Module 4. Kinetics & kinematics in lower limb muscle and tendon injury and rehabilitation

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4.1 Tendinopathy

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Epidemiology

Lower limb tendinopathies are a very common problem in occupational, recreational and a variety of field-based running sports. A tendinopathy is defined as a clinical presentation with key symptoms such as pain, swelling or thickening of the tendon, with a reduction in functional capabilities and athletic performance (Maffulli et al., 2004). Repetitive overloading of human tendon tissue often leads to overuse injuries that are acute and chronic in nature. Acute changes are characterised by a disturbed homeostasis, increased tendon CSA due in part to fluid accumulation, with no change in tendon mechanical properties (Tran et al., 2020) and pain. Chronic tendinopathy is further characterised by a change in mechanical properties and increased type III fibrillar collagen aligned in a disorganised manner along with buckling of tenocytes and a shift in the ratio from large to small collagen fibrils (Pingel et al., 2014). These alterations manifest as localised and load-dependent tendon pain, regional swelling and tendon thickening with a loss of muscular function, particularly force production (Kjaer, 2004). If symptomatic, tendinopathies often result in reduced training and match participation and impaired levels of performance (Lian et al., 2011), while asymptomatic PT may still generate a reduction in functional performance– such as decline in force production.

4.1.1 Patella Tendinopathy

Prevalence and risk factors

The prevalence of patella tendinopathy (PT) varies across sexes, ages, and sports. A prevalence of over 14% in a mixed cohort of elite athletes, 8% of which had experienced symptoms at some point in their elite career, for average durations of 32 months (Lian et al., 2011). PT is twice as common in males (13.5%) than females (5.6%) and highest in elite level volleyball (45%) and basketball (31.9%) athletes. These incidence rates are substantially lower in sub-elite levels to 14% in volleyball and 12% in basketball (Zwerber et al., 2011). Other risk factors for PT include greater body mass (BMI) (Lian et al., 2011; Backman et al., 2011), which is directly related to the greater loading demands on the connective tissues and the resultant vGRFs during landing and cutting on these structures.

The risk factors for PT increase with age (Lian et al., 2011) and was career ending in 53% of cases in a 15-year follow up of 36 jumping athletes (Kettunen et al., 2002). This is due to the ageing process being associated with a reduction of elastin within the intra-fascicular matrix (IFM) and a stiffening of the IFM (Godinho et al., 2017). Evidence from animal models suggest a reduction in the sheer number and the ability of tendon cells to proliferate and migrate (Kohler et al., 2013; Zhou et al., 2010) thereby hindering their ability to repair (Magnusson & Kjaer, 2018). From an imaging perspective, a systematic review concluded that athletes with hypoechoic regions in the patella tendon (identified with ultrasound) had a relative risk for PT of 4.97 (McAuliffe et al., 2016), highlighting the importance of a mechanically sound tensile spring in the patella tendon for the performance of pain-free movement.

Rehabilitation and risk reduction

To optimally rehabilitate patients and athletes experiencing PT, the clinician, or performance and medical teams, must understand the requirements of the contractile elements of the muscle and tendon to return to sport. However, these requirements also apply to healthy athletes - and are therefore relevant to injury risk reduction strategies. Rehabilitation and return to sport (RTS) test results must meet the minimum demands of the sport, or the risk of re-injury remains high. For example, when landing from a jump, intra-tendinous patellar tendon load magnitude exceeds 8000 N, equivalent to 6-8 times an athlete’s bodyweight (Zernicke et al., 1977). Tendon stiffness is an important aspect of tendon function and “describes the relation between the force exerted on the tendon and its change in the length” (Kubo et al., 1999).

The stiffness of the soft tissue structures, mainly the patella tendon, are critical to the transference of force by the muscle to the bone and in the production of high rates of force development (RFD).

Leg stiffness is often calculated utilizing the spring–mass model during repeated vertical hopping;

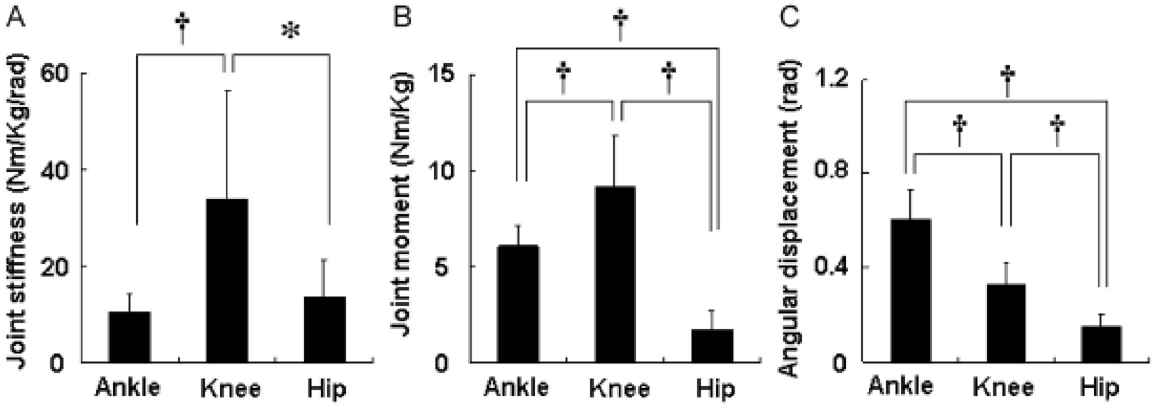
In the hop, peak vertical ground reaction force (Fmax) and leg compression coincide in the middle of the ground contact phase.

At this point, leg stiffness can be calculated as the ratio of peak vertical ground reaction force to peak leg compression (Farley and Morgenroth, 1999) with leg compression considered equal to the maximum vertical displacement of the center of mass (COM) during ground contact (Farley and Morgenroth, 1999).

Similarly, joint stiffness (Kjoint) may be calculated as the ratio of peak joint moment to joint angular displacement at the middle of the ground contact phase (Farley and Morgenroth, 1999).

The patella tendon is responsible for approximately 30% of the variability in the rate of torque development (RTD) in a maximal isometric knee extension (Bojsen-Møller et al., 2005), explaining why an overly compliant (i.e. with low stiffness) tendon compromises the ability to rapidly generate force isometrically and dynamically. The goal of any rehabilitation or risk reduction loading/programming must be to improve the mechano-characteristics of the patella tendon and its aponeurosis to attenuate and modulate force (Bojsen-Møller et al., 2005). Interestingly, in maximal hopping tasks, it is knee stiffness, particularly of the quadriceps and patella tendon, that modulates leg stiffness, not the ankle, as previously proposed (Hobara et al., 2009).

Figure 1: Comparison of stiffness, momentum and angular displacement of ankle, knee and hip in hopping.



Source: Hobara et al., 2009, p.1770.

Furthermore, knee joint stiffness is a major determinant of running and sprinting speed (Hobara et al., 2009). Moreover, in short contact vertical hopping, leg stiffness remains relatively unchanged with an increase in hopping intensity, but it was knee joint stiffness that increased while ankle stiffness remained unchanged (Kuitunen et al., 2011). When effective bodyweight increased from three to six times by increasing drop height in a double leg hopping task on force plates, ankle joint movement increased two fold whilst knee stiffness increased fivefold with the same increase in load (Kuitunen et al., 2011).

Altered kinetics and kinematics in PT

In a study of double-leg drop jump performance in 24 healthy volleyball players, those with a previous history of patellar tendinopathy demonstrated a stiffer knee joint landing. They also experienced higher loading at the ankle and knee and greater knee angular velocities but the same joint ranges of movement as those without a history of PT (Bisseling et al., 2007). However, the retrospective nature of the study means that whether this “stiff knee” load avoidance landing strategy is a consequence of prior PT or a causal factor cannot be determined. A study in a small cohort of seven elite volleyball athletes performing a stop jump task, an assessment with greater horizontal force attenuation demands compared to the drop jump, showed contrasting kinematic alterations whereby those with existing PT showed greater knee flexion and hip extension in the landing phase (Edwards et al., 2010). Therefore, there appears to be more than one landing strategy associated with current or prior PT, one of poor load acceptance by maintaining a stiffer and more extended knee joint, and the other, an increased knee flexion on landing, due to an inability to create stiffness (Helland et al., 2013; Bojsen-Møller et al., 2005). These contrasting strategies may reflect differential responses to an acute presentation of PT versus a longer adaptive response to chronic PT.

In terms of performance measures, studies in volleyball players show prospective (Helland et al., 2013; Visnes et al., 2013) and retrospective (Lian et al., 1996) associations between greater jump height and PT incidence. While this appears to suggest that athletes with greater CMJ height may be more susceptible to PT, this association could be related to those athletes with higher jump height being those playing at a higher level and, consequently, involved in a higher volume of training and jump-land activity. Therefore, it may be that greater exposure mediates these alterations in patella tendon morphology and symptoms rather than higher jump height *per se* (Lian et al., 2011; Lian et al., 1996).

In a recent analysis of professional volleyball players, we found that the development of anterior knee pain (AKP) during the season was associated with significantly lower values in several CMJ kinetic variables considered indicators of good stretch shortening cycle (SSC) function and stiffness (flight time: contraction time, eccentric deceleration phase duration, eccentric deceleration rate of force development), in an early season assessment (Del Aguilla et al., 2021). Interestingly, however, there was no significant difference in jump height between those who did and did not develop AKP. As slightly less than half the cases with AKP are diagnosed with patella tendinopathy, this data suggests that not only jump height but also CMJ kinetics should be considered in further analysis of PT risk. These preliminary findings with respect to markers of stiffness/SSC being associated with future tendon health aligns with research showing that compared to healthy controls, stiffness measures were lower in symptomatic patella tendons, while proximal tendon cross-sectional area (CSA) was higher (Helland et al., 2013).

Kinetic and kinematic risk factors

Not surprisingly, there are gender differences in jumping kinetics, with higher intra-tendinous load magnitudes and loading rates reported in males, due in part to greater knee extensor strength (Janssen et al., 2013). Kinematic analysis of running also indicates small sex differences whereby females show increased knee flexion and a reduction in hip extension velocities and an earlier onset of terminal knee flexion during the ground contact phase, which is a kinematic profile associated with the development of PT (Grau et al., 2008). Interestingly, in female runners, other kinematic risk factors for PT include peak ankle eversion, over-pronation and peak hip adduction (Mousavi et al., 2019). It is hypothesised that rear foot eversion coupled with tibial internal rotation causes overloading of the lower limb structures causing PT (Hintermann & Nigg, 1998). In addition, individuals with łower ankle dorsiflexion range of movement (ROM) (Malliaras et al., 2006; Crossley et al., 2007) have been shown to have a 1.8-2.8 times higher increase risk of PT, if ROM was below 45° (Malliaras et al., 2006). Furthermore, with respect to jump-land mechanics, in a double leg drop jump (DLDJ), limited ankle dorsiflexion ROM landings increased ankle joint moments by 14% compared to landings, with normal ankle dorsiflexion ROM. In a drop landing, the knee extensors absorb 34% and the hip extensors 22% of the impact forces (Devita & Skelly, 1992). The large differences in limited versus normal dorsiflexion landing positions observed in the DLDJ were mainly due to a more extended trunk position and were associated with 23% higher ground reaction force (GRF) impulse on initial impact (1^{st} landing of DJ). As “landing stiffness” increased (i.e. reduced dorsiflexion ROM, and less knee and trunk flexion), the relative contribution of the ankle plantar flexors also increased, while the contribution of hip and knee extensors decreased (Devita & Skelly, 1992). Overall, in the more compliant landing, the muscular system absorbed 19% more kinetic energy, highlighting the importance of kinematics in energy attenuation, as well as the specific influence of the ankle, on the landing task.

