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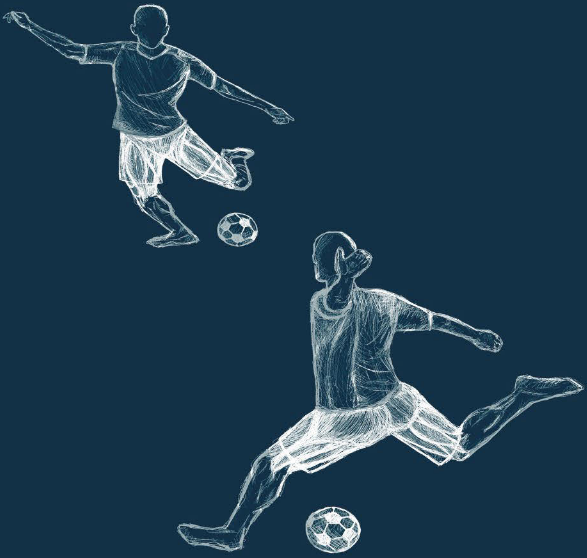

THIGH MUSCLE-TENDON INJURIES IN ATHLETES

From the Analysis of Injury Mechanisms to a Novel Diagnostic Technique and Surgical Treatment

Aleksi Jokela

TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
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To my loved ones

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ABSTRACT

Thigh muscle-tendon injuries are common among athletes. These injuries can be severe and require long rehabilitation or even surgical treatment. They also tend to recur quite often, causing prolonged time off from sports. More research on the etiology, diagnostics, and treatment of these injuries is needed to develop better prevention and management. This study was performed to investigate the mechanisms of thigh muscle-tendon injuries, a novel scanning position for diagnosing proximal hamstring tendinopathy, and patient outcomes after surgical treatment of hamstring injuries.

In the study of mechanisms of high-grade hamstring injuries in professional football (soccer in this thesis), we found injuries occurring during high-speed movements, typically involving hip flexion, knee extension, and trunk flexion, and most commonly affecting the biceps femoris. In addition to sprinting and stretching, also mixed-type injuries occurred.

Most (80%) of the rectus femoris injuries among male professional soccer players occurred during kicking, often causing total rupture of at least one tendon. Sprinting injuries also led to total ruptures, whereas change of direction only caused partial tears.

In the study of severe adductor longus injuries in professional soccer players, we found closed kinetic chain actions, such as reaching for the ball, being most frequently present at the time of injury. Hip extension, abduction, and external rotation were typically seen.

In proximal hamstring tendinopathy, diagnostics can be very challenging, and the condition may be difficult to treat. In this study, we presented the novel hip flexion scanning position and proved its additional value in magnetic resonance imaging diagnostics of proximal hamstring tendinopathy.

In a systematic review, we found that surgical treatment of hamstring tendon ruptures leads to successful outcomes, especially when surgery is performed early.

KEYWORDS: hamstring, rectus femoris, adductor longus, muscle, tendon, injury, rupture, tendinopathy, injury mechanism, diagnostics, surgical treatment

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TIIVISTELMÄ

Reiden alueen lihas-jännevammat ovat varsin yleisiä urheilijoilla. Vammat uusiutuvat herkästi ja voivat olla vakavia, vaatien pitkää kuntoutusta tai jopa kirurgista hoitoa. Näistä syistä tarvitaan lisää tutkimusta vammojen etiologiasta, diagnostiikasta ja hoidosta, jotta ennaltaehkäisyä ja hoitoa voidaan kehittää. Tutkimusaiheinamme olivat reiden lihas-jännevammojen mekanismit, uusi kuvausasento proksimaalisen hamstring-tendinopatian diagnostiikassa sekä hamstring-vammojen kirurgisen hoidon tulokset.

Hamstring-vammamekanismeja ammattilaisjalkapalloilijoilla analysoineessa tutkimuksessa vammat syntyivät pääosin nopeissa liikkeissä, tyypillisesti sisältäen polven ojennuksen sekä lonkan ja vartalon koukistuksen, useimmin vaurioittaen biceps femoris -lihas-jännekompleksia. Sprintin ja venytyksen lisäksi myös sekatyyppisiä vammamekanismeja todettiin.

Valtaosa (80 %) rectus femoris -vammoista miesammattilaisjalkapalloilijoilla tapahtui potkaisun aikana, ja ne aiheuttivat usein vähintään yhden jänteen täydellisen repeämän. Spurtin aikana syntyneet vammat johtivat myös täydellisiin repeämiin, kun taas suunnanmuutosten yhteydessä syntyi vain osittaisia repeämiä.

Vakavia adductor longus -vammoja ammattilaisjalkapalloilijoilla analysoineessa tutkimuksessa todettiin, että nämä vammat aiheutuivat useimmiten suljetun kineettisen ketjun liikkeiden, esimerkiksi palloon kurottamisen, aikana. Tyypillisesti vammahetkellä havaittiin lonkan ojennus, loitonnus ja ulkokierto.

Proksimaalisen hamstring-tendinopatian diagnostiikka voi olla erittäin haastavaa, ja vaivan hoitaminen voi olla vaikeaa. Tässä tutkimuksessa esitimme uuden kuvausasennon lonkka koukistettuna, ja osoitimme, että tästä asennosta on hyötyä kyseisen vamman magneettikuvausdiagnostiikassa.

Systemaattisessa katsauksessa totesimme, että leikkaushoito johtaa hyviin tuloksiin hamstring-jännerepeämien hoidossa, etenkin akuuttien leikkausten yhteydessä.

AVAINSANAT: hamstring, rectus femoris, adductor longus, lihas, jänne, vamma, repeämä, tendinopatia, vammamekanismi, diagnostiikka, leikkaushoito

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Abbreviations

ACL	anterior cruciate ligament
BAMIC	British Athletics Muscle Injury Classification
BF	biceps femoris
BFlh	long head of the biceps femoris
BFsh	short head of the biceps femoris
BMI	body mass index
CI	confidence interval
HF	hip flexion
H/Q	hamstring/quadriceps (ratio)
LEFS	Lower Extremity Functional Scale
MRI	magnetic resonance imaging
MTJ	myotendinous junction
OR	odds ratio
PHAT	Perth Hamstring Assessment Tool
PHT	proximal hamstring tendinopathy
PRP	platelet-rich plasma
RCT	randomized controlled trial
RF	rectus femoris
RTP	return to play
RTS	return to sports
SHORE	Sydney Hamstring Origin Rupture Evaluation
SM	semimembranosus
ST	semitendinosus
US	ultrasound
VAS	visual analogue scale

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I Jokela A, Valle X, Kosola J, Rodas G, Til L, Burova M, Pleshkov P, Andersson H, Pasta G, Manetti P, Lupón G, Pruna R, García-Romero-Pérez A, Lempainen L. Mechanisms of Hamstring Injury in Professional Soccer Players: Video Analysis and Magnetic Resonance Imaging Findings. *Clin J Sport Med*, 2023;33(3):217–224.

II Jokela A, Mechó S, Pasta G, Pleshkov P, García-Romero-Pérez A, Mazzoni S, Kosola J, Vittadini F, Yanguas J, Pruna R, Valle X, Lempainen L. Indirect Rectus Femoris Injury Mechanisms in Professional Soccer Players: Video Analysis and Magnetic Resonance Imaging Findings. *Clin J Sport Med*, 2023;33(5):475–482.

III Jokela A, Pasta G, Della Villa F, Abrantes A, Kalogiannidis D, García-Romero-Pérez A, Marano M, Skibinskyi D, Mazzoni S, Pruna R, Valle X, Lempainen L. Mechanisms of Severe Adductor Longus Injuries in Professional Soccer Players: A Systematic Visual Video Analysis. *Orthop J Sports Med*, 2025;13(2).

IV Jokela A, Niemi P, Koski I, Kosola J, Valle X, Pruna R, Orava S, Pedret C, Balius R, Pasta G, Sinikumpu J, Mäkelä K, Lempainen L. Magnetic Resonance Imaging with a Novel Hip Flexion Scanning Position for Diagnosing Proximal Hamstring Tendinopathy. *Orthop J Sports Med*, 2024;12(9): 23259671241265130.

V Jokela A, Stenroos A, Kosola J, Valle X, Lempainen L. A systematic review of surgical intervention in the treatment of hamstring tendon ruptures: current evidence on the impact on patient outcomes. *Ann Med*, 2022;54(1):978–988.

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1 Introduction

Muscle-tendon injury is the most frequently seen injury type in professional football (soccer in this thesis), accounting for 4.6 injuries per 1000 exposure hours (López-Valenciano et al., 2020). The single most common injury subtype in soccer is thigh muscle-tendon injury (Ekstrand et al., 2011b). Almost half of thigh muscle-tendon injuries affect the hamstrings, whereas approximately 30% and 25% affect the adductors and quadriceps, respectively (Ekstrand et al., 2011a). Concerning hamstring injuries alone, the proportion of all injuries is 10% in field-based team sports and 24% particularly in soccer (Ekstrand et al., 2022; Maniar et al., 2023). Acute injuries are more frequent during the competitive season, whereas overuse injuries more often occur in the preseason (Ekstrand et al., 2011b).

For the development of prevention strategies to reduce the amount of sports injuries, understanding the injury mechanisms is crucial (Bahr & Krosshaug, 2005). However, there is limited knowledge on the situations leading to thigh muscle-tendon injuries (Della Villa et al., 2023; Geiss Santos et al., 2022; Gronwald et al., 2022; Kerin et al., 2022; Serner et al., 2019).

Chronic overuse injuries such as proximal hamstring tendinopathy (PHT) may be difficult to diagnose and treat successfully (Nasser et al., 2021). Despite the difficult symptoms and clinical findings, magnetic resonance imaging (MRI) findings may be minimal or normal, often leading to a delay in diagnosis (Bowden et al., 2018).

Most acute thigh muscle-tendon injuries heal well with conservative treatment, but more severe injuries often require surgical intervention, especially among elite athletes (Allahabadi et al., 2024; Farrell et al., 2023; Lempainen, Banke, et al., 2015; Lempainen et al., 2022). Surgical treatment may also be necessary if conservative treatment fails (Lempainen, Banke, et al., 2015). High-level evidence on the best treatment methods for different injuries is still scarce.

The purpose of this doctoral thesis was to investigate the mechanisms and MRI findings of thigh muscle-tendon injuries in professional soccer players. Additionally, we researched the novel hip flexion (HF) scanning position and its value in the MRI diagnostics of PHT. Furthermore, the outcomes after surgical treatment of hamstring injuries were investigated.

2 Review of the Literature

2.1 Thigh Muscles

2.1.1 Functional Anatomy

2.1.1.1 Hamstrings

The hamstrings are powerful muscles located anatomically in the posterior thigh. Hamstring muscles are essential not only in high-speed movements, such as running and jumping, but also in daily low-demand activities, including walking and climbing stairs. The hamstring muscle group consists of four separate muscles: the long head of the biceps femoris (BFlh), the short head of the biceps femoris (BFsh), the semimembranosus (SM), and the semitendinosus (ST) (Moore, 2014; Paulsen et al., 2011; Van Der Made et al., 2015). The three biggest hamstring muscles (BFlh, SM, and ST) originate from the ischial tuberosity, whereas the BFsh has its proximal attachment at the linea aspera of the femur (Paulsen et al., 2011). The SM originates from the superolateral site of the ischial tuberosity, continuing distally beneath the proximal BFlh, while the ST has its attachment on the inferomedial part of the ischial tuberosity, forming a common tendon with the BFlh (Moore, 2014). This common tendon divides into two separate muscles (BFlh and ST) approximately 9 cm distally from the ischial tuberosity (Van Der Made et al., 2015). Also the most proximal part of the SM tendon is attached to the common tendon of the BFlh and the ST, and separates into an individual tendon at on average 2.7 cm from the ischial tuberosity (Van Der Made et al., 2015). Anatomical variances occur; for example the ST occasionally has its own insertion area (Miller et al., 2007). In mid-thigh the BFlh is located laterally, while the ST and SM position more medially, the ST being more superficial (Paulsen et al., 2011). In the mid-portion of the distal myotendinous junction (MTJ), opposing epimysial condensations at the anterolateral aspect of the BFlh and the posterolateral aspect of the BFsh converge to form a T-shaped structure known as the T-junction (Entwisle et al., 2017). Distally, the hamstring muscles attach to the knee, the ST attaching to the medial part of the superior aspect of the tibia, the SM inserting on the posterior side of the medial tibia, and the common tendon of both biceps femoris (BF) muscles attaching to the proximal head of the fibula (Moore, 2014). In addition to free tendons (part of the tendon without muscle fibers attached to it), every hamstring muscle has intramuscular tendons along the entire length of the muscle (Van Der Made et al., 2015; Woodley & Mercer, 2005). The hamstring anatomy is illustrated in Figure 1.

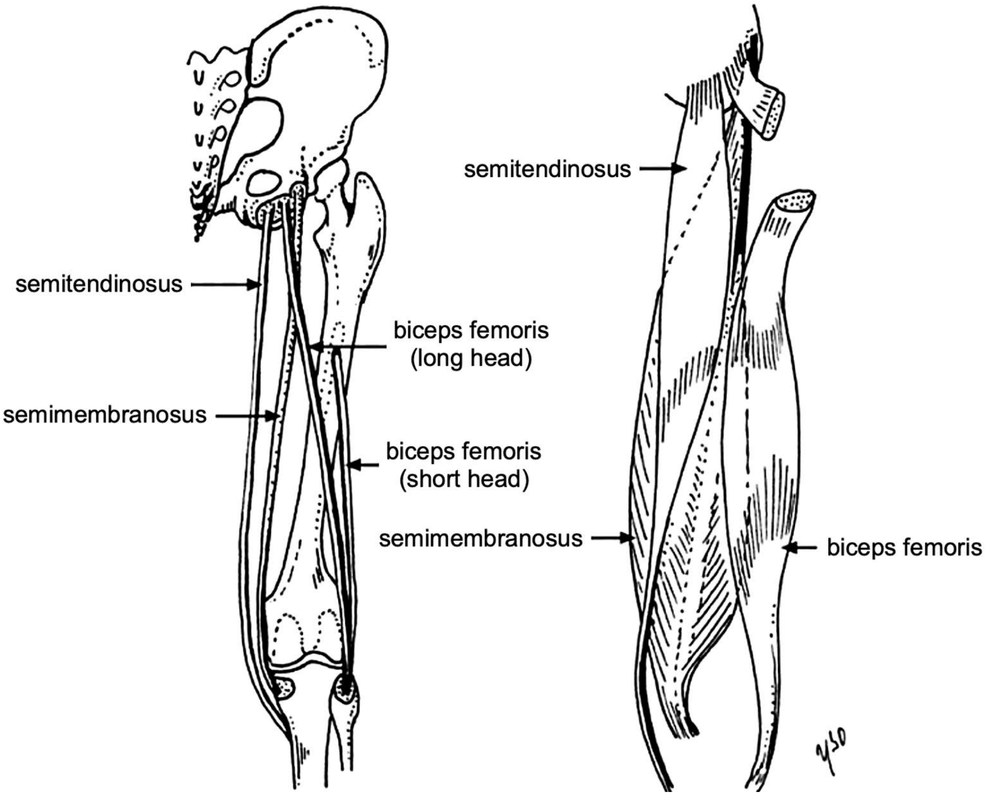

Figure 1. Anatomy of the right hamstring muscles. Illustration by Sakari Orava. Modified from Lempainen (2009).

The tibial branch of the sciatic nerve supplies innervation for the ST, SM, and BFlh, whereas the BFsh receives its innervation from the common fibular part of the sciatic nerve (Moore, 2014). However, the specific innervation anatomy can vary between individuals (Woodley & Mercer, 2005). It is also worth noting that anatomically, the sciatic nerve is located very close to the hamstring muscles, on average 1.2 cm from the most lateral part of the hamstring tendons at the ischial tuberosity (Miller et al., 2007).

The BFlh, SM, and ST span two large joints, the knee and hip. They act concentrically during hip extension and knee flexion, which are the primary roles of the hamstring muscles (Moore, 2014). They work eccentrically in opposite movements (knee extension and hip flexion) due to their nature as two-joint muscle-tendon units. Additionally, the medial hamstrings (SM and ST) act as medial rotators and the lateral hamstrings (BFlh and BFsh) as lateral rotators of the tibia at the knee (Moore, 2014). These rotatory actions are present especially when the knee is in 90° flexion.

