PLOS ONE

RESEARCH ARTICLE

The arch support insoles show benefits to people with flatfoot on stance time, cadence, plantar pressure and contact area

Yu-ping Huang[1,2☯], Hsien-Te Peng[2☯], Xin Wang[3], Zong-Rong Chen[2,4], Chen-Yi Song[5]*

1 School of Sports Science, Nantong University, Jiangsu, China, **2** Graduate Institute of Sport Coaching Science & Department of Physical Education, Chinese Culture University, Taipei, Taiwan, **3** Department of Sports Human Science, Shenyang Sport University, Shenyang, China, **4** Department of Athletic Performance, National University of Kaohsiung, Kaohsiun, Taiwan, **5** Department of Long-Term Care, National Taipei University of Nursing and Health Sciences, Taipei, Taiwan

☯ These authors contributed equally to this work.
* cysong@ntunhs.edu.tw

OPEN ACCESS

Citation: Huang Y-p, Peng H-T, Wang X, Chen Z-R, Song C-Y (2020) The arch support insoles show benefits to people with flatfoot on stance time, cadence, plantar pressure and contact area. PLoS ONE 15(8): e0237382. https://doi.org/10.1371/journal.pone.0237382

Editor: Gianluca Vernillo, University degli Studi di Milano, ITALY

Received: February 25, 2020

Accepted: July 24, 2020

Published: August 20, 2020

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pone.0237382

Data Availability Statement: All relevant data are within the manuscript.

Funding: The research leading to these results has received funding from the Ministry of Science and

Abstract

Background

Pes planus (flatfoot) is a common deformity characterized by the midfoot arch collapses during walking. As the midfoot is responsible for shock absorption, persons with flatfoot experience increased risk of injuries such as thumb valgus, tendinitis, plantar fasciitis, metatarsal pain, knee pain, lower-back pain with prolonged uphill, downhill, and level walking, depriving them of the physical and mental health benefits of walking as an exercise.

Methods

Fifteen female college students with flatfoot were recruited. A wireless plantar-pressure system was used to measure the stance time, cadence, plantar pressure, and contact area. Parameters were compared between wearing flat and arch-support insoles using a two-way repeated measures ANOVA with on an incline, decline, and level surface, respectively. The significance level α was set to 0.05. The effect size (ES) was calculated as a measure of the practical relevance of the significance using Cohen's *d*.

Results

On the level surface, the stance time in the arch-support insole was significantly shorter than in the flat insole ($p<0.05$; $ES = 0.48$). The peak pressure of the big toe in the arch-support insole was significantly greater than in the flat insole on the uphill ($p<0.05$; $ES = 0.53$) and level surfaces ($p<0.05$; $ES = 0.71$). The peak pressure of the metatarsals 2–4 and the contact area of the midfoot in the arch-support insole were significantly greater than in the flat insole on all surfaces (all $p< 0.05$).

Technology of Taiwan (Grant No. MOST 106-2410-H-034-036), Doctoral Science and Research of Nantong University (Grant No. 135419619022) and Public Welfare Research Fund of Department of Science and Technology of Liaoning (Grant No. 20170027). No authors received a salary from any of the funders. All the funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Conclusions

These results imply that wearing an arch-support insole provides benefits in the shortened stance time and generation of propulsion force to the big toe while walking on uphill and level surfaces and to the metatarsals 2–4 while walking on the level surface. More evenly distributed contact areas across the midfoot may help absorb shock during uphill, downhill and level walking.

Introduction

The foot is an integral component of the human skeletal system and plays an important role in walking. Pes planus (flatfoot) is a very common symptom frequently encountered among many diseases associated with the foot. Previous study has estimated the prevalence of mild and severe cases of the flatfoot to be 16.2% among males and 11.7% among females which was close to each other in gender [1]. Nevertheless, females are more likely to suffer from risks of lower extremity injuries in running [2] and lack of flexible foot/shank coupling coordination compared to males [3]. Approximately 1% of the population suffers from rigid flatfoot, *i.e.*, the arch height of the foot does not change between the weight-bearing and non-weight-bearing states [4, 5]. Many cases are isolated to the period while the skeletal structure is still developing: around 46% of children aged 2 to 6 years but only 14% of those 8 to 13 years suffer from the flexible flatfoot [6].

Flatfoot deformity is related to a lack of foot arch support and insufficient flexibility of the plantar ligaments and tendons [5, 7], and the collapse in the medial arch of the foot [8]. It reduces the ability to absorb the impact on the foot while walking or running [8] and can further increase the risk of foot injury and even lead to thumb valgus, tendinitis, plantar fasciitis, metatarsal pain, knee pain, lower-back pain because of the high impact forces [5, 9–12]. In people with flatfoot, the foot pronation is abnormal or excessive while walking [11–13], leading to increased fatigue in the lower extremities [8], which contributes to increased risk of the lower-extremity injury [14, 15]. As a result, people with flatfoot usually have troubles engaging in prolonged walking or running because of the lack of the load-bearing structure of the foot arch, shock dissipation and stable support of the lower extremity [9].

