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Association of arch height with ankle muscle strength and physical performance in adult men

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ABSTRACT: Differences in arch height may have a certain impact on lower extremity muscle strength and physical performance. However, there is little evidence from investigation of the possible correlation of arch height with ankle muscle strength and physical performance measures. Sixty-seven participants took part in this study. Arch height index (AHI) was assessed and categorized using a 3-dimension foot scanner. Ankle muscle strength was measured employing a dynamometer. Physical performance measures including agility, force and proprioception were randomly tested. Compared to the medium AHI, the high AHI had lower plantarflexion and inversion peak torque. The high AHI also had lower peak torque per body weight value for plantarflexion and inversion at 120°/s ($P = 0.026$ and 0.006, respectively), and dorsiflexion at 30°/s ($P = 0.042$). No significant ankle muscle strength difference was observed between the low and medium AHI. Additionally, AHI was negatively correlated with eversion and inversion peak torque at 120°/s, and negatively associated with plantarflexion, eversion and inversion peak torque per body weight at both 30°/s and 120°/s (r ranged from -0.26 to -0.36, P values < 0.050). However, no significant relationship was found between arch height and physical performance measures. The results showed that high arches had lower ankle muscle strength while low arches exhibited greater ankle muscle strength. Arch height was negatively associated with ankle muscle strength but not related to physical performance. We suggest that the lower arch with greater ankle muscle strength may be an adaptation to weight support and shock absorption.

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INTRODUCTION

Foot arch plays a crucial role in supporting body weight and absorbing ground reaction forces generated during weight bearing activities or sports. Alterations of arch structure inevitably lead to biomechanical changes of the lower extremity. Arch height is considered as a potential risk factor for lower extremity injuries and musculoskeletal pains. According to the height of the medial longitudinal arch, the arch can be categorized as high (pes cavus), normal and flat arch (pes planus) [1]. It has been reported that a high arch is related to lower extremity bony injuries and stress fractures [2], ankle injuries and knee and foot pain [3, 4], while flatfoot has been reported to be associated with metatarsal fractures [5], osteoarthritis of the first metatarsophalangeal joint [6], soft tissue injuries such as plantar fasciitis and patellar tendinitis [2], and knee pain [7].

Extremes of arch height may have a negative impact on kinematics of the lower extremity. Previous studies have shown that individuals with high arches are more susceptible to developing a malalignment of the subtalar joint which generally leads to increased calcaneal inversion [8, 9]. This high arch structure with increased calcaneal inversion may be more likely to lead to development of a supinated foot. In contrast, individuals with low arches are more prone to developing calcaneal eversion, which may be accompanied by increased forefoot eversion, abduction and dorsiflexion [10, 11]. These alterations in low arch structure may result in pronated feet. Furthermore, kinematic coupling ratios which reflect segment coordination in kinematics have been reported to have a small and modest relationship with arch height during walking [12].

Foot and ankle muscle strength plays an important role in supporting arch structure and enhancing initiation of dynamic movement. However, the higher and lower arch height are generally accompanied by supinated and pronated feet [13], lead to different plantar pressure distribution [1, 4], and thus have some influences on morphology of muscles and muscle strength of foot and ankle. For instance, many researchers have reported that degenerative flatfoot has a negative effect on both intrinsic and extrinsic muscles of the foot, such as the posterior tibial muscle and the abductor hallucis [14,15], while the high arch has been reported to reduce strength in the plantar musculature and aponeurosis [16]. In addition, due to most physical activities or sports being performed in a standing position, the arch structure seems to play an important role in static and dynamic weight bearing activities or sports. In light of these points, we hypothesized that the arch height should be associated with ankle muscle strength and physical performance.

Arch height index (AHI) is a clinical measure used to assess static foot posture and arch height [17,18]. It has been widely applied to classify static arch height in previous studies [2, 19, 20]. Although extremely high and low arch height have been reported to be related to lower extremity injury risk and kinematics [13], little evidence is available on the possible correlation of arch height with ankle muscle strength and physical performance in adults to date. Therefore, the purposes of this study were to examine the differences between arch height and ankle muscle strength and physical performance, and to determine whether arch height correlates with ankle muscle strength and physical performance.

