Biomechanical Analysis of Different Foot Morphology During Standing on a Dynamic Support Surface

Yang Shu, Jan Awrejcewicz, and Bartłomiej Zagrodny

Abstract Foot is a significant element during the balance as the main organ that connects with surface. From the research of habitually barefoot people and habitually shod people, there were significant differences in distance between the hallux and the interphalangeal joint of the second toe. Habitually shod males had a high risk of injury because of the lack of toes function. Based on these differences in foot morphology and importance of hallux during activities, expanding the distance between the hallux and other toes could increase the ability of hallux, especially the balance. In order to analyse the influence of hallux during balance tests, three conditions were set with light silica instruments: (1) normal toes, (2) expanding toes, (3) binding toes. During the experiments, the 6-DOF transportation vibration platform had continuous sinusoidal translation in the anterior-posterior and medial-lateral directions with a sine wave. From the results, binding toes showed larger movement of centre of pressure than normal toes and expending toes. In addition, people with normal toes also indicated larger sway than expending toes. It could conclude that control the toes function causes instability during static balance but improve the hallux function can increase the balance ability.

Keywords Foot morphology · Toes · Hallux function · Balance

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1 Introduction

Balance is an important ability in dynamic and static features of human in biomechanics, and it maintains the line of gravity (vertical line from centre of mass) of a body within the base of support with minimal postural sway [1]. The factors influencing balance ability including: (1) internal adjustment including somatosensory, visual and vestibular systems and motor response [2], and (2) the mechanical factors which could disrupt the orientation information. The perturbation or change of center of Mass needs somatosensory to main balance. The influence of support surface, such as support area and instability of support, would affect the somatosensory and visual inputs.

Different ethnicities, pathological factors and different forms of sport participation could bring about foot morphology differences [3–5]. Treating foot as a lever, fulcrum of Habitually shod people was forefoot but hallux and forefoot for habitually barefoot people. Habitually barefoot people have more loading under the hallux rather than the medial forefoot, could reduce the loading of the fulcrum. The functions of the remaining toes balance control under static and dynamic conditions [6]. Some studies found that tactile information feedback could be a benefit to the postural control and balance [7]. plantar perception exercises contribute to controlling balance [8]. My research of foot morphology indicated that hallux angle and the minimal distance between the hallux and the interphalangeal joint of the second toe were the main morphological differences between habitually shod people and habitually barefoot people [9, 10]. However, most normal people are habitually shod. It is convenient to expand the angle and distance forwardly. On the other hand, decreasing hallux grip force was associated with weakening and worsened balance [11]. In addition, it concluded that the active function of toes could prevent foot injuries based on the research between running between binding toes and normal toes, such as metatarsal fracture and plantar fasciitis [12]. This study is to explore the trajectory of the COP in foot morphology control when maintaining an upright standing posture on a dynamic support surface with continuous periodical multidirectional perturbations.

2 Methods

Eighteen healthy young male students volunteered to attend the experiment (see Table 1). All participants were free of lower limb pain and injury and had no history of major surgery on the lower back or lower limbs for the past 12 months. They were informed of the experimental procedure and gave written consent.

For this study, the light silica instrument was used to set the position of hallux in three conditions: (1) Normal Toes; (2) Expending Toes; (3) Binding Toes (see Fig. 1). The experiments tested 3 days in every foot condition. It aimed to prevent the

Table 1 Participant demographics

	Total
Participants	18
Age (years)	25 ± 2.1
Height (cm)	176 ± 2.3
Weight (kg)	64 ± 5.5
Right leg length (cm)*	88.3 ± 2.8
Body mass index	22.4 ± 2.0
LEFS score	81.0 ± 1.0
Tegner activity score	6.0 ± 1.0
VAS	0.0 ± 0.0

Note: Right leg length, the measurement from right anterior superior iliac spine to the medial malleolus

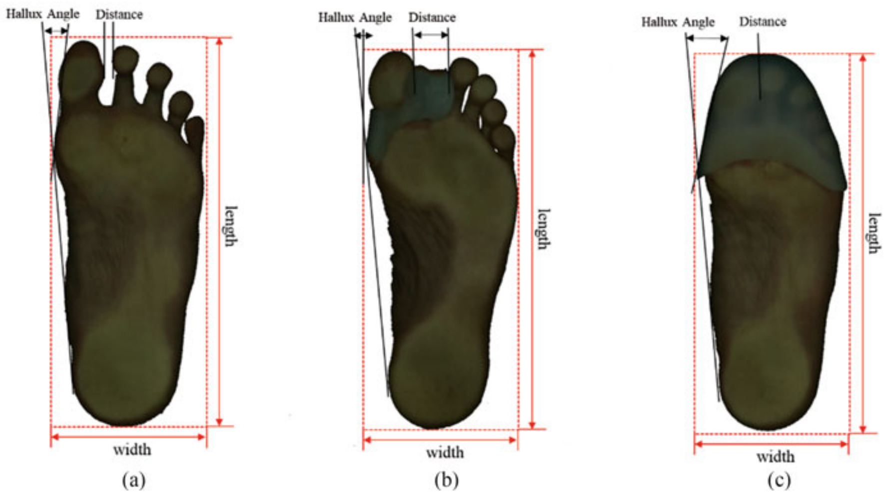

Fig. 1 2D foot print image of Natural Toes (**a**), Expanding Toes (**b**) and Binding Toes (**c**)

