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In-shoe plantar tri-axial stress profiles during maximum-effort cutting maneuvers

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ABSTRACT

Soft tissue injuries, such as anterior cruciate ligament rupture, ankle sprain and foot skin problems, frequently occur during cutting maneuvers. These injuries are often regarded as associated with abnormal joint torque and interfacial friction caused by excessive external and in-shoe shear forces. This study simultaneously investigated the dynamic in-shoe localized plantar pressure and shear stress during lateral shuffling and 45° sidestep cutting maneuvers. Tri-axial force transducers were affixed at the first and second metatarsal heads, lateral forefoot, and heel regions in the midsole of a basketball shoe. Seventeen basketball players executed both cutting maneuvers with maximum efforts. Lateral shuffling cutting had a larger mediolateral braking force than 45° sidestep cutting. This large braking force was concentrated at the first metatarsal head, as indicated by its maximum medial shear stress (312.2 ± 157.0 kPa). During propulsion phase, peak shear stress occurred at the second metatarsal head (271.3 ± 124.3 kPa). Compared with lateral shuffling cutting, 45° sidestep cutting produced larger peak propulsion shear stress (463.0 ± 272.6 kPa) but smaller peak braking shear stress (184.8 ± 181.7 kPa), of which both were found at the first metatarsal head. During both cutting maneuvers, maximum medial and posterior shear stress occurred at the first metatarsal head, whereas maximum pressure occurred at the second metatarsal head. The first and second metatarsal heads sustained relatively high pressure and shear stress and were expected to be susceptible to plantar tissue discomfort or injury. Due to different stress distribution, distinct pressure and shear cushioning mechanisms in basketball footwear might be considered over different foot regions.

1. Introduction

Lateral shuffling and sidestep cutting are frequently involved in offensive and defensive techniques in basketball. Game analysis has revealed that basketball players spend 31% of their playing time executing cutting movements, of which 20% are regarded as high-intensity movements (McInnes et al., 1995). Cutting maneuvers typically involve a sudden deceleration of the body, followed by acceleration in a new direction of movement. This places large external and internal loads on the lower limbs. McClay et al. (1994) investigated the ground reaction forces involved in 11 typical basketball movements including running, jumping, and cutting. The cutting and shuffling generated larger horizontal ground reaction forces than the other tested movements. Excessive horizontal ground reaction forces place large joint torque or shear stress on the ligaments or other soft tissues of the lower limbs, and are thought to be the mechanical factors of non-contact anterior cruciate ligament tear and ankle sprain (McKay et al., 2001; Yu and Garrett, 2007).

Foot skin and soft tissue problems are also very common, but are often neglected in studies of sports activities (De Luca et al., 2012). It has been suggested that these foot problems are associated with large in-shoe localized stress (Lord and Hosein, 2000; Mailler-Savage and Adams, 2006). A systematic review showed that up to 39% of marathon runners and 25.3% of triathletes experienced foot blisters (Gosling et al., 2010; Mailler-Savage and Adams, 2006). Foot blisters may cause intense pain and negatively influence sport performance. If serious complications arise, blisters can cause infection and subsequent disability.

The combined application of pressure and shear stress on the skin has been suggested as the critical risk factors for soft tissue problems (Yavuz and Davis, 2010; Zhang and Roberts, 1993). Excessive pressure and shear stress may occlude blood circulation (Bennet et al., 1979; Dinsdale, 1974) and reduce the tolerance and repair capability of tissues. Tissue response depends on the direction and magnitude of mechanical stress. Goldstein and Sanders (1998) found that tissue breakdown was rare at a low shear load but

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occurred at an earlier stage with greater shear stress. The level of shear stress may be a critical factor in predicting foot complaints due to cutting maneuvers. Abnormally high magnitude and frequency of shear stress may cause discomfort, hyperkeratosis, calluses and blisters on the foot (MacKenzie, 1974; Spence and Shields, 1968; Sulzberger et al., 1966), which may further affect athletic performance. Therefore, in-shoe shear evaluation is necessary to provide important biomechanical insights into the potentially harmful effects of interfacial tissue loading, especially during strenuous cutting movements.

Most of the existing cutting research has been conducted on external ground reaction forces (Cloak et al., 2010; Cordova et al., 1998; Cowley et al., 2006; McClay et al., 1994; Mclean et al., 2004) or plantar pressure (Eils et al., 2004; Orendurff et al., 2008). However, the external ground reaction forces do not directly reflect the mechanical actions at the foot–shoe interface, and in-shoe plantar pressure alone is not sufficient to predict plantar tissue problems (Cong et al., 2011; Lavery et al., 2003; Veves et al., 1992). Therefore, this study aimed to provide simultaneous measurements of regional in-shoe plantar pressure and shear stress during two typical cutting maneuvers for characterizing the loading distributions and profiles of plantar soft tissues.

2. Methods

2.1. Participants

Seventeen male university basketball players (age 23.0 ± 4.4 y; height 1.79 ± 0.05 m; mass 71.2 ± 7.0 kg), each with a shoe size of US 10.5 and a foot width of C or D only, participated in this study. The foot measurements were taken using a Brannock foot measurement device (Brannock Device, Syracuse, NY, USA). The players had at least four years of competitive basketball experience, and attended weekly practice sessions for at least 4 h. All participants reported right-leg dominance and no injuries or abnormalities in the lower extremities during the previous six months. All participants signed a written consent approved by the University Research Ethics Committee before the test.