2.1.1.2 Quadriceps

The quadriceps is a large and powerful muscle group located in the anterior thigh, covering almost all the anterior aspects of the femur (El-Ansary et al., 2021). It is especially responsible for extending the knee, which is a crucial action when rising from sitting, climbing stairs, running, jumping, or kicking (Moore, 2014). The quadriceps muscle group is formed by four separate muscles: the rectus femoris (RF), vastus lateralis, vastus intermedius, and vastus medialis (Paulsen et al., 2011).

The only quadriceps muscle to cross two joints is the RF, as it has attachments not only on the tibia via the patellar ligament, but also at the pelvic bone (Paulsen et al., 2011). Proximally, the RF actually has two origins: the direct head (or straight head) originates from the anterior inferior iliac spine, while the indirect head (or reflected head) has its origin at the ilium superior to the acetabulum (Hasselman et al., 1995). On average 2 cm distally from the proximal attachments, the direct and indirect tendons form a common tendon. The direct tendon is located superficially and covers the anterior side of the proximal third of the RF's length, while the indirect tendon lies under the direct head, extending distally to the middle of the muscle belly, covering around two thirds of the RF length (Hasselman et al., 1995). The normal anatomy and different RF ruptures are illustrated in Figure 2.

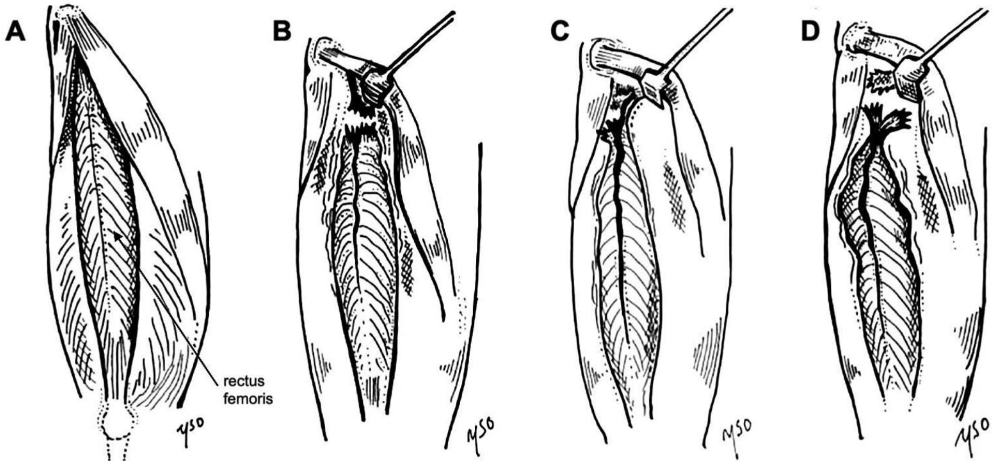

Figure 2. Illustration of the RF anatomy. **A**) Normal anatomy, **B**) total tear of the common tendon, **C**) complete rupture of the direct head, and **D**) complete avulsions of the direct and indirect heads. Illustration by Sakari Orava. Modified from Lempainen et al. (2018a).

The vastus muscles originate from the proximal femur: the vastus lateralis from the greater trochanter and the lateral part of the linea aspera, the vastus medialis from the intertrochanteric line and the medial aspect of the linea aspera, and the vastus intermedius from the anterior and lateral surfaces of the femoral shaft (Moore, 2014). The names of the vastus muscles correlate with their actual locations around the femoral shaft. Distally, the four muscles unite and form a strong and single quadriceps tendon (Moore, 2014; Paulsen et al., 2011). The quadriceps tendon inserts into the patella, and the patellar tendon extends from the patella to attach to the tibial tuberosity (Moore, 2014).

As mentioned, the most important duty of the quadriceps muscle group is to extend the knee (Moore, 2014). Additionally, the RF has the ability to flex the hip joint due to its nature as a biarticular muscle. The RF is sometimes called “the kicking muscle”, as it has a big role in kicking a soccer ball, during which it is also susceptible to injury (Geiss Santos et al., 2022; Moore, 2014). All four quadriceps muscles receive innervation from the femoral nerve (L2-L4) (Moore, 2014; Refai et al., 2024).

2.1.1.3 Adductors

The medial part of the thigh contains the adductor muscle group, which includes the adductor longus, adductor magnus, adductor brevis, pectineus, and gracilis (Moore, 2014). The hip adductors are essential in everyday movements, as their main function is to bring the lower limbs toward the midline and keep them at an appropriate distance from it. Generally, these muscles originate from the antero-inferior part of the bony pelvis, inserting on the linea aspera, except for the gracilis which attaches distally to the tibia (Paulsen et al., 2011).

The adductor longus is a large muscle and the most superficial of the adductors (Moore, 2014), as well as the most commonly injured (Serner et al., 2018). This triangular muscle originates from a strong tendon on the anterior surface of the pubis below the pubic tubercle, and extends distally to insert on the linea aspera of the femur (Moore, 2014; Paulsen et al., 2011). The proximal anatomy of the hip adductors and an adductor longus tendon rupture are illustrated in Figure 3.

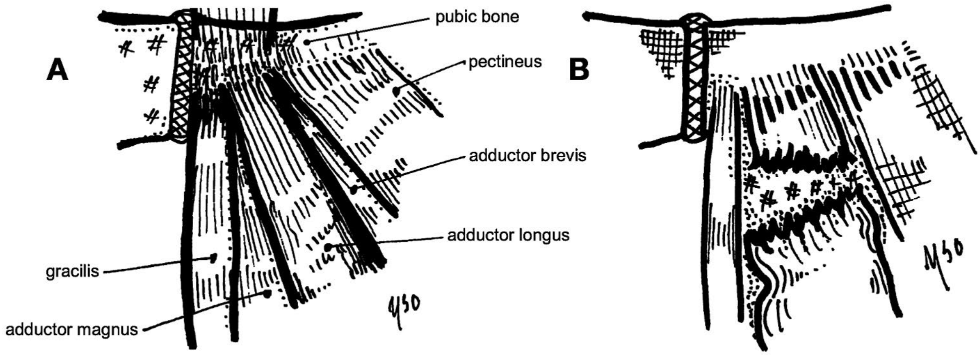

Figure 3. Proximal anatomy of **A**) the left hip adductors, and **B**) complete rupture of the left adductor longus tendon. Illustration by Sakari Orava. Modified from Orava (2012).

All the adductor muscles are innervated by the obturator nerve (L2-L4), except for the adductor magnus “hamstring part” and a portion of the pectineus (Moore, 2014). This part of the adductor magnus receives its innervation from the tibial division of the sciatic nerve, whereas the pectineus is innervated also by the femoral nerve (L2-L4) (Waschke et al., 2011).

The primary function of the hip adductors is to move the thigh inwards (Moore, 2014). The adductor longus, brevis, and magnus are active in all actions involving thigh adduction. They also help to stabilize the posture when a person is standing or moving sideways (Moore, 2014). These muscles are used when kicking a ball and when swimming (Moore, 2014; Watanabe et al., 2020).

2.1.2 Functional Characteristics

Garrett et al. (1984) studied the histochemical fiber types of thigh muscles from necropsy samples. They found that especially the RF and hamstring muscles are rich in type II muscle fibers, whereas the adductor muscles have a higher proportion of type I muscle fibers. Similar findings were reported in another study (Johnson et al., 1973). Type II muscle fibers are known for their rapid contractile abilities crucial for powerful and explosive movements, whereas muscles with a higher proportion of type I fibers tend to be slower to act and have better aerobic capacity, leading to better endurance (Garrett et al., 1984; Johnson et al., 1973; Kary, 2010).

2.1.3 Biomechanics during Running Gait Cycle

The gait cycle during running has two phases, stance and swing (Elliott & Blanksby, 1979). The stance phase starts with the foot in contact with the ground and ends when the toes leave the ground. During the ensuing swing phase, the foot is in the air and swings forward until it again makes contact with the ground, after late swing and before early stance. Both phases are further divided into early, mid, and late stages. The phases of the running gait cycle are demonstrated in Figure 4.

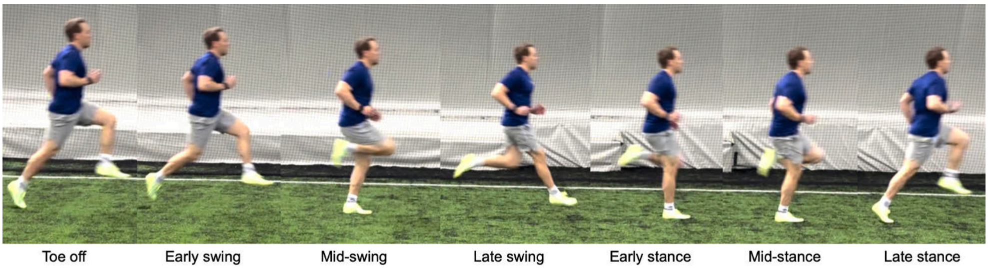

Figure 4. Phases of the running gait cycle (right leg observed).

2.1.3.1 Hamstrings

The hamstring muscles are inactive during the early swing phase, while the hip flexors are working and the hip and knee flexion angles are increasing (Higashihara et al., 2010). During mid-swing, the knee flexion angle reaches its maximum and the hamstring muscles (especially the medial hamstrings) begin to activate by working eccentrically to stabilize the knee joint (Chumanov et al., 2011; Higashihara, Nagano, Ono, et al., 2015). While the hip is maximally flexed, the knee continues to extend (Elliott & Blanksby, 1979). The peak of hamstring muscle activity occurs during the late swing phase, while the hamstrings are reaching their maximum length and preparing for ground contact (Higashihara et al., 2010, 2016; Suskens et al., 2023). Immediately before the foot strike, the hamstring muscles quickly change from eccentric to concentric work (Chumanov et al., 2011). Before and after foot contact, the activation demand is high particularly on the BF when managing hip extension (Higashihara, Nagano, Ono, et al., 2015). In the early stance, the hamstring muscles (especially the BF and SM) actively contract while the knee flexes and the hip flexes slightly to assist landing (Elliott & Blanksby, 1979; Wall-Scheffler et al., 2010). During mid-stance, all three hamstrings are actively contributing to the propulsion by assisting hip extension while the knee starts to extend. During late stance, the SM and ST are more active than the BF as they control knee extension (Higashihara, Nagano, Ono, et al., 2015). After late stance, as the toes leave the ground, the activity of the hamstring muscles decreases sharply. In general, as the running speed increases, the hamstrings work at significantly higher peak forces and negative energy (Chumanov et al., 2007; Dorn et al., 2012; Higashihara et al., 2010). Additionally, the functional demands of the medial and lateral hamstrings vary between acceleration and maximal-speed running. During early stance in an acceleration sprint, hip extension torque and the BFlh activation are higher, while knee flexion torque and the ST activation increase during the late stance and mid-swing phases of maximal-speed sprinting (Higashihara et al., 2018).

2.1.3.2 Quadriceps

The RF becomes active in the early and mid-swing phases, while the vastus muscles remain inactive (Chumanov et al., 2011; Novacheck, 1998; Wall-Scheffler et al., 2010). This is essential to assist hip flexion and prevent the tibia from moving posteriorly while the knee flexes. All the quadriceps muscles are active from late swing to mid-stance, as they prepare the lower limb for ground contact and to receive a heavy load (Novacheck, 1998; Wall-Scheffler et al., 2010). At this stage the quadriceps activates eccentrically while the knee is flexing. In mid-stance the quadriceps activity is slightly less, until late stance when it works concentrically while extending the knee to generate power for propulsion (Kakehata et al., 2021; Novacheck, 1998; Wall-Scheffler et al., 2010). During the transition to swing phase, the quadriceps decreases its activity until the RF starts working eccentrically again in the early swing phase (Dorn et al., 2012; Wall-Scheffler et al., 2010). At higher speeds, also the RF develops greater peak forces throughout the gait cycle (Dorn et al., 2012).

2.1.3.3 Adductors

The hip adductors exhibit fairly steady activity throughout the linear running gait cycle, as they do not play as big a part as the hamstring and quadriceps muscles (Wall-Scheffler et al., 2010). However, they are slightly more active during the stance, early swing, and late swing phases (Wall-Scheffler et al., 2010). Generally, during the running gait cycle the hip is in adduction during loading of the limb in the stance phase and in abduction throughout the swing phase (Novacheck, 1998). The hip adductor muscles exhibit varying activity during the early stance, late stance, and pre-swing stages. A detailed analysis of EMG activity and kinematics suggests that, in the transverse plane, these muscles may eccentrically control the internal rotation of the femur at the hip during the early stance (Leighton, 2006). Additionally, they may concentrically facilitate external rotation of the femur at the hip during the late stance and pre-swing (Leighton, 2006). Furthermore, the adductors are known to act as hip flexors when the thigh is in extension (early swing phase) and as hip extensors when the thigh is flexed (late swing phase) during running (Moore, 2014).

2.2 Thigh Muscle-Tendon Injuries

2.2.1 Epidemiology

An average professional male soccer team suffers some 15 muscle injuries every season (Ekstrand et al., 2011a). Most of the injuries are mild, causing on average 2 weeks' absence. However, 11% of muscle injuries are severe, causing longer than 28 days off from the sport. When a tendon is injured, it heals through scar tissue formation, leading to a slower healing process, a longer recovery time, and biomechanical changes (Kasperczyk et al., 1993; Sharma & Maffulli, 2006; Valle et al., 2022; Voleti et al., 2012). Severe injuries may require surgical treatment to enable a return to preinjury level and prevent reinjuries (Allahabadi et al., 2024; Farrell et al., 2023; Lempainen, Banke, et al., 2015; Lempainen, Hetsroni, et al., 2021; Lempainen et al., 2022; Plastow, Kerkhoffs, et al., 2023; Sonnery-Cottet et al., 2017). Recurrent injuries account for 16% of injuries and cause 30% longer absences (Ekstrand et al., 2011a). Furthermore, injury rates are significantly higher during matches compared to training. For example, the incidence of hamstring injuries is approximately ten times greater during matches compared to training (Ekstrand et al., 2022; Maniar et al., 2023). The vast majority (80%) of muscle injuries in male professional soccer affect the thigh muscles: hamstrings, adductors, and quadriceps (Ekstrand et al., 2011a). Thigh muscle injury is the most common injury also in elite women's soccer, with the anterior cruciate ligament (ACL) bearing the highest injury burden (Hallén et al., 2024).

2.2.1.1 Hamstring Injuries

Acute hamstring muscle-tendon injuries are very frequent in sports requiring fast, explosive actions like sprinting, kicking, jumping, and quick changes in direction or velocity (Dalton et al., 2015; Ekstrand et al., 2011a; Maniar et al., 2023; Tabben et al., 2022). Hamstring injuries have been reported to account for 37% of all muscle-tendon injuries (Ekstrand et al., 2011a). The proximal part of the BFlh is most commonly affected in these injuries (Ekstrand et al., 2016; Grange et al., 2023). Hamstring injuries have a high risk of recurrence, with 38% of hamstring injuries in American football being recurrent and around 12% occurring during the same season (Bodendorfer et al., 2023). Injuries to the BF T-junction carry an especially high risk of recurrence (Entwisle et al., 2017). Hamstring injuries are a major concern, especially for soccer players, who suffer the highest incidence of these injuries and miss the most time off the pitch (Boltz et al., 2024). In soccer, high-intensity running performance has significantly increased as the sport has evolved over time (Barnes et al., 2014; Haugen et al., 2013). The percentage of hamstring injuries among all injuries in men’s professional soccer rose from 12% to 24% between the 2001/02 and 2021/22 seasons (Ekstrand et al., 2022). Hamstring injuries are followed by poorer performance after return to play (Verrall et al., 2006) and cause significant financial consequences for athletes and their clubs (Hickey et al., 2014). It is worth noting that hamstring injuries are not exclusive to athletes; they also occur in the general population, often due to sudden slips or falls (Irger et al., 2020).

2.2.1.2 Rectus Femoris Injuries

Quadriceps injuries are prevalent especially in sports that involve kicking and sprinting activities (Brophy et al., 2010; Eckard et al., 2017; Ekstrand et al., 2011a; J. Orchard & Seward, 2002; Plastow, Raj, et al., 2023). The RF, also called “the kicking muscle”, is the most commonly injured quadriceps muscle, presenting a very high incidence particularly in soccer (Cross et al., 2004; Ekstrand et al., 2011a; Walden, 2005; Woods, 2002). Therefore, this thesis focuses on the RF injuries. Quadriceps injuries constitute approximately one-fifth of all muscle-tendon injuries in soccer, thus being the third most common muscle injury after hamstring and adductor injuries (Ekstrand et al., 2011a). More than 80% of RF injuries affect the proximal free tendon or myotendinous area (including intramuscular tendon) (Geiss Santos et al., 2022).

