The Role of the Great Toe in Balance Performance

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ABSTRACT: The objective of this study was to evaluate great toe function in maintaining static and dynamic balance. Correlation among great toe length, body height, and balance performance parameters were also investigated. Thirty females (aged 22.1 ± 1.9 years) were tested in two great toe conditions: unconstrained and constrained. Balance testing was done in the following order: (1) static balance, single-leg stance with right or left foot, eyes open or closed; (2) static balance, stance with both feet, eyes open or closed; (3) dynamic balance, left/right or forward/backward, rhythmic weight shifting; and (4) dynamic balance, target reaching test, eight targets within 90% limit of stability. Significant differences were found in sway velocity between the two toe conditions with eyes open or closed in single-leg stance ($p < 0.05$). No difference was found between the two conditions while standing with both feet. For rhythmic weight shifting, significant differences in sway velocity were found in toe conditions and in weight-shifting directions ($p < 0.05$). As to target reaching, significance was only noted in directional control scores. Great toe length was correlated with subject's height ($r = 0.553, p < 0.05$). Our results indicate that constraining the great toe deteriorated the subjects' single-leg stance performance and worsened the directional control ability during forward/backward weight shifting. The importance of the great toe in balance may be taken into account in toe amputation or transfer in the future. © 2008 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 27:549–554, 2009

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Balance is vital for people to accomplish daily tasks. Impairment in balance interferes with acquiring motor skills, leading to deterioration in performance and a higher incidence of falls. Identifying variables that deleteriously affect balance may be important in injury prevention. The base of support in standing balance is usually referred to the plantar surface of the foot. During locomotion, the foot serves as a propulsive lever and shock absorber, constantly suffering compressive, tensile, shearing, and rotatory forces. Dysfunction of foot biomechanics by disease or injury interferes with lower extremity biomechanics, posing extra pressure on other joints.

The great toe seems to play an important role in the function of the foot. In standing, the great toe exerts more pressure than those of the five metatarsal heads and the heel,[1] with a pressure twice that of the total pressure of the other four toes.[2] During walking, as the great toe passively dorsiflexes, the longitudinal arch is raised, the rearfoot supinated, the leg externally rotated, and the plantar aponeurosis tensed.[3] This so-called windlass mechanism tenses the plantar fascia, thus forming a rigid lever for push-off. If the mechanism is altered, the timing and effectiveness of push-off is affected. Therefore, great toe disorders cause inevitable changes in static and dynamic balance.

To our knowledge, none of the balance studies directly evaluated the great toe influence on balance. Tanaka et al.[2] tested subjects' single-leg stance on a moving platform and measured their sway responses and the peak pressure under the toes. Body sway was better correlated with peak anteroposterior sway than with lateral sway, and the peak pressure of the great toe was significantly greater than the sum of the peak values of the other four toes for both sides. The same group also found great toe pressure in elderly subjects was significantly greater than in younger subjects.[4] Similar results were found by Ducic et al.[5,6] in a group of patients with peripheral neuropathy.

Significant changes in the plantar pressure distribution were measured in standing and walking within patients with great toe range of motion deficits.[7,8] However, the direct impact of the great toe on balance parameters has not been investigated.

Great toe amputation affects foot bone stress. Barca et al.[9] found that patients who received microsurgical reconstruction of the thumb with great toe transfer exhibited an overload of central and lateral metatarsal bones. Thus, great toe amputation significantly altered the weight distribution pattern within the foot. This alteration would inevitably affect a subject's balance.

Due to the scant information regarding the role the great toe in balance performance, our purpose was to evaluate the function of the great toe in maintaining static or dynamic balance. We hypothesized that subjects with an unconstrained great toe would perform better during single-leg stance in an eyes open or eyes closed condition. For dynamic standing tasks, we predicted constraint of the great toe would deteriorate balance performance parameters. Relations among the length of great toe, body height, and balance ability were also investigated.

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Table 1. Descriptive Statistics of the Subjects

	Mean ± SD	Minimum	Maximum
Age (years)	22.10 ± 1.87	18.37	24.88
Height (cm)	161.11 ± 4.78	152.00	170.00
Body weight (kg)	57.02 ± 6.48	48.50	77.00
Great toe length (cm)	6.48 ± 0.45	5.60	7.50

MATERIALS AND METHODS

Thirty females, aged 18–24 years, volunteered for the study. They were recruited from local universities, and their informed consent was in accordance with institutional review board procedures at Chang-Gung Memorial Hospital. Exclusion criteria included: lower extremity diseases or injuries within the past 6 months; any visual, hearing, proprioceptive, or foot sensory impairment that would affect balance; or any other balance disorders. Descriptive statistics are listed in Table 1. Length of the big toe was measured from the first metatarsal joint line to the most distal part of the phalange. All subjects were right-leg dominant.