A prospective study of 75 athletes also found associations between ankle dorsiflexion ROM and PT. Dorsiflexion below 36.5° was associated with an 18.5% to 29.4% greater risk of developing PT at 1-year follow-up, while the risk in those with greater than 36.5° ROM was only 1.8%-2.1% (Backman et al., 2011). This is thought to be related to limited ankle dorsiflexion ROM reducing the ability of the gastroc-soleus complex to attenuate the ground reaction forces when landing from a jump (Devita & Skelly, 1992), resulting in the transmission of tensile forces proximally to the patellar tendon, increasing impact forces at the knee joint. While in athletes, poor Iliotibial band flexibility (under -0.02°/kg) measured in a modified Obers position and shank-forefoot alignment measured in 90° dorsiflexion ROM was also found to be associated with developing PT (Mendonça et al., 2016), the applicability of a measure of shank-forefoot alignment in a non-weight-bearing position is questionable, given that the soft tissues of the ankle and foot will alter in a full weight-bearing posture. Moreover, the cohort consisted of only 16 patella tendons that were positive for tendinopathy, a small cohort upon which to draw firm conclusions and influence clinical practice. Nevertheless, in a recent study examining the relationship between patella mobility, lower limb kinematics and medial or lateral patella excursion in 22 athletes (11 with PT) those with PT showed greater lateral patella mobility and hip adduction angles (Lazaro et al., 2021).

Trunk position during landing has an important influence on the loading rate through the knee extensor mechanism and is relevant for volleyball and basketball. Greater trunk flexion on landing reduces vGRF and increases quadriceps EMG activity by up to 60% (Blackburn & Padua, 2009). This effect is due to the location of the centre of mass being closer to the knee joint centre of rotation, thereby reducing the lever arm. The clinical implication of this is that when the technique of the sport allows for it, the athlete should be encouraged to adapt a more flexed landing position to reduce quadriceps loading and intra-tendinous forces within the patella tendon, by recruiting the posterior chain to dissipate forces.

In a mixed cohort of 27 male and female athletes across tennis, volleyball, basketball, netball and football, both hamstring and quad flexibility were predictive of PT (Crossley et al., 2007). Although athletes suffering unilateral PT had lower quadriceps strength, those with bilateral PT did not differ from controls (Crossley et al., 2007). In a 2-year follow-up of 138 physical education students, hamstring and quadriceps strength were the only single determinant of PT (Witvrouw et al., 2001).

4.1.2 Achilles tendinopathy

Epidemiology

Achilles tendinopathy (AT), classified as insertional and mid-portion (an area 2 cm proximal to the calcaneus insertion, extending 6 cm proximally) (Courville et al., 2009) is clinically diagnosed based on the occurrence of the combination of the following: Achilles tendon pain, swelling and impaired sports performance (Paavola et al., 2002) as well as other multifactorial causative factors such as biomechanical, clinical and training (Hein et al., 2014). Its prevalence is reported to be as high as 1.85 per 1000 of the population and is more common in men than women, with 35% of the cases related to sports activity (De Jonge et al., 2011). AT accounted for 14.3% of all injuries in a cohort of 66 novice runners with a goal of running 5 km (Van Ginckel et al., 2008) while a report examining above-average middle distance runners observed 34% (Haglund-Åkerlind & Eriksson, 1993) experienced a problem with their Achilles tendon.

Prospective risk factors for AT include prior lower limb fracture (Owens et al., 2013) and a higher BMI (over 25) (Owens et al., 2013) or bodyweight (Wezenbeek et al., 2018). A systematic review examined the impact of AT on various strength qualities in the plantar flexors; maximal (isometric and dynamic), explosive (isometric rate of force development) and reactive (i.e. SSC function in jumping and hopping). Based on comparisons between these qualities in the affected and the contralateral healthy limb, they found consistent evidence for significant isometric RFD differences (10-21% lower in AT v non-AT limb) and smaller but significant deficits in isometric peak force (5-12%). There were AT limb deficits in measures of "reactive strength", such as lower horizontal hop and repeated hop distances of 16-35% and 16-20% lower single-legged hop vertical hop height and RSI (i.e. flight time to contact time). Eccentric and concentric isokinetic plantar flexion peak torque at higher speeds showed moderate to large effect size differences between AT and non-AT limbs, but at slow speeds these differences were small (60/s). In contrast, in the bodyweight heel-raise test, traditionally used in the clinical setting, interlimb differences in number of repetitions performed between the symptomatic and non-symptomatic side of only 8% were reported (Mahieu et al., 2006; McAuliffe et al., 2019), highlighting its poorer sensitivity. As intra-tendinous tendon loads during high speed running (6 m/s) of 9000 N are reported, strength is clearly an important quality variable AT risk reduction in running and team sport athletes (Komi, 1990). While musculotendon stiffness has a positive relationship with knee extension isometric RFD (Waugh et al., 2013), as in the patella tendon (Bojsen-Møller et al., 2005). However, if AT stiffness is too high this is unfavourable for running performance due to a reduction in efficiency associated with consequential high muscle fascicle shortening velocities (Lichtwark et al., 2006). In athletes, longer AT's were associated with lower RFD's in the initial 0-10 ms of the yielding phase of the CMJ (Earp et al., 2011), and greater stiffness was associated with a shorter electromechanical delay (EMD) – with EMD reductions observed after plyometric training (Grosset et al., 2009). The importance of the ankle plantar flexors to CMJ performance is also clear; in order of the greatest to the least contribution to net joint moments during the acceleration of the body vertically during the upward phase of the movement: the soleus, medial and lateral gastrocnemius followed by the quadriceps group, with the soleus operating at near maximum capacity during the CMJ (Kipp & Kim, 2020). A prospective study of military recruits (N=69), reported that individuals with isokinetic plantar flexor strength of less than 50 Nm combined with ankle dorsiflexion of greater than 9° had a significantly elevated risk of developing AT (Mahieu et al., 2006). Although a relevant finding, demonstrating the importance of strength and joint range of motion, this military cohort had little running experience, and therefore these findings may not be generalisable to more athletic populations.

A potential anatomical mechano-kinematic cause for AT is that of compression of the medial column of the Achilles against the plantaris longus tendon. It was once thought that the plantaris longus tendon rarely occurred in the general population, but it is present in 80% to 100% of the population (Saxena & Bareither, 2001; Van Sterkenburg et al., 2011). In cadaveric specimens, the pressure measured between the Achilles and plantaris longus in end ROM plantar flexion with rear foot valgus indicates that this may be causal for AT in those suffering mid-portion AT (Stephen et al., 2018).

Kinematic and kinetic risk factors – based on analysis of running

While you may not have access to the tools required to perform kinematic and kinetic analysis of running, it is relevant to have some awareness of risk factors for AT identified in such analysis. The main factor identified was a delay in the timing of ankle eversion and weak hip abductors (Jungmalm et al., 2020). Although greater rear foot eversion is a potential kinematic risk factor for PT (Mousavi et al., 2019), the majority of evidence does not support its role in AT risk. Key characteristics in a group of athletes with both AT and medial tibial stress (MTSS) were prolonged eversion time, reduced static dorsiflexion angles and a greater standing tibial varus angle (Becker et al., 2017). In addition, runners with AT showed a more extended knee joint, less ankle dorsiflexion and a more everted (valgus) rear foot at touchdown compared with healthy controls (Hein et al., 2014; Ryan et al., 2009; Azevedo et al., 2009). This might be explained by the greater knee extension potentially producing higher rear foot eversion, resulting in a greater tibial internal rotation and increased tension on the gastroc/soleus complex. This mechanism is supported by another study that found higher rear foot eversion may be caused by lower knee flexor strength, which results in preferentially maintaining a more extended knee during the first half of the stance phase (Hein et al., 2014). Although knee flexor weakness may also be the cause, or the effect, of altered kinematics, runners in these studies may self-select a more forefoot or natural running posture which encourages greater plantar flexion, increasing AT load (Mousavi et al., 2019). altered soleus neural drive (Wang et al., 2011) with reduced isometric plantar flexion force and RFD on the tendinopathic side is also reported.

In a small running cohort with AT, less hip abduction and greater ankle dorsiflexion ROM was found (Donoghue et al., 2008) with the latter thought to be due to increased tissue compliance and a reduction in Achilles stiffness as a result of AT (Helland et al., 2013; Arya & Kulig, 2010; Child et al., 2010). Greater foot inversion at heel strike and greater eversion were also characteristics of runners with AT in this study. In a recent high-quality retrospective analysis of runners with AT, there appeared to be no difference in biomechanics at the ankle or knee compared to controls but the AT group exhibited greater hip adduction, external rotation impulse, and peak hip external rotation moments (Creaby et al., 2017). Note, however, that due to the retrospective nature of these studies, it cannot be determined if these alterations of hip biomechanics are the cause or effect of AT.

Applying the research in the "real world"

It is clear from the evidence that intra-tendinous loads on the patella tendon exceed six times body weight and close to 8 times body weight when landing from a jump. Intra-tendinous loads are greater in the Achilles tendon and can be as high as 11 times body weight. As such, regular assessment of force attenuation and production qualities is fundamental to risk reduction programs and the optimal management of athletes with PT or AT. If feasible, additionally, periodic kinematics to screen for some of the risk factors described. Nonetheless, the most common tool to evaluate kinetics in sports and clinical settings are single vertical axis dual force platforms, which have become established as a minimum requirement for performance and medical teams. As in the rehabilitation of all injuries, pre-injury benchmark data provides crucial information to guide the practitioner for the recovery of neuromuscular function and return to high performance. Profiles obtained from healthy athletes also allow for stratification and identification of those that fail to achieve cut-off points. Regarding AT/ PT the author suggests that as a guide, in the healthy athlete, and in those returning to sport following a tendon injury, a minimum strength standard of a net peak vertical force (net denoting force above body weight) of 1.5 times body weight in a single leg isometric belt squat (figure 2) should be achieved. The belt squat is a reliable and reproducible test in sports where upper limb strength is not a vital part of the athletes' requirements on the pitch, such as football, cricket, or basketball, or those that have little experience with pulling exercises, this would be preferable over an IMTP. It is also more comfortable concerning spinal loading than an "under the bar" iso squat. Conversely, in sports such as rugby, NFL, or judo with upper limb grip strength as an athletic requirement and likely more experience in pulling exercises the IMTP could be appropriate. The minimum strength standard for athletes returning from AT should be a net peak vertical force of 1.5-2 times bodyweight when tested in an isometric seated calf raise.

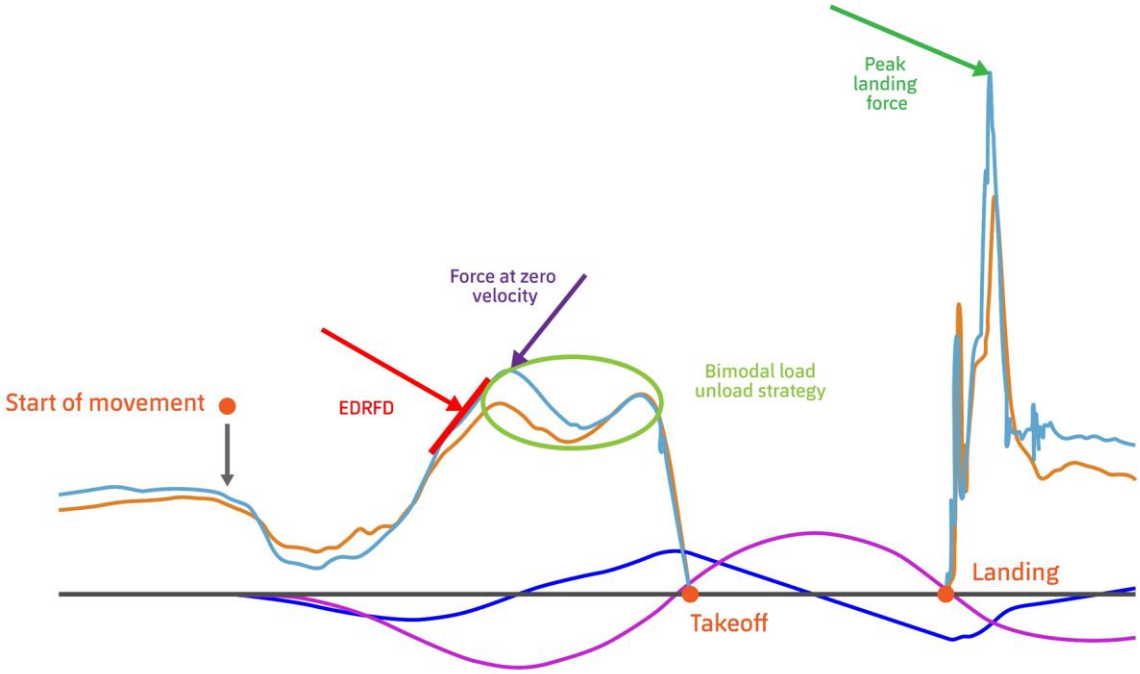
Reading and understanding not only these numerical outputs from bilateral variables and asymmetries processed by force platform software but also having a grasp of the force-time curve (the waveform), may also give some further insights into kinematic strategies employed by the athlete during a DL-CMJ or DL-DJ. As described throughout this certificate, jump phase durations and time-constrained force and impulse variables to describe how an athlete is achieving the task and provide insights beyond the jump height and flight time: contraction time output performance metrics. Countermovement jump depth and eccentric peak velocity also provide some context in terms of whole body (centre of mass) movement, in terms of how deep and how fast the athlete is moving.

