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Toe flexor strength is not related to postural stability during static upright standing in healthy young individuals

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ABSTRACT

Background: The human foot has adapted specifically to support body weight when standing upright. At the base of the postural control system, the unique arch structure of the foot still has an uncertain role in human upright standing. Because the toe flexor muscles help to support the foot arches, they might be an important contributor to postural stability. However, no research has identified the influence of the toe flexor strength or the foot arch height on postural stability in static upright standing.

Research question: The aim of this study was to examine whether the toe flexor strength and the foot arch height were related to postural stability in static standing in healthy young individuals.

Methods: Fifty healthy young individuals were recruited into this cross-sectional study. Toe flexor strength was measured using a toe grip dynamometer, and it was normalised by body mass (rTFS). Foot arch height was assessed as the distance between the navicular tuberosity of the foot and the floor, and it was normalised by height (rFAH). Postural stability was evaluated using the path of the centre of pressure (COP) during double-leg standing with eyes open and single-leg standing with eyes open.

Results: rTFS and rFAH were 2.6 ± 0.8 N/kg and 2.8 ± 0.4%, respectively, and they were not significantly correlated (r = 0.094), indicating that they were independent variables. The results of Pearson's correlation analysis revealed that any body size related variables (height, body mass, BMI) were not significantly correlated with COP variables under either double-leg or single-leg standing, rTFS was not significantly correlated with COP variables under either double-leg or single-leg standing and rFAH was not significantly correlated with COP variables under double-leg standing.

Significance: Toe flexor strength has no significant role in maintaining postural stability during static upright standing.

1. Introduction

The human foot has adapted specifically to support the body weight when standing upright. The human heel (calcaneus bone) was enlarged for increased body weight bearing through the evolutionary process [1] and contacts the ground when humans are standing upright. Twenty-six foot bones with muscles, tendons, ligaments, fascia and aponeurosis create an arcade structure of the foot. The arcade of the foot consists of three contiguous arches: the medial longitudinal, lateral longitudinal and transversal arches. A three-dimensional finite element model has revealed that the human foot is a spatial structure designed to absorb and transfer the forces [2]. Recently, we showed that the foot arch structure functioned not only as a shock absorber but also as a force amplifier of the foot muscles in human upright standing [3]. Given that the foot arch structure evolved for human upright standing by increasing the base of support on the ground, it would be interesting to know what role the unique arch or truss structure of the foot plays in human upright standing at the base of the postural control system. However, only a few studies on the relationships between the foot arch height and static postural stability have been conducted [4,5].

Because the toe flexor muscles help to support the foot arches [6], the toe flexor strength, as an indicator of foot muscle strength, is considered an important contributor to balance and functional ability in elderly individuals [7]. This assumes that stronger toe flexor strength in men compared to women [3] might be related to better postural stability in men than women. Nevertheless, no gender differences were

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found in postural sway during standing in healthy young individuals [8–10]. From these considerations, it is therefore hypothesized that a strong toe flexor might not be required to maintain static postural stability in healthy young individuals with a normal foot condition. However, no research has identified an influence of toe flexor strength on postural stability in static upright standing. To better understand the specific roles of the toe flexor strength and the foot arch height in human upright standing, it is important to consider whether these foot related variables in the body weight-bearing condition are related to postural stability in healthy young individuals with a normal foot condition. Therefore, the aim of this study was to examine whether the toe flexor strength and the foot arch height were related to postural stability in static standing in healthy young individuals.

2. Methods

2.1. Subjects

Fifty healthy young individuals (age: 21.3 ± 2.5 yrs; height: 166.1 ± 8.3 cm; body mass: 58.4 ± 9.5 kg; means ± SD) volunteered to participate in this study. After preliminary screening, including a medical history and fitness profile, subjects with no history of serious foot or leg injury or surgery, taking no medications, having no medical risk factors and having no foot deformity were included. Before the measurements, subjects warmed up with a few minutes' walking and stretched mainly the quadriceps, hamstrings and triceps surae muscles. Subjects wore short training pants and were barefoot to minimize external effects on performance. All of the subjects were informed about the experimental procedure and the purpose of the study prior to study onset. Written consent was obtained from all subjects. The methods and all procedures used in these experiments were in accordance with current local guidelines and the Declaration of Helsinki and were approved by the local Ethical Committee for Human Experiments.

