https://doi.org/10.1016/j.gaitpost.2021.05.009

Extrinsic Foot Muscle Forces and Joint Contact Forces in Flexible Flatfoot Adult with Foot Orthosis: A Parametric Study of Tibialis Posterior Muscle Weakness

Yinghu Peng [a], Yan Wang [a,b], Duo Wai-Chi Wong [a,b], Tony Lin-Wei Chen [a], Guoxin Zhang [a], Qitao Tan [a], Ming Zhang [b, a*]

[a] Department of Biomedical Engineering, Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region, China

[b] The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, China

*Corresponding author: Prof. Ming Zhang

Department of Biomedical Engineering, Faculty of Engineering,

The Hong Kong Polytechnic University,

Hung Hom, KLN,

Hong Kong, China

Email: ming.zhang@polyu.edu.hk

Abstract

Background

The posterior tibialis tendon dysfunction (PTTD) is typically associated with progressive flatfoot deformity and pain development, which could be alleviated with foot orthosis. However, the evaluation of TP weakness on lower limb mechanics of flatfoot adults with foot orthoses is scarce and requires further investigation.

Research question

This study aimed to examine the effects of tibialis posterior (TP) weakness on lower limb joint contact forces and extrinsic foot muscle forces in flatfoot adults with foot orthosis through gait analysis and musculoskeletal modelling.

Methods

Fifteen young adults with flatfoot were recruited from University to perform a gait experiment with and without foot orthoses. Data collected from the motion capture system were used to drive the musculoskeletal modelling for the estimation of the joint force and extrinsic muscle forces of the lower limb. A parametric analysis was conducted by adjusting the TP muscle strength from 40% to 100%. Two-way repeated measures ANOVA was used to compare the peak extrinsic foot muscle forces and joint forces among different levels of TP weakness and insole conditions.

Results

TP weakness significantly increased ankle joint force superoinferiorly ($F = 125.9$, $p < 0.001$) and decreased anteroposteriorly ($F = 125.9$, $p < 0.001$), in addition to a significant increase in the muscle forces of flexor hallucis longus ($p < 0.001$) and flexor digitorum longus ($p < 0.001$). Besides, the foot orthosis significantly reduced most peak muscle forces whilst significantly reduced the second peak knee force and peak ankle force compared to the control condition ($F = 8.79 – 30.9$, $p < 0.05$).

Significance

The increased extrinsic foot muscle forces (flexor hallucis longus and flexor digitorum longus) and ankle joint forces in the TP weakness condition indicated that TP weakness may induce compensatory muscle activation and attenuated joint load. The abnormal muscle and joint mechanics in flatfoot adults with TP weakness might be restored by the orthosis.

Keyword: Joint contact force; Foot orthoses; Tibialis posterior muscle; Gait analysis; Musculoskeletal dynamics simulation

1. Introduction

Posterior tibial tendon dysfunction（PTTD）is a progressive disorder in the tendon, which is generally associated with adult-acquired flatfoot [1]. In the early stage, the tendinopathy could be asymptomatic and challenging to diagnose radiographically [2]. With the progression of PTTD, patients would complain about foot pain, rigidity, and foot posture changes, even loss of function [1, 3]. In stage II PTTD, the tibialis posterior (TP) insufficiency was one of the causes of flexible flatfeet [4].

PTTD patients demonstrated a change in foot kinematics and kinetics during walking [5, 6]. Ness, Long, Marks and Harris [5] found that PTTD patients showed lower hindfoot dorsiflexion and higher hindfoot eversion than healthy participants. Some studies also indicated that the tibialis posterior (TP) muscle was less likely to be activated in PTTD, thus generating lower force during gait [7, 8]. To perform the same movement, other extrinsic foot muscles, like flexor halluces longus (FHL) and flexor digitorum longus (FDL), may generate higher forces to compensate for the weakened TP muscle [7-10]. However, the effects of TP weakness on extrinsic foot muscle forces and joint mechanics were difficult to be obtained due to the challenge of in vivo measurement of lower limb mechanics. The musculoskeletal multibody platform could be an alternative method to estimate the muscle compensation mechanism of TP weakness in patients with flatfeet, thus providing biomechanical understanding for conservative clinical treatment, such as foot orthosis intervention.

