

Article

Morphology-Related Foot Function Analysis: Implications for Jumping and Running

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Abstract: Barefoot and shod running has received increased attention in recent years, however, the influence of morphology-related foot function has not been explored. This study aimed to investigate morphology-related jumping and running biomechanical functions in habitually barefoot and shod males. A total of 90 barefoot males (Indians) and 130 shod males (Chinese), with significant forefoot and toe morphology differences, participated in a vertical jump and running test to enable the collection of kinematic and kinetic data. The difference of pressure distribution in the hallux and forefoot was shown while jumping and running. The unrestricted forefoot and toes of the barefoot group presented flexible movement and leverage functions to expand the forefoot loading area during performance of the two tasks. Findings related to morphology functions, especially in the forefoot and toe may provide useful information for footwear design.

Keywords: foot morphology; toes function; biomechanics; barefoot; jumping; running

1. Introduction

Human feet are the basic terminal structures that support human walking, running, jumping, and other locomotion. The foot is a complex structure that controls balance and movement [1,2]. Foot morphology has been studied since the early 20th century [3]. Previous studies have demonstrated that the foot differs significantly between habitually barefoot and shod people [4–6], and differences in the kinetics of walking, running, and jumping have been observed [7–9].

Different foot morphology may also be a contributory factor for injury during motion [10], and may also influence physical activity performance [11,12]. There are many reasons for morphological differences in humans, which include disease, foot malfunctions, genetics, and deformity [13]. Research findings have indicated that external factors, such as footwear, may deform foot structure, and result in conditions such as hallux valgus (HV) [3,14]. HV could induce foot dysfunction [15], influence foot morphology [16], and may impair quality of life [17], which may result in depression and pain [18].

In addition, when compared to habitually shod populations, habitually barefoot populations demonstrate more toe separation [3,4,14]. Studies on foot morphology have focused on the width and length of the foot [6], and several studies have investigated the morphological differences between the hallux and other toes [4,14]. However, whether these differences influence the motions needed for physical activity is unclear.

Jumping is a typical movement in many sports, and has attracted much attention from the research community [19,20]. Jumping performance has been evaluated using a one-foot and a two-feet jump [19], and toe flexor function has also been examined [20]. Furthermore, the countermovement jump has been important to support clinicians in the medical diagnosis of muscle power during prolonged recovery

periods following ankle injuries [21]. The contribution of the forefoot and toes has been evaluated while performing the vertical jump, and kinematics, kinetics, and spatiotemporal parameters have been recorded and analyzed [22].

Lieberman et al. [23] indicated that habitually barefoot populations and shod populations present different foot strike patterns. Habitually barefoot populations land on the forefoot, then bring down the heel, and have been observed landing with a flat foot, but seldom on the heel. Habitually shod populations mostly land with a rearfoot strike. The elevated and cushioned heel of the modern running shoe may be a contributory factor that has facilitated the differences in the strike patterns observed. However, strike patterns have been observed to be variant, even between shod or barefoot populations, in recent studies [2,7,8,24]. In spite of the conflicting opinions about barefoot locomotion, it has gained in popularity in recent years, and is now included in athletic training [25], recreational running [26], and rehabilitation [27]. A previous study has revealed the foot shape and function differences in native barefoot walkers [5] and runners [24]. The morphological differences between habitually barefoot and shod runners were found to exist in the forefoot and toe regions [4]. However, morphology based on the functions of the forefoot and toes while performing vertical jumping and running has not been investigated.

Therefore, the purpose of this study was to examine morphology-related performance differences while conducting vertical jumping and running tasks between habitually barefoot males and shod males. A further aim was to explore any functional differences in the forefoot and toes, based on foot morphological characteristics. It was hypothesized that the lower extremity kinematics and plantar forefoot loading distribution would be different due to the morphological differences in the forefoot and toes region.

2. Materials and Methods

2.1. Participants

The sample size was calculated prior to this study using the power package in R-3.6.1 (effect size = 0.5, α level = 0.05, power value = 0.9, type: two-sample, alternative: two sided). A total of 90 barefoot males (Indians) and 130 shod males (Chinese), who presented significant forefoot and toe morphology differences in a previously published study [4], volunteered to participate in the vertical jumping and running test to enable collection of kinematic and kinetic data. All participants were students in the University and had a history of running or other physical activities. Participants of Indian ethnicity originated from South India (Kerala state), were running or taking part in physical activities barefoot since birth, and wore slippers during daily life. Participants of Chinese ethnicity were shod runners since birth and wore different kinds of shoes in daily life. Participants with hallux valgus, high-arched foot, flat foot, diabetic foot, or any other foot deformities were excluded via foot scan prior the test. None of the participants had sustained injuries or surgeries to their lower limbs in the previous half year.

Data for 62 barefoot males (age: 22 ± 1.9 years; weight: 65 ± 8.6 kg; height: 1.69 ± 0.16 m), presenting with a forefoot strike during running, and 112 shod males (age: 23 ± 2.8 years; weight: 66 ± 7.8 kg; height: 1.71 ± 0.11 m), presenting with a rearfoot strike during running, were included for analysis via post data procession. This study, with detailed guidelines for participants' safety and experimental protocols, was approved by the Human Ethics Committee at the Research Institute of Ningbo University ARGH20160819. The study was conducted in accordance with the declaration of Helsinki. Prior to the test, all subjects gave informed consent, with full knowledge of test procedures and requirements.

2.2. Experiment Protocol

The test protocol was consistent with a previously reported experiment [23], which was published from our laboratory recently [1,24]. After completion of foot scanning, participants revisited the motion

capture lab for experimental vertical jumping and running tests. Participants were instructed to warm up and to familiarize themselves with the lab environment for 5 min prior to data collection. Before data collection, three familiarization trials were performed for each task.

While performing the vertical jump, participants stood on the ground in an akimbo position (right foot on the force platform) to reduce the interference from the upper body during performance of a maximal vertical jump. Each participant completed six trials with the right foot on the force platform (Model 9281B, Winterthur, Switzerland).

Running tests were conducted on a runway in the lab. Subjects performed barefoot running with the right foot striking the force platform, which was located in the middle of the runway and was used for kinetic data collection. The force platform and pressure data were used to assist in the definition of striking patterns following a previously established protocol [28,29]. Each participant performed six trials of running using a self-selected running speed, to present natural strike patterns during running and a collection of biomechanical characteristics. For both jumping and running sessions, there were 30 s rest intervals between each trial to minimize the effect of fatigue.

