DOCTORAL THESIS

Athletic Groin Pain
A diagnosis without injury?

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Award date:
2023

Awarding institution:
University of Roehampton

Athletic groin pain: A diagnosis without injury?

by

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A thesis submitted in partial fulfilment of the requirements for the degree of PhD

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Abstract

Athletic Groin pain is a chronic musculoskeletal condition common in players of multidirectional sports with an incidence between 3 and 23 %. Despite attempts at global consensus, there remains no agreement on the identification of pathological structures injured in patients presenting with pain. The aim of this research was to (i) implement a systematic clinical examination, to identify pain, combined with radiological imaging to determine if the differential diagnosis can be narrowed and (ii) analyse movement during change of direction, to determine if certain biomechanical features which associate with pubic confluence overload could be identified to inform a different approach to rehabilitation to enhance outcomes. Following original anatomical dissection, we devised a system of examination to clarify potential diagnosis. Then in a prospective cohort clinical study, we sought to enhance the clinical examination by combining this with radiological data, patient reported outcomes and a pain-provoking task. These steps did not enhance the diagnosis and led us to undertake a systematic review and meta-analysis of the outcomes of rehabilitation and surgical interventions in AGP. We found little evidence for an actual pathology and as such began to investigate causes of mechanical overload. The use of three-dimensional motion capture allowed us to analyse a pain provoking manoeuvre (change of direction) in terms of joint coordination and loads. In athletes with AGP, we identified three distinct distributions of joint work and kinematic techniques. When these data were used to guide rehabilitation intervention, patients evidenced enhanced outcomes including faster return to play and a greater success rate at return to play than generally reported in the literature. Further work is required to evidence the best use of

biomechanical data on an individual basis to inform and develop rehabilitation based on feature selection for this group to expedite return to play.

Contents

Included Papers

1. The groin triangle: a patho-anatomical approach to the diagnosis of chronic groin pain in athletes.

   Falvey EC, *Franklyn-Miller A*, McCrory PR.

   Br J Sports Med. 2009 Mar;43(3):213-20

2. Athletic groin pain (part 1): a prospective anatomical diagnosis of 382 patients--clinical findings, MRI findings and patient-reported outcome measures at baseline.

   Falvey ÉC, King E, Kinsella S, *Franklyn-Miller A.*

   Br J Sports Med. 2016 Apr;50(7):423-30.

3. Athletic groin pain: a systematic review and meta-analysis of surgical versus physical therapy rehabilitation outcomes.

   King E, Ward J, Small L, Falvey E, *Franklyn-Miller A*.

   Br J Sports Med. 2015 Nov;49(22):1447-51.

4. Biomechanical factors associated with time to complete a change of direction cutting manoeuvre.

   Marshall BM, *Franklyn-Miller AD*, King EA, Moran KA, Strike SC, Falvey ÉC.

   J Strength Cond Res. 2014 Oct;28(10):2845-51.

5. Athletic groin pain (part 2): a prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns.

   Franklyn-Miller A, Richter C, King E, Gore S, Moran K, Strike S, Falvey EC.

   Br J Sports Med. 2017 Mar;51(5):460-468.

6. Clinical and biomechanical outcomes of rehabilitation targeting intersegmental control in athletic groin pain: prospective cohort of 205 patients.

   King E, *Franklyn-Miller A,* Richter C, O'Reilly E, Doolan M, Moran K, Strike S, Falvey É.

   Br J Sports Med. 2018 Aug;52(16):1054-1062.

Acknowledgements

This work started during my Sports Medicine Fellowship at The University of Melbourne, Australia in 2005 with enormous thanks to Professor's Peter Brukner and Paul McCrory for trusting an emergent research physician. Immeasurable thanks to my colleague and co researcher Dr Eanna Falvey for the time spent analysing data and postulating theories. Thanks to Professor Chris Briggs, and Dr Priscilla Barker for allowing unlimited access to the Anatomy Lab without which we would not have understood enough.

I could not have done any of the my work without the assistance, direction and guidance of Dr Siobhan Strike, we began examining professional footballers with athletic groin pain and started to raise the hypotheses tested in this body of work posed the question could movement analysis begin to answer the questions that remined unanswered, she has been a fantastic friend and colleague and Dr Andrew Greene has proved invaluable in submitting this work as a thesis.

I have been lucky enough to lead a fantastic team of colleague's and co-authors in this work and, Dr Kieran Moran, Dr Brendan Marshall, Dr Chris Richter, Dr Katherine Daniels, Dr Enda King, Dr Shane Gore, Dr Neil Welch, and Dr Sam Baida, you have all proved inspirational, diligent, challenging and without which we would not have begun, lest finished this work and all completed their PhD before me! Thanks to the Sports Surgery Clinic Dublin and in particular Mr Geoff Moylan, for believing in the research journey and teaching me so much about investment and loyalty. Special thanks to Michelle Lynch and Rachel Ryan who led my administration team at the Sports Surgery Clinic, making my life bearable and preventing me making too many mistakes.

Enormous thanks to Craig Frost who during moments of frustration and despair, challenged me to keep going and made me commit to completion, without whom I would not have finished this work.

Introduction

This thesis presents a body of work which was motivated by the difficulty in diagnosing and managing Athletic Groin Pain (AGP). Initially, we considered the condition to be an anatomically delineated tissue-specific injury which was difficult to differentiate by clinical examination, but which could be aided by magnetic resonance imaging. This progressed, after our initial work, towards the theory that AGP is closer to a mechanical overload pain disorder which effects one or more tissues and thus a specific diagnosis is not as fundamental to successful treatment. We conclude that AGP should be considered a non-specific condition with many subclinical pathologies which may contribute to pain. This thesis suggests that pain develops because of the inability of tissue/s to tolerate the repeated loading movements experienced by an individual as a result of either training load or lack of capacity. The lack of opposing muscular control allows propagative movement patterns to lead to local overload. Our research suggests that these movement characteristics can change with successful rehabilitation intervention and relieve symptoms regardless of focal site of pain.

