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Relation	

Relationship between Foot morphologic characteristic and postural control after jump-landing in youth competitive athletes.

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Abstract

BACKGROUND: Foot arch dynamics play an important role in dynamic postural control. Association between foot arch dynamics and postural control among adolescent athletes remains poorly explored.

OBJECTIVE: To examine the relationship between foot arch dynamics, intrinsic foot muscle (IFM) morphology, and toe flexor strength and dynamic postural stability after jump landing and repetitive rebound jump performance in competitive adolescent athletes.

METHODS: Based on foot arch dynamics, evaluated from relative change in the foot arch height in sitting and standing positions, 50 adolescent athletes were classified as stiff, normal, or flexible. IFM morphology was evaluated by ultrasonography. Dynamic postural stability index (DPSI) was measured as participants jumped and landed with the right leg onto a force plate, whereas repetitive rebound jumping performance was assessed using the jump height and reactive jump index.

RESULTS: The stiff group had a significantly worse DPSI and vertical stability index than the normal group ($p=0.26$, $p=0.44$, respectively), and worse anteroposterior stability index (APSI) values than the flexible group ($p=0.005$). Multivariate regression models of the relationship between the APSI and foot arch dynamics showed adequate power (probability of error = 0.912).

CONCLUSIONS: Increased foot arch stiffness negatively affects dynamic balance during jump-landing, which may deteriorate their performance.

Keywords: jump; postural balance; ultrasonography

1. Background

The foot arch has a spring-like quality that absorbs shock during movement, reduces ground reaction forces [1], and stores and releases elastic strain energy [2]. The intrinsic foot muscles (IFMs) and tendons that form the foot arch help in shock absorption by the foot during motion, and play a role in foot flexibility. Furthermore, the IFMs contribute to the foot stiffness needed to transmit adequate forces [3], as well as to postural control [4]. However, the relationship between postural control and the foot arch height (FAH) has not been examined, and factors contributing to postural control need to be investigated in more detail. In addition, most of these reports are based on adults, and little has been examined in adolescents, who are said to have relatively flexible feet. Notably, reduced postural control caused by physiological abnormalities of the foot arch, including the pes planus (flat foot) and pes cavus (high foot), may lead to musculoskeletal injuries such as ankle sprains [5].

Reduced arch flattening is associated with toe-flexor muscle strength. A study of 448 feet of healthy young adults showed that FAD was associated with relative toe flexor strength from the sitting to standing position [6]. In addition, a comparison of foot morphology and toe flexor strength between judo athletes and 24 physically active healthy subjects each showed that the judo group had lower arch height and stronger toe flexor strength [7]. These findings suggest that FAD and toe grasping muscle strength are involved in athletic characteristics. Additionally, force attenuation and postural control during landing are essential factors for preventing sports injuries [8]. To our knowledge, the association between foot arch dynamics, cross-sectional area (CSA) of selected muscles, and physical performance, including postural control during jump-landing by adolescent competitive athletes, has not yet been explored. Hence, this study was performed to investigate whether foot arch dynamics, IFM morphology, and toe flexor strength are related to dynamic postural stability and repetitive rebound jump performance after jump-landing performed by adolescent competitive athletes. We hypothesized that foot arch dynamics would be associated with the maintenance of dynamic postural stability among adolescent competitive athletes.

2. Materials and methods

2.1 Experimental procedure

Fifty adolescent competitive athletes (28 boys: 13.5 ± 1.1 years old, and 22 girls; 13.0 ± 0.98 years old) who underwent medical and physical examinations at the Sports Medical Center at Hiroshima

University Hospital participated in this cross-sectional study, conducted between July 2021 and August 2021 (Table 1). Only those who had been selected by Hiroshima City as specially strengthened athletes in 2021 were enrolled in the study. The included athletes played sports such as rugby, badminton, sailing, judo, handball, wrestling, archery, water polo, figure skating, table tennis, kendo, hockey, and basketball. The exclusion criteria were as follows: any injury that required taking a break from sports activities within the past 3 months, any error during any of the measurements, any neurological disorder that might have affected balance, and any lower extremity injury. This study protocols complied with the tenets of the Declaration of Helsinki and was approved by the Ethical Committee for Epidemiology at Hiroshima University (file number: E-941). Informed consent was obtained from the participants, guardians and instructors of all study participants.