The pressure platform (Novel EMED System, Munich, Germany) was reported to have high reliability correlations (>0.7) [30], and the insole (Novel Pedar System, Munich, Germany) plantar pressure distribution system also displayed excellent reliability correlations (>0.9) [31]. The pressure plate was used to record barefoot jumping and running plantar pressure distribution data with a frequency of 100 Hz. The in-shoe plantar pressure measurement system was placed in the shoes for collection of the shod jumping and running plantar pressure distribution data among habitually shod males, with a frequency of 100 Hz. The habitually shod males (shod) performed shod running wearing shoes that were the same brand and model, for consistency.

2.3. Data Acquisition

Previous studies have outlined data collected from insole pressure sensors and pressure plates and show high reliability [32]. All the anatomical region division analysis was performed in the Novel Database in the data post-processing based on an auto-masking algorithm [33]. For trials of barefoot and shod vertical jumping, only the data in the forefoot and toes were included. The collected plantar pressure data while performing vertical jumping were separated into the push-off and landing phases for analysis. Thus, the plantar surface was divided into five anatomical regions: medial forefoot (MF), central forefoot (CF), lateral forefoot (LF), hallux (H), and other toes (OT), as this study mainly focused on the instant push-off and landing phase of the vertical jump. For trials using barefoot and shod running, the plantar surface was divided into eight anatomical regions, including medial rearfoot (MR), lateral rearfoot (LR), medial midfoot (MM), lateral midfoot (LM), medial forefoot (MF), lateral forefoot (LF), hallux (H), and other toes (OT). The variables for jumping and running included peak pressure, contact area, and the pressure–time integral of each anatomical region.

The kinematic test used the eight-camera Vicon motion analysis system (Oxford Metric Ltd., Oxford, UK) to collect the lower extremity kinematic data, with a frequency of 200 Hz. Sixteen reflective points (diameter: 14 mm) were attached with adhesive tape on the lower limbs of subjects, following a previously published protocol [34]. The anatomical landmarks included the anterior–superior iliac spine, posterior–superior iliac spine, lateral mid-thigh, lateral knee, lateral mid-shank, lateral malleolus, second metatarsal head, and calcaneus. A Kistler Force Platform (Model 9281B, Winterthur, Switzerland) was used to record ground reaction forces (GRFs), with a frequency set at 1000 Hz, to define the running foot striking patterns and contact time. The force platform was zero-levelled prior to testing each participant. The on and off force platform was defined from the value of vertical GRF as 20 N. Participants were required to strike the force platform with the right foot while performing the running and jumping tests on the force platform. The variables of running included spatiotemporal parameters, such as stride length, stride time and contact time, peak angles during stance, and joints range of motion (ROM) in a gait cycle. The spatiotemporal parameters were generated from the Workstation in the Vicon Nexus software (v1.8.5), including hip, knee, and ankle angles in the

sagittal plane, coronal plane, and horizontal plane, computed from the Vicon Plug-in-Gait Model using established protocols [20,30]. Vertical jump height was calculated by Equation (1) [35]:

$$\text{Jumpheight(m)} = \frac{9.80\text{m}\cdot\text{s}^{-2} \times \text{flighttime(s)}^2}{8}. \quad (1)$$

2.4. Statistical Analysis

Normal distribution was checked for all variables, including jump height, peak pressure, pressure time integral, and contact area of vertical jumping, and running spatiotemporal parameters, such as stride length, stride time and contact time, running peak angles during stance, and joints range of motion in a gait cycle. Independent-sample *T* tests were used to analyze the significance of kinematic, plantar loading, and spatiotemporal variables between the barefoot and shod group. SPSS 18.0 (SPSS Inc., Chicago, IL, USA) software was used for the analysis, with statistical significance set at $p < 0.05$.

3. Results

After calculation and comparison of jump height, there were no significant differences between the height of the barefoot jump (386.4 ± 13.6 mm) and shod jump (408.2 ± 12.9 mm), with $p > 0.05$.

As shown in Figure 1, during the take-off phase (left), significant differences ($p < 0.05$) were found between barefoot and shod jumping in H ($p = 0.02$ and 0.01), MF ($p = 0.018$ and 0.029), and CF ($p = 0.026$ and 0.03) for peak pressure and the pressure–time integral. Significance for the contact area was also found in H ($p = 0.032$).

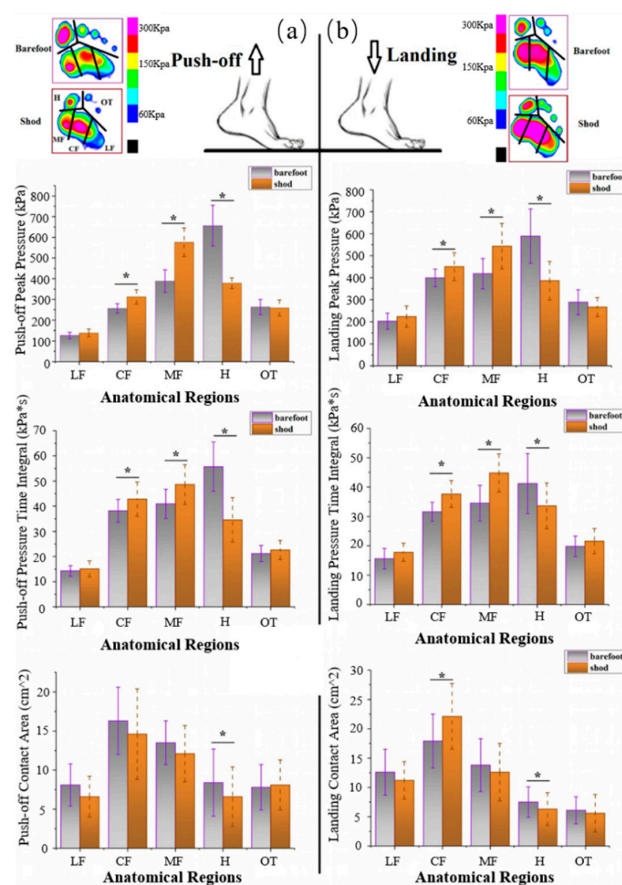


Figure 1. The peak pressure, pressure time integral, and contact area in the anatomical regions during the push-off (a) and landing (b) phases of the vertical jump. lateral forefoot (LF), central forefoot (CF), medial forefoot (MF), hallux (H), and other toes (OT). * indicates significance between variables, $p < 0.05$.

