A BIOMECHANICAL INVESTIGATION OF EXTERNALLY MANIPULATED TOES

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The objective of this study was to analyse ankle kinematics and plantar pressure while running to investigate the biomechanics of externally manipulated "deformed" toes and natural toes. Seven habitually barefoot male runners joined the test under toes binding (deformed) and separate (natural) conditions, and Vicon and Novel insole were taken synchronously to collect foot kinematics and plantar pressure. Ankle showed larger range of motion in the frontal plane while running under natural toes condition, though no obvious significance existed. The medial forefoot had smaller force time integral, and hallux had larger force time integral than those of running with deformed toes condition, with significance level $p<0.05$. The greater loading taken by hallux and smaller forefoot loading while natural toes running may attribute to the active gripping function of toes. It was important for the efficiency of windlass mechanism, which would be great beneficial for running performance improvement and foot (metatarsal) injury prevention.

KEY WORDS: toes, grip, deformation, metatarsal injury.

INTRODUCTION: Natural human foot, including 26 bones and relative muscles, tendons and ligaments, functions as the direct link between internal kinetic chain and external surroundings (Mei et al., 2016). Long term ill-fitted modern shoes-wearing has made natural gait impossible by automatically converting the normal to the abnormal and the natural to the unnatural (Rossi, 1999). The 'unnatural' foot thus came into being, with deformed toes, arch or other parts (Hoffman, 1905; Shu et al., 2015).Toes were believed to be designed with prehensile and ambulatory functions (Lambrinudi, 1932). Previous research indicated that one distinct foot morphological difference between habitually barefoot populations and shod populations exist in the toes. The hallux of habitually barefoot population individuals was quite separate from other toes (Ashizawa et al., 1997; Shu et al., 2015), or even in an abducted position (Bennett et al., 2009). Also, toes-related feet morphological characteristics differed among populations of different ethnicities, living environment or running style (Hoffmann, 1905; Rolian et al., 2009; Lieberman et al., 2010; Mei et al., 2015a; Mei et al., 2015b). Factors attributing to foot or lower extremity injuries have been extensively investigated in the previous studies, yet reason from malfunctions of deformed toes while running haven't been thoroughly clarified. The objective of this study was to analyse running ankle kinematics and plantar pressure through comparing externally manipulated 'deformed' toes and toes of natural shape.

METHODS: A total of seven habitually barefoot male runners (age: 21.34±1.36yrs; height: 170.57±2.39cm and weight: 69.14±3.24kg.) joined in the experiment, who all showed natural toes under static condition. 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. And none of them had any injuries or surgeries to the lower limb.

The experiment included barefoot running (wearing socks to fix plantar insole) under toes binding and toes non-binding conditions. The running speed was controlled at the range of 2.5-3.0m/s with timing gates. Participants were required to run five minutes on a 12-meter walkway to get familiar with testing environment and running speed controlling. The bandage was used to bind toes into the 'deformed' shape (similar with long-term wearing sharp-headed / small toe-box modern footwear) (Hoffman, 1905; Rossi, 1999; Shu et al., 2015). An eight-camera Vicon motion analysis system with Plug-in Gait model was taken to capture the kinematic data of lower limb while conducting running test with a frequency of 200Hz, and sixteen standard reflective markers were pasted to 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 running step (right leg) was collected and used for analysis, so as to define the referenced markers' anatomical positions for dynamic-running test. 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 50Hz. While running test, participants were required to wear tight socks to fix plantar insole and reflective markers were attached to the corresponding anatomical parts of both feet. Each subject performed six running trials under both conditions. Kinematic analysis mainly focused on right foot stance. Six trials' kinematics data (ankle range of motion and peak angle values) and plantar pressure data (peak pressure and force time integral) were averaged and normalized for the LSD (least significant difference) analysis of ANOVA (analysis of variables) with the SPSS 17.0. The significance level was set at $p<0.05$.

RESULTS: In this study, kinematic data of right ankle joint in a stance were collected to illustrate the three dimensional movement characteristics of running with deformed toes binding and natural toes shape. As Figure. 1 shows, the ankle's movement in frontal plane (inversion/eversion) presents difference, though without significance. The ankle's ROM in the frontal plane while running under toes binding and non-binding was 18.61±3.65° and 21.23±2.74°.

