UWS Academic Portal

Morphology-related foot function analysis

Yu, Peimin; Xiang, Liangliang; Liang, Minjun; Mei, Qichang; Baker, Julien S.; Gu, Yaodong

Published in:
Applied Sciences

DOI:
10.3390/app9163236

Published: 08/08/2019

Document Version
Peer reviewed version

applied sciences

MDPI

Article

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

Peimin Yu [1], Liangliang Xiang [1], Minjun Liang [1], Qichang Mei [2], Julien S Baker [3] and Yaodong Gu [1,2,*]

[1] Faculty of Sports Science, Ningbo University, Ningbo, China
[2] Auckland Bioengineering Institute, University of Auckland, Auckland, New Zealand
[3] School of Science, University of the West of Scotland, Hamilton, Scotland, UK
[*] Correspondence: guyaodong@hotmail.com; Tel.: +86-574-87600456

Received: date; Accepted: date; Published: date

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 the 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 toes morphology differences, participated in a vertical jump and running test to enable 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 comparing 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-foot 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 would present different foot strike patterns. Habitually barefoot populations would 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 function of the forefoot and toes' while performing vertical jumping and running has not been investigated.

Therefore, the purpose of this study was to examine the 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 the foot morphological characteristics. It was hypothesized that the lower extremity kinematics and plantar forefoot loading distribution would be different due to the morphological difference in the forefoot and toes region.

2. Materials and Methods

2.1. *Participants*

Sample size was calculated prior to this study using 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 toes morphology differences from 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 the history of running or other physical activities. Participants of Indian ethnicity originated from South India (Kerala state), who 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 kept wearing 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. All participants had no injuries or surgeries to their lower limbs in the previous half year.

Data for 62 barefoot males (age: 22±1.9yrs; weight: 65±8.6kg; height: 1.69±0.16m), presenting with a forefoot strike during running, and 112 shod males (age: 23±2.8yrs; weight: 66±7.8kg; height: 1.71±0.11m), 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 is consistent with a previously reported experiment [23], which has been published from our laboratory recently [1,24]. After completion of foot scanning, participants revisited the motion capture lab for experimental vertical jump 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, 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 collection of biomechanical characteristics. For both jumping and running sessions, there were 30 second rest intervals between each trial to minimize the effect of fatigue.

The pressure platform (Novel EMED System, Germany) was reported to have high reliability correlations (>0.7) [30], and the insole (Novel Pedar System, 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 100Hz. 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 100Hz. 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-procession 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 pressure-time integral of each anatomical region.

The kinematic test used the 8-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, respectively, 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, 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 20N. 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 horizonal plane computed from the Vicon Plug-in-Gait Model using established protocols [20,30]. Vertical jump height was calculated by the equation (1) [35]:

$$\text{Jump height (m)} = \frac{9.80\,\text{m}\cdot\text{s}^{-2} \times \text{flight time(s)}^2}{8} \quad (1)$$

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±13.6mm) and shod jump (408.2±12.9mm), 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 ($p=0.02$ & 0.01), MF ($p=0.018$ & 0.029) and CF ($p=0.026$ & 0.03) for peak pressure and the pressure time integral. Significance for contact area was also found in H ($p=0.032$).

