FOOT & ANKLE Online Journal
OFFICIAL PUBLICATION OF International Foot & Ankle Foundation
FOR EDUCATION AND RESEARCH

The influence of great toe valgus on pronation and frontal plane knee motion during running

by Richard Stoneham PhD[1], Gillian Barry PhD[1], Lee Saxby BSc[2], Mick Wilkinson PhD[1*]

The Foot and Ankle Online Journal 13 (1): 7

Injury rates in running range from 19.4-79.3%, with injuries at the knee comprising 42.1%. Pronation and altered frontal plane knee joint range of motion have been linked to such injuries. The influence of foot structure on pronation and knee kinematics has not been examined in running. This study examined associations between great toe valgus angle, peak pronation angle and frontal plane range of movement at the knee joint during overground running while barefoot. Great toe valgus angle while standing, and peak pronation angle and frontal plane range of motion of the dominant leg during stance while running barefoot on an indoor track were recorded in fifteen recreational runners. There was a large, negative association between great toe valgus angle and peak pronation angle (r = -0.52, p = 0.04), and a strong positive association between great toe valgus angle and frontal plane range of motion at the knee joint (r = 0.67, p = 0.006). The results suggest that great toe position plays an important role in foot stability and upstream knee-joint motion. The role of forefoot structure as a factor for knee-joint injury has received little attention and could be a fruitful line of enquiry in the exploration of factors underpinning running-related knee injuries.

Keywords: great toe valgus; pronation; frontal plane knee range of motion; running

Injury incidence in running ranges from 19.4-79.3% [1, 2]. The knee is the most injured site, comprising 42.1% of all running-related injuries [2, 3]. Patellofemoral Pain Syndrome (PFPS) is the most common running-related knee injury, followed closely by Iliotibial Band Syndrome (ITBS) [3]. Altered frontal plane hip and knee joint kinematics and pronation during the stance phase of running have been linked to these injury types, and differentiate injured from uninjured runners [4-6]. Knee abduction, femoral internal rotation, tibial external rotation, and foot pronation, have been theoretically linked to injury in a population of patients with PFPS [7]. As such, interventions to normalise altered frontal plane kinematics during running might be valuable for rehabilitation of this type of knee injury. Interventions have tended to focus on proximal areas linked to altered knee kinematics. However, training studies to increase hip abduction and external rotation strength have not decreased hip or knee frontal plane peak joint angles or joint excursions during the stance phase of running [8-10]. Moreover, associations between hip strength and frontal plane hip and knee peak angles and joint excursions while running and jumping are weak [9, 11]. These findings suggest that proximally-based interventions are not effective at altering lower extremity running mechanics and risk of running related injury. Studies exploring the distal end of the kinetic chain have utilised barefoot and minimal footwear, and hip and foot muscle

1 - Department of Sport, Exercise and Rehabilitation, Northumbria University, UK
2 - LeeSaxby.com, Suffolk House, Louth, Lincolnshire, UK
* - Corresponding author: mic.wilkinson@northumbria.ac.uk

strengthening interventions to reduce surrogate measures associated with injury at the knee and other sites [10, 12-14]. Injury rates, however, remain high [15]. The influence of foot structure on pronation and knee joint kinematics in running has, by contrast, received little attention.

Data comparing foot structure in habitually-barefoot and habitually-shod populations have reported consistent differences in the spread/abduction of the great toe from the other toes [16-19]. Based on Newtonian physics, larger areas of support provide greater stability. It has been suggested that an abducted great toe position might be important for controlling the direction of body weight during running, secondary to improved stability of the foot [20, 21]. Running is essentially a series of alternate single-leg jumps, where multiples of bodyweight must be supported and controlled using a spring-like action of the supporting foot and limb [22, 23]. Early research showed an active role of the toes, the great toe in particular, from midstance to toe off in running [24]. More recent data comparing habitually barefoot to habitually shod populations suggested that the abducted great toe position, characteristic of the barefoot group, reduced peak forefoot pressures during running by increasing the area of support [19]. Another comparative study from the same lab [25] found larger ankle eversion and internal rotation (which together comprise pronation) during the landing phase of jumping in habitually shod compared to habitually-barefoot participants, attributing differences to the abducted great toe position characteristic of the barefoot group. Together, these studies suggest a link between great toe position and foot and ankle stability in running, and dynamic tasks with similar demands to running. Given evidence of the link between pronation, altered frontal plane motion at the knee joint and risk of knee injury [7], there is a possible mechanistic link between great toe position, pronation and frontal plane knee joint kinematics.