Figure 2 shows DL-CMJ kinetics in an athlete with right-sided (unilateral) PT. There are obvious asymmetries across the jump-land phases – shifts toward the healthy left limb and away from the affected right limb (an avoidance strategy well described following ligament injuries). Mean asymmetry in eccentric deceleration rate of force development (EDRFD) is 26.6%, 16.7% in force at zero velocity and 23.7% in peak landing force. Asymmetries are not evident in the late concentric phase as characterised by metrics such as force at peak power or P2 concentric impulse (the 2nd 50% of the phase), but are present in the early part of this phase: quantified by the concentric impulse-100 or in P1 (1st 50% of con phase) asymmetry. However, what is not quantified by these variables, but can be identified in the figure, in the left and right curves is the bimodal shape of concentric force-time waveform (i.e. the force curve has a clear “dip” and therefore two peaks) in the concentric phase (see course “Force Assessment and an Introduction to Kinematic”, module 2 for further description of these “waveform” characteristics). In this case, this was due to their athlete’s trunk swing, possibly a consequence of pain-induced inhibition during knee flexion, combined with a shift onto their toes, also shifting their COM forward over their knees (upward phase) in a dyssynchronous movement pattern. As this assessment was performed on an athlete with existing PT, one cannot determine whether this pattern and the kinetic asymmetries and this is a consequence or a cause of the PT.

Figure 2: Bilateral isometric belt squat

Source: Prepared by the author.

Figure 3: Example of a DL-CMJ kinetics in an athlete with right sided PT



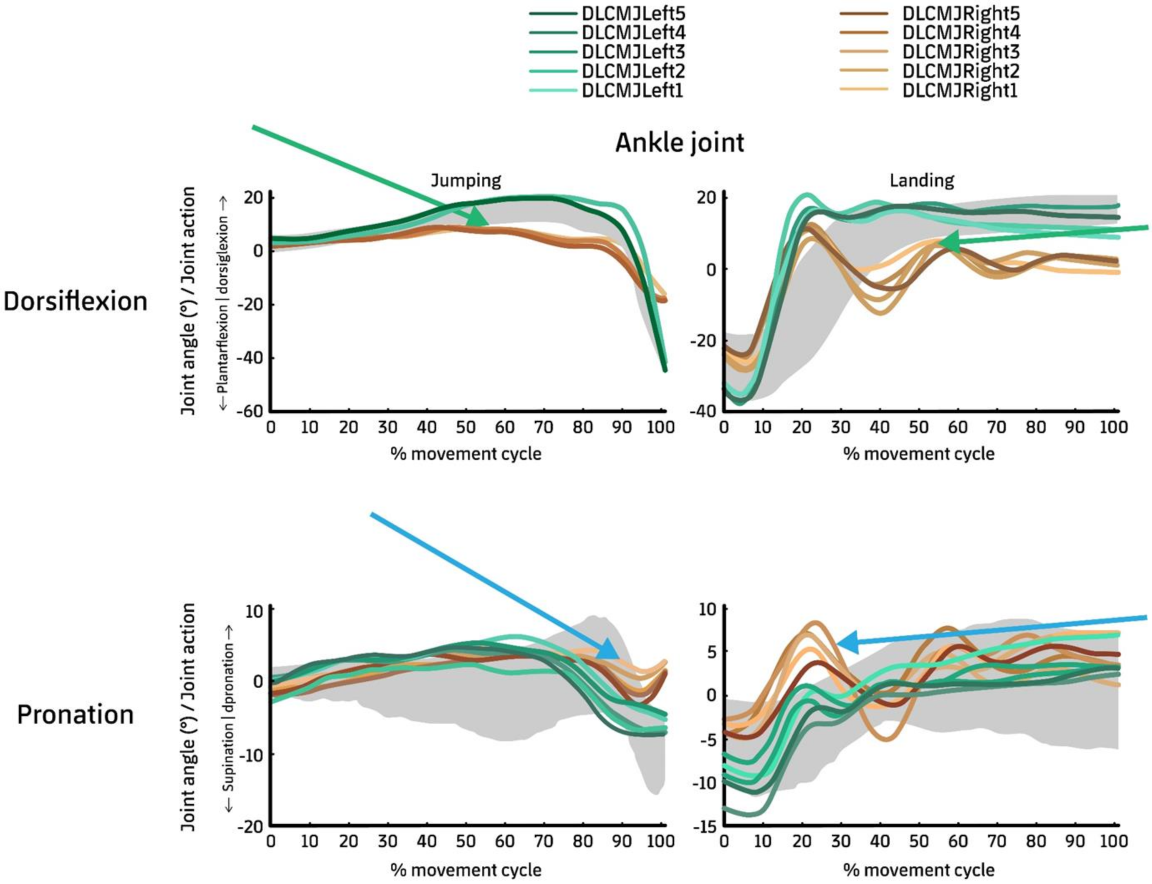
Source: Prepared by the author.

Lines: Orange = right limb force-time curve, light blue = left force-time curve, dark blue = velocity-time curve, pink = displacement-time curve

Shifts of loading to healthy limb highlighted; eccentric deceleration RFD (red slope), force at zero velocity (purple arrow), peak landing force (green arrow). The bimodal load unload strategy, is highlighted by the green circle.

A consistent theme in the literature is the need for quantitative assessment of 1) forces and 2) joint angular displacements. However, the latter is a potentially complex undertaking in elite sports settings due to several factors. These include the need for expensive equipment, time-consuming capture, complex processing, and transformation to visualisations of the data, as well as the expertise needed to interpret this information to inform meaningful interventions. Nonetheless, when kinematics are employed and this process can be implemented, the stream of meaningful information can provide context to durations and forces and better define potential joint-specific origins of deficits or asymmetries. Addressing or correcting these deficits, or poor movement patterns, requires expert knowledge that is not embedded within the studies examining risk factors or consequences of AT/PT and goes beyond mean kinetic and kinematic data for a group, requiring an understanding of the individual's strategy. As an example, a lack of ankle joint range of movement (ROM) in jumping and cutting tasks has clearly been shown to increase the risk of PT nearly threefold (Malliaras et al., 2006; Backman & Danielson, 2011; Crossley et al., 2007). However, what is not described is the alternate strategies employed by athletes to gain more ROM proximally at the knee joint by moving into more valgus knee angles. Figures 3 and 4 show the ankle and knee joint angles of an athlete with limited ankle DF-ROM as a result of a right sided Achilles repair. Clearly, there is a reduction in the right ankle DF-ROM during the take-off (particularly between 50 and 90%) and landing phases of the DL-CMJ and an increase in right foot compensatory pronation angles in take-off and landing (particularly late concentric and early landing phases) (blue arrow).

Figure 4: Ankle and knee joint angles of an athlete with limited ankle dorsiflexion-ROM

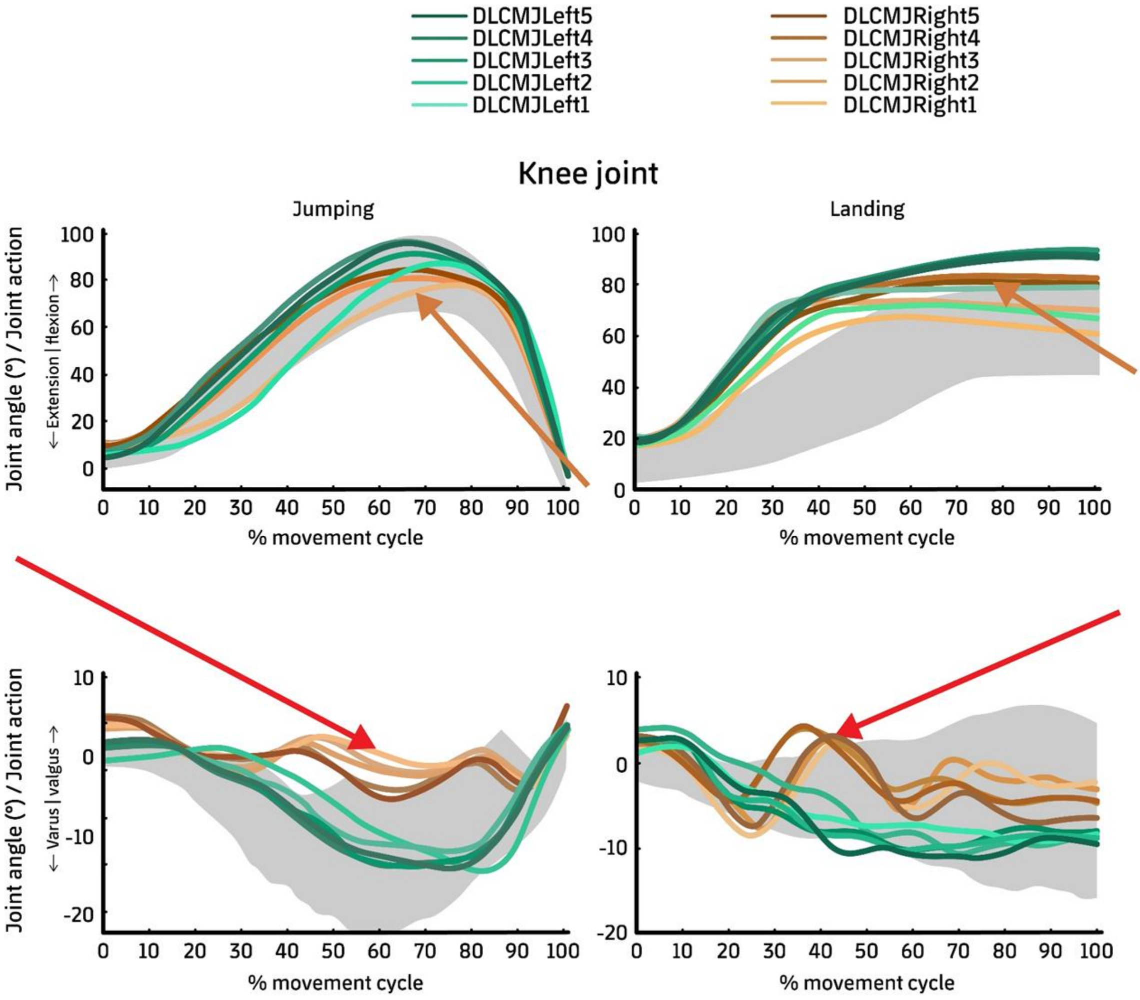


Source: Prepared by the author.

Figures 4 and 5 show the time-normalised (to 100%) take-off phase of the CMJ for 5 DL-CMJs. The left panels show the jump phase (eccentric/downward and concentric/upward) and the right panels, the landing. Green lines represent the 5 left limb curves and brown lines the 5 right limb curves. The shaded grey area is the position-specific value (within the sport) +/- 1 SD for that point in the jump movement cycle.

Furthermore, figure 5 highlights the proximal compensatory strategies at the knee, with reduced knee flexion angles (orange arrow) and considerably higher knee valgus angles (red arrow) on the right side during the take-off and landing phases.