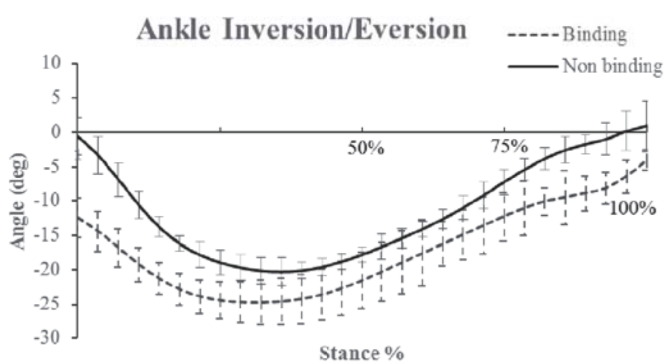

Figure. 1 The ankle's inversion (+) and eversion (-) in a stance.

Peak pressure and force time integral (impulse) through plantar pressure measurement were taken to show the foot loading distribution in the right foot stance phase. The peak pressure and force time integral in a stance were shown in the Figure. 2, and obvious significance existed in the MF and H parts of force time integral (impulse), with p<0.05. Hallux of natural toes running worked obviously to reduce loading to the forefoot, while toes binding hindered the working of toes, particularly the hallux.

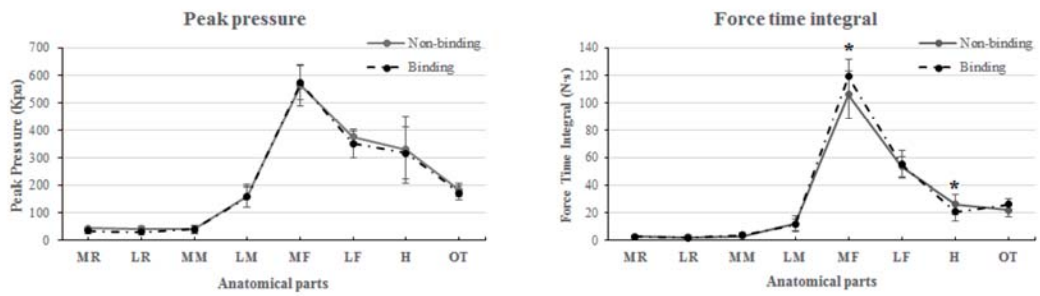

Figure. 2 The peak pressure (left) and force time integral (right) of right foot in stance. (* represents the significance level p<0.05)

DISCUSSION: In this study, participants run with manipulated deformed toes and natural toes to test foot kinematics and kinetics. As the most distinctive adaptation result of human evolution, human foot presented shorter toes and abducted hallux. While the external environments instantly variable and aesthetic reasons, human began to wear shoes to protect feet and avoid barefoot. Consequently, the toes' specialized prehensile and ambulatory functions gradually diminished (Mann et al., 1979), and toes deformities came out as long-term ill-fitted footwear wearing, even leading to sports injuries (Hoffman, 1905; Rossi, 1999; Shu et al., 2015; Mei et al., 2015a). Participants running under toes non-binding (natural toes) condition showed a bigger ROM of ankle in frontal plane than that of running with toes binding (deformed toes). This might be linked with the function of separate hallux in the propulsion phase, as medial shift of body-weight loading while locomotion (Mann et al., 1979; Mei et al., 2015a; Mei et al., 2015b; Novacheck, 1998). To further elucidate the toes work while running under toes binding and non-binding conditions, plantar pressure were collected with peak pressure and force time integral. The force time integral, also impulse, showed obvious difference to MF and H part (Figure. 2). Binding (deformed) toes running had greater impulse to MF and smaller impulse to H than non-binding (natural) toes running in stance. This could be explained with the function of hallux to expand the supporting area and alleviate loading concentrated to the metatarsal heads part (Mann et al., 1979), even could be interpreted that toes' prehensile or gripping action would enhance the efficiency of windlass mechanism (The Windlass Mechanism is the tightening action of the long plantar fascia of the foot to maintain arch stability when the heel comes off the ground) (Hoffman, 1905; Lambrinudi, 1932; Novacheck, 1998). The active gripping movement of toes (big toe and short toes) would increase endurance running performance as a result of human evolution (Caravaggi et al., 2009; Rolian et al., 2009), particularly in the push off (propulsion) phase, which was the very final and critical stage of running (Novacheck, 1998). The active toes work to windlass mechanism involved the contracted function of extrinsic and intrinsic muscles to foot and ankle (Caravaggi et al., 2009; Mann et al., 1979). The maximal force to forefoot and toes part in the push off phase was also collected though no significance existed.

CONCLUSION: This study aimed to explore toes function through simulating deformed toes of habitually barefoot runners integrating analysis of running kinematics and plantar pressure. Whilst running with natural (non-binding) toes shape, medial forefoot loading (impulse) was smaller, while hallux showed larger force time integral. This could attribute to the toes ambulatory or gripping function, thus enhance the effect of windlass mechanism. This might provide implications for modern footwear to enhance toes' locomotion functions. 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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