Previous research suggests that the toes have a stabilising function, and that great toe position influences area of support in running, and the extent of pronation in the landing phase of jumping. The influence of great toe position on pronation and on kinematics at the knee joint has not been examined in running. The aim of this study was to examine associations between great toe valgus angle, peak pronation angle and frontal plane range of movement at the knee joint during overground running while barefoot, the latter being necessary to avoid toe position being constrained by shoes.

Methods

Participants

With institutional ethics approval, 15 volunteers (ten male, five female) participated. Mean and SD age, stature and mass of all participants were 26±7 yrs, 1.71±0.01 m and 69±10.9 kg respectively. Inclusion criteria were aged 18-45 years and participation in endurance running more than once per week as part of habitual-exercise regimes, with at least one run longer than 30 minutes. Participants were excluded if they had an injury to the lower limbs in the previous six months, or any condition that could affect their normal running gait.

Design

An observational design assessed the relationship between great toe valgus angle relative to the first metatarsal, peak pronation angle and frontal plane range of movement at the knee joint of the dominant leg during stance, while running barefoot on an indoor runway. The barefoot condition was chosen as it was the only way to ensure that the toe angle recorded in standing was not altered by footwear while running. Data were collected in a single visit. Participants were provided with a short-sleeved compression top and shorts to improve skeletal representation in biomechanical modelling, and were instructed to be well rested before testing. Reflective markers were attached in 'Plug-In gait' and 'Oxford-Foot Model' formations to assess lower-limb kinematics of the dominant limb. Participants were habituated to running barefoot with a 30-minute, self-paced run. After habituation, participants ran over a 20-m runway where kinematic data were captured by 14 optoelectronic cameras. Electronic timing gates (Brower timing gates, Utah, USA) placed in the data capture area (2.7m apart) were used to record speed in each trial. The average running speed was 2.48±0.38 $m \cdot s^{-1}$.

Procedures

Great toe valgus angle

Participants stood barefoot on top of a 0.35-m high platform covered in graph paper. The non-dominant foot was placed on the platform first, aligning the most posterior aspect with a horizontal reference line on the graph paper. The dominant foot was positioned next, shoulder width apart from the other foot, and with the most posterior aspect on the same horizontal reference line. The first metatarsal proximal-and distal-dorsal protrusions, and the central and dorsal point of the interphalangeal joint of the great toe were identified by palpation, and marked using a permanent pen. A digital camera (CX240, Sony, Japan) positioned 0.3m above the platform on a tripod was aligned with the first metatarsophalangeal joint, and the zoom was adjusted so that bony prominences defining great toe angle were visible. A still image was captured and saved for analysis of great toe valgus angle.

Kinematics

Prior to habituation, anthropometric measures were recorded for use in biomechanical modelling (stature (mm), mass (kg), bilateral-leg length (mm), and knee and ankle joint width (mm)). For assessment of lower-limb joint kinematics, participants had a series of markers (Ø=14mm) attached in 'Plug-In gait' and 'Oxford-Foot Model' formations. Anatomical locations of the 'Plug-In gait' and 'Oxford-Foot Model' were sacrum, bilateral anterior-and posterior-superior iliac spines, the bilateral distal-lateral thigh, bilateral femoral-lateral epicondyle, the bilateral distal-lateral lower-leg, the bilateral lateral malleoli, the left/right toe (dorsal aspect of the second metatarsal head) and the calcaneus of the non-dominant limb at the same height as the toe marker. The following markers were placed on the dominant limb only, lateral head of the fibula, tibial tuberosity, anterior aspect of the shin, the medial malleoli, the proximal aspect of the calcaneus, a 'peg marker' extending from the most posterior aspect of the calcaneus, the inferior aspect of the calcaneus, sustentaculum tali, proximal and dorsal aspect of the first metatarsal head, the medial and distal aspect of the first metatarsal head, the proximal-and distal-lateral aspects of the fifth metatarsal and the medial aspect of the first phalanx. Fourteen infrared-optoelectronic cameras (Vicon 10 xT20 and 2 x T40, Oxford, UK) captured kinematic trajectories at 200Hz.

