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

Gherardo Pagliazzi\textsuperscript{1,2}, Enrico De Pieri\textsuperscript{3,4}, Michèle Kläusler\textsuperscript{1}, Morgan Sangeux\textsuperscript{3,5,6} and Elke Viehweger\textsuperscript{1,3,4}

\textsuperscript{1}Department of Paediatric Orthopaedics, University of Basel Children’s Hospital, Basel, Switzerland
\textsuperscript{2}Service of Orthopaedics and Traumatology, Department of Surgery, EOC, Lugano, Switzerland
\textsuperscript{3}Laboratory for Movement Analysis, University of Basel Children's Hospital, Basel, Switzerland
\textsuperscript{4}Department of Biomedical Engineering, University of Basel, Basel, Switzerland
\textsuperscript{5}Murdoch Children’s Research Institute, Melbourne, Victoria, Australia
\textsuperscript{6}The University of Melbourne, Melbourne School of Engineering, Melbourne, Victoria, Australia

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.

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.

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.

Traction apophysitis, also known as apophysitis, ephyphysitis, or osteochondrosis 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-physisal 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) transaction 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).
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.

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 apophysal 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. Seyfettinöllü 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 (PF), 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 PF 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 Hungerdorff (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
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 aetiopathology remains unknown (59). In addition to genetic, traumatic, 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. Jacoby 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 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.

**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**

E D P reports receiving internal grant called ‘Research Fund Junior Researcher’ awarded by the University of Basel. M K works as an orthopaedic surgeon at Children’s hospital, Basel and has received grants from Beatrice Ederer Stiftung, Stiftung Cerebral, and MBF Foundation. E V reports receiving travel/accommodation/meeting expenses from Allergan, France, and EUROS SAS. All other authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the work reported.

**Funding Statement**

This work did not receive any specific grant from any funding agency in the public, commercial or not-for-profit sector. The publication of this article was funded by the University of Basel Open Access Publication Fund.
References

1. Launay F. Sports-related overuse injuries in children. Orthopaedics and Traumatology, Surgery and Research 2015 101 (1 Supplement) S139–S147. (https://doi.org/10.1016/j.otsr.2014.06.030)

2. Conley R, Tulchin K, Harris G, Smith P, Humm J & Hassani S. Pediatric sports medicine: an evolution of applications of motion analysis. In Pediatric Gait: A New Millennium in Clinical Care and Motion Analysis Technology, pp. 116–123, 2000.

3. Hawkins D & Metheny J. Overuse injuries in youth sports: biomechanical considerations. Medicine and Science in Sports and Exercise 2001 33 1701–1707. (https://doi.org/10.1097/00005768-200110000-00014)

4. Difiori JP, Benjamin HJ, Brenner JS, Gregory A, Jayanthi N, Landry GL & Luke A. Overuse injuries and burnout in youth sports: a position statement from the American Medical Society for Sports Medicine. British Journal of Sports Medicine 2014 48 287–288. (https://doi.org/10.1136/bjsports-2013-09299)

5. Yang J, Tibbetts AS, Covassin T, Cheng G, Nayar S & Heiden E. Epidemiology of overuse and acute injuries among competitive collegiate athletes. Journal of Athletic Training 2012 47 198–204. (https://doi.org/10.4085/1062-6050-47.2.198)

6. Besier TF, Fredericson M, Gold GE, Beaupre GS & Delp SL. Knee muscle forces during walking and running in patellofemoral pain patients and pain-free controls. Journal of Biomechanics 2009 42 898–905. (https://doi.org/10.1016/j.jbiomech.2009.01.012)

7. Fredericson M & Misra AK. Epidemiology and etiology of marathon running injuries. Sports Medicine 2007 37 437–439. (https://doi.org/10.2165/00007256-200737040-00004)

8. Neal BS, Barton CJ, Gallie R, O’Halloran P & Morrissey D. Runners with patellofemoral pain have altered biomechanics which targeted interventions can modify: a systematic review and meta-analysis. Gait and Posture 2016 45 69–82. (https://doi.org/10.1016/j.gaitpost.2015.11.018)