MATERIALS AND METHODS

Participants

Participants were recruited through advertising in local newspapers. The inclusion criteria for the study were: 1) male adults aged 30 to 64 years, 2) no exercise habit which was defined as less than 150 minutes of physical activity per week, 3) no current or previous foot pain, foot surgery and other neuromuscular or musculoskeletal disorders which affect foot function. This study protocol was approved by the Ethics Committee of University of Tsukuba, which complied with the Declaration of Helsinki, and informed consent was obtained from all participants.

Anthropometric variables

Body height was measured without shoes to the nearest 0.1 cm using a wall-mounted stadiometer. Body weight was weighed to the nearest 0.1 kg in light clothing without shoes using a digital scale. Body mass index (BMI) was calculated as body weight (kg) divided by body height squared (m^2).

Foot structure measurements

A 3-dimension foot scanner (FSN-2100, Dream GP Inc., Japan) was employed to measure foot structure information. The 3-dimension surface scanning system has been recommended for collecting foot anthropometric data because it has relatively high precision and accuracy compared to conventional measurement methods (ICCs: from 0.94 to 0.99) [21]. In this test, right foot anthropometric data were collected for each participant with bare feet in a standing position.

Before testing, the participants were instructed to place the right foot in a specified location inside the foot scanner, and the lightproof material attached to the outer shell of the scanner was secured to participants' lower shank. Each participant was taught to stay upright, look straight ahead, put hands down at sides, and spread their body weight equally on both feet. When the test started, a laser rotated on the rail around the foot computing approximately 30,000 positions including instep, heel, sole and toe, allowing the software to rebuild the exact shape of the foot. Each measurement was completed within 15 seconds. After finishing each test, we used 70% alcohol to sanitize the glass pedal prior to measuring the next participant.

Dorsum height and truncated foot length were obtained automatically by the 3-dimension foot scanner analysis software. The dorsum height was assessed at 55% of the foot length (from the posterior heel to the longest toe), and the truncated foot length was defined as the length from the posterior heel to the first metatarsal phalangeal joint. In this study, AHI as introduced by Williams and McClay [18] was calculated as the ratio of the dorsum height divided by the truncated foot length, and the value close to 0 represents a lower arch. According to the previous study [20], AHI values were divided into three groups (low, medium and high) based on the value distributed within or beyond 0.5 standard deviations of the

TABLE 1. Participant characteristics and foot structures in low, medium and high AHI group.

	Low AHI	Medium AHI	High AHI	*P* value
No.	19	31	17	—
Age, years	48.2 ± 8.3	52.0 ± 9.3	53.1 ± 8.8	0.205
Height, cm	173.3 ± 5.7	171.1 ± 7.2	168.8 ± 5.0	0.110
Body weight, kg	77.5 ± 13.7	77.9 ± 11.8	80.2 ± 9.8	0.752
BMI, kg/m^2	25.7 ± 3.9	26.6 ± 3.6	28.1 ± 2.5	0.125
Dorsum height, mm	59.3 ± 3.2	63.8 ± 3.0	67.9 ± 3.3	< 0.001
Truncated foot length, mm	186.3 ± 8.3	181.4 ± 7.5	173.8 ± 7.5	< 0.001
AHI, ratio	0.318 ± 0.014	0.352 ± 0.010	0.391 ± 0.018	< 0.001

Note: BMI, body mass index; AHI, arch height index.

mean. The value ranges for the low, medium and high AHI were 0.289 to 0.322, 0.322 to 0.382, and 0.382 to 0.431, respectively.

Physical performance

After foot structure measurements, several items were selected to assess physical performance in a random sequence for each participant. Previous research also assessed physical performance by utilizing the same items as in our present study and found they had a good reliability and validity [22].

Stepping side to side: Each participant was instructed to stand astride the middle line of three lines positioned at intervals of 1 meter. Then the participant repeatedly stepped onto or beyond the left and right side line with one foot as rapidly as possible. The score was assessed by the number of repetitions in 20 seconds.