During the landing phase (right), significant differences were found between barefoot and shod jumping in H ($p = 0.016$ and 0.021), MF ($p = 0.026$ and 0.031), and CF ($p = 0.04$ and 0.033) for peak pressure and the pressure time integral. For contact area, significant differences were found in H ($p = 0.034$) and CF ($p = 0.02$).

As measured from the running test, participants' running speeds were self-selected as comfortable from the generated spatiotemporal parameter. The comparison of collected spatiotemporal parameters, including stride length, stride time, and contact time, in one gait cycle between barefoot and shod running, are presented in Table 1.

Table 1. The spatiotemporal parameters between barefoot and shod running.

	Stride Length (m)	Stride Time (s)	Contact Time (s)
Barefoot	2.35 ± 0.19 *	0.76 ± 0.027 *	0.252 ± 0.018 *
Shod	2.46 ± 0.21	0.794 ± 0.032	0.298 ± 0.013

Note: * Significance between barefoot and shod runners, $p < 0.05$.

As shown in Figure 2, the stances of barefoot and shod running were highlighted with solid ($33.2 \pm 0.7\%$) and dashed ($37.5 \pm 0.8\%$) vertical lines, which were calculated from the percentage of contact time in stride time. The peak angles during the stance were thus obtained between barefoot and shod running, and statistical significance was highlighted with a red dotted line with an asterisk (*), with Table 2 presenting detailed values.

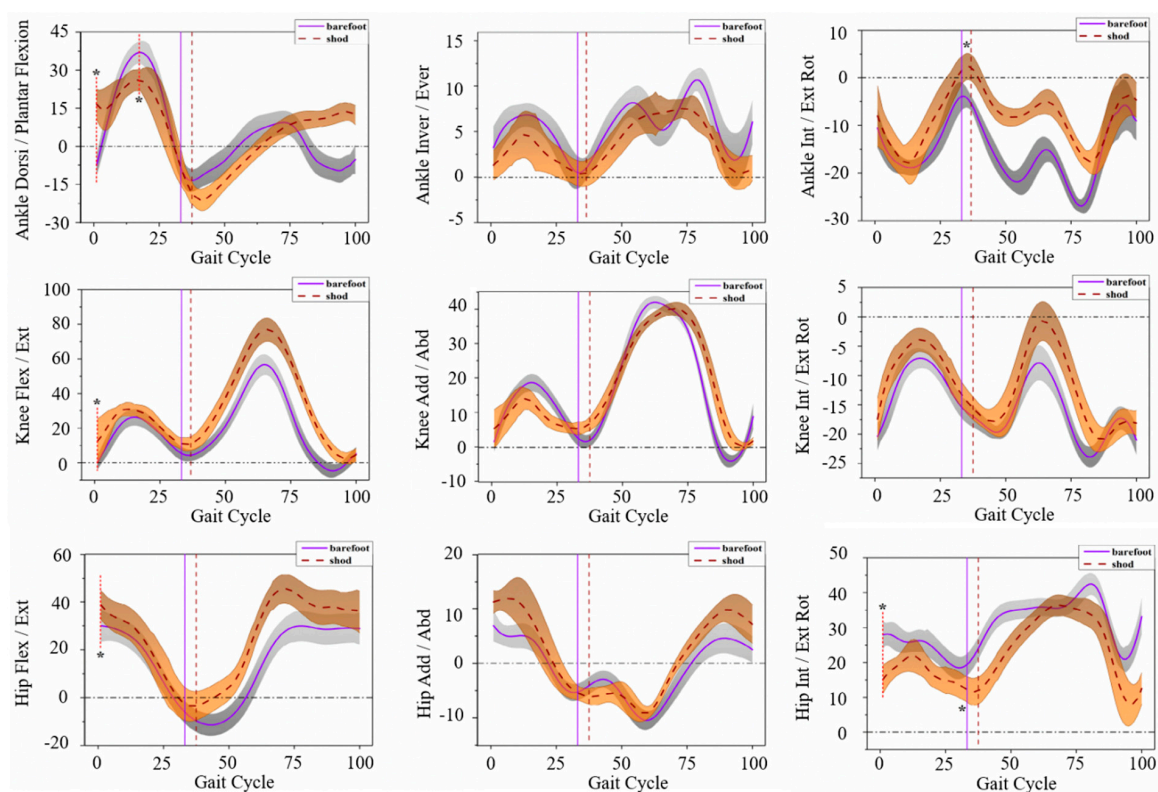


Figure 2. Joint angles curves of the ankle, knee, and hip in sagittal, frontal, and horizontal planes during one gait cycle. Red dotted lines with * indicate a significant difference, $p < 0.05$.

There was a significant difference between the foot strike angle of the ankle between shod and barefoot running, with the foot strike angle of shod running at $17.1 \pm 4.3^\circ$, and barefoot running at $-7.2 \pm 3.9^\circ$ (minus indicates plantarflexion), $p = 0.00$. Internal and external ankle rotation also showed a significant difference, $p < 0.05$. The maximal rotation angle during the push-off phase of the

stance was $3.24 \pm 2.26^\circ$ (shod running) and $-3.76 \pm 1.5^\circ$ (barefoot running). Barefoot running showed significantly larger ankle ROM than shod running, $p = 0.00$ (Table 3).

The knee joint contact angles while foot landing were $12.33 \pm 8.45^\circ$ (shod) and $0.1 \pm 2.3^\circ$ (barefoot), showing significance ($p = 0.012$) (highlighted in Figure 2). Smaller knee joint ROM in the sagittal plane was also observed, with $p = 0.021$ (Table 3).

For hip movement, shod running ($38.79 \pm 7.81^\circ$) presented a larger flexion angle than barefoot running ($30.12 \pm 5.66^\circ$) while landing ($p = 0.03$) (Table 2). A greater internal rotation angle was observed for barefoot running ($27.21 \pm 3.66^\circ$) than shod running ($14.21 \pm 2.66^\circ$), as the foot was landing ($p = 0.32$) (Figure 2). Shod running presented significantly larger ROM than barefoot running in the gait cycle (Table 3).