Foot orthoses have been widely used to improve stability and relieve pain for flatfoot individuals [11, 12]. A review of orthotic design for adults with flatfoot [13] indicated that medial posting insoles could effectively reduce the peak eversion of the rearfoot. Well-designed foot orthosis could substitute some functions of the TP that could probably be failing among the flatfoot adults. Although previous studies have investigated the effects of foot orthosis on the angles and moments of the lower limb joints during walking or running [14-16], the potential biomechanical parameters related to lower limb pain and dysfunction, such as joint contact mechanics and TP muscle forces, were commonly overlooked. Investigating the effects of foot orthosis on joint contact forces and muscle forces could provide more insights to understand the foot's biomechanical response to orthosis intervention in adult-acquired flatfoot, thereby contributing to the optimal treatment of foot deformity.

The aims of this combined experimental and computational study are two-fold: 1) to examine how muscles compensate for the TP muscle weakness in flatfoot, and 2) to investigate how foot orthoses affect the muscle force patterns and lower limb joint contact forces in TP weakness conditions. The previous study has indicated that extrinsic foot muscles, such as FHL and FDL, may attempt to substitute the functions of TP in case of PTTD [8]. Therefore, we hypothesized that the forces of FHL and FDL would increase when the strength of TP decreased. While the foot orthosis, to an extent, aimed to accommodate or restore the biomechanical environment of the foot. It was hypothesized that extrinsic foot muscle forces and lower limb joint contact forces would decrease in the foot orthosis condition.

2. Methods

2.1 Participants

The experimental data used in this study were obtained from our previous study [17]. A total of fifteen young people (21.7 ± 1.2 years, 168.5 ± 7.3 cm, and 57.8 ± 7.9 kg), including nine males and six females, were recruited from the Hong Kong Polytechnic University. The participants have regular physical activity (moderate-intensity aerobic/brisk walk for 150 minutes each week). The inclusion criteria included fallen medial foot arches with arch index (AI) > 0.28 on both sides [18], 18 - 25 years old, and not overweight (BMI>30 $kg \cdot m^{-2}$). The exclusion criteria included biomechanical abnormalities and complications, rigid flatfoot, neuromuscular disease, and foot orthoses use or physiotherapy in the last 6 months prior to the testing. Each subject signed a consent form to agree to the data collection and experimental process, which was approved by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University (Number: HSEARS20150121003).

2.2 Equipment and procedure

A motion capture system, including eight cameras (Vicon, Oxford Metrics Ltd., Oxford, England) and four force plates (OR6, AMTI, Watertown, United States), was used to capture marker trajectories and ground reaction forces. Data were collected synchronously with sampling frequencies of 100 Hz and 1000 Hz, respectively. A modified plug-in gait lower limb marker protocol was used in this study [17].

All participants underwent gait analysis under two conditions, namely walking with shoes and foot orthosis (WSFO) and walking with shoes (WS) in random order. The same running shoes (Reebok Run Supreme 4.0, Reebok, Boston, United States) with foot orthotic insole (Universal Flat Foot, Dr Kong, HK, China) were used in this study. The foot orthoses with a 3-cm thick arch support and 6° inclined medial forefoot posting was adopted, since one previous review study has indicated that medial forefoot with arch support insole could effectively control the rearfoot eversion for adults with flatfoot [13]. The design configuration of the orthosis is shown in our previous study [17]. During the gait analysis, the participants were asked to familiarize themselves with the shoes and environment. Participants were asked to walk at a self-selected comfortable speed on a 10m pathway. Six successive walking trials were collected for each condition. The trials were regarded as successful when their footsteps were placed entirely on the force plates.