2.2. Experimental procedure

2.2.1. Toe flexor strength (TFS) and foot arch height (FAH)

TFS was measured in the standing position using a specifically designed toe grip dynamometer (T.K.K.3361, Takei Scientific Instruments Co., Niigata). The details of the apparatus, measurements procedures, and on the reproducibility have been described elsewhere [3,11–17]. The experimental setup is shown in Fig. 1. The dynamometer consisted of strain gauge force transducers, and the force generating at the metatarsophalangeal (MTP) joints was measured when the grip bar was pulled. The foot was placed on the dynamometer and was fixed with the heel stopper. During the measurements, subjects placed their arms in front of their chest and were instructed to perform the task without extending their hip joint in the standing position. The opposite foot was positioned beside the dynamometer. Prior to the maximum measurement, subjects performed 3–5 trials at a submaximum level of isometric force. For measurement of maximum TFS, subjects exerted maximum force for ˜3 s on the dynamometer. The mean values of the three measurements of maximum force for each foot were averaged and used for further analysis.

FAH was measured in the standing position using a ruler [14]. The most medial prominence of the navicular tuberosity was palpated and marked with a black pen. The vertical distance between the navicular tuberosity of the foot and the floor was measured as the FAH (Fig. 1). The vertical height of the navicular bone has been used as a noninvasive clinical measure of the medial longitudinal arch [18].

2.2.2. Postural stability

Postural stability was quantified by the force platform system measuring the centre of pressure (COP) excursion during standing. COP excursion during static standing represents the distribution of the total force applied to the supportive area or the small slow irregular sway that is generated by the body [19]. COP was measured on a force plate (9281E, Kistler, Winterthur) under two conditions: double-leg standing with eyes open (DEO) and single-leg standing with eyes open (SEO). The order of testing of these conditions was chosen randomly. The dominant leg was selected for the SEO task [11,20]. Leg dominance was determined after performing three trials of three functional tests. First, subjects were asked to step onto a 40-cm box; the leg used to perform the step-up was identified as the dominant leg. Next, subjects were pushed from behind, and the leg that stepped out was identified as dominant. Then, subjects were asked to kick a soccer ball, and the leg used to kick the ball was recorded as the dominant leg. The leg that was dominant in two out of the three tests was considered the dominant leg for this study. To attain the double- and single-leg standing position, subjects were instructed to keep their standing leg still with their arms by their sides. For single-leg standing, they maintained the non-weight-bearing leg in a position of 90 degrees of knee flexion, keeping their thighs vertical. Before the test measurements were conducted, subjects practiced 3–5 trials of each test position. For the test measurements in each position, subjects were asked to stand for as long as possible, up to 30 s. The test was stopped when subjects were unable to maintain the requirements of the test position. The standing test measurements were performed once in each test position with a 10-second rest between each position.

To process the data, the output from the force plate was introduced to the computer through an analogue-to-digital converter (PH-770, DKH, Tokyo) at a sampling frequency of 1 kHz. The COP time series were passed through a Butterworth low-pass digital filter with a 6 Hz cut-off frequency. The COP trajectory was analysed for 20 s, excluding the first 5 and last 5 s during double- and single-leg standing tasks. The following variables were used to describe the movement of the COP and were analysed by TRIAS software (DKH Corp., Tokyo): total length (TL); mean velocity (MV = TL / total time); sway area (SA). TL and SA were calculated with the following equations [24]:

$$TL = \sum_{n=1}^{N-1} \sqrt{(AP_{n+1} - AP_n)^2 + (ML_{n+1} - ML_n)^2}$$

$$SA = \frac{1}{2} \sum_{n=1}^{N} |AP_{n+1} ML_n - AP_n ML_{n+1}|$$

where N is the number of data points included in the analysis (20,000 points) and n is the COP time series. TL is the total length of the COP trajectory; i.e., the sum of the distance between consecutive points of the COP trajectory. SA was estimated by the area of a convex hull: the sum of the triangulation formed by two points on the COP trajectory necessary for calculating the convex hull.

2.3. Data analysis

Data are presented as the means ± SD. Because the TFS and FAH are affected by body mass and height, respectively [3], the variables were normalized. The TFS relative to body mass (BM) was represented by relative TFS: [rTFS = TFS (N) / BM (kg)]. The FAH relative to the height was represented by relative FAH: [rFAH (%) = FAH (cm) / height (cm) × 100]. To assess the relationships between different variables, Pearson's correlation was used. For SEO, the values of the dominant leg were used for the foot variables (rTFS and rFAH). Gender differences in all parameters were examined with the unpaired t-test. The level of statistical significance was set at $p < 0.05$.