Data treatment

A trial was deemed successful when running speed was ± 5% of the predetermined running speed from the habituation run. Dominant limb data for peak pronation angle and frontal plane range of motion at the knee joint were exported to Microsoft Excel (Microsoft, USA). Foot structure images were loaded to Dartfish ClassroomPlus (version 7.0, Fribourg, Switzerland) where great toe valgus angle was measured using the angle tool. (Chicago, USA).

Statistical analysis

Statistical analysis was undertaken using JASP 0.10.2. Following verification of assumptions of linearity and uniformity of errors using Q-Q and residuals versus predicted value plots respectively, linear regression assessed associations between great toe valgus angle, peak pronation angle and frontal plane range of motion at the knee joint. Strength of associations were judged against Cohen's effect size categories for Pearson's *r* i.e. small association 0.1-0.3; moderate association 0.3-0.5; large association 0.5-1.0 [26] Significance was accepted at $p < 0.05$.

Results

Mean and SD great toe valgus angle, peak pronation angle and frontal plane knee range of motion were 9.5±6.1°, -5.2±6.6° and 6.2±2.2° respectively.

Association between great toe valgus and peak pronation angle.

There was a large, negative association of great toe valgus angle and peak pronation angle during stance ($r = -0.52$, $p = 0.04$). As great toe valgus angle increased (more positive = more valgus), peak pronation angle decreased (more negative = increased pronation) (see Figure 1). The regression equation showed a 0.59° increase in peak pronation for every additional degree of great toe valgus (95% CI 0.01 to 1.12°).

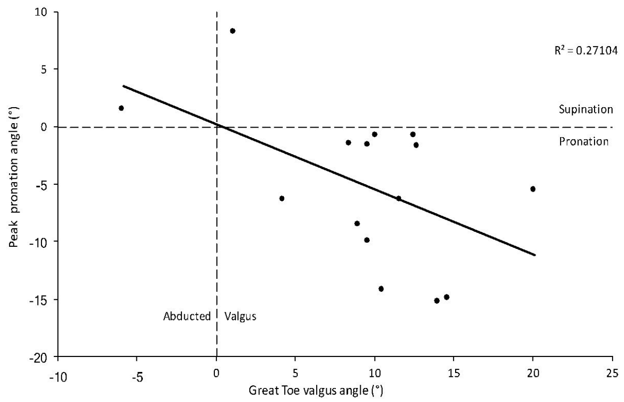

Figure 1 Association between great toe valgus angle and peak pronation angle during overground barefoot running on an indoor track in 15 recreational runners.

Association between great toe valgus and frontal plane knee range of motion.

Great toe valgus angle was strongly and positively associated with frontal plane range of motion at the knee joint (r = 0.67, p = 0.006). As great toe valgus angle increased, frontal plane knee range of motion also increased (see Figure 2). The regression equation showed a 0.24° increase in frontal plane knee joint excursion for every one degree increase in great toe valgus angle (95% CI 0.01 to 0.40°).

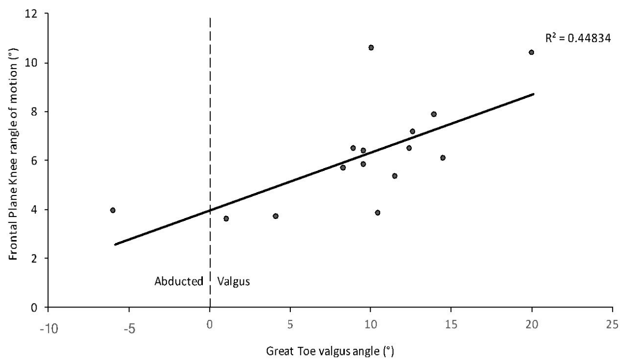

Figure 2 Association between great toe valgus angle and frontal plane range of motion at the knee joint during overground barefoot running on an indoor track in 15 recreational runners.