influence of wearing instruments. Before the experiments, participants wore these instruments and socks for both feet. Then they had free activities for 1 hour to adapt.

The Easy-Foot-Scan (EFS), OrthoBaltic (Kaunas, Lithuania) was used to scan the foot of participants. From the results of foot scan after wearing instruments, length of foot was 261.4 ± 12.3 mm, width was 119.8 ± 15.0 mm. Table 2 showed the hallux angle and distance between three different conditions:

A six degrees of freedom (6-DOF) transportation vibration platform is a motion simulation technology that can generate an infinite floor with various surfaces. Users could use this interface to experience life-like movements in multidirectional perturbations even virtual environment with various terrains. This research used the 6-DOF transportation vibration platform (MTD 6.0, TARCH, Wuhan, China). which consists of a movable platform (diameter: 2 m), six servo valves and pistons and a

Table 2 One-way analysis of variance of hallux angle and distance between Natural Toes, Expanding Toes and Binding Toes people

	Natural Toes	Expanding Toes	Binding Toes
Hallux angle (deg)	10.20 ± 5.33*,#	6.54 ± 3.05*,&	16.87 ± 4.65#,&
Distance (mm)	3.56 ± 2.31*,#	24.00 ± 5.74*,&	0.00 ± 0.12#,&

*, #, and & indicate significant differences ($p < 0.05$) for comparison between Natural Toes and Expanding Toes, between Natural Toes and Binding Toes, and between Expanding Toes and Binding Toes, respectively

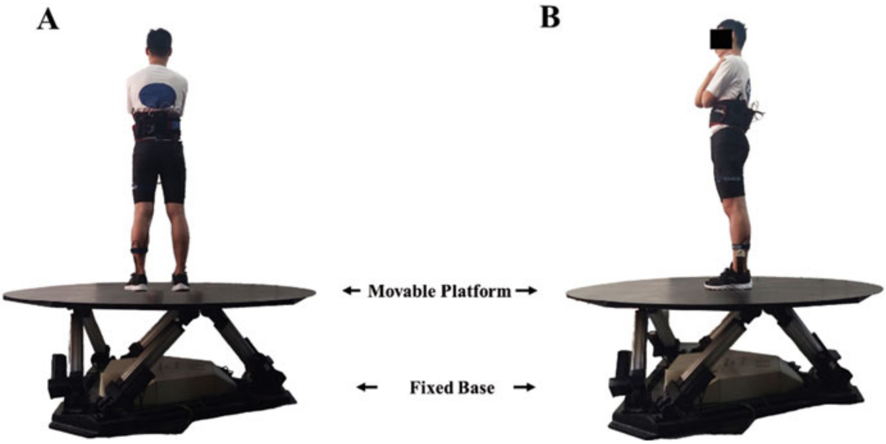

Fig. 2 Structure of the 6-DOF transportation movable platform (**a**: back, **b**: side)

fixed base. The movable platform can move in three linear movements (vertical, longitudinal and lateral), three rotations (pitch, roll, and yaw), and any combination movements in space. Each participant performed on the 6-DOF platform (see Fig. 2).

The PEDAR insole system (Novel, GmBH, Munich, Germany) was used to measure the plantar pressure distribution and the trajectory of the COP. The insoles are approximately 2.6 mm thick and contain 99 sensors which are able to measure pressures up to 120 N/cm^2.

During the experiments, the 6-DOF transportation vibration platform had continuous sinusoidal translation in the anterior-posterior (AP) and medial-lateral (ML) directions with a sine wave (frequency: 1 rad/s; amplitude: 3, see Fig. 3):

$$y = 3 \sin 2\pi x, \tag{1}$$

All trials were obtained from the right lower limbs of each participant, the in-shoe data recorded by the PEDAR system included the coordinates and trajectory of the COP. In the coordinates (Cx, Cy) of COP trajectory, Cx is coordinated in the ML direction and Cy is coordinated in the AP direction. COP excursion was defined as