9. Ferretti A, Ippolito E, Mariani P & Puddu G. Jumper’s knee. American Journal of Sports Medicine 1983 11 58–62. (https://doi.org/10.1177/036354658301100020)

10. Lian OB, Engebretsen L & Bahr R. Prevalence of Jumper’s knee among elite athletes from different sports: a cross-sectional study. American Journal of Sports Medicine 2005 33 561–567. (https://doi.org/10.1177/0363546504270454)

11. Prisk VR, O’Loughlin PF & Kenneth JG. Forefoot injuries in dancers. Clinics in Sports Medicine 2008 27 305–320. (https://doi.org/10.1016/j.csm.2007.12.005)

12. Sobrino FJ, de la Cuadra C & Guillén P. Overuse injuries in professional ballet: injury-based differences among ballet disciplines. Orthopaedic Proceedings of Sports Medicine 2015 3 2352967115590114. (https://doi.org/10.17223/2352967115590114)

13. Smith PJ, Gerrie BJ, Varner KE, McCulloch PC, Lintner DM & Harris JD. Incidence and prevalence of musculoskeletal injury in ballet: a systematic review. Orthopaedic Proceedings of Sports Medicine 2015 3 2352967115592621. (https://doi.org/10.17223/2352967115592621)

14. Bell DR, Post EG, Biesse K, Bay C & McLeod TV. Sport specialization and risk of overuse injuries: a systematic review with meta-analysis. Pediatrics 2018 142 e20180657. (https://doi.org/10.1542/peds.2018-0657)

15. Felson DT. Osteoarthritis as a disease of mechanics. Osteoarthritis and Cartilage 2013 21 10–15. (https://doi.org/10.1016/j.joca.2012.09.012)

16. Ryan JA, Eisner EA, DuRaine G, You Z & Reddi AH. Mechanical compression of articular cartilage induces chondrocyte proliferation and inhibits proteoglycan synthesis by activation of the ERK pathway: implications for tissue engineering and regenerative medicine. Journal of Tissue Engineering and Regenerative Medicine 2009 3 107–116. (https://doi.org/10.1002/ted.20146)

17. Seedhom BB. Conditioning of cartilage during normal activities is an important factor in the development of osteoarthritis. Rheumatology 2006 45 146–149. (https://doi.org/10.1093/rheumatology/kei197)

18. Wong M, Wuetrich P, Buschmann MD, Eggli P & Hunziker E. Chondrocyte biosynthesis correlates with local tissue strain in statically compressed adult articular cartilage. Journal of Orthopaedic Research 1997 15 189–196. (https://doi.org/10.1002/jor.1100150206)

19. Andriachi TP, Koo S & Scanlan SF. Gait mechanics influence healthy cartilage morphology and osteoarthritides of the knee. Journal of Bone and Joint Surgery: American Volume 2009 91 (Supplement 1) 95–101. (available at: https://journals.lww.com/jbjsjournal/Fulltext/2009/02001/Gait_Mechanics_Impact_Healthy_Cartilage_23.aspx) (https://doi.org/10.2106/JBJS.H.01408)

20. Poulsen E, Goncalves GH, Bricca A, Roos EM, Thorlund JB & Juhl CB. Knee osteoarthritis risk is increased 4–6 fold after knee injury-a systematic review and meta-analysis. British Journal of Sports Medicine 2019 53 1454–1463. (https://doi.org/10.1136/bjsports-2018-100022)

21. Lohmander LS, Englund PM, Dahl LL & Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. American Journal of Sports Medicine 2009 37 1756–1769. (https://doi.org/10.1177/0363546507307396)

22. Wilson T. The measurement of patellar alignment in patellofemoral pain syndrome: are we confusing assumptions with evidence? Journal of Orthopaedic and Sports Physical Therapy 2007 37 330–341. (https://doi.org/10.2519/jst.2007.2281)

23. Krivickas LS. Anatomical factors associated with overuse sports injuries. Sports Medicine 1997 24 132–146. (https://doi.org/10.2165/00007256-199724020-00005)

24. Bruderer-Hofstetter M, Fenner V, Payne E, Zdenek K, Klima H & Wegener R. Gait deviations and compensations in pediatric patients with increased femoral torsion. Journal of Orthopaedic Research 2015 33 155–162. (https://doi.org/10.1002/jor.22746)