We consider that a systematic clinical examination (E. C. Falvey, Franklyn-Miller and McCrory, 2009) even when combined with magnetic resonance imaging (Falvey *et al.*, 2016) are not useful for narrowing the differential diagnosis or in treating this condition, as evidenced by the relatively poor and indiscriminate outcomes between surgery and conservative treatment seen in paper three. (King *et al.*, 2015) Rather we suggest, that having analysed movement during change of direction (Marshall *et al.*, 2014) certain biomechanical features can be isolated which lead to pubic overload and by using a multi segmental analysis in paper five. (Franklyn-Miller *et al.*, 2017) This allows a different approach to rehabilitation to be implemented which results in enhanced outcomes in paper six. (King *et al.*, 2018)

It is not clear if the pain in AGP stems from injury to specific tissues or if it is a disorder affecting multiple tissues. Injury may occur because of exposure, to either singular or repetitive stresses (Hamner, Seth and Delp, 2010) and requires a clear tissue failure, which can be pathologically demonstrated, such as a fracture or tear. In a disorder such as osteoarthritis, multi joint changes may occur without total failure, but can be pathologically identified through clinical, radiological, and surgical examination. Our research is motivated by the reasoning that AGP has not been associated, yet, with a specific injury. Yet, clinical practice informed by the literature attempts to associate pain with a specific anatomical structure without evidence of failure. Our approach investigated if describing AGP as a pain disorder may be more appropriate.

Athletic Groin Pain

Athletic Groin pain (AGP) in athletes is a common chronic musculoskeletal condition. It is distinct from an acute presentation of pain in the groin which is usually related to acute muscle tears. (Serner *et al.*, 2021) The literature reports incidences of between 3 and 23% in change of direction sports, such as Gaelic, Australian rules and rugby union football. (Brooks *et al.*, 2005; Walden, Hagglund and Ekstrand, 2007; Junge and Dvorak, 2013; Orchard, Seward and Orchard, 2013) In soccer, AGP accounts for 12-16% of all injuries per season with an incidence of 1.1/1000 h (3.5/1000 match hours vs 0.6/1000 training hours, (Werner *et al.*, 2019) and in time loss morbidity due to the inability to train with pain. If a non-time loss definition is used, as many as 50% of players on a football team may experience hip-and/or groin pain (Thorborg *et al.*, 2017; Langhout *et al.*, 2019) during a single season of whom only 1% experienced sufficient pain to cause time loss injuries (Esteve *et al.*, 2020) Whether many of these cases went on to develop time loss injuries in subsequent seasons or whether the subclinical pain resulted in performance loss has not been examined. Clearly, AGP is a common problem which causes significant morbidity in athletes. It is a gradual presentation of pain in the groin, usually exacerbated by running, acceleration, change of direction, deceleration, kicking a ball or even in more chronic cases sitting, standing, or getting out of bed or putting on socks. (Serner *et al.*, 2021)

At the time of writing the first paper, clinical confirmation of the condition was usually made by palpation. The complexity of the underlying anatomy in the inguinal region (L. inguen) at the junction of the abdomen, crease of the groin and thigh, resulted in difficulties in identifying painful structures. The complexity is exacerbated as a result of the underlying and overlapping tissue attachments and the various loads applied to these given small pelvic and thorax angle changes. Consequently, the load distribution alters pain perception. Indeed, the four main cross-sectional studies varied considerably in the clinical diagnosis made despite similar presenting complaints. Renström (Renström and Peterson, 1980) described primarily adductor and rectus abdominis pathology. Lovell (Lovell, 1995) diagnosed incipient hernia in 50% of cases, and (Holmich, 2007) diagnosed adductor longus related pathology in 58% of cases and sports hernia related in 1.4%. Bradshaw (Bradshaw, Bundy and Falvey, 2008) reported pathology of the hip in 46% of cases, osteitis pubis in 22%.

The intention of paper one (E. C. Falvey, Franklyn-Miller and McCrory, 2009) was to define a systematic physical examination system, based on the Oslerian principles of history and clinical examination, with reference to the underlying anatomy. The aim was to support the clinician's ability to differentiate the potential diagnoses to better direct specific confirmatory investigation and treatment selection. Developing this system was justified, as a detailed understanding of anatomy is essential in musculoskeletal and sports medicine, to identify the structures that make up a differential diagnosis and develop effective and timely treatment (Singh *et al.*, 2022) Anatomy teaching has been in steady decline over recent years in the United Kingdom, United States and Australia. (Dyer and Thorndike, 2000; Patel and Moxham, 2006) Students are exposed to less dissection and hands on teaching than their forebears (Older, 2004) and this may lead to a lack of understanding of palpatory examination as more learning is conducted online via software rather than examination and dissection.(Turney, 2007)

Given the anatomical complexity, we had undertaken original cadaveric dissection in the University of Melbourne Department of Anatomy before this work and produced a 3G anatomical landmarks paper, which formed the underpinning background for this descriptive bridge between basic anatomy and clinical examination of the groin. (E.Falvey *et al.*, 2008) We used anatomical landmarks to divide possible pathologies and the palpable anatomical landmarks on clinical examination.

We described (E. C. Falvey, Franklyn-Miller and McCrory, 2009) how to use a system of listen and localise (history), palpate, and recreate (examination) and alleviate and investigate (examination and investigations) to break down the differential diagnoses. The purpose of this work was to develop landmarks of palpatory anatomy to de-clutter a complex anatomical area. We developed unique aide memoire illustrations including the pubic clock, which have been adopted in other diagnostic and clinical papers (Rennie and Lloyd, 2017)(Bisciotti *et al.*, 2016), (Sheen and Iqbal, 2014) and hoped to teach confidence in the anatomical structures palpated allowing the use of targeted specific clinical tests, and radiological imaging to reduce the variation in the differential diagnosis and highlight that commonly, there were multiple sites of palpatory pain.