2.2.1.3 Adductor Injuries

Injuries to adductor muscle-tendon units account for almost 70% of all acute groin injuries (Serner et al., 2015; Werner et al., 2009). Adductor injuries comprise 23% of muscle-tendon injuries in professional soccer players, ranking the second most common between hamstring and quadriceps injuries (Ekstrand et al., 2011a). They typically occur in non-contact situations and are slightly more common in the dominant leg. The adductor longus muscle is the most frequently injured, accounting for 90% of all adductor muscle-tendon injuries (Serner et al., 2015, 2018). Between the 2001/2002 and 2015/2016 seasons the number of adductor injuries dropped slightly, but the injury burden remained at the same level (Werner et al., 2019). On the other hand, groin problems are reported to be more frequent than thought, with 59% of male and 45% of female soccer players reporting a minimum of one groin problem episode over a period of 6 weeks during the competitive season (Harøy et al., 2017).

2.2.2 Risk Factors

In general, a previous injury in the same muscle-tendon unit is the most relevant factor raising the risk of muscle-tendon injury (Engebretsen et al., 2010; Hägglund et al., 2013; J. W. Orchard, 2001; Pietsch & Pizzari, 2022). As mentioned, hamstring and RF muscles have high proportions of type II muscle fibers known for their ability to contract efficiently and quickly, making them essential in explosive and powerful movements (Garrett et al., 1984; Johnson et al., 1973). These fast, high-speed movements like sprinting, kicking, and jumping, are often associated with situations leading to hamstring or RF injury (Danielsson et al., 2020; Mendiguchia et al., 2013). In addition, both the hamstring muscle group and the RF span two major joints originating from the proximal side of the hip joint and crossing the knee distally. The biarticularity of the hamstring and RF muscles is thought also to influence their vulnerability to injury (Opar et al., 2012). When it comes to external factors, teams without a winter break lose an average of 303 more days per season due to injuries compared to teams with a winter break (Ekstrand et al., 2019). In contrast, teams that perform a greater number of preseason training sessions experience a lower injury burden during the competitive season (Ekstrand et al., 2020). Furthermore, the risk of thigh injury is higher on grass than on artificial turf (Kuitunen et al., 2023; Maniar et al., 2023). Important risk factors for acute hamstring, quadriceps, and adductor injuries are listed in Table 1.

2.2.2.1 Hamstring Injuries

Several risk factors have been recognized for hamstring injuries, and they are multifactorial and complex. Age and history of hamstring injury are the clearest risk factors and are non-modifiable (Dyk et al., 2017; Engebretsen et al., 2010; Hägglund et al., 2006; Lee Dow et al., 2021; Tokutake et al., 2018). Athletes with previous hamstring injuries have a multiplied risk of recurrent injury compared to those without, especially during the same season (Green et al., 2020). Additionally, lower hamstring eccentric strength, lower hamstring flexibility, higher quadriceps peak torque, shorter BFlh fascicles, higher activation of the gluteus medius during running, low horizontal force production during acceleration, hamstring/quadriceps (H/Q) peak torque ratio less than 0.60, playing position (outfield players), body mass, and previous calf strain injury have been found to be risk factors for hamstring injury (Dyk et al., 2017; Edouard et al., 2021; Franettovich et al., 2017; Freckleton & Pizzari, 2013; Green et al., 2020; Opar et al., 2022; Timmins et al., 2016; van Beijsterveldt et al., 2013; Yeung et al., 2009). For recurrent hamstring injuries, more recent injury, lower body mass index (BMI), longer playing experience, playing position, return to play (RTP) within 2 weeks, larger volume size of initial injury, grade I hamstring injury, and previous ACL reconstruction or injury in the same leg are known to increase the risk (Bodendorfer et al., 2023; de Visser et al., 2012; Koulouris et al., 2007). The risk factors for recurrence within the same season are quicker RTP, match injury, lower BMI, and playing position (Bodendorfer et al., 2023). Additionally, according to the chief medical officers of European professional soccer clubs, poor communication between the medical team and coaches, insufficient regular exposure to high-speed soccer actions, excessive player workload, and playing matches 2–3 times a week are the most modifiable factors associated with an increased risk of hamstring injury (Ekstrand, Hallén, et al., 2023; Ekstrand, Ueblacker, et al., 2023).

Finally, factors that can increase absence and reinjury risk include recurrent injury, stretching-type injury mechanism, structural injury, high-grade injury, proximity to the ischial tuberosity, connective tissue injury, proximal free tendon injury, and involvement of the intramuscular tendon (Askling et al., 2007a, 2007b, 2013, 2014; Brukner & Connell, 2016; Day et al., 2024; Ekstrand et al., 2016; Hägglund et al., 2013; Hallén & Ekstrand, 2014; Shamji et al., 2021; Valle et al., 2022).

2.2.2.2 Rectus Femoris Injuries

A recent systematic review by Pietsch and Pizzari (2022) on risk factors for quadriceps muscle strain injury (primarily the RF) found that the dominant kicking leg, a previous quadriceps muscle injury, and a recent hamstring strain were intrinsic risk factors for this injury. Extrinsic factors related to the preseason period and competitive match play led to a higher injury risk, whereas a higher level of play was a protecting factor. Age, weight, and flexibility were not correlated with quadriceps injury risk. Additionally, shorter stature, decreased knee extensor flexibility and strength, and a dry playing field have been suggested to be risk factors for RF injuries, although evidence is limited (Mendiguchia et al., 2013).

2.2.2.3 Adductor Injuries

Risk factors for acute adductor muscle injury are previous acute injury in the groin, decreased adductor strength, any injury during the former season, and decreased range of motion in hip rotation (Farrell et al., 2023). Additionally, a higher level of play and lower levels of sport-specific training have been found to increase the risk of groin injury in sport (Whittaker et al., 2015). Adductor injuries are more common in the kicking leg and during the competitive season, whereas playing as a goalkeeper and playing at an away match have been found to decrease the risk of adductor injury (Hägglund et al., 2013).

Table 1. Risk factors for acute thigh muscle-tendon injuries.

RISK FACTORS	INTRINSIC	EXTRINSIC
Hamstring injuries	Age Previous hamstring injury Lower hamstring eccentric strength Lower hamstring flexibility Higher quadriceps peak torque Shorter BFlh fascicles Higher activation of gluteus medius during running Low horizontal force production during acceleration H/Q peak torque <0.60 Body mass Previous calf injury	Playing position (outfield players) Poor communication between medical team and coaches Lack of regular exposure to high-speed soccer actions Load on players Playing matches 2-3 times per week Playing on grass
Quadriceps injuries	Dominant kicking leg Previous quadriceps muscle injury Recent hamstring injury	Preseason period Competitive match Playing on grass
Adductor injuries	Previous acute injury in the groin area Decreased adductor strength Any injury during the previous season Decreased range of motion in hip rotation Dominant kicking leg	Higher level of play Lower levels of sport-specific training Competitive season Playing on grass

2.2.3 Injury Mechanisms

Eccentric muscle contraction is thought to play an important role in muscle strain injuries (Garrett, 1996; Opar et al., 2012). The importance of understanding injury mechanisms is the key component of sport injury prevention (Bahr & Krosshaug, 2005). The role of injury mechanism in assessing the factors leading to injury has been highlighted, and a comprehensive model to approach sport injuries has been developed (Bahr & Krosshaug, 2005). Since then, the number of papers investigating the mechanisms of sport injuries has continued to increase. Although acute tendon ruptures or tears are typically preceded by a sudden application of force that exceeds the tendon's capacity, underlying degenerative changes likely play a significant role in their occurrence, making it more susceptible to acute injuries (Steinmann et al., 2020).

2.2.3.1 Hamstring Injuries

High-speed running and stretching have been considered the two main mechanisms leading to hamstring injuries (C. Askling et al., 2002; C. M. Askling et al., 2013, 2014; Ekstrand et al., 2011a). During high-speed running, the late swing stage is the moment most susceptible to injury, as the hamstring muscles reach their maximum length and load and pass through a quick transition from eccentric to concentric contraction (C. M. Askling et al., 2014; Danielsson et al., 2020; Kenneally-Dabrowski et al., 2019; Suskens et al., 2023). Conversely, stretching-type injuries typically occur during excessive stretching of the hamstring muscles, characterized by hip flexion and ipsilateral knee extension. Soccer players performing a kick, reach or slide tackle, dancers doing movements causing elongation of hamstrings, or anyone accidentally slipping and falling into a sagittal split position are typical events in stretching-type hamstring injuries (C. Askling et al., 2002; C. M. Askling et al., 2013; Brooks et al., 2006; Sarimo et al., 2008; Wood et al., 2008).

2.2.3.2 Rectus Femoris Injuries

Quadriceps injuries mainly affecting the RF typically happen during kicking and sprinting, during which explosive movements and high eccentric demands occur (Eckard et al., 2017; Mendiguchia et al., 2013; Pietsch & Pizzari, 2022). Kicking performance in soccer starts with the back swing of the leg, during which the hip is extending, the knee is flexing, and the RF is working eccentrically (Cerrah et al., 2024; Nunome et al., 2006). Subsequently, the forward-swing stage starts when the hip is starting to flex to bring the thigh forward, while the knee continues to flex as the RF is still working eccentrically (Nunome et al., 2002). The thigh reaches its maximal angular velocity just before the knee starts to extend (Kellis & Katis, 2007). This moment, in addition to ball contact and ground contact, is suggested to be the most susceptible to RF injury during kicking (Mendiguchia et al., 2013). Next, the RF transitions to concentric action as the knee starts to extend, and the angular velocity of the thigh decreases and the shank angular velocity increases (Cerrah et al., 2024). At ball impact, the thigh angular velocity is close to zero, whereas the shank and the foot reach their maximum angular velocity (Kellis & Katis, 2007).

RF injuries also occur during high-speed running (Geiss Santos et al., 2022). The high demands of powerful eccentric contractions and peak angular velocities of the hip and knee are thought to make the RF vulnerable to injury during sprinting (Mendiguchia et al., 2013). The maximal length of the RF muscle-tendon unit during the running cycle occurs at the start of the swing stage, as the hip flexors begin to generate power and the knee extensors work eccentrically to absorb energy and prevent excessive knee flexion (Riley et al., 2010).

2.2.3.3 Adductor Longus Injuries

Acute adductor longus injuries in sports typically occur during rapid movements like kicking a ball, changing direction, stretch situations, sprinting, and jumping (Serner et al., 2015). The kicking injury mechanism, when the ball typically makes contact with the medial side of the foot, is thought to occur due to maximal stretching at the moment that the muscle reaches its highest eccentric activity during the swing phase of the kicking leg, as the hip transitions from extension to flexion (Charnock et al., 2009). The simultaneous timing of maximal activation, highest rate of stretch, and maximal hip extension may indicate that the adductor longus has a key role in controlling hip extension and initiating flexion (Charnock et al., 2009). This likely also applies to sprinting injury mechanisms, as the adductors are known to have similar roles during the running gait cycle (Moore, 2014).

2.2.3.4 Video Analysis

Video analysis as a valuable tool for analyzing injury mechanisms in soccer was introduced in 2003 by Andersen et al. (2003). The following year, the same research group published papers using video analysis to describe the mechanisms of ankle injuries in soccer (Andersen et al., 2004), ACL injuries in handball (Olsen et al., 2004), and head- (Andersen et al., 2004) and general injury situations in soccer (Arnason et al., 2004). Since then, the number of published articles using video analysis to investigate injury mechanisms in different sports has been slowly and steadily increasing. Special attention has been paid to ACL injury mechanisms (Carlson et al., 2016; Montgomery et al., 2018; Olsen et al., 2004; Della Villa et al., 2020).

To our knowledge, the first article to analyze the mechanisms related to thigh muscle-tendon injuries was published in 2019 and covered acute injuries to the adductor longus in 17 high-level soccer players (Serner et al., 2019). The study found that most injuries occurred in non-contact situations and typically during kicking the ball, change of direction, reaching for the ball, and jumping. Injury actions were further categorized into closed and open chain actions (Serner et al., 2019). In 2022, the first paper describing the patterns of hamstring injury in elite male soccer players was published by Gronwald et al. (2022). The injury mechanisms were divided into sprint-related (48%) and stretch-related injuries (52%), sprinting-type injuries including accelerating or running at high-speed. Stretching-type injuries occurred in closed kinetic chain actions such as decelerating or stopping with a simultaneous movement of lunging or landing, and open kinetic chain actions such as kicking the ball (Gronwald et al., 2022). Additionally, Kerin et al. (2022) analyzed 17 acute hamstring strain injuries in male professional rugby players who suffered the injuries during running, decelerating, kicking, tackling, and rucking.

The interest in especially hamstring injuries has continued to grow, and recently Della Villa et al. (2023) analyzed, from publicly available sources, 103 cases of lower limb muscle injuries (causing >28 days' absence) in male elite soccer. They concluded that most injuries occurred without contact during sprinting, stretching, or kicking (Della Villa et al., 2023). Aiello et al. (2023) retrospectively combined video and Global Positioning System (GPS) data to analyze non-contact injuries (17 hamstring, 3 adductor, 2 quadriceps) in male professional soccer players. They found that hamstring injuries most frequently occurred at a speed of >25 km/h and more than 80% of players' maximum velocity. Additionally, a comparison of hamstring injury mechanisms in men's and women's soccer was performed using video analysis (Della Villa et al., 2024). Women had more indirect contact, running, and kicking injuries, and less non-contact and stretch-related injuries compared to men. Finally, Vermeulen et al. (2024) identified acceleration as the most common single-player action associated with sudden-onset hamstring injuries during match play in professional soccer players.

2.2.3.5 Relation Between Injury Mechanism and Injury Type

Acute hamstring injuries during sprinting most commonly affect the proximal BF (C. M. Askling et al., 2007a, 2013, 2014; Gronwald et al., 2022). The late swing stage of the running gait cycle is the most likely moment of injury during sprinting (Danielsson et al., 2020; Kenneally-Dabrowski et al., 2019). Suskens et al. (2023) found that within the BF, the proximal area was markedly more active during late swing compared to more distal locations. It has been found that the risk of suffering an index hamstring injury is associated with the higher role of the BF (relative to other hamstring muscles) in heavy eccentric effort (Schuermans et al., 2016). Interestingly, elongation of the muscle component starts to slow when the BF is excited in the late swing phase, resulting in the tendon lengthening (Thelen et al., 2005). As the tendon compliance increases, the peak muscle fiber stretch decreases, which is suggested to be linked to the injury potential due to possible changes in the tendon's mechanical properties (Thelen et al., 2005). Maximum musculotendon length occurs simultaneously with maximal activation of the BF muscle in the late swing stage of high-speed running, which indicates a higher risk of injury than in other hamstring muscles (Thelen et al., 2005).

Stretching-type hamstring injuries are characterized by flexion of the hip combined with simultaneous knee extension. Stretch-related injuries typically result in proximal SM injuries due to excessive lengthening of the SM during simultaneous hip flexion and knee extension (C. M. Askling et al., 2007a, 2008, 2013). Also the proximal BF has been found to be injured due to stretch-related (braking or stopping with lunging or landing action) injuries in professional soccer players (Gronwald et al., 2022). Additionally, a maneuver where a player is picking up a ball from the pitch while sprinting at maximal speed has been described as a common injury mechanism in Australian football (Worth, 1969). This mechanism has characteristics from both sprinting-type and stretching-type injuries, as it occurs during high-speed running and involves stretching of the hamstring muscles due to trunk flexion, hip flexion, and knee extension. Higashihara et al. (2015) showed that forward trunk lean during sprinting causes excessive elongation of the BFlh and SM muscles during the stance phase. Predicting injury types due to more complex injury mechanisms, other than linear high-speed running or clear stretching movement, is probably more difficult.

The most severe hamstring injuries, complete proximal avulsions, are typically caused by powerful and uncontrolled excessive hip flexion with the same-side knee extended (Irger et al., 2020; Sarimo et al., 2008; Wood et al., 2008). Slipping or falling into a sagittal split position is a typical cause of these injuries.

Lesser is known about the mechanisms of the RF and adductor longus and their relation to injury types. Geiss Santos et al. (2022) investigated the mechanisms of acute RF injuries and their association with MRI findings among 105 elite soccer players. The analysis of injury mechanism was based on athlete interviews. They found both kicking and sprinting injuries mostly affecting the intramuscular MTJ and/or tendon, whereas specifically kicking injuries typically caused complete tendon ruptures and injuries to the proximal free tendon. In adductor injuries, it is known that the adductor longus is the most commonly injured muscle, but specific investigations on the relation between different injury mechanisms and injury types are lacking (Serner et al., 2015).