25. Passmore E, Graham HK, Pandy MG & Sangeux M. Hip- and patellofemoral-joint loading during gait are increased in children with idiopathic torsional deformities. Gait and Posture 2018 63 228–235. (https://doi.org/10.1016/j.gaitpost.2018.05.003)

26. Mackay J, Thomason P, Sangeux M, Passmore E, Francis K & Graham HK. The impact of symptomatic femoral neck anteversion and tibial torsion on gait, function and participation in children and adolescents. Gait and Posture 2021 86 144–149. (https://doi.org/10.1016/j.gaitpost.2021.03.004)

27. Radler C, Kranzl A, Manner HM, Höglinger M, Ganger R & Grill F. Torsional profile versus gait analysis: consistency between the anatomic torsion and the resulting gait pattern in patients with rotational malalignment of the lower extremity. Gait and Posture 2010 32 405–410. (https://doi.org/10.1016/j.gaitpost.2010.06.019)

28. Alexander N, Wegener R, Lengnick H, Payne E, Klima H, Cip J & Studer K. Compensatory gait deviations in patients with increased outward tibial torsion pre and post tibial osteotomy. Gait and Posture 2020 77 43–51. (https://doi.org/10.1016/j.gaitpost.2020.01.011)

29. Alexander N, Studer K, Lengnick H, Payne E, Klima H & Wegener R. The impact of increased femoral anteversion on gait deviations in healthy adolescents. Journal of Biomechanics 2019 86 167–174. (https://doi.org/10.1016/j.jbiomech.2019.02.005)

30. De Pieri E, Friesenbichler B, List R, Monn S, Casaretelli NC, Leunig M & Ferguson SJ. Subject-specific modeling of femoral torsion influences the prediction of hip...
loading during gait in asymptomatic adults. *Frontiers in Bioengineering and Biotechnology* 2021 **9** 679360. ([https://doi.org/10.3389/fbioe.2021.679360](https://doi.org/10.3389/fbioe.2021.679360))

31. Scharbhillig RW, Jones S & Scutter S. Severe’s disease: a prospective study of risk factors. *Journal of the American Podiatric Medical Association* 2011 **101** 135–145. ([https://doi.org/10.7547/1010133])

32. Dowling GJ, Murley GS, Munteanu SE, Franettovich Smith MM, Neal BS, Griffiths IB, Barton CJ & Collins NJ. Dynamic foot function as a risk factor for lower limb overuse injury: a systematic review. *Journal of Foot and Ankle Research* 2015 **7** 53. ([https://doi.org/10.1186/s13047-014-0053-6])

33. Becerro-de-Bengoa-Vallejo R, Losa-Iglesias ME & Rodríguez-Sanz D. Static and dynamic plantar pressures in children with and without severe disease: a case-control study. *Physical Therapy* 2014 **94** 818–826. ([https://doi.org/10.2522/ptj.20120164])

34. Becerro de Bengoa Vallejo R, Losa Iglesias ME, Rodríguez Sanz D, Prados Frutos JC, Salvador Fuentes P & Chicarro JL. Plantar pressures in children with and without Severe’s disease. *Journal of the American Podiatric Medical Association* 2011 **101** 17–24. ([https://doi.org/10.7547/1010017])

35. Liddle D, Rome K & Howe T. Vertical ground reaction forces in patients with unilateral plantar heel pain—a pilot study. *Gait and Posture* 2000 **11** 62–66. ([https://doi.org/10.1016/S0966-6362(99)00053-3])

36. McSweeney S, Reed LF & Wearing SC. Vertical ground reaction forces during gait in children with and without calcaneal apophysitis. *Gait and Posture* 2019 **71** 126–130. ([https://doi.org/10.1016/j.gaitpost.2019.04.027])

37. Ladenhauf HM, Seitlinger G & Green DW. Osgood–Schlatter disease: a 2020 update of a common knee condition in children. *Current Opinion in Pediatrics* 2020 **32** 107–112. ([https://doi.org/10.1097/MOP.0000000000001842])