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

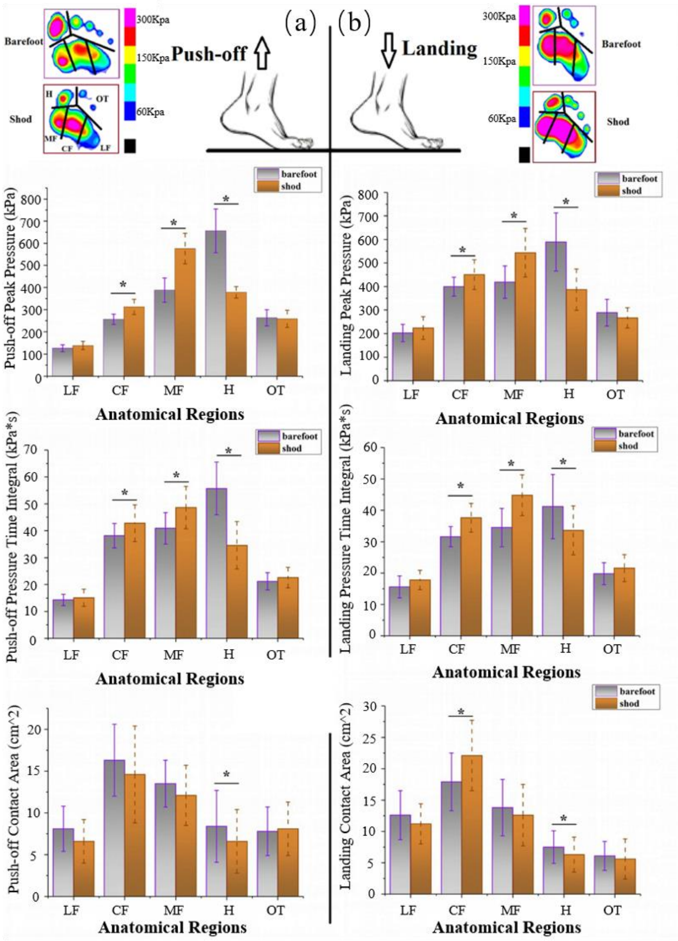

Figure 1. The peak pressure, pressure time integral and contact area in the anatomical regions during the push-off (left) and landing (right) phases of the vertical jump. lateral forefoot (LF), central forefoot (CF), medial forefoot (MF), hallux (H), and other toes (OT). * indicates significance between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

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 stance of barefoot and shod running were highlighted with solid (33.2±0.7%) and dashed (37.5±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 dot line with the asterisk (*), with Table 2 presenting detailed values.