Discussion

The aim of this study was to examine associations between great toe valgus, peak pronation and frontal plane range of motion at the knee joint during overground running. There was a strong, negative correlation between great toe valgus angle and peak pronation such that increased great toe valgus was associated with a more negative peak pronation angle (increased pronation). There was also a strong, positive correlation between great toe valgus angle and frontal plane range of motion at the knee joint such that increased great toe valgus was associated with larger knee joint excursions in the frontal plane. Altered frontal plane hip and knee joint kinematics and pronation during the stance phase of running have been linked to running-related knee injury, and can differentiate injured from uninjured runners [4-6]. Knee abduction and foot pronation have also been theoretically linked to patellofemoral pain [7]. In light of this evidence, our results suggest that forefoot structure might be an important but largely unexplored factor in running-related knee injury.

As this is the first study to explore the association between great toe valgus, pronation and frontal plane knee joint excursions during running, there are no studies with a similar approach for comparison. Nevertheless, the strong relationships observed broadly support findings from previous comparative cross-sectional studies of habitually barefoot and habitually shod participants that differed in forefoot structure with respect to the spread/abduction of the great toe [19, 25]. Shu et al. [25] observed larger ankle eversion and internal rotation (which together comprise pronation) in habitually shod compared to habitually barefoot participants in the landing phase of jumping. As running is essentially a series of single-leg jumps, the strong association of great toe valgus angle with peak pronation observed in running in our study is not surprising. The reduced and more evenly distributed forefoot peak pressures of habitually barefoot participants reported by Mei et al. [19] alludes to greater forefoot stability during the period of stance when forces are highest. It is possible that as the stability provided by the great toe decreases with increasing valgus angle, instability of the foot could manifest as higher peak pronation. Increased forefoot instability with increased great toe valgus is a plausible mechanism that could explain the strong correlation of great toe valgus angle and peak pronation that we observed. Increased postural instability with great toe valgus [27] and with splinting of the great toe into flexion [28] have been observed in single-leg balance tasks. Though these studies examined static balance and not the dynamic single-leg balance characteristic of running, the underpinning link between the area of the base of support and subsequent stability could be assumed to be common to both. Instability at the foot could have kinematic consequences further up the kinetic chain, resulting in increased frontal plane motion at the knee. The strong, positive association of great toe valgus angle with frontal plane knee joint excursion observed in the current study is consistent with this suggestion. Moreover, the kinematic links between pronation and frontal plane knee joint range, as well as the link between these factors and running-related knee injury suggested here have been suggested previously elsewhere [7] and supported by previous studies [4-6].

The main limitation of this study is that the correlational design prevents any suggestion of a causal link between great toe valgus, peak pronation and frontal plane knee joint excursions. Another limitation is that great toe valgus angle was measured during static stance, not while running, so an assumption that valgus angle remains relatively unchanged when the foot is loaded during running is implicit in the interpretation of the results. Previous research, however, suffers from similar limitations, comprising only comparative studies of foot and ankle function and pressure distributions of groups with mean abducted versus mean valgus great toe positions. As such, a correlational study like this one does add to the understanding of how foot structure might relate to pronation and knee joint kinematics in dynamic tasks like running by examining a 'dose-response' type association, in addition to the 'with and without' type evidence of previous comparative studies. Moreover, there are plausible mechanisms of action for both key findings in this study, so the data provide both direct and mechanistic evidence towards establishing a causal link [29]. A logical next step for this area of research would be randomised control trials where pronation and knee kinematics are evaluated before and after an intervention to alter great toe valgus angle in one group, with the control group foot structure remaining unchanged. Interventions could potentially include corrective surgery or corrective devices that reposition the great toe. Additional comparative studies that measure knee joint kinematics during running would, however, be a useful intermediate step.

In summary, this study observed strong associations between great toe position, peak pronation and frontal plane range of motion at the knee joint during over-ground barefoot running. The results suggest that great toe position plays an important role in foot stability and subsequent knee-joint motion. Both pronation and frontal plane knee-joint motion have been implicated in the etiology of knee injuries. The role of forefoot structure as a factor for knee-joint injury has received little attention and could be a fruitful line of enquiry in the exploration of factors underpinning running-related injuries.

This study formed part of a PhD program collaboratively funded by Northumbria University and VivoBarefoot. VivoBarefoot had no input to the design, analysis or interpretation of studies or data, or the preparation of this manuscript.