38. Nakase J, Goshima K, Numata H, Oshima T, Takata Y & Tsuchiya H. Precise risk factors for Osgood–Schlatter disease. *Archives of Orthopaedic and Trauma Surgery* 2015 **135** 1277–1281. ([https://doi.org/10.1007/s00402-015-2270-2])

39. Itoh G, Ishii H, Kato H, Nagano Y, Hayashi H & Funasaki H. Risk assessment of the onset of Osgood–Schlatter disease using kinetic analysis of various motions in sports. *PloS ONE* 2018 **13** e0190503. ([https://doi.org/10.1371/journal.pone.0190503])

40. Watanabe H, Fujii M, Yoshimoto M, Abe H, Toda N, Higashiyama R & Takahira N. Pathogenic factors associated with Osgood–Schlatter disease in adolescent male soccer players: a prospective cohort study. *Orthopaedic Journal of Sports Medicine* 2018 **6** 2325967118792192. ([https://doi.org/10.1177/2325967118792192])

41. Seyfettinoluğ F, Köse Ö, Öğur Hu, Tuhanluoğlu Ü, Çiçek H & Acar B. Is there a relationship between patellofemoral alignment and Osgood–Schlatter disease? A case-control study. *Journal of Knee Surgery* 2020 **33** 67–72. ([https://doi.org/10.1055/s-0038-1676523])

42. Petersen W, Ellermann A, Gösele-Koppenburg A, Best R, Rembitzki IV, Brüggemann GP & Liebau C. Patellofemoral pain syndrome. *Knee Surgery, Sports Traumatology, Arthroscopy* 2014 **22** 2264–2274. ([https://doi.org/10.1007/s00167-013-2759-6])

43. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: a theoretical perspective. *Journal of Orthopaedic and Sports Physical Therapy* 2003 **33** 639–646. ([available at: PubMed.ncbi.nlm.nih.gov/14669959/](https://pubmed.ncbi.nlm.nih.gov/14669959/)). ([https://doi.org/10.2519/jospt.2003.33.11.639])

44. Ficat RP & Hungerford DS. Disorders of the Patello-Femoral Joint. Williams & Wilkins, 1977.
58. Bruns J, Werner M & Habermann C. Osteochondritis dissecans: etiology, pathology, and imaging with a special focus on the knee joint. Cartilage 2018 9 346–362. (https://doi.org/10.1177/1947603517715736)

59. Andriolo L, Crawford DC, Reale D, Zaffagnini S, Candrian C, Cavicchioli A & Filardo G. Osteochondritis dissecans of the knee: etiology and pathogenetic mechanisms. A systematic review. Cartilage 2020 11 273–290. (https://doi.org/10.1177/1947603518786557)

60. Bandi W, Die retropatellaren Kniegelenkschaden. Pathogenese, Pathologische Anatomie, Klinik. Bern: Ther Begrutachtung Huber, 1982.

61. Kolp W & Fethke K. Spannungsoptische untersuchungen eines belasteten kiegelkernes als beitrag zur tylologie der osteochondritis dissecans. Beiträge zur Orthopadie und Traumatologie 1982 29 493–500.

62. Nambu T, Gasser B, Schneider E, Bandis W & Perren SM. Deformation of the distal femur: a contribution towards the pathogenesis of osteochondritis dissecans in the knee joint. Journal of Biomechanics 1991 24 421–433. (https://doi.org/10.1016/0021-9290(91)90030-q)

63. Jacobi M, Wahl P, Bouaicha S, Jakob RP & Gautier E. Association between mechanical axis of the leg and osteochondritis dissecans of the knee: radiographic study on 103 knees. American Journal of Sports Medicine 2010 38 1425–1428. (https://doi.org/10.1177/036354651035970)

64. Gonzalez-Herranz P, Rodriguez ML & de la Fuente C. Femoral osteochondritis of the knee: prognostic value of the mechanical axis. Journal of Children's Orthopaedics 2017 11 1–5. (https://doi.org/10.1302/1863-2548-11-160173)

65. Brown ML, McCauley JC, Gracitelli GC & Bugbee WD. Osteochondritis dissecans lesion location is highly concordant with mechanical axis deviation. American Journal of Sports Medicine 2020 48 871–875. (https://doi.org/10.1177/0363546520955567)

66. Turner MS & Smillie IS. The effect of tibial torsion of the pathology of the knee. Journal of Bone and Joint Surgery (British Volume) 1981 63-B 396–398.

