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Torsional deformities and overuse injuries: what does the literature tell us

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- Overuse injuries imply the occurrence of a repetitive or an increased load on a specific anatomical segment which is unable to recover from this redundant microtrauma, thus leading to an inflammatory process of tendons, physis, bursa, or bone.
- Even if the aetiology is controversial, the most accepted is the traumatic one.
- Limb malalignment has been cited as one of the major risk factors implicated in the development of overuse injuries.
- Many authors investigated correlations between anatomical deviations and overuse injuries, but results appear mainly inconclusive.
- Establishing a causal relationship between mechanical stimuli and symptoms will remain a challenge, but 3D motion analysis, musculoskeletal, and finite element modelling may help in clarifying which are the major risk factors for overuse injuries.

Keywords
- malalignment
- overuse injuries
- gait analysis

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Introduction

Each year, an increasing number of children are injured in sport competitions and in high demanding physical activities (1, 2, 3). The spectrum of sports-related injuries varies from serious ligamentous tears or bone fractures to other pathological conditions, known as overuse injuries. This term indicates the occurrence of a repetitive or an increased load on a specific anatomical segment which is unable to recover from this redundant microtrauma, thus leading to an inflammatory process of tendons, physis, bursa, or bone (1, 4). The association of higher demanding sport activities and lower baseline fitness condition due to the sedentary lifestyle among children and adolescents leads to the perfect environment for the increase of such diseases (5).

In particular, sport activities which involve repetitive forefoot contact, such as running (6, 7, 8), jumping (9, 10), or ballet (11, 12, 13), may also lead to overuse injuries, such as patellofemoral pain syndrome, patellar tendonitis, Achilles tendonitis, and forefoot injuries.

The spectrum of overuse injuries is wide. It ranges from traction apophysitis, such as Osgood–Schlatter disease (OSD) or Sever's disease (SD), to patellofemoral pain syndrome (PFPS), to injuries of the musculotendinous unit, such as patellar or supraspinatus tendinitis (3, 14).

Traction apophysitis, also known as apophysitis, epyphysitis, or ostechondrosis are injuries located in the epiphyseal cartilage.

The aetiology of traction apophysitis is controversial. Genetic, vascular, traumatic, and endocrine causes are sometimes considered. However, the most accepted aetiology is the traumatic one; strenuous activities increase the loads at the tendinous-physeal junction, leading to excessive traction on the secondary ossification centres, thus resulting in biological alteration of the cartilage and initiation of the inflammatory process (1, 3, 4, 14).

From preclinical studies, it is well known that both chondrocytes and the matrix are influenced by mechanical loads which provoke a homeostatic response (15, 16). Many studies established the role that increased loads may have on the development of knee osteoarthritis (OA) (15, 17, 18, 19). For example, the effects of biomechanical changes induced by iatrogenic injuries, such as anterior cruciate ligament (ACL) transection and meniscal injuries, have been investigated in the animal model.

ACL injury is known to cause changes in both antero-posterior translation and rotational kinematics, leading to altered loads and increased stresses which are thought to be the cause of cartilage progressive thinning (15, 20).

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Following the same concept, meniscal tears have been shown to induce knee OA (20). The removal of meniscal tissue causes higher stress contact and damages to the underline cartilage. Roos *et al.* (21) demonstrated that at least half of the patients who underwent a meniscectomy during adulthood showed signs of knee OA 21 years later, compared to only 7% among patients without any meniscal injury. While the pathomechanics of these two types of knee-induced OA has long been established, little is known about the development of overuse and cartilage injuries in young populations.

Some studies attempted to find a correlation between overuse injuries and anatomical malalignment (3, 22, 23) in young populations. The term 'miserable misalignment', first used by Stanley J. in 1979 to indicate a condition of excessive femoral neck anteversion (FNA), squinting patella, and excessive external tibial rotation, has been considered as a risk factor in the onset of overuse injuries, especially the PFPS (23). Studies combining 3D gait analysis and musculoskeletal modelling have shown that altered anatomy leads to altered kinematics (24, 25, 26, 27, 28, 29) and changes, often increases, in lower limb joint loads (25, 30). However, to date, no investigation has clearly stated a link between malalignment and overuse diseases, as findings are often conflicting.

