FACULTY OF HEALTH AND MEDICAL SCIENCES
UNIVERSITY OF COPENHAGEN

PhD thesis

Andreas Serner

Diagnosis of acute groin injuries in athletes

Aspetar Sports Groin Pain Center
Center of Excellence
Aspetar Orthopaedic and Sports Medicine Hospital
Doha, Qatar

Sports Orthopaedic Research Center-Copenhagen
(SORC-C), Department of Orthopaedic Surgery
Copenhagen University Hospital, Amager-Hvidovre
Copenhagen, Denmark

November 2016

ASPETAR سبيتار

SIGILLVM FACVLTATIS MEDICÆ VNIVERSITATIS HAFNIENSIS

Diagnosis of acute groin injuries in athletes

Andreas Serner

Aspetar Sports Groin Pain Center
Aspetar Orthopaedic and Sports Medicine Hospital, Doha, Qatar
&
Sports Orthopaedic Research Center-Copenhagen (SORC-C)
Department of Orthopaedic Surgery, Copenhagen University Hospital Amager-Hvidovre
Copenhagen, Denmark.

This thesis has been submitted to the Graduate School of Health and Medical Sciences,
University of Copenhagen, November 30th 2016.

Academic Advisor

Per Hölmich, DMSc, Professor
Sports Orthopaedic Research Center – Copenhagen
(SORC-C) Department of Orthopaedic Surgery
Copenhagen University Hospital Amager-Hvidovre
Copenhagen, Denmark
&
Aspetar Sports Groin Pain Center
Aspetar Orthopaedic and Sports Medicine Hospital
Doha, Qatar

Project Supervisors

Adam Weir, MBBS, PhD
Aspetar Sports Groin Pain Center
Department of Sports Medicine
Aspetar Orthopaedic and Sports Medicine Hospital
Doha, Qatar

Johannes Tol, MD, PhD
Department of Sports Medicine,
Aspetar Orthopaedic and Sports Medicine Hospital
Doha, Qatar.
&
Academic Center for Evidence Based Sports Medicine
Academic Medical Center Amsterdam, The Netherlands

Kristian Thorborg, PT, PhD
Sports Orthopaedic Research Center – Copenhagen
(SORC-C) Department of Orthopaedic Surgery
Copenhagen University Hospital Amager-Hvidovre
Copenhagen, Denmark

Evaluation Committee

Thøger Persson Krogh, MD, PhD
Diagnostic Center
Silkeborg Regional Hospital
Silkeborg, Denmark

Ara Kassarjian, MD, FRCPC
Consultant Musculoskeletal Radiologist
Corades, LLC
Boston, MA, USA & Madrid, Spain

Committee Chair

Michael Kjær, DMSc, Professor
Institute of Sports Medicine
Copenhagen University Hospital Bispebjerg-Frederiksberg
Copenhagen, Denmark

"For most diagnoses all that is needed is an ounce of knowledge,

an ounce of intelligence, and a pound of thoroughness."

- Arabic proverb[117]

"Twenty years from now you will be more disappointed by the things you didn't do

than the ones you did. So throw off the bowlines. Sail away from the safe harbor.

Catch the trade winds in your sails. Explore. Dream. Discover."

– H. Jackson Brown Jr.[72]

Contents

List of Tables

List of Figures

List of Publications

The thesis is based on the following papers:

I

Acute groin injury diagnosis - a prospective study of 110 athletes.

Serner A, Tol JL, Jomaah N, Weir A, Whiteley R, Thorborg K, Robinson M, Hölmich P.

Am J Sports Med. May 2015:363546515585123. doi:10.1177/0363546515585123.

II

Reliability of MRI assessment of acute musculotendinous groin injuries in athletes.

Serner A, Roemer FW, Hölmich P, Thorborg K, Niu J, Weir A, Tol JL, Guermazi A.

Eur Radiol. July 2016:1-10. doi:10.1007/s00330-016-4487-z.

III

Can standardised clinical examination of athletes with acute groin injuries predict the presence and location of MRI findings?

Serner A, Weir A, Tol JL, Thorborg K, Roemer F, Guermazi A, Hölmich P.

Br J Sports Med. August 2016:bjsports-2016-096290. doi:10.1136/bjsports-2016-096290.

IV

Characteristics of acute adductor injuries in athletes – a detailed MRI study.

Serner A, Weir A, Tol JL, Thorborg K, Roemer F, Guermazi A, Yamashiro E, Hölmich P.

Submitted.

V

Characteristics of acute groin injuries in the hip flexor muscles - a detailed MRI study.

Serner A, Weir A, Tol JL, Thorborg K, Roemer F, Guermazi A, Yamashiro E, Hölmich P.

Submitted.

Abbreviations

ALT	=	Acetabular labral tear
AUC	=	Area under the curve
BAMIC	=	British Athletics muscle injury classification
BME	=	Bone marrow edema
BTJ	=	Bone-tendon junction
DTI	=	Diffusion tensor imaging
ECM	=	Extracellular matrix
FAI	=	Femoroacetabular impingement
ICC	=	Intraclass correlation coefficients
$\mathcal{K}$	=	Kappa
LR+	=	Positive likelihood ratio
LR-	=	Negative likelihood ratio
MDC	=	Minimal detectable change
MRI	=	Magnetic resonance imaging
MSK	=	Musculoskeletal
MTJ	=	Musculotendinous junction
NPV	=	Negative predictive value
PPV	=	Positive predictive value
ROC	=	Receiver operating characteristic
SEM	=	Standard error of the measurement
Sen	=	Sensitivity
Spe	=	Specificity
T	=	Tesla
TE	=	Echo time
TR	=	Repetition time
US	=	Ultrasound

Preface

Complex!
That is one of the first things that come to mind for many health professionals when discussing hip and groin pain in athletes. This is due to the many different pathologies that can lead to pain in the groin region. In a sports medicine setting, the variance in diagnoses is however not that great. The majority of athletes presenting with groin pain have a few general clinical entities. The primary focus should therefore initially be on improving our understanding of these common injuries. This would create the most progress for the sports medicine community and for the athletes.

Nothing.
Astoundingly, research on acute groin injuries is virtually non-existent. This is despite the fact that acute groin injuries are considered some of the most frequent injuries in many multidirectional sports, such as football – the world's most popular sport. Prior to the studies included in this thesis, evidence regarding diagnosis of acute groin injuries was mainly based on a single study from the previous millennium - with considerable limitations. Currently practitioners therefore have to primarily rely on their own experiences.

Imagine…
The fear in the eyes of a nation when their most important player is carried out from the pitch with an acute groin injury during the first match of a world championship. How bad is it? What's the diagnosis? How long will it take before he can play again? What are the risks if he plays? The medical team will face a ton of questions. It is our responsibility within the sports medicine community to gather as much knowledge as possible to establish an evidence base. This base will help us answer some of these essential questions, and make the best decisions.

First steps.
An accurate diagnosis is essential for the understanding of pathology. An accurate diagnosis can give us indications of the etiology - the causes of injury. If we know where the body fails, we can better understand why, and this information is essential for the prevention of injury, which is one of our key aims as sports medicine practitioners.

Additionally, an accurate diagnosis provides the foundation for good treatment. How are you expected to choose a successful treatment if you do not know what the problem is? Inaccuracy, poor understanding, or simply differences in diagnostic terminology, have had profound effects on the management of groin pain in athletes. Numerous variations of "golden" treatment options are suggested without scientific support. For acute groin injuries specifically, this is fortunately less apparent, however, good evidence regarding optimal management is still lacking. The studies in this thesis will attempt to provide some of the first steps in improving our understanding of the diagnosis of acute groin injuries in athletes, which can hopefully assist us in improving both prevention and management of these injuries.

The future is bright

A greater focus on implementing evidence based management of injuries is evident within the sports medicine community. Clinicians are becoming more interested in research, researchers are focusing more on clinical translation, and more clinical sports medicine research is being published. Research is a numbers game; and one of the main reasons for the scarce evidence regarding acute groin injuries is the limited number of athletes at individual research locations. The globalization and interconnection of sports medicine communities across the world provides opportunities for international collaborations, which could lead to significant advances. Hopefully we will move forwards from the analysis of all hip and groin pain together, and target our research focus on specific injuries. This would provide individual practitioners and athletes with knowledge on their specific injury.

Introduction

Groin injury epidemiology in sport

Regardless of the type and level of sports participation, any type of injury is likely to influence the individual considerably. Not being able to participate in the Sunday football league, or missing out on a Champions League final may have comparable negative psychological effects for different individuals. The negative psychological effects of being side-lined due to injury is an area of increasing research, and several psychological stressors following injury have been reported, such as total mood disturbances, reduced self-esteem, and a feeling of identity-loss.[126] Additionally, not being able to participate in the preferred sport, can also highly influence the level of physical activity and the associated health benefits. For instance, participation in small-sided football games at a recreational level has shown improvements in cardiovascular function, lowering cholesterol levels and the amount of body fat, as well as increasing general functional capacity.[7]

At the highest level of sports, any injury resulting in time loss or reduced performance, cannot only be detrimental to the individual, but also to the team's success.[46,74,193] A lower position in the final standings can be associated with considerable financial loss, which in some cases can amount to millions of euros, dollars, kroner, or riyals. As such, improvement of the individual's health and participation level, as well as the team's competitiveness and associated financial benefits are obvious incentives for improving our knowledge of sports injuries.

In general, groin injuries are mainly associated with field-based team sports, such as the various football codes, but all sports involving fast change of directions expose athletes to risk of developing some form of groin pain. Acute groin injuries are, for instance, not uncommon in individual sports such as tennis and various martial arts.

It is difficult to get a reliable overview of the incidence of acute groin injuries in athletes. Many sports do not have adequate injury registration, and even the best studies often lack specific injury information. This includes differentiation regarding injury location within the hip and groin region, or information on injury onset, which might be either acute or gradual. The majority of data on groin injury incidence currently comes from football (soccer), although other sports such as Australian Rules football, rugby, baseball and ice hockey, also provide some overview of groin injury incidence.

Football

In football, groin injuries in general account for up to 19% of all time-loss injuries at senior level, and more often occur in men than women.[187] Few studies look closely at specific diagnoses or clinical entities, which might vary at different levels of play or different geographical locations. A study including clubs from the European Champions League in football over 7 seasons reported specifically on the epidemiology of hip and groin injuries.[191] Groin injuries accounted for 12-16% of all injures, and there was an incidence of 1.1 groin injury per 1000 hours of exposure.[191] Groin injuries had almost 6 times higher incidence during matches than during training.[191] This is also one of the few studies which reported specific diagnoses. Adductor-related groin injuries accounted for about two thirds of all groin injuries, followed by hip flexor-, hip- and inguinal-related injuries to a lesser degree.[191] Similarly, in football at Danish sub-elite level, adductor-related groin pain is considered to be the most frequent diagnosis of groin pain. Here it accounted for over half of reported groin injuries, followed by iliopsoas and abdominal-related groin pain.[87] This study also showed a high number of multiple clinical entities being diagnosed, and that about 2 out of 5 injuries occurred with acute onset ("traumatic").[87] Acute groin injuries are generally considered to be primarily musculotendinous. A general overview of muscle injuries in professional football showed that a typical team of 25 players can expect about 4 hip and groin muscle injuries per season.[48] The hip adductor muscles are the second most frequent injured muscle group accounting for 23% of all muscle injuries, and 7% of all injuries.[48] This distribution appears consistent over a longer period.[75]

Other sports

In Australian Rules football yearly systematic injury reports show that injuries in the groin region have consistently been one of the most frequent injury locations.[133] Groin injuries are reported to account for around 9% of all injuries, with an incidence of almost 3 injuries per 1000 hours of exposure.[132] This corresponds to about 3 new injuries per club per season.[133] A detailed specification of these injuries is however still lacking, as the studies group both acute and gradual onset groin pain together, and omit diagnostic specifications.[132,133] Groin injuries in Australian football present a challenge, because 23-25% of players experience recurrence of groin pain following return to play.[133] This is a considerably higher recurrence rate than reported in football, where re-injury rates are around 12-18%.[48,75]

In professional Rugby Union, hip and groin injuries account for around 8% of all injuries, with an incidence of 0.6 injuries per 1000 hours exposure.[192] Incidence of adductor injuries specifically is described in a different study, with 0.8 and 2.5 injuries per 1000 training and match hours, respectively.[21,22] A very high incidence of groin injuries during international matches has also been reported, with 21 injuries per 1000 match hours.[121] In Rugby League, a high proportion of groin injuries is also shown, with 11% of all injuries being groin injuries, and muscle/tendon injuries being the most common groin injury diagnosis.[61] One Rugby League study reported that 23% of the players sustained an adductor injury over a 2 year period.[129] Similarly, American Football and Gaelic football also report hip and groin injuries as common.[56,124]

Of the non-football codes, ice hockey appears to be the sport with the highest groin injury incidence. Studies from American[37,51,183], Danish,[98] Swedish,[110] Finish[120] and international[182] ice hockey, show that groin injuries account for 3-11% of all injuries.[98,110,120,183] The reported incidence is usually around 1 injury per 1000 hours of general exposure, and around 3 per 1000 hours match exposure.[37,51,182,183] Again, specific diagnostic overviews are usually lacking, but when present, adductor injuries account for the majority of groin injuries in ice hockey.[51,110,183]

Even overhead sports, such as baseball, cricket and basketball, are not immune to a considerable amount of hip and groin injuries sustained by athletes.[30,43,131]

Uniformity in diagnostic definitions and categories are essential for improving epidemiological studies. One of the main reasons for the relatively poor overviews of the specific diagnoses related to groin injuries is the heterogeneous terminology used. This also results in an incomplete overview of the incidence of acute groin injuries, which might additionally be influenced by variations in examination methods.

Groin pain terminology

The complexity of providing a good overview of groin pain is exemplified in the variety of the terminology of diagnoses used around the world. In a systematic review on management of groin pain in athletes, we found 33 different diagnoses used for groin pain in athletes in 72 studies.[162] Although many of these diagnoses are referring to different pathologies or pain presentations, there is also considerable ambiguity related to many of these, with different diagnostic terminology used for athletes presenting with similar symptoms. Some of the most common unspecific diagnoses for groin pain are for instance osteitis pubis, pubalgia, and pubic bones stress, for which definitions often differ, but can have a considerable overlap.[162] This complicates comparisons between studies and limits scientific advances in the prevention, diagnosis and treatment of groin pain in athletes.

Recently, an agreement on general clinical terminology for athletes with groin pain was published by a group of international experts.[190] Although the exact pathologies remain unidentified, this agreement enables similar classification relating the athlete's groin pain to specific areas, with defined clinical entities based on reproducible clinical examination tests.[190] In general, groin pain in athletes is then grouped into three overall categories; 1) defined clinical entities, sub-divided into adductor-related, iliopsoas-related, inguinal-related and pubic-related groin pain; 2) hip-related groin pain, and 3) other causes of groin pain in athletes.[190] In addition to this agreement on terminology a suggestion for minimum reporting standards for clinical research on groin pain in athletes followed. This aimed to improve the quality and transparency of research in this area, including the use of consistent terminology and definitions.[39] Unfortunately, it is also recognized that there is a lack of evidence pertaining to acute groin injuries. Although the general taxonomy was thought to be suitable for acute groin injuries, specific data to inform decision-making on the best clinical examination tests and further investigations in acute groin injuries is still required.[190]

"Acute", "traumatic", or "overload" are all similarly used to describe injuries with a sudden onset of pain. Describing the onset is an important part of the diagnosis. It can provide important additions to the understanding of the cause of injury, and influence elements of treatment. The etiology of most sports injuries is considered multifactorial, including both intrinsic and extrinsic risk factors.[118] Where injuries with a gradual onset of pain potentially requires more attention to individual predisposing factors, a player reporting acute onset pain can usually identify a specific inciting event. A description of the specific injury situation is key to understanding injury mechanisms,[5] and may also be helpful in the diagnostic process. For example, a female handball player reporting acute knee pain with an audible pop in the knee after it collapsed under her during a change of direction will have a very high suspicion of an anterior cruciate ligament injury. This will lead to a number of specific clinical examination tests, for which there is reported diagnostic accuracy.[12] She is also likely to receive an imaging investigation using magnetic resonance imaging (MRI) to confirm the diagnosis, which has also been shown to have high diagnostic validity.[167] In contrast, the clinician faced with a football player with acute groin pain during a fast change of direction does not have any specific evidence on the accuracy of the clinical examination test nor expected findings of imaging, or the value hereof, to assist in the diagnosis and management of the athlete.

The only prospective study on the diagnosis of acute groin injuries using both clinical examinations and imaging stated that the majority of injuries were clinically diagnosed as muscle/tendon injuries.[50] In that study the clinical examination tests were not described. As such, information on appropriate clinical examination tests may instead to be inferred from the examination of athletes with long-standing groin pain. Furthermore, in that study only 1 of the 13 clinically diagnosed injuries could be confirmed using ultrasound (US).[50] A delay of 1 to 6 months between the onset of symptoms and the US examination was described, and this delay highly limits the generalizability of these findings. Prior to this thesis, no studies have documented the clinical or imaging findings in a larger cohort of athletes with acute groin pain, and with all examinations performed shortly after injury. In order to understand what can be seen on imaging, it is important to have a detailed understanding of the regional anatomy.

Anatomical overview

Detailed anatomical variations in acute muscle injuries, such as location and extent of tissue involvement, are often considered to be relevant in the diagnosis and prognosis of time to return to sport. Several muscle injury classification systems have been suggested to assist clinicians in this regard.[76] None of these systems include a specific focus on anatomical details pertinent to injuries in the groin region.[76] The complexity surrounding groin injuries in general is partly due to anatomical complexity. Even the groin region itself is not well defined. The Medical Subject Headings (MeSH) term describes the groin without defining specific anatomical borders: “the external junctural region between the lower part of the abdomen and the thigh.”[69] Beyond the simplified general clinical taxonomy, as previously described, approaches to categorize different pathologies using anatomical reference points can increase the understanding of pain-generating structures and ensuing diagnosis.[54] Acute groin injuries are generally considered to be related to the musculotendinous units, primarily the musculotendinous junctions (MTJ). Although accurate description of all of these has not been achieved, there are several anatomical studies which can assist clinicians in their understanding of acute groin injuries. These cadaver studies usually include older age-groups, sometimes both genders, and can differ in the preservation methods used (embalmed, fresh frozen).

Despite these limitations, these studies still provide a good overview of the anatomy of the muscles in the groin region. The groin muscles can be roughly divided into the adductor muscles, the abdominal muscles, and the hip flexor muscles.

The adductor muscles

The adductor muscle group is considered to include the adductor longus, adductor brevis, adductor magnus, pectineus, gracilis and obturator externus. Of these, the adductor longus is generally considered to be most important in relation to both acute and long-standing groin pain, and the anatomy of the proximal adductor longus has been examined in several studies.[38,172,181] It has been suggested that more than half of the proximal insertion is muscular,[172] however, more recently it has been shown that the enthesis is fibrocartilaginous, and that 3 mm from the origin the adductor longus usually still consists of more than 90% tendon tissue.[38] This suggests that the insertion of the adductor longus might be completely tendinous and that the concept of a muscular insertion might be based on the very close proximity of the MTJ to the bone. The proximal tendon continues superficially, with the lateral part of the tendon transitioning intramuscularly at approximately 1-2.5 cm from the insertion (Figure 1).[181] The entire proximal tendon becomes intramuscular at about 5.5-8 cm from the insertion, where it continues as an intramuscular (central) tendon.[181] The total proximal tendon length is between 7-17 cm.[172] The adductor brevis, which originates just inferior and posterior to the adductor longus, also has an intramuscular tendon about half the length of the adductor longus (Figure 1).[38] Some muscle fibers from the adductor brevis in males, and tendinous fibers in females, are described to fuse with the gracilis, which also originates from a relatively small area on the pubic bone.[38] The gracilis does not appear to have an intramuscular tendon.[38] The origins of the pectineus on the superior pubic ramus, and the obturator externus on the ischiopubic ramus, have received less attention in relation to groin pain, and their MTJs lack specific descriptions. The adductor magnus is described to have two proximal portions.[23,128] The primarily muscular origin extends posteriorly along the ischiopubic ramus (pubofemoral portion) into a tendinous insertion at the inferior ischial tuberosity (ischiocondular portion), from where the proximal tendon extends around 9-13 cm distally.[23,128]

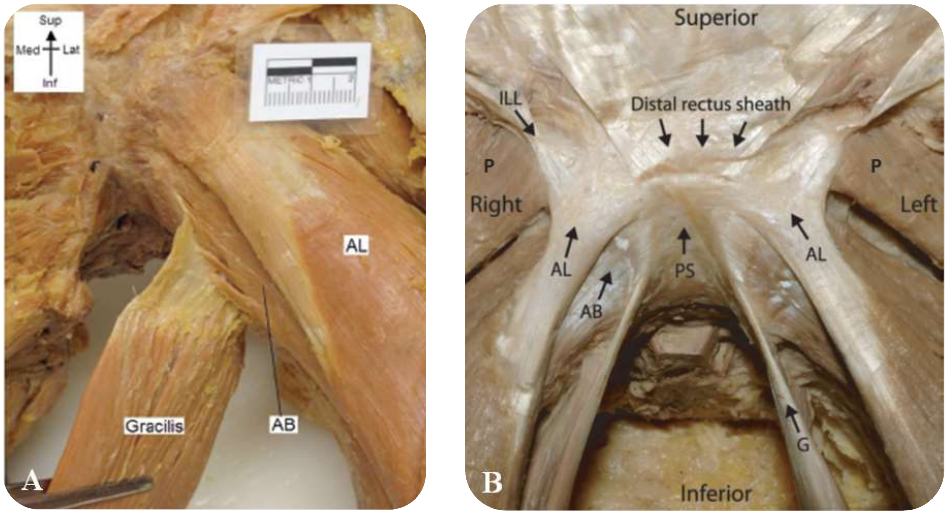


Figure 1: Anatomical images of the proximal adductor insertions.
A: Anatomical dissection of a 57–93 year-old male (age not specified) shows the proximal insertion of the left adductor longus (AL). Note the superficial diagonal line of the musculotendinous junction. Laterally, the tendon appears shorter than medially due to the intramuscular transition. Image from Davis et al, 2012,[38] with permission. **B:** Anatomical dissection of an 84 year-old female shows how close the proximal adductor tendon insertions are to each other near the pubic symphysis (PS). G = gracilis, AB = adductor brevis, P = pectineus, ILL = ilio-inguinal ligament. Image adapted from Norton-Old et al, 2013,[127] with permission.

The abdominal muscles

The structural connection between the abdominal and adductor muscles, the pubic symphysis, and their relation to groin pain is still a topic for debate among experts. The internal and external abdominal obliques, transversus abdominis, rectus abdominis, and pyramidalis muscles are all described to have relevance to groin pain due to their distal insertions on the pubic bone. This is where the complexity, and some controversy, of the anatomy appear in the literature. Some argue that there is direct structural connection between the rectus abdominis and the adductor longus.[130] In contrast, other studies appear to describe that the rectus abdominis attaches at the pubic crest, and that a potential proximal-distal connection would be due to mutual insertions onto the anterior capsular tissues of the pubic symphysis.[154] This anterior tissue has been referred to as the pubic plate, pubic aponeurosis, and rectus abdominis-adductor aponeurosis.[29,130,136] The lower abdominal wall is composed of several additional layers that form the rectus sheath anterior to the rectus abdominis. The transversus abdominis is the deepest abdominal muscle, and is described to fuse medially with the internal oblique to form a conjoint tendon distally. [171] This forms the medial part of the inguinal ring, and attaches at the pubic crest and pectineal line.[171] There is some discrepancy regarding whether there is actually a true conjoint tendon attachment to the pubic bone. Some studies report its presence in only 3% of cases, instead describing a fusion with the rectus sheath slightly proximal to the pubic bone in most cases.[32] Anterior to the internal abdominal oblique, is the external abdominal oblique, which extends diagonally from lateral proximally to medial distally, transitioning into an aponeurosis, which distally forms the inguinal ligament.[53] Medially it connects with the rectus sheath with an opening known as the external/superficial inguinal ring, which allows space for the spermatic cord in males, and the round ligament in females. Additionally, some fibers from rectus sheath, probably the distal aponeurosis of the external oblique, have been described to project diagonally across the pubic symphysis to the proximal part of the adductor longus and gracilis. These fibers are in front of the pyramidalis muscle which attaches on the pubic crest anteriorly and inferiorly to rectus abdominis.[127,165]

The hip flexor muscles

Iliacus & psoas major

The distal tendons of these two deep hip flexor muscles are usually referred to as the iliopsoas tendon; however, anatomical studies show that in the majority of cases there are distinct separate tendons originating from the iliacus and psoas major muscles (Figure 2).[66,142,177] A study of the distal insertions reports a footprint on the anterior-medial aspect of the tip of the lesser trochanter, with the iliacus insertion slightly anterior to the psoas insertion.[66] Proximal to this insertion, the psoas major tendon is located medially, while the primary iliacus tendon located slightly laterally, and an accessory iliacus tendon might also be present.[142] The iliacus tendon extends proximally into the belly of the iliacus muscle, where a division between a postero-medial and antero-lateral parts of the muscle has been shown.[70,142] The most antero-lateral fibers of the iliacus attach directly on the femur, slightly inferior to the lesser trochanter.[148] The length of the iliacus and psoas tendons and their suspected intramuscular course are still not clearly defined. However, the distal psoas major tendon is reported to have an external tendon length of around 7-11 cm, and an internal tendon length of around 5-9 cm, thereby extending to at least two lumbar levels proximally.[158] The proximal attachments of these have not been investigated thoroughly in specific anatomical studies. The psoas major is described to attach between T12-L5, at the transverse processes, intervertebral discs and vertebral margins, while the iliacus attaches at the iliac fossa and the inner lip of the iliac crest.[16,142]

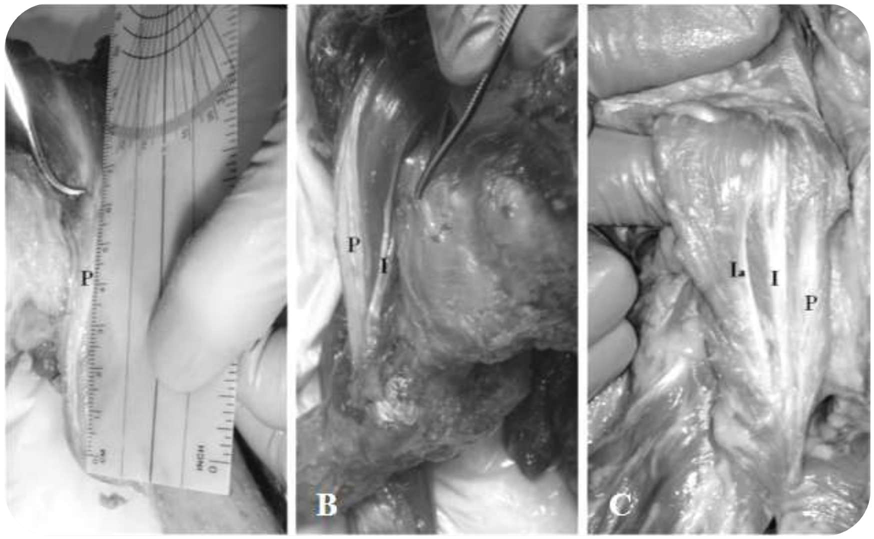


Figure 2: Anatomical images of the variance of the distal iliopsoas tendon(s).
A: Left hip with a single iliopsoas tendon. **B:** Right hip with both a psoas major tendon (P) and an iliacus tendon (I). **C:** Right hip with an additional accessory iliacus tendon (Ia). Tendons in C rotated are 180°. . Image from Philippon et al, 2014,[142] with permission (genders and age not specified).

Rectus femoris

The proximal origin of the rectus femoris is well described and includes two separate free tendon insertions, usually referred to as the direct and indirect tendon.[13,17,71,80,144] The direct tendon attaches to the superior facet of the anterior inferior iliac spine (AIIS) with a small 'tear-drop" shaped insertion, and the indirect tendon attaches about 1 cm away at the rim of the acetabulum in an oblique orientation approximately 5 cm along the rim (Figure 3A)[144,157] Slightly distal from these insertions, the two tendons form a short conjoint tendon with fibers from the direct tendon anteriorly and the indirect tendon posteriorly.[71] Distally, the indirect tendon then extends superficially, while the direct tendon extends intramuscularly (Figure 3B).[13,17,80] The superficial extent of the proximal tendon is relatively wide and short compared to the intramuscular extent of the indirect tendon, which continues distally about two thirds of the total muscle length.[13,71] The muscle fibers do not follow the entire length of the muscle, but are described to be less than 10 cm long and attach to the posterior superficial tendon aponeurosis of the distal tendon, which extends about three quarters of the muscle proximally (Figure 3C).[13,93,189] Distally the tendon forms the anterior layer of the quadriceps tendon.[93]

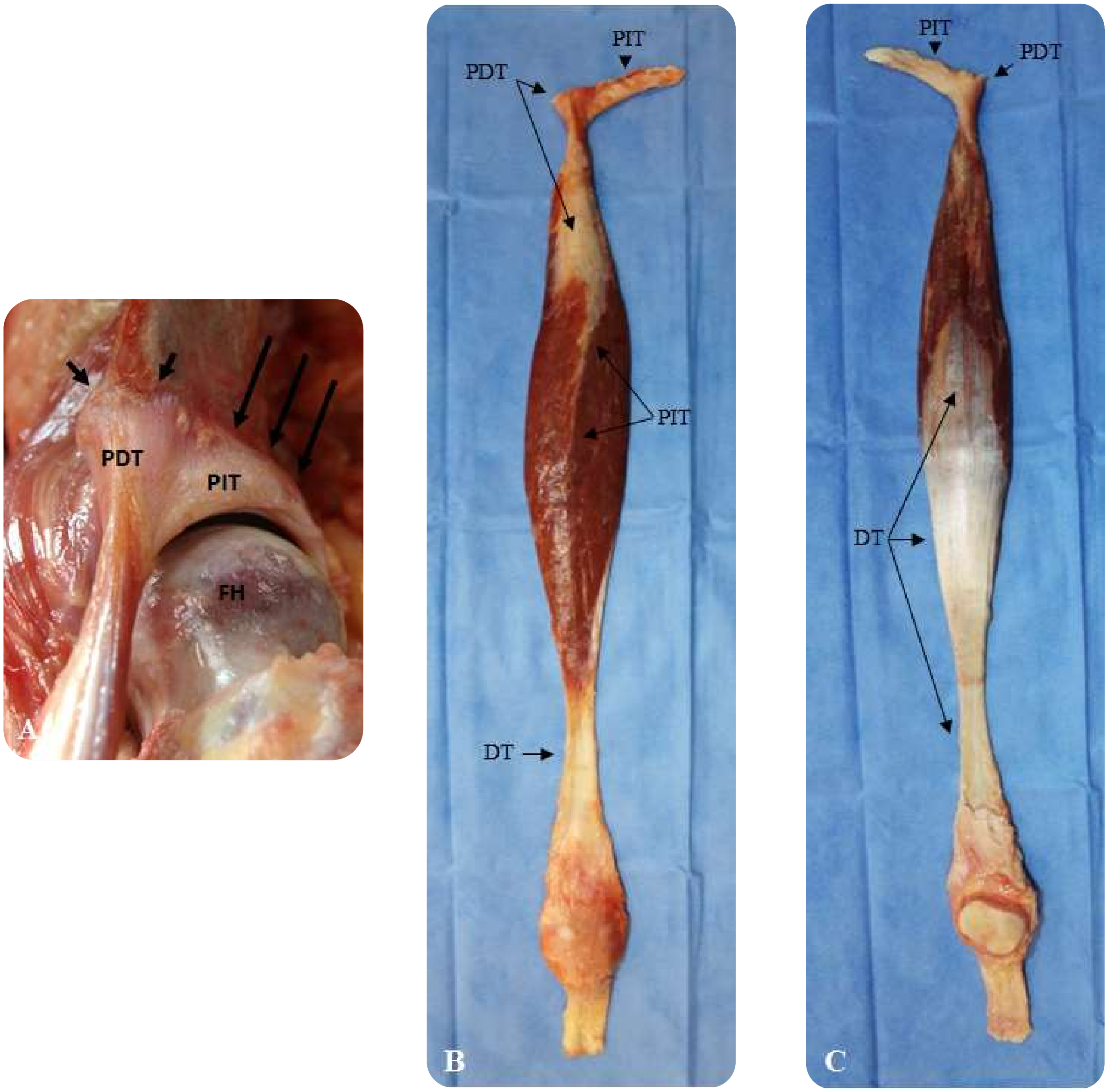


Figure 3: Anatomical images of the rectus femoris.

A: Anatomical dissection of a 46 year-old male shows the left proximal rectus femoris insertions. The direct tendon (PDT) attaches to the anterior inferior iliac spine (short arrows), and the indirect tendon (PIT) to the acetabular rim (long arrows). **B:** Anterior view of the complete rectus femoris muscle removed from its attachments in A. Note the long free PIT (arrowhead). The distal extent of the intramuscular PIT is indicated with longer arrows. C**:** Posterior view of the complete rectus femoris muscle. Note the proximal extent of the posterior superficial tendon aponeurosis of the distal tendon (DT). FH = Femoral head. Personal images from Aspetar Sports Surgery Training Centre.

Sartorius

The sartorius muscle is the longest muscle in the body, extending from the anterior superior iliac spine (ASIS) to the pes anserinus medially on the proximal tibia.[79,174,189] The proximal part of the muscle forms the lateral border of the femoral triangle, and can also be considered part of the groin region.[54] Whereas neurovascular anatomy of the muscle has been examined,[79,174,197] anatomic studies on the extent of the tendons and their MTJs are not available. However, with muscle fiber lengths close to the total muscle length,[189] both the proximal and distal tendon, as well as the related MTJs must be considered very short.

The musculotendinous junction

The connection between muscle and tendon tissue, the MTJ, is described as the most common location of injury in acute muscle strain injuries in athletes.[170,179] One of the main reasons is that the MTJ has an essential role in force transfer from active muscle fiber contraction, assisted by the extracellular matrix (ECM), to the tendon.[91,102]

Skeletal muscles consist of numerous individual muscle fibers (fiber cells), grouped in several fascicle bundles that constitute the muscle. Within each fiber cell there are a number of muscle fibrils. These are formed by a line of sarcomeres, which consist of a number of proteins, most prominently the filaments of actin and myosin. When a nerve impulse is initiated, chemical reactions will cause the myosin to pull in the actin, and this can briefly be considered a foundation of active muscle contractions and active force production.[8,122] The muscle fibers are surrounded by an ECM in different layers. The connective tissue surrounding each muscle fiber is called the endomysium, the perimysium around the fascicles, and epimysium around the entire muscle.[63,64] The ECM is considered to have a key role in the force transmission between tissues through additional shearing.[83,102] On the other side of the MTJ, the strong non-contractile tendon tissue has a similar fibrillar structure as muscle, that mainly consists of collagen.[101]

At the MTJ, the tissues connect through finger-like processes where tendon and muscle interdigitate through numerous invaginations.[103] Tendon collagen outgrowths can be seen extending into the muscle fibers, connecting with the muscle fiber sheath, the sarcolemma, and potentially actin filaments at the end of the myofibrils. At this point, the ECM also appears to fuse with the tendon (Figure 4).[103] This complex connection has recently been described as a meshwork resembling a ridge-like protusion of the tendon when viewed in three dimensions.[103] This ensures an increased surface area, which is considered to reduce the stress on the tissue. [103] It also changes the angle between the membranes and the force vector to withstand more shear forces, thereby increasing the load capacity of the junction.[103] The capacity of the MTJ to tolerate load might be related to acute injury susceptibility, as the MTJ adapts to both loading and unloading according to animal studies. Periods of specific exercise can induce increases in the branching of the tendon protrusions, as well as increasing interdigitations at the MTJ.[36,105] Similarly, unloading reduces the MTJ surface area.[178] Additionally, areas with a flat MTJ without noticeable digitations have been found. [96] This could indicate weaker areas of the MTJ that are more susceptible to injury.