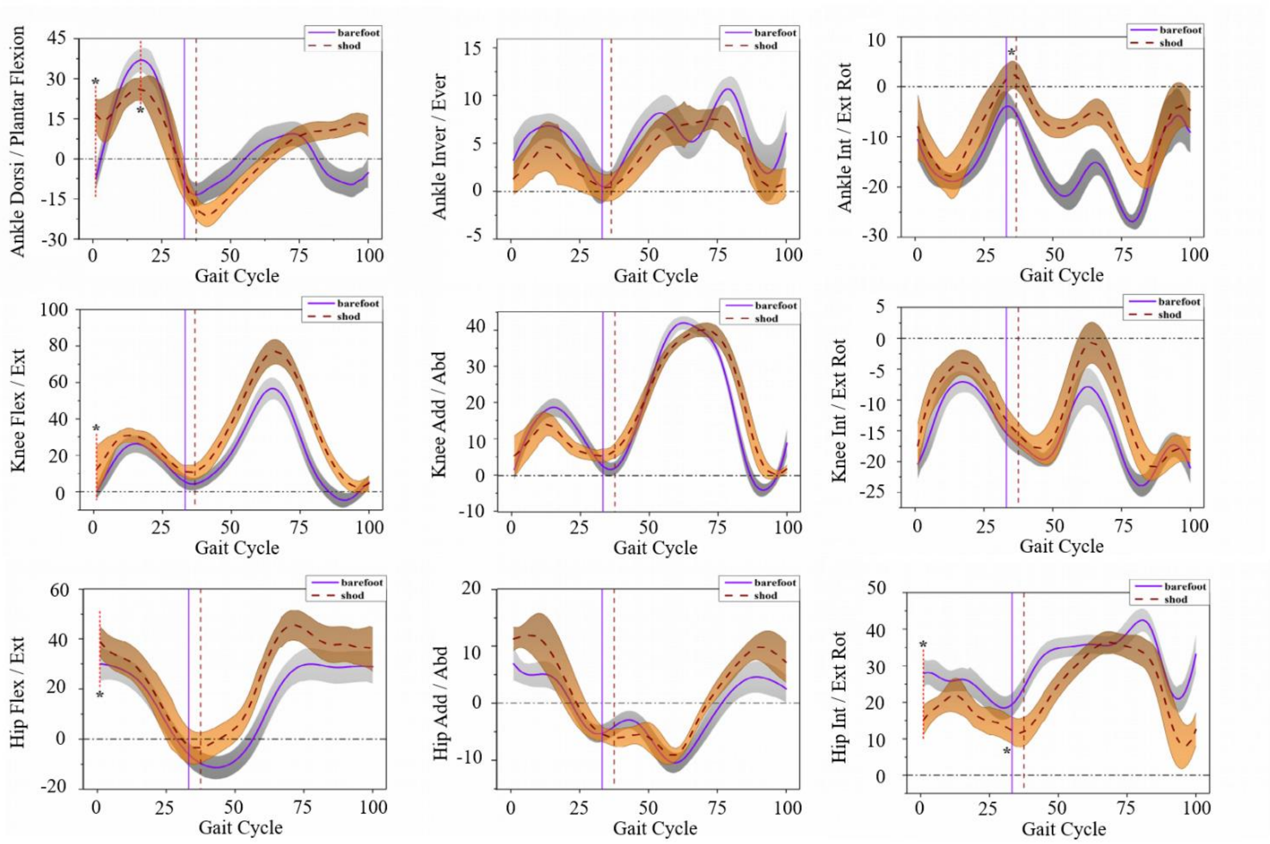

Figure 2. Joint angles curves of ankle, knee and hip in sagittal, frontal and horizontal planes during one gait cycle. *Red dot lines with* * indicate significant difference, $p<0.05$.

The foot strike angle of the ankle between shod and barefoot running showed a significant difference with the foot strike angle of shod running at 17.1±4.3°, and barefoot running at -7.2± 3.9°

(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±2.26° (shod running) and -3.76±1.5° (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±8.45° (shod) and 0.1±2.3° (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±7.81°) presented larger flexion angle than barefoot running (30.12±5.66°) while landing (p=0.03) (Table 2). Greater internal rotation angle while barefoot running (27.21±3.66°) was observed than shod running (14.21±2.66°) as the foot landing (p=0.32) (Figure 2). Shod running presented significantly larger ROM than barefoot running in gait cycle (Table 3).

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

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

Table 3. Lower extremity joints' ROM between barefoot and shod running in gait cycle.

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

Peak pressure, contact area and 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 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 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 larger area in MR (p=0.00), LR (p=0.00) and MM (p=0.00) than barefoot running.

