Abstract

Excessive or prolonged foot pronation has been linked to the development of numerous overuse injuries affecting the lower limb. The originally proposed pathomechanical model suggests foot motion affects more proximal structures through disruption of distal to proximal coupling between the foot, tibia, femur, and hip. Research evidence supports the presence of a dynamic coupling mechanism between lower limb segments, however, the direction of the coupling is inconclusive.

Recent prospective investigations of the role of the lumbo-pelvic hip complex have identified a strong association between proximal dysfunction and increased risk of lower limb injuries. Strength of muscles of the lumbo-pelvic hip complex (core muscles) is suggested to be essential to controlling hip abduction, subsequent internal rotation of the femur and potentially more distal movement. Proximal muscle weakness and altered motor control have also been implicated in the development of numerous lower limb injuries, many of which have previously been attributed to excessive foot pronation.

This review discusses the theoretical basis for the role of proximal and distal structures in biomechanical dysfunction of the lower limb and the development of lower limb overuse injury. Current prospective evidence relating to the contributions of excessive foot pronation and core muscle function to the development of lower extremity injury is evaluated.

Introduction

Generalised excessive or prolonged foot pronation has been implicated in numerous functional changes to the lower limb resulting in overuse injuries affecting the lower back, hip, knee, lower leg, ankle, and foot [1, 2]. The proposed mechanism of injury is via the propagation of abnormal functional mechanics proximally[3]. Closed chain pronation occurring at the subtalar joint (STJ) involves eversion of the calcaneus and adduction and plantarflexion of the talus [4]. The position of the talus within the ankle mortise creates a coupling mechanism, transferring pronation of the foot into rotation of the tibia via articulations at the ankle subtalar and midtarsal joints [5]. This in turn, is temporally linked to hip movement with rearfoot pronation coupled with internal rotation of the femur, and rearfoot supination synchronous with external rotation at the hip [6-8]. Disruption of the coupling mechanism has been implicated in the development of numerous musculoskeletal injuries of the lower limb [7, 9, 10]. Excessive or prolonged pronation is proposed to delay external rotation of the tibia and disrupt timing between knee extension and rearfoot supination [11-13]. This pathomechanical model has been associated with development of patellofemoral syndrome [13, 14], altered position and function of the hip and pelvis [15, 16], and the development of lower back pain [17, 18].

More recently, attention has turned to the role of proximal structures in biomechanical function of the lower limb and the development of lower extremity injury [19-21]. There is a growing body of evidence identifying strength of muscles of the lumbo-pelvic hip complex (core muscles) as being essential to controlling hip abduction, subsequent internal rotation of the femur, and potentially more distal movement [19, 22-24]. In addition, dysfunction of core muscles has been implicated in the development of various lower limb injuries, many of which have also been attributed to excessive foot pronation [19, 22, 25]. As a result, the potential for lumbopelvic instability to drive lower limb pathomechanics is increasingly being investigated.

The purpose of this review is to investigate prospective studies relating to the roles of foot pronation and core stability in biomechanical function and injury of the lower limb.

Method

The search strategy for this review consisted of an electronic database search of title and abstract. Databases included MEDLINE (1950 – 2011), SPORT discus (1985 – 2011), Cinahl (1983 – 2011) and EMBASE (1974 – 2011). Search terms used included; foot function, lumbopelvic stability, core stability, core strength, lower limb, hip, knee, kinematics and overuse injury. No language restrictions were used. Titles and abstracts were reviewed by the first author and assessed for review relevance. In relation to foot function and lower limb injury, only prospective studies which measured dynamic foot function were included in the main discussion. Review of the literature in regard to core stability and lower limb injury was restricted to prospective studies using static assessment of muscle strength and/or dynamic function. Of 161 abstracts relating to foot function and overuse injury identified, 11 studies met the above inclusion criteria. Five studies investigating core stability and lower extremity injury from the 208 abstracts retrieved met the inclusion criteria.

1. Excessive foot pronation and the development of lower limb injury

Within the foot, excessive pronation is associated with an unstable arch structure, altering propulsive mechanics, increasing strain on supporting structures including the plantar fascia, and changing load distribution under the foot [26-28]. Resulting forefoot instability is proposed to cause dysfunction of the first metatarsophalangeal joint (MTPJ) through functional restriction, producing an inefficient propulsive phase [29]. Subsequent changes to propulsive mechanics have been suggested to cause compensatory gait patterns including prolonged forefoot inversion, propulsive instability, postural perturbations and lumbopelvic-hip complex dysfunction [30, 31]. Disruption of sacroiliac nutation due to a blockade in the sagittal plane is proposed to prevent typical hip extension and reduce biceps femoris contraction. This may inhibit the normal posterior rotation of the apex of the sacrum, required to maximize lumbopelvic stability, resulting in reduced pelvic stability during the loading phase of the gait cycle [32].