2.3 Musculoskeletal modelling

In this study, the lower limb musculoskeletal multibody modelling in the AnyBody Managed Model Repository (V1.6.2) the AnyBody Modeling System (AnyBody Technology, Aalborg, Denmark, version 6.0.5) [19] was used to estimate the joint mechanics and muscle forces. The generic musculoskeletal multibody modelling is built based on an anthropometric database of the Twente Lower Extremity Model (TLEM 1.1) [20], including a spherical hip joint, a hinged patellofemoral, tibiofemoral, ankle, and subtalar joints, and approximately 160 muscle units.

Marker trajectories and force plate data obtained from the motion capture system were input into the model to estimate the joint forces and muscle forces. Prior to the calculation process of musculoskeletal modelling, the force plate data and marker trajectories were filtered using a cut-off frequency of 100 Hz and a fourth-order Butterworth zero-phase low-pass filter of 7 Hz. In this study, three steps were performed to calculate the joint forces and muscle forces. Firstly, a static trial was carried out to scale geometrical parameters of the lower limb and the model marker locations to obtain a patient-specific musculoskeletal multibody modelling [21]. After parameter optimization, kinematic analysis was performed by solved minimizing the least-square difference between modelled and experimental marker trajectories as described by Andersen and colleagues [21, 22]. In the inverse dynamic analysis step, the third-order polynomial muscle recruitment criteria were used to estimate muscles and joints forces of the lower limb [23, 24].

We reduced the isometric strength of TP by 20%, 40%, 60% to simulate different levels of TP weakness in both WS and WSFO conditions. In terms of the model output, we extracted the results of muscle forces in TP, soleus (SOL), gastrocnemius lateralis (GL), gastrocnemius medialis (GM), FHL, FDL, extensor digitorum longus (EDL), extensor hallucis longus (EHL), tibialis anterior (TA), peroneus brevis (PB), peroneus longus (PL). Besides, the joint contact forces of the hip, knee, and ankle in anterior-posterior (x), superior-inferior (y), and medial-lateral (z) directions (H/K/AFX, H/K/ACFY and H/K/ACFZ) were also estimated from the musculoskeletal modelling. The times-series of the muscle forces and joint forces were expressed from 0% to 100% stance phase and averaged over trials for each participant. In this study, the calculated joint contact forces and muscle forces were normalized to body weight (BW), respectively.

2.4 Data analysis

The influence of TP weakness (100%,80%, 60%, and 40% of the default TP muscle strength) and insole conditions (WS and WSFO) on the lower limb joint contact forces and extrinsic foot muscle forces were analyzed. Shapiro-Wilk tests had confirmed the normality of all data. Two-way repeated measures ANOVA (TP weakness × insole conditions) were used to compare peak extrinsic foot muscle forces and lower limb joint contact forces in the different conditions across the variables and examine the interaction between them. If any significant interactions were identified, we would conduct post-hoc paired t-tests with Bonferroni adjustment. Small, medium and large effects were demonstrated by Partial eta-squared (η^2p) between 0.01 and 0.06, 0.06 and 0.14, and greater than 0.14, respectively [25]. A significance level of p = 0.05 was set.

3. Results

The walking speeds did not significantly differ between WSFO and WS group (1.31± 0.21 m/s and 1.28 ± 0.19 m/s, respectively) (p > 0.05).