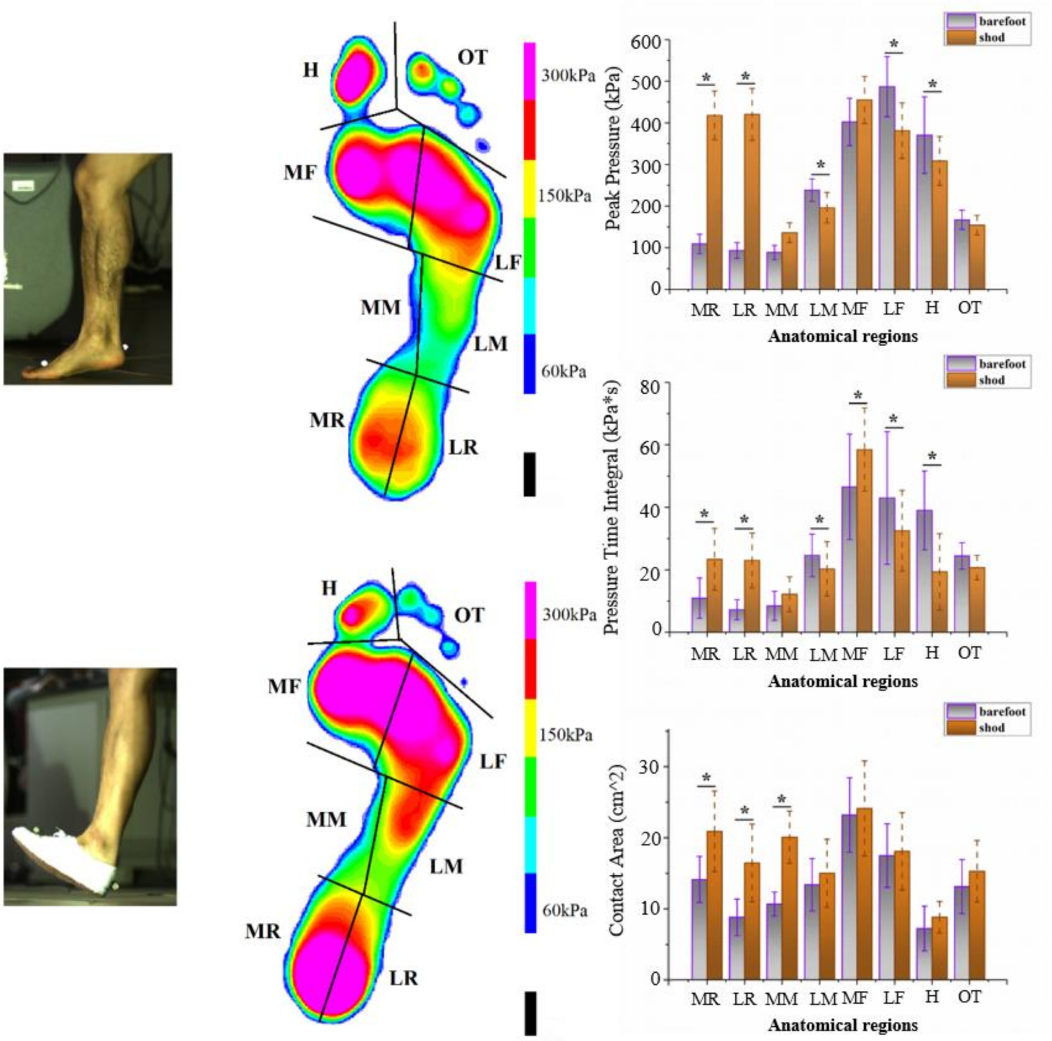

Figure 3. Foot pressure of barefoot and shod running. medial rearfoot (MR), lateral rearfoot (LR), medial midfoot (MM), lateral midfoot (LM), medial forefoot (MF), lateral forefoot (LF), hallux (H) and other toes (OT). * indicates significance, p<0.05.

4. Discussion

This study aimed to analyze the 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 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 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 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 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 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 link with a possibility of 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]. 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 toes morphology, thus shod running from barefoot group and barefoot running from shod group were not performed during the test, which was aimed to reduce the acute response of altering to shod (for barefoot group) or barefoot (for shod group) running.

During the running test, each participant performed running with 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 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 stance. The shod running resulted in landing with the rearfoot, and 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 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 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 increased peak pressure and pressure time integral during barefoot running while not significant; this was observed for the contact area. This may result from the active gripping motion of 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 presenting greater MF loading and smaller H loading. The greater ankle ROM in 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], 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 group and both genders. Secondly, this study lacked information of 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, possibly the jumping and running biomechanical performances may be different in an outdoor environment.

Previous research revealed that running injury is 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 '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.

References

1. 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. https://doi.org/10.5277/ABB-00360-2015-02
2. 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. https://doi.org/10.1016/j.gaitpost.2015.05.019
3. 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.
4. 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. https://doi.org/10.1371/ journal.pone.0131385

