.720	0.09	2.84	0.670	-0.12	-8.33	0.196	-0.27	-4.95	0.416	-0.18	7.72	0.291	-0.31	6.56	0.357	-0.27
Mean Eccentric Power (W/kg)	0.41	0.153	-0.40	0.55	0.054	-0.54	0.45	0.009	0.43	0.56	0.002	0.54	-0.03	0.831	0.03	-0.01	0.842	0.01

Minimum Eccentric Power (W/kg)	0.77	0.249	-0.33	1.14	0.079	-0.49	1.09	0.009	0.45	1.50	0.001	0.58	-0.25	0.698	0.11	-0.36	0.611	0.14
RoPD Eccentric (W.s/kg)	5.38	0.182	-0.39	6.78	0.086	-0.49	10.80	0.002	0.63	10.84	0.003	0.68	-4.15	0.403	0.24	-2.57	0.577	0.16
Average RoPD Eccentric (W.s/kg)	4.42	0.266	-0.31	5.50	0.162	-0.39	11.05	0.001	0.63	11.64	0.002	0.70	-4.39	0.398	0.24	-3.43	0.492	0.19
Work Done Eccentric Phase (J/kg)	28.59	0.747	-0.09	96.93	0.273	-0.31	-97.13	0.168	-0.26	-46.09	0.492	-0.13	125.72	0.171	-0.39	143.78	0.102	-0.46
Concentric Jump Phase																		
Mean Concentric Force	0.11	0.618	-0.14	0.08	0.731	-0.09	-0.43	0.016	-0.49	-0.40	0.043	-0.44	0.54	0.030	-0.61	0.48	0.049	-0.56
Maximum Concentric Force	0.09	0.771	-0.07	0.04	0.723	-0.04	-0.62	0.046	-0.45	-0.53	0.105	-0.37	0.71	0.069	-0.51	0.63	0.101	-0.46
Force At Peak Power	0.01	0.857	-0.01	0.00	0.764	0.07	-0.29	0.145	-0.32	-0.24	0.224	-0.29	0.30	0.234	-0.33	0.28	0.218	-0.34
Force At Start Of Jump	0.10	0.341	-0.29	-0.08	0.425	0.24	-0.04	0.468	-0.12	0.04	0.491	0.12	0.14	0.204	-0.42	-0.12	0.276	0.36
RoFD Concentric Acceleration (N.s/kg)	0.55	0.766	-0.07	0.94	0.683	-0.11	3.05	0.055	0.39	2.57	0.125	0.32	-2.53	0.276	0.34	-1.75	0.426	0.23
Concentric Impulse (N.s/kg)	-4.53	0.614	0.14	-7.12	0.404	0.24	7.50	0.304	0.20	6.41	0.381	0.18	-12.03	0.172	0.39	-13.53	0.139	0.42
Concentric Acceleration Impulse (N.s/kg)	1.41	0.845	-0.05	1.38	0.849	-0.05	8.05	0.237	0.25	8.06	0.235	0.24	-6.64	0.378	0.24	-8.90	0.235	0.34
Mean Concentric Power (W/kg)	0.01	0.907	0.00	-0.02	0.905	0.01	-0.88	0.004	-0.43	-0.84	0.008	-0.43	0.88	0.100	-0.46	0.82	0.116	-0.44
Maximum Concentric Power(W/kg)	-0.12	0.875	0.04	-0.06	0.897	0.02	-0.77	0.044	-0.23	-0.68	0.075	-0.23	0.65	0.469	-0.20	0.61	0.469	-0.20
Average RoPD Concentric (W.s/kg)	-3.80	0.614	0.14	-3.73	0.616	0.14	-17.67	0.047	-0.47	-21.65	0.007	-0.61	16.77	0.087	-0.47	16.34	0.090	-0.47

Work Done Concentric (J/kg)	-3.39	0.906	0.01	-16.14	0.878	0.03	35.93	0.673	0.06	33.33	0.698	0.06	-39.32	0.764	0.08	-50.42	0.706	0.10
Landing Phase																		
Maximum Landing Force (N/kg)	4.06	0.037	-0.59	3.49	0.057	-0.54	-3.21	0.032	-0.36	-3.27	0.001	-0.42	6.12	0.002	-0.93	5.66	0.001	-1.00
Land Impulse (N.s/kg)	18.76	0.064	-0.53	16.66	0.118	-0.44	-12.95	0.004	-0.56	-8.61	0.047	-0.27	31.16	0.001	-1.04	25.04	0.008	-0.77
Land Impulse First 40ms (N.s/kg)	3.40	0.342	-0.30	1.09	0.626	-0.10	-2.43	0.158	-0.24	1.29	0.455	0.12	5.83	0.079	-0.57	-0.20	0.626	0.02
Work Done Landing (J/kg)	93.12	0.575	-0.16	109.30	0.502	-0.19	-117.53	0.123	-0.20	-2.23	0.976	0.00	211.92	0.152	-0.42	112.06	0.470	-0.20
Temporal																		
Duration Falling (s)	0.00	0.743	0.09	0.00	0.743	0.09	-0.006	0.516	-0.13	-0.006	0.516	-0.13	0.009	0.435	-0.21	0.009	0.435	-0.21
Duration Eccentric Phase (s)	0.03	0.130	-0.42	0.03	0.130	-0.42	0.068	0.002	0.73	0.068	0.002	0.73	-0.034	0.078	0.48	-0.034	0.078	0.48
Duration Concentric Phase (s)	0.00	0.957	0.01	0.00	0.957	0.01	0.019	0.046	0.44	0.019	0.046	0.44	-0.020	0.062	0.51	-0.020	0.062	0.51
Duration Jump (s)	0.03	0.309	-0.28	0.03	0.309	-0.28	0.081	0.007	0.56	0.081	0.007	0.56	-0.047	0.145	0.40	-0.047	0.145	0.40
Time Impact to Peak Land Force (s)	0.00	0.316	0.27	0.00	0.316	0.27	0.005	0.035	0.29	0.005	0.035	0.29	-0.010	0.044	0.56	-0.010	0.044	0.56
Time Impact to Negative Peak Power (s)	0.00	0.186	0.36	0.00	0.186	0.36	0.002	0.499	0.11	0.002	0.499	0.11	-0.006	0.109	0.44	-0.006	0.109	0.44
Performance																		
Jump Height (m)	0.01	0.715	-0.10	0.01	0.715	-0.10	-0.008	0.184	-0.13	-0.008	0.184	-0.13	0.013	0.374	-0.24	0.013	0.374	-0.24
Contraction Time to Jump Height (m/s)	0.07	0.688	-0.11	0.07	0.688	-0.11	0.317	0.005	0.50	0.317	0.005	0.50	-0.250	0.109	0.44	-0.250	0.109	0.44

AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, Sx – symptomatic limb, Non-Sx limb – non-symptomatic limb, DL-CMJ – double-leg countermovement jump, ES – cohen's d, vGRF – vertical ground reaction force, ECC - eccentric, RoFD - rate of force development, RoPD - rate of power development, CoM – centre of mass, Mean Diff - mean difference

Appendix G4: All vGRF variables SL-CMJ variables

	AGP PRE				AGP POST				CON			
	Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb	
Variables	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Force At Start Of Jump (N/kg)	9.6	0.0	9.6	0.0	9.6	0.0	17.5	1.3	9.6	0.0	9.6	0.0
Eccentric Jump Phase												
Mean ECC Force (N/kg)	11.0	0.6	10.9	0.4	11.1	0.5	11.1	0.5	11.2	0.7	11.1	0.4
Max ECC Force (N/kg)	16.5	2.0	16.5	1.8	17.2	1.9	17.7	2.1	17.1	2.4	17.1	2.4
Force At Zero Velocity (N/kg)	16.5	2.0	16.4	1.9	17.2	2.0	17.7	2.1	17.1	2.3	17.1	2.3
Force At ECC Minimum Power (N/kg)	12.3	1.2	12.3	1.0	12.4	0.9	12.8	1.3	12.5	1.3	12.5	1.3
Force At ECC Minimum CoM velocity (N/kg)	9.8	0.0	9.8	0.0	9.8	0.0	9.8	0.0	9.8	0.0	9.8	0.0
Force At Start of ECC Phase (N/kg)	5.1	1.6	5.4	1.3	5.1	1.3	4.8	1.4	4.6	1.7	4.6	1.7
RoFD Eccentric Deceleration (N.s/kg)	45.3	29.6	39.5	14.7	46.5	20.6	48.1	23.6	51.4	30.9	43.3	18.4
RoFD Eccentric Breaking (N.s/kg)	36.1	20.0	35.4	15.9	41.6	19.9	46.2	21.5	40.0	21.6	40.0	21.6
Eccentric Impulse (N.s/kg)	-180.8	39.9	-169.4	41.3	-167.7	44.2	-171.3	42.3	-186.3	40.5	-186.3	40.5
Eccentric Deceleration Impulse (N.s/kg)	-115.0	22.0	-111.7	30.2	-110.5	29.0	-117.6	25.3	-122.2	26.4	-122.2	26.4
Mean Eccentric Power (W/kg)	-5.5	1.2	-5.2	1.3	-5.5	1.0	-5.7	1.2	-6.0	1.4	-6.0	1.4
Minimum Eccentric Power (W/kg)	-8.6	2.3	-8.1	2.5	-8.3	1.8	-8.9	2.5	-9.0	2.5	-9.0	2.5
RoPD Eccentric (W.s/kg)	-46.7	28.1	-40.7	18.9	-47.3	19.4	-48.2	24.1	-49.2	26.1	-44.9	18.2
Average RoPD Eccentric (W.s/kg)	-41.5	25.7	-35.2	15.8	-39.0	15.9	-41.8	21.3	-39.2	18.0	-39.2	18.0
Work Done Eccentric Phase (J/kg)	-1903.9	414.4	-1794.5	446.1	-1772.8	451.3	-1806.1	415.4	-1947.4	407.9	-1947.4	407.9
Concentric Jump Phase												
Mean Concentric Force (N/kg)	15.4	1.0	15.5	0.8	15.9	1.3	15.9	1.1	15.6	1.1	15.6	1.1
Maximum Concentric Force (N/kg)	18.9	1.7	19.1	1.3	19.6	2.3	19.7	2.1	19.3	1.7	19.3	1.7
Force At Peak Power (N/kg)	17.1	1.1	17.3	0.9	17.6	1.5	4.8	1.4	17.2	1.2	17.2	1.2

RoFD Concentric Acceleration (N.s/kg)	1.8	8.2	3.4	7.5	1.3	6.1	-1.6	9.0	-0.2	12.3	-0.2	12.3
Concentric Impulse (N.s/kg)	334.7	44.7	338.0	48.5	318.9	49.6	330.4	52.2	334.9	37.0	334.9	37.0
Concentric Acceleration Impulse (N.s/kg)	183.1	39.4	183.3	43.6	168.2	46.2	176.1	49.8	179.0	30.2	179.0	30.2
Mean Concentric Power (W/kg)	15.4	2.2	15.8	1.9	16.4	2.5	16.5	2.1	15.9	2.1	15.9	2.1
Maximum Concentric Power(W/kg)	28.9	3.9	29.5	3.0	29.9	3.9	29.8	3.2	29.4	3.6	29.4	3.6
Average RoPD Concentric (W.s/kg)	137.6	38.1	140.8	31.7	157.0	54.0	156.8	46.9	141.5	32.9	141.5	32.9
Work Done Concentric (J/kg)	4719.9	697.8	4782.5	632.4	4626.6	643.7	4742.8	723.8	4760.5	461.8	4760.5	461.8
Landing Phase												
Maximum Landing Force (N/kg)	36.0	6.1	35.1	4.9	37.1	4.7	36.7	4.3	32.8	4.7	32.8	4.7
Land Impulse (N.s/kg)	-196.6	38.8	-188.4	31.5	-166.8	32.3	-169.3	28.6	-217.5	34.0	-217.5	34.0
Land Impulse First 40ms (N.s/kg)	-74.3	7.2	-71.8	7.9	-71.5	7.0	-71.8	6.1	-78.1	4.6	-78.1	4.6
Work Done Landing (J/kg)	-3254.8	618.2	-3287.1	408.4	-3165.4	544.3	-3152.0	496.2	-3317.5	514.3	-3254.0	434.9
Temporal												
Duration Falling (s)	0.18	0.04	0.17	0.03	0.17	0.03	0.16	0.03	0.17	0.03	0.17	0.03
Duration Eccentric Phase (s)	0.36	0.08	0.35	0.06	0.33	0.08	0.32	0.06	0.34	0.08	0.34	0.08
Duration Concentric Phase (s)	0.31	0.05	0.31	0.04	0.29	0.06	0.29	0.05	0.30	0.04	0.30	0.04
Duration Jump (s)	0.84	0.13	0.82	0.10	0.80	0.15	0.77	0.11	0.81	0.12	0.81	0.12
Time Impact to Peak Land Force (s)	0.08	0.02	0.08	0.02	0.07	0.02	0.07	0.02	0.08	0.02	0.08	0.02
Time Impact to Negative Peak Power (s)	0.07	0.01	0.08	0.01	0.07	0.02	0.07	0.02	0.07	0.01	0.07	0.01
Performance												
Jump Height (m)	0.15	0.03	0.15	0.03	0.16	0.03	0.16	0.03	0.15	0.03	0.15	0.03
Contraction Time to Jump Height (m/s)	5.92	1.63	5.55	1.24	5.36	1.41	5.14	1.23	5.71	1.47	5.71	1.47

