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Investigating biomechanical function of toes through external manipulation integrating analysis

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Purpose: This study was aimed to investigate the function of toes while running through comparing bound toes by external-manipulation with natural separate toes by evaluating kinematics and plantar pressure analysis. *Methods*: Seven habitually barefoot male runners participated in the running test under toes binding and non-binding conditions, and Vicon and Novel insole plantar pressure measurement were conducted synchronously to collect kinematics and foot loading. *Results*: Ankle kinematics showed larger non-significant range of motion in the frontal plane while running with toes non-binding.The medial forefoot had a smaller force time integral, and with hallux had a larger force time integral than those of running with toes binding, with significance level $p < 0.05$. *Conclusions*: While no significance existed between bound and non-bound toes in kinematics, the medial forefoot had a smaller foot impulse and the hallux had a larger foot impulse for those with non-binding feet. This suggests that other functions such as the active gripping action of toes might be important for the efficiency of the foot windlass mechanism (the plantar fascia support), which would be beneficial for running performance improvement and foot injury prevention.

Key words: *toes, grip, windlass mechanism, metatarsal injury*

1. Introduction

The human foot, consisting of 26 bones and relative muscles, tendons and ligaments [5], serves as the link between the internal static standing or dynamic locomotion kinetic chain and the external ambulatory surroundings. The foot's movement kinematics or kinetic characteristics have been investigated from different foot types, morphological difference, gender, age and different body weight (body mass index, BMI). O'Brien et al. [20] reported, foot arch type, particularly medial longitudinal arch (MLA) correlated with BMI, and could affect the plantar pressure while barefoot walking. The study concluded that there was a connection between arch type and foot functionality with normal-arched foot and average BMI evenly distributing plantar pressure. Foot morphology differed among different ethnicities or living environment, and it was believed that habitually barefoot populations had wilder uninhibited feet [6], particularly in the forefoot and toe regions [10], and wilder feet showed evenly distributed peak pressure in contrary to short and slender feet of habitually shod feet with focal peak pressure to heel, metatarsals and hallux parts [6]. However, for elder females, morphological foot deformities like hallux valgus and varus deformity of the fifth toe between the forefoot width of left and right feet would lead to the deterioration of medial-lateral balance, which was a risk factor for falling and ankle sprains [7].

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The foot represents the adaptation of human upright bipedal locomotion on level ground, which enabled walking and running through dynamic supportive, braking, and propulsive forces across the skin–ground interface [5]. The toes' functions have been reported by Lambrunudi [12], being primarily prehensile and ambulatory. Through the gripping action of toes, the supporting base area in the push off phase of locomotion was enlarged compared with solely metatarsal heads bearing the whole bodyweight. Toes' forefoot loading sharing functions showed that normal and healthy feet without forefoot or toes deformations would be more effective than deformed feet [11]. Further, shorter toe lengths of modern human was shown to be linked with less mechanical cost and the evolutionary result of endurance running [21]. In terms of foot morphological characteristics, footprints of 1.5-million-year-old hominin provided the oldest proof that hominid possessed a modern human-like foot anatomy with relative adducted hallux, medial longitudinal arch and medial shift of loading before push-off [1]. When humans evolved into bipeds from apes, the foot morphology of the large toe became longer and straighter than the other toes [13], so as to help push internal body loading forward and upward at the end of stance. Toes' loading alleviation function might be, but not yet proven, the reason for smaller collision forces resulting into lower injury rates of habitually barefoot runners with forefoot landing [15]. However, as footwear design progresses footwear manufacturers regulated shoe lasts (a last is a mechanical form that has a shape similar to that of a human foot used by shoemakers) to be more restrictive. The idea was that the natural human foot was seen as coarse and unsightly, especially the divergent toes [10], [13]. Small, especially narrow feet were regarded as more aesthetically appealing [10], like bound feet of ancient Chinese women [25] and high-heeled shoes of modern women [9]. Plenty of evidence exists showing that long term wearing of ill-fitted shoes is responsible for foot deformation, thus leading to poor sport performance and injuries [3], [4], [17].