2.2.4 Classification

Several muscle-tendon injury classification systems are used, most commonly traditional three-level types with mild grade I (minimal damage, minor swelling, and discomfort with little to no deficit in strength and functioning), moderate grade II (incomplete rupture, clear loss of strength and activity), and severe grade III (total rupture, total lack of strength and function) (O'Donoghue, 1984). The British Athletics Muscle Injury Classification (BAMIC) proposes grades from 0 to 4 based on MR imaging, with grades 1 to 4 having an extra suffix (a, b, or c) representing 'myofascial', 'musculo-tendinous', or 'intratendinous' injuries (Pollock et al., 2014). The Munich consensus statement also differentiates between four types of muscle injury: functional muscle disorders (types 1 and 2) classifying symptoms without clear proof of muscle fiber tear, and structural injuries (type 3: incomplete ruptures and type 4: (sub)total ruptures/tendon avulsions) with subclassifications for all types (Mueller-Wohlfahrt et al., 2013). The ISMuLT guidelines categorize muscle injuries into non-structural and structural and direct and indirect injuries based on type, classification, definition, symptoms, clinical findings, imaging findings, and prognosis (Maffulli et al., 2013). The FC Barcelona-Aspetar-Duke (or MLG-R) muscle injury classification system considers the following factors: mechanism (M), location (L), grade of severity (G), and amount of reinjuries (R) (Valle et al., 2017). Finally, a nomenclature has been proposed that focuses not only on macroscopic damage but also on injury to connective tissue structures (Study Group of the Muscle and Tendon System from the Spanish Society of Sports Traumatology et al., 2020).

Proximal hamstring avulsions are often classified based on the anatomical location of the injury, degree of avulsion, amount of muscle-tendon retraction, and possible sciatic nerve tethering (Wood et al., 2008). However, more specific classification protocols have been suggested for professional athletes with higher demands, to underline the importance of accurate diagnosis and individual treatment protocols, therefore minimizing the time loss from sports and risk of reinjury (Lempainen et al., 2021). In addition, thigh muscle-tendon injuries are categorized into acute and chronic injuries, the divide being most commonly between 3 and 6 weeks, although there is a lack of clear consensus on the classification.

2.2.5 Clinical Presentation

The clinical presentation of patients suffering acute thigh muscle-tendon injuries varies widely depending on the characteristics of the injury. When clinically evaluating these injuries, patient history, injury mechanism, symptoms, and clinical findings should be considered.

The mildest injuries do not necessarily cause any structural damage to the muscle-tendon unit (Maffulli et al., 2013; Mueller-Wohlfahrt et al., 2013; Pollock et al., 2014). These injuries present with local mild pain, soreness, and stiffness of the muscle, usually increasing during exercise. Palpable pain and stiffness may be present at the site of injury and is often relieved by stretching movements (Maffulli et al., 2013). Imaging findings are usually negative or minimal, and muscle functions and strengths are normal (Pollock et al., 2014; Valle et al., 2017).

Partial lesions (type 3 in ISMuLT and Munich classifications, grade 1–3 in BAMIC, grade 2–3 in MLG-R) cause structural damage to the muscle-tendon unit and are detectable on imaging. The severity of partial injury can vary from a very mild tear to almost complete rupture (Maffulli et al., 2013; Mueller-Wohlfahrt et al., 2013; Pollock et al., 2014; Valle et al., 2017). These injuries typically involve a clear injury moment and injury mechanism, causing sharp localized pain at the time of injury and sometimes a clear ‘snap’. Clinically, there is local palpable pain and stretch-induced pain aggravation (Maffulli et al., 2013; Mueller-Wohlfahrt et al., 2013). More severe partial injuries may also present with a palpable defect in the muscle-tendon structure, difficult contraction against resistance, and sometimes a hematoma (Maffulli et al., 2013; Mueller-Wohlfahrt et al., 2013).

Total ruptures (type 4 in the ISMuLT and Munich classifications, grade 4 in BAMIC, grade 3 in MLG-R) are the most severe muscle-tendon injuries. Sudden severe pain from a clear high-energy injury mechanism (often a fall), noticeable tearing or 'snap' followed by localized pain, and functional disability are typically present in these injuries (Maffulli et al., 2013; Mueller-Wohlfahrt et al., 2013). Large defect, retraction and palpable gap in the muscle-tendon unit, hematoma, localized pain during movement, and loss of function are common clinical findings in total thigh muscle-tendon injuries (Maffulli et al., 2013; Mueller-Wohlfahrt et al., 2013).

2.2.6 Imaging

Imaging has a significant role in the diagnostics of thigh muscle-tendon injuries, as it determines the nature, extent, and severity of injury and therefore guides the treatment protocol (Schneider-Kolsky et al., 2006).

MRI is considered the gold standard and most reliable method for diagnosing muscle-tendon injuries due to its high soft-tissue contrast (Kumaravel et al., 2018). MRI is excellent for estimating crucial aspects such as retraction of the injured tendon, degree of rupture, differentiation between acuity and chronicity of injury, and accurate identification of involved muscles, tendons, and other soft tissue structures (Koulouris & Connell, 2005). However, sometimes an acute hematoma can cause interference, requiring further imaging after 1 to 2 weeks (Lempainen et al., 2018b). MRI examples of different thigh muscle-tendon injuries are shown in Figure 5.

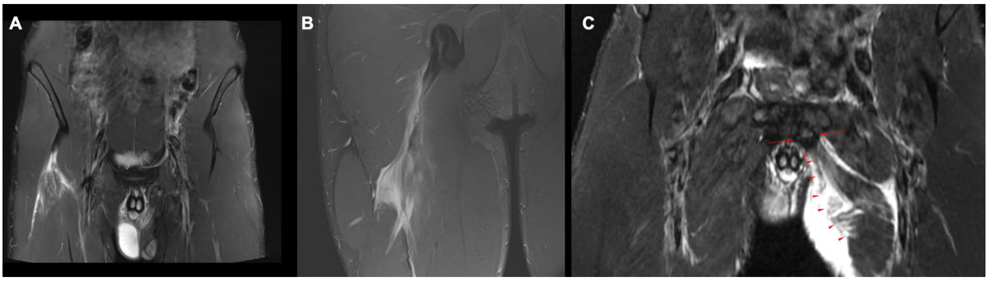

Figure 5. Examples of MRI findings in thigh muscle-tendon injuries. **A**) Complete rupture of the right RF direct tendon, **B**) total tear of the proximal BF free tendon, and **C**) complete rupture of the left proximal adductor longus tendon. MR images by Lasse Lempainen (**A**–**B**) and Arnaldo Abrantes (**C**). Modified from Original Publications I, II, and III.

Ultrasound (US) is a noteworthy alternative to MRI that offers a non-invasive and easily accessible option at lower cost. It is a valuable tool for diagnosing muscle injuries, especially on more superficial structures (Bordalo et al., 2023; Pedret, 2022). However, it is very user-dependent. MRI should be preferred particularly when planning surgical treatment or needing a precise diagnosis, for example in professional athletes (Bordalo et al., 2023; Koulouris & Connell, 2005).

2.2.7 Conservative Treatment

The choice between conservative and operative treatment in thigh muscle-tendon injuries is a multifaceted decision that should be based on accurate diagnosis, prognosis, symptoms, level of sports, and many other individual factors. There is a lack of randomized controlled trials (RCTs) comparing non-operative and operative management in certain thigh muscle-tendon injuries among high-level athletes.

The clinical principles of conservative treatment are similar in all thigh muscle-tendon injuries. The RICE (rest, ice, compression, and elevation) and PEACE & LOVE principles are good general guidelines to follow during acute, subacute, and chronic stages after an injury (Dubois & Esculier, 2020; Järvinen et al., 2014). The PEACE & LOVE acronyms denote protection, elevation, avoid anti-inflammatories, compression, education, load, optimism, vascularization, and exercise (Dubois & Esculier, 2020). In the acute phase during the first few days, pain-provoking activity should be avoided, and compression and elevation are recommended. After the acute phase, gradual mobilization and loading is advised and progressively intensified, pain guiding the return to normal activities. Progressive agility and trunk stabilization exercises and eccentric training are important factors during rehabilitation (Järvinen et al., 2014). Furthermore, Bayer et al. (2017) demonstrated that a 1-week delay in initiating rehabilitation after an acute muscle injury resulted in a 3-week delay in RTP.

Most hamstring injuries in soccer are mild and can be treated non-operatively, typically achieving RTP after 4 to 7 weeks depending on the injury mechanism and rehabilitation protocol (C. M. Askling et al., 2013; Lempainen, Banke, et al., 2015; Yetter et al., 2024). The basic cornerstones of non-operative treatment are rest, exercise modification, and targeted individualized physical therapy (Yetter et al., 2024). Hamstring-specific rehabilitation has been found to lead to better outcomes, faster RTP, and lower recurrence rates than general rehabilitation without specific focus on hamstring exercises (C. M. Askling et al., 2013; Mendiguchia et al., 2017). Eccentric training is fundamental to most rehabilitation protocols, and progressive agility and trunk stabilization are beneficial (Pas et al., 2015; Poursalehian et al., 2023; Tyler et al., 2017). Stretching exercises, sometimes combined with cryotherapy, have shown benefits in conservative treatment of hamstring injuries (Poursalehian et al., 2023).

Quadriceps muscle injuries are advised to be treated along the general guidelines for muscle-tendon injuries, with close follow-up and gradual rise of demand. Exercises including stretch and strength training, range of motion, aerobic conditioning, proprioception, and functional training are fundamental throughout the rehabilitation process (Kary, 2010). It is also important to avoid pain-provoking activities, such as kicking, to decrease the risk of recurrent injury (Kary, 2010; Lempainen et al., 2022).

Rehabilitation protocols for acute adductor longus injuries involve active exercises, with tailored progressive training including running, changes of direction, and sport-specific training (Serner et al., 2020). Close follow-up controls and gradual progression are strictly advisable, starting with passive mobilization of the hip with limited hip abduction/adduction, continuing to a light active program of cycling, unidirectional aqua jogging, and body weight exercises, followed by active exercises at increasing intensity (light running, endurance training, careful stretching), progressing to the active phase involving a gradual and careful start of strengthening exercises, coordination training, running, and sport-specific training (Ueblacker et al., 2016). The last phase includes sprints and multidirectional running, training with a ball, and return to team training (Ueblacker et al., 2016).

2.2.7.1 Injections

The use of injections such as platelet-rich plasma (PRP) has been widely investigated as a treatment for muscle-tendon injuries, with studies yielding mixed results regarding its efficacy in enhancing recovery and reducing reinjury rates. Two randomized controlled trials have found that a single PRP injection combined with rehabilitation significantly shortened RTP time and reduced pain severity in athletes with acute muscle injuries (Hamid et al., 2014; Rossi et al., 2017). However, long-term reinjury rates were not significantly different. In contrast, Reurink et al. (2014), in a double-blinded, placebo-controlled trial, found no significant difference in RTP time or recurrence rates between PRP and placebo. Furthermore, two systematic reviews have found PRP results to be inconsistent across studies (Poursalehian et al., 2023; Rudisill et al., 2021). In addition, Seow et al. (2021) performed a systematic review and meta-analysis of 10 studies (207 PRP-treated vs. 149 controls), suggesting a non-significant trend toward faster RTP and lower reinjury rates with PRP, though further high-quality research with large cohorts is needed to confirm or disprove efficacy. In general, corticosteroid injections are not recommended for muscle-tendon injury management, as they slow the healing process and reduce the biomechanical strength of the injured muscle (Kary, 2010). The cornerstone of rehabilitation is still individualized and progressive physical therapy, but methods including biologics and other injections are under study.

2.2.7.2 Return to Play

There is no clear consensus on the criteria for RTP after different thigh muscle-tendon injuries. However, a three-step RTP framework has been proposed, assessing individual medical factors, sport risk modifiers, and decision modifiers (Shrier, 2015). Additionally, comparable flexibility of both legs, painless use of injured muscles, subjective feeling of full recovery, achievement of a sport-specific test, and isokinetic testing have been described as relevant factors when determining the readiness for RTP after hamstring injuries (Lempainen, Banke, et al., 2015; Valle et al., 2015). Isokinetic testing results should be comparable (not less than 80%) to the contralateral leg, especially knee flexion strength (Looney et al., 2023). However, it is important to note that the BFsh can compensate for BFlh atrophy, potentially resulting in normal-appearing knee flexion strength (Silder et al., 2008). Additionally, maximal eccentric contraction in knee flexion and hip extension without apprehension or pain is suggested to be included in the RTP criteria after hamstring injuries (Valle et al., 2015). The type of injury should be considered when planning RTP, as grade 3^r injuries (MLG-R classification) and injuries to the free tendon of the BF have been found to lead to longer RTP times (Valle et al., 2022). Additionally, early hamstring flexibility asymmetry following an acute hamstring injury is associated with longer RTP times (Gendron et al., 2024). Moreover, clinical findings immediately after RTP that predict hamstring reinjury include the number of previous hamstring injuries, active knee extension deficit, isometric knee flexion deficit, and localized discomfort on palpation (De Vos et al., 2014).

After quadriceps injuries, full range of motion of the knee, pain resolution, normal strength values in isokinetic muscle strength testing compared to the contralateral leg, and successful sport-specific and functional field tests are required when assessing the time of RTP (Kary, 2010). Furthermore, the natural biological healing time should not be overlooked (Lempainen et al., 2022).

For adductor longus injuries, the following three-stage RTP criteria have been used: clinically pain free (7 different tasks including palpation, adduction exercises, passive stretching, full-speed sprinting, and T test at 100%), being able to complete in monitored sports training, and first full training with the team (Serner et al., 2020; Serner, Hölmich, Tol, et al., 2021).

In general, a limited number of training sessions between RTP and the first match is associated with an increased risk for injury (Bengtsson et al., 2020). Therefore, completing at least seven training sessions is recommended to reduce the risk of muscle injury during a match to the average season level.

2.2.8 Surgical Treatment

2.2.8.1 Hamstring Injuries

Many studies have concluded that complete proximal 3-tendon hamstring avulsions should be operated in the acute phase also in symptomatic non-athletes without contraindications (Blakeney et al., 2017a; Bodendorfer et al., 2018; Lempainen, Banke, et al., 2015; Rudisill et al., 2021; Yetter et al., 2024). However, only one

RCT comparing operative and non-operative treatment for proximal hamstring avulsions has been published (Pihl et al., 2024). Patient-reported outcomes were compared between 58 operatively treated and 61 non-operatively treated proximal hamstring avulsions in non-athletes (aged between 50 and 60 years) from 10 different centers, concluding that non-operative treatment was non-inferior to operative treatment (Pihl et al., 2024). In general, age, level of activity, and obesity are the most frequently used factors affecting treatment choice (Laszlo et al., 2022). In athletes, high-level randomized and comparative studies on the best treatment method are lacking. In addition to complete proximal 3-tendon ruptures, two-tendon avulsions (Figure 6) are also advised to be operated in professional athletes, and in recreational athletes if they are symptomatic or have clear tendon retraction (>2cm) (Lempainen, Banke, et al., 2015; Yetter et al., 2024). Complete 1-tendon ruptures in proximal or distal attachment usually heal well with conservative treatment; however, injuries in professional athletes may require surgical treatment also in these cases (Lempainen et al., 2007; Lempainen, Banke, et al., 2015; Rudisill et al., 2021; Yetter et al., 2024). Due to the high risk of recurrence and long rehabilitation periods, injuries to the distal musculotendinous T-junction of the BF often benefit from operative repair in professional athletes (Kayani et al., 2020). Tendinous injuries may be difficult to treat, and complete central tendon ruptures with retraction or recurrent central tendon injuries may require surgical treatment in professional athletes (Lempainen et al., 2018b). Failure of conservative treatment (3-6 months) is often an indication for surgical treatment (Barnett et al., 2015; Lempainen, Banke, et al., 2015; Yetter et al., 2024). However, high-level studies investigating the best treatment options for professional athletes are scarce.