The foot posture index, which is an assessment of the internal and external rotations of the foot in the standing position, was used to determine the pes planus alignment [9]. The index consists of the following six items: palpation of the talar head, observation of the supra- and inferior curvature of the external malleolus, calcaneal frontal plane position, prominence in region of talovavicular joint, congruence of medial longitudinal arch, and abduction/adduction of forefoot on rearfoot. Each item is scored on a 5-point scale (-2, -1, 0, +1, +2). The lowest score of -12 indicates external rotation of the foot, and the highest score of +12 indicates internal rotation. Previous study indicate that the use of only the five image-based criteria of the FPI-6 demonstrates strong intra-rater reliability [10] .

The FAH was measured using a ruler as the perpendicular distance from the navicular tuberosity to the floor in the sitting and standing positions [2]. Semi-permanent ink was used to mark the skin over the navicular tuberosity, the location of which was determined by palpation. The FAH was measured with no weight-bearing on each foot in the sitting position and with approximately 50% weight-bearing on each foot in the standing position (Fig 1). These assessments were performed by one physical therapist with at least 5 years of experience. The FAH relative to the height was determined as follows:

$$\text{relative FAH} = \left(\frac{\text{FAH}}{\text{height}}\right) \times 100$$

A digital grip dynamometer (T.K.K.3361; Takei Scientific Instruments, Niigata, Japan) comprising strain-gauge force transducers was used. Participants were asked to gradually increase their toe flexor strength for 0 to 3 s, with a maximum force maintained for 2 s. The force exerted by the metatarsophalangeal joints when the bar was pulled was measured. The foot was placed on a digital grip-measuring dynamometer, and fixed to a heel stopper and belt. During measurements, participants were instructed to perform the task in the sitting position with their hip and knee joints flexed at 90° and their arms in front of their chests [6,11]. Three measurements were recorded, and the average was calculated in Newton meters divided by body weight (Nm/kg).

The CSA of the plumpest parts of selected IFMs were measured using B-mode ultrasonography (HI Vision Avius; Hitachi Aloka Medical, Tokyo, Japan) with an 8-MHz linear array probe. These measurements were performed based on previous studies [12,13]. Morphometric evaluations of the IFMs using ultrasound have been shown to be reliable in previous studies [14,15]. The IFMs selected for this study were the abductor hallucis, flexor hallucis brevis, and flexor digitorum brevis, as they are the main supporting muscles of the medial longitudinal arch that support the foot structure [16,17]. The point on the skin at which the probe was to be placed was marked with semi-permanent ink. When performing the measurements, the probe was placed on the skin with minimal pressure. Subsequently, participants were instructed to maintain a prone position with their knees flexed at 90° and their ankles maintained in a neutral position. The probe was placed anterior to the medial malleolus in a line perpendicular to the long axis of the foot, and the CSA image of the abductor hallucis muscle was recorded. Next, the probe was placed perpendicular to a line parallel to the flexor hallucis brevis muscle, to record its CSA image. Finally, for recording the CSA image of the flexor digitorum brevis muscle, the probe was placed perpendicular to a line connecting the third toe and medial calcaneal tuberosity. This assessment was made by one physical therapist with at least 5 years of experience of using ultrasound.