2.2. Test shoe preparation

The size of the basketball shoe (Li Ning Debut) used was US 10.5 (Fig. 1a). Four tri-axial force transducers (Bioforcen Intelligent Technology Inc., Anhui, China) were used to measure in-shoe plantar pressure and shear stress during two typical cutting tasks. The thickness of each transducer was 9 mm. The top and base surfaces had diameters of 17 mm and 18 mm, respectively (Fig. 1b), to provide an annular gap of 0.5 mm around the body of the transducer surface. This design prevented contact interference and minimized the shielding effect of the surrounding midsole and insole.

A standard procedure was used to calibrate each transducer at 25 °C according to manufacturer's guideline. Known normal forces were applied directly to the top of the transducer and shear loads were applied by hanging known weights from a cord attached to the transducer and passing over a simple pulley system. The transducer had measurement errors and crosstalk between any two channels of less than 2% for full-scale force measurements of 500 N (2174 kPa) and 300 N (1304 kPa) for normal and shear forces, respectively. A maximum measurement capacity of 120% full-scale measurement was guaranteed for both normal and horizontal directions without damage to the transducer. The measurement sensitivity with temperature was less than 1%/°C.

The tri-axial force transducers were mounted in the midsole of the right shoe at four locations: the first and second metatarsal heads, the lateral forefoot, and the heel (Fig. 1c). No transducer was mounted in the left shoe. The respective foot regions were identified by measuring plantar pressure in static condition using F-Scan in-shoe pressure measurement system (Tekscan, Inc., Boston, MA) in our pilot study with nine participants. Additionally, an average foot midline passing through the center of the heel and the second metatarsal head was obtained to define the longitudinal axis of the insole. The shear forces were divided into anteroposterior and mediolateral components with the anteroposterior shear direction of all transducers aligned in parallel to the longitudinal axis of the insole.

The bottom of the transducer was glued to the sole of the shoe. To avoid overly stiff foot contact with the transducer and to ensure material congruency with its surrounding supporting surface, pieces of insole material were glued to the top surfaces of the midsole and transducers (Fig. 1d). The insole material, Nora® Lunasoft SL, was selected for its higher initial stiffness to minimize overall deformation under compression while providing a functional stiffness comparable to common cushioning insole materials at its linear region (Cheung and Zhang, 2008). The material has a hardness of 40 Shore A which is within the common range of insole materials used in therapeutic and sports footwear (Cheung and Zhang, 2008; Shariatmadari et al., 2012). The performance of this material has been tested without any reported subjective discomfort even during maximal-effort cutting maneuvers while providing consistent in-shoe force measurements. An insole with identical material hardness and thickness was inserted into the left shoe to ensure consistency of shoe perception between left and right sides.

2.3. Lateral shuffling cutting

The participants were instructed to perform lateral shuffling to the right with their maximum effort. Each participant stepped onto the force platform with his right foot (the third step) and returned to the starting point as quickly as possible (Fig. 2a).

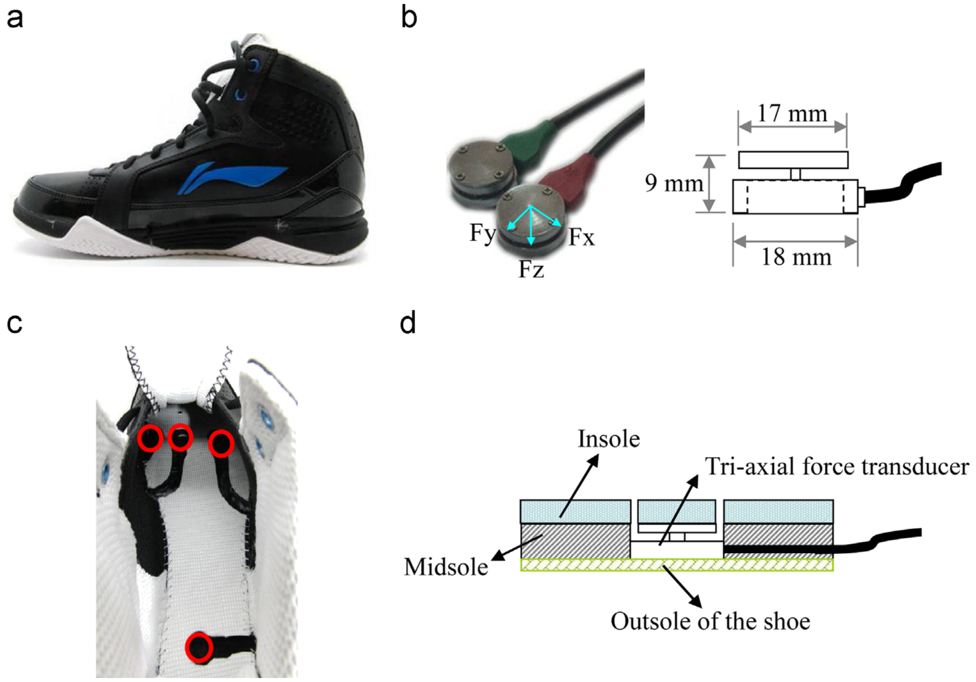

Fig. 1. (a) Basketball shoe, (b) tri-axial force transducer, (c) transducer locations, and (d) transducer installation.