Stepping forward and back: The participant was asked to stand behind a line. Then the participant stepped forward and back across the line with the entire foot on the ground as rapidly as possible. The performance was evaluated by the number of repetitions in 20 seconds.

Vertical jump: The participant was asked to stand on a circular board with a jump device (Jump-MD, TKK 5106, Takei Scientific Instruments, Tokyo, Japan) wound around their waist. The participant jumped vertically with both limbs as high as possible using a knee countermovement. The score was the centimeters of the jump height.

TABLE 2. Differences in ankle muscle strength and physical performance among AHI groups.

	Low AHI ①	Medium AHI ②	High AHI ③	*P* value[a]	*P* value[b] ① Vs. ②	*P* value[b] ② Vs. ③	*P* value[b] ① Vs. ③
Peak torque, Nm							
Plantarflexion 30°/s	90.07 ± 28.44	81.16 ± 23.47	72.51 ± 34.78	0.144	0.234	0.200	0.081
Plantarflexion 120°/s	57.24 ± 19.71	51.77 ± 15.07	42.81 ± 23.69	0.057	0.250	0.043	0.057
Dorsiflexion 30°/s	31.33 ± 5.35	31.22 ± 5.89	29.33 ± 4.16	0.489	0.818	0.311	0.285
Dorsiflexion 120°/s	18.46 ± 4.12	19.15 ± 4.08	19.16 ± 6.55	0.801	0.516	0.674	0.950
Eversion 30°/s	21.44 ± 7.25	19.37 ± 4.05	18.58 ± 4.94	0.566	0.430	0.651	0.330
Eversion 120°/s	14.52 ± 5.04	13.26 ± 2.75	12.30 ± 2.92	0.339	0.638	0.267	0.156
Inversion 30°/s	26.14 ± 9.72	25.64 ± 7.84	22.78 ± 6.80	0.521	0.810	0.281	0.379
Inversion 120°/s	18.11 ± 5.85	18.09 ± 4.79	15.15 ± 3.32	0.097	0.719	0.038	0.100
Peak torque per body weight, %							
Plantarflexion 30°/s	117.71 ± 34.55	106.46 ± 36.09	89.94 ± 39.99	0.055	0.153	0.118	0.030
Plantarflexion 120°/s	74.01 ± 23.59	67.69 ± 21.95	53.61 ± 29.51	0.020	0.267	0.026	0.012
Dorsiflexion 30°/s	40.83 ± 5.44	40.37 ± 6.39	36.65 ± 5.02	0.033	0.576	0.042	0.009
Dorsiflexion 120°/s	23.92 ± 3.57	24.80 ± 4.92	24.04 ± 8.57	0.394	0.928	0.196	0.285
Eversion 30°/s	27.98 ± 8.65	25.18 ± 5.19	23.12 ± 5.63	0.289	0.401	0.281	0.156
Eversion 120°/s	19.00 ± 5.64	17.17 ± 3.12	15.33 ± 3.48	0.065	0.466	0.068	0.025
Inversion 30°/s	34.18 ± 12.20	32.99 ± 8.73	28.57 ± 9.08	0.184	0.682	0.104	0.114
Inversion 120°/s	23.87 ± 8.00	23.28 ± 5.32	18.87 ± 3.83	0.030	0.976	0.006	0.076
Physical performances							
Stepping side to side (s)	43.58 ± 7.94	40.71 ± 7.45	38.82 ± 4.98	0.090	0.136	0.450	0.023
Stepping forward and back (s)	22.79 ± 4.70	21.23 ± 4.70	19.47 ± 3.94	0.087	0.318	0.149	0.028
Vertical jump (cm)	48.73 ± 7.02	43.06 ± 10.11	43.12 ± 9.02	0.073	0.063	0.698	0.002
Balancing on one limb with eyes closed (s)	19.37 ± 20.13	16.70 ± 15.91	15.94 ± 18.36	0.733	0.610	0.568	0.531

Note: [a] Kruskal-Wallis test; [b] Bonferroni correction of Mann-Whitney U test.