The purpose of this narrative review is to report the current knowledge on the link between anatomic deviations, altered loads, and development of overuse injuries (Fig. 1). The overuse injuries considered were SD, OSD, PFPS, and knee osteochondritis dissecans (OCD).

Sever's disease

SD, also known as calcaneal apophysitis, is the most common cause of heel pain among paediatric patients (31). It affects the secondary ossification centre of the calcaneus, and symptoms can last for several months.

The increase in loads and higher peak plantar pressure beneath the heel, especially during physical activity, has always been considered as one of the main factors responsible for the development of SD (32). Becerro-de-Bengoa-Vallejo *et al.* compared the plantar pressure and plantar surface contact area between two groups of patients, one of the healthy patients and the other group of patients affected by SD (33). The authors used pedobarography to conduct the analysis, and the results showed that patients with SD had higher heel plantar pressures during both dynamic and static conditions. The authors also identified a higher bodyweight distribution over the affected limb, thus supporting the pathophysiological mechanism of an overuse injury. These results were consistent with other previous data published by the same group (34). On the other hand, D. Little *et al.* found no significant difference in peak vertical ground reaction forces (GRFs) over an adult population affected by unilateral plantar heel pain with respect to healthy contralateral side (35). The investigation was made by the means of a Kistler portable force plate system.

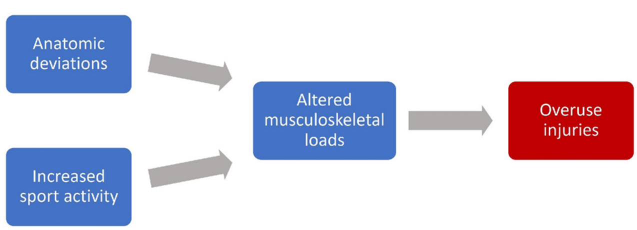

Figure 1
Proposed pathogenetic path involved in the development of overuse injuries; the interplay between anatomic deviations and increased physical activity leading top altered musculoskeletal loads, which can determine the onset of overuse pathologies.

McSweeney *et al.* investigated the role of heel increased loads during treadmill walking and running (36). The study population was composed of 28 patients, where half of them suffered from calcaneal apophysitis. The authors were not able to find any statistically significant difference in terms of maximum pressure beneath the heel and vertical GRFs. Only a higher cadence while running was found in the apophysitis group.

Biomechanical misalignment of the rear foot has also been cited as one of the possible causes of SD. Some authors observed an increased pronation thus leading to a shortened and stiffened Achilles tendon, while, on the contrary, these findings were not reported in other studies (31, 32). Literature regarding rearfoot alignment and development of SD is inconclusive, and no studies reported well documented and reproducible measurement tools.

Osgood–Schlatter disease

OSD encompasses a strain injury of the tibial tubercle apophysis in its apophyseal stage during adolescence (37). Current pathogenic factors frequently associated with OSD are muscle tightness and inflexibility, especially of quadriceps muscle, lower leg malalignment, and increase loads on the immature tibial tubercle apophysis (37, 38).

Muscle tightness has been widely investigated. Recently, Nakase *et al.* conducted a prospective analysis on 150 male soccer players (300 knees) and found a significant correlation between OSD, quadriceps femoris muscle tightness, and strength during knee extension, with an associated reduced flexibility of the hamstring muscles (38).

The traction force applied by the patellar tendon to the tibial tubercle apophysis has never been measured experimentally. Itoh *et al.* were the first to estimate the force on the tibial tubercle through gait analysis and musculoskeletal modelling (39). The authors analyzed the knee extension moment in eight patients, during the two most common activities (soccer and basketball) considered as involved in the development of OSD. Movements with the largest knee extension moment were the single-leg landing after a jump and the cutting movement, which is a fast change of direction in the frontal plane while running at maximum speed.

Little is also known about the effect of lower limb malalignment on the onset of OSD. Watanabe *et al.* found an increase of the medial longitudinal arch measurement with respect to the development of OSD, among 37 male soccer players (40). The authors also investigated the lower leg Q-angle, but no significant correlations were reported. Seyfettinoğlu *et al.* conducted a prospective observational case–control study over two groups of adolescents, one with a diagnosis of OSD and one without it (41). The Q-angle was found to be statistically significant between the groups, but the authors concluded that patellofemoral alignment did not influence the onset of OSD, as the 2° difference was considered not clinically relevant.