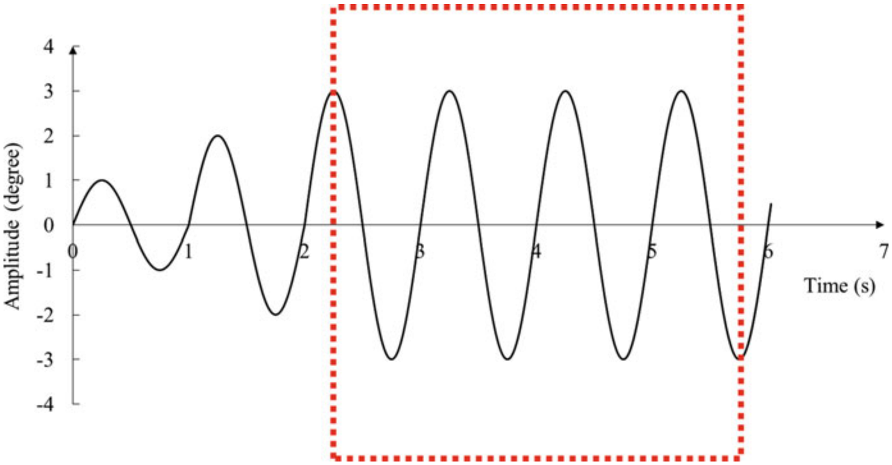

Fig. 3 6-DOF transportation vibration platform undergoing continuous sinusoidal translation. Data were collected when the amplitude of the platform reached an integral sine wave

the distance between the furthest points in the A-P and M-L directions of the COP in each sine wave.

The statistical measures were performed with SPSS 19.0 software. One-way analysis of variance with post hoc Bonferroni correction was performed to investigate the variation tendency among different weight of loads. If $p < 0.05$, statistical results were considered significant.

3 Results and Discussion

From Fig. 4, in M-L Direction, A-P Direction and COP Excursion, the length of binding toes was significantly higher than normal toes and expending toes; Moreover, the length of normal toes was also significantly higher than expending toes.

Stability is generally defined as the ability of a person to maintain or restore the equilibrium state of an upright posture without changing the support base [13]. The increase of COP parameters, such as excursion, conclude the increase of instability [14]. Recent studies indicated that lateral balance is more challenging than in the A-P direction [15, 16]. From this experiment, Binding Toes showed large postural sway in not only M-L direction, but also A-P direction and Excursion. It indicated that control the toes function would cause instability. Conversely, Expending Toes has less postural sway and instability than normal toes and binding toes. It suggested that the balance ability would increase with the increasing of toes function.

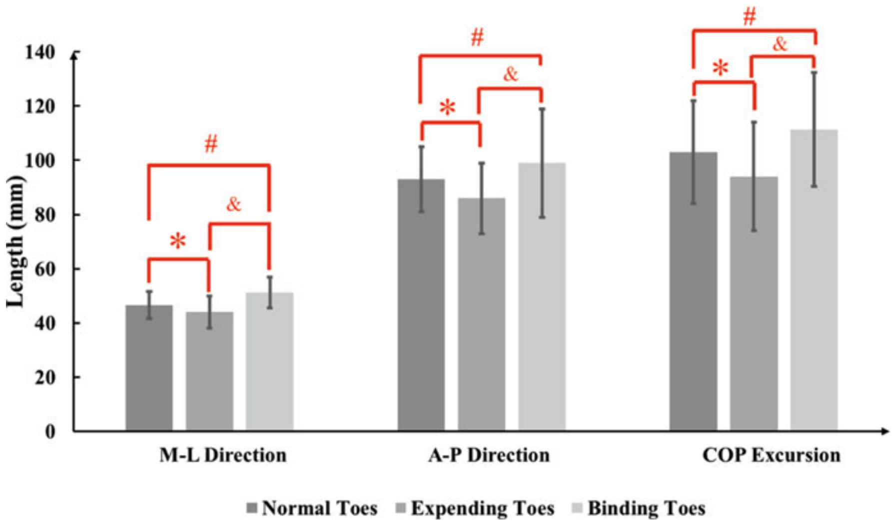

Fig. 4 6-DOF transportation vibration platform undergoing continuous sinusoidal translation. Data were collected when the amplitude of the platform reached an integral sine wave

4 Conclusions

Balance ability is crucial for movement in daily life. There were many factors could affect the performance of stability. Foot is a significant element during the balance as the main organ that connects with surface. From the research of habitually barefoot people and habitually shod people, there were significant differences in distance between the hallux and the interphalangeal joint of the second toe. Habitually shod males had a high risk of injury because of the lack of toes function. Based on these differences in foot morphology and importance of hallux during activities, expanding the distance between the hallux and other toes could increase the ability of hallux, especially the balance.

During standing on the dynamic support surface, binding toes showed larger movement of centre of pressure than normal toes and expending toes. In addition, people with normal toes also indicated larger sway than expending toes. It could conclude that control the toes function causes instability during static balance but improve the hallux function can increase the balance ability. Finding of this study provides detailed and important information for further studies on improving human movement ability.

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