Although intended as a method of teaching the complex anatomy, by focussing on the possible differential diagnoses, including history with clinical examination, this system avoided basing the diagnosis purely on palpatory pain which was propagated by Holmich. (Holmich, 2007) His approach divided the clinical sites of pain between hip flexor, adductor and inguinal regions and described clinical examination techniques to elicit pain including palpation without imaging.

Although the intention of both systems was to improve reliability of diagnosis through palpation and clinical examination, there remains a widespread use of eponymous and alternative names attached to a 'diagnosis'. A recent systematic review on treatment which included 72 studies reported thirty-three different diagnoses covering groin pain in athletes. (Serner *et al.*, 2015) The difficulty in conducting research to compare diagnosis and intervention was recognised following this paper and a group of international experts came together to write the Doha consensus (Weir *et al.*, 2015) (Holmich, 2007) with the ambition to gain surgical and clinical concordance on the identification and naming of anatomical structures. The outcome was a reframing of Holmich's existing entities with the classification of adductor-related, iliopsoas-related, and pubic-related groin pain, with an additional inguinal-related and hip–related groin pain to include the surgical approaches in existence and then other causes of groin pain in athletes.

They agreed that inclusion was primarily based on location of pain, not a specific tissue injury.

a. Adductor-related groin pain defined by palpatory adductor tenderness and pain on resisted adduction testing.
b. Iliopsoas-related groin pain defined by pain on resisted hip flexion and/or pain on stretching the hip flexors.

c. Inguinal-related groin pain defined by pain in the inguinal canal region and tenderness of the inguinal canal. No palpable inguinal hernia was defined to be present.
d. Pubic-related groin pain defined by local tenderness of the pubic symphysis and the immediately adjacent bone.

The hip is usually a separate entity in AGP as it is a primary site of osteoarthritis and hence excluded from most studies in the under 50's. Although in an athletic population the development of anatomical deformities such as femoroacetabular impingement (FAI) have been seen in adolescent athletes and a sixfold upsurgence in hip arthroscopic surgery to treat groin pain occurred in the early 2000's, (Lund *et al.*, 2017) with the aim of correcting this anatomic deformity. The belief was that the bony overgrowth led to a space reduction in certain ranges of motion (specially in flexion, adduction, and internal rotation). This was thought to lead to a progressive damage to the acetabular labrum and the adjacent chondral cartilage surface which may progress to advanced hip osteoarthritis.

The literature subsequently learned of the asymptomatic presence of FAI in athletes (Morales-Avalos *et al.*, 2021) and the natural progression of bone changes in adolescent soccer players (Agricola *et al.*, 2014), and as such, the hip surgery has been in rapid decline since then for the treatment of groin pain. (Wörner *et al.*, 2021)

The intention of Doha was to reduce the terminology and clarify the literature, however in a recent Delhi study of 51 experts (Heijboer *et al.*, 2022) suggested that the new classification was not extensively adopted. The Doha terminology was only used by 50-67% of those involved in the agreement, and 43-55% of clinicians who weren’t involved. This suggests that despite efforts to agree on terminology in Doha they were unable to agree on pathology, hence confusion still exists. There have been 4 alternative consensus statements since all which challenge the terminology and highlight the ongoing challenges in making the diagnosis where there is a clear absence of an injured attributable structure. (Sheen *et al.*, 2014, 2018; Bisciotti *et al.*, 2016, 2018) This research suggested to us that AGP is more likely a disorder rather than a specific pathological injury.

Can more reproducible anatomical examination help differentiate?

The system that we developed to enhance the wider differential diagnosis (E. C. Falvey, Franklyn-Miller and McCrory, 2009) led to the realisation that palpatory anatomy cannot be the sole criteria for determining the appropriate intervention. Radiological imaging including ultrasound examination and magnetic resonance imaging have been used to differentiate the myotendinous attachments, ultrasound dynamic examination for inguinal hernia, nerve conduction studies (Eichenberger *et al.*, 2006) and nerve block for complex nerve entrapments (Bradley *et al.*, 2003) and the use of diagnostic hip injection of local anaesthesia as a discriminator for hip pathology. (Reiman *et al.*, 2017) The requirement for adoption of these diagnostic steps, supports the argument that clinical examination cannot being relied upon in isolation.

MRI evidence has redefined the structures anterior and superior to the pubic symphysis (Omar *et al.*, 2008; Zoga *et al.*, 2008; Poor *et al.*, 2018). The pubic aponeurosis which acts as a confluence of the inguinal ligament, connects the rectus abdominus, and adductor longus to the anterior pubic bone. This common site of pain in AGP, often simplified in anatomical textbooks, has been described with radiological imaging and dissection. (Robertson *et al.*, 2009)

More recently, the discovery of the anterior pubic ligament (APL), (Pieroh *et al.*, 2021) which had been poorly described, highlights further the implausibility of fingers palpating the area to decide on pathology, given the complexity of the overlapping and intertwined attachments at the confluence. The adductor longus muscle is connected to the APL, which is identified in many studies as a source of pathology, whereas the APL is likely to provide the source of pain in the PLAC, rectus aponeurosis, pyramidalis, anterior ligament. (Schilders *et al.*, 2017)

The use of radiological imaging can result in unexpected issues and should be used with caution. (Hassan *et al.*, 2021)(Lund *et al.*, 2017)(Morales-Avalos *et al.*, 2021)(Agricola *et al.*, 2014)(Wörner *et al.*, 2021) For example, the term osteitis pubis, more commonly seen in pregnancy, is often attributed in radiological reports to pubic bone subenthesial marrow oedema and has been used to support the diagnosis of osteitis pubis as representative of AGP. However, this is also often seen in non-injured athletes (Branci *et al.*, 2015) Furthermore, this bone marrow oedema is also often referred to, unhelpfully, as a bone stress injury.(Weir *et al.*, 2015) The emergence of the descriptive term “secondary cleft sign”, to describe micro tearing at the attachment of the conjoint tendon of Gracilis and Adductor longus has been widely adopted as radiological marker of adductor related groin pain, without histological confirmatory studies and is now driving a diagnosis of adductor related groin pain. (Zajick *et al.*, 2008; Mullens *et al.*, 2012).