Patellofemoral pain syndrome

PFPS is one of the most common cause of anterior knee pain (AKP) among adolescents, with higher incidence in females (42). It has always been considered as an overuse injury, but the aetiology remains unclear (42, 43).

A widely accepted hypothesis involves an increased stress in the patellofemoral joint (PFJ), where malalignment is thought to have a crucial role (23, 42). Patellofemoral malalignment is thought to be strictly influenced by lower limb torsional defects, such as increased femoral anteversion, external tibial torsion, and abnormal pronation. These torsional deviations could affect both static and dynamic PFJ kinematics, thus leading to higher joint contact pressures (25), with subsequent articular cartilage damage and insult to the subchondral bone. Nevertheless, the literature is not able to show a clear consensus on this topic (22, 23).

Ficat and Hungerdorf (44) described a phenomenon called the 'law of valgus', where a lateral directed force acts on the patella due to the increased valgus (Q-angle) of the lower limb. Although correlation between malalignment and PFPS has been largely supported (23, 45, 46), other authors question the strength and significance of such correlation (45). A clear causal relationship between anatomic deviations and PFPS is difficult to establish, as altered patellar alignment can also be present in asymptomatic individuals, as reported by some authors who observed laterally-directed patellar alignment in asymptomatic knees with the aid of radiographic measurement or MRI (22, 43, 47).

Although femoral anteversion and foot pronation have been the focus of attention in many studies, the conclusions have been elusive here also. Increased FNA has been considered responsible for the increased femoral internal rotation, thus leading to an augmented Q-angle which causes patellar maltracking. Many authors found a positive correlation between FNA and incidence of PFPS thus supporting this theory (23, 48, 49, 50). On the contrary, Fairbank *et al.* did not find any statistically significant correlation between joint mobility, Q-angle, genu valgum, and FNA over a population of 446 'pupils', where 136 of them suffered from PFPS, when compared with a cohort of 52 hospital outpatients with knee pain (51). Likewise, other published papers supported this lack of correlation (23, 48, 52).

Erkocak *et al.* (45), reported CT-based measurements over 3 samples: 35 symptomatic knees, 35 asymptomatic contralateral knees in the same patients, and 40 healthy knees of control patients. The authors found higher Q-angle values, increased FNA, and an augmented external tibial torsion in patients with AKP compared to the healthy control group; however, no significant differences were revealed comparing symptomatic knees and the contralateral asymptomatic knee in the same patient. This led the authors to state that malalignment may not be the only factor in the development of patellofemoral (PF) symptoms.

As PF symptoms occur mainly under weight-bearing conditions, the greatest limitation in the current literature is that very few papers investigated this disease from a dynamic point of view (22). *In vivo*, non-invasive evaluation of PF kinematics is challenging (53, 54, 55), and few investigations with confusing results have been made.

Koh *et al.* were the first to compare the patellar kinematics between 10 healthy subjects and 9 patients affected by PFPS *in vivo* and non-invasively (56). The analysis was conducted thanks to a custom-made patellar clamp, infrared markers, and an optoelectronic motion capture system. The study demonstrated a higher lateral patellar translation and lateral patellar spin in the group of subjects who suffered from PFPS, thus supporting the theory of an inadequate patellar balance during weight-bearing- and dynamic activities.

Powers *et al.* utilized kinematic MRI to observe knee extension from 45° to 0° in six females with PF pain and lateral patellar subluxation (57). The authors analyzed the patients both non-weight-bearing and weight-bearing (unilateral squat), and results showed a higher lateral patellar displacement under non-weight-bearing knee extension with respect to the same weight-bearing condition.

In light of this contradictory evidence, it appears increasingly necessary to evaluate PFPS from a dynamic point of view with the aim of the more modern gait analysis and musculoskeletal modelling protocols.

Knee Osteochondritis Dissecans

OCD is typical in children and adolescents. OCD affects primarily the subchondral bone and then the overlying cartilage (58). The most common location in the knee is the inner part of the medial femoral condyle, and the aetiology remains unknown (59). In addition to genetic, trauma, and vascular insult, a mechanical malalignment origin has also been investigated.