Subjects were tested in two great toe conditions: unconstrained or constrained. In the constrained condition, the great toe was constrained in 30° dorsiflexion with a custom splint to mimic the situation without a great toe (Fig. 1). In the condition with two legs standing, both great toes were constrained. In single-leg stance, only the stance leg was constrained. Fifteen subjects performed the unconstrained toe condition first and the others the constrained toe condition first. The order was randomly assigned.

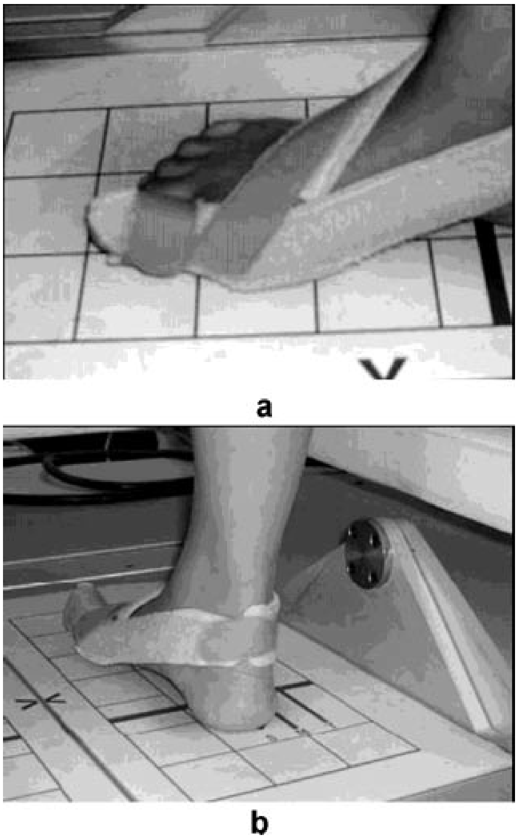

Figure 1. The great toe constraining splint: (a) lateral view; (b) posterior view.

Subjects rode a stationary bike for 3 min and then performed designed lower extremity stretching exercises. The following testing conditions were studied: (1) static balance, single-leg stance with right/left foot, eyes open and closed; (2) static balance, both feet, eyes open and closed; (3) dynamic balance, rhythmic weight shifting, left/right and forward/backward; and (4) dynamic balance, target reaching test, eight targets within 90% limit of stability (LOS). After testing, subjects sat and rested for 10 min, then performed the whole series again with the second big toe condition.

Balance parameters were measured by a commercially available balance machine (Smart Balance Master® v5.0, Neurocom Intl, Clackamas, OR). This system is constructed with transducer-mounted force platforms for measuring ground reaction forces, from which the center of pressure and the sway angles were calculated. The sampling rate was 100 Hz. The programmed software also computes LOS, that is, the greatest distance a person can lean away from the base of support without changing the base, in accordance to the subject's body height. A computer screen with adjustable height is mounted on the machine to display the sway excursion to the subject. A cursor was displayed to represent the subject's center of pressure.

In static balance testing, the subject stood with her eyes leveled with the computer screen. In single-leg stance, the subject placed her foot in the middle of the force plate. For the next condition, subjects stood with both feet shoulder width apart (the actual width depended on the body height of the subjects). Foot positioning was kept constant for each subject across all trials. Data collection did not start until the subject attained a stable condition, which was a couple of seconds after foot placement. The recording time was 20 s. Both conditions were tested with eyes open and then eyes closed; the two were treated as independent testing conditions. The sway velocity of the center of pressure was recorded. Sway velocity was calculated by the averaged movement velocity between the 5 and 95% movement distance.

During dynamic testing, subjects performed movements according to the programmed conditions. For rhythmic weight shifting, subjects swayed front and back/left and right within their 50% LOS. Each movement was tested twice. The directional control (%) of the weight shifting movement was calculated as follows:

$$\text{Directional control } (\%) = \frac{\mathrm{M_i} - \mathrm{M_e}}{\mathrm{M_i}}$$

where Mi is the the amount of movement in the intended direction and Me is the the amount of extraneous movement.