3. Results

Physical characteristics, toe flexor strength, foot arch height and COP variables are summarized in Table 1. The relative toe flexor strength (rTFS) and the relative foot arch height (rFAH) were 2.6 ± 0.8 N/kg and 2.8 ± 0.4%, respectively, and they were not

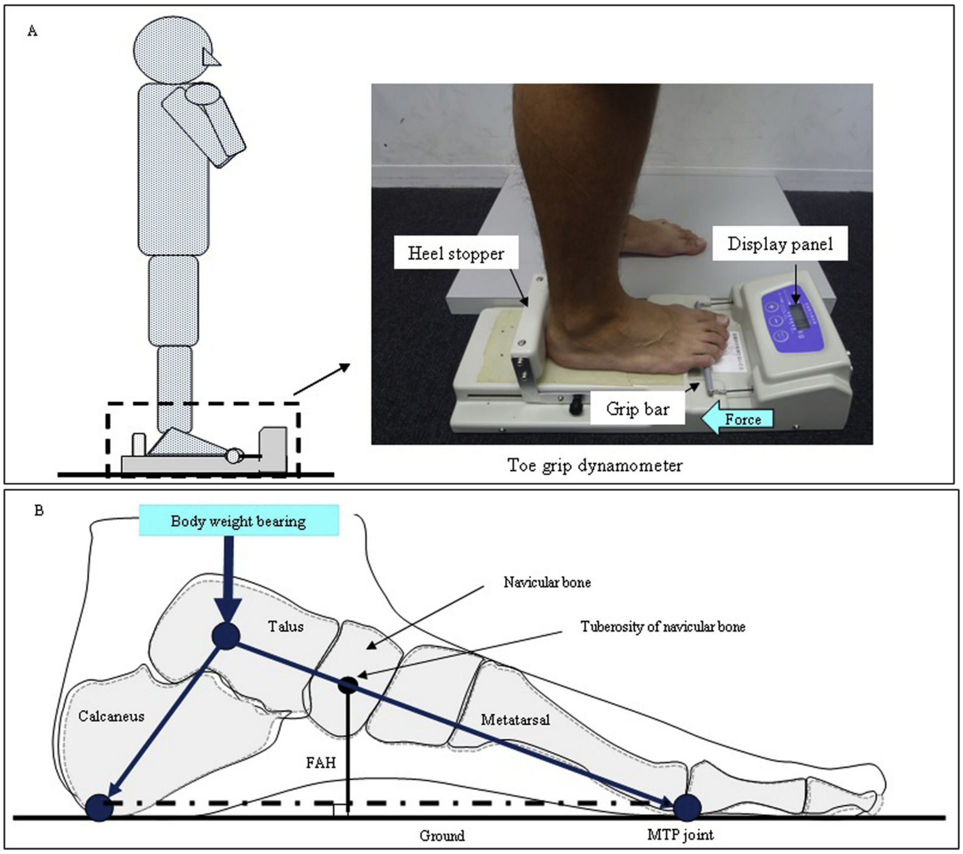

Fig. 1. Experimental set-up for the measurement of the toe flexor strength and the foot arch height. A, the toe grip dynamometer and toe flexor strength measurement in the standing position; and B, measurement sites for the foot arch height (FAH). FAH was measured as the vertical distance between the navicular tuberosity of the foot and the floor. Thicker arrows show the schema in which the vertical load applied to the talus bone is transmitted to the metatarsal and the calcaneus bones in upright standing. MTP, metatarsophalangeal joints.

Table 1
Physical characteristics, toe flexor strength, foot arch height and COP variables of healthy young individuals.