Does magnetic resonance imaging improve clinical accuracy?

To test the hypothesis that MRI imaging would be beneficial to diagnostic accuracy in paper two, we designed a cohort study including clinical examination, patient reported outcomes symptom assessment (The Copenhagen Hip and Groin Outcome Score – HAGOS), and MRI examination. (Falvey *et al.*, 2016)

We used the examination techniques described in paper one (E. C. Falvey, Franklyn-Miller and McCrory, 2009) and, to comply with the newer literature, we attempted to use an "Doha entities approach" (Weir *et al.*, 2015) adopting the entities adductor-related, hip-related, iliopsoas related, and inguinal-related categories. We were unable to use the fifth "pubic-related" entity, as it excluded pain superior or caudal to the pubic tubercle. Many of our patients presented with pain superior to the pubic tubercle representing the anterior pubic ligament or pubic aponeurosis and such were classified separately. We combined the clinical examination with MRI imaging in all patients.

Patient function and the impact of injury on physical function are important factors to assess severity at presentation and outcome of rehabilitation. The previous mentioned large cohort studies (Holmich *et al.*, 1999) (Bradshaw, Bundy and Falvey, 2008) (Lovell, 1995) (Renström and Peterson, 1980) had not attempted to classify pain or function of athletes, merely characterised them as unable to train. The HAGOS (Thorborg *et al.*, 2011) is a validated tool which reflects pain and functional changes. We included this as part of the initial assessment (King *et al.*, 2015) along with the return to play rates and time, to compare with the literature and to judge the severity of the condition. (Thorborg *et al.*, 2014)

Finally, we also included a pain provoking manoeuvre, the adductor squeeze test. (Delahunt, McEntee, *et al.*, 2011) The adductor squeeze testing has previously been described in the literature as both a reliable test for screening symptomatic athletes and diagnostic of AGP in 45° of hip flexion (Delahunt, Kennelly, *et al.*, 2011) and rectus aponeurosis diagnosis at 0°. This protocol allowed us to assess the clinical, imaging, PROM and pain of 382 patients to make the diagnosis.

Our findings suggest that pain reproduced during the adductor squeeze test represents a reaction to the transmission of mechanical load across the anterior pubic area, affecting both soft tissue (adductor, rectus abdominis and obliques) and bone (pubic bone and symphysis). This makes it less useful than we expected as a discriminatory test. When we combined the data from MRI with clinical tests, we found the probability of the diagnosis improved from a pre-test probability of 62% to 93%. Our research found that the most common clinical diagnosis was pain in the rectus aponeurosis (Khan, Zoga and Meyers, 2013) This is in contradiction to previous research in which it has not been previously isolated . (Renström and Peterson, 1980)(Holmich *et al.*, 1999; Verrall, Slavotinek and Fon, 2001; Bradshaw, Bundy and Falvey, 2008)

Previous studies describing adductor pathology did so in the absence of MRI findings, focusing on clinical examination alone. Typically, localised adductor tenderness, pain with the adductor squeeze test and painful passive abduction indicated the pathology. We showed the poor post-test probability of the adductor squeeze test and believe that this suggests, rather than a new diagnosis, rectus aponeurosis injury represents the anatomical presentation seen in many previous studies but is shown more clearly with the advent of sagittal MRI. However, the complication with our paper was that in creating a new clinical site of pain superior to our 3G triangle, and outside that of the Doha entities, we used MRI to validate the pathology without any clinical proof of the structure being injured. (Zoga, Mullens and Meyers, 2010)

Given the lack of a pathology confirmation, we relied on MRI diagnosis as the gold-standard namely, Zoga's anatomical description of the pubic aponeurosis (Zoga, Mullens and Meyers, 2010). To interpret the data used in the diagnosis, we used Fagans's nomogram. (Caraguel and Vanderstichel, 2013) This statistical analysis is used to quantify the post-test probability that an individual is affected by a condition, given an observed test result, given the probability of the individual having the condition before the test was run (pre-test probability). This becomes a circular argument either refuting the use of MRI and negating the nomogram, or using the MRI to support the clinical diagnosis, where we have highlighted the over diagnosis of pathology. We could therefore approach the argument that we are no further forward using MRI, until a time there is histological confirmation of an injury. A very different picture to that of acute injuries of the adductor muscle which correlate with MRI (Serner *et al.*, 2021) and to muscle injury at surgery. (Sharma *et al.*, 2017)(Waltenspül *et al.*, 2022)

What determines the choice between surgery or rehabilitation?

Presently, the identification of a painful structure is used to confirm the diagnosis and to direct surgical or rehabilitation management. Surgical interventions have focussed on either (i) the de-tensioning of anatomical structures including the adductor complex via tenotomy, or the rectus aponeurosis attachments via tenotomy and/or, inguinal ligament release (Meyers *et al.*, 2000; Meyers, Lanfranco and Castellanos, 2002) or (ii) tensioning interventions correcting ‘weakness’ or ‘bulging’ of the posterior inguinal wall and Gilmore, (Gilmore, 1998) Mushaweck (Muschaweck and Berger, 2010) and Brannigan (Brannigan, Kerin and McEntee, 2000) describe interventions to insert mesh reinforcement, suture reinforcement or a combination of both. None of these studies offer a clear reproducible pathology identified for the pain presentation.