For the target reaching condition, nine squares were displayed on the screen. The subject swayed in between the center cursor and the rest of the eight representing the front, right front, right, right back, back, left back, left, and left front position of the subject's 90% LOS, with a sequence programmed in the computer (Fig. 2). Each subject completed all eight directional moves, and the center of pressure reaction time (RT), movement velocity (MVL), and directional control (DCL) were recorded.

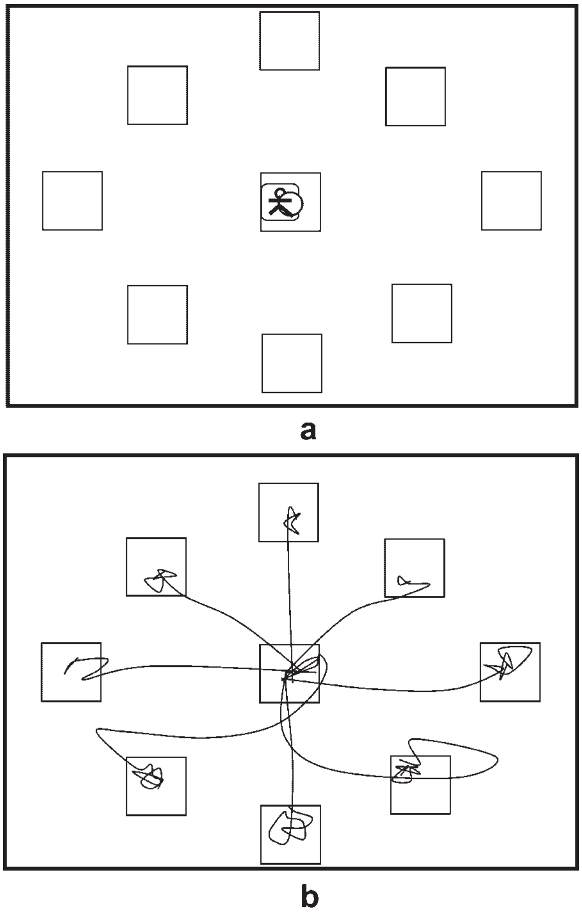

Figure 2. Target reaching test. (a) The starting position. Subject holds her center of pressure inside the center square. (b) The center of pressure excursion curves of eight target positions.

Two-way analyses of variances were used with repeated measures on the two independent variables: toe (unconstrained and constrained) and leg (left and right) for static single-leg stance with eyes open or eyes closed; toe and direction (left/right and forward/backward) for weight shifting condition; toe and target (front, right front, right, right back, back, left back, left, left front) for target reaching test. A paired *t*-test of toe condition was used for static two-leg stance with eyes open or closed. A pairwise comparison was used when a significant interaction was found between two independent variables. Significance level was set at 0.05. Pearson's correlation coefficient was calculated for correlations between great toe length and body height, great toe length and balance parameters, and the body height and balance parameters.

RESULTS

Effects of Great Toe on Static Balance

In single-leg standing, significant difference was seen in sway velocity between the two toe conditions with eyes open or closed ($p < 0.05$), but not between right and left legs. No interactions were found between toe and leg conditions with eyes open or closed. The sway velocities were smaller with the great toe unconstrained than constrained (Fig. 3). However, sway velocity in static standing with both feet did not show significant differences ($p = 0.29$) between the two toe conditions (Fig. 4).

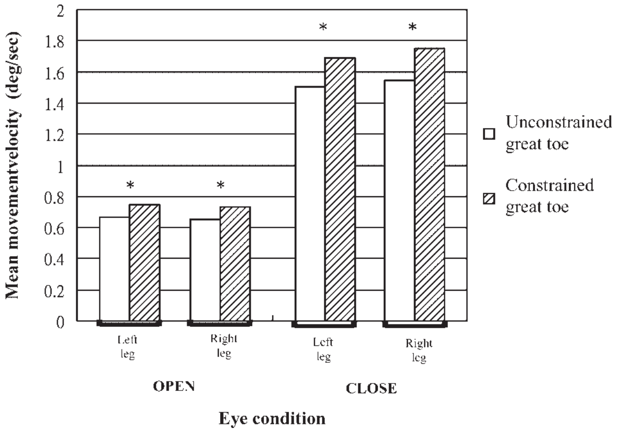

Figure 3. Significant difference was seen in sway velocity (deg/s) during single-leg standing between the two toe conditions with both eyes open and closed (*$p < 0.05$).