The first biomechanical evaluation reported were those of Bandi and Kolp in 1982 (60, 61). Bandi stated that lesion of the osteochondral unit was caused by a compressive deformation of the femur intercondylar fossa under the mechanical forces of both patella and tibial plateau. In the same year, Kolp *et al.* published a photoelastic study in support of this theory, showing a high compressive force especially at 45° of knee flexion.

Perren *et al.* in 1991 (62), hypothesized the aetiology of OCD results from femoral condyles' deformation under dynamic loads. The authors conducted the analysis by means of a finite element model derived from CT images of an adult femur, which was subjected to progressive knee flexion (30, 60, and 90°). Results demonstrated that the greatest deformation occurred at 60° of flexion, with larger values in the posterior portion of the medial condyle compared to the lateral one.

More recently, some investigations attempted to find a correlation between lower leg axis deviation and OCD. Jacobi *et al.* (63) performed a radiographic analysis on 103 knees (adolescent and adult patients), finding a correlation between medial OCD and varus alignment, and between lateral OCD and valgus deviation. Gonzalez-Herranz *et al.* reported similar findings over a case series of 53 patients, 43 of them with open physis (64). The authors stated that poor outcome and higher incidence of unstable lesions occurred when lower limb mechanical axis deviation and lesion location converged. The association between OCD lesion location and mechanical axis deviation was also found by Bugbee *et al.*, even when no correlation between mechanical axis deviation and size lesion was found (65).

The role of external tibial torsion has also been investigated. Tuner *et al.* in 1981 (66), used a clinical method to measure tibial torsion over 836 adult patients, finding a higher external tibia rotation in those patients affected by knee OCD. Later, Bramer *et al.* (67) conducted a retrospective CT-based study confirming a higher average external tibia torsion in the OCD group than in controls, and that extreme grades of torsion correlate with the persisting of symptoms.

Discussion

The present study aimed to report the current knowledge about the development of the most common overuse injuries in children and adolescents. We focused our attention on the potential role of abnormal anatomy of the lower limb in the transverse and frontal planes as well as their mechanical effects during dynamic activities.

Abnormal limb alignments have been cited as one of the major risk factors implicated in the development of overuse injuries (22, 23, 43). These anatomical deviations included FNA, genu valgum, abnormal tibial torsion, pes planus, and PF maltracking.

Many authors investigated correlations between anatomical deviations and overuse injuries, but the results appear mainly inconclusive. There is an increasing interest in clarifying the role of joint loads as missing links between anatomical deviations and over overuse injuries.

Unfortunately, the majority of the published papers put the attention on static parameters, instead of focusing on the dynamic behavior of the entire 'altered' lower limb. Furthermore, the methods used to assess the malalignment were not systematic and always reproducible.

Although the effect of torsional deformities and anatomical deviations on the gait pattern has been widely investigated in children with cerebral palsy (CP) (68), only a few studies have been published in idiopathic, otherwise healthy populations. It is well known that static measurements poorly correlate with kinematics and kinetics of the lower limb during gait. This knowledge originates from studies regarding the surgical indication of femoral derotational osteotomy in patients with idiopathic increased femoral anteversion. Radler *et al.* (27) found a poor correlation between FNA measured in CT scans and internal hip rotation during gait, while, MacWilliams *et al.* (69) demonstrated a high rate of surgical overcorrection of the increased FNA when only static measurements are considered during surgical planning.

Schranz *et al.* (70) investigated the correlation between dynamic hip internal rotation during gait and FNA in 30 adolescents affected by recurrent patella instability, with the aid of 3D gait analysis (52). The authors' hypothesis was confirmed, although static measurements of femoral anteversion (in this case carried out with MRI) poorly correlated with dynamic hip rotation.

These contradictory findings highlight that 3D gait analysis may play a role in understanding functional impairments at the root of common overuse injuries.