Rehabilitation studies tend to focus on adductor tendinopathy as the main identified diagnosis (Holmich *et al.*, 1999, 2010) on the premise that adductor tendinopathy, or more correctly adductor tendon pain on palpation, is the injury they are treating, but clinically often multiple structures are painful, and specificity cannot be achieved as easily as the literature suggests.

Surprisingly, given the lack of clear injury, many patients elect for surgical intervention over rehabilitation, even though there is a dearth of evidence that surgery results in a faster return to sport. (Jardí *et al.*, 2014) This preference for surgical intervention compares with the pressure for surgery which had been seen in the management of low back pain, where individual pathologies were isolated and ‘fixed’. However, the low overall successful outcome of back surgery for pain led to the literature (Chou *et al.*, 2009) indicating a move away from surgical solutions given the absence of critical pathology.

For AGP, in the absence of a defined injury, the effectiveness of surgical or non-operative approaches to treatment was unclear. To determine the relative effectiveness of surgical or non-operative approaches on outcomes, we conducted a systematic review and meta-analysis, as paper three. (King *et al.*, 2015)

The analysis identified only one paper which directly compared the outcome of surgery to rehabilitation (Paajanen *et al.*, 2011) which cited our work to make the anatomical diagnosis. 60 patients with pain superior to the inguinal ligament in the deep inguinal ring at palpation, with or without tenderness over the pubic symphysis or tubercle, or at the insertion of adductor tendons were included. The paper did not define the pathological injury but did exclude injury to bone or adductor specifically – although even then, 6 (10%) had additionally simultaneous adductor longus tenotomy, for involvement of adductor muscles, in addition to the inguinal canal mesh repair of the intervention.

This highlighted that the only randomised controlled trial, (Paajanen *et al.*, 2011) did not define an injury, relied on pain alone and did not detail any clear criteria outside of palpable pain as the basis for operative intervention. They showed a much higher return to play rate for surgical intervention (90%) compared with conservative management (50%) for abdominal related pathology. A limitation of the research was that no criteria for the rehabilitation intervention were detailed, bar strength training.

Paper three concluded that the outcomes of surgical and non-operative interventions were similar. (King *et al.*, 2015) This raised the question of how such widely differing approaches could be effective. If reinforcing an area or de-tensioning an opposing area are surgically effective, potentially the same outcome could be achieved non operatively by increasing opposing muscle capacity.

Using the findings from our first three papers, we developed our hypothesis that AGP is a diagnosis without an injury, i.e., there is no pathology outside that of pain and the quest to find it hampers progress towards an effective treatment strategy. This supported our perspective that AGP occurs because of mechanical overload causing pain. Consequently, we worked towards identifying load distribution and technique changes informed by strength and muscular capacity. The aim was to change how the load is experienced by the tissues. These studies which explored this treatment strategy are outlined in papers 4-6.

Is AGP a disorder, rather than injury to specific identifiable tissues?

Given this lack of discrimination and/or correlation between palpation and radiological imaging, we developed the hypothesis that AGP may be caused by overloading of connective tissue in the inguinal region causing pain due to underlying movement patterns which were tolerable and within tissue capacity in some individuals but not in others.

This builds on our previous work which described overuse conditions as a ‘biomechanical overload syndrome’ (BOS) (Franklyn-Miller *et al.*, 2014) in the lower limb, with the same mechanism as the multiple occupational overuse syndromes which have been previously described in the literature (Fry, 1986; Smet, Ghyselen and Lysens, 1998) in musicians and office workers. (Fast, 1995)

The previously diagnosed Chronic Exertional Compartment Syndrome (CECS) is an overuse condition of the lower leg presenting as pain in a region of the leg. Common features of patients at presentation were increased training load, and we identified that running technical kinematics such as overstride, ground contact time and torso position as factors in the development of the condition. (Sharma *et al.*, 2014; Zimmermann, Valderen and Beutler, 2017) The varied levels of tissue capacity of an individual seemed prognostic leading to the proposed condition of “anterior compartment biomechanical overload syndrome.” In this case, the identification of causes of the myotendinous overload, and the reversal of such using biomechanical technique retraining. The resolution of pain and symptoms becomes more important than the identification of the painful structure when any other underlying pathology is ruled out. This paradigm of overload with pain, but without injury drove our belief that AGP was similar.

There are numerous theories of tissue overload and tissue tolerance or capacity. (Kumar, 2001) Multivariate interaction theory of musculoskeletal injury precipitation, differential fatigue, cumulative load, and overexertion theory all are likely in coexistence with multiple factors including genetic, morphology, psychosocial and biomechanical variables interacting. Cumulative load and fatigue reduce the tissues' ability to tolerate the stresses. (Cook and Docking, 2015) The physical stress theory (Mueller and Maluf, 2002) proposes that excessive stress, that is, the stress that exceeds a tissue's tolerance, results in tissue injury and pain.

The concept of progressive overload supports the observation that in one team, players in the same positions, and with the same training load can develop AGP indiscriminately. That is, one player may have a lower tissue capacity or a movement pattern which reduces tissue tolerance due to biomechanical coupling, while another has greater strength capacity or a less propagative movement strategy. It is therefore feasible that AGP is the development of a subclinical overload causing pain, without a definitive, tear or bone failure. Potentially, the quest to identify the 'injury' gets in the way of treatment as all are for specific variations of the same condition.

Can we understand the propagation of load better to understand the pain?

Taking this into account, we decided to approach AGP in a different way, focussing on strength and movement pattern. AGP has a high incidence in multidirectional field sports which include rapid accelerations, deceleration, change of direction and kicking, or in some cases, striking a ball or puck across the body. These actions put significant demands on the pubic intersection/confluence as a central fulcrum. Soccer players cover between 10 and 15km in a match, about 3km is spent static or walking, but 8 minutes are typically spent sprinting over 20km/hr. The player touches the ball between 90 and 140 times, but for less than 90 seconds a game, and change of direction, acceleration and deceleration play a huge part in game success. (Bloomfield, Polman and O'Donoghue, 2007) This led to our analysing provocative tasks.