Foot orthoses can alleviate the symptoms of medial tibial stress [16] and significantly reduce the pain in the lower extremities [17]. They also mitigate the symptoms of lower-back pain [18] and plantar fasciitis [19]. Furthermore, orthopedic insoles demonstrated a 75.5% symptom improvement of excessive leg internal rotation, leg length discrepancy, patellofemoral pain syndrome, and plantar fasciitis symptoms [20]. Arch-support structures are often incorporated into foot orthoses for the flatfoot [17]. Previous studies have shown that arch-support insoles can reduce the peak vertical ground reaction force (GRF) in the heel by 6.9% of the body weight and increase the peak vertical GRF by 7% of the body weight [21]. They also lead to better medial-lateral control of the center of pressure of the foot, provide stability during walking [21], enable faster stair ascent time, and improve basic mobility, physical health, and comfort [17].

In daily life, people walk and run on surfaces with different slopes (*i.e.*, inclines and declines). However, it is still unknown whether flatfoot groups can keep the aforementioned advantages when walking on different slopes with arch support insoles, despite previous research evidence showed positive effects of the arch-support insole for the flatfoot [4, 16]. Hence, the purpose of this study was to investigate the effects of the arch-support insoles on stance time, cadence, peak pressure, and contact area of the foot with the ground while walking uphill, downhill, and on a level surface, respectively. We hypothesized that wearing arch-support insoles would decrease stance time, cadence, peak pressure, and contact area on each slope walking compared to wearing flat insoles.

Materials and methods

Participants

Since females tended to suffering from lower extremity injuries [2] and lack of flexible foot/shank coupling coordination compared to males [3], the current study only recruited 15 female college students diagnosed as flatfoot. The average age was 19.7 ± 4.3 years, the average height was 160.9 ± 6.0 cm, and the average weight was 56.5 ± 6.7 kg. Among them, the foot width was 7.7 ± 0.5 cm at the widest point and 5.0 ± 0.7 cm at the narrowest point, on average. A priori sample size calculation was performed using GPower (version 3.1.9.2, Franz Faul, University of Kiel, Kiel, Germany), with a power level of 80% and an α level of 0.05 [22]. The expected effect size was calculated using means (15.47 and 6.52) and standard deviation (6.87 and 4.7) of the midfoot contact area under soft and hard insole conditions [23]. It revealed that the sample size of 15 participants would be sufficient for the analysis. The static arch index for each participant was calculated as the foot width at the narrowest point divided by that at the widest point times 100% [8, 24]. This is also called the Chippaux and Smirakarc index (CSI) developed by Chippaux and Smirakarch [25]. The average arch indices was 64 ± 9%. Participants with arch indexes larger than 45% on both feet were considered to have flatfoot [24]. All participants were in good health and had no prior injuries or surgeries on their lower extremities.

All participants gave written informed consent prior to the experiment. The institutional review board of Antai Medical Care Corporation, Antai Tian-Sheng Memorial Hospital (TSMH, approval number 16-107-B1) reviewed and approved the study protocol.

Equipment

A wireless plantar-pressure insole system (Tekscan, Inc., Boston, MA, USA) was used to monitor the plantar pressure at a sampling rate of 100 Hz while each participant was walking. Wireless pressure insole with the F-Scan sensor (Model #3000E Tekscan, Inc., Boston, MA, USA) were placed above either the tested flat insole or arch-support insole of each foot to detect participant's plantar pressure. The insole consists of 960 individual pressure measuring sensors, which are referred to as sensing elements.

Experimental protocols

The participants were instructed to walk on a treadmill with each of three slopes, a 9 degree incline (uphill walking), a -9 degree decline (downhill walking), and a level surface (level walking) [26, 27] at 0.75 m/s (2.7 km/h) speed for all slopes [26–28]. Uphill and downhill walking were performed on different days, since walking on uphill and downhill slopes should be performed on separate days with a lapse of 24 hours to avoid interference of concentric (uphill walking) and eccentric (downhill walking) contraction [29]. Level walking was assigned to be performed with either uphill or downhill walking on a same day. Participants performed a 3 min warm-up period on the treadmill at self-selected pace. Then, they walked on the adjusted treadmill for 30 seconds at one slope. There was a 6 min resting period between uphill/downhill and level walking trials.

Table 1. Hardness of the insole.

	Flat insole	Arch-support insole
Forefoot (pointer)	34.2±0.8	20.6±1.1
Midfoot (pointer)	19±1.2	60.0±0.7
Heel (pointer)	34.8±0.8	20.6±1.5

https://doi.org/10.1371/journal.pone.0237382.t001

All participants were asked to wear the same type of shoe (Arthur Ashe Int Low Python All Over, le coq sportif, France) with either a flat insole or arch-support insole (FOOTDISC, Global Action Inc., Taipei, Taiwan). The hardness values of the forefoot, midfoot, and heel parts of the flat insole and arch-support insole were measured using a hardness tester (Teclock GS-709N Type A; Teclock Co., Tokyo, Japan). The hardness tester was hold with both hands and pressed perpendicular to the plane of the forefoot, midfoot, and heel parts of the insole for five times, respectively. The value on the tester was recorded immediately each time. The averages of the hardness of each part of the insole are shown in Table 1.

Data processing

Tekscan software (Tekscan Inc., Boston, MA., USA) was used to analyse the stance time, cadence, peak plantar pressure, and plantar contact area from the pressure data of trial. The stance time was evaluated as the elapsed time from when the foot contacted the ground to when it was lifted again. Cadence means the number of steps taken per minute. The peak pressure was calculated for the big toe (BT), metatarsals 1–5 (M1-M5), midfoot (MF), medial heel (MH) and lateral heel (LH). The contact areas of the forefoot (FF), MF, and heel (H) were calculated and normalized to the sum of the contact areas of the FF, MF, and H; all values are expressed as percentages of the whole contact area. The calculation for the contact area was referred to Cavanagh's (1987) arch index formula that was usually used to determine a flatter foot in a static standing posture [30]. Nevertheless, the current study used the formula to determine the contact area changes of the distribution of the FF, MF, and H when the foot was supported by the arch-support insole in dynamic walking movement. The aforementioned parameters were analysed for both feet, and the values from the two feet were averaged [31] to avoid discrepancies caused by the difference between the dominant and non-dominant legs.