SL-CMJ – single-leg countermovement jump, vGRF – vertical ground reaction force, AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, SD - standard deviation, ECC - eccentric, RoFD - rate of force development, RoPD - rate of power development, CoM – center of mass

Appendix G5: SL-CMJ vGRF variables: group comparisons (mean difference, p-values and effect sizes)

Variables	AGP PRE v CON						AGP PRE v AGP POST						AGP POST v CON					
	Sx Limb			Non-Sx Limb			Sx Limb			Non-Sx Limb			Sx Limb			Non-Sx Limb		
	mean diff	*p*	ES	Mean Diff	*p*	ES	*mean diff*	*p*	ES	Mean Diff	*p*	ES	*Mean diff*	*p*	ES	*Mean diff*	*p*	ES
Force At Start Of Jump (N/kg)	-0.01	0.299	1.15	0.00	0.560	1.16	0.00	0.170	0.17	0.00	0.170	0.20	0.00	0.945	1.35	0.00	0.988	1.32
Eccentric Jump Phase																		
Mean ECC Force (N/kg)	-0.18	0.371	0.28	-0.13	0.323	0.31	-0.09	0.479	0.18	-0.21	0.096	0.46	-0.08	0.638	0.14	-0.09	0.644	0.14
Max ECC Force (N/kg)	-0.57	0.395	0.26	-0.61	0.346	0.29	-0.68	0.130	0.35	-1.19	0.010	0.61	0.11	0.871	-0.05	0.58	0.399	-0.26
Force At Zero Velocity (N/kg)	-0.56	0.399	0.26	-0.64	0.324	0.30	-0.67	0.134	0.34	-1.24	0.010	0.62	0.11	0.864	-0.05	0.60	0.379	-0.27
Force At ECC Minimum Power (N/kg)	-0.19	0.618	0.15	-0.28	0.431	0.24	-0.04	0.859	0.04	-0.51	0.080	0.44	-0.15	0.652	0.14	0.23	0.564	-0.18
Force At ECC Minimum CoM velocity (N/kg)	0.01	0.254	-0.37	0.00	0.350	-0.30	0.00	0.746	-0.07	0.00	0.438	0.20	0.00	0.968	-0.01	0.00	0.515	-0.21
Force At Start of ECC Phase (N/kg)	0.50	0.336	-0.30	0.71	0.141	-0.46	0.09	0.749	-0.06	0.59	0.068	-0.43	0.40	0.389	-0.26	0.12	0.809	-0.07
RoFD Eccentric Deceleration (N.s/kg)	-6.05	0.515	0.20	-3.83	0.464	0.23	-1.14	0.847	0.04	-8.61	0.104	0.44	-4.91	0.541	0.19	-3.28	0.696	0.12

RoFD Eccentric Breaking (N.s/kg)	-3.93	0.539	0.19	-4.62	0.428	0.24	-5.45	0.304	0.27	-10.73	0.020	0.57	1.52	0.811	-0.07	6.12	0.358	-0.28
Eccentric Impulse (N.s/kg)	5.48	0.661	-0.14	16.87	0.189	-0.41	-13.16	0.183	0.31	1.92	0.822	-0.05	9.77	0.531	-0.19	14.95	0.250	-0.36
Eccentric Deceleration Impulse (N.s/kg)	7.19	0.342	-0.30	10.46	0.241	-0.37	-4.51	0.474	-0.18	5.89	0.287	-0.21	5.88	0.565	-0.18	4.57	0.571	-0.18
Mean Eccentric Power (W/kg)	0.45	0.266	-0.34	0.73	0.087	-0.53	-0.05	0.813	0.04	0.47	0.085	-0.37	0.31	0.356	-0.29	0.26	0.525	-0.20
Minimum Eccentric Power (W/kg)	0.41	0.583	-0.17	0.91	0.242	-0.37	-0.31	0.421	0.15	0.79	0.160	-0.32	0.37	0.536	-0.19	0.12	0.874	-0.05
RoPD Eccentric (W.s/kg)	2.54	0.764	-0.09	4.19	0.476	-0.23	0.64	0.902	-0.03	7.44	0.173	-0.34	-2.40	0.686	0.13	1.05	0.893	-0.04
Average RoPD Eccentric (W.s/kg)	-2.27	0.749	0.10	3.96	0.457	-0.23	-2.44	0.613	0.11	6.58	0.187	-0.35	0.17	0.974	-0.01	6.08	0.469	-0.22
Work Done Eccentric Phase (J/kg)	43.51	0.731	-0.11	152.91	0.248	-0.36	-131.08	0.159	0.30	11.64	0.876	-0.03	174.59	0.191	-0.41	141.26	0.267	-0.34
Concentric Jump Phase																		
Mean Concentric Force (N/kg)	-0.14	0.660	0.14	-0.01	0.970	0.01	-0.53	0.030	0.45	-0.38	0.030	0.39	0.39	0.314	-0.31	0.37	0.277	-0.34
Maximum Concentric Force (N/kg)	-0.43	0.405	0.26	-0.24	0.591	0.16	-0.74	0.112	0.37	-0.60	0.116	0.35	0.31	0.612	-0.16	0.35	0.540	-0.19
Force At Peak Power (N/kg)	-0.09	0.799	0.08	0.06	0.854	-0.06	-0.44	0.145	0.33	-0.22	0.347	0.20	0.35	0.414	-0.25	0.28	0.459	-0.23
RoFD Concentric Acceleration (N.s/kg)	2.01	0.530	-0.19	3.59	0.252	-0.35	0.48	0.770	-0.07	4.98	0.010	-0.60	1.54	0.605	-0.16	-1.38	0.675	0.13
Concentric Impulse (N.s/kg)	-0.15	0.990	0.00	3.17	0.812	-0.07	5.46	0.682	-0.09	7.67	0.327	-0.15	-15.98	0.243	0.37	-10.44	0.418	0.10