Rather than try to identify specific structures (to be palpated and identified), if we start to consider the structures attaching to the pubic bone as bundles of force transmitters, we can consider the situations in which they may reach tissue tolerance. Thereafter, we can develop our understanding of how rehabilitation, with the aim of increasing capacity in the tissues, and surgery, aiming to reduce the symptoms of overload and tension by de-tensioning, can both demonstrate similar outcomes as seen in paper two.

Understanding the propagative mechanisms on an individual patient basis may allow us to select better who would benefit from increase in capacity or de-tensioning, as it is likely that various movement strategies by athletes can be measured as a lack of capacity in specific structures.

To reinforce the complexity of the anatomy, and to understand how the descriptions in paper one requires a rethink of AGP, we must start to examine the muscular and tendinous attachments and how the loading of the pelvis and how these attachments alter loading in running, kicking and change of direction. The pubic symphysis is the intersection (*Clinical Sports Anatomy : Andrew Franklyn-Miller : 9780070285552 : Blackwell's*, 2010) between the two anterior pubic rami and is a joint which contributes to the transmission of load across the hip. (Dalstra and Huiskes, 1995)The hip joint is integral to bipedal movement such as running, kicking, turning and change of direction and the relationship of the muscles of the hip and pelvis have been described in detail using moment arm vectors.(Dostal, Soderberg and Andrews, 1986) At different speeds, the muscle contribution to running, acceleration and deceleration vary, (Hamner, Seth and Delp, 2010) and it follows that for any individual they may reach tissue tolerance given a decrease in conditioning, increase in load or through reaching capacity.
(Stouffer, Butler and Hosny, 1985)

In the pubic confluence, tendon attaches to bone in small areas, such as Adductor longus or larger wider areas such as Adductor magnus, via the fibrocartilage transition zone. (Benjamin *et al.*, 2002) The relationship between the mean direction and angular deviation of the fibre orientation of the transition zone creates differing stiffness leading to stress singularities at the sharp corner's around the pubic bone, resulting in stress overload. (Genin and Hutchinson, 1997;

Thomopoulos *et al.*, 2006) As a result of this, we can begin to understand why clinically palpating the differentiating pathologies is not possible. Even if a tendon is palpable, at a micro level a complex three-dimensional pattern of interlocking surfaces between mineralized fibrocartilage and bone, where fibre orientation distributions in the out-of-plane direction affect stress transfer. (Milz *et al.*, 2002) Furthermore, some aspects of the tendon may be in compression while others in tension and thus the development of 'tendinopathy' may have different loading patterns. (Cook and Purdam, BJSM 2012)

During movement in a single plane, such as hip flexion, different contributions, and magnitude of force of muscle groups are evident at different angles in the sagittal plane. (Dostal, Soderberg and Andrews, 1986) We cannot however use a linear model of pull to examine the complexity of change of direction sport. The pubic confluence needs to tolerate the changing strain in multiple directions. There is significant work to explain the position and strain on the pelvis in movements related to football, but primarily in the act of kicking the football. (Lees *et al.*, 2010)

In studies examining the biomechanics prior to ball contact in kicking, the pelvis is rotated posteriorly before contact of the support foot and rotates anteriorly as much as 30^0 to 36^0. (LEVANON and DAPENA, 1998) The torso also has an influence with abdominal muscles attaching to it, and oblique muscles, studies addressing this in kicking demonstrate a backward lean of 13^0 and 17^0 and lateral inclinations to the non-kicking side of 10^0 and 16^0 at ball contact. (Lees *et al.*, 2010)
For the kicking leg, power profiles vary for the kicking leg hip, knee, and ankle during an instep kick (Nunome *et al.*, 2007) and the positive rotational power at the

hip close to 1000 W for the side foot kick suggest that rotational effort is transferred across hip joint to orientate the foot. Alongside kicking, change of direction (cutting) ability is an important component of field sports including soccer (Bloomfield and Polman, 2007) and rugby football. (Green, Blake and Caulfield, 2011) Little research has examined running or change of direction. These are important as they highlight the lack of isolation of singular muscle forces and the role of the torso, and the stance leg particularly at the ankle in the maintaining pelvic stability. In soccer, players make approximately 723 turns and swerves per game and cutting ability has been successfully used in talent identification testing batteries to discriminate between elite and sub elite players. (Bloomfield and Polman, 2007)

The movement certainly appears to be propagative in AGP and hence understanding the components of the movement both kinetically and kinematically are important. Only one paper had examined the effects of biomechanical features on cutting performance. (Sasaki *et al.*, 2011) The authors found, contrary to the kicking movement, forward inclination of the trunk ($r = 0.61$) and ground contact time during the stance phase ($r = 0.65$) were both related to cutting time ($p < 0.05$). Unfortunately, they did not examine the influence that other body segments or joints have on performance.

We designed a reproducible change of direction test, to correlate the joint kinetic and kinematic variables with performance measures in paper four (Marshall *et al.*, 2014) as a step to understand better the mechanisms of loading. Our aim was to determine if we could identify features which could be targeted in rehabilitation. We hypothesised that specific joint features would correlate with time to complete the movement.

We identified five factors strongly related to cutting performance (2.28 +/- 0.11 seconds): peak ankle power, peak ankle plantar flexor moment, range of pelvis lateral tilt (from initial contact to peak knee flexion), maximum thorax lateral rotation angle, and total ground contact time test-retest reliability scores (ICCs) for these 5 factors ranged from good to excellent.

Peak concentric ankle power displayed the strongest correlation with time to complete the cutting task (r = 0.77). In other words, 59% of the variability in cutting time could be explained by variance in this one factor alone.