Statistical analysis

SPSS 18.0 for Windows (SPSS Science Inc., Chicago, IL, USA) was used for the statistical analyses. A two-way repeated measures ANOVA was performed to compare the parameters between trials with participants wearing flat versus arch-support insoles for each slope. Levene's test was used to test the homogeneity of the variances. A Kolmogorov-Smirnov test was used to evaluate the normality of the data, a Wilcoxon test was used when the data were not normally distributed. The Bonferroni's method was used in *post-hoc* tests where applicable. The significance level was set at $\alpha = 0.05$. The effect size (ES) for the difference between each pair of groups was calculated for each variable as a measure of the practical relevance of the significance using Cohen's *d*; ES values between 0.20 and 0.49 were considered small, those between 0.50 and 0.79 were considered moderate, and those 0.80 and above were considered large [32].

Results

Stance time, cadence and step frequency

Table 2 shows the comparison of stance time, cadence and step frequency between the arch support insole and flat insole in each slope. The interaction with marginal significance between

Table 2. Comparison of stance time, cadence and step frequency.

		Flat insole			Arch-support insole		
		Left foot	Right foot	Average	Left foot	Right foot	Average
Stance time [†] (ms)							
	Uphill	748.0±92.1	734.7± 86.2	741.3±88.6 [a]	740.0± 99.7	720.7±112.0	730.3±104.6 [a]
	Downhill	659.3±79.1	646.0±87.6	652.7±81.9 [a, b]	656.0±67.6	645.3±79.7	650.7±72.4 [a, b]
	Level [*]	795.3±66.6	776.0±70.5	785.7±67.7 [b]	766.0±79.9	735.3±80.1	750.7±77.9 [b]
Cadence [#] (step/min)							
	Uphill [a]	51.2±6.0	51.2±5.9	51.2±5.9	50.7±6.2	51.3±7.3	51.0±6.6
	Downhill [a, b]	57.3±7.1	57.1±6.9	57.2±7.0	57.0±5.9	57.0±5.8	57.0±5.8
	Level [b]	47.9±4.3	48.2±4.1	48.0±4.2	49.4±4.9	50.2±4.7	49.8±4.7
Step frequency [†] (step/min)							
	Uphill	-----	-----	103.7±11.8 [a]	-----	-----	102.5±12.4 [a]
	Downhill	-----	-----	116.1±12.5 [a, b]	-----	-----	117.3±11.8 [a, b]
	Level	-----	-----	97.5±8.3 [b]	-----	-----	100.1±10.0 [b]

[†] interaction found between the insole and slope,

[*] significant difference found between the flat insole and arch-support insole,

[#] significant difference found among the slopes,

[a] significant difference found between the uphill and downhill,

[b] significant difference found between the downhill and level, $p < 0.05$.

https://doi.org/10.1371/journal.pone.0237382.t002

insoles and slopes was found in the stance time ($p = 0.050$). Simple main effects of slopes showed that the stance time in the arch-support insole was significantly shorter than that in the flat insole ($p = 0.002$, $ES = 0.48$) on the level surface. Simple main effects of insoles showed that the stance time of the uphill and level surfaces was significantly longer than that of the downhill surface in the arch-support ($p = 0.019$, $ES = 0.89$; $p = 0.001$, $ES = 1.33$, respectively) and flat ($p = 0.009$, $ES = 1.04$; $p<0.001$, $ES = 1.77$, respectively) insole. There was no interaction between insoles and slopes in the cadence. The main effect of slopes showed that the cadence of the downhill surface was significantly shorter than the uphill and level surfaces ($p = 0.007$; $p<0.001$, respectively). There was no statistically significant difference found between the insoles ($p = 0.169$). In addition, the interaction with marginal significance between insoles and slopes was found in the step frequency ($p = 0.044$). Simple main effects of insoles showed that the step frequency of the uphill and level surfaces was significantly shorter than that of the downhill surface in the arch-support ($p< 0.001$, $ES = 1.22$; $p< 0.001$, $ES = 2.05$, respectively) and flat ($p = 0.004$, $ES = 1.02$; $p< 0.001$, $ES = 1.75$, respectively) insole. Simple main effects of slopes showed that the step frequency has no difference among uphill ($p = 0.132$, $ES = 0.10$), downhill ($p = 0.346$, $ES = 0.10$), and level ($p = 0.053$, $ES = 0.28$) surface.

Peak pressure

Table 3 shows the comparison of peak pressure between the arch-support insole and flat insole in each part of the foot for each slope. The interaction between insoles and slopes was found in the BT ($p = 0.030$) and MH ($p = 0.007$).

BT. Simple main effects of slopes showed that the peak pressure of the BT in the arch-support insole was significantly greater than that in the flat insole on the uphill ($p = 0.002$, $ES = 0.53$) and level surface ($p = 0.019$, $ES = 0.71$). Simple main effects of insoles showed that the peak pressure of the BT of the uphill and downhill surfaces was significantly greater than

Table 3. Comparison of peak pressure.