Table 2. Peak joints' angles between barefoot and shod running during stance.

		Barefoot (Mean $\pm$ SD)		Shod (Mean $\pm$ SD)	
		Max.	Min.	Max.	Min.
Ankle	Sagittal	$37.12 \pm 2.8^\circ$ *	$-11.22 \pm 5.4^\circ$	$28.47 \pm 2.6^\circ$	$-18.7 \pm 6.3^\circ$
	Coronal	$6.98 \pm 2.1^\circ$	$0.46 \pm 1.5^\circ$	$4.13 \pm 2.5^\circ$	$0.73 \pm 1.23^\circ$
	Horizontal	$-3.76 \pm 1.5^\circ$ *	$-19.14 \pm 1.66^\circ$	$3.24 \pm 2.26^\circ$	$-19.73 \pm 3.5^\circ$
Knee	Sagittal	$26.33 \pm 4.45^\circ$ *	$0.1 \pm 2.3^\circ$	$32.2 \pm 3.1^\circ$	$2.57 \pm 3.6^\circ$
	Coronal	$18.75 \pm 3.1^\circ$	$1.98 \pm 2.1^\circ$	$14.39 \pm 3.1^\circ$	$4.28 \pm 3.99^\circ$
	Horizontal	$-6.98 \pm 1.99^\circ$	$-20.4 \pm 3.1^\circ$	$-3.1 \pm 1.9^\circ$	$-18.2 \pm 2.2^\circ$
Hip	Sagittal	$30.12 \pm 5.66^\circ$ *	$-7.04 \pm 2.99^\circ$	$38.79 \pm 7.81^\circ$	$-5.57 \pm 4.88^\circ$
	Coronal	$6.9 \pm 2.89^\circ$	$-5.37 \pm 2.33^\circ$	$13.3 \pm 4.1^\circ$	$-6.1 \pm 1.68^\circ$
	Horizontal	$28.57 \pm 4.1^\circ$	$18.3 \pm 3.6^\circ$	$22.86 \pm 4.5^\circ$	$11.17 \pm 4.17^\circ$

* Significance between barefoot and shod runners.

Table 3. Lower extremity joints' range of motion (ROM) between barefoot and shod running in gait cycle.

		Barefoot (Mean $\pm$ SD)	Shod (Mean $\pm$ SD)
Ankle	Sagittal	$50.93 \pm 3.81^\circ$	$49.67 \pm 5.12^\circ$
	Coronal	$10.58 \pm 3.56^\circ$ *	$3.89 \pm 1.66^\circ$
	Horizontal	$23.86 \pm 5.22^\circ$	$24.09 \pm 7.6^\circ$
Knee	Sagittal	$61.67 \pm 8.26^\circ$ *	$74.67 \pm 9.15^\circ$
	Coronal	$46.11 \pm 7.55^\circ$	$39.9 \pm 5.45^\circ$
	Horizontal	$17.56 \pm 2.3^\circ$	$21.05 \pm 4.3^\circ$
Hip	Sagittal	$42.62 \pm 9.59^\circ$	$42.44 \pm 11.2^\circ$
	Coronal	$17.39 \pm 5.66^\circ$	$22.09 \pm 7.58^\circ$
	Horizontal	$24.43 \pm 6.89^\circ$ *	$31.61 \pm 9.16^\circ$

* Significance between barefoot and shod runners.

Peak pressure, contact area, and the pressure–time integral are shown in Figure 3. For peak pressure, MR, LR, LM, LF, and H showed significant differences between shod and barefoot running. Specifically, barefoot running demonstrated less peak pressure in MR ($p = 0.00$) and LR ($p = 0.00$) than shod running. In contrast, barefoot running showed larger peak pressure in LM ($p = 0.028$), LF ($p = 0.019$), and H ($p = 0.005$) than shod running. For the pressure–time integral, shod running showed a larger pressure–time integral in MR ($p = 0.00$), LR ($p = 0.00$), and MF ($p = 0.02$) than barefoot running. In contrast, barefoot running indicated a larger pressure–time integral in LM ($p = 0.03$), LF ($p = 0.009$), and H ($p = 0.028$) than shod running. For the contact area, shod running presented a larger area in MR ($p = 0.00$), LR ($p = 0.00$), and MM ($p = 0.00$) than barefoot running.