Balancing on one limb with eyes closed: Each participant was instructed to balance on their dominant foot with eyes closed and hands touching the waist for a maximum of 60 seconds, and the non-dominant foot was suspended in front of body approximately 10 centimeters above the ground. The score was the number of seconds between the time of eyes closed and balance lost.

Ankle strength measurements

The Biodex System 4 Dynamometer and Biodex Advantage Software Package (Biodex Medical System Inc., Shirley, NY, USA) was used to assess right ankle muscle peak torque and peak torque per body weight. Plantarflexion to dorsiflexion and eversion to inversion isokinetic strength were measured at 30 and 120 degrees/second (°/s) angular velocities.

Before each test, the isokinetic dynamometer was calibrated and positioned according to the manufacturer's recommendations. Participants performed 3-min treadmill running followed by 2-min lower extremity muscle stretching in order to avoid injuries in the test. Each participant was seated on the Biodex chair with two straps stabilizing the trunk and the hip. An attached rubber heel cup was utilized to enhance the stability of the foot on the foot plate. For each participant, the dynamometer, knee pad and positioning chair should be adjusted to align the midline of the foot with the midline of the patella, and ensure that the lower shank was parallel to the floor. In order to achieve this, the dynamometer orientation, dynamometer tilt, and seat orientation were set at 90°, 0°, 90° respectively during plantarflexion/dorsiflexion, and at 0°, 70°, 90° respectively during eversion/inversion. A range of motion was used to determine the start and stop angles for each participant based on each participant's active range of motion. The first test consisted of 3 maximal repetitions of plantarflexion to dorsiflexion at 30°/s to assess the strength of the plantarflexion and dorsiflexion muscles. The second test consisted of 5 repetitions of plantarflexion to dorsiflexion at 120°/s. The same 2 tests were then performed to assess the strength of eversion to inversion muscles at 30°/s and at 120°/s respectively. Before the start of data collection, 1 submaximal repetition was given to become

TABLE 3. Correlations of AHI with ankle muscle strength and physical performance with and without adjusted age and BMI.

	r	***P* value**	**r (adjusted)**	***P* value**
Peak torque, Nm				
Plantarflexion 30°/s	-0.24	0.051	-0.22	0.075
Plantarflexion 120°/s	-0.27	0.028	-0.24	0.056
Dorsiflexion 30°/s	-0.11	0.355	-0.03	0.814
Dorsiflexion 120°/s	0.05	0.672	0.13	0.287
Eversion 30°/s	-0.24	0.047	-0.20	0.100
Eversion 120°/s	-0.31	0.012	-0.26	0.036
Inversion 30°/s	-0.23	0.066	-0.20	0.112
Inversion 120°/s	-0.31	0.011	-0.27	0.029
Peak torque per body weight, %				
Plantarflexion 30°/s	-0.27	0.026	-0.28	0.021
Plantarflexion 120°/s	-0.29	0.018	-0.28	0.023
Dorsiflexion 30°/s	-0.22	0.079	-0.18	0.148
Dorsiflexion 120°/s	0.06	0.963	0.04	0.729
Eversion 30°/s	-0.30	0.014	-0.30	0.016
Eversion 120°/s	-0.38	0.001	-0.36	0.003
Inversion 30°/s	-0.27	0.026	-0.27	0.028
Inversion 120°/s	-0.38	0.002	-0.36	0.003
Physical performance				
Stepping side to side (s)	-0.26	0.037	-0.14	0.259
Stepping forward and back (s)	-0.31	0.012	-0.21	0.100
Vertical jump (cm)	-0.33	0.006	-0.22	0.077
Balancing on one limb with eyes closed (s)	0.02	0.883	0.07	0.602