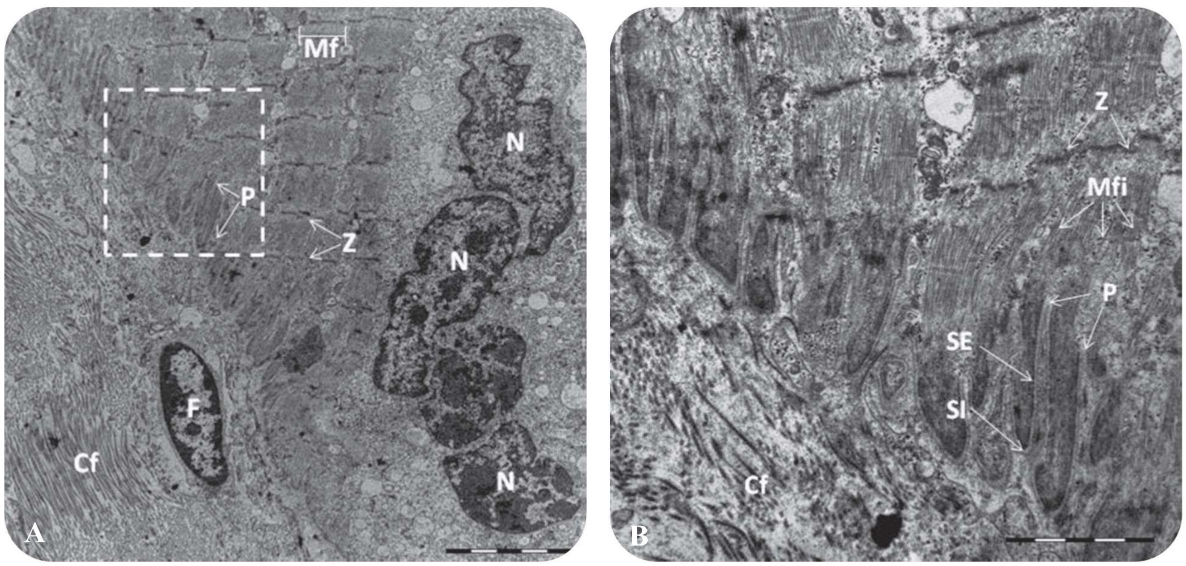


Figure 4: Transmission electron microscopy of the musculotendinous junction (MTJ) in a longitudinal section. **A:** The MTJ is shown diagonally from the top left to the bottom right. At the MTJ, the sarcolemmal invaginations form the interdigitations (P) between the myofibrils (Mf) and the tendon, where collagen fibrils (Cf) are oriented both longitudinally and transversely. Z lines (Z) of the myofibrils can also be seen. A nucleus (N) from a myofiber can be observed to the right, and a fibroblast (F) is visible in the tendon tissue. Scale bar: 5 µm. White dotted square is magnified in B. **B:** Myofilaments (Mfi) are extending from the last Z-lines toward the tendon. Close to the tendon the filaments are very thin, and these are likely actin filaments. Interdigitations (P) with sarcolemmal evaginations (SE) and sarcolemmal invaginations (SI) can be seen more clearly in this image. Scale bar: 2 µm (human MTJ). Images from Knudsen et al, 2014,[103] with permission.

The anatomical details described above demonstrate that knowledge of the location of MTJs continues to evolve. Thus the area of potential injury extends to more than just simply proximal and distal connections. Injuries can also involve intramuscular tendons and superficial aponeuroses, which could be relevant to the diagnosis of these injuries. Additionally, acute groin injuries might also occur at the insertion.

The bone-tendon junction

The enthesis is used as a general term for the attachment of soft tissue to bone.[10,112,164] This includes tendons, ligaments and joint capsules, therefore the bone-tendon junction (BTJ) more clearly refers to the specific structural transition between tendon and bone. Similar to the MTJ, the BTJ is also an area of high force transmission and therefore also a potential site of acute injury. The BTJ can involve either a fibrous or a fibrocartilaginous transition, with the latter being more common. This can be divided into four zones; bone, calcified fibrocartilage, uncalcified fibrocartilage, and dense fibrous connective tissue (tendon) (Figure 5A). [2,9] There is interlocking between the bone and the calcified fibrocartilage, as well as between the uncalcified fibrocartilage and the collagen fibers, similar to the interdigitations seen at the MTJ.[2] Between the calcified and uncalcified fibrocartilage a relatively straight line is seen, representing the border of calcification, thereby separating the hard and soft tissue. This border is called the tidemark (Figure 5B).[9,10,164] The zones of both calcified and uncalcified fibrocartilage are avascular and create a barrier to direct cell to cell communication between bone and tendon, which is considered to prevent bony ingrowths into tendons.[10] Similarly, the relatively flat division at the tidemark is considered to reduce the risk of damage to the soft tissue during movement, as it enables collagen fibers in the uncalcified fibrocartilage to bend more easily. This is also considered a force dampening function during movements, which affects the insertion angle.[2] The BTJ is also considered load responsive, with both mineral deposition and fibrocartilage formation affecting organization of fiber distribution, which can change the mechanical properties.[112] Although the BTJ appears more adaptable during developmental stages,[11,112] variable loading periods are also considered to influence injury risk, for example of tendon avulsion injury.[9] Although tendon avulsion injuries in the groin region are relatively rare, both adductor longus and rectus femoris tendon avulsions are reported in different sports.[41,60,89,94,149,159,184]

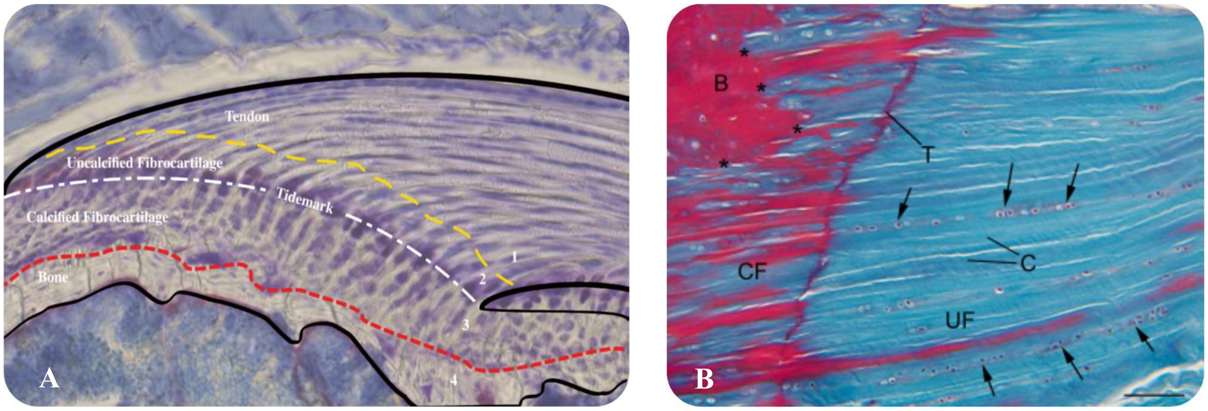


Figure 5: Histological samples of the bone-tendon junction (BTJ).
A: Illustration of the four zones of the BTJ. The compositional gradient characteristic of the BTJ is highlighted by toluidine blue staining, which shows calcified fibrocartilage, fibrocartilage, and proteoglycans in tendon in purple. Image from Apostolakos et al, 2014,[2] with permission. **B:** Higher magnification of the four zones of the BTJ (human triceps brachii). B = bone, CF = calcified fibrocartilage, T = tidemark, UF = uncalcified fibrocartilage, C = collagen fibers. Arrows indicate longitudinal rows of cells between C within the UF zone. Note that no blood vessels are present in the fibrocartilage zones. Scale bar: 100 µm (mouse supraspinatus). Image from Benjamin & McGonagle, 2009,[10] with permission.

Imaging assessment

Clinicians are often absent during imaging assessment, and have to rely on, or attempt to interpret, the at times limited information provided by the radiologists, who may not be very familiar with specific types of sports injuries. Radiologists are dependent on the quality of the clinical information provided in the referral, as they may not have seen the athlete. This clinical process can have many limitations, as the interpretation of imaging in athletes with groin pain can be difficult, even for specialized musculoskeletal radiologists. In long-standing groin pain, imaging is being used extensively despite limitations in the evidence of clinical relevance of abnormal findings.[20] Many MRI findings which may be considered to be abnormal have been shown to be normal variations associated with sports-activity rather than relevant to the reported groin pain.[19] In acute muscle injuries, the relationship between imaging findings and injury appears to be much better;[100] however, high quality imaging studies are still lacking for acute groin injuries. While examples of muscle injuries in the groin region are sometimes included in articles describing imaging of muscles injuries or groin pain in general,[125,130,199] there are no original studies focusing on MRI of athletes with acute groin injuries. As with the clinical examination, radiologists therefore have to rely on general knowledge and personal experience.

To visualize the anatomy of the groin and potential acute injury findings, a basic understanding of the various imaging examinations is required. While conventional radiography (x-ray) is sometimes used to investigate potential skeletal injury of the pelvis, the most commonly used examinations for acute groin injuries are ultrasonography and magnetic resonance imaging, due to their ability to visualize the specific musculotendinous structures.

Ultrasonography

As the name indicates, an ultrasound examination is based on sound and the amount of reflection and absorption in the tissues. Inaudible high frequency sound waves (>7Mhz) are elicited by a sonographer through various types of hand-held transducers, depending on the depth of the desired tissue evaluation.[104,139,195] An anatomical visualization, which can be dynamic, is provided immediately on a dedicated screen. The placement of the probe and the machine settings will determine the picture seen. Different tissues have different reflective/echoic abilities, which then have specific appearances on the displayed images. While muscle fibers are very hypo-echoic and appear dark, their surrounding perimysium is hyper-echoic, and appear as bright linear lines within the muscle with a longitudinal placement of the transducer, and as small bright spots with a transverse placement.[104,139,195] The epimyseum and fascia surrounding the muscles, as well as tendons are also hyper-echoic with bright visualization, and can be distinguished by their thickness and location. When examining acute musculotendinous injuries, findings of areas within the muscle with subtle hypo-echogenicity indicate smaller injuries, and areas with more clearly surrounded hypo-echogenicity, and where the bright striation of the perimysium appear disorganized, more clearly indicate larger structural injuries.[104,139,195]

Prior to this thesis, the only study focusing on imaging diagnosis of acute groin injuries used US examinations.[50] This was a relatively small study including only 25 injured football players, where 13 cases were clinically diagnosed with a musculotendinous injury. Only one of these cases was confirmed on US. In addition to a poorly controlled injury onset, the duration between injury and US examination varied between 1 to 6 months.[50] As US examination for acute muscle injuries is often recommended to be performed within 48 hours after injury onset,[139] this highly limits the knowledge gained from this study on acute groin injury and US.

Inter-examiner variability and diagnostic accuracy is a constant concern in the interpretation of US examinations.[81] The experience of the sonographer is therefore essential. There are however other benefits of using US, such as; easier availability, quick examination time, and relatively low cost compared to MRI. Additionally, US examinations are becoming more widely used by clinicians themselves, reducing the need for external advice from a specialized radiologist.

Magnetic resonance imaging

MRI has a unique ability to visualize soft tissue structures, and is currently considered to be the gold standard for imaging musculotendinous injuries.[33] Again, the name indicates the function. MRI uses a powerful magnetic field and radiofrequency pulses, which can visualize different tissues based on the electromagnetic activity of atomic nuclei.[14] These nuclei have spins, which are based on the number of protons and neutrons, which for MRI purposes need be odd-numbered in order to be MR active.[14,55] Hydrogen is the most common atom in the body, and with one proton and no neutrons, a magnetic field is generated within the atom, thus hydrogen is the preferred target in most clinical MRI.[14,55] The visualization of the tissues is based on an applied external magnetic field interacting with the magnetic field of the hydrogen nuclei, causing them to wobble, and the spin axes of the individual nuclei are aligned in a specific direction.[14,55] The radiofrequency pulse is applied at a predetermined strength and duration, causing changes in the spin angles, and when the pulse is off, the hydrogen protons gradually return to their normal state. This produces specific radio signals for different tissues, which can be measured by coils placed on the body, that turn the signals into images.[14,55] To control this wobbling, and the subsequent visualization, specific MRI sequences and settings are used.

Two key parameters determine the MR image contrast; repetition time (TR) and echo time (TE), both measured in ms.[14] Repetition time describes the time between the start of two following radiofrequency pulses, and echo time describes the time between the radiofrequency pulse and the peak of the detected echo. These two parameters are related to differences in sequence weighting, with repetition time affecting T1-weighting, and echo time affecting T2-weighting. In musculoskeletal imaging, proton density-weighting (PD) will often also be performed. A main choice between MRI sequences is determined based on whether it is desired to define normal anatomy or to examine pathology through abnormal fluid detection or contrast enhancement.[33] Furthermore, the sequences are set to visualize structures in the different planes; coronal, axial, or sagittal views, which can also be obliquely angled. The strength of the magnetic field is related to the MRI scanner itself, and measured in Tesla units (T). Usually 1.5T or 3T scanners are used for musculoskeletal injuries, with the higher scanner strength becoming more available. This can improve images through increased spatial resolution, or assist in decreasing scanning time; however, whether an increase in scanner strength influences clinical management currently appears unclear.[155]

T1

T1-weighted sequences are characterized by a low repetition time (<1000ms) and a low echo time (<30ms).[55] The short repetition times provides an ability to differentiate tissues based on the T1 relaxation time.[55] In simple terms, "tissues with high signal recovery speed" (short repetition time) will have a high MR signal on T1 sequences. As the relaxation time for fat is short, fat will appear bright and clearly distinguishable from water, which with its long relaxation time appears dark.[14] Muscle will also appear relatively dark.[65] Therefore the edema normally associated with acute injury will not be clearly distinguishable. Thus T1-weighted sequences are mainly used as anatomical reference sequences in the examination of acute muscle injuries.

T2

T2-weighted sequences are characterized by higher echo time (>60 ms), and a high repetition time (>2000 ms).[55] The long echo times enable a differentiation between tissues based on the T2 signal decay. In simple terms, "tissues with high signal endurance" (long echo time) will have a high signal on T2 sequences. As the signal decay for water is much longer than muscle, water will appear much brighter.[65] In normal T2-weighted sequences fat will also have a relatively bright signal, therefore additional fat suppression is usually applied when examining muscle injuries.[55] This will make fat darker, to more clearly distinguish fluid related to acute injury.[14]

PD

Proton density-weighted (PD) sequences can be considered an intermediate between the T1 and T2-weighting. By adjusting the repetition and echo times (long and short, respectively), differences between tissue relaxation times are minimized. Instead the visualization of tissues is based on the proton density within the tissue.[14] This enables a high signal-to-noise ratio, but reduces the sensitivity of clearly differentiating fluid. PD-sequences are mainly used to examine joints, specifically articular cartilage and menisci,[55] and in relation to groin pain; to focus on changes at the pubic symphysis.[130]

STIR

In addition to fat suppression added to T2 and PD-weighted sequences, separate short tau inversion recovery (STIR) sequences, also known as short T1 inversion recovery, can be used to eliminate the signal from fat, while also reducing potential artifacts in the normal T1-weighting.[55] As these sequences will also visualize muscles as dark, and fluid bright, they can be used as an alternative to, or complement the T2-weighted sequences. This can potentially make injury-related edema even easier to identify, although STIR sequences are also associated with a worse signal-to-noise ratio.[55]

Aims

General aim of the thesis

Given what is known about groin anatomy, the utility of various examination methods, and the limitations of previous research, the overall aim of this thesis is to improve our knowledge of the diagnosis of acute groin injuries in athletes, using both clinical and imaging examinations.

Specific study aims

Study I: Acute groin injury diagnosis - a prospective study of 110 athletes.

Aim: To describe injury situations, clinical diagnoses, and imaging findings in a cohort of athletes with acute groin injuries.

Study II: Reliability of MRI assessment of acute musculotendinous groin injuries in athletes.

Aim: To develop and describe a detailed MRI assessment approach for acute groin injuries in athletes, and to determine its intra- and inter-rater reproducibility.

Study III: Can standardized clinical examination of athletes with acute groin injuries predict the presence and location of MRI findings?

Aim: To investigate the ability of specific clinical examination tests to predict a positive or negative MRI injury in athletes with acute groin injuries. Additionally, to assess the accuracy of the clinical examination tests to predict the location of the injury in MRI positive cases.

Study IV: Characteristics of acute adductor injuries in athletes – a detailed MRI study.

Aim: To describe injury characteristics of acute adductor injuries in athletes using magnetic resonance imaging. Additionally, to compare specific muscle injuries with reported injury situations.

Study V: Characteristics of acute groin injuries in the hip flexor muscles - a detailed MRI study.

Aim: To describe injury characteristics of acute hip flexor injuries in athletes using magnetic resonance imaging. Additionally, to compare specific muscle injuries with reported injury situations.

Methods

Participants

For all five studies, we prospectively and consecutively included athletes with an acute groin injury from an outpatient department at a specialized sports medicine hospital in Doha, Qatar. Athletes are referred to this hospital via the medical staff from their club or federation through a national sports medicine program. This involves sporting clubs and federations from the entire country. Immediate consultation access is provided through a daily walk-in clinic service for the assessment of acute sports injuries for all registered athletes.

In order to be considered for inclusion in the studies, participants had to be male athletes between 18 to 40 years old, and participating in competitive individual or team sports. They had to present at the hospital within 7 days of acute-onset groin pain sustained during sport. We did not consider athletes for inclusion if they could not recall a sudden onset of pain (e.g. if a more gradual pain onset or exacerbation of previous pain during a game or training was described). Additionally, athletes were excluded if they had any clinical signs or symptoms of prostatitis or urinary tract infection, or other known coexisting chronic diseases, such as significant hip osteoarthritis. Additionally, we excluded participants from the MRI examination if they had claustrophobia or other standard MRI contraindications.

For the five studies there were minor differences in specific inclusion criteria to accommodate the individual study aims. In Study I and II, we followed the general inclusion criteria as described. In Study III-V, it was an additional inclusion criterion that MRI also had to be performed within 7 days of injury. For studies IV and V we only included athletes with an MRI positive adductor or MRI positive hip flexor injury, respectively. Similarly, there were also minor differences in the inclusion periods as a result of the study development, as illustrated in Figure 6.

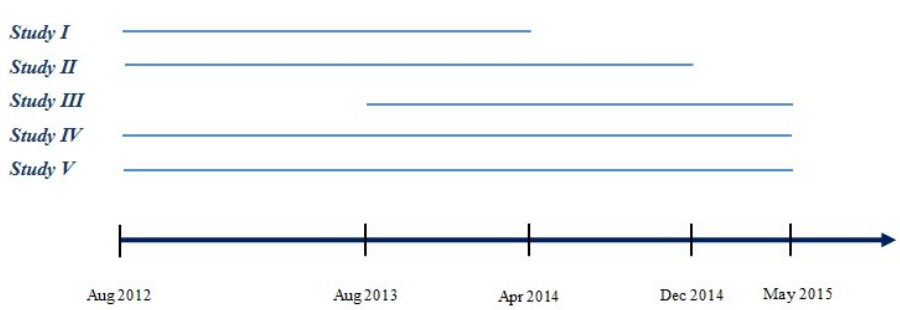


Figure 6: Specified inclusion periods for the five studies

Ethics

Informed consent was acquired from all athletes at inclusion. Official ethical approval was initially obtained from the Shafallah Medical Genetics Center Institutional Review Board (IRB project no. 2012-013), and subsequently renewed by the Anti-Doping Lab Qatar Institutional Review Board (IRB#: EXT 2014000004). These approvals cover all the five included studies.

Study process

The studies in this thesis focus on different elements of the diagnostic process. Initially the injured athlete received a clinical examination by a specialized sports medicine physician. In this process the exact techniques used were not standardized. For study III we introduced an additional clinical examination performed separately by a research physiotherapist using standardized examination procedures. After the clinical examinations, the athlete was referred for imaging, which included both US and MRI. The US examinations were originally planned to be part of study I, and discontinued subsequently due to logistical and practical reasons. For both imaging investigations, injury findings were registered by the radiologist on duty and these imaging diagnoses were used for study I only. The obtained MRI images were then further analyzed in study II, forming the basis for studies III-V.

Injury history

A standardized injury history was recorded by a sports medicine physician on a study-specific registration form during the initial clinical examination. Data were collected on the type of sport, injury situation, injury time (training or match), leg dominance (defined as the preferred kicking leg regardless of type of sport), and whether the athlete had any previous groin injuries. The injury situations were categorized into: “kicking”, “change of direction”, “stretch or reaching situations”, “sprinting or running”, “jumping”, and “other”, which was not further specified. The categorization of “kicking” included any types of passes, crosses, shots on goal, as well as combat kicks. For this category it was also noted whether the injury occurred in the kicking leg or the supporting leg. The category “stretch or reaching situations” included any movements where the player was reaching with one leg, e.g. reaching for a ball, or was sliding on the grass or floor. Injuries that were categorized into “sprinting or running” included situations where the athlete was moving straight forward either in acceleration, full sprint or deceleration. If the running or sprinting included a sideways movement, it was categorized as “change of direction”. The category “jumping” included both the take-off and landing part of any jump. All other situations were categorized together, including instances where the athlete recalled a definite sudden onset of pain, but could not describe the specific injury situation.

Initial clinical examination

The initial clinical examination performed by a sports medicine physician consisted of the three types of pain provocation tests; palpation, muscle resistance and stretch tests. These were based on previous work showing good intra- and inter-examiner reproducibility of the majority of the tests during examination of athletes with long-standing groin pain.[85] The included tests were: hip adduction squeeze tests in 0˚ and 45˚ hip flexion, resisted hip flexion in 0˚ and 90˚ hip flexion, resisted straight and oblique abdominal flexion, hip adductor stretch, modified Thomas test, FABER test (flexion, abduction, external rotation), anterior hip impingement test (FADIR: flexion, adduction, internal rotation), hip internal rotation range of motion restriction in 90˚ hip flexion, log roll, and palpation of all structures in the groin region, including an inguinal canal examination if the athlete reported any lower abdominal pain. Instructions on the clinical examination tests were presented to the group of sports medicine physicians on several occasions, and a standardized examination form was completed with a researcher present during the examination to minimize differences in examination techniques between the different sports medicine physicians. Strict control of individual variations in test execution was however not performed. As there is no general agreement on a specific algorithm for the diagnosis of acute groin injuries, the clinical diagnosis was based on a minimum of one positive finding in palpation, stretching, or muscle resistance testing, as well as the individual sports medicine physician's own experience and clinical reasoning. The sports medicine physicians' clinical diagnoses were only used in study I, where injury locations were categorized into: adductor (without differentiating between the adductor muscles), iliopsoas, abdominal, proximal rectus femoris, and/or proximal sartorius injuries. If more than one clinical injury location was present, the injury was registered for each location and as "multiple locations". It was also possible for the sports medicine physician to note a different diagnosis to include other possible causes of acute groin pain, such as suspected intra-articular hip injuries or non-musculoskeletal causes.

Standardized clinical examination tests

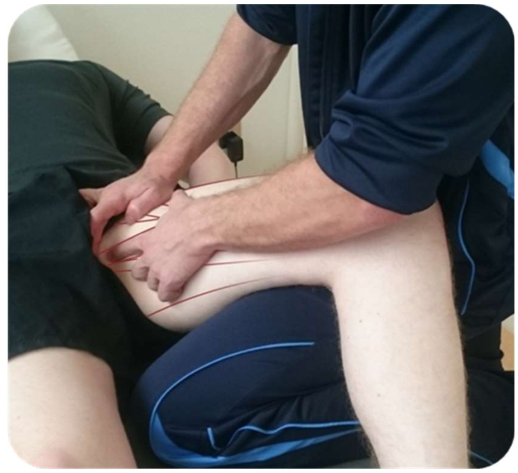
In study III we included an additional standardized clinical examination. This consisted mainly of pain provocation tests, and was performed by a physiotherapist who was blinded to the imaging results. The standardized examination tests included in Study III are described in Figure 7. For the analysis, the clinical examination tests were grouped into three categories: 1. hip adductor, 2. hip flexor, and 3. abdominal tests (Table 1). All the clinical examination tests included a bilateral comparison, and were only deemed positive if the athlete recognized the specific acute injury pain for the tested area. If the player reported pain or discomfort during a test unrelated to the acute injury pain, the test was considered negative. The Modified Thomas Test is normally used as a hip flexor test, but in this study it was also considered as an abdominal test, and hence considered positive if an athlete reported abdominal pain during the test, either in addition or isolated to/from any other groin pain.

Table 1:
Categorization of the specific clinical examination tests.

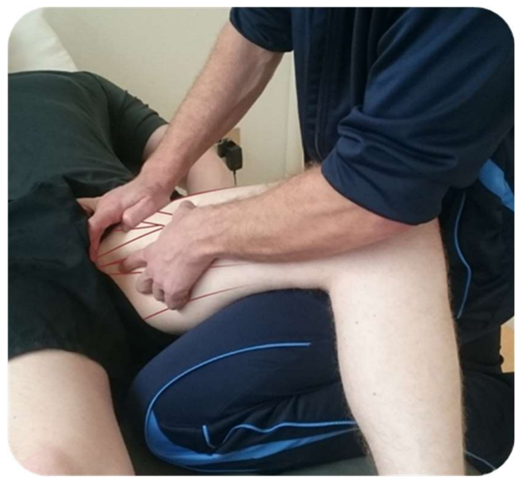
	Adductor tests	**Hip flexor tests**	**Abdominal tests**
Palpation	*Specified for:* Adductor longus Pectineus Gracilis	*Specified for:* Psoas (supra-inguinal) Iliopsoas (infra-inguinal) Proximal rectus femoris Proximal sartorius	*Specified for:* Rectus abdominis Superficial inguinal ring Inguinal canal
Resistance	Squeeze test with 0˚ hip flexion Squeeze test with 45˚ hip and 90˚ knee flexion Outer-range adduction	Hip flexion in 0˚ hip flexion Hip flexion in 90˚ hip and knee flexion Hip flexion in the modified Thomas Test Knee extension in the modified Thomas Test	Oblique sit-up Straight sit-up Hip flexion in the modified Thomas Test
Stretch	Passive adductor stretch FABER test	Passive hip extension in the modified Thomas Test Passive hip extension and knee flexion in the modified Thomas Test	Passive hip extension in the modified Thomas Test

Categorization only used in Study III.

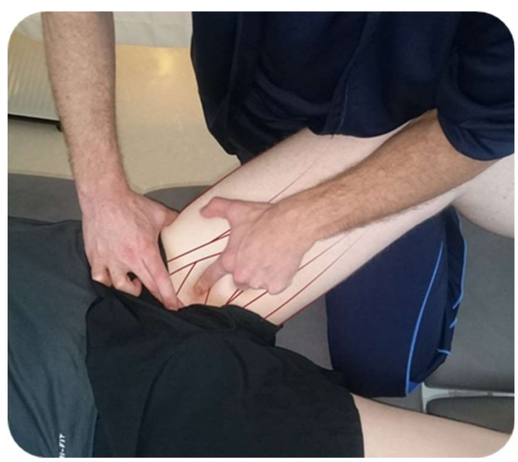
Adductor longus palpation
The patient lies supine on the examination table with the tested leg placed in a relaxed position with the knee on the examiners thigh, which is supported by the examination table. The hip of the tested leg is flexed, slightly abducted and externally rotated. The examiner palpates the adductor longus insertion on the pubic bone just inferior to the pubic tubercle and follows the adductor longus tendon and muscle distally.



Gracilis palpation
The patient lies supine on the examination table with the tested leg placed in a relaxed position with the knee on the examiners thigh, which is supported by the examination table. The hip of the tested leg is flexed, slightly abducted and externally rotated. The examiner palpates the gracilis muscle a few centimeters distal to the pubic insertion to distinguish the gracilis from the adductor longus. The gracilis is then palpated both proximally and distally from the starting point.



Pectineus palpation
The patient lies supine on the examination table with the tested leg placed in a relaxed position with the knee on the examiners thigh, which is supported by the examination table. The hip of the tested leg is flexed, slightly abducted and externally rotated. The examiner palpates the pubic tubercle and follows the superior pubic ramus a few centimeters laterally. Palpation is then performed a few centimeters distal from this point within the femoral triangle, lateral to the adductor longus, and medial to the femoral vein, artery and nerve. While the examiner palpates the pectineus with a firm pressure with one hand, the patient is asked to push against the examiners other arm which is placed medially with the elbow on the knee of the tested leg. The examiner should then be able to feel the contraction of the pectineus.



Proximal sartorius palpation
The patient lies supine on the examination table with the tested leg placed in a relaxed position with the knee on the examiners thigh, which is supported by the examination table. The hip of the tested leg is flexed, slightly abducted and externally rotated. The patient is asked to push against the examiners hand which is placed on the medial malleolus of the tested leg. This will make the sartorius appear clearly, and the muscle can be differentiated from the surrounding muscles proximally near the insertion on the anterior superior iliac spine.

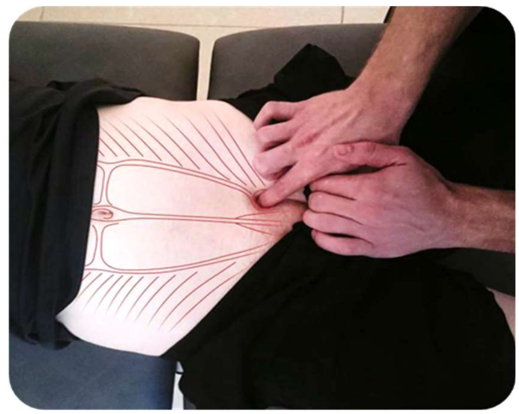
Iliopsoas palpation (infra-inguinal)
The patient lies supine on the examination table with the tested leg placed in a relaxed position with the knee on the examiners thigh, which is supported by the examination table. The hip of the tested leg is flexed, slightly abducted and externally rotated. The patient is asked to push against the examiners hand which is placed on the medial malleolus of the tested leg. This will make the sartorius appear clearly, and the examiner can locate the distal iliopsoas in the femoral triangle just medial to the sartorius below the inguinal ligament. If the examiner cannot clearly distinguish the iliopsoas a resisted hip flexion can be performed while the examiner palpates.

Proximal rectus femoris palpation
The patient lies supine on the examination table. The rectus femoris is located by asking the patient to push against the examiners hand, which is placed anteriorly on the distal tibia. The rectus femoris is then palpated proximally towards the insertion on the anterior inferior iliac spine in the small triangle between the sartorius medially and the tensor fascia latae laterally.

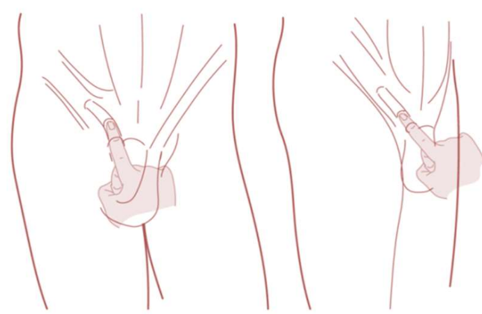
Psoas palpation (supra-inguinal)
The patient lies supine on the examination table. The examiner locates the lateral edge of the rectus abdominis muscle at the level of the anterior superior iliac spine. Palpation is performed laterally to this. The fingers are gently pressed posteriorly while pushing the abdominal structures away to reach the psoas muscle. The patient must be relaxed. When the fingers are as ‘‘deep’’ as possible, the patient is told to elevate the foot slightly on the side being tested. The psoas muscle is now palpated firmly over as large an area as possible.

Rectus abdominis palpation
The patient lies supine on the examination table. The rectus abdominis muscle is palpated slightly lateral to the umbilicus and followed distally to the pubic insertion.

Superficial inguinal ring palpation
The patient lies supine on the examination table and the pubic tubercle is located. The examiner then moves the finger slightly proximally and laterally until a clear softer area is felt, indicating the superficial inguinal ring. The examiner then palpates the borders of the inguinal ring.



Inguinal canal palpation
The patient is standing in front of the examiner. The examiner invaginates the scrotum with one finger and the external inguinal ring can be palpated slightly proximally and laterally to the pubic tubercle. The examiner then gently attempts to move the tip of the finger through the external inguinal ring into the inguinal canal.



Squeeze test with 0° hip flexion
The patient lies supine on the examination table. The examiner stands at the end of the examination table with the lower arm between the feet of the patient to hold them apart. The feet of the patient point straight up, and the patient presses the feet together with maximal force without lifting the legs or pelvis.

Squeeze test with 45° hip flexion and 90˚ knee flexion
The patient lies supine on the examination table. One leg is flexed until the medial malleolus is positioned at the level of the contralateral medial knee joint line. The other leg is then flexed similarly, so both medial malleoli are next to each other and the feet flat on the table. The hips will then be approximately 45 degrees flexed and the knees flexed approximately 90 degrees. The examiner then positions a clenched fist between the patient's knees, and the patient is asked to press the knees together with maximal force.

Passive adductor stretch
The patient lies supine on the examination table. The examiner abducts the tested leg, holding it with one hand to ensure the foot points straight up. With the other hand, the contralateral leg is supported to stabilize the testing position. The tested leg is then moved into maximal abduction.

Outer-range hip adduction
The patient lies supine on the examination table. The examiner abducts the tested leg, holding it with one hand to ensure the foot points straight up. With the other hand, the contralateral leg is supported to stabilize the testing position. The tested leg is then maximally abducted and in this position the patient is asked to push the leg in towards the examiners body.

FABER test
The patient lies supine on the examination table. The hip and knee of the tested leg is flexed, abducted and externally rotated, as the foot of the tested leg is placed on the contralateral thigh just proximal to the knee. While stabilizing the pelvis on the contralateral side, a gentle pressure is applied downwards on the knee of the tested leg.

Resisted Hip Flexion 0°
The patient lies supine on the examination table. The patient is asked to flex the hip keeping the leg straight, while the examiner applies resistance slightly proximal to the ankle of the tested leg.

Resisted Hip Flexion 90°
The patient lies supine on the examination table. The tested leg is flexed to approximately 90 degrees in both the hip and knee. The examiner tries to extend the flexed hip by pulling it with one arm wrapped around the thigh just proximal to the knee.

Resisted straight sit-up
The patient lies supine on the examination table with the hips in approximately 45 degrees flexion and the knees approximately 90 degrees flexion. The feet are flat on the examination table and the patient's arms are folded over the chest. The patient performs a sit-up movement, lifting head and scapulae from the couch, while the examiner resists the movement by holding one arm on the patient's knees and the other arm on the patient's chest.

Resisted oblique sit-up
The patient lies supine on the examination table with the hips in approximately 45 degrees flexion and the knees approximately 90 degrees flexion. The feet are flat on the examination table and the patient's arms are folded over the chest. The patient performs a diagonal sit-up movement, attempting to move one shoulder towards the contralateral knee. The examiner resists the movement by holding one arm on the patient's shoulder and the other on the contralateral knee.

Modified Thomas Test

The patient lies supine on the examination table with the legs hanging from the end. The patient then flexes one hip by holding the knee with both arms and pulling it down to the chest. The other leg is hanging relaxed from the end of the couch, and the head and shoulders are resting on the table. The examiner stands at the end of the couch supporting the position by pressing the side of the trunk against the foot of the flexed leg.

Hip extension stretch

The examiner then places one hand on the thigh of the hanging leg just above the knee, and presses the leg down applying a hip extension stretch.

Hip flexion resistance

The patient is then asked to push against the examiner's hand, while the examiner resists hip flexion movement.

Knee flexion stretch

The patient relaxes the tested leg, and hip extension pressure is applied with the examiner's hand, and with the examiner's lower leg, a maximal knee flexion pressure is applied.

Knee extension resistance

The patient is then asked to kick the examiners leg away, while the examiner resists knee extension movement.

Figure 7: Standardized clinical examination test descriptions used in Study III.

Imaging assessment

As described, imaging examination included US and MRI in study I, whereas study II-V focused on MRI only. Additionally, X-rays were performed to assess for fractures (including avulsion fractures), if considered indicated.

US examination

The US examination was performed by the musculoskeletal (MSK) radiologist on duty. All muscles in the groin region were examined in a sequential procedure using a linear array VF 10-5 and a curved array CH6-2 transducer (ACUSON Antares system, Siemens, Germany).

MRI acquisition

A 1.5T MRI system (Magnetom Espree; Siemens, Germany) with a body matrix coil centered at the pubic area was used for the MRI examinations. This allowed equal visualization of both sides so all relevant muscles could be scored bilaterally. Eight standardized sequences were used (Table 2) based on the Copenhagen Standardized MRI protocol for the pubic and adductor region.[18] In brief, the protocol included one sagittal, two coronal, three axial, and two axial oblique sequences, and took around 30-40 min. to complete.

Table 2:
Standardized MRI sequence description.

Sequence	**FOV**	**TR**	**TE**	**Slice Thickness (mm)**	**Distance Factor (Gap) %**
Coronal T1	380	600	16	4	30
Coronal STIR	380	4240	28	4	30
Axial T1	340	524	16	4	30
Axial T2 FS	340	3770	102	4	30
Axial PD	260	2000	18	5	20
Axial oblique T2 FS	200	4130	71	4	30
Axial oblique PD	200	2440	17	4	30
Sagittal PD FS	300	4280	13	4	30

FOV = field of view, TR = repetition time, TE = echo time, STIR = short tau inversion recovery, FS = fat suppressed, PD = proton density.

Clinical imaging assessment

In Study 1, the imaging assessment of both the US and MRI was performed by the MSK radiologist on duty. Reported findings were subsequently categorized dichotomously as positive or negative for each muscle in the groin region. Imaging signs of edema, with or without architectural disruption, as well as signs of complete tears or avulsions were considered positive findings. Correspondingly, when none of these imaging signs were present, the imaging result was considered negative. Injuries within the adductor muscle group were specified for the individual muscles; adductor longus, adductor brevis, adductor magnus, pectineus, gracilis and obturator externus. Similarly, injuries in the iliopsoas were divided into iliacus, psoas or both. If there were more than one injury within a muscle group, these were specified, but categorized as one injury for the respective muscle group. Any additional imaging signs, such as adductor tendinopathy, osteoarthritis, or femoroacetabular morphologies, which potentially could be related to long-standing injury or overuse, were not included in study I.