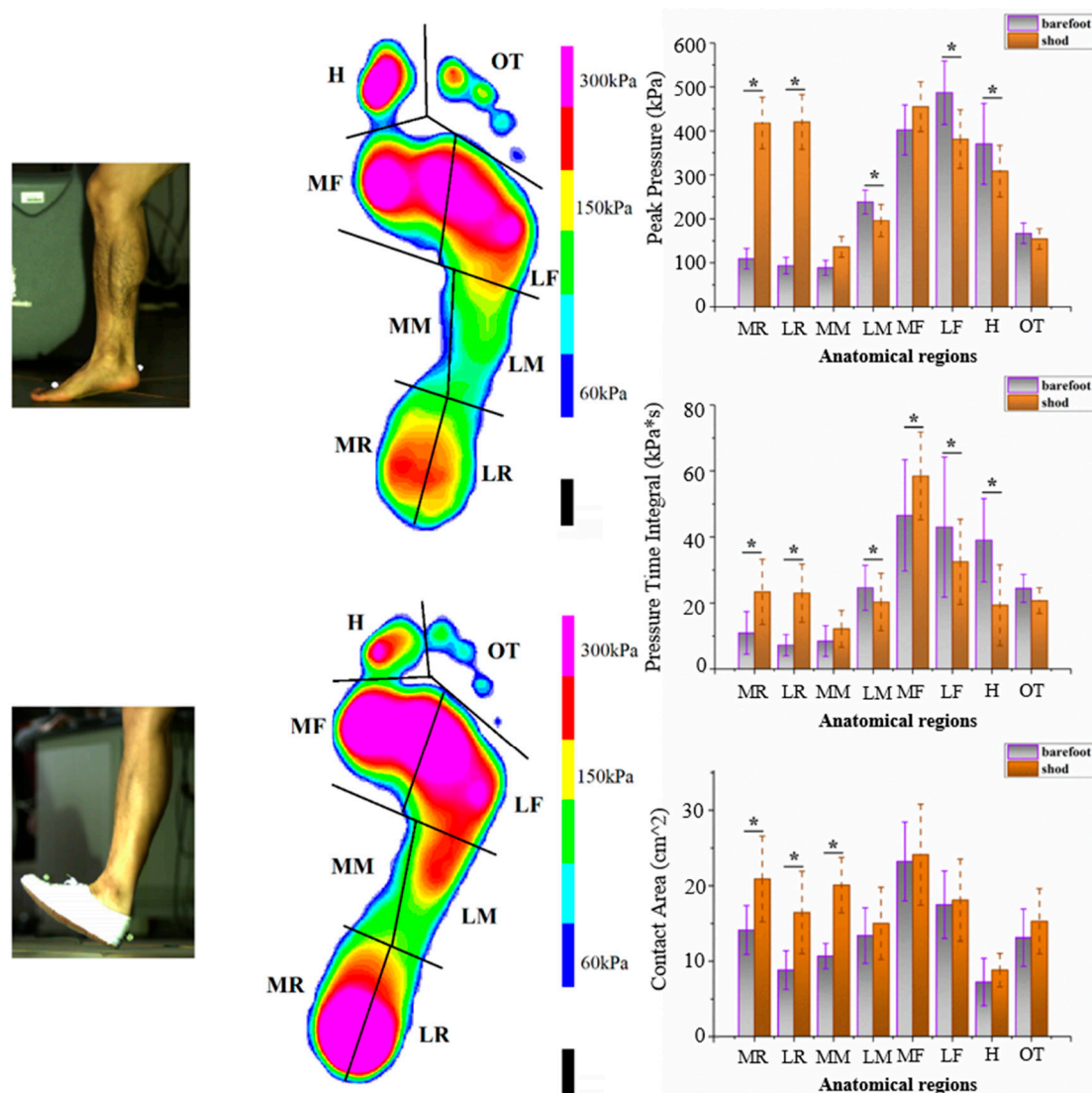


Figure 3. Foot pressure of barefoot and shod running. Medial rearfoot (MR), lateral rearfoot (LR), medial midfoot (MM), lateral midfoot (LM), medial forefoot (MF), lateral forefoot (LF), hallux (H), and other toes (OT). * indicates significance, $p < 0.05$.

4. Discussion

This study aimed to analyze foot morphology-related jumping and running biomechanics and evaluate any potential functional differences. Participants in this study were from different parts of Asia, with a barefoot group from Indian ethnicity and a shod group from Chinese ethnicity. The main findings were that, (i) during the push-off and landing phases of the vertical jump, the separate hallux of barefoot individuals shared loading from the metatarsals, and thus expanded the loading concentrated region; (ii) during the push-off phase of running, there were plantar pressure differences in the hallux and forefoot of barefoot individuals compared with shod individuals; (iii) barefoot individuals with separate toes presented a flexible range of motion, particularly in the coronal plane of the ankle, sagittal plane of the knee, and horizontal plane of the hip.

Hallux angle has been reported to be different among populations of different ethnicities [11]. However, few studies have focused on the minimal distance between the hallux and the interphalangeal joint of the second toe. Compared with results of our previous study [4], barefoot groups in this study had a larger distance and smaller hallux angle, while the shod group had a larger hallux angle and smaller distance. It may be concluded that the barefoot group had more flexible hallux than the

shod group [1,3,36]. Lambrinudi et al. [36] reported that if the separate hallux has ambulatory and prehensile functions, it could work fundamentally the same way as the fingers. However, wearing shoes may block these prehensile and separate functions of the toes, due to the sharp-headed or ill-fitted space restrictions [3,6,14]. The hallux angle and minimal distance are the basis of the morphological differences for the vertical jumping and running test in this study.

Results from the vertical jump test indicated that the hallux presented larger plantar loading in the barefoot group compared with the shod group (Figure 1). During the push-off phase, the plantar loading of the barefoot group was larger under the hallux, while the pressure of the shod group was larger under the medial forefoot and central forefoot. The same pressure time integrals were presented in these anatomical regions, which may imply that the hallux of the barefoot group was used predominantly, while the forefoot of shod group was used primarily. Moreover, the peak pressure of the barefoot reduced in the forefoot regions while landing. This suggests that the gripping function of the hallux could firm and expand the supporting base during the push-off and landing phases by the separate toes [3,36]. In addition, large loading under the hallux could reduce the impact force to the forefoot [24]. Previous research has reported that excessive loading under the metatarsal head area (forefoot) would lead to forefoot injuries [7]. These findings imply that the foot morphology related to toe gripping functions may have a possible link with forefoot metatarsal stress injuries. However, this study did not investigate the injury risks between the two population groups. The jumping height showed no significance, which implies that the morphological differences may not be linked with jumping performance, or there may be a limitation in the akimbo position. Further research is needed and should focus on jumping performance via comprehensive kinematic analysis.

Research pertaining to habitually barefoot and shod people has received increased attention in recent years. Different ethnicities [4,5,24], pathological factors [37], and different forms of sport participation [10] could influence foot morphological differences. Among all the barefoot and shod participants, biomechanical data for the forefoot strike barefoot running, and rearfoot strike shod running were included in this study. Barefoot running was reported to be different to minimalist, racing, or regular shoe conditions in a previous biomechanical study of experienced runners [38]. The extrinsic muscles of the foot presented reduced muscular activity during barefoot running, for instance, peroneus longus [39,40]. Other controversial opinions were proposed between the minimalist and barefoot running when compared to traditional shoe running [41,42]. This study focused on the biomechanics from the forefoot and toe morphology, thus, shod running from the barefoot group and barefoot running from the shod group were not performed during the test, which was aimed to reduce the acute response of altering to shod (for the barefoot group) or barefoot (for the shod group) running.

During the running test, each participant performed running at a comfortable speed so as to present natural running biomechanics [7,43]. The results indicated significant differences in strike length, strike time, and contact time between the shod and barefoot groups, which are consistent with previous studies [2,7,8]. In previous barefoot running studies, the barefoot group was observed to reduce these spatiotemporal parameters [8,44,45]. The stride time of the barefoot group was significantly less than the shod [46]. The running performance of the barefoot group was characterized by landing on the forefoot, and the ankle changed from plantarflexion to dorsiflexion in the sagittal plane, which contributed to the greater dorsiflexion angle during the stance. The shod running resulted in landing with the rearfoot, and the ankle in the dorsiflexion position, which could explain the ankle angle difference as the foot strikes. Different foot strike patterns could be a reason for the strike time differences observed [8].