		Flat insole			Arch-support insole		
		Left foot	Right foot	Average	Left foot	Right foot	Average
BT † (kpa)							
	Uphill *	303.8±186.0	284.4±173.4	294.1±172.0 a	458.5±317.1	356.9±236.1	407.7±250.0 a
	Downhill	288.6±119.6	281.1±140.9	284.8±111.1 b	370.9±208.5	274.5±135.3	322.7±133.9 b
	Level *	198.9±109.0	143.5±82.7	171.2±74.7 a, b	237.6±97.7	215.2±150.2	226.4±80.7 a, b
M1 # (kpa)							
	Uphill c	245.6±87.1	246.3±112.2	245.9±96.9	244.1±116.3	275.3±155.0	259.7±119.5
	Downhill	189.7±104.6	213.3±129.7	201.5±110.0	228.2±149.7	212.3±147.2	220.2±138.8
	Level c	208.3±96.3	202.9±72.3	205.6±77.1	193.3±93.2	238.9±111.1	216.1±93.1
M2 * (kpa)							
	Uphill	313.9±221.4	294.1±192.9	304.0±196.3	326.3±239.6	294.9±188.5	310.6±212.2
	Downhill	245.6±168.6	256.8±206.6	251.2±182.0	304.1±206.3	276.6±207.2	290.4±196.4
	Level	354.1±216.9	310.5±187.2	332.3±196.5	382.9±276.7	351.6±239.1	367.3±250.5
M3 *, #(kpa)							
	Uphill	284.0±132.9	302.2±189.1	293.1±154.5	320.8±156.4	298.2±171.6	309.5±156.3
	Downhill b	211.5±120.6	225.5±145.4	218.5±128.6	279.8±166.3	256.8±165.6	268.3±158.7
	Level b	349.6±164.9	350.7±211.4	350.2±176.9	368.0±208.7	399.1±224.1	383.6±211.4
M4 *, #(kpa)							
	Uphill	192.0±86.1	205.9±110.6	199.0±85.1	217.4±115.8	197.2±84.0	207.3±89.7
	Downhill b	121.8±48.4	142.1±61.0	132.0±45.8	150.5±74.0	153.5±80.4	152.0±66.2
	Level b	223.9±88.7	228.7±100.6	226.3±75.6	236.5±97.6	275.1±141.0	255.8±98.0
M5 # (kpa)							
	Uphill	133.5±83.6	164.3±77.1	148.9±73.4	149.8±86.7	144.4±55.6	147.1±65.2
	Downhill b	95.7±38.2	114.2±51.4	105.0±39.2	111.1±48.0	114.0±55.5	112.6±46.7
	Level b	153.9±44.8	154.8±63.7	154.3±49.9	152.4±60.3	173.5±83.3	162.9±48.3
MF (kpa)							
	Uphill	140.6±91.5	140.2±49.8	140.4±56.5	148.2±98.2	122.9±46.2	135.6±64.2
	Downhill	96.1±30.6	113.8±48.1	105.0±34.4	120.1±38.4	120.8±53.6	120.4±40.2
	Level	119.9±56.4	123.3±47.8	121.6±36.7	108.3±27.4	122.4±49.4	115.3±31.8
MH † (kpa)							
	Uphill *	165.2±67.3	169.5±61.5	167.3±60.2 c	147.8±74.5	140.9±62.3	144.3±64.4 c
	Downhill *	232.5±156.2	211.8±116.5	222.1±134.2	197.1±136.1	138.7±98.4	167.9±114.2
	Level *	206.5±80.4	179.4±52.2	193.0±63.0 c	165.7±90.0	161.7±71.2	163.7±72.6 c
LH *, # (kpa)							
	Uphill c	131.5±63.6	146.1±102.0	138.8±71.7	111.7±61.8	112.2±52.4	112.0±49.1
	Downhill	202.3±130.2	161.5±80.7	181.9±103.1	164.5±111.4	152.7±96.9	158.6±99.0
	Level c	173.7±82.0	165.1±103.3	169.4±76.1	129.3±51.7	189.1±162.6	159.2±90.5

† interaction found between the insole and slope,

* significant difference found between the flat insole and arch-support insole,

significant difference found among the slopes,

a significant difference found between the uphill and downhill,

b significant difference found between the downhill and level,

c significant difference found between the uphill and level, $p < 0.05$; BT = big toe, M1 = metatarsal 1, M2 = metatarsal 2, M3 = metatarsal 3, M4 = metatarsal 4, M5 = metatarsal 5, MF = midfoot, MH = medial heel, LH = lateral heel.

https://doi.org/10.1371/journal.pone.0237382.t003

Table 4. Comparison of contact area.