Effect of Great Toe on Dynamic Balance

For rhythmic weight shifting, significant differences occurred both with toe conditions and in weight-shifting directions ($p < 0.05$). Subjects demonstrated better directional control when the toe was unconstrained. Their directional control was better in the left/right than the forward/backward direction. A significant interaction was found between toe condition and weight-shifting direction. Forward/backward sway direction was significantly different between toe conditions ($p < 0.05$), but not the left/right (Fig. 5).

For target reaching, no significant differences occurred in reaction time ($p = 0.69$) or movement velocity ($p = 0.17$) in either constrained or unconstrained conditions. Significance was only noted in directional control scores (*$p < 0.05$). A significant difference occurred between the two toe conditions in directional control score in target position front, right front, and left front (Fig. 6). Subjects demonstrated

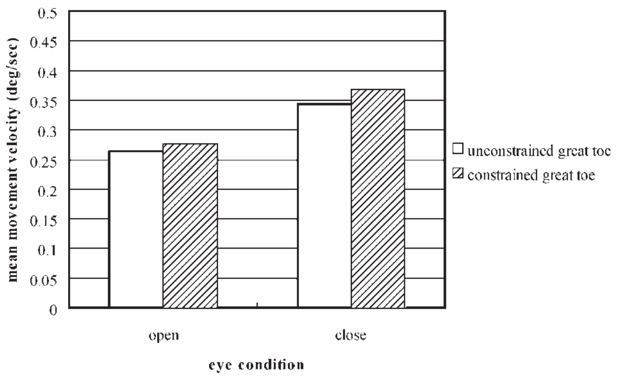

Figure 4. Sway velocity (degree/s) during two-leg stance between the two toe conditions with both eyes open and closed.

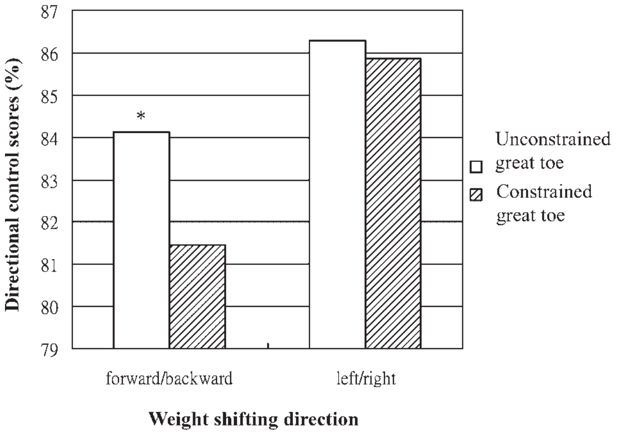

Figure 5. Directional control scores (%) during rhythmic weight shifting between the two toe conditions in forward/backward and left/right directions. Significant difference (*$p < 0.05$) was noticed between the two toe conditions in forward/backward direction.

better directional control when the great toe was unconstrained.

Correlation between Great Toe Length and Body Height/Balance Performance

Great toe length was only correlated with subject's body height ($r = 0.553$, $p < 0.01$).

Correlation between Body Height and Balance Performance

No significant correlations were found between the subject's body height and any of the balance parameters ($p > 0.05$).

DISCUSSION

Our results revealed the importance of the great toe in standing balance. The constraint status of the great toe made a significant difference in the subject's sway velocity during single-leg standing, but not in standing with both feet, supporting our hypothesis that subjects demonstrate better single-leg stance performance with an unconstrained great toe. In standing, the body's center of gravity passes through the femoral greater trochanter and falls in front of the ankle joint. The gluteus maximus and the posterior shin muscles contract to hold the body in position. During single-leg stance, the support base is relatively smaller. For the body's center of gravity to fall within the supported foot, more muscles must assist this task. The gluteus medius contracts to prevent the body from sideway leaning. Foot muscles are also of great importance while standing in this condition. Menz et al.[10] found that toe plantar flexor muscles are significant predictors of balance and functional ability. With a constrained great toe, the functions of the great toe plantar flexors would be limited.

In addition, the great toe serves as the insertion for some of the foot extrinsic and intrinsic musculatures and also the insertion of the arch-maintaining structure–plantar aponeurosis. Malfunction of the great toe would inevitably cause foot function deterioration, interfering with balance performance especially in challenging conditions such as single-leg stance.

The ability to stand with one leg is often used to evaluate balance performance. Many studies report no difference in single-leg balance between the left/right and dominant/nondominant legs,[11–13] consistent with our findings.