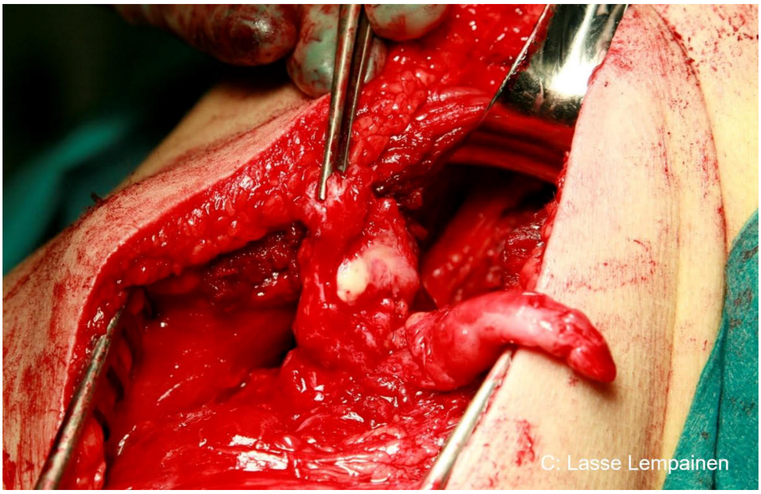

Figure 6. Intraoperative photograph of complete rupture of the BF and ST tendons. Photograph by Lasse Lempainen.

2.2.8.2 Rectus Femoris Injuries

There is limited evidence on the outcomes of different treatment methods after RF injuries (Lempainen et al., 2022; Plastow, Raj, et al., 2023). Surgical treatment is typically needed in professional athletes suffering proximal tendon avulsions with significant retraction (Begum et al., 2020; Kayani et al., 2021; Lempainen et al., 2022; Lempainen et al., 2018a). Additionally, recurrent injuries, chronic cases, central tendon re-ruptures, and complete mid-substance tears may require surgical treatment (Lempainen et al., 2019; Lempainen et al., 2021; Sonnery-Cottet et al., 2017). A photograph taken during surgery for a proximal RF tendon rupture is shown in Figure 7.

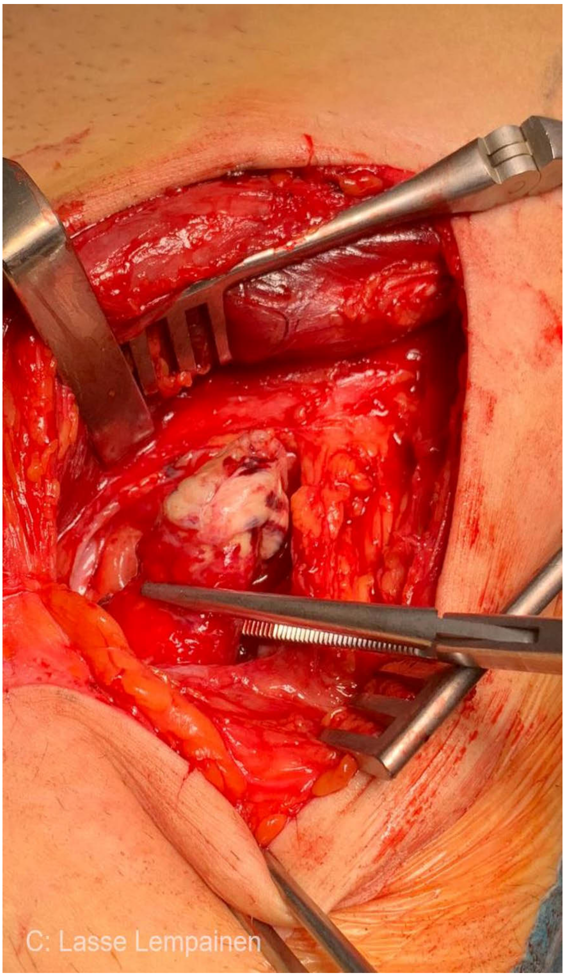

Figure 7. Intraoperative photograph of proximal RF tendon rupture. Photograph by Lasse Lempainen.

2.2.8.3 Adductor Longus Injuries

Complete adductor longus ruptures can be treated either conservatively or surgically (Farrell et al., 2023). Studies investigating operative treatment tend to include injuries with greater tendon retraction than those researching conservative treatment (Farrell et al., 2023). However, there are contradictory results concerning the size of tendon retraction as a prognostic factor in complete adductor longus tears (Pezzotta et al., 2018; Serner et al., 2021). As RCTs comparing surgical and non-operative treatment of adductor longus avulsions in professional athletes are lacking, factors such as tendon retraction, symptoms, loss of function, level of demand, and chronicity should be considered when evaluating the need for surgical treatment (Farrell et al., 2023; Lempainen, Hetsroni, et al., 2021).

2.2.9 Prevention

A cornerstone of thigh muscle-tendon injury prevention is to target known risk factors and injury mechanisms, with focus on specifically designed prevention programs (Ishøi et al., 2020). Injury prevention frameworks are recommended to focus on social, behavioral, and lifestyle factors, exercise programs, load management, recovery, and equipment (Hassanmirzaei et al., 2024). Key priorities include effective communication, the Nordic hamstring exercise (eccentric training), training load management, recovery strategies, proper nutrition, adequate sleep, warm-up routines, the Copenhagen adduction exercise (eccentric training), and core and dynamic stability.

2.2.9.1 Hamstring Injuries

A multifactorial approach has been proposed for hamstring injury prevention, emphasizing hamstring strengthening, load management, injury management, general conditioning, overall well-being, and club-related factors (Buckthorpe et al., 2019). A recent systematic review and meta-analysis of RCTs investigated the effects of prevention exercises on lowering the hamstring injury incidence (Rudisill et al., 2021). Eccentric training has been found to reduce the risk of hamstring injury and improve the strength of hamstrings, length of the fascicles, H/Q ratio, and symmetry between limbs. Additionally, exposure to high-speed running has been shown to increase the fascicle length of the BFlh (Mendiguchia et al., 2020). Exercises based on stretching training have been found to improve flexibility (Rudisill et al., 2021). Additionally, the Nordic hamstring exercise, the FIFA 11+ program (including different running, strength, plyometrics, and balance exercises), as well as core stability and balance training exercises, are effective in preventing hamstring injuries (Biz et al., 2021; Dyk et al., 2019). Injury prevention programs are advised to target warm-up, post-exercise cool down, mobility and strength training, coordination, reaction time, and endurance. Exercises that simulate realistic playing situations (drills, interval training, and agility exercises) are also impactful (Mendiguchia et al., 2017; Verrall et al., 2005).

2.2.9.2 Rectus Femoris Injuries

Hip-flexor strength training with elastic bands has been found to improve hip-flexor muscle strength, which is a simple way to potentially prevent acute RF injuries (Thorborg et al., 2016). In addition, knee extension eccentric training is advised to be included in the training programs, especially in kicking sports like soccer (LaStayo et al., 2003). Furthermore, optimal functional mobility of the hip is suggested to decrease the risk of quadriceps injury (Fousekis et al., 2011). The reverse Nordic hamstring exercise has been shown to significantly increase the RF fascicle length, muscle thickness, pennation angle, and cross-sectional area, which may have important implications for injury prevention and rehabilitation programs (Alonso-Fernandez et al., 2019). However, high-level evidence is also lacking in this field.

2.2.9.3 Adductor Injuries

According to a recent systematic review, adductor strengthening programs have had controversial results in the prevention of acute adductor ruptures (Farrell et al., 2023). Adductor strengthening seems to be beneficial especially for athletes at increased risk of acute adductor injury (history of acute groin injury, adductor weakness, any injury in the previous season, and decreased rotational hip range of motion) (Farrell et al., 2023). For example, the Copenhagen adduction exercise as an adductor strengthening program has shown good results in the prevention of groin injuries in male soccer players (Harøy et al., 2019). Additionally, the FIFA 11+ program is effective in preventing acute adductor injury (Thorborg et al., 2017).

2.3 Proximal Hamstring Tendinopathy

Proximal hamstring tendinopathy (PHT) is a remarkable clinical problem expressing itself as lower gluteal pain. Similarly to the better known Achilles tendinopathy (Alfredson, 2003), it is typically a chronic overuse or degenerative injury found in patients of different ages and levels of activity, but most commonly in the athletic population (Lempainen, Johansson, et al., 2015; Puranen & Orava, 1988). Pain is often clearly associated with prolonged sitting, running, and lunging. Moreover, the close proximity of the sciatic nerve can cause neurological symptoms in chronic hamstring conditions such as PHT (Lempainen, Johansson, et al., 2015).

2.3.1 Clinical Provocation Tests

Three provocation tests are described in the literature for clinical suspicion of PHT: Puranen-Orava, bent-knee stretch, and modified bent-knee stretch test. The Puranen-Orava test includes active stretch of the hamstrings while standing with the hip at about 90° flexion, the knee in full extension, and the foot on an examination table or other support (Puranen & Orava, 1988). In the bent-knee stretch test, the patient is lying supine with the symptomatic side hip and knee in maximal flexion, the examiner slowly moving the knee to extension (Madden et al., 2005). In the modified bent-knee test, the patient is supine with the hip neutral and knee extended. The examiner moves the symptomatic leg from the foot with one hand and from the knee with the other, starts to flex the hip and knee, then quickly extends the knee (Cacchio et al., 2011). The reliability and validity of these three tests have been studied and all were found to be potentially valuable for evaluating PHT in athletes; however, it is recommended that they be used in conjunction with other diagnostic tools such as MRI (Cacchio et al., 2012).

2.3.2 Imaging

As with acute injuries, MRI and US are the most frequently used imaging methods for diagnosing PHT, MRI being the gold standard due to its better soft tissue contrast. The typical MRI findings of PHT are increased signal intensity on T1- and T2-weighted images, tendon thickening, edema around the tendons, bone marrow edema-like changes in the ischial tuberosity, and tendon rupture in more severe cases (Lempainen, Johansson, et al., 2015). It has been found that abnormal tendon findings after the age of 45 are typical in both symptomatic and asymptomatic patients, reflecting the degenerative tendinopathy seen in older patients (Bowden et al., 2018). In contrast, PHT findings in young patients are typically symptomatic, due to their different etiology of chronic overuse-related micro-tearing of healthy tendons (Bowden et al., 2018). The size of the tendon, T2 signal around the tendon with a distal feathery pattern of edema, and edema at the ischial tuberosity have been found to be significantly correlated with PHT symptoms (De Smet et al., 2012). On the other hand, an increased T1 and T2 signal seems not to be associated with symptoms of PHT (De Smet et al., 2012).

2.3.3 Conservative Treatment

High-level evidence on the best treatment method for PHT is scarce (Nasser et al., 2021). However, conservative treatment is generally considered the first-line option, with surgical treatment relegated to more severe and recalcitrant cases (Lempainen, Johansson, et al., 2015). Different conservative interventions for PHT were compared in a recent systematic review by Dizon et al. (2023). They concluded that non-operative treatment of PHT should be tailored individually and have multiple aspects, including eccentric tendon-specific loading at high muscle-tendon lengths, exercises targeted to stabilize the lumbopelvic area, and extracorporeal shockwave therapy. Hamstring-specific exercises are also advised to include gradual loading with joint angles aiming at 100° hip flexion and knee flexion from 45° to 90° (Dizon et al., 2023). High-power laser therapy has been suggested to improve pain in athletes with PHT, but as no control group was used, the role of the therapy remains unclear (Verma et al., 2022). Contradictory results have also been found on the effect of PRP on the treatment of PHT, and as the published studies lack either control groups or a prospective study design, wider generalizations cannot be made (Auriemma et al., 2020; Davenport et al., 2015; Levy et al., 2019). As regards future research, two RCT protocols have been introduced to investigate the effect of different interventions for PHT: isometric compared with isotonic exercise (A. Rich et al., 2021) and individualized physiotherapy compared with extracorporeal shockwave therapy (Rich et al., 2023).

2.3.4 Surgical Treatment

If conservative treatment of PHT fails and impairing chronic pain remains for >3–6 months, surgical options should be considered (Lempainen, Banke, et al., 2015; Lempainen, Johansson, et al., 2015). Surgical treatment of PHT has been reported to lead to good outcomes; however, high-level RCTs on this topic are lacking (Benazzo et al., 2013; Fitzpatrick et al., 2022; Lempainen et al., 2009; Puranen & Orava, 1988; Young et al., 2008).

2.3.5 Prevention

There is a very limited amount of evidence on prevention strategies for tendinopathy, and PHT is no exception (Beatty et al., 2017; Peters et al., 2016). As described earlier, lower-limb injury prevention programs have shown good results in injury prevention, but whether these apply to PHT is unknown. However, eccentric training has been found to lower the risk of hamstring injuries and can be recommended also for prevention of PHT (Dyk et al., 2019).

3 Aims

The primary purpose of this thesis was to examine the mechanisms of thigh muscle-tendon injuries in male professional soccer players, a novel diagnostic approach in PHT, and the results of surgical treatment for hamstring injuries. The specific aims of the studies were as follows:

Study I: To systematically analyze video material to assess the mechanisms, situational patterns, and biomechanics and their relations to MRI findings after high-grade hamstring injuries in male professional soccer players.

Study II: To evaluate the mechanisms, situational patterns, and biomechanics and their relations to MRI findings associated with RF injuries in male elite soccer players, using a systematic video analysis.

Study III: To systematically analyze video footage to describe the mechanisms, situational patterns, and biomechanics of severe acute adductor longus injuries in male professional soccer players.

Study IV: To analyze the MRI findings of PHT in a novel HF scanning position and compare them with findings in the standard hip-in-neutral position.

Study V: To assess the outcomes (clinical and patient-reported) after surgical treatment of hamstring tendon ruptures using a systematic review.

4 Materials and Methods

4.1 Study Design and Patients

The subjects of this study were professional soccer players (I–III) and recreational athletes (IV). Study V included patients from all levels of sports, including professional, competitive, and recreational athletes. Studies I–III are descriptive case series studies assessing the mechanisms of hamstring (I), RF (II), and adductor longus (III) injuries using systematic video analysis. Study IV is a cohort study (diagnosis) presenting a novel MRI scanning position and analyzing its accuracy in PHT diagnosis, compared with the standard position. Study V is a systematic review of the results of operative treatment of hamstring tendon ruptures. Study approval was obtained from the local ethics committee of the Hospital District of Southwest Finland (Studies I and IV), or ethical approval was not needed (Studies II, III, and V). The patient demographics are summarized in Table 2.

Table 2. Summary of the number, mean age, and sports level of patients, and timing of injuries. NA, not available.

STUDY	NUMBER OF CASES (MALE / FEMALE)	MEAN AGE (YEARS)	TIMING OF INJURIES (YEARS)	PATIENTS' SPORTS LEVEL
I	14 (14 / 0)	24	2017–2022	Professional
II	20 (20 / 0)	24	2017–2022	Professional
III	20 (20 / 0)	27	2017–2023	Professional
IV	38 (10 / 28)	38	2019–2022	Recreational
V	1602 (NA)	45	NA	Professional (n=74) Competitive level (n=166) Recreational (n=449)

4.1.1 Hamstring, Rectus Femoris, and Adductor Longus Injuries (I–III)

Studies I, II, and III included professional male soccer players aged 18 to 40 years who suffered an acute hamstring (I), RF (II), or adductor longus (III) injury with

MRI confirmation obtained within 1 week after injury. Video material of the moment of injury had to be available. Non-musculotendinous pain, poor video quality, and refusal to permit the use of video were exclusion criteria in all studies. Injuries occurred between September 2017 and December 2023 in various elite clubs from different countries, and all injuries led to a consultation with a single orthopedic surgeon specialized in lower-limb muscle-tendon injuries. All injuries were high-grade injuries, and to be included in Study III, adductor longus injuries had to be classified as severe (complete tendon ruptures or partial lesions), leading to a recovery period of over 28 days.

4.1.2 Proximal Hamstring Tendinopathy

The participants were prospectively recruited among the patients of a single orthopedic surgeon between February 2019 and January 2022. To be included, patients had to have had chronic PHT symptoms in the subgluteal area lasting more than 3 months. All the patients (10 males and 28 females, mean age: 37.5 years) were physically active recreational athletes who participated voluntarily after being informed about the study setup. Patients were excluded if they could not get into the HF imaging position, had a history of hamstring injuries, or had contraindications to MRI. Additionally, MRI must have been performed prior to any therapeutic injections.

4.1.3 Hamstring Tendon Ruptures

This systematic review included patients aged 18 years or more with an operatively treated hamstring tendon (BF, ST, and/or SM) tear or avulsion with diagnosis confirmed intraoperatively and/or with US or MRI. Due to the lack of high-level comparative research on different treatment methods, this study aimed to review the current evidence on the impact of surgical intervention on patient outcomes in the treatment of hamstring tendon injuries. The following groups were compared: acute repair vs. chronic repair, partial/incomplete repair vs. complete repair, and acute complete repair vs. chronic complete repair. The patients had to be in follow-up using one or more clinical or patient-reported outcome measures.