The finding that ankle concentric peak power is so important to change of direction (CoD) supports similar findings for other sporting tasks such as straight-line sprinting (Debaere *et al.*, 2013) and countermovement jumping. (Vanezis and Lees, 2005) Potentially, its capacity could be associated with load transmission higher up the chain to adductor and hip flexor actions and thus could be associated with AGP. This would suggest that athletic groin pain management which focusses on the source of the pain rather than potential causes of overload at the pelvic confluence could be a limiting factor in treating the condition.

We developed the theory that multiple kinetic dynamic coupling reasons could be associated with increased load and the focus on the movement features in AGP should not be constrained to the pelvis. This theory is supported by the literature for other conditions. For instance, altered movement patterns have been identified in patients with Anterior Cruciate Ligament (ACL) injury during walking and running gait, and when completing functional movements and common rehabilitation exercises. (Trulsson *et al.*, 2015) Research has indicated the importance of ankle power as a risk factor for reinjury in ACL reinjury (Richter *et al.*, 2019; King *et al.*, 2020) and identified in cutting performance as a performance determinant. (Marshall *et al.*, 2014)

Meyers (Meyers, Greenleaf and Saad, 2005) suggests that neuromuscular control of the pelvis is important during high-speed multidirectional sports, as it provides the anchor to facilitate dynamic locomotion. Our findings support this theory, as reduced pelvic lateral tilt (contralateral drop) during the knee flexion phase of the cut was associated with faster cutting times (r = 0.54). Although previous authors have examined the relationship between frontal plane pelvis control and lower extremity injury, our study seems to be the first to have identified a relationship between this quality and cutting performance ability. Green (Green, Blake and Caulfield, 2011) suggests that the stance leg must demonstrate significant control under deceleration in a cut to facilitate efficient stretch-shortening cycle utilization. This may explain, at least in part, the relationship between pelvic control and cutting ability.

Can intersegmental linkage provide a better classification?

To develop our hypothesis that a functional approach to load could complement or replace a clinical examination to better support interventions for AGP, we developed research to analyse the joint kinetics in three planes along with synchronous joint kinematics and the relationships between torso, pelvis, knee, and ankle.

In our fifth paper, "Athletic groin pain (part 2): a prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns" (Franklyn-Miller *et al.*, 2017) we hypothesised that certain features of kinetic and kinematic assessment of the change of direction manoeuvre would correlate with the clinical examination of the painful structures.

We used 'analysis of characterising phases', a novel analysis method, (Richter, 2013) to calculate subject scores that described the behaviours of each subject during the cutting manoeuvre. These were combined into a matrix combining similarity scores to calculate a gap statistic. This gap statistic compared the within cluster dispersion of the data set. We were able to identify three distinct clusters with differences in braking and acceleration phases by joint and phase of movement kinematics and kinetics.

Unexpectedly, we found no significant relationship ($p>0.644$) between movement cluster and the anatomical diagnoses. This suggests that each represent different constructs, that is the manifestation of pain is not associated with movement pattern in this cohort, completing this task. When we examined the distribution of the subjects through clustering, we found some interesting features associated with movement technique, regardless of site of pain.

Cluster One (n =128) showed the highest proportion of work done at the knee (effect size 0.72–0.92), cluster three (n =132) showed predominant work done at the ankle with plantar flexor and evertor moments greater in the first part of the cycle, and the smallest cluster two showed the highest proportion of work done at the hip. This was new information showing that patients with AGP distribute load in different ways, but present with the same pain. This disassociation between pain and movement cluster, and the variables which distinguished the different clusters supported our theory that AGP is an overload disorder.

Although Meyers (Meyers, Greenleaf and Saad, 2005) suggests the posterior chain of the torso is probably the least important in terms of direct stability of the anterior pelvis, we found that it featured in all of our clusters and likely contributed to to overloading the anterior abdominal attachments if lateral and to the hip flexors or adductors in forward or anterior tilt.

Greater thorax anterior tilt, which we observed in cluster 2, has been associated with greater adductor longus activation (Prior *et al.*, 2014) and greater activation of the hip extensors. To date, no relationship has been demonstrated between thorax angles and hip or groin injury. Some work has suggested that changing posture in a sagittal plane whilst in double leg stance could change the activation of abdominal and back muscle activity levels when comparing active upright standing to posterior trunk sway standing. This could lead to a direct mechanism of overload.

As 35% of body mass, the torso’s position is influenced by pelvis orientation and controlled in part by the abdominal muscles (internal and external obliques, rectus abdominis and transversus abdominis), which form the inguinal ligament superiorly and join the tendinous fascia of the common adductors inferiorly to form a connection to the tri layered anterior pubic ligament at the pubic symphysis. (Robertson *et al.*, 2009) In our cohort, we identified this as the primary site of pain in >60% of cases.

If AGP is the result of uncoupling of segmental control in repetitive multi- directional movements, a continuum of musculotendinous and bony overload may be a more appropriate aetiological model. Our theory has developed such, that we believe a margin of tolerance exists anatomically and biomechanically for the task execution of propagative movements for a given individual. This margin diminishes with increased training load, genetic anatomical variation, deviation of movement pattern or other extrinsic factors. Exceeding this margin could lead to subcritical tissue overload —which we propose as a biomechanical overload, the mechanism for AGP development.

How can we use this information to improve treatment?

The most successful approach to non-surgical rehabilitation is the seminal paper by Holmich. (Holmich *et al.*, 1999) It focussed on adductor strengthening on the premise that most of the presentations had adductor pain on palpation thought to represent tendinopathy and presented 68% return to play rates and 18.5 weeks. This study was repeated and confirmed by Weir (Weir *et al.*, 2011) with a return to play rate of 48% at 17.3 weeks.

Our work led us to the hypotheses that decreasing load from the confluence of the pubic bone by a more segmental, and distributed approach to rehabilitation including running and coronal plane whole body strengthening rather than focussing on treating each entity as a separate cause would result in better outcomes.