3.1 Muscles forces

There were significant interactions in the two-way repeated ANOVA between TP weakness and insole conditions for peak TP ($F = 23.2$, $p < 0.001$, $\eta^2_p = 0.56$), SOL ($F = 14.3$, $p = 0.004$, $\eta^2_p = 0.41$), GL ($F = 11.7$, $p = 0.004$, $\eta^2_p = 0.46$), GM ($F = 11.3$, $p < 0.005$, $\eta^2_p = 0.45$), FDL ($F = 3.3$, $p = 0.031$, $\eta^2_p = 0.19$), FHL ($F = 6.3$, $p = 0.024$, $\eta^2_p = 0.31$), TA ($F = 4.7$, $p = 0.043$, $\eta^2_p = 0.25$) forces. In WS condition, significant effects were observed for the peak TP， SOL , SM , GL, GM, FDL, FHL, TA ($F = 8.1 - 272.7$, $p < 0.001$) muscle forces in different TP strength conditions (Table 1). In WSFO condition, significant effects were also observed for the peak TPL， TPM , SOL , GL, GM, FDL, FHL, TA ($F = 5.6 - 346.0$, $p < 0.001$) muscle forces in different TP strength conditions (Table 1). Specifically, lower TP muscle strength elicited higher SOL, GL, GM, FDL, FHL, TA forces and lower TP force. Meanwhile, insole with arch support (WSFO condition) significantly reduced the SOL GL, GM, FDL, FHL, TA forces compared to WS condition in 100%, 80%, 60% and 40% of the default TP strength (Table 2).

There were no significant interactions in the two-way repeated ANOVA between TP weakness and insole conditions for the peak values for PB, PL, EDL, and EHL muscles. However, there were significant main effects of TP weakness for the peak PB and PL (F = 80.09 – 96.52, p < 0.001). Specifically, lower TP muscle strength elicited lower peak PB and PL forces (Table 3). There were also significant main effects of insole conditions for peak PB and PL (F = 7.97 - 8.24, p = 0.012) (Table 4). The peak PB and PL forces were significantly reduced in WSFO condition when compared to WS condition. The curves of mean muscle forces during the stance phase in different TP muscle weakness were illustrated in Figure 1(a) (WS condition) and Figure 2(a) (WSFO condition).

3.2 Joint contact forces of lower limb

There were no significant interactions in the two-way repeated ANOVA between TP weakness and insole conditions for any peak joint contact forces. There were, however, significant main effects of TP weakness for the second peak KCFY, peak ACFX and ACFY (F = 33.8 – 125.9, p < 0.001) (Appendix A of the Supplementary file). Specifically, lower TP muscle strength elicited higher second peak KCFY and peak ACFY as well as lower peak ACFX.

There were also significant main effects of insole conditions for second peak of KCFX, second peak KCFY, second peak KCFZ, peak ACFX, peak ACFY and peak ACFZ (F = 8.79 – 30.90, $p < 0.05$) (Appendix B of the Supplementary file). Insole with arch support resulted in 12.9%, 8.3%, 21.4%, 15.6%, 6.9% and 9.3% decreases in second KCFX, KCFY, KCFZ, peak ACFX, ACFY and ACFZ compared to flat insole condition, respectively. The curves of mean joint forces in three directions during stance phase in different TP muscle weakness were illustrated in Figure 1(b) (WS condition) and Figure 2(b) (WSFO condition).

4. Discussion

This study investigated the effects of simulated TP weakness on lower limb joint and muscle mechanics in flatfoot adults with and without foot orthoses conditions. Our study revealed that some extrinsic foot muscles around the ankle joint compensated for the TP weakness in both the WS condition and the WSFO condition. Moreover, the peak ankle joint contact forces in superior/inferior direction (F = 58.4, p < 0.001) increased but decreased in anterior/posterior direction (F = 125.9, p < 0.001) after lowering the maximal isometric force of the TP muscle. These results could suggest a deteriorating tendency of TP weakness in flatfoot patients, which may account for the foot pain and tendinopathy in the adult with flatfoot [3, 9, 26]. Our study also indicated that the foot orthosis significantly reduced most extrinsic foot muscle forces and peak ankle contact force during the stance in TP weakness condition. The positive biomechanical effects of foot orthoses indicated that foot orthosis could relieve the pain in flatfoot deformities, thereby contributing to the insole optimization for patients with various lower limb symptoms [3, 26].