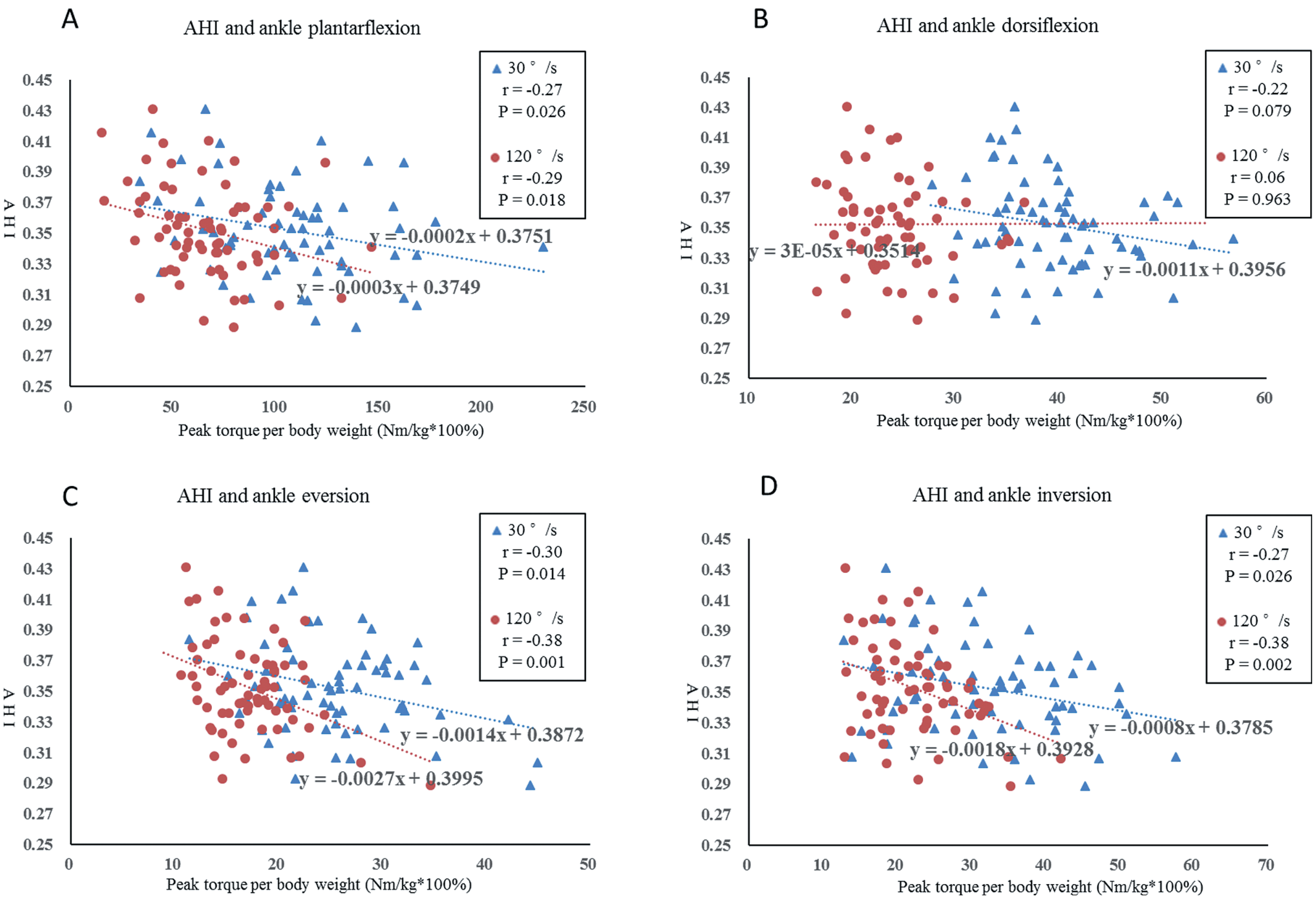

FIG. 1. Correlation of AHI with ankle muscle strength (peak torque per body weight).

familiar with the testing procedure for each participant. There was a 3-minute rest period between the two sessions. Consistent verbal encouragement was given to each participant during testing. During ankle muscle strength evaluation, the greatest muscle force output at any moment during the 3 or 5 repetitions was recorded as the peak torque (Nm) and peak torque per body weight (Nm/kg*100%). The same tester executed all measurements of the 67 participants in order to limit variability of measurements.