The observed knee contact flexion angle and peak flexion angle difference of shod running in this study may be a compensatory movement (with larger sagittal knee ROM), resulting from the previously established greater knee impact while rearfoot shod running [9,45,47]. As shown by the hip flexion angle, the contact flexion angle was larger than that of barefoot running, and this could explain the increased stride length of shod running and, although not significant, an about hip flexion-extension ROM was observed.

In terms of the plantar pressure distribution, the barefoot group showed smaller peak pressure and pressure–time integral than the shod group in the rearfoot. This may have been caused by the rear foot landing during shod running, which results in a larger contact area in MR and LR. The difference in contact area in MM may be related to the uppers and soles of the footwear while shod running. Owing to the forefoot strike of barefoot running, the larger peak pressure and pressure time integral to the LM and LF may result from the landing impact. This finding could explain the previously reported forefoot metatarsus fatigue injury due to the repetitive impact and lack of cushioning protection from footwear [1,24]. The hallux showed an increased peak pressure and pressure–time integral during barefoot running, and, while not significant, this was also observed for the contact area. This may result from the active gripping motion of the separate hallux “leverage function” expanding the push-off supporting area (fulcrum) [1,36]. Thus, less loading was found in the MF compared with shod running, which presented greater MF loading and smaller H loading. The greater ankle ROM in the coronal plane and peak angle while pushing off may be kinematic evidence for the active toes function related to the morphological differences in this study. As reported, the function of the remaining toes may also be used for balance and stability control under static and dynamic conditions [48], and it may also be useful during running and jumping performances. Further benefits from the toes in relation to balance and coordination, especially contributions to long distance endurance racing and related events [49], needs further investigation.

Several limitations should be considered in this study. Firstly, participants were physically active males in their early twenties, which may be a limiting factor for generalizing findings from this study to different age groups and genders. Secondly, this study lacked information on the vertical jump biomechanics between the two-population groups, which should be a future research project to investigate potential differences in jumping performance. Thirdly, the entire test was conducted in a lab-based environment, and it is possible the jumping and running biomechanical performances may be different in an outdoor environment.

Previous research revealed that running injuries are a multifactorial issue, including systemic factors, training (experience), health factors, and lifestyle factors [50]. The foot type, structure, or morphology were considered for musculoskeletal injuries in several studies [10,51–53]; however, morphology-related foot functions have been rarely investigated. This needs investigation as a potential contributory factor for injury research.

5. Conclusions

This study analyzed the morphology-related jumping and running biomechanical functions of habitually barefoot and shod males. The unrestricted forefoot and toes of the barefoot group presented flexible movements and a leverage function to expand the forefoot loading area during jumping and running. Findings from the study in relation to morphology-related functions, especially the contribution of the forefoot and toes, may provide useful information for footwear design and injury prevention.