		Overall (n, 50)	Men (n, 25)	Women (n, 25)
Height (cm)		166.1 ± 8.3	171.2 ± 5.8	160.9 ± 7.2#
Body mass (kg)		58.4 ± 9.5	64.0 ± 8.5	52.8 ± 6.7#
BMI (kg/m^2)		21. 1 ± 2.3	21.8 ± 2.5	20.4 ± 2.0+
Foot related variables				
TFS (N)		152.3 ± 57.4	182.9 ± 50.7	121.7 ± 46.9#
rTFS (N/kg)		2.6 ± 0.8	2.9 ± 0.8	2.3 ± 0.8+
FAH (cm)		4.6 ± 0.7	5.0 ± 0.6	4.2 ± 0.7#
rFAH (%)		2.8 ± 0.4	2.9 ± 0.3	2.6 ± 0.4+
COP variables				
DEO	TL (cm)	21.3 ± 5.7	20.5 ± 6.0	22.1 ± 5.5
	MV (cm/sec)	1.1 ± 0.3	1.0 ± 0.3	1.1 ± 0.3
	SA (cm^2)	1.4 ± 0.7	1.3 ± 0.7	1.5 ± 0.7
SEO	TL (cm)	69.5 ± 16.8	77.8 ± 17.2	61.2 ± 11.8#
	MV (cm/sec)	3.4 ± 0.8	3.8 ± 0.8	3.1 ± 0.6#
	SA (cm^2)	4.4 ± 1.6	4.6 ± 2.0	4.3 ± 1.2

Data are presented as the means ± SD. TFS: absolute value of toe flexor strength; rTFS: toe flexor strength normalized by body mass; FAH: foot arch height; rFAH: relative foot arch height; DEO: double-leg standing with eyes open; SEO: single-leg standing with eyes open; TL: total length; MV: mean velocity; SA: sway area. + and # denote significant differences between men and women at $p < 0.05$ and $p < 0.01$, respectively.

significantly correlated ($r = 0.094$), indicating that they were independent variables. Gender differences were found in all variables, except all of the COP variables in double-leg standing and the sway area of the COP variables in single-leg standing. All of the COP variables in single-leg standing were approximately 3 times higher than those in double-leg standing.

The correlation coefficients between the body size and foot related variables and the COP variables of each standing condition are shown in Table 2. Any body size related variables (height, body mass, BMI) were not significantly correlated with COP variables in either double-leg or single-leg standing. Because of these results, absolute COP variables were used for all analyses. There were no correlations between rTFS or COP variables in either double-leg or single-leg standing and there were no correlations between rFAH or COP variables in double-leg standing, but a marginally significant correlation between rFAH and the sway area of COP variables in single-leg standing was found ($r = -0.284$, $p = 0.05$).

4. Discussion

This study showed that the toe flexor strength was not related to postural stability during either double-leg or single-leg standing and the foot arch height was not related to postural stability during double-leg standing in healthy young individuals. These results confirmed the hypothesis of this study that a strong toe flexor was not required to maintain static postural stability in healthy young individuals with a normal foot condition. The toe flexor muscles may act passively as a reinforcement of the foot arch structure in supporting the body weight during static upright standing.

The toe flexor strength can be quantified as the maximum force generated when the MTP joints are flexed. The potential force of the toe flexor muscles is generated from both plantar intrinsic and extrinsic muscles and changes with the MTP and ankle joints [12,17]. The toe flexor strength has an important role in enhancing the dynamic lower-limb physical performance, such as sprinting and horizontal jumping in children [14] and adolescents [15]. Although the toe flexor strength is independent of the foot arch height [3,14], the toe flexor strength increases with decreasing foot arch height when the vertical load bearing on the foot increases [3]. In addition, the toe flexor strength was

Table 2
Correlation coefficients between the body size and foot related variables and the COP variables while standing.

	DEO TL	MV	SA	SEO TL	MV	SA
Height (n, 50)	r = -0.053, p = 0.72	r = -0.069, p = 0.64	r = -0.041, p = 0.78	r = 0.255, p = 0.07	r = 0.235, p = 0.10	r = -0.030, p = 0.83
Body mass (n, 50)	r = -0.022, p = 0.88	r = -0.021, p = 0.88	r = -0.061, p = 0.68	r = 0.243, p = 0.09	r = 0.255, p = 0.07	r = -0.007, p = 0.96
BMI (n, 50)	r = 0.029, p = 0.84	r = 0.043, p = 0.77	r = -0.034, p = 0.82	r = 0.144, p = 0.32	r = 0.177, p = 0.22	r = 0.033, p = 0.82
rTFS (n, 50)	r = -0.022, p = 0.88	r = -0.039, p = 0.79	r = 0.037, p = 0.80	r = 0.217, p = 0.13	r = 0.186, p = 0.20	r = 0.116, p = 0.42
rFAH (n, 50)	r = -0.025, p = 0.86	r = -0.053, p = 0.72	r = -0.065, p = 0.65	r = -0.180, p = 0.21	r = -0.193, p = 0.18	r = -0.284, p = 0.05

rTFS: relative toe flexor strength; rFAH: relative foot arch height; DEO: double-leg standing with eyes open; SEO: single-leg standing with eyes open; TL: total length; MV: mean velocity; SA: sway area.