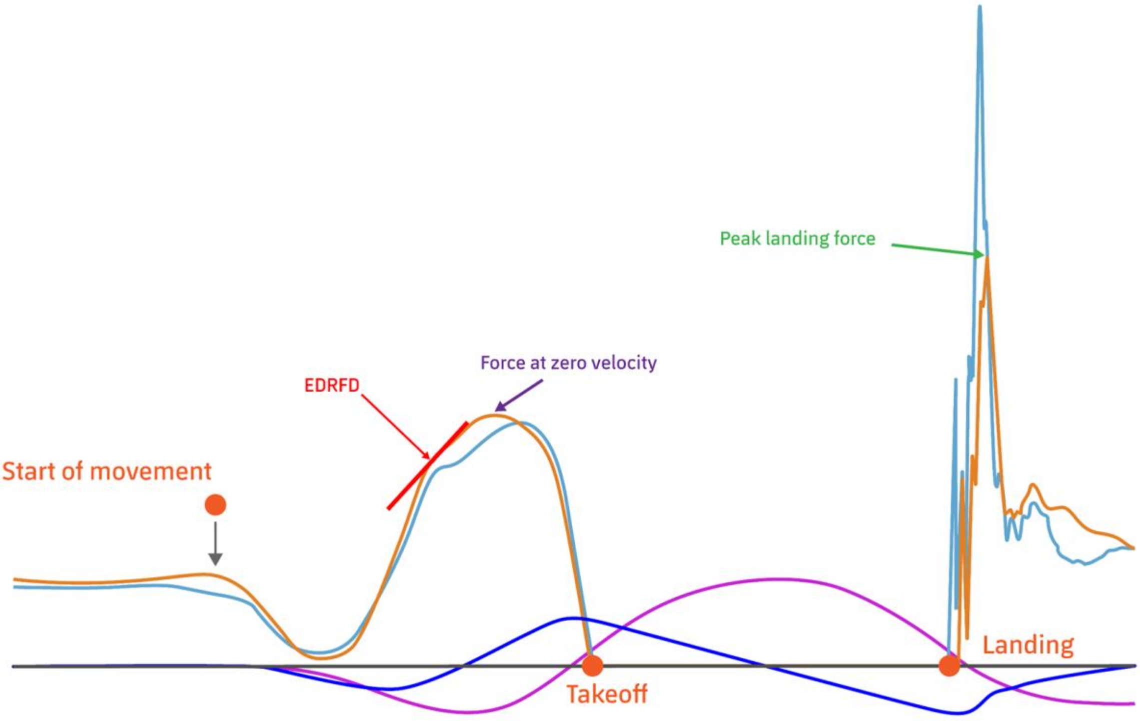
Figure 5: Proximal compensatory strategies at the knee with reduced knee flexion angles



Source: Prepared by the author

The literature clearly shows a relationship between strength and PT (Crossley et al., 2007) both prospectively; with lower strength as a risk factor for developing PT, and cross-sectionally and retrospective analysis; those experiencing PT displaying reduced peak force or RFDs. The practitioner must be aware that in jump tests – which are not direct measures of strength – this may manifest in an altered landing strategy, with a relatively stiff knee landing position (Bisseling et al., 2007) or in the acute phases, excessive unloading of the limb due to pain inhibition. Figure 5 highlights the CMJ force time curve of an athlete with left sided PT, exhibiting similar take-off phase patterns, but a divergent landing profile relative to the athlete in figure 2. Kinetic asymmetries are: 14.7% EDRFD and 11.1% force at zero velocity toward the right, but there is a 38.2% landing force asymmetry toward the left (symptomatic) side. This is indicative of a stiff, more extended knee landing position resulting in a higher peak vGRF. This also suggests that due to the compromised ability of the limb to attenuate forces through the patella tendon, the athlete's strategy is to reduce intra-tendinous loads, by directing the forces through the knee joint directly.

Figure 6: DL-CMJ force time curve of an athlete with left sided PT



Source: Prepared by the author

Bilateral CMJ kinetic variables and tendon health

A recent abstract, based on an analysis of a start-of-season CMJ in elite volleyball players (del Aguila et al., 2021) and in-season knee pain, showed that higher values in rate limited variables eccentric deceleration RFD, rate of power development, and indicators of stiffness (in the eccentric phase/downward phase) and lower phase durations, were associated with a lower incidence of anterior knee pain during the competitive volleyball season (table 1). In contrast, overall performance metrics such as jump height, concentric peak power and overall concentric and eccentric (deceleration) impulse, were not. Therefore, higher rates of application of force/power and shorter durations in both eccentric and concentric phases of the CMJ and – considered indicators of SSC function were shown to be associated with reduced risk. While this analysis is not a prospective PT risk study, given that 45% of anterior knee pain is due to PT, it is nonetheless relevant to the practitioner.

Table 1: Selected DL-CMJ bilateral variables in professional volleyball players with and without in-season anterior knee pain.

Variable	AKP	NP	*p*	ES
Jump height (cm)	44.2 ± 5.85	46.25 ± 5.94	0.164	0.34
FT:CT	0.738 ± 0.078	0.840 ± 0.091	<0.001	1.20
Eccentric (downward) phase				
Ecc yielding duration (s)	**0.144 ± 0.027**	**0.127 ± 0.022**	**0.005**	**-0.69**
Ecc decel duration (s)	**0.182 ± 0.019**	**0.148 ± 0.019**	**<0.001**	**-1.79**
CM depth (cm)	42.23 ± 7.47	38.30 ± 8.25	0.043	-0.50
Ecc decel RFD/BW	**84.27 ± 19.64**	**124.59 ± 25.71**	**<0.001**	**1.76**
Ecc decel impulse	138.69 ± 18.54	133.49 ± 19.99	0.271	-0.27
Force at 0 velocity /BW	**24.56 ± 2.37**	**27.46 ± 2.40**	**<0.001**	**1.22**
Decel stiffness	-74.22 ± 17.41	-102.66 ± 29.94	<0.001	1.16
Concentric (Upward) phase				
Con duration (s)	**0.303 ± 0.030**	**0.268 ± 0.032**	**<0.001**	**-1.13**
Con PF/BW	**25.25 ± 2.15**	**27.95 ± 2.31**	**<0.001**	**1.21**
Con Peak Power/BW	56.55 ± 5.55	59.07 ± 7.17	0.110	0.39
Con RPD 100/BW	**118.17 ± 40.61**	**185.92 ± 69.88**	**<0.001**	**1.18**
Con Impulse	259.84 ± 24.62	248.12 ± 27.60	0.069	-0.45
Con Impulse 100	115.24 ± 15.23	128.99 ± 17.64	0.001	0.83
Landing phase				
Landing PF/BW	54.69 ± 16.31	62.63 ± 12.46	0.027	0.55

CM depth at PF (landing)	16.03 ± 3.53	14.13 ± 3.67	0.033	-0.53

Source: Prepared by the author based on Del Aguilla et al., 2021

Bold script indicates the difference between groups is significant at p<0.001. AKP=anterior knee pain, NP=pain free. PF=peak force, Decel=deceleration, RFD=rate of force development, BW=bodyweight (adjusted), RPD=rate of power development, CM=countermovement Data based on start of season CMJ assessment (5 trials) and self-report knee pain during subsequent season.

Summary

It is clear from the evidence that there are a large variety of risk factors that cause AT, and many are specifically related to kinetics and kinematics. When reviewing the detailed kinematics of shod running athletes, the shoe obscures a large amount of vital kinematic data, but it is difficult to standardise running technique whilst running barefoot. Foot postures alter when barefoot, and therefore capturing lower limb kinematics in runners when shod is fraught with inaccuracies, and the assumptions inherent to the shoe-on biomechanical model may apply.

The force requirements of the lower limb musculature in running and jumping tasks are higher than previously recognised. By assessing key kinetic and kinematic variables, the practitioner can provide feedback to enhance rehabilitation. Ankle DF ROM appears to be a key arthrokinematic variable in AT and is easily assessed with a standing knee-to-wall test. However, interventions addressing DF deficits have unfortunately shown limited success in AT prevention. Strengthening the lower limb has been identified as the most effective modality for a return to sport for those suffering AT, with programs that include heavy slow resistance appearing to be the most effective (Beyer et al., 2015; Zellers et al., 2019; Silbernagel et al., 2020) in the management of AT which may not be simply dependent on a pain monitoring approach. Understanding the minimal force requirements for return to sport is an important consideration given the large forces the Achilles is subjected to during running, cutting, jumping or decelerating. Force platforms also allow the practitioner to ascertain force capacity in a standardised seated calf raise position (Figures 6 & 7) and compare to healthy benchmarks, or if not available, the contralateral limb. It should be noted that the use of a large heavy foam pad can undermine the accurate measurement and reliability of the athlete’s ability to generate rapid forces using early RFD’s / and “forces at” (i.e., @100ms and @200ms) due to the compression of the foam, but may not affect peak force assessment. Therefore, if the practitioner is intent on capturing RFD/forces metrics that include the start of contraction (i.e., 0 to 50/100/200ms) a firm block is recommended.

The author suggests a minimum net peak vertical force of 1.5 x bodyweight before the athlete begins faster rate loading, and at least twice bodyweight before returning to competition. The CMJ with arms constrained, limiting the contribution of the upper body is a dynamic test with a clear association with force generation of the plantar flexors, in particular the soleus (Kipp & Kim, 2020). In the CMJ, phase durations – in particular, eccentric deceleration and concentric - and kinetic variables such as concentric impulse-100 and eccentric deceleration RFD are some key metrics the practitioner should review as markers of the athletes' ability to produce and attenuate force rapidly, and of SSC function - with FT:CT as a high level, albeit less sensitive indicator than component phase durations and time-constrained kinetic metrics. These metrics may not be AT or PT specific, but they are neuromuscular performance qualities and subphases identified as being most affected by lower limb injury per se (i.e. module 2 of this course), fatigue and deconditioning (Course “Performance, Injury, and Rehabilitation assessment toolbox”, Module 4) where they tend to show greater sensitivity / delayed recovery relative to jump height, concentric peak power and impulses.

During bilateral assessments such as the DL-CMJ and DL-DJ, evaluating interlimb asymmetry is pivotal to understanding the athlete’s preferential loading. These data help inform rehabilitation prescription and support the aim of rehabilitating and returning the injured athlete to sport with a higher level of neuromuscular performance than pre-injury. Also, as described for ACL, asymmetries derived from single-leg jumps may complement this as a purer global measure of strength capacity (Cohen et al. 2020).

Figure 7: Force platform isometric force assessment in a seated calf position

Figure 7 A: Side View **Figure 7 B: Front View**

Source: Prepared by the author

4.2 Kinetics and kinematics in hamstring and groin injuries

Luke Hart

Kinematic data can be used to provide objective information about joint motion, independent of forces that cause that motion (Winter, 2009). This data can include both linear and angular displacements and velocities. Kinematics can be measured with simple goniometers, video analysis or 2- and 3-dimensional (2D and 3D) motion capture systems, with the latter being considered the gold standard in motion analysis. For full details of the various motion analysis techniques, the reader is referred to module 1 of this course: The Fundamentals of Biomechanics.

From a general injury perspective, altered joint kinematics can have direct consequences on how forces are applied to the body (Nigg, 1985) and therefore contribute to the onset of an injury. In sports medicine, joint kinematics can be used in several ways: (1) to identify potential risk factors for injury (Hewett et al., 2005; Paterno et al., 2007), (2) to determine the level of functional limitation due to pathology (Carriero et al 2009 - Gait & Posture), and (3) to evaluate the level of physical recovery post-rehabilitation (King et al., 2019, King et al., 2020).

The following section will examine the biomechanical factors associated with a hamstring injury and athletic groin pain which are two of the most problematic and recurrent injuries in men's professional football.