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References

- Mei, Q.; Fernandez, J.; Hume, P.; Gu, Y. Investigating biomechanical function of toes through external manipulation integrating analysis. *Acta Bioeng. Biomech.* **2016**, *18*, 87–92. [[CrossRef](#)]
- Franklin, S.; Grey, M.J.; Heneghan, N.; Bowen, L.; Li, F.X. Barefoot vs common footwear: A systematic review of the kinematic, kinetic and muscle activity differences during walking. *Gait Posture* **2015**, *42*, 230–239. [[CrossRef](#)] [[PubMed](#)]
- Hoffmann, P. Conclusions drawn from a comparative study of the feet of barefooted and shoe-wearing peoples. *Am. J. Orthop. Surg.* **1905**, *3*, 105–163.
- Shu, Y.; Mei, Q.; Fernandez, J.; Li, Z.; Feng, N.; Gu, Y. Foot morphological difference between habitually shod and unshod runners. *PLoS ONE* **2015**, *10*, e0131385. [[CrossRef](#)] [[PubMed](#)]
- D'Août, K.; Pataky, T.C.; De Clercq, D.; Aerts, P. The effects of habitual footwear use: foot shape and function in native barefoot walkers. *Footwear Sci.* **2009**, *1*, 81–94. [[CrossRef](#)]
- Kadambande, S.; Khurana, A.; Debnath, U.; Bansal, M.; Hariharan, K. Comparative anthropometric analysis of shod and unshod feet. *Foot* **2006**, *16*, 188–191. [[CrossRef](#)]
- Tam, N.; Astephon Wilson, J.L.; Noakes, T.D.; Tucker, R. Barefoot running: an evaluation of current hypothesis, future research and clinical applications. *Br. J. Sports Med.* **2014**, *48*, 349–355. [[CrossRef](#)] [[PubMed](#)]
- Lohman, E.B.; Balan Sackiriyas, K.S.; Swen, R.W. A comparison of the spatiotemporal parameters, kinematics, and biomechanics between shod, unshod, and minimally supported running as compared to walking. *Phys. Ther. Sport* **2011**, *12*, 151–163. [[CrossRef](#)]
- Yeow, C.H.; Lee, P.V.S.; Goh, J.C.H. Shod landing provides enhanced energy dissipation at the knee joint relative to barefoot landing from different heights. *Knee* **2011**, *18*, 407–411. [[CrossRef](#)]
- Cain, L.E.; Nicholson, L.L.; Adams, R.D.; Burns, J. Foot morphology and foot/ankle injury in indoor football. *J. Sci. Med. Sport* **2007**, *10*, 311–319. [[CrossRef](#)]
- Gurney, J.K.; Kersting, U.G.; Rosenbaum, D. Dynamic foot function and morphology in elite rugby league athletes of different ethnicity. *Appl. Ergon.* **2009**, *40*, 554–559. [[CrossRef](#)] [[PubMed](#)]
- Mei, Q.; Graham, M.; Gu, Y. Biomechanical analysis of the plantar and upper pressure with different sports shoes. *Int. J. Biomed. Eng. Technol.* **2014**, *14*, 181–191. [[CrossRef](#)]
- Ledoux, W.R.; Shofer, J.B.; Ahroni, J.H.; Smith, D.G.; Sangeorzan, B.J.; Boyko, E.J. Biomechanical differences among pes cavus, neutrally aligned, and pes planus feet in subjects with diabetes. *Foot Ankle Int.* **2003**, *24*, 845–850. [[CrossRef](#)] [[PubMed](#)]
- Ashizawa, K.; Kumakura, C.; Kusumoto, A.; Narasaki, S. Relative foot size and shape to general body size in Javanese, Filipinas and Japanese with special reference to habitual footwear types. *Ann. Hum. Biol.* **1997**, *24*, 117–129. [[CrossRef](#)] [[PubMed](#)]
- Xiang, L.; Mei, Q.; Fernandez, J.; Gu, Y. Minimalist shoes running intervention can alter the plantar loading distribution and deformation of hallux valgus: A pilot study. *Gait Posture* **2018**, *65*, 65–71. [[CrossRef](#)]
- Calvo-Lobo, C.; Garrido-Marín, A.; Rodríguez-Sanz, D.; López-López, D.; Palomo-López, P.; Romero-Morales, C.; Sanz-Corbalán, I. Ultrasound evaluation of intrinsic plantar muscles and fascia in hallux valgus: A case-control study. *Medicine* **2016**, *95*, e5243. [[CrossRef](#)]
- López-López, D.; Callejo-González, L.; Losa-Iglesias, M.E.; Saleta-Canosa, J.L.; Rodríguez-Sanz, D.; Calvo-Lobo, C.; Becerro-de-Bengoa-Vallejo, R. Quality of life impact related to foot health in a sample of older people with hallux valgus. *Aging Dis.* **2016**, *7*, 1–8. [[CrossRef](#)]
- López-López, D.; Vilar-Fernández, J.M.; Losa-Iglesias, M.E.; Álvarez-Castro, C.; Calvo-Lobo, C.; Ramos-Galván, J.; Becerro-de-Bengoa-Vallejo, R. Influence of depression in a sample of people with hallux valgus. *Int. J. Ment. Health Nurs.* **2016**, *25*, 574–578. [[CrossRef](#)]
- Vint, P.F.; Hinrichs, R.N. Differences between one-foot and two-foot vertical jump performances. *J. Appl. Biomech.* **1996**, *12*, 338–358. [[CrossRef](#)]
- Goldmann, J.P.; Sanno, M.; Willwacher, S.; Heinrich, K.; Brüggemann, G.P. The potential of toe flexor muscles to enhance performance. *J. Sports Sci.* **2013**, *31*, 424–433. [[CrossRef](#)]
- Sman, A.D.; Hiller, C.E.; Rae, K.; Linklater, J.; Black, D.A.; Refshauge, K.M. Prognosis of ankle syndesmosis injury. *Med. Sci. Sports Exerc.* **2014**, *46*, 671–677. [[CrossRef](#)]
- Shu, Y.; Zhang, Y.; Fu, L.; Fekete, G.; Baker, J.S.; Li, J.; Gu, Y. Dynamic loading and kinematics analysis of vertical jump based on different forefoot morphology. *SpringerPlus* **2016**, *5*, 1–9. [[CrossRef](#)] [[PubMed](#)]