Statistical analysis

Only right foot structure and ankle muscle strength data were analysed in order to meet the independence assumption of statistical analysis [23]. Normally distributed data were analysed using the Shapiro-Wilk test. Since the data did not show a normal distribution, differences of ankle muscle strength and physical performance across AHI groups were analysed using the Kruskal-Wallis test, followed by the Mann-Whitney U test using Bonferroni correction to carry out all pair-wise comparisons. We employed Pearson's bivariate and partial correlations analysis to examine associations of arch height with ankle muscle strength and physical performance with and without adjusted age and BMI. In all data analyses, *P* values less than 0.05 were considered statistically significant. Data analysis was completed with IBM Statistical Package for Social Sciences (SPSS) version 22.0.

RESULTS

In total, 67 participants completed all tests in the study. The participants' anthropometric characteristics and foot structure characteristics are presented in Table 1. There were 19, 31 and 17 feet in the low, medium and high AHI group respectively based on whether the AHI value was distributed within or beyond 0.5 standard deviations of the mean. No age, height, body weight and BMI differences were observed among the three AHI groups, while differences in dorsum height, truncated foot length and AHI were found (*P* values < 0.001).

Results of differences in ankle muscle strength and physical performance among low, medium and high AHI groups are presented in Table 2. For ankle peak torque, the high AHI group had a significantly lower value compared to the medium AHI group for plantarflexion and inversion ($P = 0.043$ and 0.038, respectively) at 120°/s. With regard to ankle peak torque per body weight, the medium and low AHI group had significantly higher plantarflexion ($P = 0.026$

and 0.012, respectively) at 120°/s, dorsiflexion ($P = 0.042$ and 0.009, respectively) at 30°/s and inversion ($P = 0.006$ and 0.076, respectively) at 120°/s compared to the high AHI group. However, significant differences were not observed between the lower and medium AHI group in any ankle muscle strength. In addition, although significant differences were found in stepping side to side, stepping forward and back and vertical jump between high and low AHI groups, no significant differences were found when comparing the medium with the high AHI group.

Correlations of AHI and ankle muscle strength and physical performance with and without adjusted age and BMI are shown in Table 3. We found that AHI was significantly associated with most of the indicators of ankle muscle strength and physical performance. When adjusted for age and BMI, we also found a significant negative correlation between AHI and eversion ($r = -0.26$, $P = 0.036$) and inversion ($r = -0.27$, $P = 0.029$) peak torque at 120°/s. Like ankle peak torque, a significant negative association was found between AHI and eversion, and inversion peak torque per body weight (r ranged from -0.27 to -0.36) at both 30 and 120°/s. AHI also was related to plantarflexion peak torque per body weight at both 30°/s ($r = -0.28$, $P = 0.021$) and 120°/s ($r = -0.28$, $P = 0.023$) (Figure 1). However, we did not find a correlation between AHI and physical performance.

DISCUSSION

This study was designed to categorize arch height as low, medium and high for comparing ankle muscle strength and physical performance, and to investigate whether arch height is associated with ankle muscle strength and physical performance. Our primary finding was that high arches exhibited lower ankle muscle strength while low arches had greater ankle muscle strength. Arch height was negatively associated with ankle muscle strength, but was not related to physical performance adjusted to age and BMI.

In the present study, we used 30°/s and 120°/s angular velocities to measure ankle muscle strength. It has been reported that 30°/s represents a slow velocity defining muscle strength, 120°/s represents a fast velocity defining muscle power, and angular velocities faster than 120°/s have a potential risk of injuries and are very hard to perform [24]. Furthermore, 30°/s and 120°/s angular velocities were comparable in previous studies and have been proved to be reliable [25, 26]. In our study, we found that ankle plantarflexion and dorsiflexion, eversion and inversion strength at 30°/s were greater than those at 120°/s angular velocities. This result is in agreement with previous studies [25, 27].

It has been documented that individuals with low arches are typically considered to have flexible feet while individuals with high arches are more likely to present stiffer feet [28]. A low arch with flexible foot has a greater ability to absorb ground reaction forces generated during activities or sports compared to a high arch with stiffer foot. In order to cope with the increased ground reaction forces, low arches require greater efforts to control the structures of the foot and maintain body balance, which may result in greater ankle muscle strength in low arches. In our study, low arches exhibited greater ankle muscle strength than high arches, and arch height was negatively associated with ankle muscle strength.