A one-leg jump with forward landing was performed to assess the dynamic postural stability index (DPSI) score of the participants. The starting position of the participants was at a distance of 40% of their height away from the force platform (AccuGait; AMTI, Hiratsuka, Kanagawa, Japan, 49.5 cm × 49.5 cm). A 30-cm high hurdle was set at the midpoint of the line connecting the starting position and edge of the force plate. Participants were asked to jump (forward) over hurdles with both feet, and land on the force plate with their right foot, and were instructed to stabilize as soon as possible after landing, place their hands on their pelvis, and remain still for 10 s. Movement of the upper limbs during the jump was not restricted; however, it was limited to placing the hands on the pelvis after stabilization. The landing task was practiced three times, and a 1-min rest was provided after each test. The trial was discarded if the jump was unsuccessful, for instance, if the participant touched the hurdle, fell when landing, landed on the ground outside the force plate, or had their right limb touch the left. This method was previously reported to have high inter-session reliability, with an intra-class correlation coefficient (3,*k*) of 0.86 [18]. (3,k) represents the inter-rater reliability of using the mean of multiple measurements with relative agreement.

The participants' repetitive rebound jump performance was evaluated using the Optojump^{TM} system (Microgate, Bolzano, Italy). This system uses two parallel infrared photocell bars; one bar was placed 0.3 cm above the surface as a transmitter unit with 96 light-emitting diodes, whereas the other was placed as a receiver. To prevent the jump performance from being affected, participants were asked to place their hands on their pelvis and repeat jumping and landing with their dominant foot five times. The dominant foot was defined as the ball kicking foot. Participants were further instructed to stand with their knees initially extended and then flexed as they jumped up and landed in the same spot at all times, while looking ahead. Participants were required to jump as high as possible with the shortest possible contact time between the floor and their feet, so that they could immediately start the next jumping motion. When the participant's foot contacted the floor, the light between the two infrared bars was interrupted, and the monitoring system sensor recorded at a sampling frequency of 1000 Hz. Two sets of five rebound jumps were used, and a 5-min rest was provided between sets. Of the five rebound jumps, the third through fifth jumps were used for analysis to obtain a stable value; this method exhibited good inter-day reliability [19].

2.2. Data collection

Foot arch dynamics refers to the relative change in the FAH in the sitting position without weight applied to the feet, and in the standing position with approximately 50% of the body weight applied to each foot [7]. The equation for calculating foot arch dynamics is as follows:

$$\text{Foot arch dynamics (\%)} = \frac{(\text{FAH sitting} - \text{FAH standing})}{\text{FAH sitting}} \times 100$$

If the foot arch dynamics is within ±1 standard deviation (SD) of the mean, the foot is classified as normal. If the foot arch dynamics is <1 SD from the mean, the foot is classified as stiff, and if the LAA is >1 SD from the mean, the foot is classified as flexible. [20].

The DPSI values were calculated using the ground reaction force (GRF) within 3 s of the first contact, and the vertical GRF more than 5% of the body weight. The force plate values were normalized to the participant’s body weight, following which the GRF data were filtered using a zero-lag, second-order, low-pass Butterworth filter with a cutoff frequency of 20 Hz. The DPSI values were calculated from the filtered data using MATLAB 2021a (MathWorks, Natick, MA, USA). The DPSI values are a composite of the anteroposterior, mediolateral, and vertical directions of GRFs in all planes, and are sensitive to force changes in the anterior (anteroposterior stability index [APSI]), mediolateral (mediolateral stability index [MLSI]), and vertical (vertical stability index [VSI]) directions. These indices were converted to APSI, MLSI, and VSI values using the following formulae [16]:1) $\mathrm{DPSI} = \frac{\sqrt{\sum(0-\mathrm{GRFx})^2+\sum(0-\mathrm{GRFy})^2+\sum(0-\mathrm{GRFz})^2}}{\text{Number of data points}} \div$ Body weight

2) $\mathrm{APSI} = \frac{\sqrt{\sum(0-\mathrm{GRFx})^2}}{\text{Number of data points}} \div \text{Body weight}$

3) $\mathrm{MLSI} = \frac{\sqrt{\sum(0-\mathrm{GRFy})^2}}{\text{Number of data points}} \div \text{Body weight}$

4) $\mathrm{VSI}=\frac{\sqrt{\sum(0\text{-}\mathrm{GRFz})^2}}{\text{Number of data points}} \div \text{Body weight}$

Further analysis was performed using the average of three successful trials [17]. GRF data used for the DPSI calculations of dynamic posture control were collected at a sampling frequency of 200 Hz. Higher DPSI values indicated worse dynamic postural stability [21].