4.1 Parametric study of TP muscle weakness

Our study demonstrated that extrinsic foot muscles, like FHL and FDL, compensated for the weakness of TP muscle, which was in line with the previous study [8]. FHL and FDL are known as contributors to the shape of the medial longitudinal arch and act by resisting midfoot dorsiflexion associated with foot pronation [27]. PTTD is generally associated with the progression of flatfoot [28]. To maintain the same posture, FHL and FDL generated higher forces during midstance and terminal stance and may compensate for the TP dysfunction and prevent low-arch structure progression. Meanwhile, the forces of GL, GM, SOL, TA muscles increased with the reduced TP muscle strength, which was in line with the previous study [8]. Greater forces in triceps surae muscle (GL, GM, SOL) mean higher tension in the Achilles tendon, which may increase the risk of tendinopathy in flatfoot patients whose Achilles tendon were thinner [9]. Our study indicated that PB and PL muscle forces reduced with the decrease of TP muscle strength. Since PB and PL are the evertors of rearfoot [10], opposing to the TP muscles, these two muscles would be less recruited to generate forces to maintain the same foot posture during the TP weakness.

The reduction of TP force in PTTD was naturally compensated by other muscles. In the superior-inferior direction, the TP force was primarily compensated by all other plantarflexors. Interestingly, our results found that these muscles were likely to overcompensate the impoverished TP force, which could lead to an increased peak ankle contact force in the superior-inferior direction. This trend was also supported by a previous study [8]. The increase in ankle joint force in the superior-inferior direction may induce the risk of articular cartilage damage, which shall not be ignored [29]. In contrast, only the FDL and FHL muscles could compensate the TP force in the anterior-posterior direction. The inadequate compensation by these muscles led to a reduction of ankle joint force in the anterior-posterior direction.

4.2 Influence of insole condition

Foot orthosis is usually used to prevent excessive rearfoot eversion in flatfoot [13]. In flatfeet, excessive rearfoot eversion is typically observed, which is assumed to put a higher load on the TP muscle [30]. Foot orthosis could help the muscles control the excessive rearfoot eversion [17]. Our study showed that in the default TP strength condition, foot orthosis significantly reduced the peak TP muscle forces during the stance phase compared to the control condition. The reduction in TP muscle force could decrease the TP muscles' tension or stress, which may delay or inhibit the onset and progression of PTTD. On the other side, intervention for early PTTD could delay the progression of flatfoot since PT muscle is the critical foot arch stabilizer [28, 31]. Other extrinsic foot muscle forces, like GM, SOL, FDL, FHL, TA, PB, and PL around the ankle joint, were overall lower in the WSFO condition. These muscles control the ankle dorsiflexion-plantarflexion and subtalar supination-pronation related to the foot-ankle complex joint contact forces. The peak ankle joint contact forces have reduced under orthosis conditions, which could result from the decrease of muscle forces around the ankle joint. Meanwhile, the second peak knee contact forces in three directions in the WSFO condition were significantly lower than those in the WSFO condition. Lower peak knee joint force could reduce the knee cartilage stress, thus protecting the knee joint from progression damage, especially in older adults [32]. However, it is questionable if the small decrease would have any clinical relevance. Regardless, the study shows that the ankle joint contact forces and muscle forces were overall lower in the WSFO condition during stance, even in impaired TP conditions.

Several limitations should be discussed. Firstly, the joint and extrinsic foot muscle mechanics were calculated based on the musculoskeletal modelling without considering the subject-specific bone geometries. The lower limb bone geometries were scaled based on the static trial. More information about bone geometries, such as MRI or CT, could be used to improve the accuracy of the model scaling and force predictions [33]. Secondly, joint and extrinsic foot muscle mechanics in TP dysfunction conditions were predicted with simulated TP strength weakness. It is assumed that marker trajectories and force plate data will not change in early-stage PTTD. As the progression of PTTD, patients could suffer from increased hindfoot eversion, foot pain, and loose foot ligaments laxity, as well as hallux valgus deformity [34]. Thirdly, the prescribed foot orthosis with arch support and medial forefoot posting was used for the participant. To relieve pain and modify the foot posture for the specific subject, foot orthosis with different designs were necessary to use [35, 36]. Further work could be performed to investigate the biomechanics and clinical outcomes of symptomatic flatfoot participants with different orthosis designs.