Physical performance in general includes force, agility and proprioception. We selected several items for inclusion in the assessment of agility, force and proprioception. Each item may be susceptible to biomechanical changes of the lower extremity. However, there are still disputes about whether arch height has an impact on physical performance. A cross-sectional study measuring physical performance in children with and without flatfoot indicated that flatfoot is related to poor motor skill and physical performance [29]. Conversely, other studies assessed the effect of the levels of flatfoot on functional motor performance, and indicated that flatfoot is not associated with physical performance [30, 31]. Our finding supports the latter viewpoint, as we did not find a relationship between arch height and physical performance. It is known that physical performance is an integrated consequence of multiple body systems and therefore using only arch height it is difficult to conclude that it may play a decisive role in physical performance.

To the best of our knowledge, only one study has utilized footprint measurement to investigate the association between arch height and ankle muscle strength. The authors reported that the arch height was negatively correlated with ankle eversion strength ($r = 0.41$, $P = 0.02$) [32]. Although a different method for assessing arch height and a different subject population was used in the present study, we obtained a similar result that AHI was negatively correlated with ankle muscle strength in adult males even adjusted for age and BMI. AHI was not only observed to be negatively associated with eversion and inversion peak torque at 120°/s, but was also associated with plantarflexion, eversion and inversion peak torque per body weight at both 30°/s and 120°/s. These findings show that the ankle eversion and inversion strength are increased when the arch height is decreased. Although a previous study considered that it is difficult to judge whether the lower arch is a physiologic adaptation or a pathologic condition [31], from our study we suggest that the lower arch is a physiologic adaptation rather than a pathologic condition in the aspect of ankle muscle strength. Further studies are needed to investigate ankle muscle strength in pes planus.

Extremes of high and low arch height have been reported to be associated with a higher risk of various lower extremity injuries than medium arch [2, 17]. A prospective study classified arch height of 295 male military recruits as low, average and high, and found that those with a high arch had a greater incidence of stress fracture than those with a low arch [33]. Another study separated arch height of 40 recreational and team runners into high and low arch groups, and revealed that high arch individuals had more foot and ankle injuries, while low arch height individuals had more soft tissue and knee injuries [2]. Moreover, to investigate the relationship between arch structure and lower extremity mechanics in runners with extreme pes planus and pes cavus, one study reported that arch structure is associated with specific lower extremity kinematics and kinetics, which may subsequently lead to differences in injury patterns in high arch and low arch runners [34]. Because ankle muscle strength has been documented to be associated with foot and ankle injuries and the occurrence of falls [35, 36], it is hypothesized that the ankle muscle weakness may be able to account for these lower extremity injuries and pains in extreme arches. However, our results can partially prove the above assumption. In our study, we found that high AHI rather than low AHI has significantly lower ankle muscle strength. We assume that the low arch but not pes planus does not have a negative impact on ankle muscle strength.

There were some limitations in this study. Balance ability of participants was measured using their dominant foot rather than both feet. Balance may be influenced by arch posture which has a feature of bilateral asymmetry [29]. The second limitation was that we did not assess pathological bone deformation of pes planus. Therefore, we did not know whether this pes planus can affect ankle muscle strength and physical performance. Additionally, although the recruited participants had no exercise habit, the physical activity in their lives, which was not investigated, may have an impact on arch posture. A final limitation was the applicability of the results. Only adult men were selected in this study, and it is unknown whether these results are applicable to women, children and the elderly.

CONCLUSIONS

In summary, this study explored the association of arch height with ankle muscle strength and physical performance. The results showed that high arches exhibited lower ankle muscle strength while low arches had greater ankle muscle strength. Arch height was negatively associated with ankle muscle strength but not related to physical performance. We suggest that the lower arch with greater ankle muscle strength may be an adaptation to supporting body weight and absorbing shock. Further longitudinal studies are needed to determine whether a change of arch height has an impact on ankle muscle strength and physical performance.

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