Rebound jump performance variables (jump height [cm], contact time [s], and reactive jump index [m/s]) were automatically calculated using the Optojump™ software (Optojump™ Next software, version 1.9.9.0). The strength of reactivity was assessed using the reactive jump index, which is a measure of an athlete's ability to efficiently absorb force (eccentrically) and generate propulsion (concentrically) within a specific time [19,22]. Higher reactive jump index values indicate better rebound jump performance. The average of the data from the three successful trials was used for additional analyses. Jump height was calculated as follows:

$$\text{Jump height} = (1/2 \times \text{Tair} \times g)^2 \times (2\,g) - 1$$

where "Tair" is the time of flight (s) between the recorded force on the force plate and "g" is the acceleration due to gravity (9.81 $\mathrm{m/s^2}$). The reactive jump index was calculated as follows:

$$\text{Reactive jump index} = \frac{1}{8} \text{x}\, g\, \text{x} \frac{\text{Tair}^2}{\text{contact time}}$$

These analyses were performed using the mean value of the three repeated jumps.

2.3 Statistical analysis

All measurement values were analyzed using SPSS software (version 27.0; IBM Japan, Tokyo, Japan). Normality was confirmed using the Shapiro–Wilk test, and normally distributed variables are presented as the mean ± SD. Participants were stratified into three groups (flexible, normal, and stiff) according to the mean and SD values of their foot arch dynamics. Chi-square tests were used to check for differences in the male-female ratios between the three groups. A one-factor analysis of variance was used to investigate differences in the morphological characteristics of the foot, CSA of the IFMs, DPSI values, and repetitive rebound jump values. The relationship between the foot arch dynamics and DPSI was examined using multiple linear regression with the stepwise method. Foot arch dynamics was defined as the dependent variable, and DPSI was defined as an independent variable. The significance level was set at 5%. The post hoc power analysis was performed as previously described [22]. This procedure estimated the power of the omnibus F-test by considering the population effect size (f^2), probability of error (α), sample size, and number of predictors included in the regression model [23].

3. Results

There were no significant differences in the physical characteristics of the participants among all the groups (Table 1). Table 2 shows the foot characteristics of participants in the stiff, normal, and flexible groups. Overall, there were no significant differences in the CSA of the abductor hallucis, flexor hallucis brevis, and flexor digitorum brevis muscles among the groups (p=0.863, p=0.913, and p=0.983, respectively). Table 3 shows the DPSI values and rebound jump performance of the stiff, normal, and flexible groups. The stiff group had significantly higher DPSI and VSI values than the normal group (p=0.026, p=0.044, respectively), as well as a significantly higher APSI value than the flexible group (p=0.005). There were no differences in DPSI or VSI values between the stiff and flexible groups, or between the normal and flexible groups. Additionally, there were no significant differences in the jump heights and reactive jump indices among the groups. Finally, only APSI was correlated with foot arch dynamics. In the post hoc power analysis, the multivariate regression models for the association between the APSI and foot arch dynamics showed adequate power (β=-0.45; *p*=0.001; 95% confidence interval, -50.175 to -13.502; R^2=0.127; probability of error = 0.912) (Table 4).

4. Discussion

This is the first experimental study to explain the integration of the force perception of the foot and mechanical function of the foot arch after jump-landing performed by adolescent competitive athletes. The main finding of this study was that adolescent competitive athletes with stiff foot arches had considerably low postural control after jump-landing. In addition, the APSI, which is a measure of dynamic postural balance, was associated with foot arch dynamics. Our findings indicate that the mechanism of postural control after jump-landing was controlled by foot arch dynamics associated with stretching and contraction of the foot muscle–tendon complex.

Overall, the relationship between foot arch stiffness and balancing ability remains controversial. The height of the medial longitudinal arch positively correlates with rebound jump ability [2].