Excessive pronation has also been implicated in the development of numerous lower limb injuries including plantar fasciitis, stress fractures of the foot and tibia [33, 34], medial tibial stress syndrome (MTSS) [29, 35, 36], patellofemoral pain (PFP) syndrome [13, 14] and anterior cruciate ligament (ACL) injury [37, 38]. The proposed mechanism of injury is via a coupling mechanism between the foot, tibia, femur and hip, in which foot pronation occurs with internal tibial and femoral rotation, and foot supination with external tibial and femoral rotation [13, 25]. Based on the assumption of a distally to proximally directed coupling mechanism, excessive foot pronation has been suggested to prolong tibial and femoral internal rotation [7, 13]. This coupling mechanism is supported by evidence of excessive internal limb rotation [39, 40] and delayed external tibial rotation [39] during running occurring in association with a pronated foot type. The resulting limb position is proposed to create an internally rotated knee position [7, 25, 41], moving the patella laterally on the femur, increasing compression of the lateral knee compartment, and predisposing to patella maltracking and PFP syndrome [13]. More proximally, excessive foot pronation has been hypothesised to cause femoral head pressure to be directed onto the posterior portion of the acetabulum resulting in anterior pelvic tilt [15]. The altered pelvis position is suggested to place increased strain on muscles of the pelvis and hip, including iliopsoas and piriformis. There is subsequent narrowing of the greater sciatic notch and compression of the sciatic nerve due to anterior rotation of the pelvis, potentially causing sagittal plane wedging of intervertebral discs [9, 17, 42]. In cases of asymmetrical STJ pronation, associated functional shortening of the leg is linked to lowering of the ipsilateral innominate and rotation of the lumbar vertebrae towards the more pronated foot [43]. This causes secondary lateral trunk tilt toward the functionally longer limb and frontal plane wedging of the lumbar intervertebral disks [17]. The functional changes associated with excessive foot pronation are proposed to place significant strain on the sacroiliac and lumbosacral joints and to cause lumbosacral instability [17, 18]. However, despite a well-developed theoretical pathomechanical model, the nature of the contribution of foot pronation to the development of overuse injury remains unclear.

1.1 General lower limb injury

Excessive pronation has frequently been suggested as a risk factor for the development of a number of overuse injuries of the lower limb. Theoretical models and cross-sectional studies using measures of static arch height have linked a low-arched foot to development of numerous lower limb pathologies [13, 14, 34, 36, 37, 44]. However, prospective investigations of the relationship between dynamic foot function and development of a number of injuries traditionally attributed to excessive pronation demonstrate limited evidence to support a causal relationship (Table 1). In a prospective study of foot function and relative risk of lower limb injury, Hesar et al. [45] recruited 131 healthy subjects (20 males, 111 females) with no recent history of lower limb injury to participate in a start-to-run program. The program consisted of three running sessions per week over a 10 week period. Baseline measurements were performed using a pressure plate to determine dynamic barefoot function. During the study, 27 participants developed a lower limb injury, with 8 participants having bilateral injuries. Plantar pressure analysis demonstrated increased lateral pressure during late midstance and propulsion and was associated with significantly higher risk of injury. The authors concluded that a less pronated or higher arch dynamic foot type was more likely to develop a lower limb injury [45]. These findings are supported by similar results in prospective studies investigating the role of pronation in development of specific lower limb injuries.

1.2 Stress fractures

Several cross-sectional, retrospective studies have implicated excessive foot pronation in the development of stress fractures, citing a strong association between increased range and velocity of pronation and higher incidence of stress fracture [46, 47]. However, a low static arch structure has also been identified as potentially having a preventative effect on rates of stress reaction and stress fracture [48]. Furthermore, research investigating the effect of dynamic foot pronation on incidence of femoral and tibial stress fractures suggests prolonged pronation during stance phase reduces the risk of injury [49]. In a prospective study investigating incidence of tibial and femoral stress fractures during military training, Hetsroni et al. [49] used two-dimensional analysis to measure rearfoot motion during barefoot treadmill walking in 473 recruits prior to the commencement of 14 weeks of infantry training. Rearfoot eversion angle relative to the lower leg was used to represent STJ position and foot pronation. During the study 42 participants developed 71 stress fractures of the tibia and femur, with 22 participants developing two or more. No significant association was found between the spatial measures of maximum pronation angle or range of pronation and risk of stress fracture. Participants demonstrating increased time to maximum pronation and a greater proportion of stance phase in pronation demonstrated lower risk of tibial or femoral stress fracture, with odds reduced by between 11% and 47% compared to participants demonstrating normal or limited rearfoot pronation [49].