Concentric Acceleration Impulse (N.s/kg)	4.13	0.703	-0.12	4.33	0.708	-0.12	6.37	0.585	-0.13	7.19	0.329	0.35	-10.77	0.376	0.28	-2.86	0.822	0.07
Mean Concentric Power (W/kg)	-0.42	0.524	0.20	-0.10	0.866	0.05	-0.95	0.010	0.41	-0.71	0.010	0.10	0.53	0.452	-0.23	0.61	0.350	-0.29
Maximum Concentric Power(W/kg)	-0.52	0.651	0.14	0.10	0.921	-0.03	-0.98	0.117	0.25	-0.31	0.455	-0.34	0.46	0.688	-0.12	0.41	0.694	-0.12
Average RoPD Concentric (W.s/kg)	-3.92	0.721	0.11	-0.70	0.943	0.02	-19.41	0.075	0.42	-15.99	0.067	0.40	15.49	0.265	-0.35	15.29	0.225	-0.38
Work Done Concentric (J/kg)	-40.62	0.824	0.07	22.02	0.897	-0.04	-26.44	0.874	0.03	39.77	0.728	-0.06	-133.96	0.443	0.24	-17.76	0.924	0.03
Landing Phase																		
Maximum Landing Force (N/kg)	3.15	0.065	-0.58	2.31	0.123	-0.48	-2.13	0.040	0.33	-2.10	0.010	0.49	4.24	0.005	-0.91	3.85	0.008	-0.86
Land Impulse (N.s/kg)	20.86	0.068	-0.57	29.09	0.006	-0.89	-29.74	0.000	0.83	-16.11	0.010	0.56	50.60	0.000	-1.53	48.14	0.000	-1.53
Land Impulse First 40ms (N.s/kg)	3.83	0.046	-0.63	6.31	0.003	-0.97	-2.77	0.020	0.39	-0.03	0.975	0.00	6.60	0.001	-1.11	6.35	0.000	-1.17
Work Done Landing (J/kg)	62.72	0.720	-0.11	-33.09	0.803	0.08	-89.38	0.247	0.15	-203.53	0.001	0.51	172.76	0.185	-0.18	113.75	0.346	-0.10
Temporal																		
Duration Falling (s)	0.00	0.836	-0.06	0.00	0.854	0.06	0.003	0.707	-0.08	0.010	0.181	-0.40	-0.001	0.953	0.02	-0.013	0.113	0.28
Duration Eccentric Phase (s)	0.02	0.395	-0.26	0.01	0.485	-0.21	0.025	0.184	-0.32	0.029	0.055	-0.48	-0.005	0.824	0.07	-0.014	0.499	0.21
Duration Concentric Phase (s)	0.01	0.703	-0.12	0.00	0.835	-0.06	0.014	0.235	-0.26	0.015	0.093	-0.33	-0.018	0.219	0.17	-0.013	0.370	0.28
Duration Jump (s)	0.03	0.512	-0.20	0.01	0.746	-0.10	0.041	0.174	-0.29	0.051	0.040	-0.47	-0.016	0.712	0.11	-0.040	0.277	0.34

Time Impact to Peak Land Force (s)	0.00	0.514	-0.20	0.01	0.276	-0.34	0.007	0.030	-0.43	0.010	0.003	-0.54	-0.005	0.378	0.27	-0.005	0.446	0.24
Time Impact to Negative Peak Power (s)	0.00	0.538	-0.19	0.01	0.122	-0.48	0.002	0.367	-0.16	0.005	0.010	-0.36	0.001	0.727	0.20	-0.002	0.707	0.12
Performance																		
Jump Height (m)	0.00	0.982	0.01	0.01	0.530	-0.19	-0.007	0.218	0.22	-0.001	0.829	0.03	0.005	0.543	-0.15	0.007	0.445	-0.24
Contraction Time to Jump Height (m/s)	0.21	0.655	-0.14	-0.35	0.344	0.11	0.559	0.034	-0.37	0.345	0.104	-0.36	-0.296	0.423	0.21	-0.565	0.178	0.42

AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, Sx – symptomatic limb, Non-Sx limb – non-symptomatic limb, SL-CMJ – single-leg countermovement jump, ES – cohen's d, vGRF – vertical ground reaction force, ECC - eccentric, RoFD - rate of force development, RoPD - rate of power development, CoM – centre of mass, Mean Diff - mean difference.