4.2 Methods

4.2.1 Video Analysis (I–III)

The injuries occurred in top-level male professional soccer players aged 18 to 40 years from various elite clubs across multiple countries between September 2017 and December 2023. The included injuries were broadcast on public sources or recorded by a team crew. Videos were processed with editing software (Wondershare Filmora9 V.9.5.3, Final Cut Pro V.10.5.2, or iMovie V.10.1.2) and converted to QuickTime (.mov) to allow frame-by-frame analysis. Following the protocol described by Serner et al. (2019), injury situations were processed to include the entire performance before, during, and after injury, as well as slow-motion clips from multiple camera angles to enable detailed review.

Injury movement and specific moment of injury were identified through interviews with the athletes (within 48 hours of injury in most cases), along with analysis of the mechanism of injury, body position, and player reactions.

Based on a comprehensive model for injury causation (Bahr & Krosshaug, 2005) and standardized scoring forms (Andersen et al., 2004; Klein et al., 2020; Serner et al., 2019; Della Villa et al., 2020), specific questionnaires were developed and used to analyze the injury mechanisms and patterns. Two authors independently analyzed each video in real time, slow motion, and frame-by-frame, focusing on playing situations, players' behavior, movements, and biomechanical factors. Discrepancies were resolved in consensus meetings.

4.2.2 Imaging (I–IV)

MRI was routinely used to assess the diagnosis and evaluate more accurately the location, extent, and severity of the injury. In Study IV, which focused on imaging, the MRI protocol involved two parts: (1) a standard pelvic exam with the patient positioned in the supine position with neutral hip and (2) an MRI with the symptomatic (or both) hip(s) in flexion, aiming for a HF angle of 90° (Figure 8).

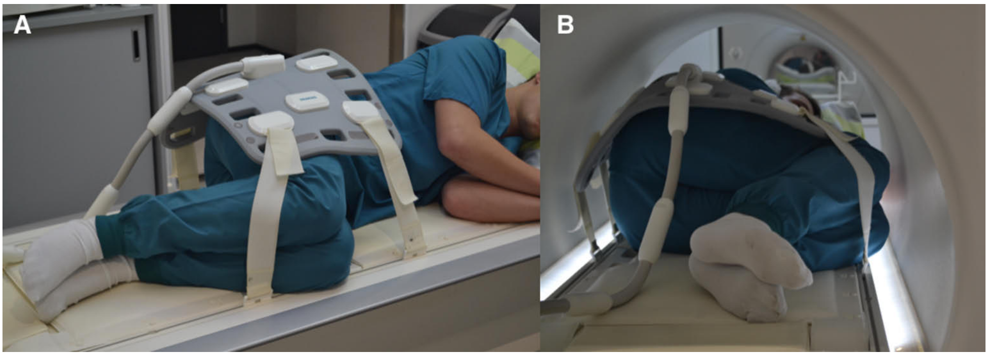

Figure 8. Novel HF scanning position **A**) before and **B**) during the scan. Picture from Original Publication IV.

All patients underwent MRI with a 3.0-T system at the radiology unit of a private sports hospital. A combination of a 32-channel spine coil and an 18-channel flexible surface coil was used for signal reception. The standard part of the MRI protocol included the following turbo spin echo sequences: T2-weighted Dixon sequence in the coronal and sagittal planes, T1-weighted sequence in the coronal and axial planes, and T2- and intermediate-weighted sequences with fat suppression in the axial plane. The HF part included T2-weighted Dixon sequence in the coronal, axial, and sagittal planes.

Two experienced musculoskeletal radiologists independently evaluated the MRIs for signs of PHT. They assessed the tendon insertion areas of the SM and the common tendon of the BF and the ST. Tendons were classified as normal, tendinosis, or ruptured. Additionally, the severity of tendinosis was visually categorized based on tendon thickening and inhomogeneity. Ruptures were classified as small (<50% of the cross-sectional area), wide (>50% of the cross-sectional area), or complete (loss of continuity). Discrepancies were resolved in a consensus meeting. The findings from the HF and standard positions were compared for each patient to determine differences in diagnosis and to assess the diagnostic value of the novel HF position.

4.2.3 Systematic Review (V)

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).

A comprehensive literature search was conducted in PubMed, CINAHL, Cochrane Library, EMBASE, and Web of Science up to July 2021. Keywords related to hamstring injuries were used, and Boolean operators “OR” and “AND” were applied to combine synonyms and categories. Reference lists of included articles and previously published review articles were also examined for additional studies. Three reviewers independently screened the database results, resolving discrepancies by consensus. Two additional authors confirmed the final study inclusion (Figure 9).

Three reviewers independently assessed each study and extracted relevant data, including number of patients, mean age, treatment method, follow-up time, return to sports (RTS), outcome measures (clinical and patient-reported), and complications. The data were organized into categories comparing acute vs. chronic repair, partial vs. complete repair, and acute complete vs. chronic complete repair.

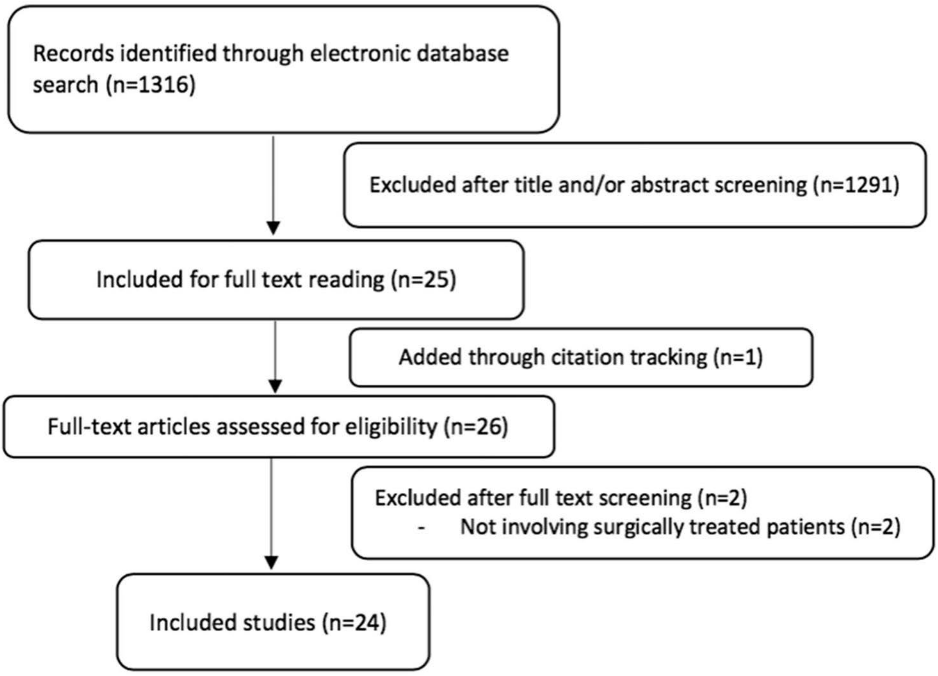

Figure 9. Selection process for included studies, picture from Original Publication V.

Outcomes were categorized and analyzed based on surgical treatment results. Categories included patient-reported outcomes, adverse events, and clinical outcomes.

4.2.4 Surgical Technique (V)

In Study V, 96% of the patients were operated with open surgery and 4% with an endoscopic procedure. Most patients were treated with primary repair, whereas 24 chronic complete avulsions were treated with graft augmentation.

4.2.5 Statistical Methods (V)

Point estimates were calculated by pooling estimated means and corresponding standard deviations from the included studies. Weighted means and standard deviations were derived across these studies. For continuous variables, p-values were obtained using Mann-Whitney U tests, while categorical variables were analyzed using chi-square tests. Comparisons of complications were performed using a test of difference in proportions. Analysis of variance (ANOVA) was employed to evaluate outcome differences between acute and chronic repair groups, with statistical significance set at a p-value of 0.05.

5 Results

5.1 Injury Mechanisms and MRI findings (I–III)

In Studies I–III, the mechanisms of different thigh muscle-tendon (hamstring, RF, and adductor longus) injuries were analyzed using systematic visual video analysis. MRI findings and their relation to injury mechanism were specifically assessed in Studies I and II, whereas Study III included only MRI-confirmed complete or partial ruptures of the proximal adductor longus tendon.

5.1.1 Hamstring Injuries (I)

Fourteen videos of acute high-grade hamstring injuries in 13 professional male soccer players were included. One player sustained injuries in both legs over a 4-year period, resulting in 14 total cases. The median age of the participants was 23 years (range 20–37). Player positions included one goalkeeper, four defenders, three midfielders, and five forwards.

The video analysis identified three distinct hamstring injury mechanisms: mixed-type injuries (both sprint- and stretch-related) in 43% of cases, stretch-type injuries in 36%, and sprint-type injuries in 21% (Figure 10). The injuries occurred most frequently during kicking (29%), change of direction (29%), and running (21%). High or very high horizontal speed was found in 71% of the cases. The trunk was flexed in 57% of cases, and the hip flexion angle was 45–90° in 57% and knee flexion angle <45° in 93% of the injuries. Open and closed chain injuries divided into half, and 50% were non-contact injuries, whereas 43% of cases involved indirect contact before the injury. The characteristics of each injury are presented in Table 3.

MRI findings showed that 71% of the injuries involved the BF, with five cases (36%) being isolated proximal BF injuries, two cases (14%) distal BF injuries, and three cases (21%) proximal avulsions involving the proximal BF and ST tendons. Three cases (21%) were isolated SM injuries, distributed across proximal, distal, and mid-thigh locations. One injury was located at the distal MTJ of the ST.

All the sprint-type injuries affected the proximal BF, whereas most of the stretch-type injuries were either isolated SM injuries or proximal avulsions involving the BF and ST. More variation was seen in injury locations after mixed-type hamstring injuries.

Figure 10. Examples of hamstring injury mechanisms frame by frame, 0 being the defined injury frame. **A**) stretch-type, **B**) sprint-type, **C**) mixed-type, and **D**) stretch-type.

Table 3. Characteristics of each case in Study I. CoD, change of direction; dist, distal; mid, mid-thigh; prox, proximal. Modified from Original Publication I.

Case	Injury location	Action	Injury mechanism	Trunk	Hip	Knee	Open/closed chain
1	Prox BF	Running	Mixed	Flexion 45–90°	Flexion 45–90°	Flexion 45-90°	Closed
2	Prox BF	Running	Sprint	Neutral	Flexion 45–90°	Flexion <45°	Open
3	Prox BF	Running	Sprint	Flexion <45°	Flexion 45–90°	Flexion <45°	Open
4	Prox BF	CoD	Sprint	Neutral	Flexion 45–90°	Flexion <45°	Open
5	Mid SM	CoD	Mixed	Neutral	Flexion 45–90°	Flexion <45°	Open
6	Dist BF	CoD	Mixed	Flexion <45°	Flexion <45°	Flexion <45°	Closed
7	Prox BF + ST	CoD	Mixed	Flexion >90°	Flexion <45°	Flexion <45°	Closed
8	Dist SM	Kicking	Stretch	Flexion <45°	Flexion 45–90°	Flexion <45°	Closed
9	Prox BF	Kicking	Mixed	Neutral	Flexion <45°	Flexion <45°	Open
10	Dist ST	Kicking	Mixed	Neutral	Flexion <45°	Flexion <45°	Closed
11	Dist BF	Kicking	Stretch	Neutral	Flexion >90°	Flexion <45°	Open
12	Prox BF + ST	Jumping	Stretch	Flexion <45°	Flexion >90°	Flexion <45°	Open
13	Prox SM	Reaching	Stretch	Flexion 45-90°	Flexion 45–90°	Flexion <45°	Closed
14	Prox BF + ST	Shielding	Stretch	Flexion >90°	Flexion 45–90°	Flexion <45°	Closed

5.1.2 Rectus Femoris Injuries (II)

A total of 20 videos showing acute RF injuries in 19 professional male soccer players were included. One player suffered a recurrent injury after 8 weeks from the first injury, resulting in 20 cases. The athletes had a median age of 24.5 years (range 18–38 years) and the group included four goalkeepers and 15 outfield players.

Three mechanisms of injury were identified: kicking (80%), sprinting (10%), and change of direction (10%). In kicking injuries, 56% involved ball impact with the instep (full kick), while 38% involved side-foot impact (pass kick). Kicking injuries typically involved a rapid transition of movement from hip extension to flexion and knee flexion to extension. However, two kicking injuries affected the supporting leg, involving a change of movement in the hip and knee opposite to the injuries affecting the kicking leg. Sprinting injuries occurred during maximal high-speed sprinting, whereas change-of-direction injuries took place when handling the ball. Most (90%) of the injuries occurred during non-contact situations.

MRI investigations revealed 12 isolated single-tendon injuries (four direct tendon, three common tendon, two central septum, and three distal MTJ) and eight combined tendon injuries. Twelve cases were classified as complete ruptures and eight as partial. Complete tendon ruptures were found in 63% of the kicking injuries, while both running injuries and none of the change of direction injuries were total tears. Of the isolated tendon injuries, the direct tendon was affected in 33%, whereas all combined tendon injuries involved the common tendon. The characteristics of each case are shown in Table 4.

Table 4. Characteristics of each case in Study II. CoD, change of direction; CS, central septum; CT, common tendon; DT, direct tendon, DDP, distal direct portion; IT, indirect tendon; SL, supporting leg injured. Modified from Original Publication II.

CASE	ACTION	IF KICKING: TYPE / BALL IMPACT	INJURY LOCATION (COMPLETE RUPTURES BOLDED)
1	Kicking	Cross / side foot	IT + **CT**
2	Kicking	Shot on goal / side foot	**DT**
3	Kicking	Shot on goal / side foot	Distal MTJ
4	Kicking	Shot on goal / instep	IT + CT + **DDP**
5	Kicking	Clearing / instep	**CT** + **DDP** + **CS**
6	Kicking (SL)	Shot on goal / instep	CS
7	Kicking	Goal kick / instep	**DT**
8	Kicking (SL)	Shot on goal / instep	**Distal MTJ**
9	Kicking	Cross / instep	CT
10	Kicking	Goal kick / instep	**CT**
11	Kicking	Long pass / side foot	DT + IT + CT
12	Kicking	Clearing / instep	DT
13	Kicking	Goal kick / instep	**DT**
14	Kicking	Clearing / toe kick	**Distal MTJ**
15	Kicking	Long pass / side foot	**IT + CT**
16	Kicking	Shot on goal / side foot	IT + CT + DDP
17	Running	-	IT + **CT**
18	Running	-	**CT**
19	CoD	-	CS
20	CoD	-	CT + DDP

5.1.3 Adductor Longus Injuries (III)

The study included 20 male professional soccer players with severe acute adductor longus injuries. The median age was 27 years, range 18–35. The participants were one goalkeeper, eight defenders, seven forwards, and four midfielders. Of the injuries, 16 were complete proximal adductor longus tendon ruptures and four were partial tears.

Most injuries (65%) were non-contact, whereas 35% involved indirect contact. Closed kinetic chain injury mechanisms were predominant, accounting for 70% of cases, while an open kinetic chain mechanism was found in 15%. In 15% of cases the injuries occurred during high-speed running. The most common action at the time of injury was reaching with the uninjured leg (closed kinetic chain stretching), accounting for 55% of cases (Figure 11), followed by reaching with the injured leg (open kinetic chain stretching, 10%), dribbling (10%), landing (10%), pressing (5%), jumping (5%), and running (5%).

Figure 11. Examples (**A**–**D**) of the most common injury mechanism in Study III: reaching for the ball with the uninjured leg (closed kinetic chain stretching). Picture from Original Publication III.

Hip extension, abduction, and external rotation on the injured side were seen in 64% of the closed kinetic chain injuries. All the open kinetic chain injuries included hip abduction, external rotation, and a rapid change from hip extension to flexion. Knee flexion angle was typically <45°, whereas trunk position showed high variability. The main characteristics of the injuries are described in Table 5.

Table 5. Summary of the following factors in each case in Study III: action at the time of injury, whether the injury occurred during open or closed kinetic chain movement, and injured side hip and knee biomechanics at the time of injury. I, with the injured leg; UI, with the uninjured leg. Modified from Original Publication III.