Plantar pressure measurement of foot pronation through calculation of the dynamic arch index (the ratio of the area of contact of the midfoot to the total area of the foot) supports increased risk of stress fracture with limited pronation, but also suggests a relationship between excessive pronation and stress fracture injury [33]. In a 2 year prospective study, Kaufman et al. [33] assessed the risk factors contributing to the development of overuse injuries including stress fractures in 449 18-29 year old male military candidates undertaking fitness and combat training. Shod (military boot) and barefoot plantar pressures were measured and used to calculate a dynamic arch index. Statistically significant increased relative risk of stress fracture in association with arch index was demonstrated in shod and barefoot conditions with dynamic pes cavus (high arch), and shod condition only with dynamic pes planus (low arch). However, dynamic arch index was found to be higher (indicating a more pronated foot type) across all groups in the shod condition. The authors proposed this may have been associated with increased forces on the arch from lacing of the boots and, therefore, may have potentially overestimated the strength of the relationship between dynamic pes planus and incidence of injury in the shod condition [33]. Lack of significant relationship in the barefoot condition is in agreement with the findings of Hetsroni et al. [47] and may also indicate an effect of footwear on injury risk.

1.3 Achilles tendonopathy

Biomechanical theory underlying the development of Achilles tendonopathy (AT) attributes rapid transition of the rearfoot from a supinated to a pronated position to producing a whipping action in the tendon [50-53]. Prolonged pronation particularly following a more inverted heel strike angle, is proposed to exacerbate this, producing high tensile forces along the medial aspect of the tendon [54, 55]. The theory has been, in part, supported by evidence from cross-sectional studies demonstrating a more inverted heel strike angle and increased extent and velocity of pronation in runners with AT [51, 56, 57]. However, prospective studies investigating dynamic foot function as a risk factor for AT fail to support a relationship between excessive foot pronation and injury [33, 58].

In their previously described study, Kaufman et al. [33] also assessed dynamic arch index as a risk factor for AT. No significant increase in relative risk for AT was demonstrated with either a dynamic pes planus or a dynamic pes cavus in barefoot or shod conditions, although non-weight bearing measures of increased rearfoot inversion and gastrocnemius tightness were associated with AT [33].

Similarly, Van Ginckel et al. [58] assessed barefoot plantar force distribution using a floor-mounted pressure plate in 129 participants undertaking a running program. During the 10 weeks of training, 10 cases of clinically diagnosed AT were reported. In contrast to previous cross-sectional studies, results suggest limited foot pronation may play a role in the development of AT. Participants with AT were found to have significantly more laterally directed force distribution under the forefoot at the end of midstance and reduced total forward progression of the centre of force (CoF) beneath the foot. The authors proposed these results may be due to reduced duration of STJ eversion and a more lateral foot rollover following heel strike, causing increased impact and more strain on the lateral side of the Achilles tendon [58]. The decrease in anterior progression of the CoF was suggested to result in a decreased plantarflexor moment of the muscle–tendon unit and an inefficient propulsive phase. Proposed alterations to propulsion were supported by a significant increase in medial forefoot plantar pressure in the injured group. This was suggested to be due to increased forefoot pronation as compensation for the initial reduction in STJ pronation and higher lateral forces at heel contact [58]. The prospective results reported by both Kaufman et al. [33] and Van Ginckel et al. [58] indicate excessive foot pronation is not a causative factor in the development of AT.

1.4 Exercise related lower leg pain and medial tibial stress syndrome

Exercise related lower leg pain (ERLLP) covers a broad range of pathologies affecting the lower leg including shin splints, shin pain, compartment syndrome, MTSS and stress fractures [59]. Several retrospective studies have demonstrated a link between a static, pronated foot posture and a history of ERLLP [46, 47]. Furthermore results of prospective studies investigating intrinsic risk factors for the development of ERLLP and MTSS support a causal relationship between excessive dynamic foot pronation and injury [53, 60].