		Flat Insole			Arch-support insole		
		Left foot	Right foot	Average	Left foot	Right foot	Average
FF * (%)							
	Uphill	44.0±6.2	40.5±6.4	42.2±5.3	42.5±6.1	40.0±4.3	41.3±4.5
	Downhill	43.3±6.0	40.4±3.7	41.8±4.1	41.3±7.1	39.9±5.7	40.6±6.0
	Level	43.4±4.6	41.2±4.6	42.3±4.4	41.2±4.2	40.1±4.8	40.6±3.8
MF * (%)							
	Uphill	28.6±7.7	30.1±6.3	29.4±6.2	30.8±6.6	31.0±5.1	30.9±5.2
	Downhill	31.0±4.5	27.4±9.6	29.2±6.1	32.1±4.1	28.0±10.3	30.0±5.4
	Level	30.2±6.4	27.7±7.4	29.0±6.1	32.1±5.1	29.0±7.9	30.5±4.8
H (%)							
	Uphill	28.4±4.0	28.4±2.9	28.4±2.2	28.4±3.5	27.2±4.1	27.8±2.3
	Downhill	29.0±3.2	28.9±3.2	28.9±2.5	31.4±3.9	27.3±5.4	29.4±2.3
	Level	27.9±2.5	29.5±3.6	28.7±2.5	29.4±5.3	28.3±2.2	28.8±2.6

* significant difference found between the flat insole and arch-support insole, $p < 0.05$; FF = forefoot, MF = midfoot, H = heel.

https://doi.org/10.1371/journal.pone.0237382.t004

that of the level surface in the arch-support ($p = 0.016$, $ES = 0.98$; $p = 0.033$, $ES = 0.87$, respectively) and flat ($p = 0.018$, $ES = 0.59$; $p = 0.007$, $ES = 1.20$, respectively) insole.

MH. Simple main effects of slopes showed that the peak pressure of the MH in the arch-support insole was significantly smaller than that in the flat insole on the uphill ($p = 0.003$, $ES = 0.37$), downhill ($p<0.001$, $ES = 0.44$) and level surface ($p = 0.024$, $ES = 0.43$). Simple main effects of insoles showed that the peak pressure of the MH on the uphill surface was significantly smaller than that of the level surface in the flat insole ($p = 0.037$, $ES = 0.42$).

There was no interaction between insoles and slopes in the peak pressure of the M1, M2, M3, M4, M5, MF and LH. The main effect of insoles showed that the peak pressure of the M2 ($p = 0.036$), M3 ($p = 0.013$) and M4 ($p = 0.013$) in the arch-support insole was significantly greater than that in the flat insole, while the LH ($p = 0.013$) in the arch-support insole was significantly smaller than that in the flat insole. The main effect of slopes showed that the peak pressure of the M1 ($p = 0.028$) on the uphill surface was significantly greater than that of the level surface, while the peak pressure of the LH ($p = 0.028$) on the uphill surface was significantly smaller than that of the level surface. The main effect of slopes showed that the peak pressure of the M3 ($p = 0.006$), M4 ($p = 0.001$) and M5 ($p = 0.005$) on the level surface was significantly greater than that on the downhill surface.

Contact area

Table 4 shows the comparison of contact areas of the FF, MF and H. There was no interaction between insoles and slopes in the FF, MF and H. The main effect of insoles showed that the contact area of the MF ($p = 0.001$) in the arch-support insole was significantly greater than that in the flat insole, while the contact area of the FF ($p = 0.001$) in the arch-support insole was significantly smaller than that in the flat insole.

Discussion

The results of the current study showed that wearing the arch-support insole shortened the stance time compared with wearing the flat insole. Furthermore, the arch-support insole reduced the peak pressure on the medial heel when the foot contacted the surface during uphill, downhill and level walking. It also increased the peak pressure on the big toe, thus assisting the foot propulsion during uphill and level walking. Moreover, the arch-support insole also increased the peak pressures on metatarsals 2–4 to assist the propulsion during walking. The arch-support insole increased the contact area of the midfoot compared with the flat insole, providing support to the medial arch, which is important for people with flatfoot.

The result of the current study showed that the stance time had an interaction effect across insole and slope. However, the stance time of the arch-support being shorter than the flat insole only occurred in level walking, but not in uphill and downhill walking. The change in the stance time upon wearing the arch-support insole could reflect a change from a pathological gait to a normal one with respect to multiple characteristics [33]. Longer stance time reflects lower gait speed that is predictive of increased mortality in middle-aged and elderly people in level walking [34]. Previous studies indicated that mid-soles composed of harder materials provide better foot support and, thereby, shorten the stance time in level walking [35]. Moreover, greater insole hardness has been shown to not only improve the efficiency of each stance but also enhance the physiological sensation during level walking [36]. The midfoot of the arch-support insole used in the current study was harder than that of the flat insole and, as a result, the arch-support insole was associated with a significantly shorter stance time than the flat insole during level walking on a treadmill. It was suggested that the arch-support insole provided better support for the midfoot, which effectively shortened the stance time when walking on a level treadmill and may increase the gait speed when walking on the level ground [34].

Although the peak pressure of the MH demonstrated an interaction effect across insole and slope, it was significantly reduced in the arch-support insole during uphill, downhill and level walking compared to the flat insole. Walking requires periodic motion of the lower extremities, and many injuries to the lower extremities are related to the loading impact and over-pronation of the foot [13, 37]. Previous studies have shown that most of the physical stresses associated with walking are concentrated around the medial calcaneal tubercle [38]. Furthermore, the flatoot is closely associated with pain in the medial calcaneal tubercle [39, 40]. The function of the arch-support insole is thought to help restore the elasticity of the foot arch [41] for people with flatfoot, thereby reducing the foot pronation during uphill, downhill and level walking. The reduced medial heel peak pressure in the arch-support insole was speculated to reduce the heel striking impact and further facilitate the transfer of loading to improve stability and comfort [42] that would benefit people with flatfoot.