Studies investigating the role of altered joint loads on the onset and the worsening of cartilage defects or osteoarthritis have been informative. However, similar studies investigating the effect of sustained musculoskeletal loads on the onset of overuse injuries are still lacking and appear to be needed. Computational methods such as musculoskeletal modelling and finite element analysis that combine patient-specific anatomy, kinematics, and kinetics can estimate the mechanical stimulus experienced in the regions of interest, such as cartilage stresses and contact pressures (71, 72, 73, 74); ligament forces, strains and elongation patterns (75, 76); strains and stresses on the bone (77, 78, 79); as well as on specific sub-regions of the bone, such as the proximal femur growth plate (80, 81, 82). The computational nature of these methods enables a thorough evaluation of the musculoskeletal loads occurring during various activities of daily living, demanding occupational tasks, sport activities, and strengthening programs across large samples of the population (83, 84, 85, 86, 87). Motion analysis of specific tasks and activities could help identifying some of the overuse and traumatic injury mechanisms and risk factors (2, 88, 89, 90, 91), especially through the use of wearable technologies (92, 93). Establishing causal relationship between mechanical stimuli and symptoms will remain a challenge, but 3D motion analysis, musculoskeletal, and finite element modelling may help in clarifying which are the major risk factors for overuse injuries. Figures 2 and 3 report on two examples from our clinical practice in which gait analysis and musculoskeletal modelling are routinely used for the assessment of adolescent patients with orthopaedic conditions. A more systematic use of these technologies in a clinical setting would provide clinicians, physiotherapists, sports coaches, and families with quantitative information for a more evidence-based decision making in the management of injuries and return to sports in children and adolescents.

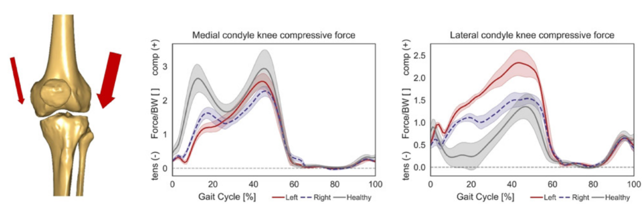

Figure 2
Medial and lateral condyle knee compressive forces during gait computed by means of musculoskeletal modelling (AnyBody Technology A/S, Aalborg, Denmark). Knee compressive forces are normalized by body weight (BW) and reported over the gait cycle for left (red solid line) and right (blue dashed line) leg. The example refers to the clinical gait analysis of one adolescent patient with knee pain. The patient presented CT-confirmed femoral retroversion on both sides, as well as dynamic genu valgum and foot external rotation during gait. The analysis of joint loads indicates an altered load distribution, with an overload of the lateral compartment during gait, more pronounced on the left knee.

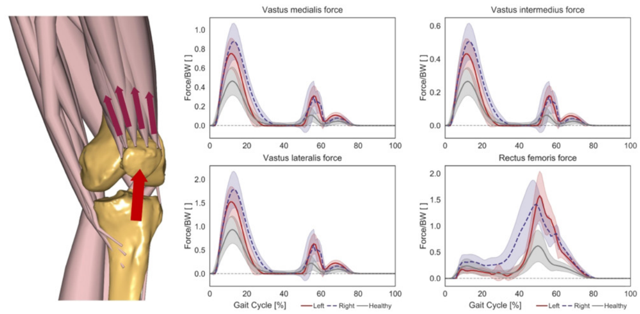

Figure 3
Forces transmitted from the quadriceps to the patella during gait, computed by means of musculoskeletal modelling (AnyBody Technology A/S, Aalborg, Denmark). Muscle forces are normalized by body weight (BW) and reported over the gait cycle for left (red solid line) and right (blue dashed line) leg. The example refers to the clinical gait analysis of one adolescent patient with bilateral Osgood–Schlatter disease. The patient is habitual toe-walker, and his gait pattern is associated with larger forces produced by the knee extensors. Repetitive high loads on the patella might lead to an overload of the patellar ligament and the onset of Osgood–Schlatter disease.

Conclusions

The aim of this narrative review is to present the current knowledge on the link between anatomic deviations, altered loads and development of overuse injuries. Even if this field has been widely investigated, establishing a causal relationship between alteration of mechanical stimuli caused by anatomical deviations and symptoms still remains a challenge. The major concern of the current literature is that the majority of the published papers put the attention on static parameters. In this light, 3D motion analysis and musculoskeletal modelling may help in clarifying which are the major risk factors implicated in the development overuse injuries.

ICMJE Conflict of Interest Statement
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