Willems et al. [53, 60] prospectively examined gait-related risk factors for the development of ERLLP in 400 physical education students participating in a weekly sports program over the course of an academic year for between one and three years. Baseline measures of plantar pressures, three-dimensional lower limb motion and static measures of lower limb alignment were taken in barefoot [60] and shod [53] conditions. Rearfoot motion in barefoot and shod conditions was determined via skin-mounted and shoe-mounted markers respectively. Forty-six participants developed ERLLP. Injured participants demonstrated increased maximum eversion and abduction angles, increased pronation and abduction excursion and an increased re-inversion velocity, indicating prolonged and excessive foot pronation. These findings were supported by evidence of a more central heel strike angle and increased medially directed plantar pressures, implicating excessive pronation in the development of ERLLP [53, 60]

Biomechanical dysfunction represented by increased medially-orientated plantar pressures has also been identified as a primary risk factor for the development of MTSS in infantry recruits [61]. In a study of 468 recruits undertaking military training, 37 recruits developed MTSS. Of the 37 injured, 26 demonstrated 'poor' foot biomechanics (determined via medial plantar pressures falling one standard deviation outside the mean in a medial direction) in comparison to 11 participants sustaining MTSS injury who demonstrated 'good' foot biomechanics. Other variables investigated, including aerobic fitness and history of smoking, were determined to be additive risk factors. However, although poor foot mechanics was considered the strongest predictive factor, when considered in isolation, biomechanical variables were only able to predict 31.6% of the MTSS group. This increased to 67.5% when biomechanical variables were combined with smoking and fitness variables [61]. Current research therefore supports the role of excessive foot pronation in the development of ERLLP and MTSS, however, further investigation of MTSS in particular is required.

1.5 Patellofemoral pain

The theoretical pathomechanical model for the development of PFP proposed by Tiberio [13] suggests excessive pronation at the STJ may cause compensatory changes to gait that result in PFP. Tiberio [13] proposed excessive pronation during the midstance phase of gait prolongs internal rotation of the lower leg. This results in disruption of the synchronised external rotation of the tibia with the femur required for extension of the tibiofemoral joint. As compensation, the femur internally rotates on the tibia, allowing knee extension but causing relative lateral deviation of the patella. Subsequent increased joint compression force between the lateral articular surface of the patella and the lateral femoral condyle is suggested to produce PFP [13]. A number of studies have retrospectively investigated the relationship between foot function and the presence of PFP, however, only two studies have assessed dynamic foot function and development of PFP prospectively [62, 63]. Thijs et al. [62, 63] investigated gait-related risk factors for the development of PFP in 84 recruits undertaking military training [63] and 102 novice runners participating in a recreational running program [62]. Barefoot plantar pressure measurements were used to determine dynamic foot motion for both groups. During the study, 36 of the 84 infantry recruits and 17 of the 102 runners developed PFP.

Injured recruits demonstrated increased lateral pressure distribution at heel strike, higher loading rate under the fourth metatarsal and delayed lateral-to-medial shift of the centre of pressure. The authors concluded the lateral pressure distribution at heel strike and the delayed lateral-to-medial transfer could reduce shock absorption, propagating higher ground reaction forces to the knee [63]. The more lateral pressure distribution was also hypothesised to indicate less pronation, potentially placing the tibia in a more laterally rotated position relative to the femur, increasing lateral patella tracking.

Dynamic risk factors for runners developing PFP were similar to their earlier study on infantry recruits, including higher peak vertical forces under the lateral heel and forefoot and more rapid loading at the rearfoot. No differences in medio-lateral force patterns for the phases of stance between the injured and control groups were demonstrated [62]. In both studies the authors concluded higher impact forces contribute to the development of PFP and excessive dynamic foot pronation did not appear to be implicated [62, 63].

1.6 Anterior knee pain

In the same cohort as used in their previously discussed study of stress fractures, Hetsroni et al. [47] also investigated the relationship between anterior knee pain and foot pronation [64]. During the 14 weeks of military training 61 of the 473 participants developed anterior knee pain. However, no consistent association was demonstrated between dynamic parameters of foot pronation measured including range, extent, timing during stance phase or pronation velocity and the incidence of injury. The relationship between anterior knee pain and pronation velocity was found to be statistically significant for the right foot, however, this finding was contradicted by a non-significant relationship for the left foot. Based on these results

Hetsroni et al. [64] concluded that development of anterior knee pain was not linked to excessive pronation.

1.7 Iliotibial band friction syndrome

Increased rearfoot eversion and subsequent internal tibial rotation has been suggested to cause an elongation of the iliotibial band. This has been proposed to be a possible aetiology of iliotibial band friction syndrome (ITBFS), however, prospective evidence is contradictory. Noerhen et al. [65] investigated biomechanical risk factors for the development of ITBFS in 400 female runners. Bilateral three-dimensional lower limb kinematic and kinetic data in running gait were collected with rearfoot motion determined via markers fixed to the heel counter of the shoe. Each participant was followed for two years with all diagnosed lower limb injuries reported. Eighteen participants developed ITBFS and their kinematic and kinetic data were compared to 18 uninjured participants matched for age and monthly mileage. No difference in peak rearfoot eversion, inversion moment or peak internal tibial rotation was demonstrated between the groups, however, a trend towards reduced peak eversion and reduced peak internal rotation in the injured group suggests excessive foot pronation was not related to injury occurrence. A more proximal contribution to the development of ITBFS is further supported by significantly higher peak hip adduction and peak knee internal rotation angles reported in the injured group [65].