Standardized MRI assessment

In Study II-V, we described and used a standardized MRI assessment. In study II, two independent MSK radiologists, with 13 and 16 years of experience in applying semi-quantitative scoring of MSK MRI in a research setting, assessed the MRIs blinded to patient information. Twenty hours of calibration and discussion with the thesis author was performed prior to scoring. For the reproducibility study, MRI assessment was performed independently on 75 MR images. For intra-rater reproducibility one radiologist re-assessed the same images after an interval of 6 weeks to avoid recognition bias. This radiologist is referred to as R1 (followed by a or b signifying the first or second scoring), and the radiologist scoring the images only once is referred to as R2. In Study III, only one radiologist (R1) assessed all included MRIs. For Study IV and V all cases were additionally reviewed by the thesis author after primary assessment by RI, and any discrepancies were discussed with a third experienced musculoskeletal radiologist (R3), and adapted if agreement was reached. If thesis author and R3 did not agree on a certain parameter, the assessment of R3 was used. Overall assessment of each case took between 20 and 40 min. The assessment was based on the most commonly encountered pathologies, but also aimed to account for more rare findings. The following parameters were assessed:

Muscle location

The following muscles in the groin region were evaluated in all studies and for study III grouped as below:

- Adductor group: adductor longus, adductor brevis, pectineus, adductor magnus, gracilis, and obturator externus.
- Hip flexor group: rectus femoris, sartorius, iliacus, and psoas major.
- Abdominal group: rectus abdominis, transverse abdominis, internal and external obliques, and conjoint tendon.
- Other: vastus medialis, tensor fasciae latae.

Injury grading

Muscle injury grading was defined by the extent of fluid seen on the MRI and graded identical for acute and non-acute injuries on an ordinal scale from 0-3:[78,139]

- 0 = no imaging abnormality.
- 1 = diffuse intramuscular hyper-intensity representing edema without architectural disruption.
- 2 = architectural disruption (partial tear) defined as fluid-equivalent intramuscular collection.
- 3 = complete musculotendinous disruption/tear or avulsion from the tendinous attachment.

Non-acute musculotendinous injuries were defined as an area with a more subtle, diffusely appearing intramuscular hyper-intensity of lesser contrast than acute injuries (Figure 8). In study III-V, only acute muscle injuries were included, and in Study III, each acute muscle injury was categorized as MRI negative (grade 0) or MRI positive (grade 1-3).

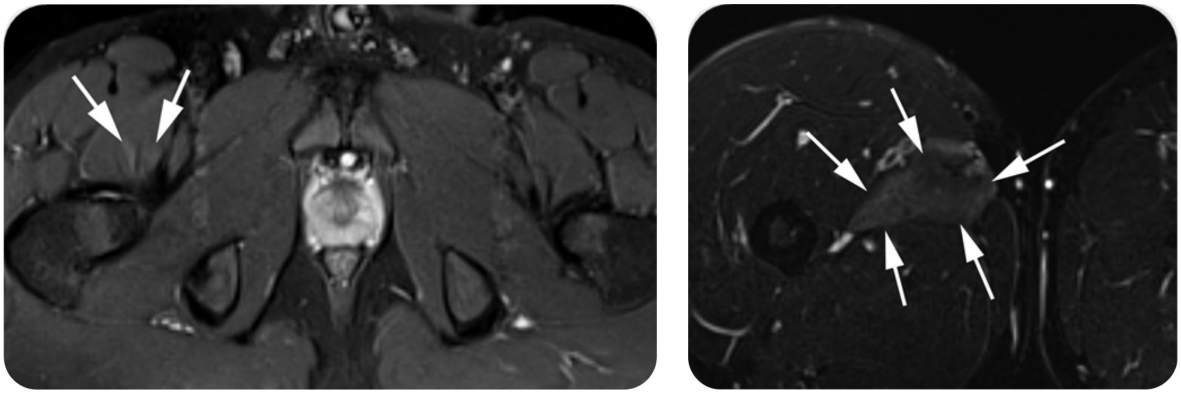


Figure 8: Non-acute injuries.
Injuries with more subtle signal changes were differentiated from acute injuries and described as non-acute injuries in this study. **A:** Axial T2-weighted fat suppressed image shows a non-acute injury of the iliopsoas with subtle peri-tendinous edema (arrows). **B:** Axial T2-weighted fat suppressed image shows diffuse subtle hyper-intensity of the adductor longus (arrows), which was also scored as a non-acute injury.

Anatomical location

In the proximal-distal direction the edema was scored as being related to either the proximal or distal tendon. This was further categorized into insertional (BTJ) or musculotendinous junction (MTJ). The location of intramuscular edema was also scored as being either primarily central within the muscle belly, mainly peripheral (reaching the limits of the muscle in the axial plane), or a combination of both on the axial images. Additionally, the distance from the most proximal border of edema to the proximal insertion at the pubic bone or the distance from the most distal border of edema to the distal insertion on the to the femur was recorded. Each injury was scored individually if multiple injuries were observed.

Furthermore, two characteristic injury locations of the adductor longus were scored, with injuries primarily located in the anterior-medial or in the posterior-lateral aspect on axial images. These two locations signify injuries related to the proximal and distal tendon, respectively (Figure 9).

For Study IV, we further divided the adductor longus and brevis MTJ injuries of the proximal tendon into superficial tendon and intramuscular tendon. This differentiation was made at the point where the proximal tendon first becomes intramuscular. For the adductor longus this is described to be approximately 1-2.5 cm from the insertion.[172,181] The proximal rectus femoris direct and indirect tendon insertions were also assessed and graded separately.

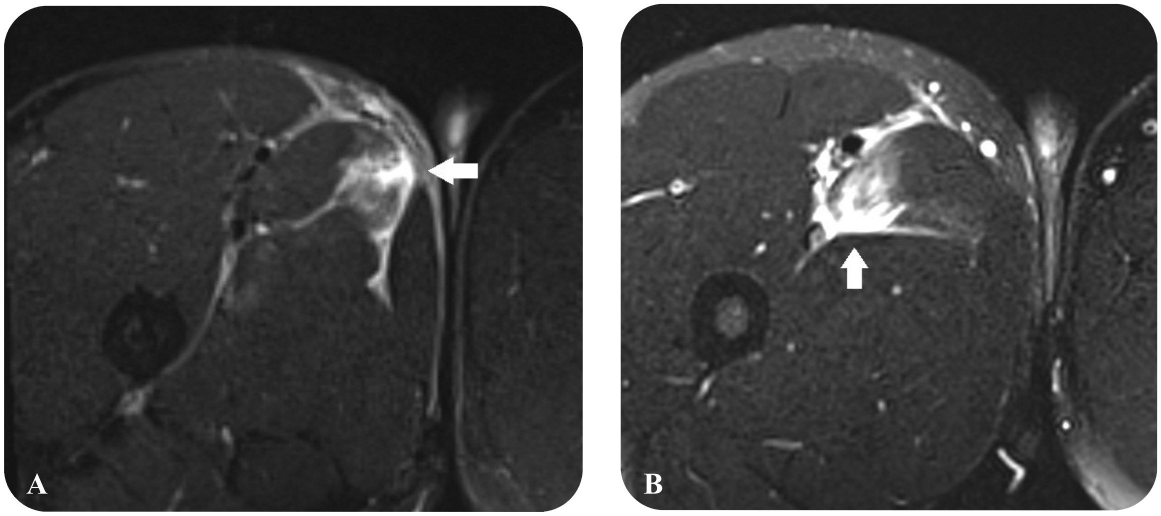


Figure 9: Specification of adductor longus injuries.
The scoring differentiates between primary anterior-medial and posterior-lateral involvement of the adductor longus in the axial imaging plane. **A:** T2-weighted fat suppressed image shows intramuscular fluid-equivalent signal representing a grade 2 injury (tear) in the anterior-medial location of the right adductor longus (short thick arrow). In addition there is accompanying muscle edema adjacent to this injury. **B:** T2-weighted fat suppressed image shows a grade 2 injury in the posterior-medial location of the left adductor longus (short thick arrow) with more discrete adjacent edema.

Extent of edema

Assessment of the extent of edema was performed using three-dimensional measurements, i.e. mm measures in proximal-distal, medial-lateral, and anterior-posterior directions (Figure 10A&B). In order to optimize applicability to clinical situations we used the slice with the maximum extent of injury, rather than injury segmentation, which can be considered superior.[113] Muscle cross sectional area (CSA) was calculated in the axial slice where maximum edema was present, and this was used to calculate a ratio of muscle CSA affected by edema. The formula for the CSA approximations was:

$$\frac{\text{medial}-\text{latera distance}}{2} \times \frac{\text{anterior}-\text{posterior distance}}{2} \times \pi.$$

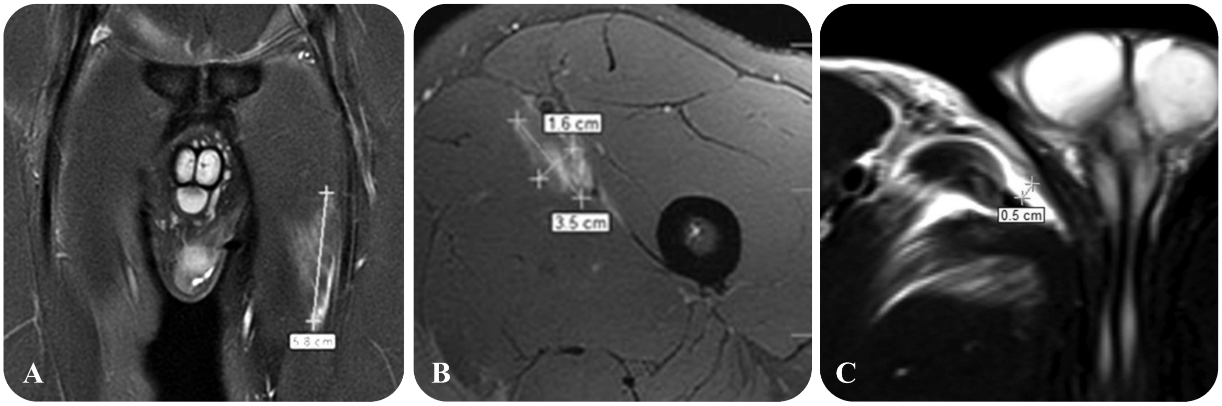


Figure 10: Continuous measurements of edema in acute injuries.
A. Coronal proton density-weighted fat suppressed image shows the measure of proximal-distal extent of edema in an distal adductor longus injury. **B.** Corresponding axial proton density-weighted fat suppressed image of the same patient shows the measures of extent of edema in the anterior-posterior and medial-lateral directions. **C.** Axial proton density-weighted fat suppressed image shows a measure of the maximum thickness of peri-muscular fluid-equivalent signal in a proximal adductor longus injury.

Extent of muscle tear

Similar to the total extent of edema, the extent of collection, indicating a grade 2 injury, was also measured in three directions, and the distance from the insertion was measured. Indication of tendinous injury was scored by the presence or absence of intramuscular tendon waviness (Figure 11), as this has been described as a potential prognostic parameter particularly for hamstring injuries.[31] The amount of retraction for tendon avulsion injuries, or the substance gap and the distance from the insertion for complete musculotendinous disruption was scored for the grade 3 injuries. For both grade 2 and 3 injuries, the amount of concomitant peri-muscular edema was measured by its maximum thickness on axial images (Figure 10C).

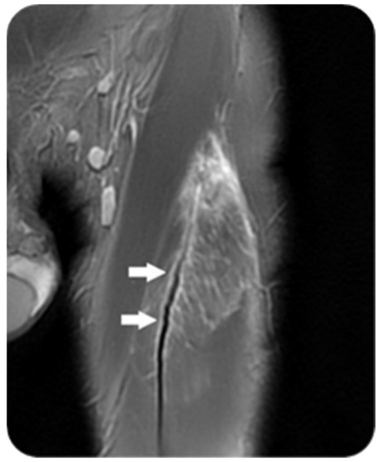


Figure 11: Tendon waviness.
Coronal proton density-weighted image shows tendon waviness
(short thick arrows) accompanying an extensive rectus femoris injury.

Additional non-acute findings

Imaging findings suggesting non-acute changes, which potentially could be related to long-standing injury, were evaluated based on previously published MRI scoring.[18] The presence or absence of the following features was also scored; pubic bone marrow edema (BME) (including grading from 0-3), iliac BME, acetabular BME, secondary cleft sign, superior cleft sign, symphyseal sclerosis, para-symphyseal high intensity line, symphyseal subchondral cysts or joint surface irregularities, fatty infiltration of bone marrow around symphysis, central disc protrusion or presence of a superior osteophyte, iliopectineal bursitis, acetabular labral tear, as well as adductor longus, rectus abdominis, rectus femoris, and iliopsoas tendinopathy.

Statistical analyses

For all studies statistical analyses were performed using SPSS software (v 21; IBM Corporation, USA). Additionally, an online statistical calculator (vassarstats.net/clin1.html) was used for the diagnostic statistics in Study III. Descriptive statistics were used to provide overviews of demographic data, as well as for muscle injury distributions and scored MRI parameters. For distributional comparisons of injury situations and injury locations in Study I, a chi-square test for independence was performed with a level of significance at $p \leq 0.05$.

In Study II, intra- and inter-rater reproducibility of the categorical scoring, measures were analyzed using simple kappa statistics ($\mathcal{K}$) for features that were scored as present or absent, and with weighted $\mathcal{K}$ for features that were ordinally graded. Additionally, overall percent agreement was calculated, as a low prevalence of certain features may adversely affect the kappa results. For the dichotomous variables we also calculated the prevalence (P) and bias index (BI) from 2x2 tables. $\mathcal{K}$ results were considered almost perfect if 0.81-1.00, substantial 0.61-0.80, moderate 0.41-0.60, fair 0.21-0.40, slight 0-0.20, and poor if <0.[109] To determine reproducibility of the continuous measurements, intraclass correlation coefficients (ICC 2, 1) were analyzed with a two-way random model, using single measures analysis and absolute agreement. Furthermore, we analyzed the standard error of the measurement (SEM) and the minimal detectable change (MDC). Additionally, paired t-tests were used to assess for systematic differences between raters.

For the comparison between the standardized clinical examination tests and MRI findings in Study III, we analyzed the data in two parts. When aiming at predicting a positive or negative MRI, we used the categorization of the clinical examination tests as described in Table 1. We created 2x2 tables using both the positive and negative tests results for each individual clinical examination test result and compared that to the positive or negative MRI result in the location relevant for that specific test, e.g. a "true positive" could be a positive adductor stretch test and a positive MRI injury in the adductors. A "false positive" could be a positive adductor stretch test and no acute injury on MRI in the adductors. Sensitivity (Sen), specificity (Spe), positive and negative likelihood ratios (LR+ & LR-) and predictive values (PPV and NPV, reported in percent) were calculated for all tests including continuity corrected confidence intervals. We also calculated the prevalence of the positive examination tests. To determine an optimal cut off point for the number of tests discriminating between a positive and negative MRI in the tested area, we used a receiver operating characteristic (ROC) curve including analysis of the area under the curve (AUC), which was also analyzed for all tests individually.

In the analysis of predicting an accurate injury location, we used only MRI positive cases. We excluded all MRI negative cases for this analysis, as there is no definitive way of determining which structure is actually injured in these cases. We thereby consider MRI as the reference standard for this part of the analysis. This should provide a clearer overview of the accuracy of the individual tests, which can then be used to guide diagnosis of athletes without an MRI performed, as well as athletes with a negative MRI. We therefore created different 2x2 tables, now using the specific test results in comparison to a positive/negative MRI in a different location, i.e. a "true positive" could be a positive adductor stretch test and an MRI injury in the adductors, and a "false positive" could be a positive adductor stretch test, but an MRI injury in the rectus femoris and not the adductors. Again we also calculated Sen, Spe, LR+, LR-, PPV, NPV, as well as AUC for each test. For both parts of the analysis, we additionally analyzed values for cases where all the examination tests were positive or all tests were negative.

Results

Study I

Participants

In the inclusion period of Study I, August 2012 – April 2014, 121 athletes with an acute groin injury were considered for inclusion. Seven of these athletes reported a more gradual onset during the clinical examination and were therefore determined ineligible. Additionally, three athletes did not wish to take part in the study, thus 111 participants were included. After inclusion, one athlete did not attend any imaging appointments, and was omitted from the analysis. The study results are therefore based on 110 athletes (mean age 25.6±4.7 y (SD), range 18-36 y). These athletes were participating in different sports, primarily different types of football (n=84, 76%). In total there were 63 football players (57%), 19 futsal players (17%), 11 basketball players (10%), 9 handball players (8%), 2 volleyball players (2%), and 1 athlete from each of the following sports (5%); beach football, Australian rules football, taekwondo, decathlon, shot put, and goal ball.

Injury history

An overview of injury situations is shown in Table 3, where we also include a differentiation between athletes from football codes and athletes from other sports. Training injuries accounted for 45% of the injuries, and 55% occurred during matches. The dominant leg was injured in 67 the athletes (61%), the non-dominant leg in 42 (38%), and one athlete reported bilateral symptoms. There were 36 kicking injuries, with 29 in the kicking leg (81%), compared to 4 in the supporting leg (11%). Six athletes (17%) reported that they were kicking with their non-dominant leg. Specification of kicking injuries was missing in 3 athletes (8%). For the injury situations, which did not occur during kicking, the dominant leg was injured in 48 (55%), the non-dominant leg in 32 (44%), and one athlete (1%) was injured bilaterally. Almost half of the athletes (n=53, 48%) reported that they had previously had a groin injury, which has caused them to miss training or matches.

Table 3:
Injury situations for all athletes in Study I.

Injury situations	Total (n=110)	Football codes (n=84)	Other sports (n=26)
Kicking	36 (33)	34 (40)	2 (8)
Change of direction	22 (20)	14 (17)	8 (31)
Reaching/stretch situation	19 (17)	14 (17)	5 (19)
Sprinting/running	16 (15)	11 (13)	5 (19)
Jumping	8 (7)	5 (6)	3 (12)
Other situations	9 (8)	6 (7)	3 (12)

Data are presented as n (%).

Injury location

The clinical examination was performed on all athletes (n=110), and the majority of the athletes also had both US and MRI examination performed (n=90, 81%). There were 15 athletes (14%) who only had a clinical examination and an MRI, and 5 athletes (5%), who only had clinical examination and US. The clinical examinations were performed by 18 different sports medicine physicians, the MRI examinations were assessed by 9 different radiologists, and the US examinations were performed by 6 different radiologists. An overview of diagnosed and categorized injury locations for all examination types is presented in Table 4. There was no significant difference in overall injury distribution between the three different examination types (p=0.803).

The majority of the athletes (n=86, 78%) received an additional radiographic examination; however no signs of acute bony injury were reported in any athlete. In two athletes, the radiologist assessing the MRI reported a possible acetabular labral tear (one unilateral and one bilateral). These athletes were then reexamined after imaging, and in both cases the potential labral tears were considered as incidental findings.

Clinical diagnosis and imaging findings

In a post hoc analysis we compared the clinical diagnosis and the imaging findings (Table 5).

Table 4:
Location of acute groin injuries on clinical, MRI, and US examinations.

	Clinical	**MRI**	**US**
Total examinations, n	*110*	*105*	*95*
Imaging negative	n/a	23 (22)	24 (25)
Injury location*			
Adductor	73 (66)	54 (66)	45 (63)
Adductor longus	-	50 (93)	41 (91)
Adductor magnus	-	1 (2)	1 (2)
Adductor brevis	-	9 (17)	7 (16)
Pectineus	-	10 (19)	5 (11)
Gracilis	-	1 (2)	2 (5)
Iliopsoas	28 (25)	14 (17)	13 (18)
Iliacus only	-	7 (50)	10 (77)
Psoas only	-	1 (7)	3 (23)
Iliacus and psoas	-	6 (43)	-
Rectus Femoris	25 (23)	12 (15)	13 (18)
Abdominal	11 (10)	5 (6)	4 (6)
Sartorius	7 (6)	3 (4)	1 (1)
Multiple injury locations	*32 (29)*	*7 (9)*	*6 (8)*
Adductor & iliopsoas	12 (11)	-	1 (1)
Iliopsoas & rectus femoris	5 (5)	1 (1)	1 (1)
Rectus femoris & sartorius	4 (4)	-	1 (1)
Adductor & abdominal	3 (3)	5 (6)	3 (4)
Adductor, abdominal & iliopsoas	2 (2)	-	-
Adductor & rectus femoris	2 (2)	-	-
Iliopsoas & abdominal	2 (2)	-	-
Iliopsoas & sartorius	2 (2)	-	-
Adductor & sartorius	-	1 (1)	-

Data are presented as n (%); MRI = magnetic resonance imaging; US = ultrasound; n/a = not applicable.

* If imaging showed signs of injury at more than one location, the injury is counted in each location and as multiple injury locations with the combination described below. The sum of injuries is therefore higher than the total number of examinations. The injuries are noted as the percentage of positive examinations for the respective examination modality. A specific injury distribution within the adductor and iliopsoas muscles is presented as the percentage of total positive imaging findings within the muscle group.

Table 5:
Clinical diagnosis compared to imaging findings.

Clinical diagnosis	**MRI** Same location	Different location	Imaging negative	**US** Same location	Different location	Imaging negative
Adductor	50 (72)	4 (6)	15 (22)	42 (68)	2 (3)	18 (29)
Iliopsoas	10 (38)	9 (35)	7 (27)	8 (35)	9 (39)	6 (26)
Rectus femoris	10 (42)	11 (46)	3 (12)	10 (45)	9 (41)	3 (14)
Abdominal	2 (18)	3 (27)	6 (55)	3 (33)	2 (22)	4 (45)
Sartorius	-	4 (67)	2 (33)	1 (14)	5 (72)	1 (14)
Total	72 (53)	31 (23)	33 (24)	64 (52)	27 (22)	32 (26)

Data are presented as n (%); MRI = magnetic resonance imaging; US = ultrasound.
Injuries are noted as “same location” if both the clinical examination and imaging showed positive findings in the respective location, and “other location” if the imaging did not show positive findings in the clinically diagnosed location, but findings in another location. Data are presented as the percentage of the number of injuries in the respective clinical location where the respective imaging examination was performed (number of injuries in brackets).

Study II

Participants

In Study II, MRI images from 75 male athletes, included between August 2012 and December 2014, were randomly selected. These athletes were on average 26.6 ± 4.4 years with a range of 18-37 years. The athletes represented a similar distribution of sports as in study I, with 76% football players, 9% basketball players, 9% handball players, and 5% were from other sports. The MRI examinations were performed a median of 4 days (IQR 3, range 1-13) after injury.

Acute injuries

There were 85 different acute muscle injuries reported in the 75 MRI examinations. R1 reported 18 imaging negative examinations, and R2 reported 17 imaging negative examinations. Specification of the reported injury locations is presented in Table 6.

Non-acute injuries and additional non-acute findings

There were 19 different non-acute muscle injuries reported (R1a: 15, R1b: 17, and R2: 13). Furthermore different additional non-acute findings were reported, most frequently pubic BME. Pubic BME was reported in at least one side in 55% of the athletes (R1a: 56%, R1b: 52%, R2: 57%). Additionally, central disc protrusions/superior osteophytes and peri-symhyseal sclerosis were not uncommon additional findings. The prevalence of the individual non-acute findings is reported with the reproducibility results.

Reproducibility

Intra- and inter-rater agreement was almost perfect ($\mathcal{K}$=0.81-1.00) for the scoring parameters of injury presence or absence, number of acute injuries per athlete, muscle location, as well as injury grading and edema location in the axial plane (Table 7). Substantial agreement ($\mathcal{K}$=0.70-0.85) was found for the location of edema in the coronal plane. Almost perfect ICCs (0.89-0.99) were found for the continuous measures of edema for both acute injuries (Table 8) and non-acute injuries (Table 9). Similarly, ICCs between 0.83-0.99 were found for the continuous measures of the extent of the partial muscle tears (Table 8). Table 10 shows the agreement results for the additional non-acute findings.

Table 6:
Descriptive statistics of all injuries in Study II.

Parameter	R1a	R1b	R2
Injury type			
Total	94	96	97
Acute	79 (84)	79 (82)	84 (87)
Non-acute	15 (16)	17 (18)	13 (13)
Number of acute injuries per athlete			
0 injuries	18 (24)	18 (24)	17 (23)
1 injury	43 (57)	44 (59)	42 (56)
2 injuries	8 (11)	7 (9)	10 (13)
3 injuries	4 (5)	4 (5)	4 (5)
4 injuries	2 (3)	1 (1)	1 (1)
5 injuries	-	1 (1)	-
6 injuries	-	-	1 (1)
Muscles with acute injuries			
Adductor longus	34 (43)	34 (43)	35 (42)
Adductor brevis	6 (8)	6 (8)	6 (7)
Adductor magnus	1 (1)	1 (1)	1 (1)
Pectineus	7 (9)	7 (9)	9 (11)
Gracilis	4 (5)	4 (5)	4 (5)
Rectus abdominis	3 (4)	4 (5)	4 (5)
Iliopsoas (including iliacus and	6 (8)	6 (8)	6 (7)
Rectus femoris	13 (16)	13 (16)	14 (17)
Sartorius	3 (4)	3 (4)	3 (4)
Vastus medialis	2 (3)	1 (1)	2 (2)
Location in positive adductor longus injuries			
Anterior-medial	17 (50)	17 (50)	18 (51)
Posterior-lateral	11 (32)	11 (32)	12 (34)
Both	6 (17)	6 (17)	5 (14)
Grading 1-3			
Grade 1	42 (53)	46 (58)	47 (56)
Grade 2	25 (32)	20 (25)	24 (29)
Grade 3	12 (15)	13 (17)	13 (16)
Main location of edema – transverse plane			
Central	6 (8)	6 (8)	6 (7)
Peripheral	17 (22)	15 (19)	19 (23)
Both	54 (68)	56 (71)	56 (67)
Indeterminable	2 (3)	2 (3)	3 (4)
Main location of edema – coronal plane			
Insertion	7 (9)	11 (14)	14 (17)
Proximal tendon	17 (22)	13 (17)	20 (24)
Central tendon	25 (32)	28 (35)	23 (27)
Distal tendon	8 (10)	6 (8)	9 (11)
Indeterminable	22 (28)	21 (27)	17 (20)

Presence of intramuscular waviness in grade 2 injuries	4 (16)	2 (10)	4 (17)

Data are presented as n (%). R1 and R2 refers to the two different radiologists with a & b signifying R1's first and second scoring.

Table 7:
Reproducibility of MRI scoring of acute injuries – Categorical measures.

Parameter	**Intra-rater** Kappa (95% CI)	**Intra-rater** Overall agreement (%)	**Inter-rater** Kappa (95% CI)	**Inter-rater** Overall agreement (%)
Acute injury presence vs. absence on athlete level; (n=75).	1.00 (1.00, 1.00)	100.0	0.89 (0.76, 1.00)	96.0
Number of acute injuries per athlete; (n =75) weighted kappa, [weighted agreement],	0.94 (0.79, 1.00)	94.7 [98.9]	0.91 (0.77, 1.00)	92.0 [98.4]
Acute vs. chronic injury differentiation; (n=92)	1.00 (1.00, 1.00)	100.0	0.86 (0.71, 1.00)	96.7
Acute injury location/ muscle; (n=85)	0.94 (0.88, 1.00)	95.3	0.90 (0.82, 0.97)	91.8
Acute injury grading (1-3);(N_{intra} = 77, N_{inter} = 78) weighted kappa, [weighted agreement]	0.92 (0.74, 1.00)	93.5 [96.8]	0.97 (0.79, 1.00)	97.4 [98.7]
Location of edema (central, peripheral, both); (N_{intra} = 77, N_{inter} = 78)	0.94 (0.87, 1.00)	97.4	0.81 (0.68, 0.95)	91.0
Location of edema: (tendo-periosteal, proximal tendon, central tendon, distal tendon); (N_{intra} = 77, N_{inter} = 78)	0.85 (0.75, 0.94)	88.3	0.70 (0.59, 0.82)	76.9
Location in positive adductor longus injuries (anterior-medial, posterior-lateral, both); (n =34)	1.00 (1.00, 1.00)	100.0	0.95, (0.86, 1.00)	97.1
Iliopsoas differentiation (Iliacus, Psoas, both or indistinguishable); (n=6)	0.71 (0.26, 1.00)	83.3	0.71 (0.26, 1.00)	83.3
Rectus femoris free tendon, direct head, injury grading (0-3), weighted kappa, [weighted agreement]; (N_{intra} = 13, N_{inter} = 12)	0.46 (0.09, 0.83)	92.3 [92.3]	0.45, (0.07, 0.86)	83.3 [91.7]
Rectus femoris free tendon, indirect head, injury grading (0-3), weighted kappa, [weighted agreement]; (N_{intra} = 13, N_{inter} = 12)	0.84 (0.38, 1.00)	84.6 [94.9]	0.70 (0.24, 1.00)	75.0 [88.9]

CI = confidence interval.

Table 8:
Reproducibility of MRI scoring of acute injuries – Continuous measures.

		Intra-rater						Inter-rater					
Measure	**Parameter**	ICC (95%CI)	Mean R1a (SD)	Mean R1b (SD)	Mean difference (p-value)	SEM (SEM%)	MDC (MDC%)	ICC (95%CI)	Mean R1a (SD)	Mean R2 (SD)	Mean difference (p-value)	SEM (SEM%)	MDC (MDC%)
Edema (N_{intra} = 77 N_{inter} = 78)	Dimension 1: Medial-Lateral	0.94 (0.90,0.96)	27.4 (13.3)	28.5 (14.0)	1.1 (0.047)	3.4 (12)	9.3 (33)	0.96 (0.94,0.98)	27.3 (13.4)	28.5 (14.0)	1.2 (0.006)	2.6 (9)	7.1 (25)
	Dimension 2: Anterior-posterior	0.93 (0.89, 0.96)	21.8 (10.3)	23.0 (10.4)	1.1 (0.008)	2.6 (11)	7.1 (32)	0.96 (0.93, 0.97)	21.4 (10.4)	21.9 (10.6)	0.9 (0.008)	2.1 (10)	5.9 (27)
	Dimension 3: Proximal-distal	0.96 (0.93,0.97)	47.6 (22.6)	49.8 (22.5)	2,2 (0.003)	4.5 (9)	12.4 (25)	0.96 (0.92, 0.98)	47.2 (23.0)	50.1 (24.5)	2.9 (<0.001)	4.3 (9)	12.0 (25)
	Distance from insertion	0.99 (0.98, 0.99)	39.1 (38.4)	38.5 (37.5)	-0.7 (0.373)	4.6 (12)	12.7 (33)	0.98 (0.98, 0.99)	39.6 (38.9)	39.8 (38.5)	0.2 (0.796)	4.9 (12)	13.7 (34)
	Thickness of peripheral fluid	0.95 (0.92, 0.97)	3.8 (3.8)	4.0 (3.8)	0.2 (0.123)	0.9 (22)	2.4 (62)	0.97 (0.96, 0.98)	3.9 (3.8)	3.9 (3.8)	0.0 (0.699)	0.6 (16)	1.7 (44)
	Injury index: Edema CSA / Muscle CSA	0.89 (0.83, 0.93)	0.42 (0.26)	0.43 (0.26)	0.01 (0.414)	0.08 (19)	0.23 (55)	0.90 (0.85, 0.94)	0.41 (0.26)	0.42 (0.24)	0.004 (0.760)	0.08 (19)	0.21 (52)
Partial tears (N_{intra} = 20 N_{inter} = 22)	Dimension 1: Medial-Lateral	0.92 (0.80, 0.97)	11.2 (5.1)	10.8 (4.6)	-0.4 (0.385)	1.4 (13)	3.9 (36)	0.88 (0.72, 0.95)	10.6 (5.2)	10.4 (5.4)	-0.3 (0.640)	1.9 (18)	5.3 (50)
	Dimension 2: Anterior-Posterior	0.86 (0.68, 0.94)	10.1 (4.4)	10.8 (4.3)	0.7 (0.189)	1.6 (16)	4.5 (43)	0.83 (0.64, 0.93)	9.7 (4.4)	10.0 (4.1)	0.2 (0.675)	1.8 (18)	4.9 (50)
	Dimension 3: Proximal-Distal	0.92 (0.80, 0.97)	19.4 (10.1)	19.5 (9.0)	0.1 (0.956)	2.9 (15)	7.9 (41)	0.96 (0.90, 0.98)	18.4 (10.2)	18.9 (10.4)	0.5 (0.486)	2.1 (11)	5.9 (32)
	Distance from insertion	0.99 (0.97, 1.00)	52.6 (35.6)	51.2 (32.5)	-1.4 (0.285)	3.9 (7)	10.8 (21)	0.99 (0.98, 1.00)	50.5 (35.5)	51.4 (34.7)	0.9 (0.366)	3.3 (6)	9.1 (18)
Avulsions /complete tears (N_{intra} = 12 N_{inter} = 12)	Distance from insertion	0.99 (0.96, 1.00)	4.6 (15.9)	5.3 (18.5)	0.8 (0.339)	1.8 (37)	5.1 (103)	1.00 (1.00, 1.00)	4.6 (15.9)	4.8 (16.7)	0.3 (0.339)	0.6 (13)	1.7 (36)
	Distance of retraction/gap	0.97 (0.91, 0.99)	18.4 (10.4)	17.8 (10.2)	-0.7 (0.361)	1.7 (9)	4.7 (26)	0.99 (0.97, 1.00)	18.4 (10.4)	18.2 (10.7)	-0.3 (0.536)	1.0 (5)	2.7 (15)

Measures reported in mm. n=75 athletes; in these, 85 different acute injuries were measured for edema; Radiologist 1 first scoring (R1a): 79, Radiologist 1 second scoring (R1b): 79, Radiologist 2 (R2): 84, 26 different partial tears; R1a: 25, R1b: 21, R2: 24, and 13 different avulsions/complete tears; R1a: 12, R1b: 12, R2: 13. ICC = intraclass correlation coefficient, CI = confidence interval, CSA = cross sectional area. SEM = standard error of the measurement, MDC = minimal detectable change.

Table 9:
Reproducibility of MRI scoring of non-acute injuries – Continuous measures.

		Intra-rater						Inter-rater					
Measure	**Parameter**	ICC (95%CI)	Mean R1a (SD)	Mean R1b (SD)	Mean difference (p-value)	SEM (SEM%)	MDC (MDC%)	ICC (95%CI)	Mean R1a (SD)	Mean R2 (SD)	Mean difference (p-value)	SEM (SEM%)	MDC (MDC%)
Edema (N_{intra}= 15 N_{inter} = 10)	Dimension 1: Medial-Lateral	0.99 (0.96, 1.00)	20.3 (15.8)	19.1 (16.6)	-1.3 (0.042)	1.5 (7.8)	4.3 (22)	0.96 (0.86, 0.99)	21.1 (19.0)	23.3 (18.5)	2.2 (0.187)	3.4 (16)	9.5 (43)
	Dimension 2: Anterior-posterior	0.95 (0.85, 0.98)	17.1 (10.1)	15.7 (8.5)	-1.3 (0.076)	1.9 (12)	5.3 (32)	0.87 (0.58, 0.97)	19.2 (11.8)	20.5 (9.9)	1.3 (0.483)	4.0 (20)	11.0 (55)
	Dimension 3: Proximal-distal	0.95 (0.86, 098)	32.5 (16.3)	30.5 (16.3)	-2.0 (0.131)	3.4 (11)	9.5 (30)	0.99 (0.94, 1.00)	35.3 (18.6)	35.0 (18.4)	-0.3 (0.782)	2.4 (7)	6.5 (19)
	Distance from insertion	0.89 (0.70, 0.96)	94.9 (66.2)	82.8 (50.2)	-12.1 (0.085)	18.0 (20)	49.8 (56)	0.96 (0.87, 0.99)	101.7 (68.8)	94.5 (56.9)	-7.2 (0.195)	11.5 (12)	31.9 (32)
	Injury index: Edema CSA / Muscle CSA	0.98 (0.93, 1.00)	0.20 (0.25)	0.18 (0.25)	-0.03 (0.033)	0.03 (17)	0.09 (47)	0.99 (0.97, 1.00)	0.27 (0.31)	0.27 (0.33)	0.004 (0.763)	0.03 (12)	0.09 (32)

Measures reported in mm. n=75 athletes; in these, 19 different non-acute injuries were measured for edema; Rater 1 first scoring (R1a): 15, Rater 1 second scoring (R1b): 17, Rater 2 (R2): 13. ICC = intraclass correlation coefficient, CI = confidence interval, SEM = standard error of the measurement, MDC = minimal detectable change, CSA = cross sectional area.

Table 10:
Reproducibility of MRI scoring of non-acute findings.

Parameter	Intra-rater				Inter-rater			
	Kappa (95% CI)	Percent agreement	Prevalence	Bias Index	Kappa (95% CI)	Percent agreement	Prevalence	Bias Index
Pubic BME - presence vs. absence (n=150)	0.79 (0.69, 0.89)	90.6	0.33	0	0.81 (0.72, 0.91)	91.3	0.36	0.06
Pubic BME – grading (0-3) (n=150); weighted kappa, [weighted agreement]	0.79 (0.66, 0.91)	83.3 [94.2]	.	.	0.82 (0.70, 0.94)	86.0 [95.11]	.	.
Iliac BME (n=75)	n/a	100	0	0	n/a	100	0	0
Femoral BME (n=75)	n/a	100	0	0	n/a	100	0	0
Fatty infiltration in bone marrow around symphyseal joint (n=75)	0.63 (0.42, 0.83)	86.7	0.23	0.11	0.74 (0.54, 0.93)	92.0	0.19	0.03
Peri-symphyseal sclerosis (n=75)	0.87 (0.75, 0.99)	94.7	0.29	0.03	0.69 (0.51, 0.87)	86.7	0.31	0.05
Parasymphyseal high-intensity line (n=75)	n/a	100	0	0	n/a	100	0	0
Secondary cleft sign (n=150)	0.85 (0.74, 0.97)	96.0	0.16	0.01	0.84 (0.72, 0.96)	96.0	0.15	-0.01
Subchondral cysts/joint surface irregularities(n=75)	0.60 (0.38, 0.82)	86.7	0.21	-0.03	0.64 (0.44, 0.83)	85.3	0.27	0.09
Central disc protrusion /superior osteophyte (n=75)	0.81 (0.67, 0.94)	90.7	0.41	0.07	0.56 (0.38, 0.75)	78.7	0.41	0.08
Superior cleft sign (n=75)	n/a	100	0	0	n/a	100	0	0
Adductor longus tendinopathy (n=75)	0.78 (0.54, 1.00)	96.0	0.10	-0.04	0.53 (0.21, 0.86)	92.0	0.09	-0.05
Rectus abdominis tendinopathy (n=75)	1.00 (1.00, 1.00)	100.0	0.01	0	n/a	98.7	0.01	-0.01
Rectus femoris tendinopathy (n=75)	n/a	100	0	0	n/a	100	0	0
Iliopsoas tendinopathy(n=75)	n/a	100	0	0	n/a	100	0	0
Iliopectineal bursitis(n=75)	n/a	100	0	0	n/a	100	0	0
Labral tear (n=75)	1.00 (1.00, 1.00)	100	0.04	0	1.00 (1.00, 1.00)	100	0.04	0

Data are analyzed with normal/simple kappa, except grading of Pubic BME. CI = confidence interval, BME = bone marrow edema, n/a = not applicable.