5. Conclusion

This study adopted the musculoskeletal multibody modelling to evaluate the effects of TP muscle weakness and foot orthosis on the extrinsic foot muscle forces and lower limb joint contact forces. Some extrinsic foot muscles that have the same function as TP may compensate for TP muscle weakness. Meanwhile, foot orthoses with arch support and medial forefoot posting could significantly reduce most extrinsic foot muscle forces and ankle joint contact forces during TP weakness. Lower extrinsic foot muscle forces and joint contact forces indicated lower stress in soft tissues, which could account for the pain and fatigue relief during daily activities with the foot orthosis intervention for the flatfoot adults.

Acknowledgments

The work was supported by the Key R&D Program granted by the Ministry of Science and Technology of China (grant number: 2018YFB1107000), General Research Fund granted by the Hong Kong Research Grant Council (grant number: PolyU152065/17E), NSFC granted by the National Natural Science Foundation of China (grant number: 11732015, 11972315).

Declarations of Competing Interest

None.

REFERENCES

[1] J. Kohls-Gatzoulis, J.C. Angel, D. Singh, F. Haddad, J. Livingstone, G. Berry, Tibialis posterior dysfunction: A common and treatable cause of adult acquired flatfoot, BMJ 329(7478) (2004) 1328-1333. https://doi.org/10.1136/bmj.329.7478.1328.

[2] J.T. Deland, R.J. De Asla, I.H. Sung, L.A. Ernberg, H.G. Potter, Posterior tibial tendon insufficiency: Which ligaments are involved?, Foot Ankle Int. 26(6) (2005) 427-435. https://doi.org/10.1177/107110070502600601.

[3] K.A. Johnson, Tibialis posterior tendon rupture, Clin Orthop Relat Res (177) (1983) 140-147.

[4] G.C. Pomeroy, R.H. Pike, T.C. Beals, A. Manoli, 2nd, Acquired flatfoot in adults due to dysfunction of the posterior tibial tendon, Bone Joint J. 81(8) (1999) 1173-1182. https://doi.org/10.2106/00004623-199908000-00014.

[5] M.E. Ness, J. Long, R. Marks, G. Harris, Foot and ankle kinematics in patients with posterior tibial tendon dysfunction, Gait & Posture 27(2) (2008) 331-339. https://doi.org/10.1016/j.gaitpost.2007.04.014.

[6] G.J. Sammarco, R.T. Hockenbury, Treatment of stage II posterior tibial tendon dysfunction with flexor hallucis longus transfer and medial displacement calcaneal osteotomy, Foot Ankle Int. 22(4) (2001) 305-312. https://doi.org/10.1177/107110070102200406.

[7] C.S. Simpson, M.H. Sohn, J.L. Allen, L.H. Ting, Feasible muscle activation ranges based on inverse dynamics analyses of human walking, J. Biomech. 48(12) (2015) 2990-2997. https://doi.org/10.1016/j.jbiomech.2015.07.037.

[8] M.B. Simonsen, A. Yurtsever, K. Naesborg-Andersen, P.D.C. Leutscher, K. Horslev-Petersen, R.P. Hirata, et al., A parametric study of effect of experimental tibialis posterior muscle pain on joint loading and muscle forces-Implications for patients with rheumatoid arthritis?, Gait Posture 72 (2019) 102-108.

[9] G.S. Murley, J.M. Tan, R.M. Edwards, J. De Luca, S.E. Munteanu, J.L. Cook, Foot posture is associated with morphometry of the peroneus longus muscle, tibialis anterior tendon, and Achilles tendon, Scand J Med Sci Sports 24(3) (2014) 535-41. https://doi.org/10.1111/sms.12025.

[10] S. Angin, G. Crofts, K.J. Mickle, C.J. Nester, Ultrasound evaluation of foot muscles and plantar fascia in pes planus, Gait Posture 40(1) (2014) 48-52. https://doi.org/10.1016/j.gaitpost.2014.02.008.