1.8 Summary: Foot pronation and lower limb injury

Evidence from current prospective trials is limited, but generally fails to support a causal relationship between excessive foot pronation and lower limb injuries such as stress fractures, AT, PFP, anterior knee pain, and ITBFS. Based on prospective research, excessive pronation has only been demonstrated to be a risk factor for ERLLP and MTSS. However these findings need to be considered in light of the methodological limitations of the research. Most studies rely on plantar pressure assessment alone to categorise dynamic foot function without further investigation of rearfoot kinematics [33, 45, 56, 62, 63]. Generally, laterally and medially directed plantar pressures are assumed to represent restricted and increased dynamic foot pronation respectively. However, the accuracy of these methods of determining dynamic function is unclear. Several kinematic investigations of rearfoot motion use two-dimensional techniques, only reporting the frontal plane component of triplanar rearfoot motion [47, 64]. Furthermore studies that do use three-dimensional motion analysis use motion of the heel counter of the shoe to represent rearfoot motion, potentially affecting strength of reported relationships [51, 65]. In light of the limited quantity of prospective evidence and the aforementioned methodological considerations, it is evident further investigation of the role of foot pronation in the development of lower limb overuse injury is required.

2. Core Stability

A growing body of research links core dysfunction to the development of lower extremity injuries traditionally attributed to excessive foot pronation [19, 22, 24, 25, 66, 67]. These findings indicate that proximal dysfunction of the core may have significant implications for distal limb functioning. The term “core” relates to the osseous and soft tissue structures of the lumbopelvic-hip complex [68]. Osseous and ligamentous components of the spine create passive stability, but only make small contributions to overall stability. Spinal ligaments fulfil an essential proprioceptive role providing afferent feedback on lumbar vertebral segments [69]. The largest stabilising forces are produced by active muscle contraction with trunk, pelvis, and hip muscles contributing to the maintenance of core stability [70].

Core stability refers to the ability of the core muscles to stabilise the spine through muscle contraction and maintenance of intra-abdominal pressure [68]. Core stability is required to increase stiffness of the trunk and hip in preparation for, and in response to, spinal loading, to prevent instability of the vertebral column, and to facilitate return to equilibrium following perturbation [71]. The increased stiffness of the core provides proximal stability for movement of lower and upper limbs, maintenance of the centre of mass (COM) within the base of support, and efficient absorption of distally generated forces [24, 68]. Core stability is instantaneous and requires both substantial muscular endurance (core strength) and high level neuromuscular control [24].

Numerous muscles cross the spine and contribute to core stability. These muscles can be classified as either "local" or "global" muscles [72, 73]. The local muscular system consists of deep muscles that attach to the lumbar vertebrae such as transversus abdominus (TrA) and the multifidi. The local muscles have shorter muscle lengths and play a role in controlling the stiffness and intevertebral relationships of the spine. The global muscular system consists of the large superficial muscles of the trunk such as the paraspinal muscles and the superficial abdominals. These muscle are responsible for spinal motion and handle the external loads applied to the spine [74].

2.1 Core stability and lower limb function

Walking and running gait requires tonic activation of local muscles, such as TrA, and phasic activity of global muscles, including the superficial abdominal muscles and paraspinal muscles [75-79]. Peak periods of activity of both local and global muscles occur with heel strike, attenuating forces transmitted through the lower extremity to the spine and controlling sagittal and frontal plane position of the pelvis [77-80]. Gait produces relatively large femoral adduction moments acting across the hip, creating high demand on lateral hip muscles particularly through single leg weight bearing [81]. The hip musculature acts in conjunction with quadratus lumborum to stabilise the trunk over the lower limb and transfer force from the lower extremities to the pelvis and spine [82]. This maintains the level position of the pelvis and controls adduction of the femur [83-85]. In periods of single leg weight bearing the ground reaction force vector is reported to lie medial to the hip joint creating an external abduction moment at the hip joint [21]. Contraction of the lateral core musculature creates an opposing internal moment, preventing excessive adduction of the femur [21]. Investigations of associated kinematic changes occurring with poor core stability support a pathomechanical model of femoral adduction and internal rotation with valgus knee positioning [86-91]. This model may also have implications for more distal biomechanical function including excessive foot pronation, and subsequent mechanisms of leg and foot injury. Evidence of effective lower limb injury management following core strengthening programs targeting hip muscle strength, supports the role of proximal dysfunction in the development of lower limb injury [22, 87].