Case	Action	Open/closed chain	Injured side hip (sagittal	frontal	transverse)	Injured side knee
1	Reaching (I)	Open	Flexion	Abduction	External rotation	Flexion <45°
2	Landing	Open	Flexion	Abduction	External rotation	Flexion <45°
3	Reaching (I)	Open	Flexion	Abduction	External rotation	Flexion <45°
4	Reaching (UI)	Closed	Extension	Abduction	External rotation	Flexion <45°
5	Reaching (UI)	Closed	Extension	Abduction	External rotation	Flexion <45°
6	Reaching (UI)	Closed	Flexion	Abduction	External rotation	Flexion 45-90°
7	Pressing	Closed	Extension	Abduction	External rotation	Flexion <45°
8	Reaching (UI)	Closed	Extension	Abduction	External rotation	Flexion <45°
9	Reaching (UI)	Closed	Extension	Abduction	External rotation	Flexion <45°
10	Jumping	Closed	Flexion	Abduction	External rotation	Flexion <45°
11	Landing	Closed	Extension	Abduction	External rotation	Flexion <45°
12	Reaching (UI)	Closed	Extension	Abduction	External rotation	Flexion <45°
13	Reaching (UI)	Closed	Extension	Abduction	Neutral	Flexion <45°
14	Reaching (UI)	Closed	Extension	Neutral	Neutral	Flexion <45°
15	Reaching (UI)	Closed	Extension	Abduction	External rotation	Flexion <45°
16	Reaching (UI)	Closed	Extension	Neutral	External rotation	Flexion <45°
17	Reaching (UI)	Closed	Extension	Abduction	External rotation	Flexion <45°
18	Dribbling	Unsure	Unsure			Unsure
19	Running	Unsure	Unsure			Unsure
20	Dribbling	Unsure	Unsure			Unsure

5.2 MRI Findings in Standard and Hip Flexion Position (IV)

This study included 38 patients (67 thighs) with typical PHT symptoms, involving 10 males and 28 females, with a mean age of 37.5 years (range 14–58). The average HF angle in the HF position was 54° (range 28–81°).

In the standard position, the SM tendon was considered normal in 39%, tendinosis in 28%, and rupture in 33% of the thighs. The state of the BF tendon was normal in 15%, tendinosis 54%, and rupture in 31% of the cases. In the HF position, the SM tendon was classified as normal in 30%, tendinosis in 28%, and rupture in 42%. BF tendon findings were normal in 15%, tendinosis in 48%, and rupture in 37% in the HF position. Statistical comparison between positions was not performed.

More severe injury in the HF position compared to the standard position was found in 71% of the patients. In tendons initially classified as tendinosis, the HF position revealed a rupture in 16%. Additionally, 6% of tendons classified as normal in the standard position were diagnosed with a rupture in the HF position, and 11% of tendons classified as normal in the standard position were found to have tendinosis in the HF position. These findings are summarized in Table 6.

Table 6. Diagnostic value of HF position compared with standard position. Table from Original Publication IV.

COMPARISON	N / TOTAL (%)
HF position revealed more severe injury	
All patients	27 / 38 (71)
SM tendon	26 / 67 (39)
BF tendon	21 / 67 (31)
HF position revealed a rupture, although	
Standard position showed tendinosis	9 / 55 (16)
Standard position showed normal findings	2 / 36 (6)
HF position revealed tendinosis, although standard position showed normal findings	4 / 36 (11)

5.3 Outcomes after Surgical Treatment of Hamstring Tendon Ruptures (V)

The review included 24 studies on hamstring injuries, 16 covering both acute and chronic injuries and three focusing only on acute ruptures. All but one study examined proximal injuries, with 12 including both complete and partial ruptures, five examining only complete, and three only partial injuries.

A total of 1602 patients were included, with a mean age of 44.8 years (range 16-77). The mean follow-up across studies varied from 12 to 78 months. The study included 74 professional athletes, 166 competitive-level athletes, and 449 recreational athletes.

All injuries were operated, most (96%) of the patients underwent open surgery, with only 4% treated endoscopically. Most cases involved primary repair, while 24 chronic complete avulsions were repaired with graft augmentations. Information on conservatively treated patients was not available.

RTS was the most frequently used outcome (63%), followed by patient satisfaction (50%) and strength (38%). Validated clinical assessment tools specific to hamstring injuries, the Perth Hamstring Assessment Tool (PHAT), and the Sydney Hamstring Origin Rupture Evaluation (SHORE) were used in 17% and 4% of the studies, respectively. The Lower Extremity Functional Scale (LEFS) and visual analog scale (VAS) were used in 29% of the studies and Marx and endurance in 17%.

In most studies, satisfaction was defined using a binary satisfaction measure, with patients reporting whether they were satisfied with the outcome of the surgery or not. After surgery, 89% of patients reported satisfaction with the outcome and 80% (range 62.5–100%) returned to the preinjury level in sports. The total complication rate was 16%, most of the complications being miscellaneous (5%), neurological issues (4%), peri-incisional numbness (3%), and infection/wound problems (2%). Re-rupture and reoperation rates were 0.7% and 0.5%, respectively.

Acute ruptures (surgery within 6 weeks) had better outcomes than chronic cases (surgery after 6 weeks). Satisfaction was statistically significantly higher in acute cases (95% vs. 77%, $p<0.001$; 95% confidence interval [CI]: 0.108–0.234; odds ratio [OR]: 4.94; 95% CI 2.44–10), as was RTS at preinjury level (92% vs. 85%, $p<0.001$; 95% CI: 0.17% to 13.2%; OR: 1.93; 95% CI: 1.03–3.61). The mean time to RTS was 4.5 months with acute repair versus 5.6 months with chronic repair ($p<0.001$). Additionally, strength test results compared to the contralateral leg were better in the acute group compared to the chronic repair group (mean 88.6% vs. 84.9%, $p<0.001$). These main outcomes are presented in Table 7. No statistically significant difference was found in LEFS (74 vs. 72) at one year.

Table 7. The most frequently used outcomes after surgical treatment of hamstring tendon ruptures (Study V) in total, in the acute repair group, and in the chronic repair group. MO, months; NA, not available.

Outcomes after surgical treatment	Overall	Acute repair	Chronic repair	P value (acute vs chronic)
Satisfaction (%)	89	95	77	<0.001
RTS at preinjury level (%)	80	92	85	<0.001
Mean RTS time (MO)	NA	4.5	5.6	<0.001
Strength (% of the contralateral leg)	NA	88.6	84.9	<0.001

After repair, 92% of the patients with complete 3-tendon ruptures were satisfied with the outcome, and 87% with incomplete 1- or 2-tendon avulsions (95% CI: 81.7–96.1%; OR: 0.6, 95% CI: 0.28–1.25). VAS pain scores were lower in complete avulsions (1.87 vs. 3.76, p<0.001; 95% CI: 1.48–2.30), and RTS rate at the same level was slightly higher in complete avulsions (81% vs. 78%; 95% CI: -10.73% to 5.20%). No statistically significant difference was found in strength testing between partial and complete rupture groups (89% vs. 88%, p=0.748; 95% CI: -7.01% to 9.75%).

Reliable comparisons between partial acute and partial chronic injuries could not be made due to insufficient data.

6 Discussion

6.1 Video Analysis

Studies I-III demonstrated the value of systematic video analysis in assessing the mechanisms of thigh muscle-tendon injuries in professional soccer. When seeking to understand the injury mechanisms and their relations to injury types and prognoses, video analysis can be a useful tool for immediate assessment of the severity and prognosis of the injury and/or possible treatment strategy. When designing rehabilitation, video analysis of the primary injury can help to adjust exercises or simulate risky situations when evaluating possible RTP. Video analysis can also be a crucial tool for injury prevention in both first-time and recurrent thigh muscle-tendon injuries. Furthermore, it can be used to identify risky movement patterns during performance, such as poor trunk control. The development of individualized prevention programs with realistic high-risk situations and based on risk factors and demands is highly recommended.

6.2 Hamstring Injury Mechanisms and MRI Findings

According to Study I, most high-grade hamstring injuries involve single-tendon lesions, but severe avulsions of several tendons are also seen. We found that in addition to the described sprint- and stretch-related injuries, mixed-type injury mechanisms also occur combining elements of both sprinting and stretching. Regarding biomechanics, hip and trunk flexion were common factors linked to hamstring injuries, and a knee flexion angle of <45° was found in all cases but one.

When a player feels acute-onset pain in the posterior thigh due to a typical injury mechanism, a hamstring injury should be suspected. Confirmation of the clinical diagnosis requires imaging, typically MRI (Schneider-Kolsky et al., 2006; Six et al., 2021). Video analysis helps to understand injury mechanisms, offering tools and perspective for diagnosis, treatment, and prevention. Hamstring injuries (especially the BF) are frequent in soccer due to the demands of rapid accelerations, decelerations, directional changes, high-speed running, and stretching movements. All sprint-type injuries in Study I occurred during linear or curved high-speed running and affected the proximal BF, which is in contrast to previous findings (C. M. Askling et al., 2013; Gronwald et al., 2022). This highlights the important role of the BF during the running gait cycle, during which the late swing phase is the most likely injury moment (Kenneally-Dabrowski et al., 2019).

Stretch-type injuries occur in different sports during movements causing elongation to the posterior thigh and hamstring muscles, such as splits, kicks, stretching, or reaching, and typically affect the proximal SM (C. M. Askling et al., 2008). The SM is thought to be vulnerable to injury in extreme joint positions in simultaneous hip flexion and knee extension (C. M. Askling et al., 2008). These injuries typically involve the proximal free tendon and require longer rehabilitation than most sprint-type BF injuries (C. M. Askling et al., 2013, 2014). More severe injuries are also possible, as forceful overstretching movements have been found to cause avulsions of several tendons, for example in waterskiing, rugby, and soccer (Sallay et al., 1996; Subbu et al., 2015). In Study I, stretch-type injuries mostly caused isolated SM injuries, and when the energy was higher, proximal avulsions of BF and ST were found. All these injuries occurred during quick movement with combined hip flexion and knee extension. The results of Study I are therefore consistent with previously published findings.

An injury mechanism was classified as mixed type if it included elements from both sprint-related (high-speed running or acceleration) and stretch-related (hamstring elongation, e.g. lunging, landing, or kicking) movements. Almost half (43%) of the cases in Study I were mixed-type injuries, the MRI findings varying substantially with injuries to different muscles and locations. An example of a mixed-type injury mechanism is the common hamstring injury mechanism in Australian football, as the player is running at high speed while trying to pick up the ball from the pitch (Worth, 1969). At the moment of injury, the player is not only sprinting and placing significant demand on the hamstring muscles, but is also causing excessive stretching of the hamstrings while the trunk is bent for pickup, the hip is flexed, and the knee is extended (Higashihara, Nagano, Takahashi, et al., 2015). It can be speculated that in these cases the injury would probably not result from only stretching or sprinting, but it is the combination of these risky movements that leads to injury. With more complex injury mechanisms, predicting the injury type is more difficult.

Gronwald et al. (2022) found the BF to be the most frequently injured muscle in both stretching- and sprinting-type injuries in soccer (70% and 88%), which differs from previous findings (C. M. Askling et al., 2013). However, they had broader criteria for stretch-related categorization and each injury was classified as either stretch- or sprint-related, which may explain the differences between injury mechanism and injury type. We also suspect that some of the stretch-related injuries in that study (Gronwald et al., 2022) would have been classified as mixed-type injuries in our Study I, which may have changed the prevalence of BF injuries in the stretch-related injury category. However, hamstring injuries are very complex when it comes to injury mechanisms and types, and more research with consistent methods is needed.

Preventing hamstring injuries is vital and understanding the injury mechanisms involved is a good place to start. We suggest that prevention strategies should include sport-specific exercises focusing on eccentric loads, high-speed running, and quick movements with emphasis on trunk control (Biz et al., 2021; Dyk et al., 2019; Mendiguchia et al., 2020; Rudisill et al., 2021). Most hamstring injuries in soccer affect the BFlh, and prevention programs should particularly address it to strengthen especially the proximal BF due to its vulnerability to injury when running at high speeds, especially in the late swing and early stance (C. M. Askling et al., 2013; Gronwald et al., 2022; Kenneally-Dabrowski et al., 2019). Strengthening the hamstrings close to full knee extension is found to selectively activate the BFlh, which should be taken into account in injury prevention (Hegyi et al., 2019; Kellis et al., 2017). In general, the BFlh and the SM are more active at slight knee flexion angles and hip extension, whereas the ST is more active at deeper knee flexion angles and during eccentric knee flexion (Bourne et al., 2016; Hirose et al., 2021; Hirose & Tsuruike, 2018; Kubota et al., 2007; Makihara et al., 2006; Ono et al., 2011). Since hamstring injuries are more common during match play and related to exposures to near-to-maximal sprinting speeds (Buchheit et al., 2023), it may be worth considering whether implementing more maximal speed sprints and high-speed actions during training and simulating game situations would be beneficial in injury prevention. Additionally, controlled simulation of real-life situations with a high risk of injury, such as picking up an object from the ground while sprinting to mimic a mixed-type injury mechanism with both sprint- and stretch-type patterns, could be beneficial. In terms of prevention, a more aggressive approach should be used for players with risk factors such as higher age, a history of injuries, or inadequate trunk and hamstring muscle control (Green et al., 2020).

6.3 Rectus Femoris Injury Mechanisms and MRI Findings

Study II showed that RF injuries in soccer occur mainly during kicking, but also in sprinting and change of direction. Movements including high eccentric loading and explosive contractions seem to be associated with RF injury mechanisms. The common tendon is the most frequently injured location, but variation also occurs in injury types. Study II was the first study to investigate RF injury mechanisms using accurate methods such as video analysis.

Kicking was the most frequent RF injury mechanism in Study II, which is in line with earlier findings (Geiss Santos et al., 2022; Woods, 2002). Additionally, kicking has typically been found to cause complete RF tears and injuries to the proximal free tendon (Geiss Santos et al., 2022). To understand the kicking injury mechanism, it is important to understand the biomechanics during kicking. These are described in Section 2.2.3.2 of this thesis. The wind-up phase (the moment of greatest angular velocity and highest angle of knee flexion), in addition to ball contact and ground contact, has been suggested to be the most likely moment of RF injury during kicking (Mendiguchia et al., 2013). It can be speculated whether kicking injuries with a maximal back-swing phase occur during the wind-up phase, and whether injuries with a short swing and bigger angular velocity and impact loads occur at ball impact. Also the supporting leg can be affected during kicking, as shown in Study II. In addition to the kicking leg, the supporting leg plays a key role in soccer kick performance, as it stabilizes the body while the kicking leg swings (Lees et al., 2010). The supporting leg is positioned next to the ball, with the knee flexed as the leg absorbs the impact of landing. This leg experiences high ground reaction forces during the kick, which can sometimes lead to RF injury (Katis et al., 2013).

The two typical kicks in soccer are the full kick and pass kick. The full kick is used to create a high ball speed, and ball contact occurs with the medial-superior site of the instep. The pass kick is used for more precise kicks, with contact occurring at the medial part of the foot (Levanon & Dapena, 1998). Despite the differences in orientation of the thigh during the kick, most of the power during ball contact is created by knee extension in both kick types, highlighting the role of the RF (Levanon & Dapena, 1998). In Study II, the type of kick was distributed as follows: full kick 56%, pass kick 38%, and toe kick 6%.

Complete rupture of at least one tendon accounted for 63% of kicking injuries in Study II, with a similar percentage of proximal free tendon injuries, which is in line with the findings of Geiss Santos et al. (2022).

In addition to kicking, also non-kicking injuries occurred: two during sprinting and two during change of direction. Both sprinting injuries involved a complete tendon rupture, whereas both change-of-direction injuries were partial tears. During sprinting, the RF has been suggested to be injury prone due to high angular velocities during the swing stage along with high eccentric activity (Mendiguchia et al., 2013). The RF reaches its maximal length at 55% of the sprint cycle, during the swing phase between maximal hip extension and maximum knee and hip flexion (Riley et al., 2010). During a rapid change of direction, high eccentric loads and forces are rapidly absorbed through the RF, which may determine the injury.

When it comes to prevention, eccentric training and range of motion are the potential cornerstones of RF injuries. As the vast majority of RF injuries occur during kicking and affect the proximal RF, prevention should address mainly these two factors. Integrating the kicking mechanism into strength training exercises to load the RF at longer fascicle lengths and during explosive movements may be beneficial for injury prevention and rehabilitation. The hip flexion angle affects the activation of each longitudinal section of the RF, and knee extension training with a hip flexion angle of 40° has been found to target the proximal RF specifically, which should be noted in the prevention of these injuries (Mitsuya et al., 2023). Furthermore, it is known that RF injuries are more common during the preseason (Pietsch & Pizzari, 2022), possibly due to the lower number of full kicks during that time compared with the competitive season. Thus, focusing on maintaining a high number of powerful kicks during the preseason would keep the RF load stable, probably decreasing the risk of acute RF injury.