stronger in men than women, in accordance with our previous studies in children [13,14], adolescents [15] and adults [3]. The greater toe flexor strength in men compared with women could reflect muscle and body size and may be affected by some neural factors. When the toe flexor strength is normalized by the foot muscle size, there is no significant difference between men and women [12]. However, differences in the toe flexor strength relative to body mass between genders were still seen in this study. This might be due to the differences in body composition between men and women, because the percentage of body fat was significantly higher in women than men [21].

The toe flexor strength was not related to COP variables in double-leg or single-leg standing. Postural control in double-leg standing requires little muscular activity in the lower limbs [22,23]. Our recent study also confirmed that the decreased foot muscle strength after fatiguing foot muscle exercises is not associated with changed postural sway during static standing after the exercises [11]. Because the toe flexor strength is not particularly related to the postural stability, it may be presumed that the role of the toe flexor strength is rather passive action in supporting the body weight in upright standing. When the vertical load to the truss structure of the foot is increased, the foot arch height is lowered, with increasing the tension of the foot muscle-tendon complex, and the potential force-generating capacity of the toe flexor muscles is increased [3]. No relationships between the foot arch height and COP variables during double-leg standing were found in this study or other studies [4,5]. The significance of the truss structure's having two levels hierarchically arranged at the hip and ankle could be simply to determine COP variables in double-leg standing. The truss structure makes a strong and stable structure. In the case of the truss structure arranged at the hip and ankle in human double-leg standing, the body weight vertically applied to the pelvic bone is dispersed to the left and right legs, and then it is further applied to the talus bone and dispersed, via the heads of the metatarsal bones in the front and the calcaneus bone in the rear, to the ground (Fig. 1). To maintain postural control during double-leg standing, the anterior-posterior direction of the COP is related to an ankle strategy, while the medial-lateral direction of the COP is related to a hip strategy [24]. Single-leg standing loses the base of the body support at the hip, so it increases COP variables. Because the relative foot arch height was negatively correlated with the sway area in single-leg standing, a high arch of the foot may have an advantage for maintaining postural stability when increasing body weight on the foot in single-leg standing. However, it should be acknowledged that other factors, such as the body weight, foot arch dynamics or foot flexibility, may affect the foot arch height under the body weight-bearing condition to some extent [3]. Together, these data suggest that the archaeological structure of the foot plays an important role in maintaining postural stability in human upright standing.

No differences between men and women were found in the COP variables in double-leg standing, in accordance with previous studies [8–10], while in single-leg standing, total length and mean velocity of COP variables in women were better than those in men, although the toe flexor strength was weaker in women than men. The mechanism of better postural stability during single-leg standing in women than men remain unclear. Because COP variables were not significantly correlated with any factors of body size (height, body mass, BMI), differences in the body size did not affect the results of gender differences in the COP variables in single-leg standing. Postural sway in static standing may not be largely influenced by peripheral factors of the foot musculoskeletal components but by a central origin or neural components. Indeed, improvement of plantar cutaneous sensation after foot massage can improve dynamic balance performance in type II diabetic patients [25]. Further studies are needed to investigate gender differences in postural stability with respect to neural components in single-leg standing.

There are several limitations to this study. The subjects were only selected from among healthy young individuals with a normal foot. This might have caused the small ranges of the measurement variables (e.g., foot arch height) in the correlation analysis. Therefore, further study is needed to specifically address the subgroups of some clinical conditions of the foot, including flat (low-arch) foot and cavus (high-arch) foot. Despite these limitations, our findings contribute to the advancement of the general understanding of the roles of the toe flexor strength and the foot arch height in postural stability of human upright standing.

5. Conclusion

The toe flexor strength has no significant role in maintaining postural stability during static upright standing in healthy young individuals.

Declaration of Competing Interest

The authors report no conflicts of interest related to this work.

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