2.2 General lower limb injury

Research investigating the role of core stability in the development of lower limb injury has associated lack of strength of core muscles with changes to lower extremity function and a variety of lower limb injuries [19, 22, 92-94]. Theoretically, increased anterior rotation of the pelvis has been suggested to increase strain on the iliopsoas muscle causing internal rotation of the femur and subsequent dysfunction of the lesser gluteals [2, 9, 17]. Dysfunction of hip abductors and external rotators has been suggested to lead to similar biomechanical changes as those attributed to excessive foot pronation. The body of research linking core dysfunction, particularly in relation to hip muscle external rotation and abduction strength, to a range of knee injuries is significant. Investigations of kinematic changes occurring with poor core strength support a pathomechanical model of femoral adduction leading to frontal plane pelvic drop [85] and internal hip rotation [83] with an internally rotated and adducted knee position during single leg weightbearing [86-91]. This model may also have implications for more distal biomechanical function and is proposed to produce tightness in the tensor fascia lata and iliotibial band, predisposing to a number of lower limb injuries at the knee and more distally [19, 22, 25, 66, 95]. Evidence of effective lower limb injury management following core strengthening programs targeting hip muscle strength strongly supports the role of proximal dysfunction in the development of lower limb injury [22, 87].

The proposed link between hip strength and the development of lower limb injury is supported by a growing body of prospective studies investigating the relationship between core stability and lower limb injury (Table 2). Leetun et al. [24] measured hip abduction and external rotation strength, and anterior, posterior and lateral trunk muscle endurance in 80 female and 60 male intercollegiate basketball and track athletes prior to their competitive season. Female participants demonstrated significantly lower lateral trunk muscle endurance and hip abduction and external rotation isometric strength when compared with the male group. Over the course of the season 41 (28 females, 13 males) of 130 athletes developed 48 back or lower extremity injuries. A great percentage of female participants sustained an injury, with the foot and ankle the most commonly injured sites for both groups. Following completion of the relevant competitive seasons, regression analysis demonstrated that hip rotation strength was a useful predictor for injury status in both male and female competitors, with weakness of external rotators linked to increased risk of injury [24]. These findings are supported by a number of prospective studies reporting strong associations between presence of knee pathology and reduced core muscle strength [19, 22, 83].

2.3 Patellofemoral pain

A retrospective relationship between reduced core stability and PFP has been well established in the literature. Deficits in external hip rotation and abduction strength [19], delayed onset of contraction of anterior and posterior fibres of gluteus medius, and a reduction in lateral core strength [96] have been demonstrated in people with PFP. Hip muscle weakness has been suggested to cause increased adduction and internal rotation of the knee, increasing the lateral retropatella pressure and subsequently causing patellofemoral pain symptoms. Increases in internal femoral rotation (greater than 30°) and internal tibial rotation have been shown to cause increases in patellofemoral joint pressures, which supports an association between increased relative knee valgus and dysfunction of the patellofemoral joint [88, 97]. In contrast, morphologic characteristics of the femur, including femoral inclination and femoral anteversion measured via medical resonance imaging, were not found to be correlated to internal rotation excursion, further supporting the integral role of hip muscle activity in controlling rotation of the thigh [91].

Prospective investigations of intrinsic risk factors for PFP support the role of proximal dysfunction in injury development. Boling et al. [98] undertook a prospective investigation of biomechanical risk factors for the development of PFP in cohort of 1597 military recruits. Baseline kinematic and kinetic variables were collected prior to the commencement of military training including internal hip rotation angle, knee flexion angle, and vertical ground reaction force during a vertical jump exercise. Lower extremity isometric strength tests including knee extension, hip external rotation, hip internal rotation, knee flexion, hip extension and hip abduction and static measures of biomechanical alignment including Q-angle and navicular drop were also measured. Forty-two of the participants developed PFP while enrolled in the study. Kinetic and kinematic risk factors for PFP were determined to be increased hip internal rotation angle, knee flexion angle and a lower vertical ground reaction force. Reduced isometric measures of knee flexion and extension and increased navicular drop were demonstrated in the injured group, supporting existing biomechanical theory of the development of PFP [98]. However, evidence of increased external hip rotator strength in the injured group is not consistent with previous retrospective evidence and appears contradictory to findings of increased internal hip rotation angle, suggesting neuromuscular control rather than isometric strength may affect recruitment of hip external rotators in dynamic activity.