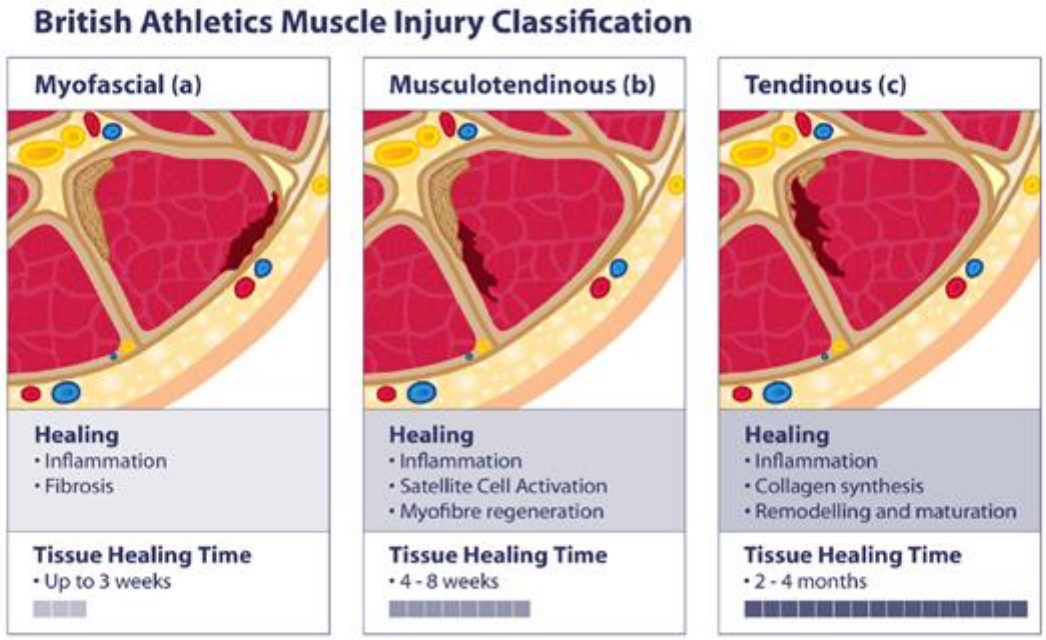
Overview: Hamstring Injuries

Hamstring strain injuries (HSI) are highly prevalent in many sports which involve high-speed running and sprinting (Brooks et al., 2006; Elliott et al., 2011; Ekstrand et al., 2011a; Orchard et al., 2013). In professional football, HSI is the most common non-contact muscle injury, representing 12% of all injuries (Ekstrand et al., 2011b). In a 25-player squad, this represents approximately 5–6 hamstring injuries and > 80 days of missed football activities (training or matches) due to HSI each season (Ekstrand et al., 2011b). The rate of HSI remains high and unchanged in men's professional football in more than a decade (Ekstrand et al., 2013). Recurrence of a hamstring injury has been reported to range from 12 to 41%, with the second injury often being more severe than the index injury (Buckthorpe et al., 2018). Strength training is typically the primary focus for HSI injury prevention and rehabilitation programs (Arnason et al., 2008; Petersen et al., 2011; Askling et al., 2013). However, given the aforementioned high injury and reinjury rates, this suggests other movement related factors, outside of muscle strength alone, are crucial in the management of hamstring injuries. High-speed running requires highly coordinated multi-planar, multi-segmental kinematic control and altered kinematics have been associated with increased risk of hamstring injury (Schache et al., 2000; Lee et al., 2009; Daly et al., 2016). The kinematics associated with HSI is explored later in this section.

Hamstring Injury Classification and Mechanism

Hamstring strain injuries can differ regarding both location and extent of injury. The British Athletics Muscle Injury Classification (BAMIC) provides a reliable MRI classification system that allows hamstring injury to be graded according to both location and extent of injury (Patel et al., 2015). When assessing a HIS using the BAMIC, the location of an injury is classed as: (a) myofascial, (b) muscle-tendon junction, or (c) intra-tendon injury. While the extent of on injury is classed from: (1) small, (2) moderate, (3) extensive, and (4) full thickness tear (see figure below) (Pollock et al., 2014; Patel et al., 2015). Injuries that involve the tendinous structures tend to have longer return to play/train times (Pollock et al., 2021). Pollock et al. (2021) found that when determining return to play times based on the classification of tendon involvement, only the cross-sectional area and not the longitudinal length of tendon involvement was significantly related to longer RTP times. It was suggested that this may result from the loss of tendon or myotendinous unit tension (Pollock et al., 2021).

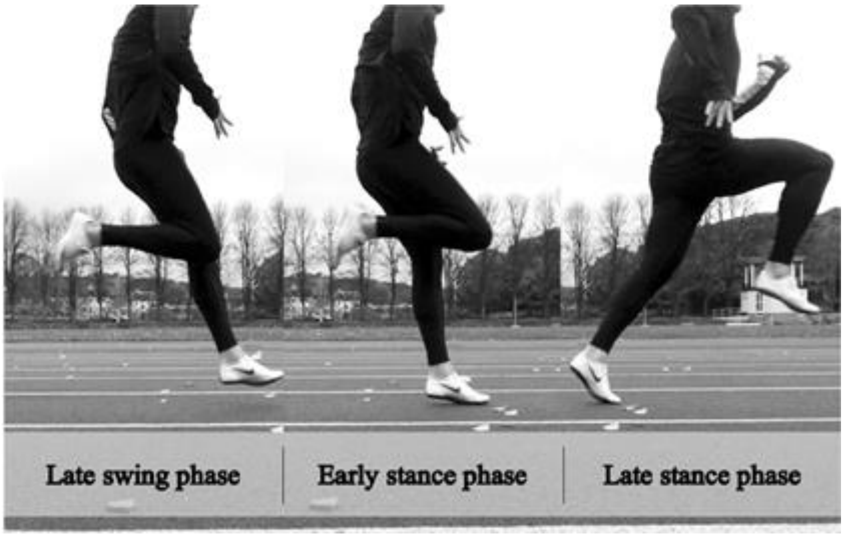
Figure 9: British Athletics Muscle Injury Classification



From Hamstring rehabilitation in elite track and field athletes: applying the British Athletics Muscle Injury Classification in clinical practice, by B. Macdonald et al., 2019, *British journal of sports medicine*, *53*(23), 1464–1473. https://doi.org/10.1136/bjsports-2017-098971

Two injury mechanism types have been proposed by Askling et al. (2012) that can result in hamstring strain injury: (1) high-speed running type, and (2) stretching type. The most common mechanism of injury is the high-speed running type (Gabbe et al., 2005). During high-speed running, there are several phases in the gait cycle in which hamstrings are believed to be most susceptible to injury due to excessive strain on the hamstring musculature. Firstly, injury can occur during the late swing phase of gait when the hamstring muscles are actively lengthening and undergoing an eccentric contraction (Lieber and Friden, 1993; Yu et al., 2008). This injury mechanism typically involves the proximal myotendinous junction of the long head of the bicep femoris muscle (Askling et al., 2007), which is subject to the largest peak strain during sprinting when compared to the other hamstring musculature (Schache et al., 2012). Secondly, injury can occur at initial contact of early stance due to the large forces experienced by the hamstring musculature concerning both rate and magnitude of the loading (Mann & Sprague, 1980). During maximum-speed sprinting, both the semimembranosus and biceps femoris play an important role in absorbing force during the early stance phase and therefore may be more susceptible to injury during this phase (Diamond et al., 2016; Higashihara et al., 2018). During acceleration sprints, the bicep femoris is more activated during early stance when compared to the semitendinosus and may likely be subject to a greater injury risk during acceleration movements (Higashihara et al., 2018). The bicep femoris muscle has been shown to be highly activated during hip extension movements when compared to other hamstring muscles (Ono et al., 2011), and this can explain the high activation pattern of the bicep femoris muscle during accelerations, where large hip extension movements are required to help produce horizontal forces against the ground to propel the body forward (Higashihara et al., 2018). Finally, and less commonly considered, is the late stance phase of the running cycle (Yu et al., 2008). During this phase, it has been found that the hamstring muscles undergo an eccentric contraction similar to that experienced during the late swing phase of the gait cycle. Furthermore, during the late stance phase, the muscle-tendon length at peak elongation velocity of all hamstring muscles was significantly greater than during the late swing phase, with the greater muscle-tendon length found in the semimembranosus muscle (Yu et al., 2008). During the late stance of running, the knee is in a relatively extended position requiring large knee flexion torque, which increases the demands on the semitendinosus muscle due to the greater production of eccentric knee flexion moment (Higashihara et al., 2018). Gaining a better understanding of HIS injury mechanism during the running cycle can give important insight for rehabilitation post hamstring injury as to which muscle groups and neuromuscular functions should be targeted (MacDonald et al., 2019). For example, if the bicep femoris hamstring is injured rehabilitation should consider hip extension movements and exercises and if the semimembranosus or semi-tendinous is injured rehabilitation should consider knee flexion exercises and movement patterns.

Figure 10: The running gait cycle



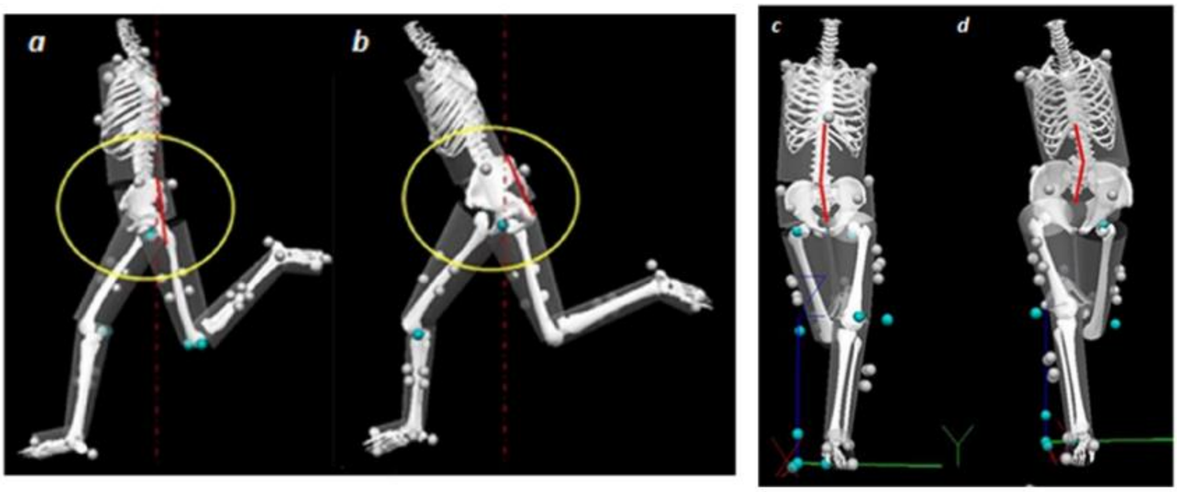
From The mechanism of hamstring injuries - a systematic review, by A. Danielsson et al., 2020, *BMC musculoskeletal disorders, 21*(1), 641. https://doi.org/10.1186/s12891-020-03658-8

Hamstring strains have been shown to cost European Football Clubs an excess of 500,000 euros per month.

Kinematics in Hamstring Injury

Altered trunk and pelvis kinematics have been reported prospectively during maximum overground running in athletes who sustained a hamstring injury (Schuermans et al., 2017). Schuermans et al (2017) found that the athletes who sustained a hamstring injury demonstrated substantially more anterior pelvic tilt throughout the entire stride cycle, with a significant difference during the backswing phase (p=0.045) when compared to the athletes who did not sustain a hamstring injury (see Figure below). It has been theorized that increased anterior pelvic tilt increases the strain placed on the hamstring muscles due to the increased lengthening of ischial tuberosity moving superiorly (Mendiguchia et al., 2021). In addition, this prospective study also found that athletes who suffered a hamstring injury demonstrated significantly greater trunk side flexion throughout the front-swing phase compared to healthy controls (p=0.028) (see Figure below). Together these findings represent poor control of the thoraco-lumbar-pelvic unit (core stability) evident in running gait kinematics in the injured athletes making them more susceptible to a hamstring injury. In line with these findings, previous research has found increased hamstring muscle activation patterns with altered trunk and pelvis postures during single-leg standing in healthy individuals (Prior et al., 2014). This gives further support for the need to assess and correct kinematics/running techniques as part of hamstring injury prevention programs (Prior et al., 2014; Schuermans et al., 2017; Mendiguchia et al., 2021).

Figure 10: Sagittal plane pelvis angle in late front swing phase & Coronal plane pelvis thorax angle in late swing phase.



Source: (a) controls, (b) hamstring injury group: Sagittal plane pelvis angle in late front swing phase. (c) Controls, (d) hamstring injury group: Coronal plane pelvis thorax angle in late swing phase. (Schuermans et al., 2017)

Running kinematics has also been reported to differ when comparing athletes with a previous hamstring injury and those with uninjured controls. Daly et al (2016) examined a cohort of Gaelic football players (9 with previous hamstring injuries and 9 controls) and reported significant kinematic movement asymmetries in the previously injured group when compared to the uninjured controls (Daly et al., 2016). Specifically, in the sagittal plane increased asymmetry in anterior pelvic tilt (4°, p=0.020) and hip flexion (8°, p=0.010) were reported in the previously injured group during a late swing. In addition, the previously injured group also displayed significantly greater asymmetry in the transverse plane, with increased medial knee rotation asymmetry (6°, p=0.030) during the terminal swing and early stance. These authors suggested that the combined kinematic asymmetries of increased anterior pelvic tilt, increased hip flex hip and increased medial knee rotation in the previously injured group may increase the strain on the long head of bicep femoris (compared to the medial hamstring muscles) potentially increasing the risk of hamstring strain injury. In support of this, the long head of the bicep femoris is the most commonly injured muscle of the hamstring group (Thelen et al., 2005; Askling et al., 2007). These persistent kinematic asymmetries observed in athletes with a previous hamstring injury provide further support for the need to address running kinematic patterns as part of a comprehensive rehabilitation program. This may then help to reduce the risk of recurrent hamstring strain which is high in athletes who suffer a hamstring injury.