Appendix G6: DL-CMJ vGRF asymmetries all variables group mean (SD) and comparisons

Variables	AGP PRE		CON		AGP POST		AGP PRE v UNINJ			AGP PRE v AGP POST			AGP POST v UNINJ		
	mean	*SD*	mean	*SD*	mean	*SD*	*P*	ES	Sx >	*p*	ES	Sx >	*p*	ES	Sx >
Force At Start Of Jump (N/kg)	0.12	0.08	0.11	0.08	0.11	0.10	0.755	0.08	36%	0.387	0.17	36%	0.487	-0.08	39%
Eccentric Jump Phase															
Mean ECC Force (N/kg)	0.14	0.10	0.12	0.10	0.11	0.07	0.414	0.21	46%	0.056	0.15	46%	0.993	-0.11	46%
Max ECC Force (N/kg)	0.08	0.07	0.10	0.07	0.08	0.05	0.474	-0.21	50%	0.554	0.00	50%	0.333	-0.32	39%
Force At Zero Velocity (N/kg)	0.09	0.07	0.10	0.07	0.08	0.05	0.506	-0.18	50%	0.339	0.02	50%	0.293	-0.35	39%
Force At ECC Minimum Power (N/kg)	0.14	0.10	0.14	0.11	0.13	0.09	0.833	0.03	39%	0.285	0.06	39%	0.743	-0.14	46%
Force At ECC Minimum CoM velocity (N/kg)	0.20	0.16	0.19	0.13	0.17	0.12	0.900	0.08	46%	0.362	0.05	46%	0.833	-0.11	46%
Force At Start of ECC Phase (N/kg)	0.19	0.13	0.26	0.22	0.22	0.22	0.516	-0.39	50%	0.469	-0.04	50%	0.529	-0.17	50%
RoFD Eccentric Deceleration (N.s/kg)	0.20	0.15	0.22	0.17	0.16	0.12	0.820	-0.10	36%	0.139	0.16	36%	0.204	-0.39	43%
RoFD Eccentric Breaking (N.s/kg)	0.17	0.16	0.15	0.11	0.15	0.14	0.649	0.21	46%	0.203	0.12	44%	0.924	0.04	43%
Eccentric Impulse (N.s/kg)	0.17	0.14	0.16	0.14	0.15	0.11	0.409	0.12	54%	0.603	0.05	54%	0.563	-0.02	50%
Eccentric Deceleration Impulse (N.s/kg)	0.20	0.17	0.18	0.17	0.18	0.13	0.392	0.13	54%	0.585	0.08	54%	0.539	-0.02	50%
Mean Eccentric Power (W/kg)	0.16	0.12	0.13	0.11	0.12	0.09	0.377	0.23	46%	0.036	0.17	46%	0.913	-0.09	43%
Minimum Eccentric Power (W/kg)	0.14	0.10	0.14	0.11	0.13	0.09	0.953	-0.01	39%	0.439	0.08	39%	0.807	-0.13	46%
RoPD Eccentric (W.s/kg)	0.23	0.20	0.22	0.17	0.18	0.14	0.743	0.01	43%	0.072	0.14	43%	0.270	-0.29	54%
Average RoPD Eccentric (W.s/kg)	0.17	0.11	0.17	0.13	0.14	0.11	0.717	0.01	36%	0.194	0.18	36%	0.539	-0.22	50%
Work Done Eccentric Phase (J/kg)	0.16	0.12	0.13	0.11	0.12	0.09	0.414	0.21	46%	0.056	0.15	46%	0.926	-0.08	46%
Concentric Jump Phase															
Mean Concentric Force (N/kg)	0.05	0.03	0.04	0.04	0.04	0.03	0.072	0.26	46%	0.088	0.22	46%	0.281	0.16	46%
Maximum Concentric Force (N/kg)	0.05	0.04	0.06	0.05	0.04	0.03	0.953	-0.21	54%	0.101	0.16	54%	0.249	-0.42	43%
Force At Peak Power (N/kg)	0.04	0.03	0.03	0.03	0.04	0.03	0.377	0.23	54%	0.750	-0.04	54%	0.249	0.28	54%
RoFD Concentric Acceleration (N.s/kg)	0.77	0.64	1.30	1.17	1.29	1.41	0.101	-0.56	64%	0.378	-0.09	61%	0.458	-0.15	45%

Concentric Impulse (N.s/kg)	0.08	0.06	0.09	0.07	0.06	0.06	0.993	-0.07	46%	0.088	0.19	46%	0.350	-0.34	50%
Concentric Acceleration Impulse (N.s/kg)	0.04	0.03	0.04	0.04	0.04	0.03	0.581	0.07	54%	0.387	0.08	54%	0.843	-0.03	50%
Mean Concentric Power (W/kg)	0.04	0.03	0.04	0.04	0.04	0.03	0.385	0.14	43%	0.122	0.11	43%	0.946	0.13	50%
Maximum Concentric Power(W/kg)	0.04	0.03	0.03	0.03	0.04	0.03	0.349	0.24	54%	0.716	-0.06	54%	0.181	0.30	54%
Average RoPD Concentric (W.s/kg)	0.04	0.03	0.03	0.03	0.04	0.03	0.395	0.23	57%	0.802	-0.05	57%	0.221	0.28	54%
Work Done Concentric (J/kg)	0.04	0.03	0.04	0.04	0.04	0.03	0.366	0.15	43%	0.111	0.14	43%	0.982	0.13	54%
Landing Phase															
Maximum Landing Force (N/kg)	0.17	0.15	0.12	0.07	0.16	0.12	0.343	0.44	57%	0.982	0.01	57%	0.377	0.38	50%
Land Impulse (N.s/kg)	0.23	0.15	0.21	0.13	0.20	0.12	0.608	0.13	46%	0.399	0.09	46%	0.873	-0.07	75%
Land Impulse First 40ms (N.s/kg)	0.32	0.20	0.34	0.24	0.30	0.16	0.953	-0.07	43%	0.452	0.06	43%	0.730	-0.19	75%
Work Done Landing (J/kg)	0.19	0.16	0.14	0.10	0.16	0.13	0.351	0.37	61%	0.399	0.15	61%	1.000	0.12	50%

DL-CMJ – double-leg countermovement jump, vGRF – vertical ground reaction force, AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, SD - standard deviation, ECC - eccentric, RoFD - rate of force development, RoPD - rate of power development, CoM – center of mass, Mean Diff - mean difference, Sx > - proportion of times magnitude of inter-limb asymmetry was greater on symptomatic limb.