2.4 Iliotibial band friction syndrome

Alterations to lower limb mechanics and hip abduction weakness have also been identified in conjunction with the development of ITBFS [20, 86, 87]. Several studies have implicated biomechanical dysfunction at the hip to incidence of ITBFS. Increased internal rotation of the knee is suggested to move the attachments of the ITB medially, causing increased compression on the lateral femoral condyle. In their prospective investigation of biomechanical risk factors for the development of ITBFS previously describe in this review, Noehren et al. [65] reported that increased hip adduction and knee internal rotation in female runners were the strongest predictors for the subsequent development of ITBFS. Analysis of segmental rotation of the femur and tibia supported a proximally generated mechanism of injury for the majority of injured runners - a more internally rotated knee position did not correspond with a global increase in internal rotation or increased rearfoot eversion. A sub-group of four injured athletes with the highest rearfoot eversion demonstrated high internal tibial rotation. However, it is unknown if this is the result of foot position or proximal limb function as similarly high knee internal rotation was also reported in these participants. The authors concluded interventions for ITBFS should target hip strength and neuromuscular control [65].

2.5 Anterior cruciate ligament injury

Core dysfunction has been suggested as a contributing aetiology in the development of ACL injury. Cadaver studies have demonstrated that knee valgus increases the load on the ACL, particularly when occurring in combination with internal tibial rotation [99]. This biomechanical position is associated with direct impingement of the ACL on the intercondyler notch, increasing risk of strain [100]. Deficiencies in strength of hip abductors and extensors are suggested to allow adduction and internal rotation of the femur relative to the knee to the extent as to render an ACL injury [90, 101]. Hip muscle stiffness has been demonstrated to play an important role in reducing the risk of ACL injury. This is supported by prospective evidence implicating increased dynamic knee valgus in the occurrence of ACL injury in female athletes. Hewett et al. [102] performed pre-season assessment of kinematic and kinetic variables during a vertical drop jump including maximum knee flexion and knee abduction in 205 female adolescent soccer, basketball and volleyball players. Over the course of the playing season 9 players suffered an ACL injury. Injured players demonstrated a 2.5 fold increase in peak knee abduction angle (directing the distal tibia away from the midline), with a 20% increase in peak ground reaction force and increased knee abduction moment compared to the non-injured group. The magnitude of the knee abduction moment predicted ACL injury status with 73% specificity and 78% sensitivity. The authors equated the altered kinematic and kinetic variables to an increase in dynamic knee valgus loading on landing, which has previously been demonstrated to increase ACL strain in both cadavers and in vivo [103-106]. Dynamic knee valgus was also strongly predictive of ACL injury (r^2=0.88). The authors concluded poor neuromuscular control associated with increased dynamic valgus and knee adduction moment increased risk of ACL injury [102].

The findings above are supported by evidence of increased knee, knee ligament and ACL injuries occurring in collegiate athletes demonstrating increased trunk displacement following a sudden force release [107]. In the cohort of 277 athletes, 25 athletes developed knee injury over a period of three years. Lateral trunk displacement (used as an indicator of poor neuromuscular control) was demonstrated to be the strongest predictor of knee ligament injury. A model of trunk proprioception (measured by the difference between the actual starting position of the trunk and the position the athlete perceived was the original start position following perturbation), trunk displacement and history of low back pain predicted knee ligament injury with 91% sensitivity and 68% specificity [107]. The predictive capacity of the model was greatest in female athletes, which is in agreement with other evidence of reduced core stability and increased incidence of knee injury in females.

3. Conclusions

Traditionally excessive foot pronation has been linked to the development of numerous lower limb pathologies via a pathomechanical model of a distal to proximal dynamic coupling between the foot, knee and hip. This review highlights the lack of prospective evidence supporting a cause–effect relationship between excessive foot pronation and development of common lower limb injuries. Current evidence is limited, however, suggests excessive foot pronation increases risk of ERLLP and MTSS, but has not been demonstrated to be a risk factor for the development of AT, anterior knee pain, PFP and ITBFS. There is also evidence to suggest pronation may have a protective effect against the development of tibial and femoral stress fractures.

In contrast reduced core stability (in the form of hip abduction and external rotation weakness and poor neuromuscular control of the lumbopelvic-hip complex) is implicated in the development of general overuse injury affecting the foot and ankle, PFP, ITBFS and ACL injury. Based on these findings hip muscle strengthening and neuromuscular retraining of the lumbopelvic-hip complex should form the basis for rehabilitation of these injuries and also be considered as a means of injury prevention. However, further studies are required to determine proximal and distal contributions to other specific lower limb injuries and address methodological limitations of current research in relation to measurement of dynamic foot pronation.