In this study, habitually barefoot runners with natural separate toes participated in running tests with natural toes (non-binding) position and toes binding condition. Bound toes running was proposed to simulate the deformed toes running situation as previously reported. Therefore, this study aimed to investigate the toes gripping (ambulatory) function while running in natural(separate) and deformed (compressed) positions as exhibited through kinematics, foot pressure and force time integral (impulse).

2. Materials and method

2.1. Subjects

A total of seven habitually barefoot male runners (age: 21.34 ± 1.36 years; height: 170.57 ± 2.39 cm and weight: 69.14 ± 3.24 kg) participated in the experiment, and all showed an abducted or separate hallux of both feet under static standing as shown in Fig. 1. This study was approved by the Ethics Committee of Ningbo University. Before the experiment, written consent was obtained from subjects and they were informed of the objectives and procedures of this running test. Participants were recreational runners without any athletic training history prior to the test. No participants had any injuries or surgeries to the lower limb.

Fig. 1. The illustration of separate hallux of habitually barefoot runners while static standing

2.2. Experiment protocol

The experiment including two sections, barefoot running (wearing socks to fix plantar insole) under toes binding (Fig. 2a) and toes non-binding (Fig. 2b) conditions, was conducted randomly in the gait analysis and biomechanics laboratory. The running speed was controlled at the range of 2.5–3.0 m/s. Participants were required to run five minutes on a 12-meter walkway to get familiar with the testing environment and running speed control. The bandage was used to compress toes into the shape of feet with long-term wearing sharp-headed modern footwear [10]. An eight-camera Vicon motion analysis system was used to capture the lower limb kinematics while conducting running tests with a frequency of 200 Hz. Sixteen standard reflective markers were pasted to the anterior-superior iliac spine, posterior-superior iliac spine, lateral mid-thigh, lateral knee, lateral mid-shank, lateral malleolus, second metatarsal head and calcaneus of the left and right legs. Prior to the running test, a static-standing trial was conducted in the middle of the walkway, where data of the running step (right leg) was collected and used for analysis, so as to define the referenced markers' anatomical positions for dynamic-running tests. Simultaneously, an in-shoe pressure measurement system (Novel Pedar System, Germany) was employed in this study to measure the pressure and force exerted on the insole pressure sensors with a frequency of 50 Hz. The calibration of insole was conducted, so as to minimize the error of sensors' linear response to external applied loads. While running, participants were required to wear socks to fix the plantar insole and reflective markers were attached to the corresponding anatomical parts of both feet. One gait cycle was defined as the right forefoot of participants successively contacting the ground twice. Each subject performed six running trials under toes binding (Fig. 2a) and toes non-binding (Fig. 2b) conditions.

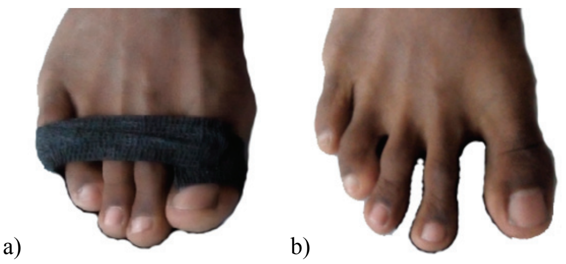

Fig. 2. Participants running with toes binding (a) and toe non-binding (b). A normal bandage was taken to bind separate toes into a compressed position similar to the foot shape of long term wearing modern shoes

2.3. Data collection and statistics analysis

Kinematic data of each participant's six running trials under two conditions were separately collected and normalized to get an averaged ankle joint angle profile during stance. The insole was divided into eight parts according to anatomical regions, including medial rearfoot (MR), lateral rearfoot (LR), medial midfoot (MM), lateral midfoot (LM), medial forefoot (MF), lateral forefoot (LF), hallux (H) and other toes (OT). Peak pressure, force time integral (impulse) and maximal force were utilized for the analysis of foot loading characteristics. SPSS 16.0 was used with LSD (least significant difference) of ANOVA (analysis of variance) for the statistics analysis. The significance level was set at $p < 0.05$.