[11] W.J. Hurd, S.J. Kavros, K.R. Kaufman, Comparative biomechanical effectiveness of over-the-counter devices for individuals with a flexible flatfoot secondary to forefoot varus, Clin J Sport Med 20(6) (2010) 428-35. https://doi.org/10.1097/JSM.0b013e3181fb539f.

[12] P. Saraswat, M.S. Andersen, B.A. Macwilliams, A musculoskeletal foot model for clinical gait analysis, J Biomech 43(9) (2010) 1645-52. https://doi.org/10.1016/j.jbiomech.2010.03.005.

[13] G. Desmyttere, M. Hajizadeh, J. Bleau, M. Begon, Effect of foot orthosis design on lower limb joint kinematics and kinetics during walking in flexible pes planovalgus: A systematic review and meta-analysis, Clin. Biomech. 59 (2018) 117-129. https://doi.org/10.1016/j.clinbiomech.2018.09.018.

[14] J. Kosonen, J.-P. Kulmala, E. Müller, J. Avela, Effects of medially posted insoles on foot and lower limb mechanics across walking and running in overpronating men, J. Biomech. 54 (2017) 58-63. https://doi.org/10.1016/j.jbiomech.2017.01.041.

[15] S.F. Tang, C.H. Chen, C.K. Wu, W.H. Hong, K.J. Chen, C.K. Chen, The effects of total contact insole with forefoot medial posting on rearfoot movement and foot pressure distributions in patients with flexible flatfoot, Clin Neurol Neurosurg 129 Suppl 1 (2015) S8-11. https://doi.org/10.1016/S0303-8467(15)30004-4.

[16] S. Telfer, M. Abbott, M.P. Steultjens, J. Woodburn, Dose-response effects of customised foot

orthoses on lower limb kinematics and kinetics in pronated foot type, J Biomech 46(9) (2013) 1489-1495. https://doi.org/10.1016/j.jbiomech.2013.03.036.
[17] Y. Peng, D.W. Wong, Y. Wang, T.L. Chen, Q. Tan, Z. Chen, et al., Immediate Effects of Medially Posted Insoles on Lower Limb Joint Contact Forces in Adult Acquired Flatfoot: A Pilot Study, Int J Environ Res Public Health 17(7) (2020). https://doi.org/10.3390/ijerph17072226.
[18] P.R. Cavanagh, M.M. Rodgers, The arch index: a useful measure from footprints, J Biomech 20(5) (1987) 547-551. https://doi.org/10.1016/0021-9290(87)90255-7.
[19] M. Damsgaard, J. Rasmussen, S.T. Christensen, E. Surma, M. De Zee, Analysis of musculoskeletal systems in the AnyBody Modeling System, Simul Model Pract Theory 14(8) (2006) 1100-1111. https://doi.org/10.1016/j.simpat.2006.09.001.
[20] M.K. Horsman, H.F. Koopman, F.C. van der Helm, L.P. Prosé, H. Veeger, Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity, Clin. Biomech. 22(2) (2007) 239-247. https://doi.org/10.1016/j.clinbiomech.2006.10.003.
[21] M.S. Andersen, M. Damsgaard, B. MacWilliams, J. Rasmussen, A computationally efficient optimisation-based method for parameter identification of kinematically determinate and over-determinate biomechanical systems, Comput Methods Biomech Biomed Engin 13(2) (2010) 171-183. https://doi.org/10.1080/10255840903067080.
[22] M.S. Andersen, M. Damsgaard, J. Rasmussen, Kinematic analysis of over-determinate biomechanical systems, Comput Methods Biomech Biomed Engin 12(4) (2009) 371-384. https://doi.org/10.1080/10255840802459412.
[23] M. Mannisi, A. Dell'Isola, M.S. Andersen, J. Woodburn, Effect of lateral wedged insoles on the knee internal contact forces in medial knee osteoarthritis, Gait Posture 68 (2019) 443-448. https://doi.org/10.1016/j.gaitpost.2018.12.030.
[24] R.E. Richards, M.S. Andersen, J. Harlaar, J.C. van den Noort, Relationship between knee joint contact forces and external knee joint moments in patients with medial knee osteoarthritis: effects of gait modifications, Osteoarthritis Cartilage 26(9) (2018) 1203-1214. https://doi.org/10.1016/j.joca.2018.04.011,
[25] J.T.E. Richardson, Eta squared and partial eta squared as measures of effect size in educational research, Educational Research Review 6(2) (2011) 135-147. https://doi.org/10.1016/j.edurev.2010.12.001.
[26] N. Shibuya, D.C. Jupiter, L.J. Ciliberti, V. VanBuren, J. La Fontaine, Characteristics of adult flatfoot in the United States, J Foot Ankle Surg 49(4) (2010) 363-368. https://doi.org/10.1053/j.jfas.2010.04.001.
[27] B. Hintermann, B.M. Nigg, C. Sommer, Foot Movement and Tendon Excursion: An In Vitro Study, Foot Ankle Int 15(7) (1994) 386-395. https://doi.org/10.1177/107110079401500708.
[28] D.W.-C. Wong, Y. Wang, A.K.-L. Leung, M. Yang, M. Zhang, Finite element simulation on posterior tibial tendinopathy: Load transfer alteration and implications to the onset of pes planus, Clin. Biomech. 51 (2018) 10-16. https://doi.org/10.1016/j.clinbiomech.2017.11.001.
[29] K. Huch, K.E. Kuettner, P. Dieppe, Osteoarthritis in ankle and knee joints, Semin Arthritis Rheum 26(4) (1997) 667-674. https://doi.org/10.1016/S0049-0172(97)80002-9.
[30] M. Rabbito, M.B. Pohl, N. Humble, R. Ferber, Biomechanical and clinical factors related to stage I posterior tibial tendon dysfunction, The Journal of orthopaedic and sports physical therapy 41(10) (2011) 776-784. https://www.jospt.org/doi/10.2519/jospt.2011.3545.
[31] R. Semple, S. Murley George, J. Woodburn, E. Turner Deborah, Tibialis posterior in health and disease: a review of structure and function with specific reference to electromyographic studies, J Foot