Study III

Participants

In the inclusion period of Study III, August 2013 – May 2015, 100 athletes with an acute groin injury were considered for inclusion. Thirteen of these athletes did not want to participate in the study, and six athletes had the MRI examination more than 7 days after injury. This study analysis therefore included 81 athletes (mean age 25.8 y, (SD 4.4, range 18-37), mean height 179.7 cm (SD 9.1, range 162-210), mean weight 77.5 kg (SD 14.1, range 47-125). Again the type of sports were similar to the other studies with 47 football players (58%), 16 futsal (20%), 7 basketball (9%), 5 handball (6%), 4 volleyball (5%), 1 table tennis player, and 1 shot putter.

Acute groin injuries

No acute injury was reported in 17 athletes (21%), and in the 64 athletes with a positive MRI, there were 85 different acute injuries reported (Table 11). The most frequently injured muscle on MRI was the adductor longus (52% of all athletes), whereas only one injury (1%) was reported in the abdominal muscles. In addition to the muscles initially considered part of the groin, the MRI assessment showed acute injury in four muscles. One tensor fascia latae injury was reported in isolation, and there were three vastus medialis injuries reported in conjunction with an adductor injury. Two athletes had an MRI positive injury in two of the classified muscle groups; in one athlete there was both an MRI positive adductor and abdominal injury (adductor longus and rectus abdominis), and in one athlete there was both an MRI positive adductor and hip flexor injury (adductor longus, gracilis and sartorius).

Table 11:
MRI positive muscle injuries subdivided in the four categories.

MRI injury location (n = 110)	
Imaging negative	17 (21%)
Adductors	46 (56.8%)
Adductor longus	42 (51.9%)
Adductor brevis	8 (9.9%)
Adductor magnus	1 (1.2%)
Pectineus	6 (7.4%)
Gracilis	3 (3.7%)
Obturator externus	1 (1.2%)
Hip flexor	18 (22.2%)
Rectus femoris	8 (9.9%)
Iliopsoas	8 (9.9%)
Iliacus	3 (3.7%)
Psoas	3 (3.7%)
Both/indistinguishable	2 (2.5%)
Sartorius	2 (2.5%)
Abdominal	1 (1.2%)
Rectus abdominis	1 (1.2%)
Other	4 (4.9%)
Vastus medialis	3 (3.7%)
Tensor fascia latae	1 (1.2%)

Predicting a positive or negative MRI

The individual examination tests' ability to predict an MRI injury in the tested muscles are presented in Table 12 for the adductor tests, and Table 13 for the hip flexor tests. Resisted adduction in outer-range, the Squeeze-0˚, and the passive adductor stretch showed the highest PPVs of a positive MRI in the adductor muscles (PPVs 80-81% [95%CI 63-91]). In contrast, the hip flexor tests generally showed poor PPVs of a positive MRI in the hip flexors (PPV 34-63% [95%CI 20-84]). We did not perform the statistical analysis for the abdominal tests, as only one MRI positive abdominal injury was found. In Table 14 we instead present a simple overview of the positive abdominal tests, where we can see that the clinical examination test were often painful in the abdominal area without an MRI positive abdominal injury.

Two athletes did not perform the modified Thomas tests due to severe pain, and four additional athletes could only perform the first part of this test, and were therefore excluded from those test analyses. Of these six athletes, four were diagnosed with an adductor longus avulsion. The cut off number of positive tests found through the ROC curve analysis showed that it was 3 for both the adductors and hip flexors injuries (both $p<0.001$).

Predicting injury location in MRI positive cases

The accuracy of the individual clinical examination tests is presented in Table 12B, Table 13B, and Table 14C. In general adductor tests showed high accuracy (PPV 89-100% [95%CI 60-100]), although specific palpation of the gracilis and pectineus, had low PPVs of 33% (95% 2-87) and 38% (95%CI 10-74), respectively, indicating poor accuracy. Both iliopsoas and rectus femoris tests generally had poor accuracy (PPVs 17-71% [95%CI 7-85]).

Table 12:
Overview of clinical examination tests for the hip adductor muscles.

(A) Adductor Tests	Prevalence (positive test)	Sen	Spe	LR+	LR-	PPV (%)	NPV (%)	AUC
Adductor palpation	0.73	**0.96** (0.84, 0.99)	**0.57** (0.39, 0.99)	**2.23** (1.51, 3.29)	**0.08** (0.02, 0.31)	**75** (61, 82)	**91** (69, 98)	**0.76** (0.65, 0.88)
Squeeze test 0˚	0.57	**0.80** (0.66, 0.90)	**0.74** (0.56, 0.87)	**3.13** (1.75, 5.59)	**0.26** (0.14, 0.48)	**80** (66, 90)	**74** (56, 87)	**0.77** (0.67, 0.88)
Squeeze test 45˚	0.54	**0.67** (0.52, 0.80)	**0.63** (0.45, 0.78)	**1.81** (1.13, 2.92)	**0.52** (0.33, 0.81)	**70** (55, 83)	**59** (42, 75)	**0.65** (0.53, 0.77)
Outer-range adduction	0.59	**0.85** (0.71, 0.93)	**0.74** (0.56, 0.87)	**3.30** (1.85, 5.87)	**0.20** (0.10, 0.41)	**81** (67, 91)	**79** (61, 90)	**0.80** (0.69, 0.90)
Passive adductor stretch	0.43	**0.61** (0.45, 0.75)	**0.80** (0.63, 0.91)	**3.04** (1.51, 6.14)	**0.49** (0.34, 0.71)	**80** (63, 91)	**61** (45, 75)	**0.70** (0.59, 0.82)
FABER	0.40	**0.46** (0.31, 0.61)	**0.69** (0.51, 0.83)	**1.45** (0.81, 2.60)	**0.79** (0.59, 1.06)	**66** (47, 81)	**49** (35, 63)	**0.57** (0.45, 0.70)
3+ positive tests	0.63	**0.85** (0.71, 0.93)	**0.66** (0.48, 0.80)	**2.47** (1.54, 3.98)	**0.23** (0.11, 0.47)	**76** (62, 87)	**77** (57, 89)	**0.75** (0.64, 0.87)
All tests positive (6 of 6)	0.22	**0.33** (0.20, 0.48)	**0.91** (0.76, 0.98)	**3.80** (1.19, 12.12)	**0.74** (0.60, 0.91)	**83** (58, 96)	**51** (38, 63)	**0.62** (0.50, 0.74)
All tests negative (0 of 6)	0.20	**0.00** (0.00, 0.10)	**0.54** (0.37, 0.71)	**0.00** (NA)	**1.84** (1.76, 1.93)	**0** (0, 24)	**29** (19, 42)	**0.27** (0.15, 0.39)
(B) Adductor Tests	Prevalence (positive test)	Sen	Spe	LR+	LR-	PPV (%)	NPV (%)	AUC
Adductor palpation	0.75	**0.96** (0.84, 0.99)	**0.78** (0.52, 0.93)	**4.30** (1.81, 10.24)	**0.06** (0.01, 0.22)	**92** (79, 97)	**88** (60, 98)	**0.87** (0.75, 0.99)
Squeeze test 0˚	0.59	**0.80** (0.66, 0.90)	**0.94** (0.71, 1.00)	**14.48** (2.14, 97.78)	**0.21** (0.11, 0.37)	**97** (85, 100)	**65** (44, 82)	**0.87** (0.78, 0.97)
Squeeze test 45˚	0.55	**0.67** (0.52, 0.80)	**0.78** (0.52, 0.93)	**3.03** (1.25, 7.37)	**0.42** (0.27, 0.66)	**89** (72, 96)	**48** (30, 67)	**0.73** (0.59, 0.86)
Outer range adduction	0.64	**0.85** (0.71, 0.93)	**0.89** (0.64, 0.98)	**7.63** (2.05, 28.35)	**0.17** (0.09, 0.34)	**95** (82, 99)	**70** (47, 86)	**0.87** (0.76, 0.97)
Passive adductor stretch	0.47	**0.61** (0.45, 0.75)	**0.89** (0.63, 0.98)	**5.48** (1.45, 20.65)	**0.44** (0.30, 0.64)	**93** (76, 99)	**47** (30, 65)	**0.75** (0.62, 0.88)
FABER test	0.41	**0.46** (0.31, 0.61)	**0.72** (0.46, 0.89)	**1.64** (0.73, 3.69)	**0.75** (0.55, 1.02)	**81** (60, 93)	**34** (20, 51)	**0.59** (0.44, 0.74)
All tests positive (6 of 6)	0.23	**0.33** (0.20, 0.48)	**1.00** (0.78, 1.00)	**NA**	**0.67** (0.55, 0.82)	**100** (75, 100)	**37** (24, 52)	**0.66** (0.53, 0.80)
All tests negative (0 of 6)	0.17	**0.00** (0.00, 0.10)	**0.39** (0.18, 0.64)	**0.00** (NA)	**2.57** (2.17, 3.05)	**0** (0, 32)	**13** (6, 26)	**0.19** (0.05, 0.34)
Adductor longus palpation	0.69	**0.98** (0.85, 1.00)	**0.79** (0.57, 0.92)	**4.68** (2.14, 10.22)	**0.03** (0.00, 0.22)	**89** (75, 96)	**95** (73, 100)	**0.88** (0.78, 0.99)
Pectineus palpation	0.13	**0.50** (0.14, 0.86)	**0.91** (0.80, 0.97)	**5.80** (1.82, 18.48)	**0.55** (0.25, 1.22)	**38** (10, 74)	**95** (84, 99)	**0.71** (0.45, 0.96)
Gracilis palpation	0.05	**0.33** (0.02, 0.87)	**0.97** (0.88, 0.99)	**10.17** (1.24, 83.19)	**0.69** (0.31, 1.54)	**33** (2, 87)	**97** (88, 99)	A.65 (0.27, 1.00)

All values are in relation to a positive or negative MRI finding in the adductors. (A) in all athletes, (B) in athletes with a positive MRI only. Sixty-four out of 81 (79%) athletes had a positive MRI, and 46 out of 64 (72%) athletes with a MRI positive result had an MRI adductor injury (57% of all). Test descriptions can be found in Figure 7. Sen = Sensitivity, Spe = Specificity, LR+ = Positive likelihood ratio, LR- = Negative likelihood ratio, PPV = Positive predictive value, NPV = Negative predictive value, AUC = Area under the Receiver Operating Characteristic curve. n/a = not applicable. Continuity corrected 95% confidence intervals presented in brackets.

Table 13:
Overview of clinical examination tests for the hip flexor muscles.

(A) Hip flexor tests	Prevalence (positive test)	Sen	Spe	LR+	LR-	PPV (%)	NPV (%)	AUC
Palpation	0.37	**0.89** (0.64, 0.98)	**0.78** (0.65, 0.87)	**4.00** (2.45, 6.53)	**0.14** (0.04, 0.53)	**53** (35, 71)	**96** (85, 99)	**0.83** (0.73, 0.94)
Resisted hip flexion 0 deg.	0.47	**0.72** (0.46, 0.89)	**0.60** (0.47, 0.72)	**1.82** (1.20, 2.76)	**0.46** (0.21, 0.99)	**34** (20, 51)	**88** (74, 96)	**0.66** (0.52, 0.80)
Resisted hip flexion 90 deg.	0.31	**0.67** (0.41, 0.86)	**0.79** (0.67, 0.88)	**3.23** (1.80, 5.79)	**0.42** (0.22, 0.81)	**48** (28, 68)	**89** (77, 96)	**0.73** (0.59, 0.87)
Resisted hip flexion (TT)	0.42	**0.72** (0.46, 0.89)	**0.67** (0.54, 0.78)	**2.20** (1.39, 3.49)	**0.41** (0.19, 0.88)	**39** (23, 58)	**89** (76, 96)	**0.70** (0.56, 0.84)
Resisted knee extension (TT)	0.29	**0.67** (0.41, 0.86)	**0.82** (0.70, 0.91)	**3.80** (1.98, 7.28)	**0.40** (0.21, 0.78)	**55** (33, 75)	**89** (76, 95)	**0.75** (0.60, 0.89)
Passive hip extension(TT)	0.33	**0.61** (0.36, 0.82)	**0.75** (0.62, 0.85)	**2.49** (1.40, 4.41)	**0.52** (0.29, 0.93)	**42** (24, 63)	**87** (74, 94)	**0.68** (0.54, 0.83)
Passive knee flexion (TT)	0.21	**0.56** (0.31, 0.78)	**0.89** (0.78, 0.96)	**5.28** (2.22, 12.50)	**0.50** (0.30, 0.84)	**63** (36, 84)	**86** (74, 94)	**0.73** (0.58, 0.88)
3+ positive tests	0.35	**0.78** (0.52, 0.93)	**0.79** (0.66, 0.88)	**3.69** (2.11, 6.47)	**0.28** (0.12, 0.67)	**54** (34, 73)	**92** (80, 97)	**0.78** (0.66, 0.91)
All tests positive (7 of 7)	0.09	**0.33** (0.14, 0.59)	**0.98** (0.89, 1.00)	**19.00** (2.47, 147.53)	**0.68** (0.49, 0.94)	**86** (42, 99)	**82** (71, 90)	**0.66** (0.50, 0.82)
All tests negative (0 of 7)	0.39	**0.11** (0.02, 0.36)	**0.53** (0.39, 0.66)	**0.23** (0.01, 0.24)	**1.69** (1.39, 2.05)	**7** (1, 24)	**65** (50, 78)	**0.32** (0.19, 0.45)
(B) Iliopsoas tests	Prevalence (positive test)	Sen	Spe	LR+	LR-	PPV (%)	NPV (%)	AUC
Iliopsoas palpation	0.25	**1.00** (0.60, 1.00)	**0.86** (0.73, 0.93)	**7.00** (3.69, 13.30)	**0.00** (0.00, n/a)	**50** (26, 74)	**1.00** (91, 100)	**0.93** (0.87, 0.99)
Resisted hip flexion 0 deg.	0.55	**0.88** (0.47, 0.99)	**0.50** (0.36, 0.64)	**1.75** (1.21, 2.53)	**0.25** (0.04, 1.62)	**20** (9, 37)	**97** (80, 100)	**0.69** (0.51, 0.86)
Resisted hip flexion 90 deg.	0.36	**0.75** (0.36, 0.96)	**0.70** (0.56, 0.81)	**2.47** (1.41, 4.34)	**0.36** (0.11, 1.21)	**26** (11, 49)	**95** (82, 99)	**0.72** (0.54, 0.91)
Resisted hip flexion (TT)	0.44	**0.75** (0.36, 0.96)	**0.61** (0.47, 0.74)	**1.93** (1.14, 3.25)	**0.41** (0.12, 1.39)	**22** (9, 43)	**94** (79, 99)	**0.68** (0.49, 0.87)
Passive hip extension stretch (TT)	0.34	**0.63** (0.26, 0.90)	**0.70** (0.56, 0.82)	**2.11** (1.07, 4.15)	**0.53** (0.21, 1.32)	**24** (9, 48)	**93** (79, 98)	**0.66** (0.46, 0.87)
All tests positive (5 of 5)	0.11	**0.63** (0.26, 0.90)	**0.96** (0.86, 0.99)	**16.88** (3.91, 72.81)	**0.39** (0.16, 0.95)	**71** (30, 95)	**95** (84, 99)	**0.79** (0.58, 1.00)
All tests negative (0 of 5)	0.34	**0.00** (0.00, 0.40)	**0.61** (0.47, 0.74)	**0.00** (0.00, n/a)	**1.64** (1.60, 1.67)	**0** (0, 19)	**80** (65, 91)	**0.31** (0.15, 0.46)
(C) Rectus Femoris tests	Prevalence (positive test)	Sen	Spe	LR+	LR-	PPV (%)	NPV (%)	AUC
Rectus femoris Palpation	0.20	**1.00** (0.60, 1.00)	**0.91** (0.80, 0.97)	**11.20** (4.85, 25.86)	**0.00** (0.00, n/a)	**62** (32, 85)	**100** (91, 100)	**0.96** (0.91, 1.00)
Resisted hip flexion 0 deg.	0.55	**0.75** (0.36, 0.96)	**0.48** (0.35, 0.62)	**1.45** (0.90, 2.32)	**0.52** (0.15, 1.79)	**17** (7, 34)	**93** (76, 99)	**0.62** (0.42, 0.82)
Resisted hip flexion 90 deg.	0.36	**0.75** (0.36, 0.96)	**0.70** (0.56, 0.81)	**2.47** (1.41, 4.34)	**0.36** (0.11, 1.21)	**26** (11, 49)	**95** (82, 99)	**0.72** (0.54, 0.91)
Resisted hip flexion (TT)	0.44	**0.88** (0.47, 0.99)	**0.63** (0.49, 0.75)	**2.36** (1.53, 3.66)	**0.20** (0.03, 1.27)	**26** (12, 47)	**97** (83, 100)	**0.75** (0.59, 0.92)
Resisted knee extension (TT)	0.34	**1.00** (0.60, 1.00)	**0.76** (0.62, 0.86)	**4.17** (2.54, 6.82)	**0.00** (0.00, n/a)	**40** (20, 64)	**100** (89, 100)	**0.88** (0.79, 0.97)
Passive hip extension (TT)	0.34	**0.75** (0.36, 0.96)	**0.72** (0.58, 0.83)	**2.70** (1.50, 4.86)	**0.35** (0.10, 1.17)	**29** (12, 52)	**95** (82, 99)	**0.74** (0.55, 0.92)
Passive knee flexion (TT)	0.26	**0.88** (0.47, 0.99)	**0.84** (0.70, 0.92)	**5.47** (2.75, 10.87)	**0.15** (0.02, 0.94)	**47** (22, 73)	**98** (86, 100)	**0.86** (0.71, 1.00)
All tests positive (7 of 7)	0.12	**0.38** (0.10, 0.74)	**0.92** (0.80, 0.97)	**4.69** (1.28, 17.16)	**0.68** (0.40, 1.17)	**43** (12, 80)	**96** (78, 96)	**0.65** (0.42, 0.88)
All tests negative (0 of 7)	0.36	**0.00** (0.00, 0.40)	**0.58** (0.43, 0.72)	**0.00** (0.00, n/a)	**1.72** (1.68, 1.77)	**0** (0, 19)	**78** (51, 90)	**0.29** (0.14, 0.44)

(A) in relation to a positive or negative finding in the hip flexors on MRI in all athletes, (B) in relation to a positive or negative finding in the iliopsoas on MRI with athletes with a negative MRI excluded, (C) in relation to a positive or negative finding in the rectus femoris on MRI with athletes with a negative MRI excluded. Sixty-four out of 81 athletes (79%) had a positive MRI, and 18 out of 81 athletes (22%) had an MRI hip flexor injury (n=8 psoas, n=8 rectus femoris, n=2 sartorius). Eight out of 64 athletes (13%) with a MRI positive result had an acute injury in the iliopsoas, and 8 (13%) in the rectus femoris. Test descriptions can be found in Figure 7. TT = Modified Thomas Test position, Sen = Sensitivity, Spe = Specificity, LR+ = Positive likelihood ratio, LR- = Negative likelihood ratio, PPV = Positive predictive value, NPV = Negative predictive value, AUC = Area under the Receiver Operating Characteristic curve. Continuity corrected 95% confidence intervals presented in brackets, n/a = not applicable.

Table 14:
Frequency of positive clinical abdominal examination tests.

Abdominal test	All athletes	Athlete with MRI+ RA
Palpation	11 (13.6%)	Yes
Superficial inguinal ring	8 (9.9%)	No
Inguinal canal	8 (9.9%)	No
Rectus abdominis	6 (7.4%)	Yes
Straight sit-up	15 (18.5%)	Yes
Oblique sit-up	18 (22.2%)	Yes
Hip flexion resistance (TT)	10 (12.3%)	Yes
Hip extension stretch (TT)	10 (12.3%)	Yes

* Data presented in relation to all 81 athletes. Separately for the one athlete with a positive MRI injury in the rectus abdominis (MRI+ RA). This reported injury was in combination with a complete adductor longus avulsion. TT = Modified Thomas Test position. MRI = Magnetic resonance imaging.

Study IV & V

Participants

In the inclusion period of Study IV and V, August 2012 – May 2015, 156 athletes with an acute groin injury were considered for inclusion. Of these, 102 athletes were included for analysis in the two studies (Flow diagram in Figure 12). In Study IV, 71 athletes were included, and in Study V, 33 athletes were included. Two athletes were included in both studies, as they had an MRI positive injury in both in an adductor and a hip flexor muscle. Demographic data can be found in Table 15.

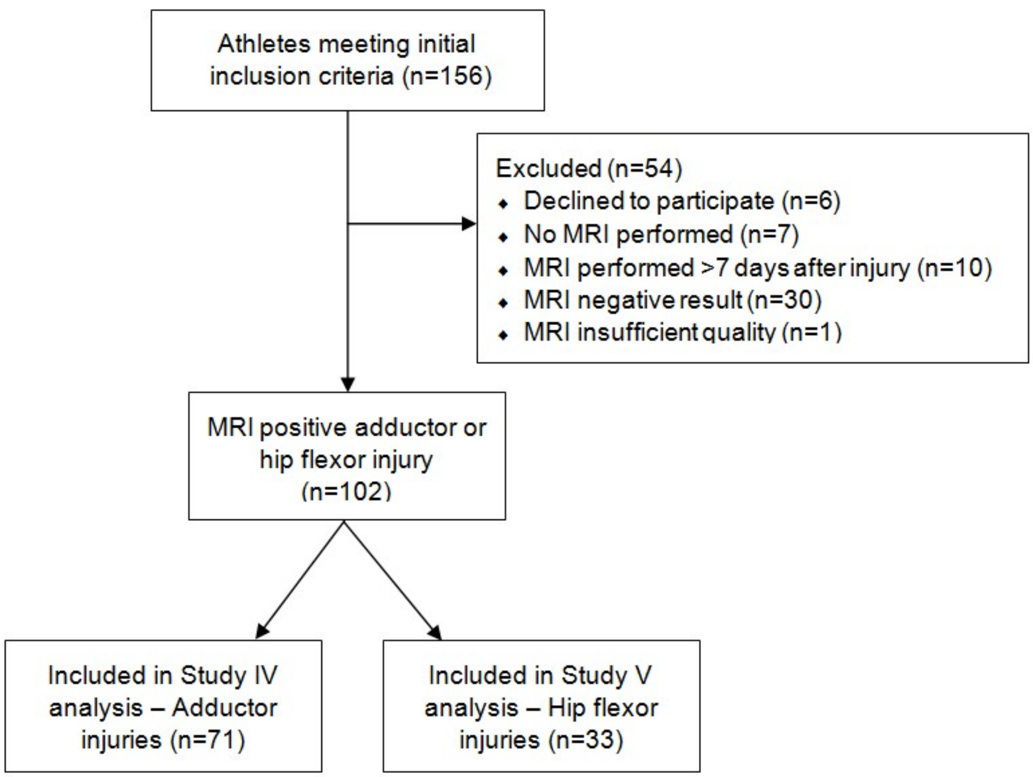


Figure 12: Flow diagram of athlete inclusion and exclusion in Study IV &V. Two athletes were included in both studies.

Table 15:
Demographic data for athletes included in Study IV & V.

	Study IV (n=71)		**Study V** (n=33)	
Age	27 years	(IQR 23-29, range 18-37)	26 years	(IQR 23-31, range 18-35)
Height	177 cm	(IQR 173-184, range 159-202)	179 cm	(IQR 173-184, range 164-210)
Weight	76 kg	(IQR 68-86, range 47-131)	75 kg	(IQR 66-84, range 60-125)
Sports				
Football		39 (55%)		22 (67%)
Futsal		11 (15%)		5 (15%)
Handball		8 (11%)		1 (3%)
Basketball		4 (6%)		4 (12%)
Volleyball		4 (6%)		-
Other		5 (7%)		1 (3%)

Two athletes are included in both study IV & V.

Acute adductor injuries

The 71 athletes included in Study IV reported a number of different injury situations as shown in Table 16. In some cases more than one muscle was found to be affected on MRI. In total, the MRI identified 121 acute injuries, of which 111 were adductor injuries and 10 were additional injuries in other muscles (Table 17). Forty six athletes (65%) had isolated muscle injuries, and 25 (35%) had multiple acute muscle injuries, with 18 different muscle injury combinations as shown in Table 18. The most frequently injured muscle was again the adductor longus, which was injured in 62 cases in total (87%), as well as in 23 of the cases (92%) where multiple adductor injuries were reported. There were 49 acute injuries in the other adductor muscles, of which the adductor brevis and pectineus were most frequently injured. Nine athletes (13%) had an isolated adductor injury not involving the adductor longus

Table 16:
Overview of injury situations for athletes with an MRI positive adductor injury.

Injury situation	Total	Adductor longus	Adductor brevis	Pectineus	Obturator externus	Gracilis	Adductor magnus
Kicking	17 (24)	15 (24)	4 (22)	3 (18)	3 (33)	1 (25)	1 (100)
Change of direction	17 (24)	14 (23)	3 (17)	4 (24)	1 (11)	-	-
Reaching/stretch	12 (17)	12 (19)	4 (22)	3 (18)	2 (22)	1 (25)	-
Running/Sprinting	8 (11)	7 (11)	2 (11)	3 (18)	-	2 (50)	-
Jumping	7 (10)	7 (11)	2 (11)	2 (12)	-	-	-
Tackling	7 (10)	5 (8)	1 (6)	1 (6)	2 (22)	-	-
Sliding	2 (3)	2 (3)	1 (6)	1 (6)	-	-	-
Pulled by opponent	1 (1)	-	1 (6)	-	1 (11)	-	-

Data are presented as n (%). n = 71. In athletes with multiple adductor injuries, the injury situation is reported for each involved muscle.

Table 17:
Distribution of muscle injuries in athletes with an MRI positive adductor injury.

Muscle injury location	
Adductor longus	62 (87)
Adductor brevis	18 (25)
Pectineus	17 (24)
Obturator externus	9 (13)
Gracilis	4 (6)
Vastus medialis	4 (6)
Rectus abdominis	3 (4)
Sartorius	2 (3)
Adductor magnus	1 (1)
Obturator internus	1 (1)
Total	121

Data are presented as total number of injuries with percentage of cases in brackets (n=71).

Table 18:
Overview of isolated injuries and specific combinations of muscle injuries, including injury grading.

Isolated injuries (n=46)		**Two injury locations** (n=11)		**Three injury locations** (n=7)		**Four injury locations** (n=4)		**Five injury locations** (n=2)		**Six injury locations** (n=1)	
Adductor longus *grade 1: 18* *grade 2: 19*	37	Adductor longus & vastus medialis *grade 1 & 1: 2* *grade 2 & 1: 1*	3	Adductor longus & adductor brevis & pectineus *grade 3, 2 & 1: 2* *grade 3, 3 & 1: 1* *grade 3, 1 & 1: 1* *grade 1,1 & 1: 1*	5	Adductor longus & adductor brevis & pectineus & obturator externus *grade 3, 2, 1 & 1: 2*	2	Adductor longus & pectineus & adductor brevis & obturator externus & gracilis *grade 3, 3, 2, 1 & 1*	1	Adductor longus & adductor brevis & pectineus & rectus abdominis & contralateral adductor longus & contralateral adductor brevis *grade 3, 2, 2, 1, 1 & 1*	1
Pectineus *grade 1: 2* *grade 2: 2*	4	Adductor longus & adductor brevis *grade 2 & 1*	1	Adductor longus & adductor brevis & gracilis *grade 3,1 & 1*	1	Adductor longus & adductor brevis & pectineus & gracilis *grade 3, 1, 1 & 1*	1	Adductor longus & adductor brevis & pectineus & obturator externus & rectus abdominis *grade 3, 1, 1, 1 & 1*	1		
Obturator externus *grade 1:1* *grade 2:2*	3	Adductor longus & pectineus *grade 1 & 1*	1	Adductor longus & gracilis & sartorius *grade 2, 1 & 1*	1	Adductor longus & adductor brevis & rectus abdominis & pectineus *grade 3, 3, 2 & 1*	1				
Adductor brevis *grade 1: 2*	2	Adductor longus & obturator externus *grade 1 & 2*	1								
		Adductor longus & sartorius *grade 2 & 1*	1								
		Adductor longus & obturator internus *grade 1 & 1*	1								
		Adductor longus & contralateral adductor longus *grade 2 & 1*	1								
		Adductor brevis & obturator externus *grade 2 & 1*	1								
		Adductor magnus & vastus medialis *grade 1 & 1*	1								

N=71.

Anatomical location

The specific locations within the adductor longus injuries are presented in Table 19. Three characteristic injury locations could be observed (Figure 13):

1) The proximal insertion (BTJ).
    - Avulsion injuries accounted for 75% of injuries at the proximal insertion.
2) The intramuscular MTJ of the proximal tendon.
    - These injuries mainly involved the anterior muscles fibers.
    - Intramuscular tendon injury was only seen in 1 athlete.
3) The MTJ of the distal tendon.
    - These injuries were mainly observed at the proximal part of the MTJ.

The location of the intramuscular edema and disruption in adductor longus injuries specified for injuries related to the proximal and distal tendon MTJ injuries is presented in Table 20, with examples in Figure 14. Only one intramuscular adductor tendon injury was reported, and found in the adductor longus. Individual specifications of the location and the extent of edema and disruption in the other adductor muscles are not presented due to the relatively low number of injuries.

Table 19:
Proximal-distal injury location in the adductor longus.

Location	Total	Grade 1	Grade 2	Grade 3
Total number of injuries	62	26	24	12
Proximal tendon insertion	16 (26%)	3 (19%)	1 (6%)	12 (75%)
Proximal tendon MTJ	19 (31%)	8 (42%)	11 (58%)	0
- Superficial MTJ	- 1 (2%)	- 1	- 0	-
- Intramuscular MTJ	- 16 (26%)	- 5	- 11	-
- Non-differentiable	- 2 (3%)	- 2	- 0	-
Distal tendon MTJ	23 (37%)	12 (52%)	11 (48%)	0
Non-differentiable	4 (6%)	3 (75%)	1 (25%)	0

MTJ = musculotendinous junction

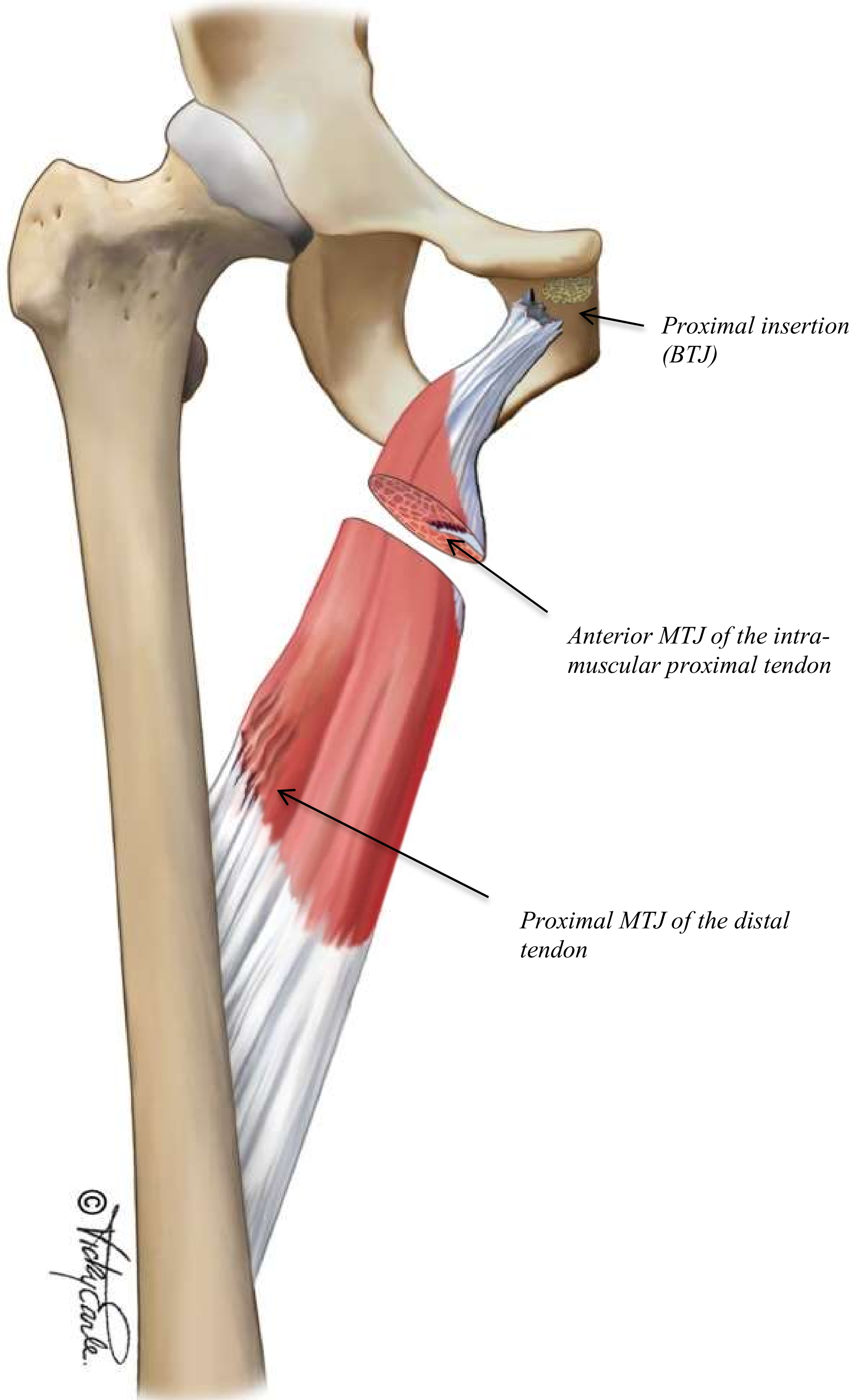
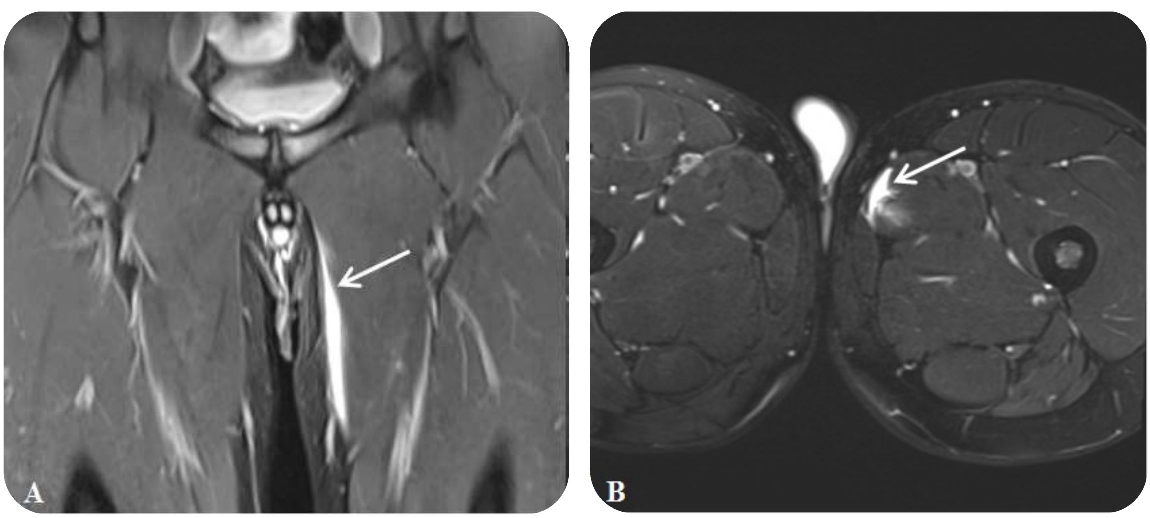


Figure 13: Anatomical illustration of the three most common adductor longus injury locations.

Table 20:
Distances from the pubic insertion to the border of edema/disruption
(grade 1 & 2 adductor longus injuries only).