Kinetics in Hamstring Injury:

Isokinetic Dynamometry

Isokinetic dynamometry (IKD) is one of the most researched areas in utilizing kinetics for hamstring rehabilitation. IKD has been widely researched as both a predictive tool for hamstring injury, but also as a method of preventing hamstring injury recurrence. Isokinetic dynamometry testing has been utilized but has often not been standardised, which is important to note as there is such a conflict in the literature about its utility in the rehabilitation and screening process.

Bennell et al. (1998) investigated the use of IKD in Australian rules for football players and found that, of the 9 players who went on to get injured, IKD testing at 60 deg/s and 180 deg/s showed no relationship or significant differences to those who did not get injured. However, this was a small sample size and did not include many of the metrics later investigated.

Because hamstring injuries tend to occur in the later phase of running and during eccentric actions, many of the more recent studies have investigated the role of eccentric hamstring strength on the IKD. Croisier et al. (2000) demonstrated that IKD including eccentric muscle actions detected 70% of hamstring strains with on average 20% reduction in normalized force, and suggested that recurrent hamstring strains can be put down to inadequate rehabilitation, lack of eccentric strength and asymmetry. Furthermore, they found that the angle of peak torque significantly differed from that of the non-operated side, suggesting that the hamstring was weaker in a more lengthened position.

This would suggest that hamstring isokinetic testing is a good metric for RTP testing. Hamstring RTP criteria are reported to be very mixed, with many clinicians using an absence of pain or pain-free running as the only criteria. However, meta analysis of RTP criteria and reinjury rates have demonstrated that utilizing IKD assessment over clinical assessment alone resulted in reduced reinjury rates. Studies involving IKD all have below <15% reinjury, whereas clinical assessment alone ranged from between 9.1%-63.3%. This demonstrates the utility of having objective makers that take human error and athlete bias out of the rehabilitation paradigm (Hickey et al., 2017,).

The conflicting nature of the previous studies presented might suggest that it is a very beneficial tool for RTP and minimizing risk of recurrent injury, but that it is limited in its use to prospectively identify those who are to get injured. However, recent research studies that have been conducted on larger cohorts of professional soccer players have demonstrated that certain metrics within isokinetic testing do , in fact, correlate with heightened risk of injury. Croisier et al. (2008) later demonstrated that, in a sample of 687 professional soccer players, an increased muscle imbalance was the highest risk factor for future hamstring injury. Furthermore, the use of mixed ratios, this means utilizing multiple speeds and muscle actions, had the highest sensitivity of all tests for predicting hamstring injury. They found that using a mixed hamstring : quadricep ratio (H:Q) of eccentric 30 deg/s—240 deg/s concentric had the highest sensitivity and that specifically eccentric muscles testing was of the most importance. It is important to note that no player who had a H:Q ratio of above 1.4 sustained a hamstring injury. The use of mixed ratios was first introduced by Agaard et al. (1998); however, it has subsequently been utilised specially in hamstring injuries for being the best test for predicting future hamstring injury (Croisier et al., 2008; Daly et al., 2016; Van Dyk et al., 2016; Lee et al., 2017).

Other IKD parameters that have highlighted increased risk are H:Q ratio at 60 deg.s and concentric and eccentric knee flexion at 60 deg/s. The wide variation in different metrics has demonstrated that it is important to not try to rely on just one test or metric when looking at hamstring injury risk or rehabilitation status, but that a full diagnostic and evaluation is vital to ascertain whether the hamstring is optimally performing or is back to full function. This could be true, since hamstring injuries are multifactorial in nature and occur through different mechanisms and causes.

It is important to note that isokinetic testing is just one method of assessing hamstring risk and absolutely should be combined with kinematic assessment that will also be spoken about in this chapter. It is important for rehabilitation professionals to build a picture of where the athlete is currently at. We would suggest that isokinetic assessment is a vital component to hamstring rehabilitation and return to play and is an excellent method of assessing the hamstring ability to produce and resist force. However, this must be combined with a rigorous kinematic assessment.

Isometric Force profiles

Whilst IKD assessment is seen as the gold standard there are limitations and as previously discussed the evidence is not completely in favour of it for its use of predicting hamstring strain risk (Toonstra & Mattacola, 2013). The main issues with utilizing IKD are that it is very intensive, usually using multiple speeds, tests, and muscle actions including both eccentric and concentric, potentially causing high amounts of muscle damage. Therefore, this testing, while it can be performed pre-season, is unlikely to be a suitable option for in season testing especially to measure compounding fatigue from game schedules or hard training cycles.

Secondly, IKD testing requires highly specialized equipment typically only found in University's or medical clinics due to its cost, which makes the barrier to entry for most professional players quite high. Lastly, there is a significant time commitment to IKD, usually taking exceeding 30 minutes per test which makes routine screening of a whole team of athletes unrealistic for performance staff.

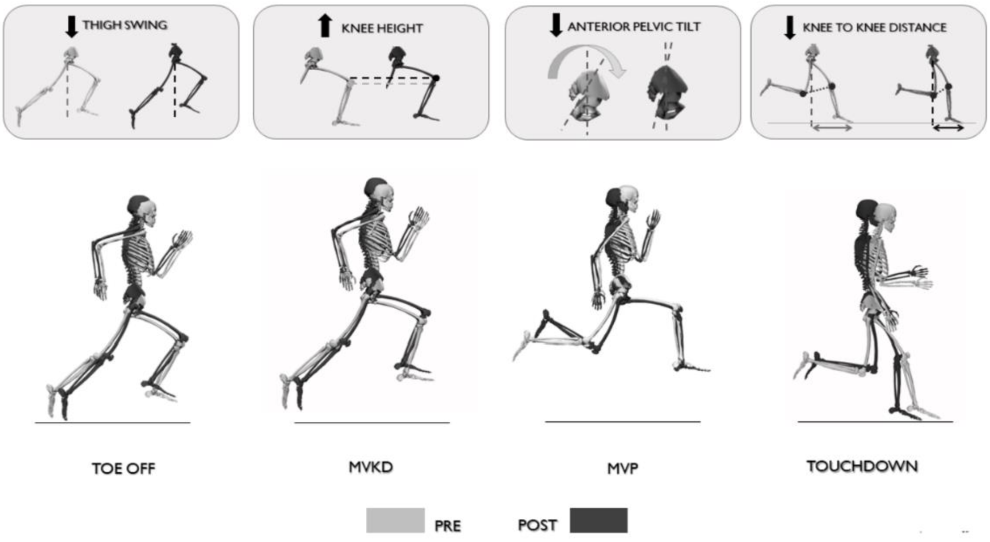
Therefore, it is important to have other methods of measuring hamstring muscle fatigue, asymmetry, and force production that do not incur high amounts of muscle damage, have a lower barrier to entry and that are time efficient for groups and teams of athletes.

Previously handheld dynamometers have been utilised, but still, they do not have the reliability in comparison to IKD testing and whilst they do not take as long as IKD to perform they still have a significant time cost (Toonstra & Mattacola, 2013). Adapted sphygmomanometer has also been studied to look at hamstring strength isometrically; however, it had poor reliability, especially when assessing interlimb asymmetry between sides (Mondin et al., 2018).

Rehabilitation of Hamstring Injury

There are many components that should constitute comprehensive hamstring injury prevention and rehabilitation programs (Mendiguchia and Brughelli, 2011; MacDonald et al., 2019). These include hamstring strength, hip muscle flexibility, hip range-of-motion and core stability, however, given the association between hamstring injury and altered running kinematics improved running mechanics must form an integral part of any management program. Mendiguchia et al (2021) have demonstrated that running mechanics can be altered with the use of a multi-modal intervention program that promotes ‘front-side’ running technique and lumbopelvic strength training. Specifically, this 6-week program led to a reduction in anterior pelvic tilt, increased knee height and improved swing leg recovery during the running gait cycle (see below figure).

Figure 11: Visual representation of the identified changes between PRE and POST for the intervention group.



Source: Mendiguchia et al., 2021.

MVP – maximal vertical, MKVD – maximal knee vertical displacement

Mendiguchia et al (2021) suggested that these alterations in the running gait cycle could reduce the strain placed on the bicep femoris muscle leading to a decreased risk of injury. This is supported by the prospective findings from Schuermans et al (2017) who reported increased anterior pelvic during running in athletes who sustained a hamstring injury (Schuermans et al., 2017). In addition, the multi-modal training program led to improved performance with a reduction in sprint times (Mendiguchia et al., 2021).

The focus of training to improve lower limb and trunk kinematics can help to ensure that efficient movement patterns and muscles are trained concurrently (MacDonald et al., 2019). Given the various functions and specific activation patterns of the hamstring muscles during sprinting (Thelen et al., 2005; Higashihara et al., 2018) the inclusion of running mechanic drills in prevention and/or rehabilitation programs can be the ideal way to retrain and increase the capacity of all hamstring muscles and their specific running functionality (Cameron, Adams and Maher, 2003; Mendiguchia and Brughelli, 2011; MacDonald et al., 2019). When considering drills to improve trunk, pelvis and hip kinematic function post hamstring injury, low load drills can be started very early as part of management programs (e.g. high-knee march step etc.), and can be progressed to higher intensity drills (e.g. A-skip, ankle dribbles etc.) as part of pre-running warm-up routine as athletes progress through the various stages of recovery.

Summary

Trunk, pelvis and hip kinematics are important considerations in relation to a hamstring injury. As the hamstring muscles originate on the ischial tuberosity, the functional output of these muscles will be directly influenced by thoraco-lumbar-pelvic function. Rehabilitation and injury prevention programs should target improved kinematic control of the trunk, pelvis and hip throughout the running gait cycle. Training should include exercises to build core stability capacity and promote increased knee drive, improved swing leg recovery and a neutral pelvis throughout the running gait.