67. Bramer JAM, Maas M, Dallinga RJ, Te Slaa RL & Vergroesen DA. Increased external tibial torsion and osteochondritis dissecans of the knee. Clinical Orthopaedics and Related Research 2004 422 175–179. (https://doi.org/10.1097/01.blo.0000126306.26311.2d)

68. Graham HK, Rosenbaum P, Paneth N, Dan B, Lin JP, Damiano DL, Becher JG, Gaebler-Spira D, Colver A, Reddihoough DS et al. Cerebral Palsy. Volume. 2, Nature Reviews Disease Primers, pp. 1–25. Nature Publishing Group, 2016. (https://doi.org/10.1038/nrdp.2015.82)

69. MacWilliams BA, McMulkin ML, Davis RB, Westberry DE, Baird GO & Stevens PM. Biomechanical changes associated with femoral derotational osteotomy. Gait and Posture 2016 49 202–206. (https://doi.org/10.1016/j.gaitpost.2016.07.002)

70. Schranz C, Belohlavek T, Sperl M, Kraus T & Svehlik M. Does femoral anteversion and internally rotated gait correlate in subjects with patellofemoral instability? Clinical Biomechanics 2021 84 105333. (https://doi.org/10.1016/j.clinbiomech.2021.105333)

71. Ng KCG, Mantovani G, Lamontagne M, Labrosse MR & Beaulé PE. Increased hip stresses resulting from a cam deformity and decreased femoral neck-shaft angle during level walking. Clinical Orthopaedics and Related Research 2017 475 998–1008. (https://doi.org/10.1002/cnr.23596)

72. Halonen KS, Dzialo CM, Mannisi M, Venäläinen MS, de Zee M & Andersen MS. Workflow assessing the effect of gait alterations on stresses in the medial tibial cartilage – combined musculoskeletal modelling and finite element analysis. Scientific Reports 2017 7 1–14. (https://doi.org/10.1038/s41598-017-17228-x)

73. Lenhart RL, Kaiser J, Smith CR & Thelen DG. Prediction and validation of load-dependent behavior of the tibiofemoral and patellofemoral joints during movement. Annals of Biomedical Engineering 2015 43 2675–2685. (https://doi.org/10.1007/s10439-015-1326-3)

74. Sangeux M, Marin F, Charleux F & Ho Ba Tho MC. In vivo personalized finite element modelling of the knee joint derived from MRI images: methodology applied on one contact problem including bones, cartilages and menisci. European Journal of Computational Mechanics 2009 18 81–92. (https://doi.org/10.3166/ejcm.18.81-92)

75. Hosseini Nasab SH, Smith CR, Schütz P, Postolka B, List R & Taylor WR. Elongation patterns of the collateral ligaments after total knee arthroplasty are dominated by the knee flexion angle. Frontiers in Bioengineering and Biotechnology 2019 7 323. (https://doi.org/10.3389/fbioe.2019.00323)

76. Dejtiar DL, Dzialo CM, Pedersen PH, Jensen KK, Fleron MK & Andersen MS. Development and evaluation of a subject-specific lower limb model with an eleven-degrees-of-freedom natural knee model using magnetic resonance and bipolar X-ray imaging during a quasi-static lunge. Journal of Biomechanical Engineering 2020 142 061001. (available at: https://asmedigitalcollection.asme.org/biomechanical/article-pdf/142/6/061001/6475989/341242-061001.pdf). (https://doi.org/10.1115/1.4044245)

77. Xu C, Silder A, Zhang J, Hughes J, Unnikrishnan G, Reifman J & Rakesh V. An integrated musculoskeletal-finite element model to evaluate effects of load carries on the tibia during walking. Journal of Biomechanical Engineering 2016 138 101001. (https://doi.org/10.1115/1.4034216)

78. Seo JW, Kang DW, Kim JY, Yang ST, Kim DH, Choi JS & Tack GR. Finite element analysis of the femur during stance phase of gait based on musculoskeletal model simulation. Bio-Medical Materials and Engineering 2014 24 2485–2493. (https://doi.org/10.3233/BME-141062)