Appendix G7: SL-CMJ vGRF inter-limb asymmetries each group mean (SD) and comparisons

Variables	AGP PRE		CON		AGP POST		AGP PRE v CON			AGP PRE v AGP POST			AGP POST v CON		
	mean	*SD*	mean	*SD*	mean	*SD*	*P*	ES	Sx >	*p*	ES	Sx >	*p*	ES	Sx >
Force At Start Of Jump (N/kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.867	0.02	60%	0.351	-0.16	60%	0.329	0.24	68%
Eccentric Jump Phase															
Mean ECC Force (N/kg)	0.02	0.02	0.02	0.01	0.03	0.02	0.880	0.22	52%	0.758	-0.17	50%	0.106	0.67	59%
Max ECC Force (N/kg)	0.05	0.06	0.05	0.04	0.07	0.06	0.667	0.16	50%	0.277	-0.19	50%	0.063	0.61	59%
Force At Zero Velocity (N/kg)	0.05	0.06	0.04	0.03	0.08	0.05	0.797	0.25	55%	0.263	-0.19	55%	0.096	0.53	59%
Force At ECC Minimum Power (N/kg)	0.06	0.06	0.05	0.03	0.06	0.04	0.689	0.32	45%	0.808	-0.04	45%	0.653	0.24	59%
Force At ECC Minimum CoM velocity (N/kg)	0.00	0.00	0.00	0.00	0.00	0.00	0.465	0.10	57%	0.821	-0.07	57%	0.214	0.21	64%
Force At Start of ECC Phase (N/kg)	0.13	0.12	0.18	0.17	0.18	0.15	0.237	-0.40	57%	0.408	-0.21	59%	0.761	-0.01	36%
RoFD Eccentric Deceleration (N.s/kg)	0.23	0.18	0.21	0.15	0.25	0.19	0.782	0.09	52%	0.783	-0.02	50%	0.504	0.26	50%
RoFD Eccentric Breaking (N.s/kg)	0.34	0.34	0.17	0.15	0.29	0.21	0.280	0.63	50%	0.884	-0.01	50%	0.050	0.61	59%
Eccentric Impulse (N.s/kg)	0.14	0.13	0.13	0.09	0.11	0.08	0.588	0.03	41%	0.741	0.14	43%	0.345	-0.33	55%
Eccentric Deceleration Impulse (N.s/kg)	0.18	0.16	0.16	0.11	0.13	0.08	0.753	0.11	50%	0.465	0.10	50%	0.332	-0.35	64%
Mean Eccentric Power (W/kg)	0.13	0.09	0.10	0.07	0.13	0.10	0.239	0.43	23%	0.833	0.00	23%	0.325	0.42	55%
RoPD Eccentric (W.s/kg)	0.24	0.24	0.20	0.16	0.27	0.21	0.799	0.20	45%	0.661	-0.14	45%	0.325	0.36	55%
Average RoPD Eccentric (W.s/kg)	0.23	0.18	0.17	0.14	0.25	0.18	0.268	0.36	38%	0.783	-0.05	36%	0.129	0.51	59%
Work Done Eccentric Phase (J/kg)	0.11	0.07	0.14	0.09	0.12	0.08	0.269	-0.32	23%	0.808	-0.01	23%	0.402	-0.26	50%
Concentric Jump Phase															
Maximum Concentric Force (N/kg)	0.04	0.03	0.04	0.04	0.04	0.03	0.780	0.00	64%	0.661	0.11	64%	0.817	-0.11	59%
Force At Peak Power (N/kg)	0.04	0.03	0.04	0.03	0.03	0.03	0.536	0.14	59%	0.211	0.21	59%	0.585	-0.13	45%
RoFD Concentric Acceleration (N.s/kg)	1.08	1.03	0.69	0.76	1.21	1.21	0.141	0.44	42%	0.601	0.01	37%	0.190	0.51	62%
Concentric Impulse (N.s/kg)	0.07	0.06	0.06	0.05	0.09	0.05	0.875	0.14	55%	0.211	-0.24	55%	0.123	0.47	55%
Concentric Acceleration Impulse (N.s/kg)	0.11	0.09	0.10	0.09	0.12	0.08	0.913	0.02	50%	0.465	-0.16	50%	0.362	0.19	50%

Maximum Concentric Power(W/kg)	0.08	0.06	0.05	0.04	0.05	0.04	0.129	0.58	59%	0.033	0.33	59%	0.520	-0.09	55%
Average RoPD Concentric (W.s/kg)	0.15	0.09	0.10	0.10	0.14	0.09	0.050	0.45	59%	0.570	0.08	59%	0.142	0.33	55%
Work Done Concentric (J/kg)	0.07	0.06	0.05	0.05	0.07	0.05	0.178	0.41	50%	0.884	0.00	50%	0.269	0.34	50%
Landing Phase															
Maximum Landing Force (N/kg)	0.09	0.07	0.08	0.05	0.06	0.05	0.855	0.19	41%	0.189	0.26	41%	0.229	-0.34	41%
Land Impulse (N.s/kg)	0.12	0.11	0.14	0.12	0.07	0.06	0.801	-0.16	43%	0.030	0.25	45%	0.101	-0.70	55%
Land Impulse First 40ms (N.s/kg)	0.07	0.06	0.05	0.05	0.06	0.05	0.313	0.33	36%	0.445	0.07	36%	0.430	0.15	55%
Work Done Landing (J/kg)	0.11	0.10	0.10	0.07	0.07	0.05	0.932	0.17	68%	0.244	0.19	67%	0.170	-0.51	59%
Temporal															
Duration Falling (s)	0.13	0.11	0.15	0.11	0.15	0.12	0.618	-0.14	36%	0.465	-0.07	36%	0.990	0.03	32%
Duration Eccentric Phase (s)	0.11	0.13	0.10	0.07	0.12	0.10	0.259	0.05	55%	0.615	-0.23	55%	0.671	0.27	45%
Duration Concentric Phase (s)	0.08	0.06	0.06	0.05	0.09	0.06	0.239	0.37	36%	0.685	-0.11	36%	0.091	0.47	45%
Duration Jump (s)	0.08	0.08	0.06	0.04	0.08	0.06	0.817	0.35	45%	0.833	-0.11	45%	0.325	0.42	41%
Time Impact to Peak Land Force (s)	0.10	0.11	0.13	0.10	0.10	0.11	0.213	-0.26	73%	0.351	-0.13	75%	0.284	-0.26	64%
Time Impact to Negative Peak Power (s)	0.13	0.11	0.13	0.11	0.08	0.06	0.811	0.00	77%	0.244	0.25	81%	0.163	-0.59	76%
Performance															
Jump Height (m)	0.11	0.08	0.07	0.07	0.10	0.08	0.056	0.55	62%	0.355	0.20	64%	0.313	0.30	41%
Contraction Time to Jump Height (m/s)	0.15	0.12	0.10	0.06	0.13	0.11	0.142	0.54	45%	0.592	0.14	45%	0.706	0.31	41%