4.3 Overview: Athletic Groin Pain

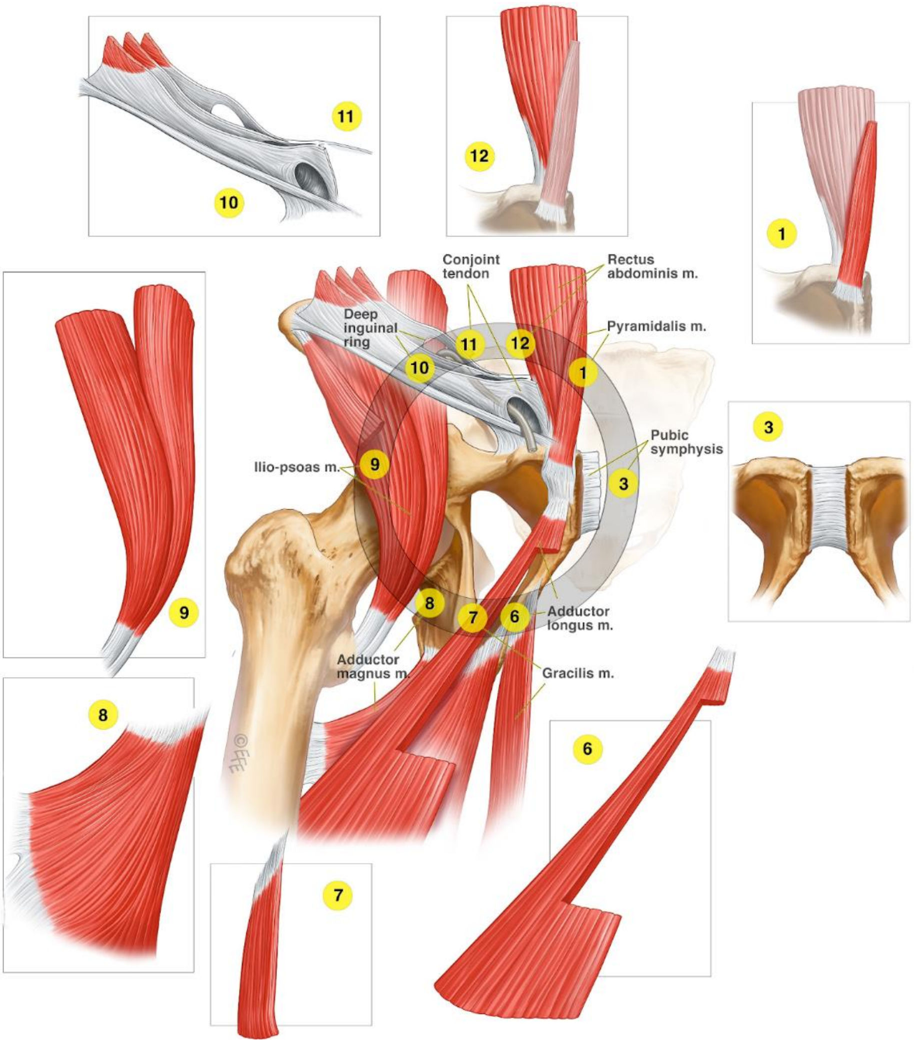
Sam Baida

Overuse athletic groin injury is common in sports which involve repetitive sprinting, change-of-direction, kicking and jump/landing actions. It is thought that injury is caused by the repetitive forces experienced across the anterior pelvis during such sporting actions. In men's senior club football, hip and groin injuries account for between 4% and 19% of all time loss injuries per season, while in women's football this figure ranges from between 2 and 14% (Walden et al., 2015). The rate of injury is between 0.2 to 2.1/1000 exposure hours in men's football and between 0.1 to 0.6/1000 hours in women's football. These findings are consistent with other sporting codes such as Australian football (8.8%, 2.7/1000hrs) (Orchard et al., 2013), Gaelic football (9.4%, 5.8/1000hrs) (Pruyn et al., 2012), rugby league (6.7%, 2.3/1000hrs) (O'Connor, 2004) and professional football (14%, 1.0/1000hrs) (Werner et al., 2019). It is typical for athletes to continue playing with symptoms by modifying their training/match loads to prevent time-off, and therefore the recording of non-time loss injuries can better capture the true extent of the problem. Studies which have recorded all hip and groin 'complaints' have demonstrated a ten-fold increase in the weekly prevalence of groin problems (time-loss injury 1.3% versus non-time loss injury 10.4%) (Esteve et al., 2020) and much higher seasonal prevalence values which have been reported to range from 50-70% (Hanna et al., 2010; Harøy et al., 2017; Thorborg et al., 2017).

Athletic Groin Pain Classification and Mechanism

Many different diagnostic labels have been used to describe overuse hip and groin pain in athletic populations that is of gradual onset. A systematic review by Serner et al. (2015) reported thirty-three different diagnostic labels were used to describe long-standing groin pain in athletes including; Gilmore's groin, sport's man hernia, long-standing adductor pain and osteitis pubis (Serner et al., 2015). To improve clarity surrounding the diagnosis of sports-related groin pain, Falvey et al. (2009) presented a systematic examination technique primarily based on palpation around a 'pubic clock' (figure below) to identify the potential pathological structures. The various pathological structures fall under the umbrella term 'athletic groin pain' (AGP) which is used to describe all diagnoses concerning the pubic symphysis, hip, and myotendinous and fascial structures which are overuse in nature and occur with sporting activity. The pathological structures outlined by Falvey et al. (2009) can be found below and are based on clinical and radiological examination (Falvey et al., 2015). These diagnoses are in line with a recent international consensus statement on terminology and definitions of long-standing groin pain in athletes (Weir et al., 2015).

Figure 12: Pubic clock. schematic representation of the myotendinous attachments across the anterior pelvic region.



From Sports Surgery Clinic, unpublished.

- Adductor injury: Palpation tenderness at the adductor tendon origin on the inferior aspect of pubic bone, pain on resisted adduction testing, Magnetic Resonance imaging (MRI) scan findings of high signal at, micro-tearing of, or separation of the adductor from the pubic bone.
- Hip flexor injury: Palpation pain over the iliopsoas muscle belly, pain of resisted hip flexion and passive hip extension in modified Thomas test position, stretching into hip extension.
- Inguinal injury: Palpation tenderness over the inguinal canal, pain on resisted ipsilateral rotation of the trunk, or on Valsalva/cough/sneeze.
- Pubic aponeurosis injury: Palpation pain over rectus abdominis insertion into the superomedial aspect of the pubic bone. Pain with squeeze test, cross-over test, resisted lower abdominal contraction. MRI scan findings of high signal at, micro-tearing of, or separation of the pubic aponeurosis from the pubic bone.
- Hip injury: Signs of hip pathology (e.g. clicking, catching), limited hip passive hip range-of-motion (<30° with the hip flexed to 90°), the pain of combined movements of the hip joint (flexion-adduction-internal rotation, flexion-abduction-external rotation).

MRI scan findings are consistent with hip pathology – femoral-acetabular impingement, osteochondral or chondrolabral pathology.

Other non-musculoskeletal or more sinister causes of groin pain can present and must be excluded for a diagnosis of AGP including nerve entrapments (i.e., ilioinguinal nerve, genitofemoral nerve), pelvic and femoral stress fractures, visceral referred pain, arterial endofibrosis, neurological, rheumatological and urological conditions (Falvey et al., 2009).

A clear diagnosis of AGP is an important consideration for management, however, this can be challenging as it is typical for patients to present with coexisting pathologies all located within proximity on the anterior pelvis (Falvey et al., 2015; Lovell, 1995; Holmich, 2007). In line with this, three large diagnostic studies have been conducted investigating patients with long-standing groin pain and have shown between 27 and 60% of patients had two or more pathologies at the pelvis concurrently when examined clinically or with imaging (Falvey et al., 2015; Lovell, 1995; Holmich, 2007). This can make treatment planning difficult as an athlete is likely to have multiple pathologies present at any time which is contributing to pain. Therefore, it has been suggested that interventions focussing on the potential injury mechanics, rather than on attempting to isolate individual pathological structures may be more effective when treating AGP (Falvey et al., 2015, King et al., 2018).

It has been suggested that poor movement control between the trunk, pelvis and hips during sporting movements (e.g., change-of-direction, sprinting, kicking) may result in excessive repetitive forces being applied to the specific structures contributing to the ongoing pain (Edwards et al., 2017; Franklyn-Miller et al., 2017; Severin et al., 2017). It is likely that the high mechanical forces experienced in one structure will be experienced across all surrounding structures and hence the multiple pathological structures evident in athletes with AGP.

In AGP research, the investigation of movement patterns via the examination of 3D kinematics is a recently emerging area of interest, with the first biomechanical study on the topic being published by Edwards et al. in 2017 (Edwards et al., 2017). Since that time, many further papers have been published which have examined whole-body kinematics in AGP during a running cut task (Edwards et al., 2017; King et al., 2018), a lateral hurdle hop task (Gore et al., 2018; 2020), a single leg drop landing (Janse van Rensburg et al., 2017), and an instep soccer kick (Severin et al., 2017). The following section covers the kinematics movement patterns that are related to AGP during the various tasks that have been examined.

Kinematics and AGP

Hip and Pelvis Kinematics

Numerous kinematic differences have been reported at the hip and pelvis, the region of the body local to the painful structures. Altered kinematics at the hip and pelvis can result in excessive loading across the anterior pelvis and the myotendinous structures that attach here. During a single leg drop landing, Janse van Rensburg et al. (2017) reported increased frontal and transverse plane hip (abduction d=1.12, external rotation d=0.61, total rotation d=0.52), and pelvis (lateral downward tilt d=0.52 to 0.75, internal rotation d=0.62) motion in athletes with AGP when compared to uninjured controls. During a single lateral hurdle hop, Gore et al. (2018; 2020) found significantly reduced hip abductor moment and stiffness in athletes with AGP compared to uninjured athletes. Importantly, hip abductor moment and stiffness measures improved following successful rehabilitation in the athletes with AGP and were no longer significantly different when compared to controls post-rehabilitation (Gore et al., 2018; 2020). The gluteal muscles, in particular, the extensors and abductors play a major role in controlling frontal and transverse hip and pelvic stability (Neumann, 2010). Increased gluteal function and strength can lead to increased stability across the pelvis and hip and therefore is important to target these muscles in the management of athletes with AGP (Baida et al. 2021, O’Connor, 2004; Morrissey et al., 2012).

Altered kinematics at the pelvis and hip have also been reported during a maximal in-step soccer kick in a cohort of athletes with a previous history of AGP when compared to uninjured control athletes (Severin et al., 2017). Severin et al. (2017) reported the altered kinematics appear to reflect compensatory movement strategies that may be used to reduce loading on the anterior pelvis during the kicking action (Brophy et al., 2007; Lees et al., 2010); however, this could shift load to other nearby structures in the region leading to increased injury risk. Specifically, during the backswing of the kick, increased anterior pelvic tilt and less hip extension was evident in the AGP group compared to the control group. In addition, slower hip flexion velocities on the stance and swing legs (d=0.41 to 0.78) were also found in the AGP group.

Trunk Kinematics

During change-of-direction (CoD) movements, there is consistent evidence that athletes with AGP display altered trunk kinematics. Specifically, increased trunk sway and rotation towards the stance leg (i.e., in the opposite direction to the intended direction of travel) has been observed in athletes with AGP in comparison to healthy athletes (Edwards et al., 2017; Rivadulla et al., 2020). These altered trunk kinematics may lead to increased loading across the anterior pelvis via two mechanisms. Firstly, via the direct connection of the trunk musculature (e.g., rectus abdominis, external oblique) to the anterior pubic and inguinal regions which may result in excessive stress on the myotendinous and fascial attachments that are commonly implicated in AGP (Meyers et al., 2012; Franklyn-Miller et al., 2017). Secondly, increased trunk and leaning over the stance leg may increase loading on the adductor muscles. In line with this, increased adductor muscle activation has been observed in a single standing task with increased trunk lean over the stance limb in healthy individuals (Prior et al., 2014). Following the successful rehabilitation of 120 athletes with AGP, reduced trunk sway and rotation towards the stance leg (i.e., more towards the intended direction of travel) was shown during a 110° planned cut which highlights the importance of targeting trunk control in the management of AGP (King et al., 2018).

Ankle Kinematics

In addition to altered kinematics at the trunk, pelvis and hips, athletes with AGP also have displayed altered kinematics at the ankle in comparison to uninjured athletes (Edwards et al., 2017; Rivadulla et al., 2020), and following successful rehabilitation (Gore et al., 2018; 2020; King et al., 2018). During a lateral hurdle hop task, Gore et al. (2020) found significantly reduced ankle plantar flexion angle in a cohort of subjects with AGP compared to controls (p=0.020, d=0.46) and following successful rehabilitation this difference was no longer evident when comparing the groups. This reduction in ankle PF angle may limit the effectiveness of the calf musculature when contacting the ground in absorbing and producing force. Supporting this, in athletes with AGP reduced ankle plantar flexion moment, power, and stiffness has been found in comparison to uninjured control athletes (Gore et al., 2018; 2020). These findings highlight the l importance of ankle function in AGP management. A reduction in the force management strategy at the ankle joint may lead to increased forces up the kinetic chain, which can affect the magnitude of loading at the hip and pelvis region (Lewis and Ferris, 2008; Rowley and Richards, 2015). This has previously been demonstrated in healthy individuals during walking gait whereby increased ankle plantar flexion moment during the push-off action resulted in concurrent decreases in sagittal plane hip moments, peak powers and angular impulse (Lewis and Ferris, 2008).