Adductor longus injury location	Edema		Disruption
	Proximal distance from proximal insertion	Distal distance from proximal insertion	Proximal distance from proximal insertion
MTJ of the proximal tendon	34 mm (SD 25, range 0-87)	97 mm (SD 39, range 13-165)	53 mm (SD 27, range 2-93)
MTJ of the distal tendon	95 mm (SD 26, range 54-145)	155 mm (36, range 99-252)	114 mm (SD 14, range 92-132)

Notice the considerable overlap in the range of the location of edema between the proximal and distal injuries, as well as the possibility of similar distance of disruption between these two injury locations. MTJ = musculotendinous junction.



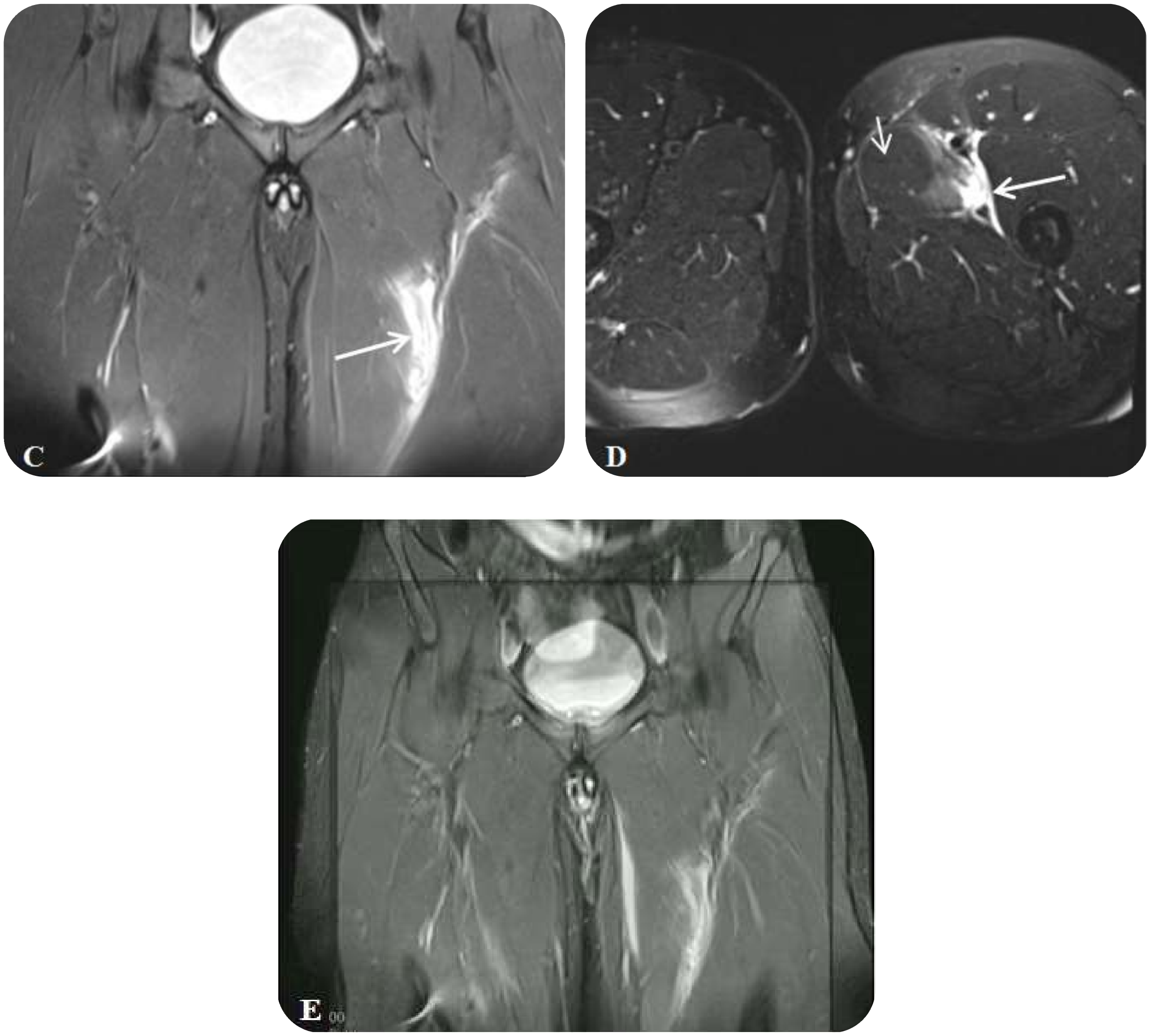


Figure 14: MRI images of adductor longus MTJ injuries at the proximal and distal tendon.
A & B: Coronal STIR image and T2 axial image with fat suppression showing a typical grade 2 adductor longus proximal intramuscular MTJ injury (white arrow) in a 25-year-old futsal player injured during change of direction. **C & D:** Coronal STIR image and T2 axial image with fat suppression showing a typical distal adductor longus MTJ injury (large white arrow) in a 33-year-old football player injured while reaching for the ball. The small arrow in image D indicates the proximal intramuscular adductor longus tendon. **E:** A combined image of figure A and C adjusted according to anatomical landmarks illustrating a potential overlap of edema from a proximal and distal adductor longus MTJ injury.

Injury grading and extent

Grade 1 or 2 injuries accounted for the majority of the adductor injuries (n=59, 83%), and grade 3 injuries were observed in 12 (17%) athletes. These 12 athletes all had a proximal adductor longus avulsion with a mean retraction of the adductor longus tendon/fibrocartilage of 17 mm (SD 10 mm, range 2-31 mm), and at least two other adductor muscles injured. An additional adductor brevis or pectineus avulsion was seen in 3 of the 12 cases (25%). In 95% of the athletes with multiple adductor injuries, the adductor longus injury had the same or a higher injury grading as the other muscle injures. In the partial adductor longus injuries, the mean CSA of disruption was 99 mm^2 (SD 73, range 20-275), with a mean of 91 mm^2 (SD 66, range 20-224) for the proximal injuries, and 107 mm^2 (SD 81, range 25-275) for the distal injuries. The mean length of disruption in the proximal-distal direction was 24 mm (SD 11, range 10-51), with 24 mm (SD 12, range 10-51) for the proximal injuries, and 24 mm (SD 10, range (12-39) for the distal injuries.

Acute hip flexor injuries

In 33 athletes with MRI positive acute hip flexor injuries included in Study V, 40 individual acute muscle injuries were identified (Table 21). The injury situations for these athletes are presented in Table 22, including specification according to the different muscle injuries.

Table 21:
Number and grade of injured hip flexor muscles.

Grade \ Muscle	Rectus femoris	Iliacus	Psoas major	Sartorius	Tensor fascia latae
Total	16	12	7	4	1
I	5	-	4	4	1
II	10	11	3	-	-
III	1	1	-	-	-

N = 33 athletes.

Table 22:
Reported injury situations including specification for the different hip flexor muscles.

Injury situation	Total	Rectus femoris	Iliacus	Psoas major	Sartorius	Tensor fascia latae
Kicking	14	10	2	2	1	1
Sprinting	7	4	1	-	2	-
Change of direction	5	-	5	1	-	-
Tackling	2	1	2	1	-	-
Reaching for ball	1	-	-	-	1	-
Sliding	1	-	1	1	-	-
Passive stretch	1	1	-	-	-	-
Falling on floor	1	-	-	1	-	-
No recollection	1	-	1	1	-	-

N = 33 athletes.

Acute rectus femoris injuries

Sixteen of the athletes in Study V (48%) had an MRI positive acute rectus femoris injury. In 15 of these (94%), the rectus femoris was injured in isolation, and in one athlete a grade 2 iliacus injury was reported in combination with a grade 1 rectus femoris injury. In general, there were 5 characteristic rectus femoris injury locations as illustrated in Figure 15. In 15 athletes (94%) the proximal rectus femoris tendons were involved (tendon insertions and MTJs of the direct and indirect tendons), and in one athlete (6%) an injury involving the distal tendon was observed at the most proximal part of the posterior tendon aponeurosis up to 56 mm from the proximal insertion (Figure 16). The free rectus femoris tendons (proximal to the MTJ) were injured in six cases; in all six cases there was an injury of the indirect tendon (two grade 1, two grade 2, and two grade 3 injuries), and in two cases there was an additional injury of the direct tendon (one grade 1 and one grade 3 injury). Tendon waviness of the indirect tendon was observed in 8 athletes (50%), of which 4 were considered intramuscular tendon injuries. In total there were 9 injuries (56%) at the intramuscular tendon. In one athlete an injury was seen at the MTJ of the anterior superficial tendon aponeurosis of the proximal direct tendon. In one athlete there was a complete rupture of the rectus femoris 16 mm from the proximal insertion. For all rectus femoris injuries the proximal border of intramuscular edema was located at a mean of 45 mm (SD 21, range 12-72) from the proximal insertion, and the distal border of intramuscular edema at a mean of 91 mm (SD 34, range 24-160). The location of disruption was at a mean of 40 mm. from the proximal insertion (SD 22, range 0-64).

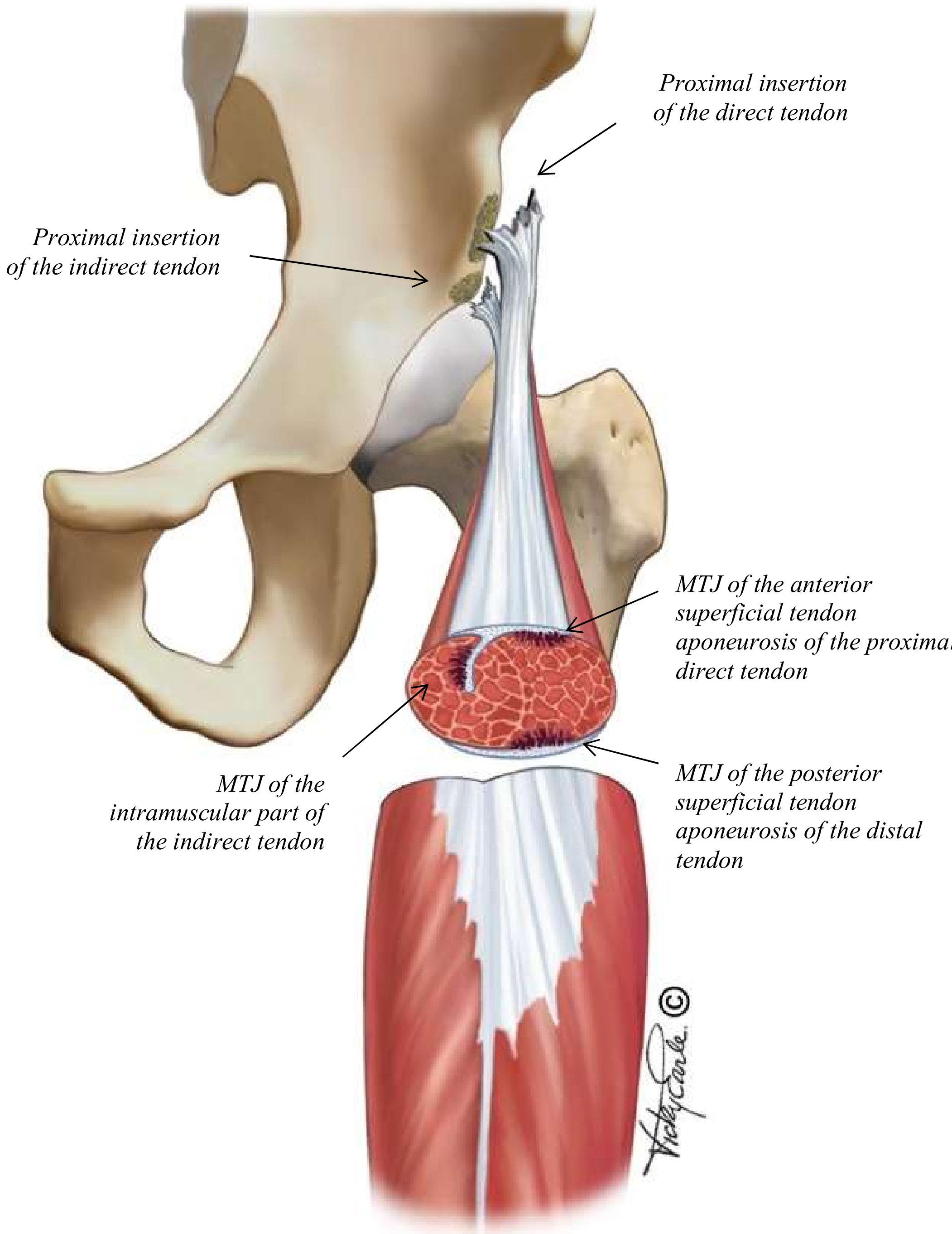


Figure 15: Generalized anatomical illustration of acute injuries of the proximal rectus femoris. At the insertion complete avulsions are illustrated, however, lower grade injuries might also be seen. At the musculotendinous junction (MTJ) of the intramuscular part of the indirect tendon, injuries were often observed mainly involving the medial fibers (as illustrated), but can also include the lateral part of the MTJ, as well as tendinous injury.

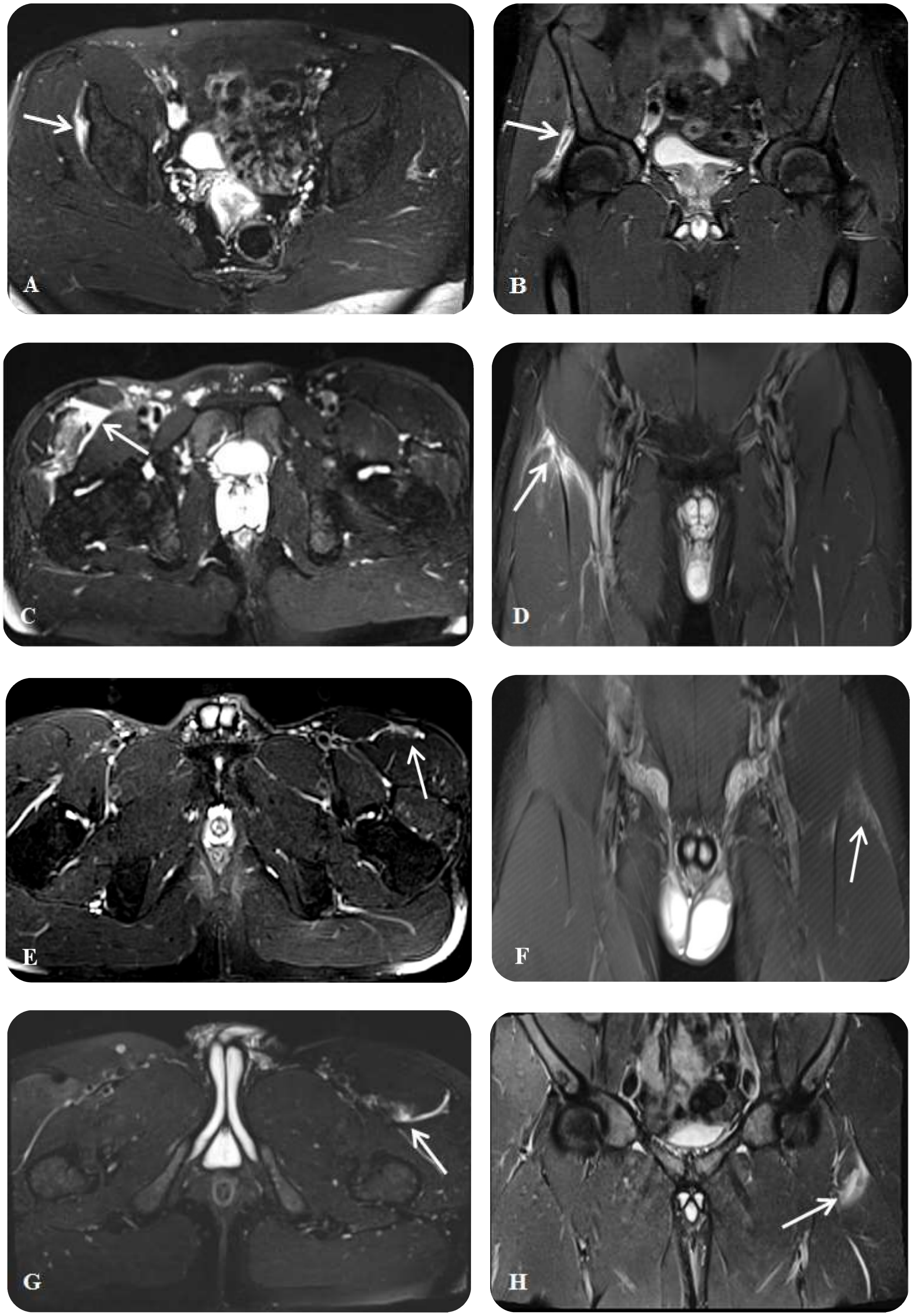


Figure 16: MRI images of acute proximal rectus femoris injuries.

A & B: Axial T2-weighted image with fat suppression, and coronal STIR image showing a grade 3 (avulsion) injury of the proximal insertion of the indirect tendon of the rectus femoris in a 31-year-old basketball player injured during sprinting. **C & D**: Axial T2-weighted image with fat suppression, and coronal STIR image showing a tendon injury of the rectus femoris indirect tendon in a 26-year-old football player injured during kicking. **E & F:** Axial T2-weighted image with fat suppression, and coronal STIR image showing a grade 2 injury at the superficial tendon aponeurosis of the direct tendon of the rectus femoris in a 23-year-old football player injured during kicking. **G & H:** Axial T2-weighted image with fat suppression, and coronal STIR image of a distal tendon MTJ (posterior tendon aponeurosis) rectus femoris injury in a 35-year-old handball player injured during a sprint.

Acute iliopsoas injuries

An MRI positive acute injury in the iliacus or psoas major muscles was found in 13 athletes. In 12 of these athletes, the iliacus was injured. A psoas major injury was found in 7 athletes (Table 21). Three characteristic injury locations were seen, as illustrated in Figure 17. There were 6 athletes (46%) with isolated injuries, and 7 (54%) with more than one acute muscle injury. In 5 athletes (38%) an isolated iliacus injury was observed, and 1 athlete (8%) had an isolated psoas major injury. Of the combined injuries 6 athletes (46%) had a combination of an iliacus and psoas major injury (Figure 18), and 1 athlete (8%) had a combined iliacus and rectus femoris injury also reported previously. Two locations within the iliacus were injured in 4 of the 12 athletes (33%), with both a distal injury and an injury near the proximal insertion on the iliac fossa. It could not be clearly differentiated whether proximal injuries occurred at the insertion or at the MTJ. In one athlete there was a grade 3 avulsion injury of the distal iliacus tendon with 12 mm retraction in combination with a grade 2 psoas major injury. Tendon waviness of the distal psoas major tendon was reported in one athlete in combination with a grade 2 iliacus injury. The MRI sequences generally did not include visualization of the proximal insertions of the psoas major. The location of edema showed that the distal iliacus injuries generally occurred slightly closer to the distal insertion than the psoas major injuries with a mean distance of edema from the insertion of 16 mm (IQR 6-27, range 0-57) compared to 31 mm (IQR 20-78, range 0-89) for the psoas injuries. The iliacus injuries also had a longer mean proximal-distant length of intramuscular edema than the psoas major injuries, with 98 mm (IQR 87-152, range 52-170) for iliacus injuries compared to 28 mm (IQR 18-133, range 15-157) for psoas major injuries.

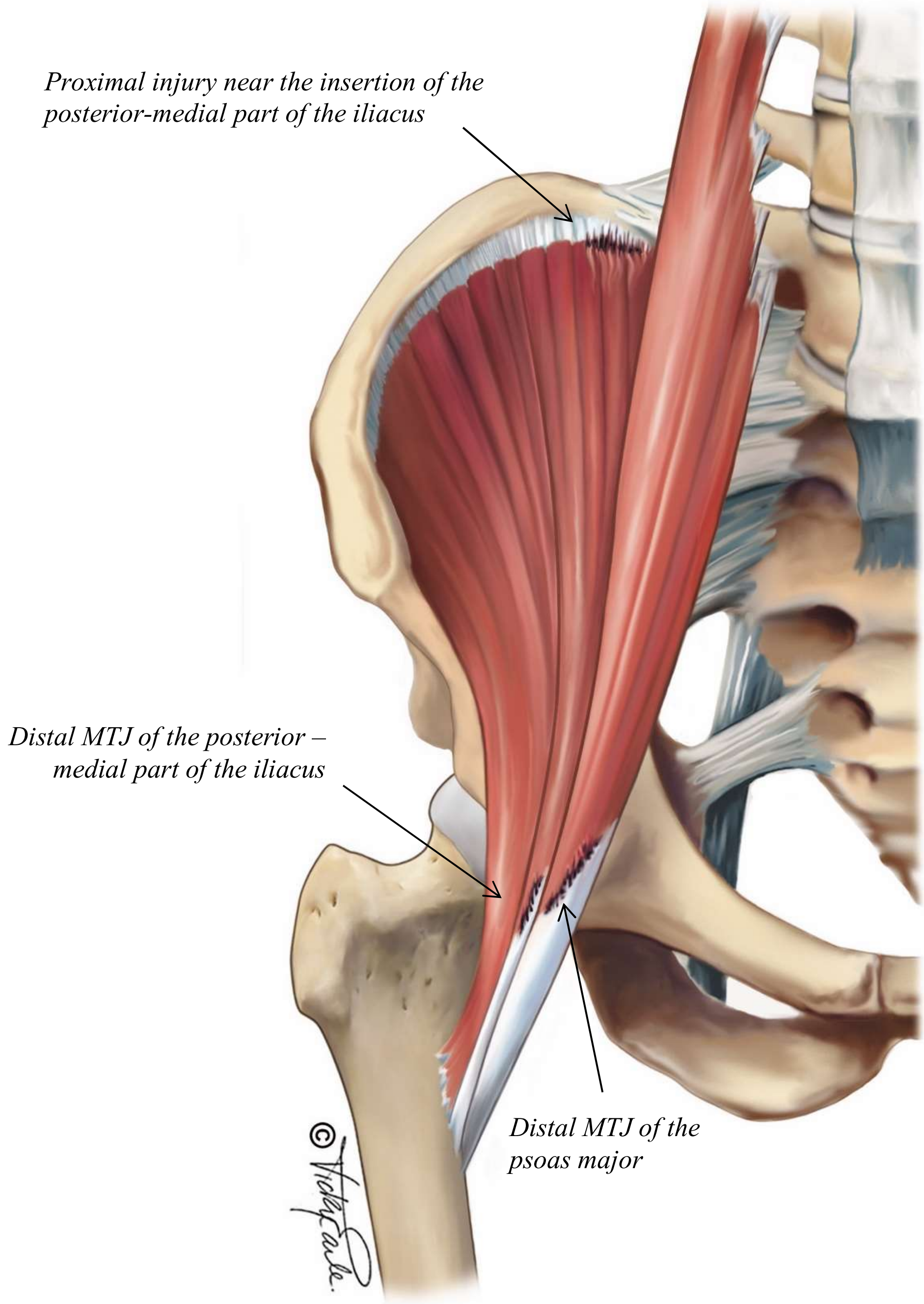


Figure 17: Generalized anatomical illustration of acute injuries of the iliacus and psoas major. MRI assessment could not clearly differentiate the structural involvement of the proximal iliacus injuries near the insertion. MTJ = Musculotendinous junction.

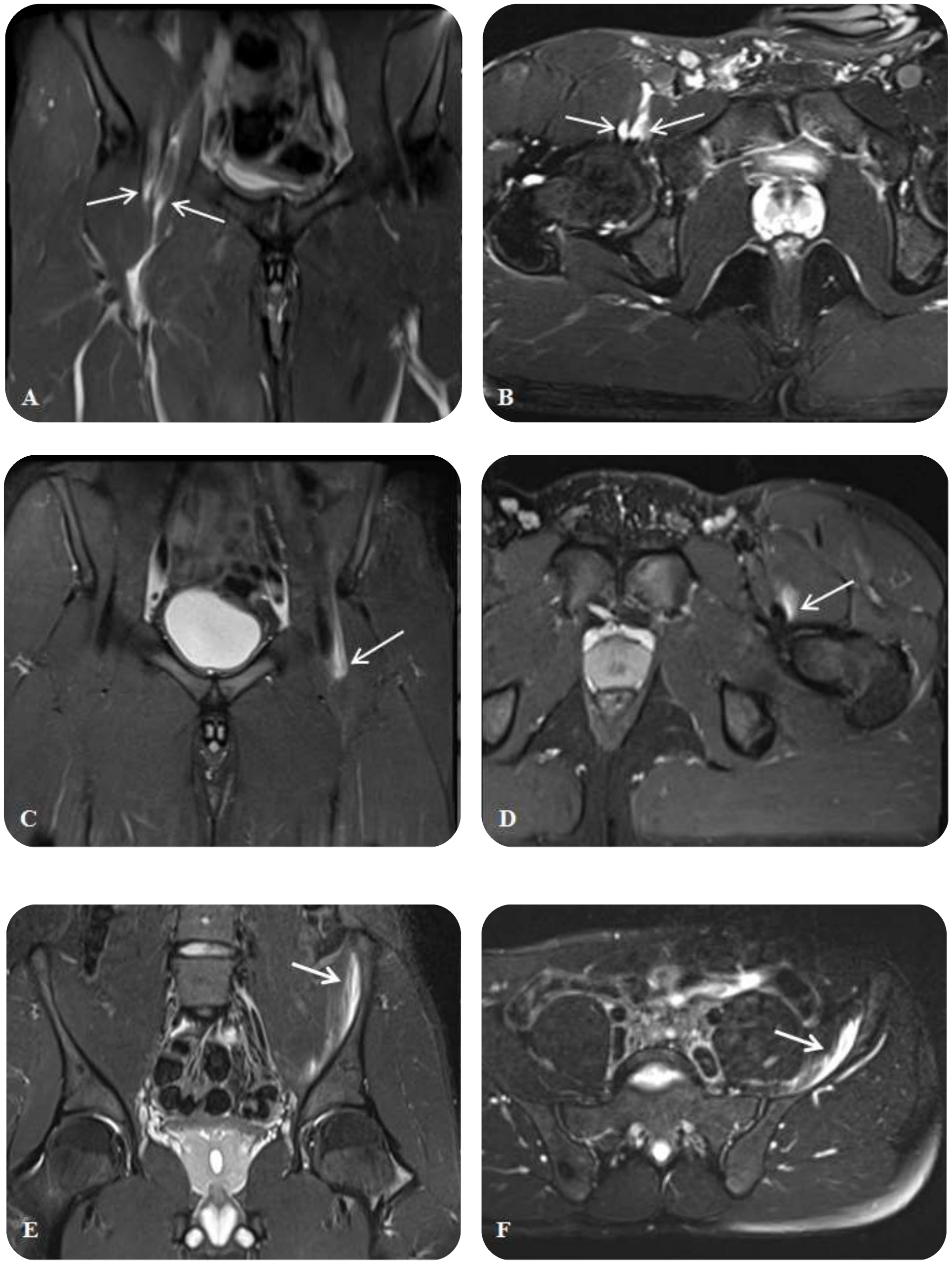


Figure 18: MRI images of acute iliacus and psoas major injuries.

A & B: Coronal STIR image and axial T2-weighted image with fat suppression showing an acute injury in both the iliacus and psoas major muscles in a 25-year-old football player injured during a sliding movement. **C & D:** Coronal STIR image and axial STIR image showing an acute isolated iliacus injury in an 18-year-old football player injured during a tackle. **E & F:** Coronal STIR and axial T2-weighted image with fat suppression showing a proximal iliacus injury in a 21-year-old football player injured during change of direction.

Other acute hip flexor injuries

There were 5 acute injuries in other hip flexor muscles. Four acute grade 1 sartorius injuries were observed, with two isolated injuries near the proximal insertion (Figure 19A&B), and two injuries more distal. These two injuries were in combination with a higher grade distal adductor longus injury that was clinically considered the primary injury (Figure 19C&D). Additionally, one isolated grade 1 proximal TFL injury was reported. In this case the edema tracked medially and had a total proximal-distal length of 10.9 cm. (Figure 20).

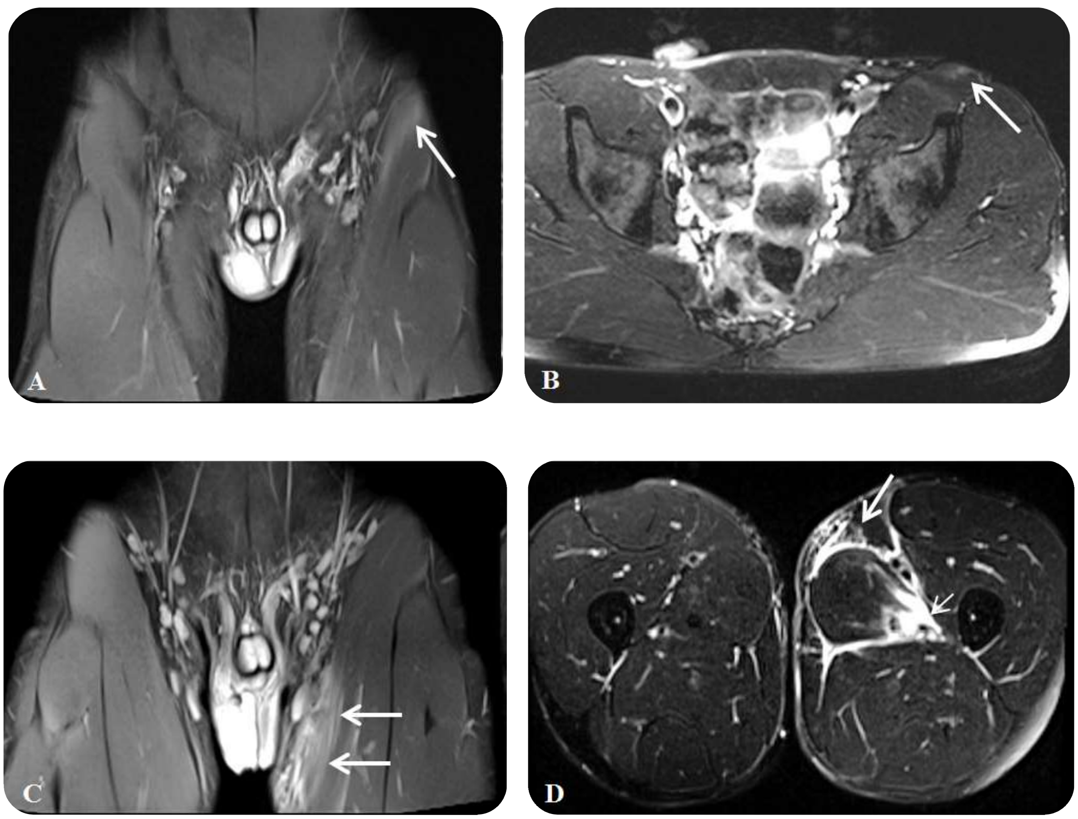


Figure 19: MRI images of acute sartorius injuries.
A & B: Coronal STIR image and axial T2-weighted image with fat saturation showing an isolated proximal left sartorius injury in a 19-year-old football player injured during kicking. **C & D:** Coronal STIR image and axial T2-weighted image showing edema in the sartorius (large arrows) in combination with a distal adductor longus injury (small arrow in D – not seen in C) in a 29-year-old futsal player injured during the acceleration phase of a sprint.

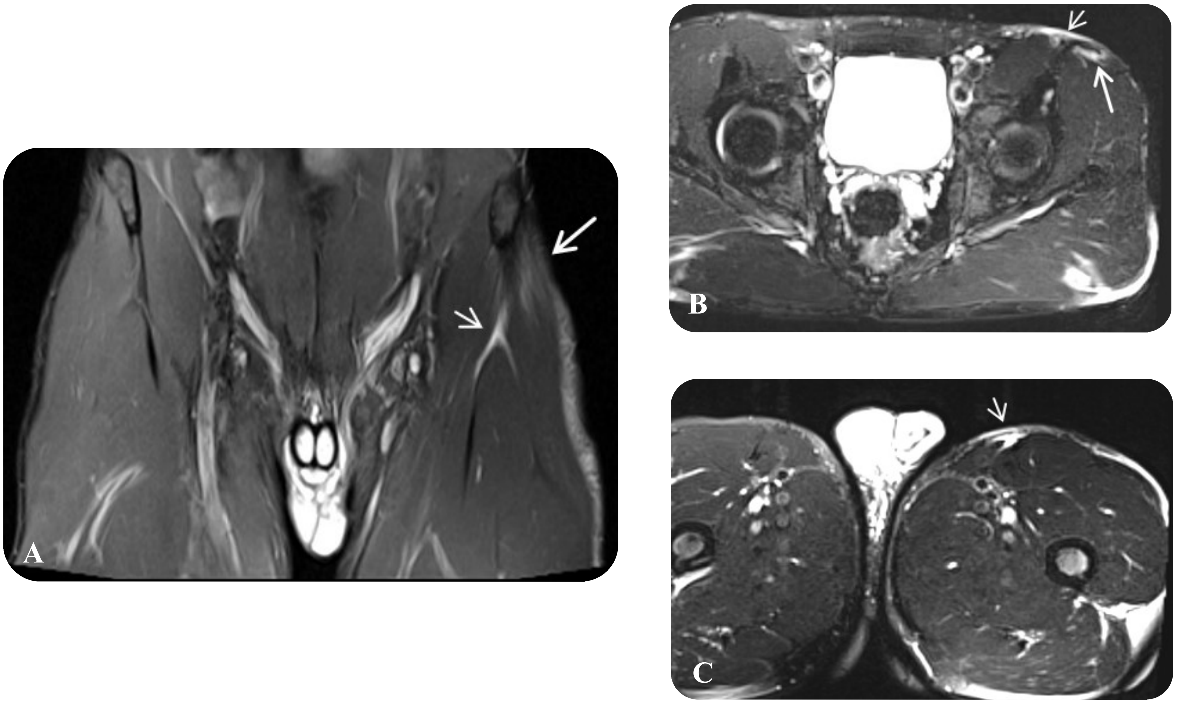


Figure 20: MRI images of an acute tensor fascia latae injury.
A: Coronal STIR image showing an acute grade 1 tensor fascia latae injury close to the proximal insertion (large arrow) in 29-year old football player injured during kicking. Small arrow indicates the medial tracking of intermuscular edema. **B & C**: Axial T2-weighted images with fat suppression of the same patient. Note that in the more distal slice, C, the tensor fascia latae injury cannot be seen, instead only edema located between the rectus femoris and sartorius is observed.

Discussion

In this thesis we examined the diagnoses of acute groin injuries from a clinical practice perspective in Study I. This provided a general overview of injury situations and distribution of muscle injury locations. We also saw that the clinical diagnosis sometimes did not match the imaging diagnosis on either US or MRI. There could be several reasons for these discrepancies, for instance inadequacies of imaging reporting or the clinical examination. In study II, we therefore examined the reproducibility of a standardized MRI assessment of the acute groin injuries. In this study we found good intra- and inter-rater reproducibility of the majority of the MRI scoring parameters. In study III, we further examined the standardized clinical examination tests by comparing them to the standardized MRI assessment. We found that clinicians can be confident in locating or ruling out adductor injuries using simple clinical tests. In contrast, accurately locating hip flexor injuries appears more challenging, which suggests that MRI could improve the accuracy of the diagnosis in these cases. In study IV & V we looked at the MRI positive acute groin injuries in more detail with a focus on MRI positive adductor and hip flexor injuries, respectively. We identified different characteristic injury locations in the adductor longus, proximal rectus femoris, iliacus and psoas. For the adductor injuries, multiple adductor muscles injuries were observed in about one third of the athletes, whereas a combination with injuries in other muscles was rare. In general, acute groin injuries rarely affected more than one muscle group.

New information on the diagnosis of acute groin injuries was found in all the studies in this thesis. While we have included the highest number of athletes with acute groin injuries to date, there are still relatively low numbers when sub-grouping specific injuries. This should be considered in the interpretation and generalization of the results. Irrespectively, we hope the new information provided in this thesis will improve the management of acute groin injuries, not only in relation to the diagnosis, but also prevention and treatment.

Injury situations

Injury mechanism is an important element in understanding the causes of acute injuries.[5] We therefore gathered information on injury situations from all athletes. In study I, we showed that kicking was the most frequent injury situation in football, and change of direction was most frequent in other sports. In general the findings in study I confirm descriptions from previous studies, which usually describe groin injuries as occurring in sports with kicking, change of directions, twisting and turning.[145,150] The kicking leg was injured in 81% of kicking injuries and the adductor longus was the most frequently injured muscle. This supports the hypothesis that the adductor longus is at high risk of acute injury when the muscle reaches its highest muscle activity and maximal rate of stretch in the swing phase of the kicking leg.[28] Change of direction has mainly been investigated in relation to ACL injuries[82,107,175] and performance.[24,115,198] Change of direction movements in relation to long-standing groin pain has been studied recently, and specific differences in movement patterns suggested as potential targets in rehabilitation.[58] This thesis confirms that change of direction is a frequent injury situation for acute groin injuries, but specific information on what the contributing factors during change of direction are is still lacking.

Injury situation information might also be helpful to consider when making a diagnosis. Study IV provides an overview of injury situations for adductor injuries, and Study V for hip flexor injuries with specifications for the individual muscles. For adductor injuries, our categorization of injury situations shows that they occur in the same situations as described for acute groin injuries in general, and with a similar distribution. We present an overview with specification according to the individual muscles; however, there did not appear to be any noticeable differences. This is likely influenced by the fact that the adductor longus was injured in about 9 of 10 adductor injuries. The number of isolated injuries in other muscles was too low to present a relevant overview. In contrast, we noticed differences between injury situations for specific hip flexor injuries. The rectus femoris injuries primarily occurred during kicking and sprinting, while the iliacus and psoas were the only muscles injured during change of the direction. Despite several papers focusing on rectus femoris injuries, injury situations are rarely reported.[6,13,34] Our findings of kicking and sprinting as the two main injury situations for rectus femoris injuries is in line with both a previous study,[90] and description of clinical experiences.[119] Injury situations for acute iliacus and psoas major injuries have not previously been reported. The difference between injury situations for these muscles could suggest that if a clinician is faced with a patient with acute hip flexor-related groin pain and an unclear clinical examination, the injury situation could be helpful to consider. If the injury situation was change of direction, an iliacus or psoas major injury would be more likely than a rectus femoris injury.