SL-CMJ – single-leg countermovement jump, vGRF – vertical ground reaction force, AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, SD - standard deviation, ECC - eccentric, RoFD - rate of force development, RoPD - rate of power development, CoM – center of mass, Mean Diff - mean difference, Sx > - proportion of times magnitude of inter-limb asymmetry was greater on symptomatic limb

Appendix G8: DL-CMJ sagittal plane kinematic and kinetics variables: Mean (*SD*) and group comparisons

	AGP PRE				CON				AGP POST				AGP PRE v CON				AGP PRE v AGP POST				AGP POST v CON			
Variables	Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb	
sagittal joint angle at land impact	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	*p*	ES	*p*	ES	*p*	ES	*p*	ES	*p*	ES	*p*	ES
Ankle	-17.0	10.4	-18.5	9.8	-15.1	6.8	-15.4	7.9	-16.7	11.5	-19.0	10.7	0.476	-0.22	0.289	-0.33	0.903	-0.02	0.956	0.01	0.740	-0.10	0.198	-0.38
Knee	21.3	4.3	21.3	4.9	21.8	4.1	20.9	4.8	20.3	3.8	21.3	5.6	0.686	-0.13	0.714	0.11	0.491	0.15	0.655	0.06	0.674	-0.13	0.787	0.08
Hip	24.0	6.7	24.8	7.0	22.4	6.6	21.9	7.9	25.2	4.5	25.5	6.5	0.419	0.25	0.170	0.42	0.245	-0.29	0.472	-0.17	0.153	0.42	0.101	0.48
Thorax	5.3	7.1	4.5	5.9	3.9	6.4	3.9	6.4	3.9	5.5	4.3	6.2	0.512	0.20	0.512	0.20	0.605	0.10	0.605	0.10	0.846	0.06	0.846	0.06
Δ CoM max / CoM at Impact	311.9	62.1	316.5	62.6	316.6	37.9	316.6	37.9	317.4	56.8	318.2	62.8	0.764	-0.09	0.764	-0.09	0.915	-0.02	0.915	-0.02	0.920	0.03	0.920	0.03
Δ Ankle Angle during first 40ms	20.5	5.4	20.8	6.1	25.5	3.0	25.4	4.4	18.7	6.2	21.9	4.4	0.001	-1.00	0.006	-0.82	0.388	0.15	0.413	-0.21	0.000	-1.13	0.008	-0.76
Δ Ankle Moment first 40ms	1.15	0.3	1.07	0.3	1.27	0.4	1.28	0.4	1.16	0.3	1.30	0.4	0.332	-0.30	0.073	-0.55	0.553	-0.16	0.004	-0.70	0.342	-0.28	0.975	0.01
Ankle Stiffness first 40ms	0.05	0.01	0.05	0.01	0.05	0.02	0.05	.01	0.06	0.01	0.06	0.01	0.585	0.17	0.904	0.04	0.399	-0.27	0.036	-0.67	0.206	0.39	0.027	0.68
Δ Knee Angle first 40ms	13.8	2.8	13.5	3.8	16.2	2.6	16.1	2.9	13.1	3.2	13.0	3.1	0.005	-0.82	0.015	-0.73	0.002	0.51	0.230	0.21	0.001	-0.93	0.012	-0.73
Δ Knee Moment first 40ms	1.01	0.5	0.96	0.5	1.28	0.5	1.14	0.4	1.04	0.6	0.99	0.4	0.074	-0.54	0.173	-0.42	0.587	0.12	0.841	0.05	0.138	-0.44	0.590	-0.16
Knee Stiffness first 40ms	0.07	0.03	0.06	0.03	0.08	0.03	0.07	0.02	0.07	0.03	0.07	0.03	0.488	-0.22	0.569	-0.18	0.809	-0.06	0.462	-0.18	0.800	-0.08	0.519	0.20
Δ Hip Angle first 40ms	4.4	2.7	4.3	2.8	5.9	2.7	6.0	2.6	4.0	3.1	3.6	2.3	0.072	-0.55	0.044	-0.61	0.021	0.34	0.120	0.27	0.029	-0.64	0.021	-0.67
Δ Hip Moment first 40ms	-0.87	0.5	-1.00	0.9	-1.27	0.7	-1.14	0.7	-0.80	0.9	-0.91	0.9	0.049	0.60	0.573	0.17	0.578	-0.10	0.210	-0.23	0.056	0.56	0.217	0.37

Hip Stiffness first 40ms	-0.2	0.1	-0.3	0.3	-0.2	0.1	-0.3	0.3	-0.2	0.2	-0.2	0.3	0.561	0.19	0.830	0.07	0.472	-0.26	0.559	-0.19	0.486	0.23	0.369	0.28
∆ CoM z first 40ms	-103.1	9.8	-103.1	9.8	-103.0	5.4	-103.0	5.4	-103.9	8.8	-104.3	9.0	0.977	-0.01	0.977	-0.01	0.677	0.05	0.677	0.05	0.696	-0.12	0.696	-0.12
∆ GRF z first 40ms	11.6	6.4	11.0	6.1	10.6	3.7	10.5	2.9	12.2	7.0	12.9	6.5	0.556	0.18	0.741	0.10	0.642	-0.11	0.230	-0.28	0.342	0.28	0.158	0.42
CoM Stiffness first 40ms	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	-0.1	0.0	0.307	0.33	0.203	0.42	0.371	0.26	0.013	0.88	0.721	-0.11	0.440	-0.25