In paper six, "Clinical and biomechanical outcomes of rehabilitation targeting intersegmental control in athletic groin pain: prospective cohort of 205 patients." (King *et al.*, 2018) We included all "Doha entities", and we demonstrated the fastest return to play (RTP) times in the literature of 9.9±3.4 weeks. The pain-free RTP rate of those who entered the study was 73% (150/205). Although we included all entities, we did not perform the intervention based on those entities and yet, there was no difference in time to RTP based on sub classification of anatomical entity ($p=0.56$). The rehabilitation programming was based on the redistribution of load to the lower limb and torso, and standardised across the patient cohort, we did not program rehabilitation work on individual deficits seen in the clustering. This allows us to suggest that the underlying anatomical entity is less important than previously thought, and that once pelvic movement overload is addressed, outcomes are improved. This differed from previous rehabilitation programs which focussed on a singular deficient or painful muscle group.

Post rehabilitation, kinetic analysis demonstrated increased ankle plantar flexion moment and reduced hip extensor moment as well as reduced hip adduction moment during push-off. Analysis of total work done at each joint showed a large increase in total work done at the ankle, a moderate reduction in the total work done at the hip and a small reduction at the knee after rehabilitation. This primarily was affected by large increases in work in the sagittal plane of the ankle and moderate reductions in work in all three planes at the hip and frontal plane at the knee.

All the kinematic changes were seen across the group, without specific targeted intervention, these include reduced ground contact time. (Sasaki *et al.*, 2011) Increased centre of mass distance to the centre of pressure in the frontal plane (Havens and Sigward, 2015), reduced trunk side flexion towards the stance leg, reduced knee flexion (Dai *et al.*, 2015) and increased ankle power and plantar flexion moment. (Marshall *et al.*, 2014) These changes also concurrently reduced the load around the hip and groin as work in all three planes of the hip and the adductor moment were reduced.

Conclusion

Athletic Groin pain is a chronic condition, lacking a firm pathology and this underpins the confusion over the diagnosis and management, rather than any significant complexity over the differential diagnosis. This is in direct conflict with our initial belief that an increased level of palpatory anatomy knowledge, and clinical accuracy could be confirmed by magnetic resonance imaging and result in discrimination. Our published works have shown that rehabilitation is possible in the same time frame regardless of the painful site(s) and as such the differentiation of anatomical pain matters little to outcome. Interestingly this was also borne out by our meta-analysis as there was little difference seen in rehabilitation and surgical interventions despite the suggestion of many different pathologies.

Without a terminal injury, radiological imaging offers little outside of exclusion of such injury, in seeking confirmation bias by correlating clinical palpation with features that might be painful but not structurally injured, we add to an argument that AGP is not an injury but a disorder. To date, no study has demonstrated any significant pathology linked to a structure being painful and as such we propose that our novel approach understanding the mechanism behind AGP allows us to focus a different approach on rehabilitation.

Anatomical classifications have also failed to adapt to the confirmation of an anterior pubic ligament or the rectus abdominus insertion as a cause of athletic groin pain and over 70% of our subjects, had pain in this site. The confluence of attachments to the pubic bone cannot be differentiated by palpation and inequalities in strain in the transition zone could be an overload in any direction. Our scrutiny of adductor squeeze testing suggests that as a clinical test it is highly sensitive for athletic groin pain but cannot differentiate structures by isolation either adding little value to diagnosis.

We collected the largest set of biomechanical data in the literature in patients with AGP, and initially we utilised a technique of clustering to handle the large amounts of data. As this led us to examine different clusters it allowed us to begin to identify the of biomechanical features on an individual subject level. Our work to date found no correlation with individual sites of pain which initially was a disappointment, but in fact is support for a new approach.

When we evoked the changes in biomechanics using a new approach to rehabilitation, focussing on offloading the pubic confluence, we were successful in demonstrating both higher RTP rates and faster RTP times than any other study. The results post rehabilitation positively affected features that were also associated with CoD performance, indicating a successful intervention.

Although we originally believed that surgery was misplaced in AGP, it may allow a faster approach in some instances as the time taken to increase capacity in opposing segments may be bettered by the de-tensioning of a structure causing pain. This is supported the very similar outcomes of surgery versus rehabilitation in paper three, in almost all entities. It may be that surgery alters strain in the myotendinous unit and a reduction in muscle volume and in torque, (Song, Heu and Song, 2018). Further research is required to assess if surgical tenotomy merely reassigns load to other muscle groups, making recurrence likely or is it indeed a faster option than generating tissue capacity. This is unlikely to be easily achieved without the use of indwelling strain gauges which has not been widely acceptable, although we have demonstrated their use in cadaveric models previously. (Clark *et al.*, 2009)

We did not design individual rehabilitation based on the cluster or indeed the individualised deficits seen in change of direction testing. We did go on to examine the changes seen post successful rehabilitation (Gore *et al.*, 2020; Rivadulla *et al.*, 2020; Welch *et al.*, 2020; Baida *et al.*, 2022) and this work can help identify specific targets to focus rehabilitation on using a BIOmechanical Assisted Rehabilitation Matrix (BioARM) approach. This future work may improve the program outcomes further (less morbidity and time loss for athletes). This may also lead to an opportunity to use BioARM as a screening process with potential to reduce susceptibility overall to athletes of AGP.

We believe that understanding the biomechanics of AGP and the subsequent changes post successful rehabilitation allows a new direction away from pain into targeted personalised rehabilitation on segmental control of the body. The most significant finding in this body of work is in the ability to apply an intervention to all entities and achieve comparable outcomes, and the focus on torso and ankle in the treatment in a rehabilitation approach. This successfully adds weight to the concept of load distribution underpinning the development of AGP.

Finally, this work hopefully throws doubt on current practice of attempting to palpate for a diagnosis which is yet to be proven and offers a new approach which can expedite recovery and minimise morbidity in the population alongside providing clear direction for future work.

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