With these muscle specific sub-groupings we are still limited by numbers and therefore encourage further research to investigate differences in injury situation patterns. Furthermore, to describe the injury mechanisms in this thesis, only history taking was used. Future research could also include video analyses, where the inciting event can be expanded to include the athlete and opponent behavior, as well as biomechanical characteristics, as suggested in a comprehensive model for injury causation.[5] We are currently gathering data for such a video analysis study, and hope to be able to provide further details on some of the most common injuries in the near future.

Muscle injury locations

This thesis provides a more detailed overview of acute groin injuries than previously available. Study I looked at the general diagnosis provided through clinical practice. We found that acute adductor injuries were diagnosed in about 2 out of 3 cases, irrespective of examination modality. We also found that acute hip flexor injuries accounted for about 1 in 3 cases.

Previous studies have also found adductor injuries to be one of the most frequent muscle injury locations in athletes. Iliopsoas injuries are rarely included in these overviews, and rectus femoris injuries are often included as "quadriceps injuries" without further specification.[47,48,73,170,186,194] Of quadriceps muscles, the rectus femoris is reported to be the most frequently injured muscle.[34,170] Our findings suggest that it is also clinically relevant to include proximal rectus femoris injury in the differential diagnosis in the examination of acute groin injuries.

A recent large prospective study on all muscle injuries in professional football contains data on the groin pertinent to our study. In that study all injuries were clinically diagnosed, and they also found adductor injuries to be the most common groin injury. [48] These were followed by quadriceps, iliopsoas, sartorius, and abdominal muscle strains.[48] As there is an overlap of included participants between the different studies in this thesis, the muscle injury distribution presented in the individual studies naturally does not vary much. In order to get the most accurate picture of injury distribution, we can therefore use the standardized MRI scoring, where an overview including the largest number of participants can be observed from Study IV and V. In total 102 athletes had a positive MRI, of whom 70% had an adductor injury, with 90% of these, i.e. 62% of the total number of injuries, found in the adductor longus. The majority of the adductor injuries occurred in a single muscle, but injuries in multiple adductor muscles were observed in about one third of the cases. The importance of the adductor longus is also highlighted in that, in almost all of these multiple adductor cases, the injury severity of the adductor longus was similar or greater than the other adductor muscle injuries.

As a good rule of thumb, about 2 out of 3 acute groin injuries are adductor longus injuries. The primary focus in the prevention of acute groin injuries in athletes could therefore potentially benefit from a more focused intervention specifically targeting the adductor longus. Currently, randomized trials aimed at preventing groin injuries with general strengthening programs have not found significant reductions in groin injury incidence.[52,86,169] As such, a review of the included exercises is warranted. There is a growing amount of studies specifically related to exercise selection for the adductor muscles, which could assist in further optimization of prevention strategies of these injuries.[40,95,97,163]

Multiple injury locations were frequent in the clinical diagnoses in Study 1 (29%). This is in line with previous findings of 24-33% in athletes with long-standing groin pain.[84,87,111] Injuries in multiple muscle groups were, however, less common in the imaging reports with <10%. This is similar to the detailed results of Study IV and V, which also show that acute injuries across muscle groups were less common. In the standardized MRI assessment, we observed that only 5 athletes (5%) had injuries across muscle groups in the groin.

In three athletes, we saw edema in the rectus abdominis in combination with a complete adductor longus avulsion injury. Rectus abdominis avulsions have also been reported in combination with adductor avulsions,[176] however, we only observed low grade injuries in the rectus abdominis. These findings indicate that MRI positive abdominal injuries may be present in adductor longus avulsions, but that they are unlikely in lower grade adductor injuries. In Study III, we did see a considerable number of athletes reporting abdominal pain during the clinical examination, but the nature of this pain still remains unknown.

In two athletes, a combination of a distal adductor longus injury and an MRI positive sartorius injury was found. The sartorius injuries were low grade and it is possible that the edema in these injuries could instead be edema spreading from the adductor longus rather than a muscle strain injury in the sartorius itself. In addition to these combinations there were also four athletes with an MRI positive vastus medialis injury in combination with a distal adductor injury. In contrast to the combined sartorius injuries, these injuries appeared more as separate MTJ strain injuries. This is likely due to the very close proximity of the insertions at the linea aspera medially on the femur, possibly involving some connection of connective tissue.

In study I, iliopsoas injuries were clinically often reported in combination with either an adductor or a rectus femoris injury (18%). While the standardized MRI assessment showed that the iliacus and psoas major injuries often occurred together, there were no cases where either an iliacus or a psoas major injury occurred in combination with an adductor injury. In only one athlete minor edema was found in the rectus femoris in combination with a larger iliacus injury. Similarly, the MRI assessment showed that rectus femoris injuries primarily occurred in isolation. Therefore multiple acute muscle injuries involving the hip flexor muscles appear unlikely.

Detailed injury characteristics

In studies IV and V, the standardized MRI assessment was used to give a more detailed impression of the acute injuries. This enabled a characterization of specific injury location within the different muscles, which could potentially influence the management of these injuries.

Acute adductor longus injuries

Three characteristic injury locations of the adductor longus was found; the proximal insertion, the intramuscular MTJ of the proximal tendon, and the MTJ of the distal tendon. At the proximal insertion there were 12 complete adductor longus avulsions accounting for 75% of injuries at this location, and 17% of all cases. Usually information on complete adductor longus ruptures in athletes is presented as case-reports or smaller case series. The largest studies to date are on complete avulsion injuries, and include 6-19 complete adductor longus ruptures corresponding to less than two injuries per year.[159,176,184] This highlights that these injuries are not very common. The 12 injuries in the 3-year period of Study IV are therefore a relatively high number. Similarly, the proportion of avulsion injuries of all the adductor injuries is also relatively high compared to other acute muscle injuries.[75] This proportion might be influenced by referral bias. As athletes were included at a sports medicine hospital rather than through direct information from the clubs, more minor injuries might not have been referred. In order to achieve a more accurate distribution of injury types, specific information should therefore be investigated further in sports-specific epidemiological studies.

In addition to avulsion injuries, complete adductor longus injuries have been reported to occur at the intramuscular MTJ of the proximal tendon and as avulsions or complete MTJ ruptures at the distal tendon.[67,116,141] We did not observe any of these in the studies included in this thesis, but we have seen patients with both these injury types at the hospital, which unfortunately did not meet the inclusion criteria. Previous studies on proximal adductor longus avulsions usually describe tendon retraction of about 1-3 cm,[159,184] which is similar to our results. In two of the avulsion injuries in this thesis only minimal retraction was observed. In these cases we noticed a minimal connection of the most anterior fibers of the adductor longus (Figure 21). This might affect the clinical examination, as there is a chance that a gap might not be detectable on palpation. Particularly in cases with pain at the proximal insertion, imaging could therefore assist in establishing a definite diagnosis. This could be relevant for the prognosis, as avulsion injuries are generally associated with longer recovery duration.[75,159,184]

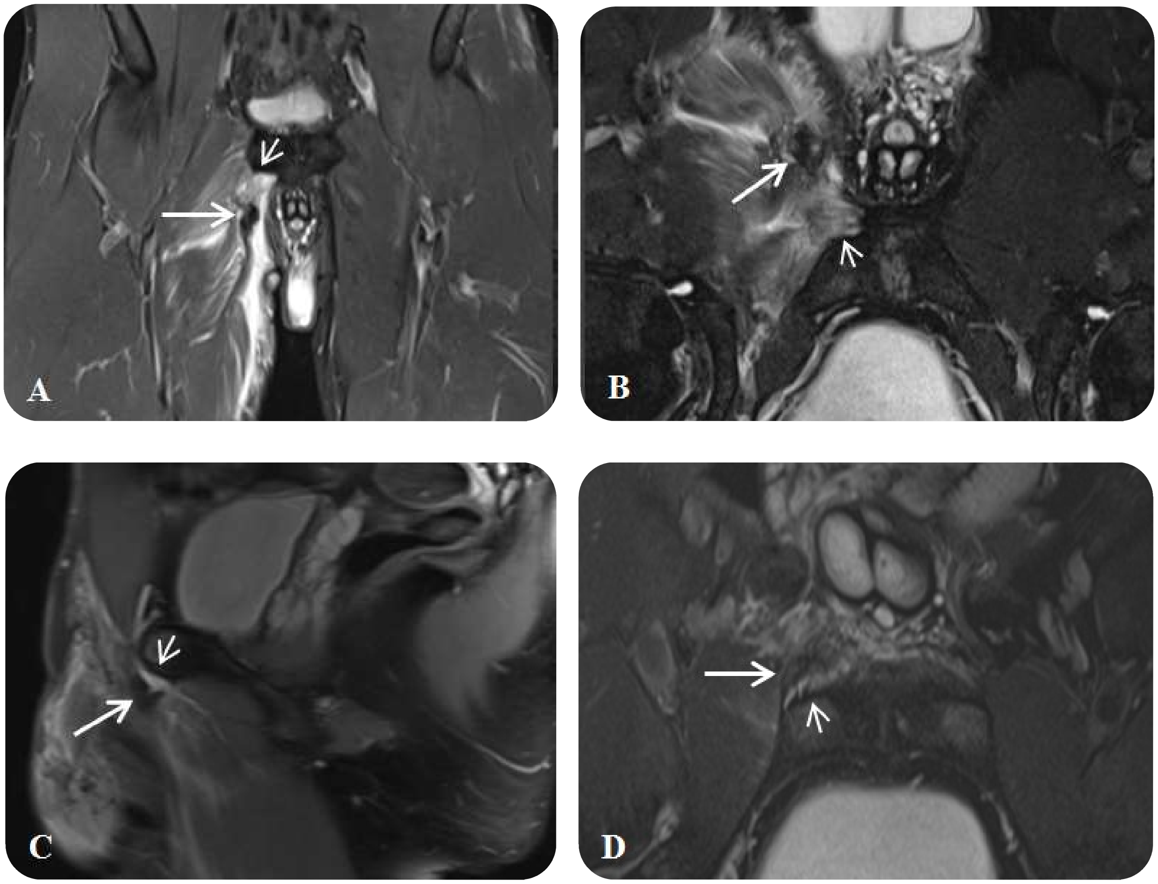


Figure 21: MRI images of two different types of avulsion injuries.

A & B: Coronal STIR and axial oblique T2-weighted with fat-suppression images showing a complete adductor longus avulsion in a 32-year-old football player injured while reaching for the ball. **C & D:** sagittal PD with fat-suppression and axial oblique T2-weighted with fat-suppression images showing an adductor longus avulsion with minimal anterior connection in a 24-year-old football player injured during a change of direction (large white arrows indicate the proximal adductor longus tendon, and small arrows indicate the pubic insertion).

MTJ injuries of the proximal tendon were mainly located at the anterior side of the intramuscular tendon (Figure 22). This was not scored specifically in the standardized MRI assessment, but appeared to be the case in most of these injuries. This probably indicates a higher force requirement of the corresponding muscle fibers during the specific injury situations. There has recently been an increasing focus on intramuscular tendon injuries, and their potential higher severity.[25,147] This appears to be of minor concern in adductor injuries, as there was only one injury with evident tendon waviness, indicating injury to the intramuscular tendon itself. This is considerably less than in acute hamstring injuries, where about a quarter of injuries are reported include tendon injury,[31,147] and less than in the proximal rectus femoris injuries as found in Study V.

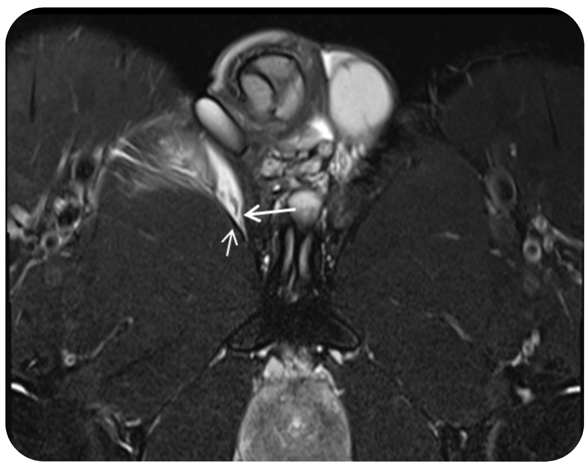


Figure 22: Anterior location of the MTJ injuries at the proximal tendon.
Axial oblique T2-weighted image with fat suppression showing a grade 2 injury (large arrow) at the anterior part of the proximal intramuscular tendon (small arrow) of the right adductor longus in a 32-year-old football player injured during a change of direction.

Injuries at the MTJ of the distal adductor longus tendon accounted for about half of the partial adductor longus injuries. There are no previous studies focusing on these injuries, and correspondingly, the anatomy of the distal adductor longus tendon and its MTJ remains unreported. In both injured and non-injured sides, it was difficult to determine the actual extent of the distal tendon on the MRI images. The injuries appeared to be located at the proximal end of the distal MTJ, with edema extending further proximally. Our understanding of the exact location and specific tissue involvement in these injuries could be improved by research using more specific MRI sequences, as well as comparison with anatomical studies.

In Figure 14, the potential overlap of edema of the MTJ injuries of the proximal and distal adductor longus tendons is illustrated. The measures of edema extent show that the edema from an injury at the intramuscular MTJ of a proximal tendon injury can extend distally down to 16.5 cm from the pubic insertion. This is a lot further distal than the 5.4 cm from the pubic insertion, which is shown as the most proximal border of edema from an injury at the MTJ of the distal tendon. If the location of edema is considered to be related to pain, this might make it difficult to distinguish between a proximal and distal MTJ injury on clinical examination. Similarly, partial tears from either injury type might be located around the middle of the muscle. This means that even if the palpation pain was completely accurate of the location of injury, these two injury locations could not be differentiated based on the distance from the insertion. From our clinical experience with these athletes, it appears the injuries at the MTJ of the distal tendon can be diagnosed by palpating more laterally around the prominent adductor longus muscle bulk, however, further study is required to determine the specificity of this approach. Additionally, whether this differentiation has implications for the management or prognosis is also unknown. We plan to examine this in future studies, where athletes will have performed a standardized treatment protocol, and duration of rehabilitation and return to sport will be assessed using standardized criteria.

Many different ways of classifying the severity of muscle injuries have been suggested.[76] The type of tissue involvement is sometimes included; however, a primary focus on the size of the injury is usually present. In this regard, the most common way to determine this is a four grade classification from 0 to 3, such as used in this thesis. Grade 2 injuries, referring to partial tears, are sometimes further divided based on the extent of the tear. In the recent Munich consensus statement on muscle injuries, minor and moderate partial tears are, for instance, defined as lesser or greater than a fascicle/bundle. [123] We did not use this approach as that can be very difficult to distinguish, and because it is also highly influenced by the quality of the imaging. We instead measured the extent of the disruption, which has also been suggested in other classification systems, such as the British Athletics muscle injury classification (BAMIC).[146] In this system, the differentiation between moderate and extensive disruption is set by a cut-off of more or less than 5 cm of architectural fiber disruption.[146] This injury classification system is mainly based on the relatively long hamstring muscles, which questions the used in shorter muscles, such as the majority of the adductors.

In this thesis, we show that the proximal-distal length measures of disruption for the adductor longus injuries ranged between 10 - 51 mm. This suggests that the way of defining injury grading in BAMIC system is not appropriate for adductor longus injuries. In the BAMIC system the use of the CSA of disruption as a percentage of the muscle CSA is also suggested, and cutoffs are set at above 10% and 50%.[146] In this thesis, we show that the calculated CSAs of disruption were very similar in the proximal and distal adductor longus injuries. As the muscle CSA of the adductor longus is considerably larger in the distal part of the muscle than proximally, it also questions the clinical relevance of this differentiation. For instance a small difference in the proximal-distal direction might lead to a relatively large change in the muscle CSA measured in the axial images, and thereby influence the percentage value, even with the exact same CSA of disruption. A different way of determining the severity or size of the partial tear could instead be a muscle specific measure of the disruption in relation to the total length of the MTJ; however, a clinical relevance of such should first be explored. As a result of these comparisons, it is therefore recommended that future muscle injury classifications consider specific variances between muscles to determine relevant categorizations.

Other acute adductor muscle injuries

The majority of injuries in the other adductor muscles occurred in combination with an adductor longus injury; however there were 9 athletes (13%) with isolated adductor injuries on the MRI not involving the adductor longus. These were in the pectineus, obturator externus and adductor brevis. The majority of these were near the proximal insertion, except from the pectineus injuries, where three of the four isolated injuries occurred at the distal MTJ (Figure 23). This might be relevant for the clinical examination as this location is very close to the distal iliacus and psoas major injuries, and could therefore be mistaken for such. In contrast the pectineus injuries, which occurred in combination with an adductor longus injury, were at the proximal insertion. The adductor brevis were also injured in isolation in three cases. Similar to the adductor longus the adductor brevis has an intramuscular course of the proximal tendon. [38] This was not identifiable on the MRI, therefore a differentiated overview of specific injury location for these injuries is not included, and there is no comparable literature.

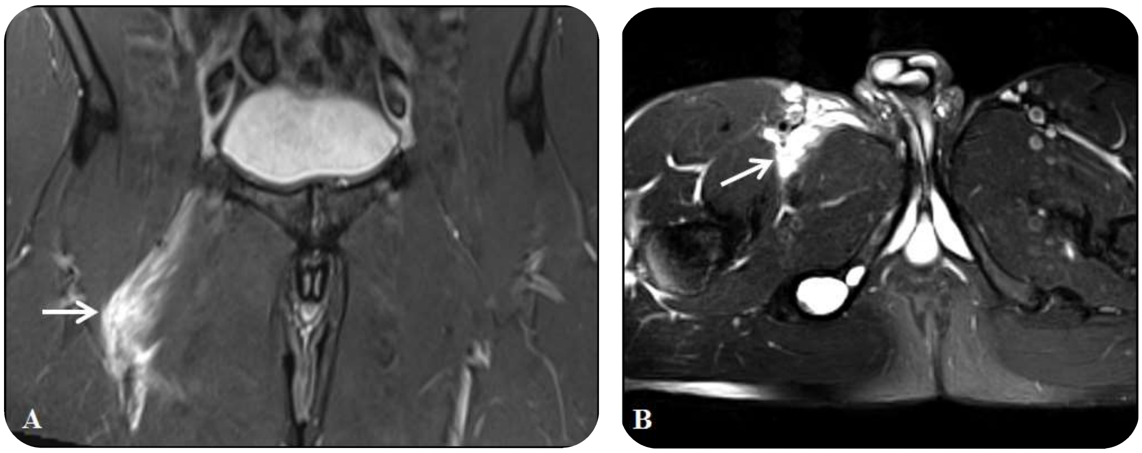


Figure 23: MRI image of a distal pectineus injury
A: Coronal STIR image showing a right distal grade 2 pectineus injury (white arrow) in a 27-year-old football injured during a sprint. **B:** Axial T2-weighted image with fat suppression of the same patient clearly depicts the intramuscular fluid-equivalent signal.

There were four gracilis injuries, which were all in combination with a larger proximal adductor longus injury. Isolated gracilis injuries are generally rare. A single study describes 7 athletes with isolated injuries, which all were located at the most proximal portion of the distal MTJ.[137] These injuries occurred during hip adduction and hip flexion movements; however, the pain was reported in the posterior thigh and can therefore not be considered as a groin injury.[137] Similarly, it is our clinical experience that posterior thigh pain is also reported in athletes with acute adductor magnus injuries. The posterior location of pain is likely related to the posterior extent of the proximal insertion on the inferior pubic ramus to the ischial tuberosity.[23,128] This also leads the ischiocondylar portion of the adductor magnus to be considered as part of the hamstring muscle group.[23,128] As only athletes with acute groin pain were included, this can explain the low number of adductor magnus injuries in our studies. The adductor minimus has been reported as a separate muscle in the adductor muscle group, but also as an upper part of the adductor magnus muscle.[23,180] In this thesis, we did not consider this muscle separately, and as the reported adductor magnus injury was observed distally, we do not consider this muscle or muscle part, as a probable groin injury location. Gracilis and adductor magnus injuries can be therefore be considered rare findings in athletes with acute groin pain, but could be considered if the pain is located more posteriorly in the medial thigh.

Acute rectus femoris injuries

Proximal rectus femoris injuries were the most common hip flexor muscle injuries. Rectus femoris injuries are also the most common acute quadriceps muscle injuries, and can be located all along the anterior thigh.[17,34,75,99] In our studies we focus only on athletes with groin pain, therefore the generalizability of the results will primarily related to injuries at the proximal tendons.

In study V, we show that all but one rectus femoris injury (94%) involved the proximal tendons, with a much higher proportion of injuries of the indirect tendon than the direct tendon injuries (93% vs. 27%, with 20% combined). This is similar to previously reported for proximal rectus femoris injuries, where one study describes that 89% of injuries involved the indirect tendon.[135] We also observed one injury at the proximal part of the posterior aponeurosis of the distal tendon, which indicates that these injuries cannot always be ruled out in athletes with acute groin pain. In more than half of rectus femoris injuries the injury was located at the intramuscular part of the indirect tendon, and almost half of these included injury of the tendon itself rather than the MTJ only. While injuries at the intramuscular tendon are often the focus of other studies on rectus femoris injuries, these studies do not report the presence of injury to the tendon itself.[6,35] As intramuscular tendon injury has been associated with a longer treatment duration in hamstring injuries, [25,31,147] it could also be a potential explanation for the large variations in reported treatment duration of proximal rectus femoris injuries.[6,35] The relatively low number of these injuries included in this thesis should be considered, and further studies are required to confirm this assumption.

Acute iliacus and psoas major injuries

Iliopsoas injuries were divided into iliacus and psoas major injuries. In most cases a distinct injury in one or both muscles was observed. In total 13 athletes had iliopsoas injuries, accounting for 40% of the hip flexor injuries. There is a general perception that iliacus and psoas have a combined iliopsoas tendon, yet recent anatomical studies have revealed that there are very often separate tendons for psoas major and iliacus, and in some cases also an accessory iliacus tendon.[142,177] Our results show that a division is also possible in acute injuries. Iliacus MTJ injuries were most common (92%), and half of these were in the iliacus alone. In contrast only one isolated psoas major injury was seen, with the remaining psoas injuries being combined with iliacus injuries.

The literature on iliopsoas injuries is very limited. In one study, a retrospective review of almost 5000 hip and pelvis MRI examinations was performed. Of these only 16 iliopsoas injuries were found in adults younger than 65, and only 10 of these were athletes.[26] Half of these 16 injuries were described as MTJ injuries, and the other half as partial tendon tears. In that study no muscle specific division was made. Further studies should clarify whether differentiation between injuries in these two muscles is clinically relevant for diagnosis or prognosis. Differentiation could provide a better understanding of the injury mechanisms, and potentially inform adjustments of the focus in rehabilitation programs.

Other acute hip flexor muscle injuries

Although there were few MRI positive sartorius injuries, these should be considered in the differential diagnosis of acute groin injuries. Similarly, we also observed one isolated injury in the tensor fascia latae, which we initially did not consider as a possible cause of groin pain due to its lateral location. The low numbers of these injuries prevent any in depth conclusions, and there is no additional information in the scientific literature. On MRI we observed short intramuscular courses of the proximal tendons in both muscles. The two proximal sartorius injuries and the TFL injury in our study appeared to be at the MTJ of these tendons, however further specification is not possible.

Acute hip-related injuries

Hip-related injuries are reported to account for around 5% of all hip and groin injuries in football, with synovitis being the most common diagnosis.[191] The proportion of acute hip injuries is however unknown. In athletes, acute hip injuries might be related to acetabular labral tears (ALTs), although these are often described as a results of repetitive trauma.[27,92] ALTs might occur during forceful hip rotation and extension movements, but could potentially also be a result of a traction from the distal iliopsoas or proximal rectus femoris insertions.[27,42,57,88,92] Clear evidence of such causative relationship is lacking. In both study I and II we observed a very low number of ALTs on the MRI (2% and 4%), with none of these being clinically diagnosed as a cause of acute groin pain. Similarly, only 2 out of 628 of hip and groin injuries (0.3%) were diagnosed as labral tears in the previously mentioned football injury epidemiology study.[191] We used non-contrast MRI, however, even MR-arthrography cannot detect all ALTs.[153] Therefore we cannot exclude an underreporting of ALTs in the thesis. As the corresponding symptoms were not present in the clinical examination, we can however still consider acute ALT as a rare differential diagnosis in male athletes with acute groin pain.

We did not consider different hip morphologies, such as cam or pincer morphologies, as specific diagnoses. These bony morphologies of the femoral head-neck junction or acetabular rim have been suggested as possible risk factors for both ALTs and soft-tissue injuries. Therefore these are often reported as separate diagnoses or as femoroacetabular impingement (FAI). Recent studies suggests that these morphologies are acquired during skeletal maturation where the type of sports and activity are related factors,[1,108,143,173] and that they are also seen in up to 75% of asymptomatic athletes depending on the definition criteria.[143] A recent consensus statement describes "FAI syndrome", as a combination of symptoms, clinical signs and imaging findings,[68] similar to followed in the included studies. These factors support the approached used in this thesis.

Imaging negative injuries

There were a relatively high number of athletes without any acute injuries found on imaging. In study I, we observed that this was the case for both US and MRI to a similar extent. About 1 out of 5 injuries were MRI negative, and this proportion was similar throughout the studies. As previously described, a high number of imaging negative muscle injuries (92%) was reported in an older study using US in the diagnosis of acute groin injuries.[50] This is not surprising as most of these injuries were actually reported to have a gradual onset, but mainly because of the long duration between injury and US examination (1-6 months). This study should therefore not be used as a comparison. Instead we can compare to other acute muscle injury locations were similar proportion of imaging negative injuries are reported. In acute hamstring injuries the proportion of imaging negative injuries are reported to be between 12-45%.[49,62,75,160,166,185] A proposed muscle injury classification system based on hamstring injuries, classify imaging negative cases as "functional muscle disorders".[123] These disorders are further divided into "overexertion-related muscle disorders" (fatigue-induced or delayed-onset muscle soreness) or "neuromuscular muscle disorders" (spine-related or muscle-related). Common for the descriptions of these four sub-types is that they are mainly of gradual onset and involve the entire length of the muscle. The acute imaging negative groin injuries in this thesis therefore do not fit readily into this classification system. The previously mentioned BAMIC system, includes a suitable a description of MRI negative muscle injuries.[146] A classification of grade 0a injuries includes injuries with focal muscle soreness occurring during exercise. These injuries are suggested to be a result of microscopic muscle damage or peripheral nerve irritation.[146] The reasons for the imaging negative injuries in our studies remain unclear. As described for the grade 0a injuries, it could be that these are smaller injuries, which current imaging examinations cannot detect. They could instead also be acute exacerbation of an underlying previously asymptomatic pathology of more long-standing nature.

Discrepancy between clinical diagnosis and imaging findings

During Study I, we noticed that there were some discrepancies between the clinical diagnosis and the imaging findings. We therefore performed a post hoc analysis where we found that clinically diagnosed adductor injuries were usually confirmed by imaging, but that there was a high discrepancy for all other injury locations. Clinically diagnosed adductor injuries showed an injury in a different location on imaging with no adductor injury in only 3-6% of cases. In contrast, when an iliopsoas or a rectus femoris injury was clinically diagnosed, there was only about a 50% chance of this injury being confirmed on imaging. Clinically diagnosed sartorius injuries were only confirmed on imaging in 1 out of 7 cases.

The difficulty in accurately diagnosing the injuries in the initial examination is also highlighted by the higher number of athletes diagnosed with multiple injuries in the clinical examination compared to imaging. This discrepancy between clinical examination and imaging findings should be kept in mind when interpreting the results of epidemiological studies, where some studies only use clinical diagnosis, some only imaging, and others a combination of both. As a result, potential differences between studies might be influenced by the approach rather than actual differences between populations. A gold standard examination for acute groin injuries is therefore also difficult to recommend, as there might be a higher risk of a misdiagnosis on clinical examination, whereas there is a risk of underreporting injuries by using imaging given the number of imaging negative cases.

There can be different reasons for this discrepancy. One reason could be the reliability of the MRI assessment. We therefore aimed at standardizing the MRI assessment and testing the reproducibility of that in Study II. The discrepancy could also be caused by different diagnostic techniques by the different sports medicine physicians, as well as of their interpretation of the clinical examination tests. For instance, the close anatomical proximity of the muscles in the groin might make it hard to differentiate the exact injured structures. In acute presentations, resistance tests might be less specific and palpation pain might be present in a larger area than the actual injury. Prior to this thesis there was no evidence for specific combinations of tests for acute groin injuries, such as suggested for long-standing groin pain.[84,87] We therefore investigated the clinical examination tests further in Study III, where individual clinical examination tests were compared to the standardized MRI assessment.

MRI reproducibility

In Study II, we described an MRI assessment approach that enables reproducible reporting of acute groin injuries in athletes. This assessment includes a focus on location of which muscle is injured and where the injury is located within the muscle. It also describes the extent, with ordinal grading and continuous measures of injury. There was almost perfect reproducibility for whether the MRI was positive or negative, and also for the specific muscle location when positive. This allows confidence that an MRI examination can provide a more accurate diagnosis of the location, if the clinician is uncertain during clinical examination. Due to imaging negative cases, there will however still be situations were the clinician will have to rely on the clinical assessment only.

There was also almost perfect reproducibility for the simple ordinal grading. This is in line with the results of MRI grading of acute hamstring injuries,[77] and shows that relatively simple definitions can provide a basic idea of the structural severity of the injury. The relevance of distinguishing between the lower grade injuries is a topic for debate, as a recent study show only negligible additional value for predicting return to play time when MRI grading was used compared to a structured clinical examination alone.[188] Grade 3 injuries are generally reported and accepted to have longer healing time.[60,75,114,184]

The measures of edema and disruption also showed high reproducibility. These measures can give a more detailed overview of the variation in size within each grading, and might be used to track the structural healing process. It is therefore important to know how the size of the measurement error, in order to be certain that differences in measurements are related to actual changes. The SEM for both edema and disruption was in general <20% between the radiologists, as well as between the first and second scoring by the same radiologist. This resulted in MDCs between 18-62%. This is comparable to acute hamstring injuries where MDCs have also been reported between 7-64%.[77] As radiologists will often be measuring smaller injuries, which are therefore sensitive to minor measurement errors, a good rule of thumb is that a measure needs to change more than 50% in order to be accurate in reporting an improvement between two measures. It is still questionable how much changes in MRI measurements are related to clinical and functional progress. This is indicated by a study on athletes with acute hamstring injuries, where increased intramuscular signal intensity on MRI was found in 93% athletes at return to play, despite the athletes having clinically recovered.[152]

We also analyzed the reproducibility of scoring findings of a non-acute nature. The prevalence of these findings was low, which affects the confidence in the results. Pubic BME, central disc protusion, and peri-symhyseal sclerosis were the most frequent findings in Study III. For pubic BME there was substantial intra-and inter-rater agreement. Central disc protusion and peri-symphyseal sclerosis also showed high intra-rater agreement, but a slightly lower inter-rater agreement. The results of these three findings are generally higher than previously reported for the same measures.[18] That study, also showed generally higher intra-rater reproducibility than inter-rater reproducibility of non-acute findings, similar to our findings.[18] The clinical relevance of the non-acute findings in the athletes with acute groin injuries is probably low, as there was generally a low prevalence of these, and as many of these findings are also shown to be present in football players without groin pain.[19] Additionally, most athletes had clear imaging signs of acute injuries. For the athletes with negative imaging it can however not be excluded that some of these non-acute findings could be related to the clinical presentation. Larger studies would be required to investigate such relation.

Comparing clinical tests to MRI findings

As there was high reproducibility of the MRI assessment, we assumed that the discrepancy between clinical diagnosis and imaging location was related to the clinical examination. In study III we tested standardized clinical examination tests in comparison to the MRI findings. In this study, we found that clinicians can be confident in using simple clinical test to locate or rule out adductor injuries. In contrast accurately locating hip flexor injuries appears more challenging.

Predicting a negative MRI

Similar to the other studies in the thesis, we found that about 1 out of 5 athletes had a negative MRI in Study III. By evaluating the NPVs, we can provide the probability of which athletes are likely to have a negative MRI. We found that the highest probability of a negative MRI was when all tests for the specific muscle group were negative. In the adductors, there were no cases where all clinical tests were negative and there was a positive MRI. This corresponds to 0 percent chance of an MRI positive adductor injury if all adductor tests are negative. In the hip flexors there were two cases where an injury was found despite all clinical tests being negative, corresponding to a 7% risk. These injuries were both seen in the sartorius, for which we did not include specific resistance or stretch tests. Overall, we can conclude that it is very unlikely to have a positive MRI if all clinical examination tests are negative.

It might become more difficult when some tests are negative and others are positive. The best individual test to predict a negative MRI was palpation. If there was no palpation pain in the adductors there was a 91% probability of not finding an adductor injury on the MRI. Similarly, there was a 96% probability of not having an MRI positive hip flexor injury, if there was no palpation pain in the hip flexor muscles. Palpation can therefore be considered a key test to predict a negative MRI.

Predicting a positive MRI

Similar to predicting a negative MRI, the highest probability of a positive MRI was found when all grouped clinical examination tests were positive. When all adductor tests were positive there was 83% percent probability of an MRI positive adductor injury. When all hip flexor tests were positive there was 86% probability of an MRI positive hip flexor injury. Understandably, when all tests are pointing in one direction, clinicians are most likely to predict a correct result. This was only the case in 31% of the athletes, which tells us that athletes present with fewer positive test in the majority of cases. We also examined the probability of a specific cut-off number of positive tests.

The results show that the optimum cut-off number of positive tests was three. The PPV using this cut-off was, however, worse than for the majority of the individual tests for both the adductors and the hip flexors. Clinicians are therefore better off relying on the interpretation of the individual tests.

To predict a positive MRI in the adductors, the highest probabilities were found for the resisted outer-range adduction test, the squeeze test with neutral hip and long lever-arm (Squeeze-0˚), and the passive adductor stretch test. Each of these individual tests showed similar positive predictive values to when all adductor tests were positive. Clinicians will probably find more utility of these individual test as they are each more often positive than cases with all adductor tests positive, 43-59%, compared to 22%, respectively.

To predict a positive MRI in the hip flexors, there were no good individual examination tests. As shown by the AUC results, palpation was the best test to discriminate between a positive and negative MRI, but even palpation had a similar ability to predict a positive MRI as chance. This indicates that these tests are often positive without positive MRI findings in the hip flexors, and clinicians should therefore be careful not to over-interpret positive tests.

Predicting an accurate injury location

The high number of imaging negative cases demonstrates the limitations of using MRI as gold standard in determining an accurate injury location. In order to get optimal knowledge on the accuracy of the clinical tests we therefore chose to exclude all imaging negative cases, and then consider MRI as the gold standard for determining injury location in MRI positive cases. The high reproducibility of MRI injury location found in Study II, adds support to this choice.

Similar to the first analysis, the highest accuracy was found when all clinical tests for either the adductors or hip flexors were positive. In all cases where all adductor tests were positive there was an acute adductor injury on the MRI (PPV 100%). This suggests that there is no need for an MRI to determine injury location, when clinicians find all adductor tests positive in the clinical examination. The accuracy of the iliopsoas and rectus femoris tests were considerably lower. Having all clinical examination tests positive provided only a PPV of 71% for an MRI positive iliacus or psoas injury, and 43% for an MRI positive rectus femoris injury. This leaves the clinician with a relatively high uncertainty in differentiating between injuries in the hip flexor muscle group with this approach. An imaging examination should therefore be considered if a higher level of confidence regarding injury location is required.

The individual examination tests for the adductors also showed very high accuracy. This suggests that an acute adductor injury can comfortably be diagnosed using clinical examination tests only. The squeeze test with the hip in neutral position and a long lever, Squeeze-0˚, showed the highest accuracy (PPV 97%). This position of the squeeze tests has also been shown to be superior to other hip flexion angles for pain provocation, in a study where it was compared to the hip in 45° & 90° flexion.[44] This position therefore seems to be the best resistance test position for both acute and long-standing adductor-related groin pain. In the Doha agreement on terminology of groin pain, the clinical diagnosis of adductor-related groin pain is defined as: "adductor tenderness AND pain on resisted adduction testing".[190] In Study III, we also showed a high accuracy of adductor palpation (PPV 92%). This indicates that it is reasonable to use this definition for acute adductor injuries as well. Specifying injured muscles within the adductors becomes slightly more uncertain, as we found low accuracy for both palpation of the pectineus and the gracilis compared to the adductor longus. The low prevalence of these injuries is reflected in the results; however, clinicians should still be cautious in specifying injuries to these muscles through the clinical examination only.