Our study also showed directional control deficits during forward/backward weight shifting in the constrained great toe condition, but not during left/right weight shifting. Winter[14] indicated that during quiet standing, the forward/backward center of pressure excursion was primarily controlled by the foot plantar- and dorsiflexors, while the left/right center excursion was mainly adjusted by hip abductors and the foot invertors and evertors. The constrained great toe condition in our study limited functional control of the foot, not the hip; therefore, the forward/backward weight-shifting performance might be deteriorated more obviously. The amount of forward/backward sway during single-leg stance is more obvious than the amount of left/right sway,[15] indicating that left/right sway, which is controlled by larger hip abductors, is more stable than the forward/backward sway, which is adjusted by foot dorsi and plantar flexors.

No significant difference was found in reaction time and movement velocity in the target reaching test

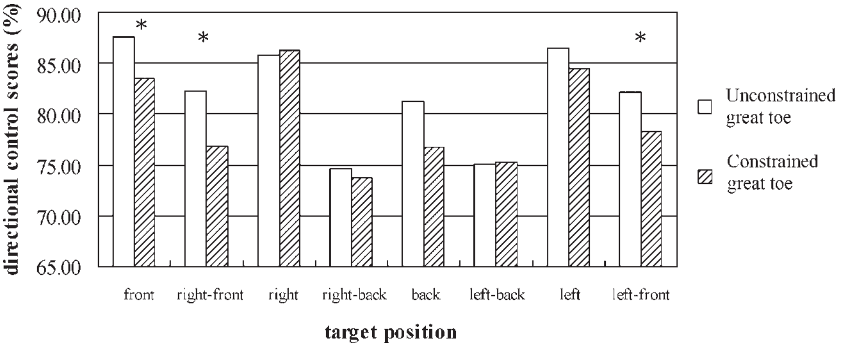

Figure 6. Directional control scores (%) of eight target positions for target reaching test. Paired t-test revealed significant differences in directional scores for target position front, right-front, and left-front (*$p < 0.05$).

regardless of the great toe condition. This might be because the target reaching movement was mainly generated by the large lower extremity muscles to move the center of pressure, and the muscles in the great toe are primarily for fine motor control. Similar explanations apply to the movement velocity. Because the center of pressure movement velocity is mainly controlled by the contraction of large muscle groups, the great toe condition has no great influence.

On the other hand, significant differences were noticed in the directional control during target reaching between the toe conditions. When the great toe was constrained, subjects demonstrated worse directional control. The worse performances were front, right front, and left front target positions. Limitation of foot dorsi and plantar flexors would affect a subject's forward/backward sway performance. Considering plantar pressure distribution, the great toe sustains about 1.7% of the total load carried by the foot during regular stance.[16] It is reasonable to infer, therefore, that subjects with the great toe constrained in a dorsiflexed position would encounter difficulties while shifting forward—including the front, right front, and left front target reaching tasks. Further research with only one side of the great toe being constrained is needed to test the specificity of the great toe on to the target reaching direction. The results of the target reaching test also follows Fitts' Law of speed-accuracy tradeoff.[17] The great toe functions predominantly in controlling accuracy, not speed.

The correlation between great toe length and the subject's body height shows that taller subjects have longer great toes; however, the long great toes do not positively or negatively affect their balance.

Different body characteristics would affect balance differently; however, the exact mechanism is unclear. Inconsistent results have been published regarding this issue. We found no correlations between the subject's body height and balance parameters. Era[18] pointed out that as body height increases, postural sway increases. In contrast, Davis et al.[19] found that older women who were short demonstrated poor balance and were prone to falls. On the other hand, Keionen et al.[20] found no relationships between body height and balance.

In conclusion, our study shows the importance of the great toe in static and dynamic standing balance. A constrained great toe interfered with balance during single-leg stance and worsened the directional control ability during forward/backward shifting. Because the great toe flexors were restricted while the toe was constrained, they could not participate fully in balance adjustment. Diminished toe–floor contact area due to constrained great toe might also contribute to the balance deterioration. Constraint of the great toe not only limits first metatarsohalangeal joint movement during balancing tasks, it also alters the movement of the entire lower extremity kinetic chain, including ankle, knee, and hip joint motion. However, the impact on performance was mainly from the constrained area, namely the great toe. The limited function of the great toe and its interaction with all other kinetic linkages resulted in balance performance. Further research is needed to clarify whether the balance deteriorations come from deficits in the foot supporting surfaces, great toe flexor muscle activities, or plantar surface sensory feedbacks. The importance of the great toe in balance should be considered in toe amputation or transfer. Individuals with great toe amputation will be recruited for testing for a more conclusive summary of the importance of the great toe in human balance.

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