3. Results

In this study, kinematic data of the right ankle joint during stance were collected to illustrate the three dimensional movement characteristics of habitually barefoot runners running with toes binding and non-binding. Figures 3a, 3b and 3c separately show the ankle's movement in the sagittal plane (dorsi/plantar flexion), frontal plane (inversion/eversion) and transverse plane (internal/external rotation), respectively. The ankle's range of motion (ROM) while running under toes binding and non-binding were 51.49 ± 6.25° and 47.89 ± 4.73° (sagittal plane), 18.61 ± 3.65° and 21.23 ± 2.74° (frontal plane) and 5.78 ± 2.68° and 4.25 ± 1.79° (transverse plane). While there were some non-significant differences in mean trends between ankle inversion/eversion and internal and external rotation between bound and non-bound feet, overall there were no significant differences between these groups for all ankle angles (Fig. 3).

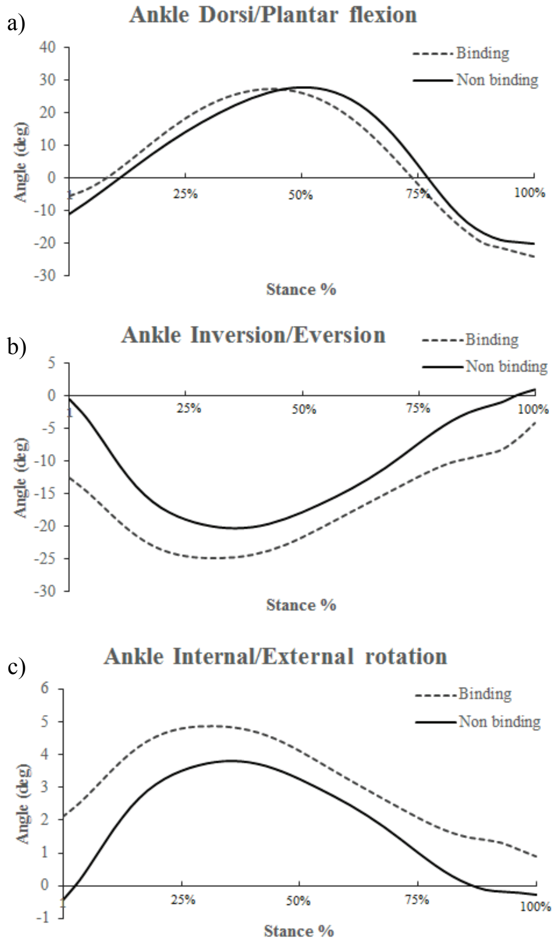

Fig. 3. The ankle's three dimensional motion characters in stance. ((a) – ankle's dorsiflexion (+) and plantar flexion (–), (b) ankle's inversion (+) and eversion (–), (c) ankle's external rotation (+) and internal rotation (–))