DL-CMJ - double-leg countermovement jump, SD - standard deviation, Sx – symptomatic, Non-Sx – non-symptomatic, AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, ES – Cohen's d, CoM – center of mass, max – maximum jump height, z – vertical, ∆ - change, internal net moment units – Nm/k

]]Appendix G9: SL-CMJ sagittal plane kinematic and kinetics variables; Mean (*SD*) and group comparisons

	AGP PRE				CON				AGP POST				AGP PRE v CON				AGP PRE v AGP POST				AGP POST v CON			
Variables	Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb		Sx Limb		Non-Sx Limb	
sagittal joint angle at land impact	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	*p*	ES	*p*	ES	*p*	ES	*p*	ES	*p*	ES	*p*	ES
Ankle	-17.8	8.3	-19.0	8.7	-9.3	10.8	-9.4	12.3	-16.5	14.1	-18.1	14.5	0.007	-0.81	0.006	-0.82	0.649	-0.11	0.568	-0.12	0.046	-0.61	0.040	-0.63
Knee	23.5	10.7	21.0	6.9	34.3	24.1	33.4	22.2	19.8	4.7	18.6	5.8	0.076	-0.55	0.024	-0.68	0.193	0.43	0.297	0.27	0.011	-0.76	0.007	-0.80
Hip	26.4	3.8	27.8	5.6	27.0	10.0	26.5	7.6	27.1	4.6	25.4	7.0	0.805	-0.08	0.558	0.18	0.620	-0.14	0.352	0.26	0.713	-0.11	0.616	-0.16
Thorax	8.2	6.4	7.8	6.3	7.2	7.5	7.9	8.4	7.8	8.2	6.9	9.6	0.649	0.14	0.959	-0.02	0.534	0.12	0.560	0.11	0.987	0.00	0.723	-0.11
Δ CoM max / CoM at Impact	149.1	29.3	148.5	26.4	168.3	30.1	184.9	79.3	151.4	44.3	153.1	44.2	0.042	-0.62	0.063	-0.57	0.748	-0.08	0.523	-0.14	0.145	-0.45	0.126	-0.47
Δ Ankle Angle during first 40ms	16.2	2.9	16.8	2.9	17.9	6.0	18.0	5.7	15.5	4.4	15.3	4.0	0.243	-0.36	0.394	-0.27	0.619	0.18	0.092	0.44	0.114	-0.49	0.086	-0.53
Δ Ankle Moment first 40ms	1.23	0.3	1.31	0.3	1.36	0.7	1.36	0.5	1.40	0.3	1.35	0.3	0.397	-0.26	0.710	-0.12	0.059	-0.51	0.748	-0.07	0.865	0.05	0.933	-0.03
Ankle Stiffness first 40ms	0.07	0.02	0.07	0.02	0.07	0.02	0.06	0.02	0.09	0.02	0.08	0.03	0.843	0.06	0.018	0.73	0.046	-0.57	0.148	-0.43	0.028	0.69	0.000	1.20
Δ Knee Angle first 40ms	8.0	1.9	8.8	2.8	8.9	2.9	8.8	3.6	7.2	3.4	8.1	4.1	0.230	-0.37	0.939	-0.02	0.185	0.37	0.389	0.23	0.094	-0.52	0.642	-0.15
Δ Knee Moment first 40ms	0.41	0.3	0.60	0.3	0.66	0.3	0.72	0.6	0.58	0.7	0.78	0.9	0.009	-0.78	0.401	-0.26	0.291	-0.33	0.427	-0.25	0.574	-0.18	0.949	0.02

Knee Stiffness first 40ms	0.06	0.04	0.07	0.03	0.07	0.03	0.06	0.05	0.06	0.04	0.07	0.04	0.420	-0.25	0.504	0.21	0.432	-0.29	0.772	-0.09	0.721	-0.12	0.635	0.16
∆ Hip Angle first 40ms	0.9	1.8	1.2	1.7	2.3	2.1	2.4	3.4	0.7	2.1	1.1	2.9	0.033	-0.65	0.158	-0.44	0.191	0.26	0.693	0.08	0.020	-0.70	0.219	-0.38
∆ Hip Moment first 40ms	-0.37	0.4	-0.46	0.5	-0.79	0.7	-0.89	0.7	-0.079	0.8	-0.12	0.9	0.030	0.66	0.028	0.67	0.144	-0.46	0.109	-0.47	0.004	0.86	0.003	0.88
Hip Stiffness first 40ms	-0.2	0.5	-0.1	0.7	-0.2	0.6	-0.3	0.5	0.2	0.8	0.05	0.6	0.990	0.00	0.447	0.26	0.137	-0.54	0.634	-0.26	0.035	0.69	0.258	0.37
∆ CoM z first 40ms	-74.2	6.5	-73.8	5.7	-77.4	5.8	-62.6	74.6	-75.0	8.3	-74.9	7.3	0.097	0.51	0.515	-0.20	0.956	0.01	0.754	0.05	0.162	0.43	0.504	-0.21
∆ GRF z first 40ms	11.0	4.4	12.1	4.1	11.0	4.9	12.2	7.2	14.9	9.3	15.7	9.9	0.966	-0.01	0.962	-0.02	0.055	-0.52	0.064	-0.45	0.090	0.52	0.210	0.39
CoM Stiffness first 40ms	-0.1	0.0	-0.2	0.0	-0.1	0.1	-0.1	0.0	-0.2	0.0	-0.2	0.0	0.949	0.02	0.130	-0.50	0.012	0.61	0.102	0.37	0.245	-0.38	0.008	-0.87

SL-CMJ - double-leg countermovement jump, SD - standard deviation, Sx – symptomatic, Non-Sx – non-symptomatic, AGP - athletic groin pain, PRE – pre-rehabilitation, POST – post-rehabilitation, CON – uninjured controls, ES – Cohen's d, CoM – center of mass, max – maximum jump height, z – vertical, ∆ - change, internal net moment units – Nm/kg

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