Ankle Res 2(1) (2009) 24. https://doi.org/10.1186/1757-1146-2-24.
[32] T. Miyazaki, M. Wada, H. Kawahara, M. Sato, H. Baba, S. Shimada, Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis, Ann Rheum Dis 61(7) (2002) 617-622. https://doi.org/10.1136/ard.61.7.617.
[33] Y. Peng, Z. Zhang, Y. Gao, Z. Chen, H. Xin, Q. Zhang, et al., Concurrent prediction of ground reaction forces and moments and tibiofemoral contact forces during walking using musculoskeletal modelling, Med Eng Phys 52 (2018) 31-40. https://doi.org/10.1016/j.medengphy.2017.11.008.
[34] D.W.-C. Wong, Y. Wang, T.L.-W. Chen, F. Yan, Y. Peng, Q. Tan, et al., Finite Element Analysis of Generalized Ligament Laxity on the Deterioration of Hallux Valgus Deformity (Bunion), Front Bioeng Biotechnol 8 (2020) 571192-571192. https://doi.org/ 10.3389/fbioe.2020.571192.
[35] D. López-López, J.M. Vilar-Fernández, G. Barros-García, M.E. Losa-Iglesias, P. Palomo-López, R. Becerro-de-Bengoa-Vallejo, et al., Foot arch height and quality of life in adults: a strobe observational study, Int J Environ Res Public Health 15(7) (2018) 1555. https://doi.org/ 10.3389/10.3390/ijerph15071555.
[36] H. Zhang, M.L. Lv, J. Yang, W. Niu, J. Chung-Wai, Computational Modelling of Foot Orthosis for Midfoot Arthritis: A Taguchi Approach for Design Optimization, Acta Bioeng Biomech (2020). https://doi.org/10.37190/ABB-01694-2020-03.