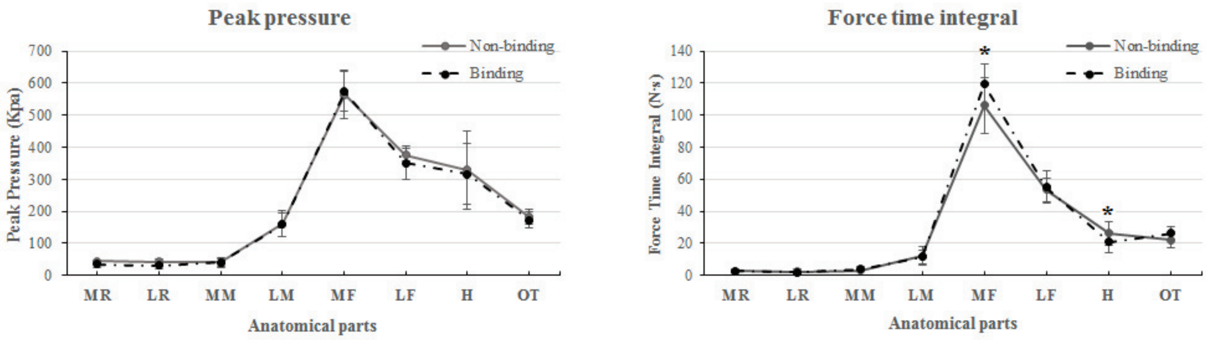

Fig. 4. The peak pressure (left) and force time integral (right) of the right foot in stance.
(* represents the significance level $p < 0.05$)

Peak pressure, force time integral (impulse) and maximal force through plantar pressure measurement were taken to show the foot loading properties in the right foot supporting phase. The peak pressure and force time integral in stance are shown in Fig. 4, and significant differences are exhibited in the MF and H parts of the force time integral (impulse), with $p < 0.05$.

As previous studies reported, forefoot parts, particularly the metatarsals, bore most of the loading (body weight) in the push-off phase. For the work performed by the toes region, especially the big toe, the supporting area would expand and forefoot loading would be decreased. The maximal force in the forefoot and toe parts are shown in Fig. 5, with maximum, minimum, median, upper quartile and lower quartile exhibiting no significance between groups.

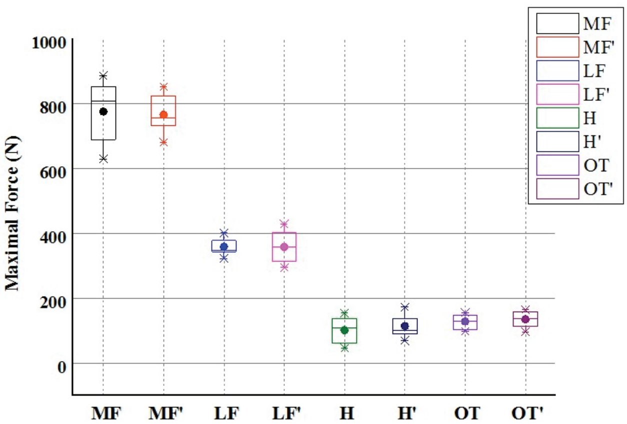

Fig. 5. The maximal force to forefoot region in the pushing-off phase of the stance (MF, LF, H and OT represent medial forefoot, lateral forefoot, hallux and other toes of running under toes non-binding condition; conversely, MF′, LF′, H′ and OT′ represent medial forefoot, lateral forefoot, hallux and other toes of running under toes binding condition)

4. Discussion

Humans have become more upright with bipedal locomotion with evolution compared with early apes. The human foot showed the most distinctive adaptation, with shorter toes and abducted hallux [1], [5], [13]. Another evolutionary emergence to the human foot was the medial longitudinal arch. It acted as an impact shock absorber and stiff lever in the landing and push off phase, which enabled greater propulsive forces to forefoot and greater propulsive leverage to the ankle in locomotion [1], [2], [5], [13]. Toes' main functions have been described as prehensile and ambulatory in 1932 by Lambrinudi [12]. Due to the highly variable external environment and for aesthetic reasons, humans began to wear shoes to protect feet and avoid bare feet. As a result, the toes' specialized function gradually diminished [18], and toe deformities appeared due to long-term ill-fitted footwear wearing, even leading to sports injuries [3], [4].