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Table 1: Prospective studies: Foot pronation and lower limb overuse injury

Injury	Authors	Sample Size	Study duration	Injury rate (n)	Measurement technique	Results
General lower limb injury	Hesar et al. [45]	131 (20 males, 111 females) Recreational runners	10 weeks start to run program	27 (5 males, 22 females), 8 bilateral	Plantar pressures barefoot	No association between excessive pronation and injury risk
Stress fractures	Hetsroni et al. [49]	473 (males) Military recruits	14 weeks military training	42 (males) , 22 with 2 or more stress fractures	2-D frontal plane rearfoot motion barefoot	Excessive pronation reduced injury risk by between 11 and 47%
	Kaufman et al. [33]	449 (males) Military recruits	2 years military training	60 (males)	Plantar pressures, using dynamic arch index barefoot and shod	Excessive pronation increased risk in shod gait only
Achilles tendonopathy	Van Ginckel et al. [58]	129 (19 males, 110 females) Recreational runners	10 weeks running program	10 (2 males, 8 females), 3 bilateral, (1 male, 2 females)	Plantar force patterns barefoot	No association between excessive pronation and injury risk
	Kaufman et al. [33]	449 (males) Military recruits	2 years military training	30 (males)	Plantar pressures, using dynamic arch index barefoot and shod	No association between excessive pronation and injury risk
Exercise related lower leg pain	Willems et al. [53, 60]	400 (241 males, 159 females) Physical education students	26 weeks (3 consecutive 1st year physical education degree cohorts)	46 (17 males, 29 females), 29 bilateral (13 males, 16 females)	3-D lower limb kinematics and kinetics and plantar pressures barefoot [60] and shod [53]	Prolonged and excessive pronation associated with injury in shod and barefoot gait

Medial tibial stress syndrome	Sharma et al. [61]	468 (males) Military recruits	26 weeks military training	37 (males), 15 bilateral	Plantar pressures barefoot	Excessive pronation predicted 31.6% of MTSS injuries
Patellofemoral pain	Thijs et al. [62]	102 (13 males, 89 females) Novice runners	10 weeks running program	17 (16 females, 1 male)	Plantar pressures barefoot	No association between excessive pronation and injury risk
	Thijs et al. [63]	84 (65 males, 19 females) Infantry recruits	6 weeks military training	36 (males)	Plantar pressures barefoot	No association between excessive pronation and injury risk
Anterior knee pain	Hetsroni et al. [64]	473 (males) Military recruits	14 weeks military training	61 (males)	2-D frontal plane rearfoot motion barefoot	No association between excessive pronation and injury risk
Iliotibial band friction syndrome	Noerhen et al. [65]	400 (females) Regular runners, 20+ miles per week	2 years	18 (females)	3-D lower limb kinematics and kinetics shod	No association between excessive pronation and injury risk

Table 2: Summary of prospective studies: core stability and lower limb overuse Injury

Injury	Authors	Sample Size	Study duration	Injury rate (n)	Measurement technique	Results
General lower limb injury	Leetun et al. [24]	139 (60 males, 79 females) Collegiate athletes	2 seasons of collegiate cross country	41 (13 males, 28 females), 48 injuries	Strength testing of anterior, posterior and lateral core stabiliser s, including hip abduction and external rotation	Reduced hip external rotation strength associated with increased risk of injury
Patellofemoral pain	Boling et al. [98]	1597 (991 males, 606 females) Military recruits	3 years of military training	40 (16 males, 24 females)	3-D motion analysis of jump landing and lower extremity strength tests	Increased hip rotation associated with increased risk of injury
Anterior cruciate ligament injury	Hewett et al. [102]	205 (females) Soccer, basketball & volleyball players	1 playing season	9 (females)	3-D motion analysis kinematic and kinetic variables during a vertical drop jump including maximum knee flexion and knee abduction	Increased dynamic valgus and knee adduction moment associated with increased risk of injury
Generalised knee injury	Zazulak et al. [107]	277 (137 males, 140 females) Collegiate athletes	3 years of collegiate athletics	25 (14 males, 11 females)	3-D motion analysis of trunk motion after sudden force release	Reduced trunk proprioception, trunk displacement and presence of a history of low back pain predicts injury
Iliotibial band friction syndrome	Noerhen et al. [65]	400 (females) Regular runners, 20+ miles per week	2 years	18 (females)	3-D motion analysis of lower limb kinematics and kinetics	Increased hip adduction and knee internal rotation associated with increased risk of injury