6.4 Mechanisms of Severe Adductor Longus Injuries

Study III showed that most severe and acute adductor longus injuries in soccer occur during closed kinetic chain actions, typically when reaching for the ball with the uninjured leg. These movements are generally characterized by injured side hip extension, abduction, external rotation, and knee extension. Similarly to previous studies (Della Villa et al., 2023; Serner et al., 2019), Study III found reaching actions to be causing adductor injuries. While this was the most common action in Study III, other studies analyzing mechanisms of adductor injuries have found change of direction and kicking to be a more frequent cause (Della Villa et al., 2023; Serner et al., 2019). The difference may be explained by the patient population, as we only included MRI-confirmed severe adductor longus injuries, whereas Serner et al. (2019) included all adductor longus injuries regardless of severity, and Della Villa et al. (2023) did not identify the specific diagnosis or adductor muscles injured.

The typical movement causing severe adductor longus injury in Study III involved hip extension, abduction, external rotation, and knee extension on the injured side, which is consistent with previous findings on all adductor longus injuries (Serner et al., 2019). This is a position in which the adductor longus experiences rapid lengthening while subjected to a high eccentric load, which may lead to injury (Serner et al., 2019).

In Study III, the injuries occurred during rapid events with additional disruptive factors, typically while reaching, affecting the back leg and causing excessive lengthening and high eccentric load on the adductor longus. This highlights the importance of eccentric strengthening in a lengthened state, which has been found to be effective in preventing adductor injuries (Harøy et al., 2019). The common position at the onset of injury (hip extension, abduction, external rotation, and knee extension) could be added to prevention programs when focusing on eccentric training, range of motion (in all dimensions), and realistic injury-prone on-field situations. This would address known risk factors such as weak adductor strength and poor range of motion in hip rotation, simulating high-risk situations as part of injury prevention. We further suggest that body control, synergistic muscle training, and neurocognitive training be considered as part of general adductor injury prevention.

6.5 Proximal Hamstring Tendinopathy

Study IV showed that in most (71%) patients, MRI performed with the hip flexed is better than the standard position for revealing more severe PHT findings. Of tendons diagnosed as normal in the standard position, in the HF position 11% showed signs of tendinosis and 6% revealed a rupture. Additionally, a rupture was found in the HF position in 16% of tendons classified as tendinosis in the standard position.

The diagnostics of PHT is often very challenging, leading to delays in diagnosis and treatment, less successful outcomes, and prolonged time off from sports. The number of differential diagnoses is one factor making the diagnostics of PHT difficult. Conditions that mimic the symptoms of PHT include piriformis syndrome, in which the piriformis muscle compresses the sciatic nerve and buttock and distally radiating pain is typically present (Probst et al., 2019), and, as in PHT, is usually exacerbated by prolonged sitting. Obviously, there are several conditions that can affect the sciatic nerve and cause symptoms in the posterior thigh and hip. Often in PHT, adhesions between the sciatic nerve and proximal hamstring tendons, or even compression caused by thickened tendons, cause irritation of the sciatic nerve with resulting typical symptoms (Lempainen, Johansson, et al., 2015). Given the complex anatomy, pathology, and variety of differential diagnoses, imaging plays a crucial role in early and accurate diagnostics.

MRI is the best method for diagnosing PHT due to its excellent soft tissue contrast (De Smet et al., 2012; Koulouris & Connell, 2005). The goal of MRI examination is to confirm the diagnosis and assess injury severity, which will guide the choice between conservative and surgical treatment (Lempainen, Johansson, et al., 2015). A crucial aspect of PHT diagnostics is the correlation between imaging findings and clinical symptoms. Some PHT findings like signal changes on T1- and T2-weighted images have also been found in patients without symptoms (De Smet et al., 2012) and are thought to occur due to reaction of the tendons to increased loading. Peritendinous edema with a distal feathery pattern, bone marrow edema-like changes, and tendon thickening are more reliable findings of PHT on MR images (Lempainen, Johansson, et al., 2015). Occasionally, MRI findings are normal or minimal despite clear symptoms of PHT. A study found eight of 31 clinically diagnosed symptomatic PHT patients presenting with normal MRI findings

(Bowden et al., 2018). This emphasizes the challenge of PHT diagnostics and the need to develop proper diagnostic protocols for early and accurate diagnosis and to improve treatment outcomes. Based on Study IV, the HF position during MR imaging is very promising in this regard.

The reasons for the HF position being more accurate in MRI diagnostics of PHT compared to the standard position are mainly mechanical. The greatest benefit of the HF position is a better view of the distal parts of the tendon attachments. In the standard position, smaller ruptures may not be detected due to proximity of the tendon to the bone. The HF position causes greater elongation of the hamstring muscles and tendons, offering better visibility of pathological changes and tears.

Clinically, the most important purpose of this study was to develop the early and precise diagnostics of PHT. This is important to ensure the timely start of appropriate treatment, enable quick RTP, and prevent future injuries. PHT can be treated mainly conservatively, but some chronic cases may require surgical intervention (Lempainen et al., 2009). Because of a lack of high-level comparative research, there is limited evidence of any treatment being better than another (Nasser et al., 2021). Study IV offers novel tools for earlier diagnosis of PHT, which may improve the outcomes of conservative treatment, as both the appropriate treatment and prevention can be started at an earlier stage.

6.6 Outcomes after Surgical Treatment of Hamstring Tendon Ruptures

The most important finding of Study V (a systematic review) was that operative treatment of hamstring tendon rupture results in high patient satisfaction and good functional outcomes, with early surgery showing better results and fewer complications than chronic repairs. However, all patients in this study were treated operatively, and a comparison group was not available; therefore, conservatively treated cases were not included in the review.

To date, only one RCT comparing operative and non-operative treatment for proximal hamstring avulsions has been published. Pihl et al. (2024) recently conducted a multicenter study involving 58 operatively treated and 61 conservatively treated patients aged 50 to 60, concluding that non-operative treatment was non-inferior to surgical treatment. A slight variation has been found in the results of previous systematic reviews investigating outcomes after surgical treatment of hamstring injuries. Two studies (795 and 300 cases) found better outcomes after acute repair than chronic repair, similarly to our results (Bodendorfer et al., 2018; Harris et al., 2011). On the other hand, Belk et al. (2019) found that acute surgery led to a quicker time to RTP, but a statistically significant difference was not found (467 cases). Additionally, van der Made et al. (2015) found little or no differences in outcome of early and chronic repairs, with comparative results in main outcome measures (387 cases); however, the quality of the included studies was poor. Coughlin et al. (2020) found no major differences, either, between acute versus chronic repairs (846 cases) but reported that the criteria of chronicity varied greatly between studies. In Study V, we included 1340 cases that reported the acuity of surgery (858 acute and 482 chronic) and found that early surgery led to statistically significantly superior outcomes in patient satisfaction (p<0.001), RTS (p<0.001), and strength (p<0.001). Early repair was more commonly performed in complete 3-tendon ruptures, whereas the chronic group more often involved incomplete 1- or 2-tendon injuries. Many reasons have been suggested for better outcomes and fewer complications in early surgery compared to delayed repair. It is technically easier to operate an acute rupture due to the smaller amount of scar tissue. Chronic cases often present with symptoms of sciatic nerve irritation and pressure, causing pain and tenderness. Additionally, restoration of normal anatomy is often more difficult in chronic cases, especially with clear tendon retraction.

In Study V, the satisfaction rate was 89% among patients treated surgically, and 80% returned to the preinjury level of sports. The most frequently used outcomes were RTS (63%), satisfaction (50%), and strength (38%). We found very high variability in outcome measures, of which most were non-specific and non-validated, making the comparison of studies and generalization of the results difficult. The use of validated hamstring-specific clinical assessment tools was scarce, as PHAT (Blakeney et al., 2017b) was used in 17% and SHORE (French et al., 2020) in 4% of the included studies. Therefore, the use of validated outcome measures specific to hamstring repair is recommended, alongside objective outcome measures such as isokinetic strength testing and RTP (Reza et al., 2021).

Previous systematic reviews have compared surgical and non-surgical treatment of proximal hamstring ruptures, finding that operative treatment led to better results in terms of satisfaction, strength, single-legged hop test, LEFS, RTS, and endurance levels (Bodendorfer et al., 2018; Harris et al., 2011). However, conservatively treated groups were quite small, making a reliable comparison more challenging. In a recent multicenter RCT investigating patient-reported outcomes after proximal hamstring avulsion, PHAT and LEFS scores in the non-operative group (mean age: 53.4 years) were non-inferior to those in the operative group (mean age: 54.4 years) (Pihl et al., 2024).

We found in Study V that the total incidence of complications was roughly 16%, occurring more frequently after delayed repairs (25%) than after acute surgery (14%). Re-ruptures and reoperations were found in 0.7% and 0.5% of cases, respectively. Similarly, Harris et al. (2011) found that acute repair has a low risk of complications and re-rupture. On the other hand, Bodendorfer et al. (2018) and van der Made et al. (2015) reported slightly higher complication rates of 23% and 29%, respectively. However, the risk of major complications has been found to be low, as rates of re-rupture, reoperation, deep vein thrombosis, wound infection, postoperative hematoma, and stiffness were 1–3%. Overall, high variability was found in the reporting of complications and criteria for major versus minor complications, which may partially explain the high complication rates and differences between studies.

In Study V, 75 professional (12%), 166 competitive (27%), and 449 recreational athletes (50%) were included. Only one study involved solely professional athletes, reporting high satisfaction, improved muscle strength, increased functional outcome scores, and high rate of return to preinjury level of sport, with low risk of reinjury (Kayani et al., 2020). This highlights the need for future research focusing on professional athletes, as there is a lack of these studies and sample sizes in existing ones are relatively small.

The categorization between acute and chronic injury remains highly variable. Early diagnosis and appropriate decision-making are crucial, especially for athletes. For example, in cases of clear tendon retraction, early surgical intervention is likely more beneficial, as it is associated with better expected outcomes and a lower risk of complications. The threshold between acuity and chronicity was 6 weeks in this study, thus it can be speculated that a stricter value (e.g. 3 weeks) would have led to even better results, favoring acute surgery.

Surgical treatment of partial/incomplete (1- or 2-tendon) avulsion led to higher pain scores compared to complete tears (3.76 vs. 1.87, $p<0.001$), likely due to a higher proportion of chronic repairs or other mechanical, biological, neurological, and psychological factors. However, there were only small differences in satisfaction between partial and complete repair (87% vs. 92%), return to sport at preinjury level (78% vs. 81%), complication rate (22% vs. 24%), and strength testing. Bodendorfer et al. (2018) found that partial avulsion repair led to better strength and endurance ($p<0.001$), while the complete avulsion group reported better satisfaction ($p<0.001$) and lower pain levels ($p<0.001$). RTS rates were similar between partial and complete rupture groups in two previous systematic reviews (Belk et al., 2019; Coughlin et al., 2020). Partial/incomplete hamstring tendon ruptures are often chronic and have traditionally been treated conservatively, meaning that a remarkable portion of surgically treated partial ruptures received delayed surgical treatment.

Tendon retraction is a crucial aspect of planning appropriate treatment. It is often considered that one indication for acute surgery after complete proximal hamstring avulsion is a minimum of 2 cm of tendon retraction (Cohen & Bradley, 2007; Harris et al., 2011). Subsequently, most chronic cases are treated surgically after failed conservative treatment, even with less than 2 cm tendon retraction after injury. Incomplete ruptures can be challenging and cause persistent symptoms leading to a need for surgery, even though the tendon retraction is usually smaller in these injuries (Piposar et al., 2017). Therefore, it is highly recommended to assess each case carefully and opt for treatment methods based on the individual's symptoms, imaging findings, and level of activity (Arner et al., 2019; Lempainen et al., 2021).

6.7 Limitations

This study has several limitations. Studies I-III were visual video analysis studies, which involve subjective interpretation and variation in video quality and availability of camera views and limit how deep an analysis can be made. However, we used systematic methods, standardized questionnaires, and several analysts to address these limitations. Additionally, sample sizes were relatively small in these studies, limiting the generalizability of the results. Only a small number of similar studies have been published and our sample sizes are comparable to those. The patients in our video analysis studies had been treated by the authors and the exact diagnoses were known, whereas many other studies used only public sources without knowledge or confirmation of the exact injury type. Furthermore, even with high-level evidence of the injury mechanism and injury moment, it is impossible to be 100% sure that the injury happened at that precise moment.

In Study IV, the clearest limitation was that the radiologists knew that hamstring-related pathology was suspected, thus complete blinding was not possible. Additionally, no further statistical analysis or observer reliability testing was performed. However, these are typical aspects of introducing a completely novel imaging protocol that potentially offers beneficial information. The radiologists all experienced a learning curve whereby after evaluating a great amount of HF position images, one starts to evaluate the standard images differently. This is also natural when introducing a totally new protocol.

In Study V, the main limitation was the lack of high methodological quality in the included studies. The wide heterogeneity of outcome measures also created difficulties generalizing and aggregating the results from those studies. There were inconsistencies in the categorization of complications, populations, and injury types. Such heterogeneity of important factors can cause bias in the interpretation of outcomes.

6.8 Future Perspectives

Thigh muscle-tendon injuries are a tremendous problem in professional sports, causing significant harm to athletes' careers and clubs' economics. Not only athletes but also the general population suffer from these injuries and disorders, leading to disabilities in hobbies and work.

The scientific community has shown growing interest in thigh muscle-tendon injuries over the past few decades. Simultaneously, these injuries have become increasingly common. As the number of competitive matches in professional soccer continues to rise, we can assume that thigh muscle-tendon injuries will follow suit. Future high-quality research is greatly needed to understand, treat, and prevent these injuries with success.

Video analysis has shed light on injury mechanisms and deepened our understanding of the patterns and mechanisms behind thigh muscle-tendon injuries. Developing technology offers greater possibilities to analyze video footage more effectively and accurately. While more video analysis research with bigger sample sizes combined with consistent methods and categorization is needed, there should also be greater focus on using the findings of injury mechanism studies for injury prevention. Risk factors and injury mechanisms are complex, so prevention strategies should be both multifactorial and individualized. Integrating injury-prone actions and realistic game situations systematically in prevention programs, and investigating their efficacy with high-quality methods, should be the next step in thigh muscle-tendon injury prevention research. Special attention should be paid to selective allocation of injury prevention to the most common injury locations, such as proximal parts of the BF and the RF, which can potentially be targeted with modification of the hip and knee joint angles during strength training. These prevention programs should be tailored specifically to athletes with known risk factors. Furthermore, modern technology can be used also in monitoring and data collection to deeply analyze muscle activity and patterns in detail, which could also be utilized in injury prevention.

Future research should also focus on individual management of thigh muscle-tendon injuries. Each muscle-tendon unit is a unique complex in terms of anatomy, function, and injury patterns, which should be taken into consideration. Furthermore, each patient is also a unique individual in terms of level of sports, sports discipline, playing position, injury type, physical characteristics, risk factors, and demands. Thigh muscle-tendon injuries are complex, and "one-size-fits-all" does not apply to managing these injuries. For example, hamstring injuries differ significantly depending on the location of the injury and the muscle-tendon units involved. This individualization should be considered in future studies investigating thigh muscle-tendon injuries.

Finally, more high-level research comparing surgical and conservative treatment in different thigh muscle-tendon injuries is needed. Validated and objective outcome measures with appropriate follow-up should be used consistently, special attention being paid to the selection of population and injury type. Different muscle-specific rehabilitation protocols and RTP criteria, including isokinetic strength testing, could also be considered. Additionally, therapeutic use of biologics should be further studied also in the future to develop muscle-tendon injury treatment and lower risk of reinjuries.

7 Conclusions

The findings of this study led to the following conclusions:

I. High-grade hamstring injuries typically occur during high-speed movements (such as change of direction, kicking, or running) and involve hip flexion, knee extension, and trunk flexion. In addition to sprint- and stretch-type injuries, also mixed-type injury mechanisms occur. Injuries affect mainly the proximal tendons, most often the BF.

II. Kicking is the dominant injury mechanism causing RF injuries in professional soccer, and also the supporting leg can be affected. Kicking and sprinting often lead to complete tendon ruptures, whereas change of direction seems to cause mainly partial tears.

III. Severe adductor longus injuries occur mainly during closed kinetic chain actions, typically when reaching for the ball with the uninjured leg. These injuries are characterized by hip extension, abduction, external rotation, and knee extension.

IV. The novel HF scanning position reveals more severe PHT findings in symptomatic patients compared to the standard position.

V. Surgical treatment of hamstring tendon ruptures leads to good patient outcomes, especially when surgery is performed in the acute phase.

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