References

1. Louw M and Deary C. The biomechanical variables involved in the aetiology of iliotibial band syndrome in distance runners - A systematic review of the literature. Phys Ther Sport. 2014 15(1): 64-75.
2. van Gent RN, et al. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. Br J Sports Med 2007 41: 469-480.
3. Taunton J, et al. A retrospective case-control analysis of 2002 running injuries. Br J Sports Med 2002 36(2): 95-101.
4. Tiberio D. The effects of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. J Orthop Sports Phys Ther. 1987 19(4): 160-165.
5. Stefanyshyn DJ, et al. Knee angular impulse as a predictor of patellofemoral pain in runners. Am J Sports Med 2006 43(11): 1844-1851.
6. Nakagawa TH, et al. Frontal plane biomechanics in males and females with and without patellofemoral pain. Med Sci Sports Exer 2012 44(9): 1747-1755.
7. Powers CM. The influence of altered lower-extremity kinematics on patellofemoral joint dysfunction: A theoretical perspective commentary. J Orthop Sports Phys Ther 2003 33: 639-646.
8. Snyder K, et al. Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. Clin Biomech 2009 24(1): 26-34.
9. Ferber R, Kendall K, and Farr L. Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome. J Athl Train 2011 46(2): 142-149.
10. Willy RW and Davis IS. The effect of a hip-strengthening program on mechanics during running and during a single-leg squat. J Orthop Sports Phys Ther 2011 41(9): 625-632.
11. Dierks T, et al. Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. JOrthop Sports Phys Ther 2008 38(8): 448-456.

12. McKeon PO, et al. The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br J Sports Med 2015 49(290): 1-9.
13. Sinclair J. Effects of barefoot and barefoot inspired footwear on knee and ankle loading during running. Clin Biomech 2014 29(4): 395-399.
14. Roper JL, et al. The effects of gait retraining in runners with patellofemoral pain: a randomized trial. Clin Biomech 2016 35: 14-22.
15. Videbaek S, et al. Incidence of running-related injuries per 1000h of running in different types of runners: A systematic review and meta-analysis. Sports Med 2015 45(7): 1017-1026.
16. Shu Y, et al. Foot Morphological difference between habitually shod and unshod runners. PLoS ONE 2015 10(7).
17. Hoffman P. Conclusions drawn for a comparative study of the feet of barefooted and shoe-wearing peoples. J Bone Joint Surg 1905 3: 105-136.
18. D'Aout K, et al. The effects of habitual footwear use: foot shape and function in native barefoot walkers. Footwear Sci 2009 1(2): 81-94.
19. Mei Q, et al. A comparative biomechanical analysis of habitually unshod and shod runners based on foot morphological difference. Hum Mov Sci 2015 42: 38-53.
20. Wilkinson M and Saxby L. Form determines function: Forgotten application to the human foot? . Foot Ank On J 2016 9(2): 5-8.
21. Wilkinson M, Stoneham R, and Saxby L. Feet and footwear: Applying biological design and mismatch theory to running injuries. Int J Sport Exer Med. 2018 4(2).
22. Srinivasan M and Ruina A. Computer optimization of a minimal biped model discovers walking and running. Nature 2006 439: 72-75.
23. Mann RA and Hagy JL. Biomechanics of walking, running and sprinting. Am J Sports Med 1980 8: 345-350.
24. Mann RA and Hagy JL. Function of toes in walking, jogging and running. Clin Orthop Relat Res 1979 142: 24-29.
25. Shu Y, et al. Dynamic loading and kinematics analysis of vertical jump based on different forefoot morphology. SpringerPlus 2016 5: 1999.
26. Cohen J, *Statistical power analysis for the behavioural sciences*. 1969, New York: Academic Press.
27. Hoogvliet P, et al. Variations in foot breadth: effects on aspects of postural control during one-leg stance. Arch Phys Med Rehab 1997 78(3): 284-289.
28. Chou S, et al. The role of the great toe in balance performance. J Orthop Res 2009 27: 549-554.
29. Howick J, Glasziou P, and Aronson JK. The evolution of evidence hierarchies: What can Bradford Hill's "Guidelines for Causation" contribute? J R Soc Med 2009 102: 186-194.