Recently, barefoot running with forefoot strike was reported with public health implications for its lower impact collisions, thus lowering the injury risk of tibial stress fracture and plantar fasciitis, which were common among rear foot strike runners [15]. One reason for lower injury risk of barefoot forefoot running was that humans had adapted into a barefoot running style over millions of years from an evolutionary perspective [14], and the proprioceptive feedback and musculoskeletal functions to leg and feet could be enhanced and trained through direct contact with variable external surfaces [24]. As toes' function was aforementioned to expand the bodyweight supporting base focused on the metatarsals part in the push-off phase [10], [11], recent investigation of barefoot running with lower injury rates has not yet discussed about the effect of toes activity. One unique function concerned was the windlass mechanism of the plantar aponeurosis (PA), which originated from the calcaneus, fans out into five slips that run underneath the metatarsal heads and attached to the plantar side of the proximal phalanx of each toe [17]. PA maintains static longitudinal arch and dynamic impact shock absorption [8], [17], and also the basis of a solid structural platform for propulsion. While forefoot pushing off the ground, the metatarsophalangeal joint extended with tightening of PA, which heightened the longitudinal arch, flexed the transverse tarsal joint and formed a solid support for the metatarsal heads and toes. It was one of the most critical reasons responsible for the calluses formed on the metatarsal heads and toes [14].

However, with long-term shoes wearing, the specialized function of toes was gradually degenerated leading to clumsy toe motion [18]. Moreover, toe deformation could be widely observed in clinical pathology or daily activities from ill-fitted shoe wearing [3], [4], [10]. The constantly high injury rate of runners might also attribute to the deterioration of toe ambulatory and prehensile functions.

In this study, habitually barefoot runners from India with natural un-deformed foot shape and divergent toes (abduct hallux) participated in a running test under toes non-binding and toes binding conditions. While running with non-binding toes, a reference set of foot and toe motion (kinematics and plantar pressure properties) was determined. Running with toes binding simulated deformed toes and the externally-manipulated deformed foot and toes motion characteristics. As Fig. 3 shows, there was no significant difference between bound and non-bound feet in the motion of the ankle in all three planes. However, participants running under toes non-binding condition showed a bigger ROM (21.23 ± 2.74°) in the frontal plane (inversion and eversion) than that (18.61 ± 3.65°) of running with toes binding. This might be linked with the function of the separate hallux in the propulsion phase, as a medial shift of bodyweight loading during locomotion [1], [8], [18]. To further elucidate the toes work while running under toes binding and non-binding conditions, plantar pressure was collected with peak pressure and force time integral. The force time integral (impulse), showed differences to the MF and H foot regions (Fig. 4). Binding toes running had greater impulse to MF and smaller impulse to H than non-binding toes running during stance. This could be explained with the function of hallux to expand the supporting area and alleviate loading concentrated on the metatarsal heads [11]. It may also be interpreted that toes' prehensile or gripping action could enhance the efficiency of the windlass mechanism [8], [10], [12]. The active gripping movement of toes (big toe and short toes) would increase endurance running performance as a result of human evolution [21], particularly in the push off (propulsion) phase, which is the very final and critical stage of running [8], [19]. The active toes contribution to the windlass mechanism involved the contracted function of extrinsic and intrinsic muscles to the foot and ankle [18], as body static toes gripping action and function analysis were reported to be related with surface electromyogram changes of femoral muscles, gastrocnemius and longus peroneal [22], [23]. The maximal force to forefoot and toes part in the push off phase was also collected though no significance existed. Figure 5 disclosed the properties of forefoot loading distribution.

One limitation of this study that should be considered is that muscle activity related to the toes gripping action was not collected during the experiment, and this would be the next step of toes function analysis of habitually barefoot and shod populations while standing under static condition or under external perturbation, walking and running. Moreover, further study needs to be conducted to investigate the relationship between toes' function and forefoot loading distribution with increased participant numbers.

5. Conclusions

This study aimed to explore toes function through simulating deformed toes of habitually barefoot runners integrating analysis of running kinematics and plantar pressure. While running with natural-positioned (non-binding) toes, medial forefoot loading (impulse) was smaller with hallux bearing parts of body weight loading. This could be attributed to the toes ambulatory or gripping function, thus enhancing the effect of the windlass mechanism. The active function of toes should be encouraged for foot injuries (plantar fasciitis and metatarsal fracture) prevention and running performance improvement.

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