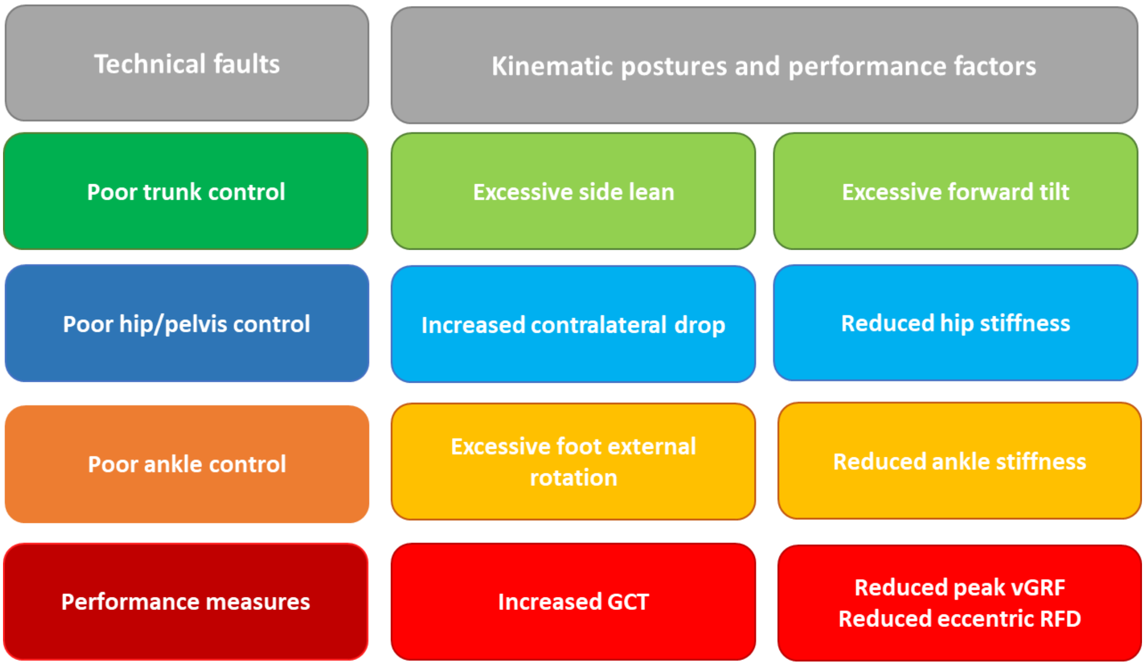
Overall, these findings highlight the importance of examining total lower limb and trunk kinematics when assessing and managing athletes with AGP. Further to this point, recent research has highlighted that athletes with a past injury history at the knee or ankle had an increased risk of a groin injury (Langhout et al., 2018). It is likely that altered biomechanics resulting from injury to the knee or ankle may result in unwanted compensatory motor control strategies affecting the hip and pelvis. In clinical practice, it is not uncommon to find athletes reporting overuse hip or groin pain several months after a past ankle injury. If the ankle injury was never fully rehabilitated as the athlete was rushed back into competition, this may result in reduced force absorption and production capacity at the ankle joint and increased loading further up the kinetic chain.

Kinematics during change-of-direction movement and AGP

Three-dimensional examination of cutting techniques, 110° cuts (Rivadulla et al. 2020) and lateral reactive hops (S. Baida et al. 2022; Gore et al. 2020), has provided important insights into potential contributing factors to overload and injury (Gore et al. 2018; Daniels et al. 2021; Edwards, Brooke, and Cook 2017; Rivadulla et al. 2020; S. Baida et al. 2022; King et al. 2018).

When assessing change of direction technique, 2D video analysis provides a useful tool that can help to identify common movement faults observed in athletes with AGP. The kinematics commonly observed with these movement faults have been described above in detail and are presented in the below figure.

Figure 13: change of direction assessment – technical faults commonly observed in athletes with AGP and associated kinematic body postures and performance deficits.



Technical faults	Kinematic postures and performance factors	
Poor trunk control	Excessive side lean	Excessive forward tilt
Poor hip/pelvis control	Increased contralateral drop	Reduced hip stiffness
Poor ankle control	Excessive foot external rotation	Reduced ankle stiffness
Performance measures	Increased GCT	Reduced peak vGRF Reduced eccentric RFD

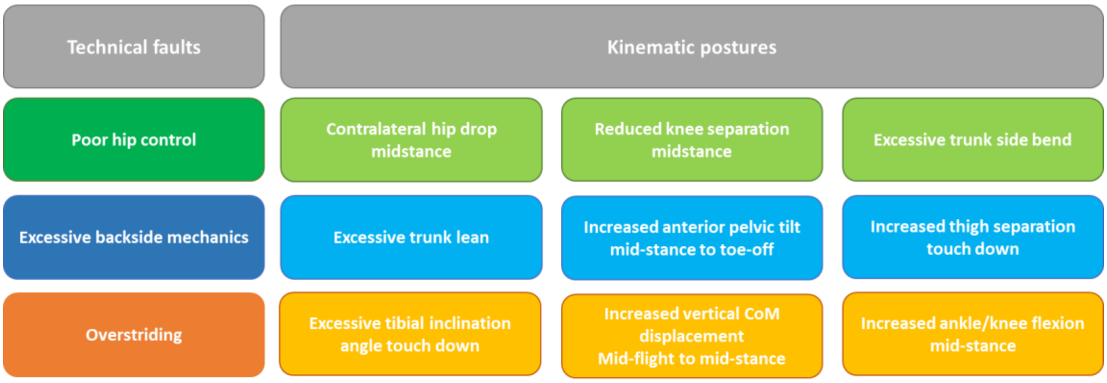
Source: Prepared by the author.

Kinematics during running and AGP

Athletes involved in field-based sports involving repetitive running and sprinting commonly report AGP (JW, 2000; O'Connor, 2004; Pruyn et al., 2012; Weir, 2015). Trunk and lower limb kinematics during running should be screened as potential contributors to the propagation of pain, although the precise kinematics remain unclear. Two-dimensional video assessment of running gait can be a reliable way to identify specific gait events (e.g. touch down, toe off) and kinematic variables 37 that have been identified as contributors to lower limb running injuries (Bramah et al., 2018).

For athletes with AGP, the analysis should include the sagittal and coronal planes and should be assessed running at high speeds (> 3.5 m/s) in order to best detect poor patterns contributing to injury. Commonly observed technical faults and associated kinematical body postures are listed in the figure below.

Figure 14: Linear gait assessment – technical faults commonly observed in athletes with AGP and associated kinematic body postures.



Technical faults	Kinematic postures		
Poor hip control	Contralateral hip drop midstance	Reduced knee separation midstance	Excessive trunk side bend
Excessive backside mechanics	Excessive trunk lean	Increased anterior pelvic tilt mid-stance to toe-off	Increased thigh separation touch down
Overstriding	Excessive tibial inclination angle touch down	Increased vertical CoM displacement Mid-flight to mid-stance	Increased ankle/knee flexion mid-stance

Source: Prepared by the author.

Poor dynamic hip control during running gait likely reflects deficits in gluteal muscle function involving a combination of reduced: strength (S. R. Baida et al. 2021), rate of force development (Kierkegaard et al. 2017), and hip stiffness (Gore et al. 2018). This can be observed during mid-stance as contralateral hip drop, reduced knee separation (excessive femoral IR/ADD), and/or compensatory trunk side bend over the stance leg. This may result in excessive shear and torsional forces at the pubis symphysis and overload on the supporting capsular and myotendinous supporting structures.

Overstriding can be observed kinematically at initial contact with increased tibial inclination angle, increased ankle dorsi-flexion and foot position more anterior relative to the hip. These kinematics are relevant to injury as a reduction in overstriding can increase loading at the ankle and reduce loading at hip, in addition to reducing braking impulses and vertical oscillations of the centre of mass (Rowley and Richards 2015; Lieberman et al. 2015).

Backside running mechanics can result in excessive anterior pelvic tilt (APT) at toe-off leading to increased tensile loading on the abdominal-pubic aponeurosis-adductor complex. Additionally, with increased APT at toe-off, the shortened position of the psoas muscle may reduce its capacity to flex the hip through early swing phase, leading to increased loading demands on the adductor longus complex which has a large flexor moment arm (Neumann 2010) and helps flex the hip from terminal stance to early swing (Lenhart, Thelen, and Heiderscheit 2014).

These technical faults are commonly observed in field sport athletes as running is generally coupled with other match actions (e.g. closing space on opposition player to make tackle, running and bouncing or passing a ball, etc.) which can make the optimization of optimal running mechanics difficult to achieve. Compounding these movement faults is the fact that field sport athletes have generally had limited exposure to the teaching and training of optimal running mechanics. This leaves a great space for rehabilitation/training where athletes can be given the tools to optimise running mechanics in controlled situations and progressed into more challenging match situations.

Rehabilitation

Rehabilitation involving overuse hip and groin injuries should target movement strategies locally at the hip and pelvis, proximally at the trunk and distally at the ankle. Regarding movement strategies at the hip and pelvis, particular attention should be paid to transverse and coronal plane control (Janse van Rensburg et al., 2017; Severin et al., 2017). Inadequate control in these planes of motion during landing or kicking movements may lead to excessive loading on the myotendinous structures across the anterior pelvis. The posterolateral hip musculature plays a primary role in transverse and coronal plane hip and pelvis control and therefore should be considered as an integral part of rehabilitation. Recent research by Baida et al. (2021) demonstrated that hip abductor and extensor strength significantly increased following a rehabilitation program targeting intersegmental control in athletes with athletic hip and groin pain. Furthermore, increased hip abductor and extensor strength could explain 11% of the improvement in self-perceived sporting and recreational activity in athletes with AGP following successful rehabilitation. The trunk is also an important consideration for hip and groin rehabilitation. The trunk accounts for upwards of 35% of body mass (Winter, 2009) and is controlled, in part, by the abdominal muscles (rectus abdominis, EO, IO) which have myofascial connections to the pubic symphysis and proximal adductor myofascial structures via the pubic aponeurosis and anterior pubic capsule (Robertson et al., 2009). Changes in trunk kinematics have been shown to alter hip muscle activation. Specifically, increased trunk anterior or side lead (away from standing leg) could increase adductor longus activation and reduce activation in the hip abductor muscles (Prior et al., 2014). Research has shown that following successful rehabilitation in athletes with AGP trunk kinematics improved during 110 cutting tasks, with athletes demonstrating reduced trunk side flexion towards the stance limb (Franklyn Miller et al., 2017). In addition to the improved trunk kinematics, the athletes with AGP also demonstrated improvement in other specific variables which have been associated with improved cutting performance, namely; reduced ground contact time, increased centre of mass distance to the centre of pressure in the frontal plane, reduced knee flexion and increased ankle power and plantar flexion movement. It was found that the combination of these biomechanical changes lead to reduced work at the hip and reduced adductor movement (King et al., 2017).

Rehabilitation strategies may also consider targeting ankle kinematics. While the impact of altered ankle kinematics relating to hip and groin pain is less clear (as compared to hip, pelvis and trunk kinematics), it has been suggested that improved ankle function may reduce loading further up the kinetic chain (King et al., 2017; Gore et al., 2018; Rivadulla et al., 2020).

This has previously been demonstrated during walking gait in healthy individuals, whereby increasing ankle plantar flexion moment reduced loading on the hip.

Summary

Altered kinematics have been identified in athletes with AGP which affect trunk, pelvis and ankle movement patterns. These altered patterns may lead to increased loading at the anterior pelvis and the myofascial attachments inserting here, which are commonly implicated in AGP. The altered kinematics identified in AGP athletes may represent both potential risk factors and compensation strategies following injury, however, due to the retrospective design of the studies no causal relationship can be determined. However, regardless of this, any altered movement patterns evident must be addressed as part of any effective management program. The movement patterns that must be assessed and targeted in athletes with AGP included altered control at the trunk (Edwards et al., 2017; King et al., 2018; Rivadulla et al., 2020), pelvis (Janse van Rensburg et al., 2017; Severin et al., 2017) and ankle (Gore et al., 2018; 2020; Rivadulla et al., 2020). Rehabilitation programs which have targeted inter-segmental control in athletes with AGP have demonstrated excellent return to play rates and time (King et al., 2018; Baida et al., 2021). Following rehabilitation, athletes with AGP have demonstrated changes in various biomechanical variables which have led to reduced loading around the hip and groin as work in all three planes of the hip (King et al., 2018) and the adductor movement were reduced (King et al., 2018; Gore et al., 2020) including reduced trunk side flexion towards the stance leg in cutting, increased hip abductor moment and stiffness (Gore et al., 2020), and increased ankle plantar flexion angle, movement, power, and stiffness during a hop task (Gore et al., 2020; 2018).

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