79. Wang H & Dueball S. Subject-specific musculoskeletal model for studying bone strain during dynamic motion. 2018 134 56759. (https://doi.org/10.3791/56759)

80. Shefelbine SJ & Carter DR. Mechanobiological predictions of growth front morphology in developmental hip dysplasia. Journal of Orthopaedic Research 2004 22 346–352. (https://doi.org/10.1002/jor.20303.08.004)

81. Sadeghian SM, Lewis CL & Shefelbine SJ. Predicting growth plate orientation with altered hip loading: potential cause of cam morphology. Biomechanics and Modeling in Mechanobiology 2019 19 701–712. (https://doi.org/10.1007/s10237-019-01241-2)

82. Kainz H, Killen BA, Wesseling M, Perez-Boerema F, Pittlo L, Aznar JMG, Shefelbine SJ & Jonkers I. A multi-scale modelling framework combining musculoskeletal rigid-body simulations with adaptive finite element analyses, to evaluate the impact of femoral geometry on hip joint contact forces and femoral bone growth. PLoS ONE 2020 15 e0235966. (https://doi.org/10.1371/journal.pone.0235966.t001)

83. Lunn DE, De Pieri E, Chapman GJ, Lund ME, Redmond AC & Ferguson SJ. Current preclinical testing of new hip arthroplasty technologies does not reflect real-world loadings: capturing patient-specific and activity-related variation in hip contact forces. Journal of Arthroplasty 2020 35 877–885. (https://doi.org/10.1016/j.arth.2019.10.006)

84. De Pieri E, Lunn DE, Chapman GJ, Rasmussen KP, Ferguson SJ & Redmond AC. Patient characteristics affect hip contact forces during gait. Osteoarthritis and Cartilage 2019 27 895–905. (https://doi.org/10.1016/j.joca.2019.01.016)
85. Skals S, Bláfoss R, Andersen LL, Andersen MS & de Zee M. Manual material handling in the supermarket sector. Part 2: Knee, spine and shoulder joint reaction forces. Applied Ergonomics 2021 92 103345. (https://doi.org/10.1016/j.apergo.2020.103345)

86. Dupré T, Tryba J & Potthast W. Muscle activity of cutting manoeuvres and soccer inside passing suggests an increased groin injury risk during these movements. Scientific Reports 2021 11 1–9. (available at: https://www.nature.com/articles/s41598-021-86666-5)

87. Schellenberg F, Taylor WR & Lorenzetti S. Towards evidence based strength training: a comparison of muscle forces during deadlifts, goodmornings and split squats. BMC Sports Science, Medicine and Rehabilitation 2017 91 1–10. (https://doi.org/10.1186/s13102-017-0077-x)

88. Ford KR, Myer GD & Hewett TE. Valgus knee motion during landing in high school female and male basketball players. Medicine and Science in Sports and Exercise 2003 35 1745–1750. (https://doi.org/10.1249/01.MSS.0000089346.85744.D9)

89. Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterbeck JR, Hewett TE & Bahr R. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. American Journal of Sports Medicine 2007 35 359–367. (https://doi.org/10.1177/0363546506293899)

90. Abernethy L & Bleakley C. Strategies to prevent injury in adolescent sport: a systematic review. British Journal of Sports Medicine 2007 41 627–638. (available at: https://bjsm.bmj.com/content/41/10/627). (https://doi.org/10.1136/bjsm.2007.035691)

91. Bates NA & Hewett TE. Motion analysis and the anterior cruciate ligament: classification of injury risk. Journal of Knee Surgery 2016 29 117–125. (https://doi.org/10.1055/s-0035-1558855)

92. Di S, Lopomo NF, Villa F Della, Paolini G, Figari G, Bragonzoni L, Grassi A & Zaffagnini S. Rehabilitation and return to sport assessment after anterior cruciate ligament injury: quantifying joint kinematics during complex high-speed tasks through wearable sensors. Sensors 2021 21 2331. (https://doi.org/10.3390/s21072331)

93. Adesida Y, Papi E & McGregor AH. Exploring the role of wearable technology in sport kinematics and kinetics: a systematic review. Sensors 2019 19 1597. (https://doi.org/10.3390/s19071597)