The peak pressure of the BT has an interaction effect across insole and slope in the current study. It was significantly greater in the arch-support insole than in the flat insole during uphill and level walking. Most people used the heel-strike strategy, in which the midfoot is responsible for transferring the plantar weight-bearing from the heel to the forefoot. The forefoot plays a crucial role in propulsion in the last phase of a stride [23, 43]. The BT of the forefoot in the arch-support insole was suggested to provide propulsion in uphill and level walking. Moreover, participants exhibited greater peak pressures on metatarsals 2–4 of the forefoot while wearing the arch-support insole than with the flat insole during level walking. This effect can be explained as an optimization of the heel lift by sharing a part of the heel load and assisting the foot propulsion during walking [43]. The arch-support insole may restore the function of medial foot arch, thereby facilitating the natural elastic stretch of the plantar fascia tension associated with the windlass mechanism [38, 44].

In the current study, the proportion of the contact area of the midfoot to that of the whole foot was greater with the arch-support insole than with the flat insole during uphill, downhill, and level walking. The finding is in agreement with a previous study showing that foot orthotics with a 30˚ inverted angle can increase the contact area of the medial midfoot [45]. Using the arch-support insole like using the foot orthotics inserted beneath the midfoot makes the contact area of the midfoot increased during walking. This increase in midfoot contact area in people with flatfoot may be associated with the support of the medial longitudinal foot-arch [46]. It was suggested that arch-support insoles can extend the contact area more evenly across in the forefoot, midfoot, and heel and, therefore, may better disperse the cumulative foot pressure over time to reduce the risk of soft-tissue injuries to the foot [47] during walking.

There were some limitations in the current study. The uphill, downhill, and level walking were performed on a treadmill in a laboratory, which did not realistically replicate the performance in an outdoor environment. Our finding did not apply to the male counterpart and people without the flatfoot problem. Only the static footprint index was used to evaluate the flatfoot in the current study, even though there are many methods, such as the navicular drop, rear foot eversion, foot posture index values, and many others, to determine the flatfoot population in the clinic [48]. The current study did not assess arch deformation in any way, thus discussion regarding the windlass mechanism were only speculations. In addition, the arch support insole did have higher hardness in the midsole and the flat insole was harder in the forefoot and the heel. This difference in stiffness could be a confounding variable to the results in the study and therefore, we cannot conclude that the differences were due to differences in hardness or the presence vs absence of an arch support.

Conclusions

These results imply that wearing an arch-support insole provides benefits in the shortened stance time. The arch-support insole helps absorb shock at the medial heel during uphill, downhill, and level walking, provided big toe propulsion during uphill and level walking, and applied metatarsals 2–4 propulsion during level walking compared with the flat insole. Furthermore, it facilitates more evenly distributed contact area over the entire foot. Based on these findings, we recommend that people with flatfoot wear arch-support insoles to restore the function of an elastic foot arch.

Supporting information

S1 Data.
(ZIP)

Author Contributions

Conceptualization: Yu-ping Huang, Hsien-Te Peng.

Data curation: Chen-Yi Song.

Formal analysis: Yu-ping Huang, Hsien-Te Peng, Xin Wang, Chen-Yi Song.

Methodology: Yu-ping Huang, Hsien-Te Peng, Xin Wang.

Supervision: Chen-Yi Song.

Writing – original draft: Yu-ping Huang, Hsien-Te Peng, Chen-Yi Song.

Writing – review & editing: Zong-Rong Chen, Chen-Yi Song.

References

1. Tenenbaum S, Hershkovich O, Gordon B, Bruck N, Thein R, Derazne E, et al. Flexible pes planus in adolescents: body mass index, body height, and gender—an epidemiological study. Foot & Ankle International. 2013; 34(6): 811–817. https://doi.org/10.1177/1071100712472327 PMID: 23696185