Additionally, the stiffness of the intrinsic plantar muscles that make up the foot arch increase the sensitivity of the muscle spindles, which improves a balance ability, through improved kinesthesia in athletes [26→24]. Notably, a previous study by Simkin et al. [27→25] reported that a low-arch foot was better at absorbing shock than a high-arch foot. In the present study, the association between the dynamic function of the foot arch and postural control after jump-landing in adolescent competitive athletes was clarified. Increased foot arch stiffness leads to the deterioration of the dynamic postural control in the anterior and posterior directions in adolescent athletes. Previous studies of arch structure and injury patterns have demonstrated that ankle and foot injuries occur more frequently in those with a high arch than in those with a low arch [5]. Therefore, adequate foot flexibility may play an important role in postural control and injury prevention.

The foot arch acts as a spring that stores and releases elastic energy as the load on the foot increases. This function is accomplished by achieving changes in the foot arch, which comprises extrinsic and intrinsic foot muscles. In particular, the IFMs and tendons maintain the foot arch and help it to adapt during standing and while changing walking speed [23→26]. Therefore, the entire foot may become unstable if the intrinsic foot muscles and tendons are not functioning properly during movement. This may reduce the ability of the foot to adapt to dynamic movement, leading to static and dynamic imbalances [24→27]. Furthermore, the relationship between foot arch dynamics and the performance of jump-landing may be associated with the sensorimotor interaction among the components of the foot, contributing to the consolidation of the sensory information necessary for dynamic postural control [17,25→27].

This study has some limitations. First, our sample size was too small to allow for a comparison of athletes who performed different types of sports. Future research involving large-scale, targeted recruitment of participants involved in different types of sports is necessary. Second, sex differences in participants were not examined. A previous study reported that women had lower arches than men and that there was a gender difference [28]. Therefore, we intend to increase the number of subjects and examine the relationship between foot arch dynamics and dynamic postural control from the perspective of gender differences. Finally, the present study has a strength to investigate the association between the foot arch dynamics and dynamic postural stability in adolescent competitive athletes, however it is only a cross-sectional study. Future studies should prospectively examine how the actual incidence of sports injuries relates to the foot arch dynamics and dynamic postural control of the present study and should also be linked to the prevention of injury occurrence during adolescence.

5. Conclusions

In conclusion, the foot arch dynamics play an important role in the dynamic postural control of adolescent competitive athletes. From the viewpoint of daily clinical practice, identifying and screening adolescent athletes with foot arch stiffness is important to improve physical performance and prevent sports injuries..

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Conflict of interest

The authors declare that they have no conflict of interest.

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Tables

Table 1. Physical characteristics of the study participants

	Stiff group (n=10)	**Normal group (n=30)**	**Flexible group (n=10)**	**F**	***p*-value**	**η^2**
Sex (Male: Female)	6:4	19:11	3:7	-	0.17[a]	-
Age (years)	13.6 ± 0.8	12.9 ± 1.3	13.1 ± 1.1	1.13	0.33[b]	0.05
Height (cm)	161.1 ± 8.8	159.0 ± 11.5	159.2 ± 10.0	0.14	0.87[b]	0.01
Weight (kg)	48.2 ± 7.4	52.2 ± 12.0	54.2 ± 15.5	0.67	0.52[b]	0.03
BMI (kg/m^2)	18.6 ± 2.1	20.5 ± 3.3	21.0 ± 3.8	1.76	0.18[b]	0.07

All variables are presented as mean ± standard deviation. BMI, body mass index; [a]Results of the Chi-Square test, [b]Results of the one-way analysis of variance; F, F-Value; η^2, partial eta-squared.