23. Lieberman, D.E.; Venkadesan, M.; Werbel, W.A.; Daoud, A.I.; D'Andrea, S.; Davis, I.S.; Mang'Eni, R.O.; Pitsiladis, Y. Foot strike patterns and collision forces in habitually barefoot versus shod runners. *Nature* **2010**, *463*, 531–535. [[CrossRef](#)] [[PubMed](#)]
24. Mei, Q.; Fernandez, J.; Fu, W.; Feng, N.; Gu, Y. A comparative biomechanical analysis of habitually unshod and shod runners based on a foot morphological difference. *Hum. Mov. Sci.* **2015**, *42*, 38–53. [[CrossRef](#)] [[PubMed](#)]
25. Krabak, B.J.; Hoffman, M.D.; Millet, G.Y.; Chimes, G.P. Barefoot running. *PM&R J.* **2011**, *3*, 1142–1149. [[CrossRef](#)]
26. De Cock, A.; Vanrenterghem, J.; Willems, T.; Witvrouw, E.; De Clercq, D. The trajectory of the centre of pressure during barefoot running as a potential measure for foot function. *Gait Posture* **2008**, *27*, 669–675. [[CrossRef](#)] [[PubMed](#)]
27. Hall, J.P.L.; Barton, C.; Jones, P.R.; Morrissey, D. The biomechanical differences between barefoot and shod distance running: A systematic review and preliminary meta-analysis. *Sport. Med.* **2013**, *43*, 1335–1353. [[CrossRef](#)] [[PubMed](#)]
28. Santuz, A.; Ekizos, A.; Arampatzis, A. A pressure plate-based method for the automatic assessment of foot strike patterns during running. *Ann. Biomed. Eng.* **2016**, *44*, 1646–1655. [[CrossRef](#)] [[PubMed](#)]
29. Santuz, A.; Ekizos, A.; Janshen, L.; Baltzopoulos, V.; Arampatzis, A. The influence of footwear on the modular organization of running. *Front. Physiol.* **2017**, *8*, 1–10. [[CrossRef](#)] [[PubMed](#)]
30. Hafer, J.F.; Lenhoff, M.W.; Song, J.; Jordan, J.M.; Hannan, M.T.; Hillstrom, H.J. Reliability of plantar pressure platforms. *Gait Posture* **2013**, *38*, 544–548. [[CrossRef](#)]
31. Godi, M.; Turcato, A.M.; Schieppati, M.; Nardone, A. Test-retest reliability of an insole plantar pressure system to assess gait along linear and curved trajectories. *J. Neuroeng. Rehabil.* **2014**, *11*, 1–8. [[CrossRef](#)] [[PubMed](#)]
32. Razak, A.; Hadi, A.; Zayegh, A.; Begg, R.K.; Wahab, Y. Foot plantar pressure measurement system: A review. *Sensors* **2012**, *12*, 9884–9912. [[CrossRef](#)] [[PubMed](#)]
33. Ellis, S.J.; Stoecklein, H.; Yu, J.C.; Syркин, G.; Hillstrom, H.; Deland, J.T. The accuracy of an automasking algorithm in plantar pressure measurements. *HSS J.* **2011**, *7*, 57–63. [[CrossRef](#)] [[PubMed](#)]
34. Gu, Y.; Lu, Y.; Mei, Q.; Li, J.; Ren, J. Effects of different unstable sole construction on kinematics and muscle activity of lower limb. *Hum. Mov. Sci.* **2014**, *36*, 46–57. [[CrossRef](#)] [[PubMed](#)]
35. Bosco, C.; Luhtanen, P.; Komi, P.V. A simple method for measurement of mechanical power in jumping. *Eur. J. Appl. Physiol.* **1983**, *50*, 273–282. [[CrossRef](#)]
36. Lambrinudi, C. Use and abuse of toes. *Postgrad. Med. J.* **1932**, *8*, 459–464. [[CrossRef](#)] [[PubMed](#)]
37. Hillstrom, H.J.; Song, J.; Kraszewski, A.P.; Hafer, J.F.; Mootanah, R.; Dufour, A.B.; Chow, B.S.; Deland, J.T. Foot type biomechanics part 1: Structure and function of the asymptomatic foot. *Gait Posture* **2013**, *37*, 445–451. [[CrossRef](#)] [[PubMed](#)]
38. Bonacci, J.; Saunders, P.U.; Hicks, A.; Rantalainen, T.; Vicenzino, B.T.; Spratford, W. Running in a minimalist and lightweight shoe is not the same as running barefoot: a biomechanical study. *Br. J. Sports Med.* **2013**, *47*, 387–392. [[CrossRef](#)] [[PubMed](#)]
39. Roca-Dols, A.; Losa-Iglesias, M.E.; Sánchez-Gómez, R.; Becerro-de-Bengoa-Vallejo, R.; López-López, D.; Palomo-López, P.; Rodríguez-Sanz, D.; Calvo-Lobo, C. Electromyography activity of triceps surae and tibialis anterior muscles related to various sports shoes. *J. Mech. Behav. Biomed.* **2018**, *86*, 158–171. [[CrossRef](#)]
40. Roca-Dols, A.; Losa-Iglesias, M.E.; Sánchez-Gómez, R.; López-López, D.; Becerro-de-Bengoa-Vallejo, R.; Calvo-Lobo, C. Electromyography comparison of the effects of various footwear in the activity patterns of the peroneus longus and brevis muscles. *J. Mech. Behav. Biomed.* **2018**, *82*, 126–132. [[CrossRef](#)]
41. Squadrone, R.; Gallozzi, C. Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. *J. Sports Med. Phys. Fitness* **2009**, *49*, 6–13. [[PubMed](#)]
42. Paquette, M.; Zhang, S.; Baumgartner, L. Acute effects of barefoot, minimal shoes and running shoes on lower limb mechanics in rear and forefoot strike runners. *Footwear Sci.* **2013**, *5*, 9–18. [[CrossRef](#)]
43. Hatala, K.G.; Dingwall, H.L.; Wunderlich, R.E.; Richmond, B.G. Variation in foot strike patterns during running among habitually barefoot populations. *PLoS ONE* **2013**, *8*, 4–9. [[CrossRef](#)] [[PubMed](#)]
44. Altman, A.R.; Davis, I.S. A kinematic method for footstrike pattern detection in barefoot and shod runners. *Gait Posture* **2013**, *35*, 298–300. [[CrossRef](#)] [[PubMed](#)]

45. Daoud, A.I.; Geissler, G.J.; Wang, F.; Saretsky, J.; Daoud, Y.A.; Lieberman, D.E. Foot strike and injury rates in endurance runners: A retrospective study. *Med. Sci. Sports Exerc.* **2012**, *44*, 1325–1334. [[CrossRef](#)] [[PubMed](#)]
46. Roca-Dols, A.; Losa-Iglesias, M.E.; Sánchez-Gómez, R.; Becerro-de-Bengoa-Vallejo, R.; López-López, D.; Rodríguez-Sanz, D.; Martínez-Jiménez, E.M.; Calvo-Lobo, C. Effect of the cushioning running shoes in ground contact time of phases of gait. *J. Mech. Behav. Biomed.* **2018**, *88*, 196–200. [[CrossRef](#)] [[PubMed](#)]
47. Cheung, R.T.H.; Rainbow, M.J. Landing pattern and vertical loading rates during first attempt of barefoot running in habitual shod runners. *Hum. Mov. Sci.* **2014**, *34*, 120–127. [[CrossRef](#)]
48. Ku, P.X.; Abu Osman, N.A.; Yusof, A.; Abas, W.A.B. The effect on human balance of standing with toe-extension. *PLoS ONE* **2012**, *7*, e41539. [[CrossRef](#)]
49. Rolian, C.; Lieberman, D.E.; Hamill, J.; Scott, J.W.; Werbel, W. Walking, running and the evolution of short toes in humans. *J. Exp. Biol.* **2009**, *212*, 713–721. [[CrossRef](#)]
50. Van Gent, R.N.; Siem, D.; van Middelkoop, M.; van Os, A.G.; Bierma-Zeinstra, S.M.A.; Koes, B.W. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. *Br. J. Sports Med.* **2007**, *40*, 16–29. [[CrossRef](#)]
51. Kaufman, K.R.; Brodine, S.K.; Shaffer, R.A.; Johnson, C.W.; Cullison, T.R. The effect of foot structure and range of motion on musculoskeletal overuse injuries. *Am. J. Sports Med.* **1999**, *27*, 585–593. [[CrossRef](#)] [[PubMed](#)]
52. Barnes, A.; Wheat, J.; Milner, C. Association between foot type and tibial stress injuries: a systematic review. *Br. J. Sports Med.* **2008**, *42*, 93–98. [[CrossRef](#)] [[PubMed](#)]
53. Sánchez-Sáez, J.M.; Palomo-López, P.; Becerro-de-Bengoa-Vallejo, R.; Calvo-Lobo, C.; Losa-Iglesias, M.E.; López-Del-Amo-Lorente, A.; López-López, D. Stability of Three Different Sanitary Shoes on Healthcare Workers: A Cross-Sectional Study. *Int. J. Environ. Res. Public Health* **2019**, *16*, 2126. [[CrossRef](#)] [[PubMed](#)]



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