2. Alomonroeder TG, Benson LC. Sex differences in lower extremity kinematics and patellofemoral kinetics during running. J Sport Sci. 2017; 35(16): 1575–1581. https://doi.org/10.1080/02640414.2016.1225972 PMID: 27571504
3. Noghondar FA, Yazdi NK. Assessment of patterns and variability in lower extremity coordination between genders with different shoe insole stiffness during jump-landing tasks. Human Movement. 2017; 18(1): 37–43. https://doi.org/10.1515/humo-2017-0002
4. Evans AM. The flat-footed child—to treat or not to treat: what is the clinician to do?. Journal of the American Podiatric Medical Associatio. 2008; 98(5): 386–393. https://doi.org/10.7547/0980386 PMID: 18820042
5. Harris EJ, Vanore JV, Thomas JL, Kravitz SR, Mendelson SA, Mendicino RW, et al. Diagnosis and treatment of pediatric flatfoot. Journal of Foot & Ankle Surgery. 2004; 43(6): 341–373. https://doi.org/10.1053/j.jfas.2004.09.013 PMID: 15605048
6. Panichawit C, Bovonsunthonchai S, Vachalathiti R, Limpasutirachata K. Effects of foot muscles training on plantar pressure distribution during gait, foot muscle strength, and foot function in persons with flexible flatfoot. Journal of the Medical Association of Thailand. 2015; 98(5): S12–7. PMID: 26387405
7. Atik A, Ozyurek S. Flexible flatfoot. northern clinics of istanbul. 2014; 1(1): 57–64. https://doi.org/10.14744/nci.2014.29292 PMID: 28058304
8. Chang CH, Chen YC, Yang WT, Ho PC, Hwang AW, Chen CH, et al. Flatfoot diagnosis by a unique bimodal distribution of footprint index in children. Plos One. 2014; 9(12): e115808. https://doi.org/10.1371/journal.pone.0115808 PMID: 25551228
9. Saltzman CL, Nawoczenski DA. Complexities of foot architecture as a base of support. Journal of Orthopaedic & Sports Physical Therapy. 1995; 21(6): 354–360. https://doi.org/10.2519/jospt.1995.21.6.354 PMID: 7655479
10. Lee CR, Kim MK, Cho MS. The relationship between balance and foot pressure in fatigue of the plantar intrinsic foot muscles of adults with flexible flatfoot. Journal of Physical Therapy Science. 2012; 24(8): 699–701. https://doi.org/10.1589/jpts.24.699
11. Levinger P, Murley GS, Barton CJ, Cotchett MP, Mcsweeney SR, Menz HB. A comparison of foot kinematics in people with normal- and flat-arched feet using the Oxford Foot Model. Gait & Posture. 2010; 32(4): 519–523. https://doi.org/10.1016/j.gaitpost.2010.07.013 PMID: 20696579
12. Tweed JL, Campbell JA, Avil SJ. Biomechanical risk factors in the development of medial tibial stress syndrome in distance runners. Journal of the American Podiatric Medical Association. 2008; 98(6): 436–444. https://doi.org/10.7547/0980436 PMID: 19017851
13. Neal BS, Griffiths IB, Dowling GJ, Murley GS, Munteanu SE, Smith MMF, et al. Foot posture as a risk factor for lower limb overuse injury: a systematic review and meta-analysis. Journal of Foot & Ankle Research. 2014; 7(1): 55–67. https://doi.org/10.1186/s13047-014-0055-4 PMID: 25558288
14. Barnes A, Wheat J, Milner C. Association between foot type and tibial stress injuries: a systematic review. British Journal of Sports Medicine. 2008; 42(2): 93–98. https://doi.org/10.1136/bjsm.2007.036533 PMID: 17984194
15. Kosashvili Y, Fridman T, Backstein D, Safir O, Bar ZY. The correlation between pes planus and anterior knee or intermittent low back pain. Foot & Ankle International. 2008; 29(9): 910–913. https://doi.org/10.3113/FAI.2008.0910 PMID: 18778669
16. Loudon JK, Dolphino MR. Use of foot orthoses and calf stretching for individuals with medial tibial stress syndrome. Foot Ankle Spec. 2010; 3(1): 15–20. https://doi.org/10.1177/1938640009355659 PMID: 20400435
17. Hsieh RL, Peng HL, Lee WC. Short-term effects of customized arch support insoles on symptomatic flexible flatfoot in children: A randomized controlled trial. Medicine. 2018; 97: 1–9. https://doi.org/10.1097/MD.0000000000010655 PMID: 29768332
18. Dananberg HJ, Guiliano M. Chronic low-back pain and its response to custom-made foot orthoses. Journal of the American Podiatric Medical Association. 1999; 89(3): 109–117. https://doi.org/10.7547/87507315-89-3-109 PMID: 10095332
19. Lynch DM, Goforth WP, Martin JE, Odom RD, Preece CK, Kotter MW. Conservative treatment of plantar fasciitis. A prospective study. Journal of the American Podiatric Medical Association. 1998; 88(8): 375–380. https://doi.org/10.7547/87507315-88-8-375 PMID: 9735623
20. Gross ML, Davlin LB, Evanski PM. Effectiveness of orthotic shoe inserts in the long-distance runner. American Journal of Sports Medicine. 1991; 19(19): 409–412. https://doi.org/10.1177/036354659101900416 PMID: 1897659
21. Jafarnezhadgero A, Farahpour N, Damavandi M. The immediate effects of arch support insole on ground reaction forces during walking. Journal of Research in Rehabilitation Sciences. 2015; 11: 145–159. https://doi.org/10.22122/jrrs.v11i3.2297

22. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods. 2007; 39: 175–191. https://doi.org/10.3758/bf03193146 PMID: 17695343

23. Zhang X, Li B. Influence of in-shoe heel lifts on plantar pressure and center of pressure in the medial–lateral direction during walking. Gait & Posture. 2014; 39(4): 1012–1016. https://doi.org/10.1016/j.gaitpost.2013.12.025 PMID: 24440428

24. Riddiford-Harland DL, Steele JR, Storlien LH. Does obesity influence foot structure in prepubescent children?. International Journal of Obesity. 2000; 24(5): 541–544. https://doi.org/10.1038/sj.ijo.0801192 PMID: 10849573

25. Gill SV, Lewis CL, DeSilva JM. Arch Height Mediation of Obesity-Related Walking in Adults: Contributors to Physical Activity Limitations. Physiology Journal. 2014; Article ID 821482 https://doi.org/10.1155/2014/821482

26. Franz JR, Kram R. The effects of grade and speed on leg muscle activations during walking. Gait & Posture. 2012; 35(1): 143–147. https://doi.org/10.1016/j.gaitpost.2011.08.025 PMID: 21962846

27. Haight DJ, Lerner ZF, Board WJ, Browning RC. A comparison of slow, uphill and fast, level walking on lower extremity biomechanics and tibiofemoral joint loading in obese and nonobese adults. Journal of Orthopaedic Research. 2014; 32(2): 324–330. https://doi.org/10.1002/jor.22497 PMID: 24127395

28. Huang YP, Kim K, Song CY, Chen YH, Peng HT. How arch support insoles help persons with flatfoot on uphill and downhill walking. Journal of Healthcare Engineering. 2017; Article ID 9342789 https://doi.org/10.1155/2017/9342789 PMID: 29065668