For MRI positive iliopsoas and rectus femoris injuries, palpation was the most accurate clinical examination test. There were no cases where palpation was negative in either muscles and an injury was found in that muscle on MRI. On the other hand, when palpation was positive the probability of actually having an MRI positive injury was similar to chance. The results therefore indicate that it can be challenging to accurately diagnose acute hip flexor injuries using clinical examination. In the Doha agreement on terminology of groin pain, the clinical diagnosis of iliopsoas-related groin pain is defined as "iliopsoas tenderness, and more likely if there is pain on resisted hip flexion and/or pain on stretching."[190] The results of Study III suggest that this definition might result in many inaccurate diagnoses of acute groin injuries, as these clinical tests are related to a high uncertainty. Further research including a larger number of athletes should therefore be performed to make more accurate recommendations.

Limitations

Although we have attempted to optimize the methods used in all studies in this thesis, there are a number of limitations, which should be considered in relation to the different studies.

In study I, there were 18 different sports medicine physicians who performed the clinical examinations. This might be a strength in relation to the generalizability of the results, but it also adds uncertainty with regard to the reliability of the clinical diagnoses. As there was no evidence on the clinical examination of acute groin injuries prior to this thesis, we modified the recommendations for long-standing groin pain, which have shown good reliability.[84,85,190] In Study I, only a minimum of one positive finding on palpation, stretch, or resistance tests was required to make a diagnosis. Considering the results of Study III, showing low accuracy of the clinical hip flexor tests, this decision might have contributed to a higher number of injuries being diagnosed on clinical examination. This probably contributed to the discrepancies between the clinical diagnosis and imaging location of hip flexor injuries.

Similarly there were several radiologists involved in the imaging assessment. In study I, only the presence or absence of injury was included, and in Study II, we show that this differentiation has good reproducibility in the MRI assessment between two different radiologists. This indicates a good probability that the distribution of MRI injuries can be generalized to similar populations. This is also supported by a similar injury distribution found throughout the studies. We still do not have reproducibility of the US scoring, but as the injury distribution was similar to the MRI findings, it can be assumed that there is not a big difference between these two imaging modalities when determining location. This comparison does not account for the fact that injuries from the US and MRI could represent different individuals, and that not all athletes had both US and MRI examination. The latter was primarily a result of the imaging availability within the required timeframe. Therefore further studies on the reproducibility and validity of the US examination should be performed.

In Study II, we found high reproducibility for the majority of the MRI scoring parameters despite the anatomically complexity of the groin region. It is important to note that two experienced MSK radiologists performed the MRI assessment and a thorough discussion of the scoring variables was performed prior to the study. This was an attempt to prevent that differences in scoring would be related to disagreements of the definitions, but simply would be related to the difficulty of scoring the specific variable. This might in turn also mean that the reproducibility results of study II might be higher than found between radiologists at different locations without direct contact. When multiple radiologists are involved in the assessment of acute groin injuries it can therefore be recommended to ensure agreement on terminology and definitions for the scoring parameters prior to assessment. To further minimize any potential uncertainty in the imaging assessment, the images in Study IV and V were reviewed again, and any discrepancies were further discussed with additional radiologist. There is a risk that some scoring variables might have been affected by image artifacts, such motion artifacts, inadequate fat suppression or magic angle artifacts.[140] These can potentially affect the interpretation of the images however, as there was still high reproducibility, this was likely a minor concern.

As discussed there are limitations in considering MRI as the gold standard for diagnosing acute groin injuries. This is due to the considerable number of imaging negative cases, but also that we cannot be completely certain that the high-intensity signal corresponds to an actual injury. Currently there is no alternative gold standard, such as a biopsy or surgical exploration. Given the fact that the vast majority of these injuries are treated without surgery we do not expect this to change in the future. An option to improve validation could therefore be to perform an MRI assessment in a group of healthy athletes to indicate the prevalence of acute MRI injury findings. It has been shown that in the MRI assessment of asymptomatic athletes, there is a small chance that the MRI will show signs of injury at the MTJ.[19] In that study, these higher-intensity signals are however not specified as having an acute or non-acute appearance. In all studies in this thesis, we only included acute injuries as a primary focus. In study II, we show that there is high reproducibility of the differentiation between acute and non-acute injuries. This should reduce the number of false positives and provide support that the acute injuries are actually related to the athlete's complaints. Further validation of the assessment could for instance be related to clinical findings and clinical outcomes. This would also be able to show whether a shortened assessment protocol could be applied only including clinically important parameters, and thereby reduce the assessment burden and related costs.

A 1.5T MRI system was used for all studies in this thesis. A higher field strength system, such as the 3T can improve spatial resolution and potentially influencing injury findings.[155] As we found high reproducibility of the MRI assessment, it is doubtful that 3T MRI would be able to influence the reproducibility results in a clinically meaningful way. As ultra-high field systems at 7T and above are being introduced,[106] there is a chance that these might improve the sensitivity, which may provide further information about imagine negative cases. At the moment such scanners are, however, mainly used for neurological and cardiac assessment, rather than sports injuries.

A limitation of Studies III-V is the low prevalence of some of the sub-categorized injuries. This applies to the results for the hip flexor examination tests in Study III, where the low power led to relatively large confidence intervals. This affects the generalizability, as we can therefore not draw firm conclusions on these examination tests yet. Despite the low prevalence, the uncertainty of the hip flexor tests should still be considered by clinicians, and requesting additional imaging to improve diagnostic accuracy can therefore in many cases be reasonable. In contrast there was a higher prevalence of adductor injuries, and the results from Study III offer clinicians confidence when diagnosing an acute adductor injury.

Low prevalence also affected the detailed overviews on injury characteristics in Studies IV and V. In study IV, we were not able to provide relevant detailed information on the extent of injury within muscles other than the adductor longus. In Study V, we were able to see interesting injury characteristics for the iliacus, psoas major and rectus femoris muscles. However, as there were only 33 athletes included, there is a chance that some injury locations are more relevant than others, and potentially that alternative injury types were missed.

The low prevalence of acute hip flexor injuries appears to be a general challenge in sports medicine research. In previous studies similar numbers of rectus femoris injuries are reported.[6,13,35,71,90,135] These studies often consist of heterogeneous groups, as they include both adolescents and elderly,[71,135] females and males,[13,71,90,135] and both acute and non-acute injuries.[71,90,135] We are aware of a single acute iliopsoas injury study that included 10 sports injuries,[26] and there are no studies on sartorius or TFL injuries in athletes. Multicenter research could therefore increase the speed of data collection and power to investigate specific details on acute groin injuries. Additionally, more general epidemiology studies should include more specific injury information, such as discussed in this thesis.

Conclusion

In this thesis we have been able to provide an unprecedented overview of the diagnosis of acute groin injuries in athletes. From the five included studies we can now conclude that:

- Acute groin injuries most frequently occur during kicking in football codes, and change of direction in other sports. Other common injury situations are reaching/stretching, sprinting and jumping.
  - Adductor injuries can occur in all these situations, but primarily happen during kicking and change of direction movements.
  - In hip flexor injuries, differences in injury situations appear present. Of the hip flexor muscles, only the iliacus and psoas major were injured during change of direction, whereas rectus femoris injuries primarily occur during kicking and sprinting.

- More than 1 out of 5 athletes with acute groin pain do not have an acute injury on imaging.
  - The absence of palpation pain is best at predicting an MRI negative result.

- Acute adductor injuries account for about two thirds of acute groin injuries.
  - Acute adductor injuries generally occur in isolation from other muscle groups.
  - The adductor longus is the most frequently injured muscle, both in isolation and in combination with other adductor injuries.
  - There a three characteristic injury locations within the adductor longus:
    - The proximal insertion, which are often avulsion injuries.
    - The intramuscular MTJ of the proximal tendon, often with injury of the anterior fibers
    - The proximal part of the MTJ of distal tendon, where edema usually extends proximally
  - Intramuscular tendon injury is rare in adductor longus injuries.
  - Clinically diagnosed adductor injuries are often confirmed on imaging.
    - Specific adductor examination tests can individually provide ~80% probability of predicting a positive MRI in the adductors. The highest positive predictive values are found for resisted outer range adduction, squeeze test with hip neutral and long lever, and the passive adductor stretch test.
    - These clinical examination tests also provide more than 90% probability of predicting an accurate injury location on MRI.

- Acute hip flexor injuries account for about a third of acute groin injuries.
    - Hip flexor injuries generally do not occur in combination with acute adductor injuries.
    - Proximal rectus femoris injuries often include the tendon, predominantly the indirect tendon.
    - Acute iliopsoas injuries can be divided into distinct iliacus and psoas injuries, which predominantly occur at their MTJs.
    - When iliopsoas, rectus femoris, and sartorius injuries are diagnosed clinically, an injury is often found in a different muscle on imaging without an injury in the clinically diagnosed muscle.
        - Clinical hip flexor examination tests are poor at predicting an MRI positive hip flexor injury, and are also poor at accurately localizing MRI injuries in the individual hip flexor muscles.

- MRI positive abdominal injuries are very rare.

- MRI assessment of acute groin injuries generally has good intra and inter-rater reproducibility, when using a standardized approach.

Perspectives

Groin pain in athletes has often been referred to as the Bermuda triangle of sports medicine.[15] Despite the high incidence and evolving understanding of the complex anatomy, as described in the introduction, a true understanding of the etiology of groin pain has still not appeared on the horizon. Additionally, a large amount of research on long-standing groin pain has been of inadequate quality.[162] The complexity of groin pain has probably affected the desire of researchers to choose the groin as a focus area, and as a result the amount of studies on acute groin injuries is severely limited. With the studies in this thesis we have sown new grass on the playing field, and expect new players to get involved in the game. There are many games ahead to play!

In this thesis, we provided an overview of acute injury situations, which can now be used to improve clinical practice. By knowing which injury situations are likely to involve a higher injury risk, prevention, treatment, and return to play decisions can be optimized. In comparison, acute hamstring injuries often occur during high speed running.[3,185,196] It has also been described that large changes in the amount high speed running is associated with a higher hamstring injury risk.[45,156] Therefore monitoring the athletes' amount of running at various speeds has become an essential part of many sports clubs' attempts to reduce the number of hamstring injuries. Similarly, by knowing that most acute groin injuries occur during kicking and change of direction, it can be assumed that better monitoring of the amounts of these movements in the individual sports, could assist in reducing injuries. Additionally, these movements appear important to train and test during rehabilitation after injuries to ensure that the athlete is able to withstand the associated risk, and reduce the chances of re-injury. Correspondingly, knowledge on the athlete's ability and performance of these movements during rehabilitation could be included as part of the return to sport decision.

Further details on the injury mechanisms are still required. For instance, we show that there are many different groin muscles, which can be injured during kicking. As only a categorization of the athlete's description of the injury situation is included in this thesis, specific details on biomechanical differences related to injuries in one muscle over another is lacking. To improve the knowledge on variations in injury mechanisms, further studies could therefore involve video analysis of the actual occurrences. With such approach, other important elements, such as the playing situation and specific athlete and opponent behavior, could also be analyzed. This could potentially also give further insight in elements related to different injury locations within specific muscles.

In this thesis, we have provided an overview of the variation in muscle injury locations, both between muscles and within muscles. This information can provide deeper understanding of the physiological injury mechanisms, which can assist in the prevention of injuries. Furthermore, an understanding of specific injury characteristics will assist in the management after injury. Not only can the rehabilitation be targeted more specifically towards the specific injury location, but it can potentially also provide information on an expected duration. While specific prognostic injury characteristics still lack clarity, there are certain indications that specific injury locations seen in other muscle injury locations might be relevant. For instance, a shorter distance between injury site and insertion, as well as structural injury to the intramuscular tendon itself, have been linked with a longer return to play time in hamstring and rectus femoris injuries.[6,25,31,147,151] Similarly, a difference in return to play time has been shown in soleus muscles injuries, with injuries of the central tendon aponeurosis having longer recovery time than medial and medial tendon aponeurosis injuries.[138]

While we report on parameters related to the physiological severity as seen on MRI, we are still not aware whether this relates to the severity the athletes actually experience. It has been shown that severity, described through ordinal injury grading on MRI, has large variations in return to play duration within each grading,[4,31,75,188] and might therefore not add specific prognostic information in addition to a thorough physical examination.[151,188] Therefore further information on clinical measures of severity might be helpful in relation to standardized clinical outcomes. We have tested the ability to determine the injury location through the clinical examination; however, it is still uncertain how we best can determine the clinical severity of the injury. Several studies have been performed on potential prognostic clinical measures in hamstring injuries.[161] There is moderate evidence for a few elements of the history taking, and only limited evidence for some clinical measures, such as the extent of palpation pain, pain on active stretch, and visible bruising.[161] For acute groin injuries there are still no prognostic studies including either imaging or clinical findings as potential predictors. These studies should be initiated considering the findings in this thesis.

We included several elements in our standardized MRI assessment for this purpose, and showed that these have good reproducibility. The inclusion of all these elements also made the assessment protocol relatively long and time consuming. To optimize this approach for practical implementation it is therefore essential that further research is able to elucidate the most important parameters to include in daily practice. Improved technological advances in imaging, such as stronger MRI scanners, can also assist in this regard. Additionally, new imaging techniques might be able to provide further advances in the assessment of structural damage. Diffusion tensor imaging (DTI) is one of the newer imaging techniques, which can be used to assess muscle injuries. DTI is based on conventional MRI, but uses the water diffusion rate to image the architecture of the tissue by applying specific post-processing analysis models to diffusion weighted-sequences.[134,168] DTI shows potential in providing detailed assessment of the microstructure of muscle fiber integrity and orientation by quantifying differences and enabling 3D muscle fiber tractography.[134] This could thereby give more precise information of specific fiber injury even in minor injuries, which might otherwise be imaging negative.[59,134]

Summary

Background

Acute groin injuries are some of the most common injuries in multidirectional team sports. Research on these injuries is however close to non-existent. Anatomical studies have been able to provide a greater insight into the complexity of the musculotendinous structures in the groin region, but the relationship with acute injury is unknown. Exploring the anatomical location of acute groin injuries will be able to provide clinicians with improved ability to diagnose these injuries. A greater understanding of the diagnosis of acute groin injuries can also assist in improving prevention and management of these injuries.

Aim

The overall aim of this thesis was to improve knowledge related to the diagnosis of acute groin injuries in athletes using standardized clinical and imaging examinations.

Methods

Five studies were included in this thesis. These studies had similar inclusion criteria, but different focus areas. For all studies, participants were competitive athletes with acute groin pain, who were examined within a week after their injury. In Study I, we standardized the registration of the clinical diagnosis, US and MRI findings performed by sports medicine physicians and radiologists in daily clinical practice. In study II we developed a standardized MRI assessment approach, which we tested for reproducibility by two radiologists, who were blinded to the clinical information. In Study III, we introduced an additional standardized clinical examination, which was performed by a physiotherapist. We then compared these standardized examination tests to the standardized MRI assessment. We analyzed the ability of the examination tests to predict a positive or negative MRI, and also examined the accuracy of the tests compared to the MRI determined injury location. In Study IV, we evaluated the standardized MRI scoring of the adductor injuries in detail to see if there where specific characteristic variations within the adductor injuries. In Study V, we did the same for the hip flexor injuries.

Results

The most common injury situations were kicking, change of direction, reaching/stretching, and running/sprinting. The majority of the injuries occurred during kicking in the football codes, and during change of direction in other sports. More than 20% of athletes with acute groin pain do not have an acute injury on imaging. When an injury was found, there was no significant difference in overall injury distribution between the clinical examination, US and MRI. The standardized MRI assessment showed good intra- and inter-rater reproducibility, with both kappa values and ICCs generally above 0.8. Adductor injuries were most frequent and accounted for about 2 out of 3 injuries. The adductor longus was the most frequently injured muscle, and three characteristic injury locations within the muscle were observed: the proximal insertion, the anterior MTJ of the intramuscular proximal tendon, and the proximal part of the MTJ of distal tendon. Acute hip flexor injuries accounted for about a third of acute groin injuries. Of these, proximal rectus femoris injuries were most frequent. These injuries often included injury to the tendon itself, predominantly the indirect tendon. Iliopsoas injuries can be divided into distinct iliacus and psoas injuries, whereof iliacus injuries were most frequent. These injuries predominantly occur at the MTJ. Clinically diagnosed adductor injuries are often confirmed on imaging. Specific adductor examination tests can individually provide about 80% probability of predicting a positive MRI in the adductors. These tests can also provide more than 90% probability of predicting an accurate injury location on MRI. When iliopsoas, rectus femoris, and sartorius injuries are diagnosed clinically, an injury is often found in a different muscle on imaging without an injury in the clinically diagnosed muscle. Clinical hip flexor examination tests are poor at predicting an MRI positive hip flexor injury, and are also poor at accurately localizing MRI injuries in the individual hip flexor muscles with PPVs not far from 50%.

Conclusion

This thesis provides an extensive overview of the diagnosis of acute groin injuries in athletes. We have provided overviews of the most frequent injury situations in general, in relation to the type of sports, and specified for individual muscle injuries. We introduced a standardized MRI assessment approach for acute groin injuries, which showed high inter- and intra-rater reproducibility. Radiologists can thus use this assessment to provide a detailed report, which the clinicians can have confidence in. We have provided an overview of muscle injury locations, and show that adductor injuries account for about two thirds of acute groin injuries and hip flexor injuries for about a third. We have also provided detailed injury characteristics within the most commonly injured muscles, which could be related to prognosis. Furthermore, we compared standardized clinical examination tests to the MRI findings. This can help the clinician asses the probability of predicting positive or a negative MRI, as well the probability of diagnosing an accurate injury location through the clinical examination.

Sammenfatning på dansk

Baggrund

Akutte lyskeskader er en af de mest hyppigste skadestyper i sportsgrene med hurtige retningsskift. Forskning af akutte lyskeskader er tilgengæld næsten ikke-eksisterende. Anatomien i lyskeregionen er generelt betragtet som kompleks, men nyere antomiske studier har givet større indsigt i muskel-sene strukturers forløb og forbindelser i regionen. Undersøgelse af akutte lyskeskaders anatomiske lokalisationer kan gøre klinikere bedre til at diagnosticere disse skader. En større forståelse af variationen af typer af lyskeskader kan desuden være med til at forbedre forebyggelse og behandling af disse skader.

Formål

Formålet med denne afhandling er af optimere viden omkring elementer relateret til diagnosticering af akutte lyskeskader ved hjælp af standardiserede kliniske og billeddiagnostiske undersøgelsesmetoder.

Metode

Afhandlingen består af fem studier. Disse studier har sammenlignelige inklusionskriterier, men forskellige fokusområder. I alle studier inkluderede vi kun idrætsudøvere med akutte lyskeskader der blev undersøgt inden en uge efter skadestidspunktet. I det første studie standardiserede vi registreringen af de kliniske diagnoser, samt skanningsresultater fra ultralyds- og MR undersøgelser, der blev udført af henholdsvis idrætsmedicinske læger og radiologer på et idrætmedicinsk hospital. I det andet studie udarbejdede vi en standardiseret MR scoringsprotokol, som blev testet for både intra- og inter-rater reproducerbarhed mellem to radiologer, der ikke havde kendskab til klinisk information. I det tredje studie tilføjede vi en standardiseret klinisk undersøgelse udført af en fysioterapeut. Vi sammenlignede derefter de specifikke undersøgelsestests med de standardiserede MR scoringsresultater. Vi analyserede de individuelle undersøgelsestests' evne til at forudsige om MR scoringen var negativ eller posititv, dvs. om radiologen rapporterede en skade i den muskelgruppe undersøgelsetesten testede. Derudover blev nøjagtigheden af undersøgelsestestene analyseret i forhold til den skadeslokalisation, som blev rapporteret fra MR undersøgelsen. I det fjerde studie brugte vi den standardiserede MR scoring til at give et mere detaljeret indblik i forskellige skadesvariationer i hofteadduktorerne, og i det femte studie gjorde vi det samme for skaderne i hoftefleksorerne.

Resultater

De hyppigste skadesituationer var spark, retningsskift, strækbevægelser, og løb eller sprint. Størstedelen af skaderne i de forskellige typer fodbold skete under spark, og i andre sportsgrene hyppigst ved retninsgskift. I mere end 20% af spillere med en akut lyskeskade kunne der ikke ses nogen akut skade på de billeddiagnostiske undersøgelser. Den standardiserede MR scoringsprotokol viste god intra- og inter-rater reproducerbarhed, med både kappa og ICC værdier generelt over 0.8. Af de rapporterede skader var der ingen signifikant forskel i distributionen af skadelokalisationer imellem de forskellige undersøgelsesmetoder.

Skader i hofteadduktorerne var hyppigste og udgjorde omkring to tredjedele af alle de akutte lyskeskader. Adduktor longus var den oftest skadede muskel og vi kunne se tre karakteristiske skadeslokalisationer i musklen: den proximale tilhæftning, den anteriore muskelseneovergang af den intramuskulære proximal sene, og den proximale del af den distale sene's muskelseneovergang. Akutte skader i hoftefleksormusklerne udgjorde omkring en tredjedel af de akutte lyskeskader. Proximale rectus femoris skader var de hyppigste hofteflexorskader. Disse skader involverede ofte skade af selve senen, primært af den indirekte sene, både ved tilhæftningen og af dens intramuskulære forløb. Iliopsoas skader kan inddeles i iliacus og psoas major skader. Heraf var iliacusskader de hyppigste. Disse skader skete oftest ved muskelseneovergangen. Skader af abdominalmusklerne var sjældent set på MR scanningerne.

Klinisk diagnosticerede skader i adduktorerne blev ofte bekræftet i de billeddiagnostiske scanninger. Specifikke undersøgelsestests for adduktorerne kunne med omkring 80% sandsynlighed forudsige en akut adduktorskade på MR scanningen. Disse tests kunne også give over 90% sandsynlighed for en korrekt lokalisation. Når iliopsoas, rectus femoris, og sartoriusskader blev klinisk diagnosticeret, blev der ofte fundet en skade i en anden muskel på billeddiagnostikken end den der blev diagnosticeret klinisk. De kliniske hoftefleksortests var dårlige til at forudsige en akut skade i hofteflekxorene på MR scanningen, og var ikke nøjagtige i forhold til de individuelle muskelskader på MR, da de kun havde PPV værdier omkring 50%.

Konklusion

Denne afhandling giver et detaljeret overblik over akute lyskeskader i idrætudovere. Vi har præsenteret oversigter over de hyppigste skadessituationer overordnet, i forhold til type af sportsgren, og for individuelle muskelskader. Vi har introduceret en standardiseret MR scoringsprotokol for akutte lyskeskader, som viste god reproducerbarhed. Radiologer kan derfor bruge denne protokol til at give en mere detaljeret rapportering, som klinikere kan have tillid til.
Vi har præsenteret oversigter over muskelskadeslokalisationer, hvor vi viser at adduktorskader udgør omkring to tredjedele af alle lyskeskader og hoftefleksorskader omkring en tredjedel. Vi har også kategoriseret karakteristiske skader i disse muskler, som potentielt er relateret til forskelle i prognose.
Vi sammnelignede desuden de standardiserede kliniske undersøgelstests med MR resultaterne. Dette kan hjælpe klinikere med at vurdere sandsynligheden for et positivt eller negativt MR resultat, samt vurdere sandsynligheden for en nøjagtig diagnose.

Acknowledgements

When I was heading off for the PhD project, I was unaware of how many challenges I was going to face, and how many people would eventually get affected by smaller or larger changes in their daily work as a result of this project. It is therefore with immense gratitude that I thank everyone at Aspetar for their openness to discussions and willingness to assist in making this project achievable. The potential for multidisciplinary work at this hospital is truly exceptional, and during my time here I have been lucky to be in contact with basically all departments. Additionally, the multinational environment has been extremely rewarding. It provides a unique blend of minds with diverse perspectives, which I believe in many cases leads to improved clinical care, as well as personal development.

To all the doctors and physiotherapists in the National Sports Medicine Programme, this project would not have been possible without you. Thank you for the great collaboration, for all the interesting discussions along the way, and for allowing us to take part in the management of your athletes.

To all the athletes, who have taken part in the studies, I appreciate your willingness and time to participate in the additional examinations. I hope it has also been helpful for you, and that we have been able to assist you in reaching your full potential during the injury period.

I was lucky to meet a lot of great people straight after my arrival to Doha. There are too many to mention, but particularly Roald, Amir, Emad, Farrukh, Anders, Nathan, Ryan, and Brendan made the transition easy and ensured that the after work hours were even more enjoyable.

Roald, you have not only been a great friend, but also a strong support at work throughout your time at Aspetar. I still hope that you might return soon.

Thank you to my fellow Scandinavians in the Norwegian research gang, Arnhild, Arnlaug and Tone. It has been great to have someone to share the boat with, and thank you for stepping in and helping out from time to time. Arnlaug, I have truly enjoyed sharing office with you, and all the interesting discussions resulting from our very similar projects. You are the most kind and genuine person I know, and I am sure the hamstring world will continue to benefit from your dedication.

Thank you to all my colleagues and friends who have been part of office 214 along the way, Arnlaug, Farrukh, Louisa, Elsbeth, Robert-Jan, Angela, Rachel, Andrea, Rintje, Omar, Anne & Robin. Both workwise and socially, I am positive that we have been the best office at Aspetar!

Thank you to everyone in the Rehabilitation Department for making a great team. A special appreciation to all the guys who have been involved in the project along the way, Sean, Roald, Rod, Damien, Simon, Philip, Abdallah, Kostas, Einar, Grani, & Dermot. I have highly appreciated all the discussions on testing and treatment, the flexibility with the always urgent scheduling requests, and that you have put up with my often persistent ways. In the same regard, I also have to thank all the GSOs for the continuous assistance, and to Rania, I apologize for always being a bit louder than the average.

To everyone in the Sports Medicine Department, thank you for remembering #2120. I feel very fortunate that you have all been so open to the research projects and interested in further discussions. Never a high horse.

Thank you to everyone in the radiology department. To Emad for always being open and accommodating, to Eduardo for stepping in with important assistance in the end, and especially to Natalia, Rashid and Leyla, for doing everything within your capability to help me out when timelines were short.

Thank you Ivan for being a good friend and adding some great illustrations to the images for both this thesis and other projects.

Thank you Lasse for involving me and giving me the opportunity to challenge myself in different ways during the PhD. I am certain, this will be helpful in the future.

Thank you to all my co-authors for ensuring that the project was always aiming for the highest quality, and to Frank and Ali for the many hours of discussing and reviewing MRI images.

Thank you to my Sports Groin Pain Center team. Andrea, it has been truly amazing to share this fantastic journey with you from the beginning to the end. Thank you for the countless discussion and chats about everything under the desert sun. It would not have been the same without you here. Zarko, thank you for being a great friend and a good support all the way. Your knowledge and humbleness has been highly appreciated, and I look forward to working further with you the coming years.

To all my supervisor team, you have pushed me further and made me continuously want to improve, each in your different ways. Kristian, thank you for being my lead-in to research, and for having been part of my research journey all the way. Although you have been far away you have managed to play a great role, and the project is undoubtedly of higher quality as a result. Hans, thank you for giving me responsibility from day one. Although you said I was the boss, it was pretty clear that things are not always that easy. Thank you for making things happen and for your always candid comments. Adam, thank you for stepping up. Your support has been invaluable. You have always been supportive and constructive, and you have always made time. Thank you for being an all-around good guy and a great friend. Per, thank you for giving me the opportunity. I feel fortunate to have had a supervisor, who I could not only have respectful professional discussions with, but also consider a friend. It would have been great to have had you around all the time!

To my dad, mom, and Hans, thank you for always having given me freedom to do what I have wanted. I am sorry it ended up being a bit further away than you would have liked.

I came to Doha for the project, but I ended up with so much more. To my amazing wife, you took me by surprise from the beginning, and you have changed my life so much more than a PhD ever could. Thank you for all your loving support, thank you for accepting that I am never home on time, and thank you for always ensuring that our lives are filled with so much more than work. Most of all, thank you for giving me a princess.

References

1. Agricola R, Heijboer MP, Ginai AZ, et al. A cam deformity is gradually acquired during skeletal maturation in adolescent and young male soccer players: a prospective study with minimum 2-year follow-up. *Am J Sports Med*. 2014;42(4):798-806. doi:10.1177/0363546514524364.

2. Apostolakos J, Durant TJ, Dwyer CR, et al. The enthesis: a review of the tendon-to-bone insertion. *Muscles Ligaments Tendons J*. 2014;4(3):333-342.

3. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute First-Time Hamstring Strains During High-Speed Running A Longitudinal Study Including Clinical and Magnetic Resonance Imaging Findings. *Am J Sports Med*. 2007;35(2):197-206. doi:10.1177/0363546506294679.

4. Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite football: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. *Br J Sports Med*. March 2013. doi:10.1136/bjsports-2013-092165.

5. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med*. 2005;39(6):324-329. doi:10.1136/bjsm.2005.018341.

6. Balius R, Maestro A, Pedret C, et al. Central aponeurosis tears of the rectus femoris: practical sonographic prognosis. *Br J Sports Med*. 2009;43(11):818–824.

7. Bangsbo J, Hansen PR, Dvorak J, Krustrup P. Recreational football for disease prevention and treatment in untrained men: a narrative review examining cardiovascular health, lipid profile, body composition, muscle strength and functional capacity. *Br J Sports Med*. 2015;49(9):568-576. doi:10.1136/bjsports-2015-094781.

8. Batters C, Veigel C, Homsher E, Sellers JR. To understand muscle you must take it apart. *Front Physiol*. 2014;5. doi:10.3389/fphys.2014.00090.

9. Benjamin M, Kumai T, Milz S, Boszczyk BM, Boszczyk AA, Ralphs JR. The skeletal attachment of tendons—tendon "entheses." *Comp Biochem Physiol A Mol Integr Physiol*. 2002;133(4):931-945. doi:10.1016/S1095-6433(02)00138-1.

10. Benjamin M, McGonagle D. Entheses: tendon and ligament attachment sites. *Scand J Med Sci Sports*. 2009;19(4):520-527. doi:10.1111/j.1600-0838.2009.00906.x.

11. Benjamin M, Ralphs JR. Fibrocartilage in tendons and ligaments--an adaptation to compressive load. *J Anat*. 1998;193 (Pt 4):481-494.

12. Benjaminse A, Gokeler A, van der Schans CP. Clinical diagnosis of an anterior cruciate ligament rupture: a meta-analysis. *J Orthop Sports Phys Ther*. 2006;36(5):267-288. doi:10.2519/jospt.2006.2011.

13. Bianchi S, Martinoli C, Waser N, Bianchi-Zamorani M, Federici E, Fasel J. Central aponeurosis tears of the rectus femoris: sonographic findings. *Skeletal Radiol*. 2002;31(10):581-586. doi:10.1007/s00256-002-0559-z.

14. Bitar R, Leung G, Perng R, et al. MR Pulse Sequences: What Every Radiologist Wants to Know but Is Afraid to Ask. *RadioGraphics*. 2006;26(2):513-537. doi:10.1148/rg.262055063.

15. Bizzini M. The groin area: the Bermuda triangle of sports medicine? *Br J Sports Med*. 2011;45(1):1-1. doi:10.1136/bjsm.2010.081828.

16. Blankenbaker D, Tuite M. Iliopsoas Musculotendinous Unit. *Semin Musculoskelet Radiol*. 2008;12(1):013-027. doi:10.1055/s-2008-1067934.

17. Bordalo-Rodrigues M, Rosenberg ZS. MR imaging of the proximal rectus femoris musculotendinous unit. *Magn Reson Imaging Clin N Am*. 2005;13(4):717-725. doi:10.1016/j.mric.2005.08.005.

18. Branci S, Thorborg K, Bech BH, et al. The Copenhagen Standardised MRI protocol to assess the pubic symphysis and adductor regions of athletes: outline and intratester and intertester reliability. *Br J Sports Med*. 2015;49(10):692-699. doi:10.1136/bjsports-2014-094239.

19. Branci S, Thorborg K, Bech BH, Boesen M, Nielsen MB, Holmich P. MRI findings in soccer players with long-standing adductor-related groin pain and asymptomatic controls. *Br J Sports Med*. December 2014. doi:10.1136/bjsports-2014-093710.

20. Branci S, Thorborg K, Nielsen MB, Hölmich P. Radiological findings in symphyseal and adductor-related groin pain in athletes: a critical review of the literature. *Br J Sports Med*. February 2013. doi:10.1136/bjsports-2012-091905.

21. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 1 match injuries. *Br J Sports Med*. 2005;39(10):757-766. doi:10.1136/bjsm.2005.018135.

22. Brooks JHM, Fuller CW, Kemp SPT, Reddin DB. Epidemiology of injuries in English professional rugby union: part 2 training Injuries. *Br J Sports Med*. 2005;39(10):767-775. doi:10.1136/bjsm.2005.018408.

23. Broski SM, Murthy NS, Krych AJ, Obey MR, Collins MS. The adductor magnus “mini-hamstring”: MRI appearance and potential pitfalls. *Skeletal Radiol*. 2016;45(2):213-219. doi:10.1007/s00256-015-2291-5.

24. Brughelli M, Cronin J, Levin G, Chaouachi A. Understanding change of direction ability in sport: a review of resistance training studies. *Sports Med Auckl NZ*. 2008;38(12):1045-1063.

25. Brukner P, Connell D. “Serious thigh muscle strains”: beware the intramuscular tendon which plays an important role in difficult hamstring and quadriceps muscle strains. *Br J Sports Med*. 2016;50(4):205-208. doi:10.1136/bjsports-2015-095136.

26. Bui KL, Ilaslan H, Recht M, Sundaram M. Iliopsoas injury: an MRI study of patterns and prevalence correlated with clinical findings. *Skeletal Radiol*. 2007;37(3):245-249. doi:10.1007/s00256-007-0414-3.

27. Byrd JWT. Labral lesions: An elusive source of hip pain case reports and literature review. *Arthrosc J Arthrosc Relat Surg*. 1996;12(5):603-612. doi:10.1016/S0749-8063(96)90201-7.

28. Charnock BL, Lewis CL, Garrett WE, Queen RM. Adductor longus mechanics during the maximal effort soccer kick. *Sports Biomech Int Soc Biomech Sports*. 2009;8(3):223-234.

29. Coker DJ, Zoga AC. The Role of Magnetic Resonance Imaging in Athletic Pubalgia and Core Muscle Injury. *Top Magn Reson Imaging TMRI*. 2015;24(4):183-191. doi:10.1097/RMR.0000000000000056.

30. Coleman SH, Mayer SW, Tyson JJ, Pollack KM, Curriero FC. The Epidemiology of Hip and Groin Injuries in Professional Baseball Players. *Am J Orthop Belle Mead NJ*. 2016;45(3):168-175.

31. Comin J, Malliaras P, Baquie P, Barbour T, Connell D. Return to competitive play after hamstring injuries involving disruption of the central tendon. *Am J Sports Med*. 2013;41(1):111-115. doi:10.1177/0363546512463679.

32. Condon RE. Reassessment of groin anatomy during the evolution of preperitoneal hernia repair. *Am J Surg*. 1996;172(1):5-8. doi:10.1016/S0002-9610(96)00056-6.

33. Crema MD, Yamada AF, Guermazi A, Roemer FW, Skaf AY. Imaging techniques for muscle injury in sports medicine and clinical relevance. *Curr Rev Musculoskelet Med*. February 2015:1-8. doi:10.1007/s12178-015-9260-4.

34. Cross TM. Acute Quadriceps Muscle Strains: Magnetic Resonance Imaging Features and Prognosis. *Am J Sports Med*. 2004;32(3):710-719. doi:10.1177/0363546503261734.

35. Cross TM, Gibbs N, Houang MT, Cameron M. Acute quadriceps muscle strains: magnetic resonance imaging features and prognosis. *Am J Sports Med*. 2004;32(3):710-719.

36. Curzi D, Salucci S, Marini M, et al. How physical exercise changes rat myotendinous junctions: an ultrastructural study. *Eur J Histochem EJH*. 2012;56(2):e19. doi:10.4081/ejh.2012.19.

37. Dalton SL, Zupon AB, Gardner EC, Djoko A, Dompier TP, Kerr ZY. The Epidemiology of Hip/Groin Injuries in National Collegiate Athletic Association Men's and Women's Ice Hockey. *Orthop J Sports Med*. 2016;4(3). doi:10.1177/2325967116632692.

38. Davis JA, Stringer MD, Woodley SJ. New insights into the proximal tendons of adductor longus, adductor brevis and gracilis. *Br J Sports Med*. 2012;46(12):871-876. doi:10.1136/bjsports-2011-090044.

39. Delahunt E, Thorborg K, Khan KM, Robinson P, Hölmich P, Weir A. Minimum reporting standards for clinical research on groin pain in athletes. *Br J Sports Med*. 2015;49(12):775-781. doi:10.1136/bjsports-2015-094839.

40. Delmore RJ, Laudner KG, Torry MR. Adductor longus activation during common hip exercises. *J Sport Rehabil*. 2014;23(2):79-87. doi:10.1123/jsr.2012-0046.

41. Dimitrakopoulou A, Schilders EM, Talbot JC, Bismil Q. Acute avulsion of the fibrocartilage origin of the adductor longus in professional soccer players: a report of two cases. *Clin J Sport Med*. 2008;18(2):167–169.

42. Domb BG, Shindle MK, McArthur B, Voos JE, Magennis EM, Kelly BT. Iliopsoas impingement: a newly identified cause of labral pathology in the hip. *HSS J Musculoskelet J Hosp Spec Surg*. 2011;7(2):145-150. doi:10.1007/s11420-011-9198-z.

43. Drakos MC, Domb B, Starkey C, Callahan L, Allen AA. Injury in the National Basketball Association. *Sports Health*. 2010;2(4):284-290. doi:10.1177/1941738109357303.