Table 2. Foot characteristics of the participants

	Stiff group (n=10)	**Normal group (n=30)**	**Flexible group (n=10)**	**F**	***p*-value**	**η^2**
Foot length (cm)	23.64 ± 1.53	23.87 ± 1.55	23.75 ± 1.87	0.08	0.92	0.00
FPI	3.40 ± 2.55†§	4.07 ± 2.10	6.20 ± 1.69	5.06	**0.01***	0.18
FAH (cm)						
Sitting	4.67 ± 0.57	4.67 ± 0.53	4.43 ± 0.53	0.78	0.47	0.03
Standing	4.46 ± 0.51†§	3.95 ± 0.48	3.22 ± 0.40	17.63	**<0.001***	0.43
Differences	0.21 ± 0.12†§	0.71 ± 0.25	1.21 ± 1.80	53.11	**<0.001***	0.69
rFAH						
Sitting	2.90 ± 0.28	2.95 ± 0.36	2.78 ± 0.23	1.01	0.37	0.04
Standing	2.77 ± 0.24†§	2.49 ± 0.31	2.02 ± 0.18	19.27	**<0.001***	0.45
Differences	0.13 ± 0.73†§	0.45 ± 0.16	0.76 ± 0.88	51.68	**<0.001***	0.69
Foot arch dynamics (%)	4.41 ± 2.34	15.23 ± 4.72	27.32 ± 2.27	83.25	**<0.001***	0.78
CSA of the intrinsic foot muscles (mm^2)						
Abductor hallucis	197.23 ± 49.79	207.23 ± 50.67	207.42 ± 59.18	0.148	0.863	0.006

Flexor hallucis brevis	268.25 ± 48.05	264.28 ± 46.76	270.86 ± 34.40	0.091	0.913	0.004
Flexor digitorum brevis	179.83 ± 45.89	177.54 ± 41.03	176.31 ± 48.97	0.017	0.983	0.001
Toe flexor strength (Nm/kg)	0.40 ± 0.12	0.36 ± 0.10	0.36 ± 0.09	0.820	0.447	0.035

All variables are presented as mean ± standard deviation. FPI, foot posture index; FAH, foot arch height; rFAH, relative foot arch height; CSA, cross-sectional area. *p<0.05, Bonferroni test; $^{\dagger}p$<0.05 (vs normal); $^{\S}p$<0.05 (vs flexible); [a]Results of the chi-Square test; [b]Results of the one-way analysis of variance; F, F-Value; η^2, partial eta-squared.

Table 3. DPSI and RJ performance of the stiff, normal, and flexible groups

	Stiff group (n=10)	**Normal group (n=30)**	**Flexible group (n=10)**	**F**	***p*-value**	**η^2**
Scores						
DPSI	0.311 ± 0.029†	0.283 ± 0.021	0.283 ± 0.044	3.965	**0.026***	0.136
MLSI	0.024 ± 0.006	0.028 ± 0.006	0.026 ± 0.004	2.043	0.141	0.000
APSI	0.137 ± 0.009§	0.131 ± 0.006	0.124 ± 0.012	6.030	**0.005***	0.250
VSI	0.278 ± 0.029†	0.248 ± 0.025	0.251 ± 0.049	3.350	**0.044***	0.130
Repetitive rebound jump						
Jump height (cm)	12.68 ± 3.50	11.38 ± 3.26	11.52 ± 1.61	0.685	0.509	0.028
Reactive jump index (cm/s)	0.396 ± 0.129	0.345 ± 0.065	0.345 ± 0.065	0.607	0.549	0.026

All variables are presented as mean ± standard deviation. DPSI, dynamic postural stability index; MLSI, medial lateral stability index; APSI, anterior posterior stability index; RJ, rebound jump; VSI, vertical stability index. *$p<0.05$, Bonferroni test; $^{\dagger}p<0.05$ (vs normal); $^{\S}p<0.05$ (vs flexible); F, F-Value; η^2, partial eta-squared.

Table 4. Multiple regression analysis of the associations between dynamic posture stability index and foot arch dynamics

DPSI	Foot arch dynamics (%)				
	β	**95% CI**		***p*-value**	**R^2**
		Lower	Upper		
APSI	-0.45	-50.175	-13.502	0.001	0.127

The explanatory variable was APSI. β, standardized partial regression coefficient; DPSI, dynamic postural stability index; CI, confidential interval; APSI, anterior posterior stability index

Figure captions

Fig 1. Measurement of the foot arch height (in the sitting and standing positions) and dynamics

Figures