29. Gollhofer A, Komi PV, Miyashita M, Aura O. Fatigue during stretch-shortening cycle exercises: changes in mechanical performance of human skeletal muscle. International Journal of Sports Medicine. 1987; 8(2): 71–78. https://doi.org/10.1055/s-2008-1025644 PMID: 3596879

30. Cavanagh PR, Rodgers MM. The arch index: a useful measure from footprints. Journal of Biomechanics. 1987; 20(5): 547–51. https://doi.org/10.1016/0021-9290(87)90255-7 PMID: 3611129

31. Saadah H, Furqonita D, Tulaar A. The effect of medial arch support over the plantar pressure and triceps surae muscle strength after prolonged standing. Medical Journal of Indonesia. 2015; 24(3): 146–149. https://doi.org/10.13181/mji.v24i3.1198

32. Cohen J. Statistical power analysis for the behavioral sciences, 2nd ed: Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1988.

33. Guo G, Guffey K, Chen W, Pergami P. Classification of normal and pathological gait in young children based on foot pressure data. Neuroinformatics. 2017; 15(1): 1–12. https://doi.org/10.1007/s12021-016-9321-x PMID: 28058618

34. Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, et al. Gait speed and survival in older adults. Jama. 2011; 305(1): 50–58. https://doi.org/10.1001/jama.2010.1923 PMID: 21205966

35. Perry SD, Radtke A, Goodwin CR. Influence of footwear midsole material hardness on dynamic balance control during unexpected gait termination. Gait & Posture. 2007; 25(1): 94–98. https://doi.org/10.1016/j.gaitpost.2006.01.005 PMID: 16504511

36. Losa Iglesias ME, Becerro dBVR, Palacios PD. Impact of soft and hard insole density on postural stability in older adults. Geriatric Nursing. 2012; 33(4): 264–271. https://doi.org/10.1016/j.gerinurse.2012.01.007 PMID: 22401984

37. Hootman JM, Macera CA, Ainsworth BE, Martin M, Addy CL, Blair SN. Predictors of lower extremity injury among recreationally active adults. Clinical Journal of Sport Medicine. 2002; 12(2): 99–106. https://doi.org/10.1097/00042752-200203000-00006 PMID: 11953556

38. Cheng HYK, Lin CL, Wang HW, Chou SW. Finite element analysis of plantar fascia under stretch-the relative contribution of windlass mechanism and Achilles tendon force. Journal of Biomechanics. 2008; 41(9): 1937–1944. https://doi.org/10.1016/j.jbiomech.2008.03.028 PMID: 18502428

39. Shivam S, Hae Ryong S, Hak Jun K, Sik PM, Yeoung Chool Y, Heon SS. Medial arch orthosis for paediatric flatfoot. Journal of Orthopaedic Surgery. 2013; 21(1): 37–43. https://doi.org/10.1177/230949901302100111 PMID: 23629985

40. Zeininger A, Schmitt D, Jensen JL, Shapiro LJ. Ontogenetic changes in foot strike pattern and calcaneal loading during walking in young children. Gait & Posture. 2017; 59: 18–22. https://doi.org/10.1016/j.gaitpost.2017.09.027 PMID: 28982055

41. Janisse DJ, Janisse E. Shoe modification and the use of orthoses in the treatment of foot and ankle pathology. Journal of the American Academy of Orthopaedic Surgeons. 2008; 16(3): 152–158. https://doi.org/10.5435/00124635-200803000-00006 PMID: 18316713

42. Zhang X, Li B, Hu K, Wan Q, Ding Y, Vanwanseele B. Adding an arch support to a heel lift improves stability and comfort during gait. Gait Posture. 2017; 58: 94–97. https://doi.org/10.1016/j.gaitpost.2017.07.110 PMID: 28763715

43. Zhang X, Li B, Liang K, Wan Q, Vanwanseele B. An optimized design of in-shoe heel lifts reduces plantar pressure of healthy males. Gait & Posture. 2016; 47: 43–47. https://doi.org/10.1016/j.gaitpost.2016.04.003 PMID: 27264401

44. Hicks JH. The mechanics of the foot. II. The plantar aponeurosis and the arch. Journal of Anatomy. 1954; 88(1): 25–30. PMID: 13129168

45. Bok SK, Lee H, Kim BO, Ahn S, Song Y, Park I. The effect of different foot orthosis inverted angles on plantar pressure in children with flexible flatfeet. Plos One. 2016; 11(7): e0159831. https://doi.org/10.1371/journal.pone.0159831 PMID: 27458719

46. Zhai JN, Wang J, Qiu YS. Plantar pressure differences among adults with mild flexible flatfoot, severe flexible flatfoot and normal foot when walking on level surface, walking upstairs and downstairs. Journal of Physical Therapy Science. 2017; 29(4): 641–646. https://doi.org/10.1589/jpts.29.641 PMID: 28533601

47. Nigg BM, Cole GK, Nachbauer W. Effects of arch height of the foot on angular motion of the lower extremities in running. Journal of Biomechanics. 1993; 26(3): 909–916. https://doi.org/10.1016/0021-9290(93)90053-H

48. Banwell HA, Paris ME, Mackintosh S, Williams CM. Paediatric flexible flat foot: how are we measuring it and are we getting it right? A systematic review. Journal of Foot & Ankle Research. 2018; 11(1): 21–33. https://doi.org/10.1186/s13047-018-0264-3 PMID: 29854006