5. 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. https://doi.org/10.1080/19424280903386411
6. Kadambande, S.; Khurana, A.; Debnath, U.; Bansal, M.; Hariharan, K. Comparative anthropometric analysis of shod and unshod feet. *Foot* **2006**, *16*, 188–191. https://doi.org/ 10.1016/j.foot.2006.06.001
7. Tam, N.; Astephen 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*, 349–55. https://doi.org/10.1136/bjsports-2013-092404
8. 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. https://doi. org/10.1016/j.ptsp.2011.09.004
9. 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. https://doi.org/10.1016/j.knee.2010.07.011
10. 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. https://doi.org/10.1016/j.jsams. 2006.07.012
11. 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. https://doi.org/10.1016/j.apergo.2008.11.001
12. 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.
13. 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. https://doi.org/10.1177/ 107110070302401107
14. 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. https://doi.org/10.1080/030144697 00004862
15. 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. https://doi.org/10.1016/j.gaitpost.2018.07.002
16. 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. https://doi: 10.1097/MD.0000000000005243
17. 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. https://doi: 10.14336/AD.2015.0914
18. 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. https://doi.org/10.1111/inm.12196
19. Vint, P. F.; Hinrichs, R. N. Differences between one-foot and two-foot vertical jump performances. *J. Appl. Biomech.* **1996**, *12*, 338–358.
20. 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. https://doi.org/10.1080/02640414.

2012.736627

21. 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. https://doi.org/10.1249/MSS.0000000000000151
22. 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. https://doi.org/10.1186/s40064-016-3682-3
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. https://doi.org/10.1038/nature08723
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. https://doi.org/10.1016/j.humov.2015.04.007
25. Krabak, B. J.; Hoffman, M. D.; Millet, G. Y.; Chimes, G. P. Barefoot running. *PM R* **2011**, *3*, 1142–1149. https://doi.org/10.1016/j.pmrj.2011.11.001
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. https://doi.org/10.1016/j.gaitpost.2007.08.013
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. https://doi.org/10.1007/s40279-013-0084-3
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. https://doi.org/10.1007/s10439-015-1484-3
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. https://doi.org/10.3389/fphys.2017. 00958
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. https://doi.org/10.1016/j.gaitpost.2013.01.028
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. https://doi.org/10.1186/1743-0003-11-95
32. Razak, A.; Hadi, A.; Zayegh, A.; Begg, R. K.; Wahab, Y. Foot plantar pressure measurement system: A review. *Sensors*. **2012**, *12*, 9884-9912. https://doi.org/10.3390/s120709884
33. Ellis, S. J.; Stoecklein, H.; Yu, J. C.; Syrkin, G.; Hillstrom, H.; Deland, J. T. The accuracy of an automasking algorithm in plantar pressure measurements. *HSS J.* **2011**, *7*, 57–63. https://doi: 10.1007/s11420-010-9185-9
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. https://doi.org/10.1016/j.humov. 2014.04.008
35. Bosco, C.; Luhtanen, P.; Komi, P. V. A simple method for measurement of mechanical power in jumping. *Eur. Jounal Appl. Physiol.* **1983**, *50*, 273–282.
36. Lambrinudi, C. Use and abuse of toes. *Postgrad. Med. J.* **1932**, *8*, 459–464.
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. https://doi.org/10.1016/j.gaitpost. 2012.09.007

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*, 387–92. http://doi.org/10.1136/bjsports-2012-091837
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. Electromyo-graphy activity of triceps surae and tibialis anterior muscles related to various sports shoes. *J. Mech Behav Biomed.* **2018**, *86*, 158-171. https://doi.org/10.1016/j.jmbbm.2018.05.039
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. https://doi.org/10.1016/j.jmbbm.2018.03.003
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.
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. https://doi. org/10.1080/19424280.2012.692724
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. https://doi.org /10.1371/journal.pone.0052548
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. https://doi.org/10.1016/j.gaitpost. 2011.09.104
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. https://doi.org/10.1249/MSS.0b013e3182465115
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. https://doi. org/10.1016/j.jmbbm.2018.08.032
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. https://doi.org /10.1016/j.humov.2014.01.006
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. https://doi.org/10.1371/journal. pone.0041539
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. http://doi.org/10.1242/jeb. 019885
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. http://doi.org/10. 1136/bjsm.2006.033548
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. https://doi.org/10.1177/03635465990270050701
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. http://.doi.org/10.1136/bjsm.2007. 036533

53. Sánchez-Sáez, JM; Palomo-López, P; Becerro-de-Bengoa-Vallejo, R; Calvo-Lobo, C; Losa-Iglesias, ME; 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(12), 2126; https://doi.org/10.3390/ijerph16122126