44. Drew MK, Palsson TS, Izumi M, et al. Resisted adduction in hip neutral is a superior provocation test to assess adductor longus pain: An experimental pain study. *Scand J Med Sci Sports*. September 2015:n/a-n/a. doi:10.1111/sms.12529.

45. Duhig S, Shield AJ, Opar D, Gabbett TJ, Ferguson C, Williams M. Effect of high-speed running on hamstring strain injury risk. *Br J Sports Med*. June 2016. doi:10.1136/bjsports-2015-095679.

46. Eirale C, Tol JL, Farooq A, Smiley F, Chalabi H. Low injury rate strongly correlates with team success in Qatari professional football. *Br J Sports Med*. 2013;47(12):807-808. doi:10.1136/bjsports-2012-091040.

47. Ekstrand J, Gillquist J. The frequency of muscle tightness and injuries in soccer players. *Am J Sports Med*. 1982;10(2):75-78.

48. Ekstrand J, Hägglund M, Waldén M. Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med*. 2011;39(6):1226-1232. doi:10.1177/0363546510395879.

49. Ekstrand J, Healy JC, Waldén M, Lee JC, English B, Hägglund M. Hamstring muscle injuries in professional football: the correlation of MRI findings with return to play. *Br J Sports Med*. 2012;46(2):112-117. doi:10.1136/bjsports-2011-090155.

50. Ekstrand J, Hilding J. The incidence and differential diagnosis of acute groin injuries in male soccer players. *Scand J Med Sci Sports*. 1999;9(2):98-103.

51. Emery CA, Meeuwisse WH, Powell JW. Groin and abdominal strain injuries in the National Hockey League. *Clin J Sport Med Off J Can Acad Sport Med*. 1999;9(3):151-156.

52. Engebretsen AH, Myklebust G, Holme I, Engebretsen L, Bahr R. Prevention of injuries among male soccer players: a prospective, randomized intervention study targeting players with previous injuries or reduced function. *Am J Sports Med*. 2008;36(6):1052-1060. doi:10.1177/0363546508314432.

53. Fagan SP, Awad SS. Abdominal wall anatomy: the key to a successful inguinal hernia repair. *Am J Surg*. 2004;188(6A Suppl):3S-8S. doi:10.1016/j.amjsurg.2004.09.004.

54. Falvey EC, Franklyn-Miller A, McCrory PR. The groin triangle: a patho-anatomical approach to the diagnosis of chronic groin pain in athletes. *Br J Sports Med*. 2009;43(3):213-220. doi:10.1136/bjsm.2007.042259.

55. Farjoodi P, Mesfin A, Carrino JA, Khanna AJ. Magnetic Resonance Imaging of the Musculoskeletal System. *J Bone Jt Surg Am*. 2010;92(Supplement 2):105-116. doi:10.2106/JBJS.J.00783.

56. Feeley BT, Powell JW, Muller MS, Barnes RP, Warren RF, Kelly BT. Hip injuries and labral tears in the national football league. *Am J Sports Med*. 2008;36(11):2187-2195. doi:10.1177/0363546508319898.

57. Foote CJ, Maizlin ZV, Shrouder J, Grant MM, Bedi A, Ayeni OR. The association between avulsions of the reflected head of the rectus femoris and labral tears: a retrospective study. *J Pediatr Orthop*. 2013;33(3):227-231. doi:10.1097/BPO.0b013e3182880978.

58. Franklyn-Miller A, Richter C, King E, et al. Athletic groin pain (part 2): a prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns. *Br J Sports Med*. October 2016:bjsports-2016-096050. doi:10.1136/bjsports-2016-096050.

59. Froeling M, Oudeman J, Strijkers GJ, et al. Muscle Changes Detected with Diffusion-Tensor Imaging after Long-Distance Running. *Radiology*. 2014;274(2):548-562. doi:10.1148/radiol.14140702.

60. Gamradt SC, Brophy RH, Barnes R, Warren RF, Thomas Byrd JW, Kelly BT. Nonoperative Treatment for Proximal Avulsion of the Rectus Femoris in Professional American Football. *Am J Sports Med*. 2009;37(7):1370-1374. doi:10.1177/0363546509333477.

61. Gibbs N. Injuries in professional rugby league A three-year prospective study of the South Sydney Professional Rugby League Football Club. *Am J Sports Med*. 1993;21(5):696-700. doi:10.1177/036354659302100510.

62. Gibbs NJ, Cross TM, Cameron M, Houang MT. The accuracy of MRI in predicting recovery and recurrence of acute grade one hamstring muscle strains within the same season in Australian Rules football players. *J Sci Med Sport Sports Med Aust*. 2004;7(2):248-258.

63. Gillies AR, Bushong EA, Deerinck TJ, Ellisman MH, Lieber RL. Three-dimensional reconstruction of skeletal muscle extracellular matrix ultrastructure. *Microsc Microanal Off J Microsc Soc Am Microbeam Anal Soc Microsc Soc Can*. 2014;20(6):1835-1840. doi:10.1017/S1431927614013300.

64. Gillies AR, Lieber RL. Structure and function of the skeletal muscle extracellular matrix. *Muscle Nerve*. 2011;44(3):318-331. doi:10.1002/mus.22094.

65. Gold GE, Han E, Stainsby J, Wright G, Brittain J, Beaulieu C. Musculoskeletal MRI at 3.0 T: Relaxation Times and Image Contrast. *Am J Roentgenol*. 2004;183(2):343-351. doi:10.2214/ajr.183.2.1830343.

66. Gómez-Hoyos J, Schröder R, Palmer IJ, Reddy M, Khoury A, Martin HD. Iliopsoas tendon insertion footprint with surgical implications in lesser trochanterplasty for treating ischiofemoral impingement: an anatomic study. *J Hip Preserv Surg*. 2015;2(4):385-391. doi:10.1093/jhps/hnv060.

67. Greditzer IV HG, Nawabi D, Li AE, Jawetz ST. Distal rupture of the adductor longus in a skier. *Clin Imaging*. 2017;41:144-148. doi:10.1016/j.clinimag.2016.10.006.

68. Griffin DR, Dickenson EJ, O'Donnell J, et al. The Warwick Agreement on femoroacetabular impingement syndrome (FAI syndrome): an international consensus statement. *Br J Sports Med*. 2016;50(19):1169-1176. doi:10.1136/bjsports-2016-096743.

69. Groin - MeSH - NCBI. http://www.ncbi.nlm.nih.gov/mesh/?term=Groin. Accessed May 14, 2016.

70. Guillin R, Cardinal E, Bureau NJ. Sonographic anatomy and dynamic study of the normal iliopsoas musculotendinous junction. *Eur Radiol*. 2009;19(4):995-1001. doi:10.1007/s00330-008-1212-6.

71. Gyftopoulos S, Rosenberg ZS, Schweitzer ME, Bordalo-Rodrigues M. Normal Anatomy and Strains of the Deep Musculotendinous Junction of the Proximal Rectus Femoris: MRI Features. *Am J Roentgenol*. 2008;190(3):W182-W186. doi:10.2214/AJR.07.2947.

72. H Jackson Brown Jr. *P.S. I Love You*. S.l.: Rutledge Hill Press; 2000.

73. Hägglund M, Waldén M, Ekstrand J. Risk factors for lower extremity muscle injury in professional soccer: the UEFA Injury Study. *Am J Sports Med*. 2013;41(2):327-335. doi:10.1177/0363546512470634.

74. Hägglund M, Waldén M, Magnusson H, Kristenson K, Bengtsson H, Ekstrand J. Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. *Br J Sports Med*. 2013;47(12):738-742. doi:10.1136/bjsports-2013-092215.

75. Hallén A, Ekstrand J. Return to play following muscle injuries in professional footballers. *J Sports Sci*. 2014;32(13):1229-1236. doi:10.1080/02640414.2014.905695.

76. Hamilton B, Valle X, Rodas G, et al. Classification and grading of muscle injuries: a narrative review. *Br J Sports Med*. 2015;49(5):306. doi:10.1136/bjsports-2014-093551.

77. Hamilton B, Whiteley R, Almusa E, Roger B, Geertsema C, Tol JL. Excellent reliability for MRI grading and prognostic parameters in acute hamstring injuries. *Br J Sports Med*. 2014;48(18):1385-1387. doi:10.1136/bjsports-2013-092564.

78. Hancock CR, Sanders TG, Zlatkin MB, Clifford PD, Pevsner D. Flexor femoris muscle complex: grading systems used to describe the complete spectrum of injury. *Clin Imaging*. 2009;33(2):130-135. doi:10.1016/j.clinimag.2008.06.021.

79. Harris AJ. Muscle Fiber and Motor Unit Behavior in the Longest Human Skeletal Muscle. *J Neurosci*. 2005;25(37):8528-8533. doi:10.1523/JNEUROSCI.0923-05.2005.

80. Hasselman CT, Best TM, Hughes C, Martinez S, Garrett WE. An explanation for various rectus femoris strain injuries using previously undescribed muscle architecture. *Am J Sports Med*. 1995;23(4):493–499.

81. Henderson REA, Walker BF, Young KJ. The accuracy of diagnostic ultrasound imaging for musculoskeletal soft tissue pathology of the extremities: a comprehensive review of the literature. *Chiropr Man Ther*. 2015;23. doi:10.1186/s12998-015-0076-5.

82. Hewett TE, Torg JS, Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *Br J Sports Med*. 2009;43(6):417-422. doi:10.1136/bjsm.2009.059162.

83. Hinds S, Bian W, Dennis RG, Bursac N. The Role of Extracellular Matrix Composition in Structure and Function of Bioengineered Skeletal Muscle. *Biomaterials*. 2011;32(14):3575-3583. doi:10.1016/j.biomaterials.2011.01.062.

84. Hölmich P. Long-standing groin pain in sportspeople falls into three primary patterns, a “clinical entity” approach: a prospective study of 207 patients. *Br J Sports Med*. 2007;41(4):247-252; discussion 252. doi:10.1136/bjsm.2006.033373.

85. Hölmich P, Hölmich LR, Bjerg AM. Clinical examination of athletes with groin pain: an intraobserver and interobserver reliability study. *Br J Sports Med*. 2004;38(4):446-451. doi:10.1136/bjsm.2003.004754.

86. Hölmich P, Larsen K, Krogsgaard K, Gluud C. Exercise program for prevention of groin pain in football players: a cluster-randomized trial. *Scand J Med Sci Sports*. 2010;20(6):814-821. doi:10.1111/j.1600-0838.2009.00998.x.

87. Holmich P, Thorborg K, Dehlendorff C, Krogsgaard K, Gluud C. Incidence and clinical presentation of groin injuries in sub-elite male soccer. *Br J Sports Med*. 2014;48(16):1245-1250. doi:10.1136/bjsports-2013-092627.

88. Hosalkar HS, Pennock AT, Zaps D, Schmitz MR, Bomar JD, Bittersohl B. The hip antero-superior labral tear with avulsion of rectus femoris (HALTAR) lesion: does the SLAP equivalent in the hip exist? *Hip Int J Clin Exp Res Hip Pathol Ther*. 2012;22(4):391-396. doi:10.5301/HIP.2012.9470.

89. Hsu JC. Proximal Rectus Femoris Avulsions in National Football League Kickers: A Report of 2 Cases. *Am J Sports Med*. 2005;33(7):1085-1087. doi:10.1177/0363546504273045.

90. Hughes C, Hasselman CT, Best TM, Martinez S, Garrett WE. Incomplete, intrasubstance strain injuries of the rectus femoris muscle. *Am J Sports Med*. 1995;23(4):500–506.

91. Huijing PA. Muscle as a collagen fiber reinforced composite: a review of force transmission in muscle and whole limb. *J Biomech*. 1999;32(4):329-345. doi:10.1016/S0021-9290(98)00186-9.

92. Ikeda T, Awaya G, Suzuki S, Okada Y, Tada H. Torn acetabular labrum in young patients. Arthroscopic diagnosis and management. *J Bone Joint Surg Br*. 1988;70-B(1):13-16.

93. Iriuchishima T, Shirakura K, Yorifuji H, Fu FH. Anatomical evaluation of the rectus femoris tendon and its related structures. *Arch Orthop Trauma Surg*. 2012;132(11):1665-1668. doi:10.1007/s00402-012-1597-1.

94. Irmola T, Heikkilä JT, Orava S, Sarimo J. Total proximal tendon avulsion of the rectus femoris muscle. *Scand J Med Sci Sports*. 2006;0(0):061120070736034-??? doi:10.1111/j.1600-0838.2006.00564.x.

95. Ishøi L, Sørensen CN, Kaae NM, Jørgensen LB, Hölmich P, Serner A. Large eccentric strength increase using the Copenhagen Adduction exercise in football: A randomized controlled trial. *Scand J Med Sci Sports*. November 2015. doi:10.1111/sms.12585.

96. Jakobsen JR, Mackey AL, Knudsen AB, Koch M, Kjaer M, Krogsgaard MR. Composition and adaptation of human myotendinous junction and neighboring muscle fibers to heavy resistance training. *Scand J Med Sci Sports*. October 2016. doi:10.1111/sms.12794.

97. Jensen J, Hölmich P, Bandholm T, Zebis MK, Andersen LL, Thorborg K. Eccentric strengthening effect of hip-adductor training with elastic bands in soccer players: a randomised controlled trial. *Br J Sports Med*. July 2012. doi:10.1136/bjsports-2012-091095.

98. Jørgensen U, Schmidt-Olsen S. The epidemiology of ice hockey injuries. *Br J Sports Med*. 1986;20(1):7–9.

99. Kassarjian A, Rodrigo RM, Santisteban JM. Intramuscular Degloving Injuries to the Rectus Femoris: Findings at MRI. *Am J Roentgenol*. 2014;202(5):W475-W480. doi:10.2214/AJR.13.10931.

100. Kerkhoffs GMMJ, van Es N, Wieldraaijer T, Sierevelt IN, Ekstrand J, van Dijk CN. Diagnosis and prognosis of acute hamstring injuries in athletes. *Knee Surg Sports Traumatol Arthrosc Off J ESSKA*. 2013;21(2):500-509. doi:10.1007/s00167-012-2055-x.

101. Kjaer M. Role of extracellular matrix in adaptation of tendon and skeletal muscle to mechanical loading. *Physiol Rev*. 2004;84(2):649-698. doi:10.1152/physrev.00031.2003.

102. Kjær M, Magnusson P, Krogsgaard M, et al. Extracellular matrix adaptation of tendon and skeletal muscle to exercise. *J Anat*. 2006;208(4):445-450. doi:10.1111/j.1469-7580.2006.00549.x.

103. Knudsen AB, Larsen M, Mackey AL, et al. The human myotendinous junction: An ultrastructural and 3D analysis study: The human myotendinous junction. *Scand J Med Sci Sports*. May 2014:n/a-n/a. doi:10.1111/sms.12221.

104. Koh ESC, McNally EG. Ultrasound of skeletal muscle injury. *Semin Musculoskelet Radiol*. 2007;11(2):162-173. doi:10.1055/s-2007-1001881.

105. Kojima H, Sakuma E, Mabuchi Y, et al. Ultrastructural changes at the myotendinous junction induced by exercise. *J Orthop Sci Off J Jpn Orthop Assoc*. 2008;13(3):233-239. doi:10.1007/s00776-008-1211-0.

106. Kraff O, Fischer A, Nagel AM, Mönninghoff C, Ladd ME. MRI at 7 Tesla and above: demonstrated and potential capabilities. *J Magn Reson Imaging JMRI*. 2015;41(1):13-33. doi:10.1002/jmri.24573.

107. Kristianslund E, Faul O, Bahr R, Myklebust G, Krosshaug T. Sidestep cutting technique and knee abduction loading: implications for ACL prevention exercises. *Br J Sports Med*. 2014;48(9):779-783. doi:10.1136/bjsports-2012-091370.

108. Lahner M, Walter PA, von Schulze Pellengahr C, Hagen M, von Engelhardt LV, Lukas C. Comparative study of the femoroacetabular impingement (FAI) prevalence in male semiprofessional and amateur soccer players. *Arch Orthop Trauma Surg*. 2014;134(8):1135-1141. doi:10.1007/s00402-014-2008-6.

109. Landis JR, Koch GG. The Measurement of Observer Agreement for Categorical Data. *Biometrics*. 1977;33(1):159-174. doi:10.2307/2529310.

110. Lorentzon R, Wedrèn H, Pietilä T. Incidence, nature, and causes of ice hockey injuries A three-year prospective study of a Swedish elite ice hockey team. *Am J Sports Med*. 1988;16(4):392–396.

111. Lovell G. The diagnosis of chronic groin pain in athletes: a review of 189 cases. *Aust J Sci Med Sport*. 1995;27(3):76-79.

112. Lu HH, Thomopoulos S. Functional Attachment of Soft Tissues to Bone: Development, Healing, and Tissue Engineering. *Annu Rev Biomed Eng*. 2013;15:201-226. doi:10.1146/annurev-bioeng-071910-124656.

113. Lube J, Cotofana S, Bechmann I, et al. Reference data on muscle volumes of healthy human pelvis and lower extremity muscles: an in vivo magnetic resonance imaging feasibility study. *Surg Radiol Anat SRA*. 2016;38(1):97-106. doi:10.1007/s00276-015-1526-4.

114. van der Made AD, Reurink G, Gouttebarge V, Tol JL, Kerkhoffs GM. Outcome After Surgical Repair of Proximal Hamstring Avulsions: A Systematic Review. *Am J Sports Med*. 2015;43(11):2841-2851. doi:10.1177/0363546514555327.

115. Marshall BM, Franklyn-Miller AD, King EA, Moran KA, Strike SC, Falvey ÉC. Biomechanical factors associated with time to complete a change of direction cutting maneuver. *J Strength Cond Res*. 2014;28(10):2845-2851. doi:10.1519/JSC.0000000000000463.

116. Masionis P, Popov K, Kurtinaitis J, Uvarovas V, Porvaneckas N. Surgical treatment of the adductor longus muscle's distal tendon total rupture in a soccer player. *Orthop Traumatol Surg Res*. 2016;102(5):673-676. doi:10.1016/j.otsr.2016.03.011.

117. McDonald P. *Oxford Dictionary of Medical Quotations*. Oxford; New York: Oxford University Press; 2004.

118. Meeuwisse WHMD. Assessing Causation in Sport Injury: A Multifactorial Model. [Editorial]. *J Sport Med*. 1994;4(3):166-170.

119. Mendiguchia J, Alentorn-Geli E, Idoate F, Myer GD. Rectus femoris muscle injuries in football: a clinically relevant review of mechanisms of injury, risk factors and preventive strategies. *Br J Sports Med*. August 2012. doi:10.1136/bjsports-2012-091250.

120. Mölsä J, Airaksinen O, Näsman O, Torstila I. Ice Hockey Injuries in Finland A Prospective Epidemiologic Study. *Am J Sports Med*. 1997;25(4):495-499. doi:10.1177/036354659702500412.

121. Moore IS, Ranson C, Mathema P. Injury Risk in International Rugby Union. *Orthop J Sports Med*. 2015;3(7). doi:10.1177/2325967115596194.

122. Moore JR, Campbell SG, Lehman W. Structural determinants of muscle thin filament cooperativity. *Arch Biochem Biophys*. 2016;594:8-17. doi:10.1016/j.abb.2016.02.016.

123. Mueller-Wohlfahrt H-W, Haensel L, Mithoefer K, et al. Terminology and classification of muscle injuries in sport: the Munich consensus statement. *Br J Sports Med*. 2013;47(6):342-350. doi:10.1136/bjsports-2012-091448.

124. Murphy JC, O'Malley E, Gissane C, Blake C. Incidence of Injury in Gaelic Football A 4-Year Prospective Study. *Am J Sports Med*. 2012;40(9):2113-2120. doi:10.1177/0363546512455315.

125. Nelson EN, Kassarjian A, Palmer WE. MR Imaging of Sports-Related Groin Pain. *Magn Reson Imaging Clin N Am*. 2005;13(4):727-742. doi:10.1016/j.mric.2005.08.009.

126. Nippert AH, Smith AM. Psychologic stress related to injury and impact on sport performance. *Phys Med Rehabil Clin N Am*. 2008;19(2):399-418, x. doi:10.1016/j.pmr.2007.12.003.

127. Norton-Old KJ, Schache AG, Barker PJ, Clark RA, Harrison SM, Briggs CA. Anatomical and mechanical relationship between the proximal attachment of adductor longus and the distal rectus sheath. *Clin Anat N Y N*. 2013;26(4):522-530. doi:10.1002/ca.22116.

128. Obey MR, Broski SM, Spinner RJ, Collins MS, Krych AJ. Anatomy of the Adductor Magnus Origin: Implications for Proximal Hamstring Injuries. *Orthop J Sports Med*. 2016;4(1):2325967115625055. doi:10.1177/2325967115625055.

129. O'Connor DM. Groin injuries in professional rugby league players: a prospective study. *J Sports Sci*. 2004;22(7):629-636. doi:10.1080/02640410310001655804.

130. Omar IM, Zoga AC, Kavanagh EC, et al. Athletic pubalgia and "sports hernia": optimal MR imaging technique and findings. *Radiogr Rev Publ Radiol Soc N Am Inc*. 2008;28(5):1415-1438. doi:10.1148/rg.285075217.

131. Orchard J, James T, Kountouris A, Portus M. Changes to injury profile (and recommended cricket injury definitions) based on the increased frequency of Twenty20 cricket matches. *Open Access J Sports Med*. 2010;1:63-76.

132. Orchard JW. Men at higher risk of groin injuries in elite team sports: a systematic review. *Br J Sports Med*. 2015;49(12):798-802. doi:10.1136/bjsports-2014-094272.

133. Orchard JW, Seward H, Orchard JJ. Results of 2 Decades of Injury Surveillance and Public Release of Data in the Australian Football League. *Am J Sports Med*. 2013;41(4):734-741. doi:10.1177/0363546513476270.

134. Oudeman J, Nederveen AJ, Strijkers GJ, Maas M, Luijten PR, Froeling M. Techniques and applications of skeletal muscle diffusion tensor imaging: A review. *J Magn Reson Imaging JMRI*. 2016;43(4):773-788. doi:10.1002/jmri.25016.

135. Ouellette H, Thomas BJ, Nelson E, Torriani M. MR imaging of rectus femoris origin injuries. *Skeletal Radiol*. 2006;35(9):665-672. doi:10.1007/s00256-006-0162-9.

136. Palisch A, Zoga AC, Meyers WC. Imaging of athletic pubalgia and core muscle injuries: clinical and therapeutic correlations. *Clin Sports Med*. 2013;32(3):427-447. doi:10.1016/j.csm.2013.03.002.

137. Pedret C, Balius R, Barceló P, et al. Isolated tears of the gracilis muscle. *Am J Sports Med*. 2011;39(5):1077-1080. doi:10.1177/0363546510394436.

138. Pedret C, Rodas G, Balius R, et al. Return to Play After Soleus Muscle Injuries. *Orthop J Sports Med*. 2015;3(7):2325967115595802. doi:10.1177/2325967115595802.

139. Peetrons P. Ultrasound of muscles. *Eur Radiol*. 2002;12(1):35-43. doi:10.1007/s00330-001-1164-6.

140. Peh WC, Chan JH. Artifacts in musculoskeletal magnetic resonance imaging: identification and correction. *Skeletal Radiol*. 2001;30(4):179-191.

141. Peterson L, Stener B. Old Total Rupture of the Adductor Longus Muscle: A Report of Seven Cases. *Acta Orthop Scand*. 1976;47(6):653-657. doi:10.3109/17453677608988754.

142. Philippon MJ, Devitt BM, Campbell KJ, et al. Anatomic variance of the iliopsoas tendon. *Am J Sports Med*. 2014;42(4):807-811. doi:10.1177/0363546513518414.

143. Philippon MJ, Ho CP, Briggs KK, Stull J, LaPrade RF. Prevalence of Increased Alpha Angles as a Measure of Cam-Type Femoroacetabular Impingement in Youth Ice Hockey Players. *Am J Sports Med*. 2013;41(6):1357-1362. doi:10.1177/0363546513483448.

144. Philippon MJ, Michalski MP, Campbell KJ, et al. An Anatomical Study of the Acetabulum with Clinical Applications to Hip Arthroscopy. *J Bone Jt Surg*. 2014;96(20):1673-1682. doi:10.2106/JBJS.M.01502.

145. Polglase AL, Frydman GM, Farmer KC. Inguinal surgery for debilitating chronic groin pain in athletes. *Med J Aust*. 1991;155(10):674-677.

146. Pollock N, James SLJ, Lee JC, Chakraverty R. British athletics muscle injury classification: a new grading system. *Br J Sports Med*. 2014;48(18):1347-1351. doi:10.1136/bjsports-2013-093302.

147. Pollock N, Patel A, Chakraverty J, Suokas A, James SLJ, Chakraverty R. Time to return to full training is delayed and recurrence rate is higher in intratendinous ('c') acute hamstring injury in

elite track and field athletes: clinical application of the British Athletics Muscle Injury Classification. *Br J Sports Med*. 2016;50(5):305-310. doi:10.1136/bjsports-2015-094657.

148. Polster JM, Elgabaly M, Lee H, Klika A, Drake R, Barsoum W. MRI and gross anatomy of the iliopsoas tendon complex. *Skeletal Radiol*. 2007;37(1):55-58. doi:10.1007/s00256-007-0393-4.

149. Quah C, Cottam A, Hutchinson J. Surgical management of a completely avulsed adductor longus muscle in a professional equestrian rider. *Case Rep Orthop*. 2014;2014:828314. doi:10.1155/2014/828314.

150. Renström P, Peterson L. Groin injuries in athletes. *Br J Sports Med*. 1980;14(1):30-36.

151. Reurink G, Brilman EG, Vos R-J de, et al. Magnetic Resonance Imaging in Acute Hamstring Injury: Can We Provide a Return to Play Prognosis? *Sports Med*. 2014;45(1):133-146. doi:10.1007/s40279-014-0243-1.

152. Reurink G, Goudswaard GJ, Tol JL, et al. MRI observations at return to play of clinically recovered hamstring injuries. *Br J Sports Med*. November 2013. doi:10.1136/bjsports-2013-092450.

153. Reurink G, Jansen SPL, Bisselink JM, Vincken PWJ, Weir A, Moen MH. Reliability and validity of diagnosing acetabular labral lesions with magnetic resonance arthrography. *J Bone Joint Surg Am*. 2012;94(18):1643-1648. doi:10.2106/JBJS.K.01342.

154. Robinson P, Salehi F, Grainger A, et al. Cadaveric and MRI study of the musculotendinous contributions to the capsule of the symphysis pubis. *AJR Am J Roentgenol*. 2007;188(5):W440-445. doi:10.2214/AJR.06.1238.

155. Roemer FW, Guermazi A. What is the role of 3 T MRI in sports medicine? Revisiting the marriage after the honeymoon. *Br J Sports Med*. October 2015:bjsports-2015-095139. doi:10.1136/bjsports-2015-095139.

156. Ruddy JD, Pollard CW, Timmins RG, Williams MD, Shield AJ, Opar DA. Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers. *Br J Sports Med*. November 2016. doi:10.1136/bjsports-2016-096777.

157. Ryan JM, Harris JD, Graham WC, Virk SS, Ellis TJ. Origin of the Direct and Reflected Head of the Rectus Femoris: An Anatomic Study. *Arthrosc J Arthrosc Relat Surg*. 2014;30(7):796-802. doi:10.1016/j.arthro.2014.03.003.

158. Santaguida PL, McGill SM. The psoas major muscle: A three-dimensional geometric study. *J Biomech*. 1995;28(3):339-345. doi:10.1016/0021-9290(94)00064-B.

159. Schlegel TF, Bushnell BD, Godfrey J, Boublik M. Success of nonoperative management of adductor longus tendon ruptures in National Football League athletes. *Am J Sports Med*. 2009;37(7):1394-1399. doi:10.1177/0363546509332501.

160. Schneider-Kolsky ME, Hoving JL, Warren P, Connell DA. A Comparison Between Clinical Assessment and Magnetic Resonance Imaging of Acute Hamstring Injuries. *Am J Sports Med*. 2006;34(6):1008-1015. doi:10.1177/0363546505283835.

161. Schut L, Wangensteen A, Maaskant J, Tol JL, Bahr R, Moen M. Can Clinical Evaluation Predict Return to Sport after Acute Hamstring Injuries? A Systematic Review. *Sports Med*. October 2016:1-22. doi:10.1007/s40279-016-0639-1.

162. Serner A, van Eijck CH, Beumer BR, Hölmich P, Weir A, de Vos R-J. Study quality on groin injury management remains low: a systematic review on treatment of groin pain in athletes. *Br J Sports Med*. 2015;49(12):813. doi:10.1136/bjsports-2014-094256.

163. Serner A, Jakobsen MD, Andersen LL, Hölmich P, Sundstrup E, Thorborg K. EMG evaluation of hip adduction exercises for soccer players: implications for exercise selection in prevention and treatment of groin injuries. *Br J Sports Med*. 2014;48(14):1108-1114. doi:10.1136/bjsports-2012-091746.

164. Shaw HM, Benjamin M. Structure–function relationships of entheses in relation to mechanical load and exercise. *Scand J Med Sci Sports*. 2007;17(4):303-315. doi:10.1111/j.1600-0838.2007.00689.x.

165. Sinha DN, Kumar V. Study of human pyramidalis muscle in Indian subjects. *Anthropol Anz*. 1985;43(2):173-177.

166. Slavotinek JP, Verrall GM, Fon GT. Hamstring injury in athletes: using MR imaging measurements to compare extent of muscle injury with amount of time lost from competition. *AJR Am J Roentgenol*. 2002;179(6):1621-1628. doi:10.2214/ajr.179.6.1791621.

167. Smith C, McGarvey C, Harb Z, et al. Diagnostic Efficacy of 3-T MRI for Knee Injuries Using Arthroscopy as a Reference Standard: A Meta-Analysis. *AJR Am J Roentgenol*. June 2016:1-9. doi:10.2214/AJR.15.15795.

168. Soares JM, Marques P, Alves V, Sousa N. A hitchhiker's guide to diffusion tensor imaging. *Front Neurosci*. 2013;7. doi:10.3389/fnins.2013.00031.

169. Soligard T, Myklebust G, Steffen K, et al. Comprehensive warm-up programme to prevent injuries in young female footballers: cluster randomised controlled trial. *BMJ*. 2008;337:a2469.

170. Speer KP, Lohnes J, Garrett WE Jr. Radiographic imaging of muscle strain injury. *Am J Sports Med*. 1993;21(1):89-95; discussion 96.

171. Standring S, Ananad N, Gray H, eds. *Gray's Anatomy: The Anatomical Basis of Clinical Practice.* 41. ed. Philadelphia, Pa., p. 1078.: Elsevier; 2016.

172. Strauss EJ, Campbell K, Bosco JA. Analysis of the Cross-Sectional Area of the Adductor Longus Tendon: A Descriptive Anatomic Study. *Am J Sports Med*. 2007;35(6):996-999. doi:10.1177/0363546506298583.

173. Tak I, Weir A, Langhout R, et al. The relationship between the frequency of football practice during skeletal growth and the presence of a cam deformity in adult elite football players. *Br J Sports Med*. January 2015. doi:10.1136/bjsports-2014-094130.

174. Tanaka C, Ide MR, Junior AJR. Anatomical contribution to the surgical construction of the sartorius muscle flap. *Surg Radiol Anat*. 2006;28(3):277-283. doi:10.1007/s00276-006-0088-x.

175. Tanikawa H, Matsumoto H, Komiyama I, Kiriyama Y, Toyama Y, Nagura T. Comparison of knee mechanics among risky athletic motions for noncontact anterior cruciate ligament injury. *J Appl Biomech*. 2013;29(6):749-755.

176. Tansey RJ, Benjamin-Laing H, Jassim S, Liekens K, Shankar A, Haddad FS. Successful return to high-level sports following early surgical repair of combined adductor complex and rectus abdominis avulsion. *Bone Jt J*. 2015;97-B(11):1488-1492. doi:10.1302/0301-620X.97B11.32924.

177. Tatu L, Parratte B, Vuillier F, Diop M, Monnier G. Descriptive anatomy of the femoral portion of the iliopsoas muscle. Anatomical basis of anterior snapping of the hip. *Surg Radiol Anat*. 2002;23(6):371–374.

178. Tidball JG, Quan DM. Reduction in myotendinous junction surface area of rats subjected to 4-day spaceflight. *J Appl Physiol*. 1992;73(1):59-64.

179. Tidball JG, Salem G, Zernicke R. Site and mechanical conditions for failure of skeletal muscle in experimental strain injuries. *J Appl Physiol*. 1993;74(3):1280-1286.

180. Tubbs RS, Griessenauer CJ, Marshall T, et al. The adductor minimus muscle revisited. *Surg Radiol Anat SRA*. 2011;33(5):429-432. doi:10.1007/s00276-010-0741-2.

181. Tuite DJ, Finegan PJ, Saliaris AP, Renström P, Donne B, O'Brien M. Anatomy of the proximal musculotendinous junction of the adductor longus muscle. *Knee Surg Sports Traumatol Arthrosc*. 1998;6(2):134–137.

182. Tuominen M, Stuart MJ, Aubry M, Kannus P, Parkkari J. Injuries in men's international ice hockey: a 7-year study of the International Ice Hockey Federation Adult World Championship Tournaments and Olympic Winter Games. *Br J Sports Med*. 2015;49(1):30-36. doi:10.1136/bjsports-2014-093688.

183. Tyler TF, Nicholas SJ, Campbell RJ, McHugh MP. The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. *Am J Sports Med*. 2001;29(2):124-128.

184. Ueblacker P, English B, Mueller-Wohlfahrt H-W. Nonoperative treatment and return to play after complete proximal adductor avulsion in high-performance athletes. *Knee Surg Sports Traumatol Arthrosc*. June 2015:1-7. doi:10.1007/s00167-015-3669-6.

185. Verrall GM, Slavotinek JP, Barnes PG, Fon GT. Diagnostic and Prognostic Value of Clinical Findings in 83 Athletes with Posterior Thigh Injury Comparison of Clinical Findings with Magnetic Resonance Imaging Documentation of Hamstring Muscle Strain*. *Am J Sports Med*. 2003;31(6):969-973.

186. Volpi P, Melegati G, Tornese D, Bandi M. Muscle strains in soccer: a five-year survey of an Italian major league team. *Knee Surg Sports Traumatol Arthrosc Off J ESSKA*. 2004;12(5):482-485. doi:10.1007/s00167-003-0478-0.

187. Walden M, Hagglund M, Ekstrand J. The epidemiology of groin injury in senior football: a systematic review of prospective studies. *Br J Sports Med*. 2015;49(12):792-797. doi:10.1136/bjsports-2015-094705.

188. Wangensteen A, Almusa E, Boukarroum S, et al. MRI does not add value over and above patient history and clinical examination in predicting time to return to sport after acute hamstring injuries: a prospective cohort of 180 male athletes. *Br J Sports Med*. August 2015:bjsports-2015-094892. doi:10.1136/bjsports-2015-094892.

189. Ward SR, Eng CM, Smallwood LH, Lieber RL. Are Current Measurements of Lower Extremity Muscle Architecture Accurate? *Clin Orthop*. 2009;467(4):1074-1082. doi:10.1007/s11999-008-0594-8.

190. Weir A, Brukner P, Delahunt E, et al. Doha agreement meeting on terminology and definitions in groin pain in athletes. *Br J Sports Med*. 2015;49(12):768-774. doi:10.1136/bjsports-2015-094869.

191. Werner J, Hägglund M, Waldén M, Ekstrand J. UEFA injury study: a prospective study of hip and groin injuries in professional football over seven consecutive seasons. *Br J Sports Med*. 2009;43(13):1036-1040. doi:10.1136/bjsm.2009.066944.

192. Whitehouse T, Orr R, Fitzgerald E, Harries S, McLellan CP. The Epidemiology of Injuries in Australian Professional Rugby Union 2014 Super Rugby Competition. *Orthop J Sports Med*. 2016;4(3). doi:10.1177/2325967116634075.

193. Williams S, Trewartha G, Kemp SPT, et al. Time loss injuries compromise team success in Elite Rugby Union: a 7-year prospective study. *Br J Sports Med*. 2016;50(11):651-656. doi:10.1136/bjsports-2015-094798.

194. Witvrouw E, Danneels L, Asselman P, D'Have T, Cambier D. Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. *Am J Sports Med*. 2003;31(1):41-46.

195. Woodhouse JB, McNally EG. Ultrasound of skeletal muscle injury: an update. *Semin Ultrasound CT MR*. 2011;32(2):91-100. doi:10.1053/j.sult.2010.12.002.

196. Woods C, Hawkins RD, Maltby S, Hulse M, Thomas A, Hodson A. The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries. *Br J Sports Med*. 2004;38(1):36-41.

197. Yang D, Morris SF, Sigurdson L. The sartorius muscle: anatomic considerations for reconstructive surgeons. *Surg Radiol Anat SRA*. 1998;20(5):307-310.

198. Young WB, James R, Montgomery I. Is muscle power related to running speed with changes of direction? *J Sports Med Phys Fitness*. 2002;42(3):282-288.

199. Zoga AC, Mullens FE, Meyers WC. The spectrum of MR imaging in athletic pubalgia. *Radiol Clin North Am*. 2010;48(6):1179-1197. doi:10.1016/j.rcl.2010.07.009.

ASPETAR سبيتار

SIGILLVM FACVLTATIS MEDICÆ UNIVERSITATIS HAFNIENSIS