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Effects of mid-foot contact area ratio on lower body kinetics/kinematics in sagittal plane during stair descent in women

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ABSTRACT

The mid-foot contact area relative to the total foot contact area can facilitate foot arch structure evaluation. A stair descent motion consistently provides initial fore-foot contact and utilizes the foot arch more actively for energy absorption. The purpose of this study was to compare ankle and knee joint angle, moment, and work in sagittal plane during stair descending between low and high Mid-Foot-Contact-Area (MFCA) ratio group. The twenty-two female subjects were tested and classified into two groups (high MFCA and low MFCA) using their static MFCA ratios. The ground reaction force (GRF) and kinematics of ankle and knee joints were measured while stair descending. During the period between initial contact and the first peak in vertical GRF (early absorption phase), ankle negative work for the low MFCA ratio group was 33% higher than that for the high MFCA ratio group ($p < 0.05$). However, ankle negative work was not significantly different between the two groups during the period between initial contact and peak dorsiflexion angle (early absorption phase + late absorption phase). The peak ankle dorsiflexion angle was smaller in the low MFCA ratio group ($p < 0.05$). Our results suggest that strategy of energy absorption at the ankle and foot differs depending upon foot arch types classified by MFCA. The low MFCA ratio group seemed to absorb more impact energy using strain in the planar fascia during early absorption phase, whereas the high MFCA ratio group absorbed more impact energy using increased dorsiflexion during late absorption phase.

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1. Introduction

The human foot is a complex structure comprising numerous bones, muscles, ligaments, and joints that sustain high pressure during daily activities. The medial longitudinal arch of foot plays an important role in shock absorption and different arch types affect the kinetics, kinematics, and injury risk of the lower extremities [1]. Several studies examining the effect of foot arch type on lower extremity mechanics have mainly focused on the rear-foot contact motion [1–6] because people who wear shoes mostly strike with rear-foot contact [7]. However people who walk with rear-foot striking experience little or no arch compression at impact because most of the GRFs are transmitted posterior to ankle joint and the muscle force from tibialis anterior applies the arch's apex at the cuneiform [8]. These forces likely stiffen the arch and prevent the arch from efficient storing elastic energy [8]. Thus, a large amount of impact force appears to be absorbed in rear-foot region through the ankle joint, instead of arch structure, during the initial rear-foot-contact motion [8].

In contrast to rear-foot striking, fore-foot striking initially loads the arch in the three-point bending: upward GRF at the metatarsal heads, downward body force through the ankle (talus), and upward force in Achilles tendon (calcaneus) [8]. At initial fore-foot contact, the plantar fascia is initially taut and is capable of storing large amount of elastic energy through lengthening [8]. Therefore, the foot arch stores more energy in fore-foot contact motion than rear-foot contact motion [8]. One therefore predicts the foot arch likely plays more sensitive role for storing and releasing energy in fore-foot motion than rear-foot motion. To our knowledge, no studies have examined the functional relationships between foot arch type and lower extremity mechanics during a fore-foot contact motion. A stair descent motion consistently provides initial fore-foot contact and utilizes the foot arch more actively [7–9]. Thus, the relationship between the foot arch type and its influence on lower extremity mechanics may be better investigated using a stair descent motion.

Static foot pressure has been utilized to classify foot arch types objectively and to investigate its relationship with foot arch types

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[2–4]. The accurate measurement of foot pressure including mid-foot-contact-area ratio has a great potential for revealing relationships between foot structure and foot function [4,5]. The mid-foot-contact-area (MFCA) ratio (Fig. 1) is the ratio of the mid-foot contact area relative to the total foot contact area and it is associated with foot arch type because high MFCA indicates a lower arched foot [5]. The MFCA method has shown high reliability of foot classification (intraclass correlation coefficient = 0.990) [10,11] and has been widely used foot arch studies [12]. However, reproducibility of MFCA ratio over several days using foot pressure sensor in this study has not been verified yet. Thus it is worthwhile to test reproducibility of MFCA ratio using foot pressure sensor in this study.

In addition, injury rate of plantar fascia in normal arched foot (low MFCA ratio in this study) was lower than low arched foot (high MFCA ratio in this study) [13], which suggests that low MFCA ratio might have more capability of shock absorption and restoration in arch structure. The foot arch includes elastic elements such as the plantar fascia, which maintain the arch structure of the foot and absorbs ground reaction force (GRF) through tensile lengthening [14]. During fore-foot strike, the musculotendinous complex of triceps-surae and the Achilles tendon undergo increasing strain [8]. As a result of this increasing strain, the elastic energy is stored in the Achilles tendon [8] and this elastic energy of Achilles tendon is stored during the negative work phase of the ankle joint [15,16]. The strain of Achilles tendon is positively correlated to the strain in the plantar fascia [17,18]. Thus, one can assume that the elastic energy stored in the plantar fascia may be estimated by the ankle negative work and low MFCA ratio subject may show more negative work in ankle than high MFCA ratio subject during fore-foot contact motion. Therefore, the main purpose of this study was to compare ankle and knee joint angle, moment and work in sagittal plane during stair descending between low and high MFCA group classified by MFCA ratio. It was hypothesized that ankle negative work of the low MFCA groups is greater than that of high MFCA group. In addition, the reproducibility of MFCA ratio measurement was tested.

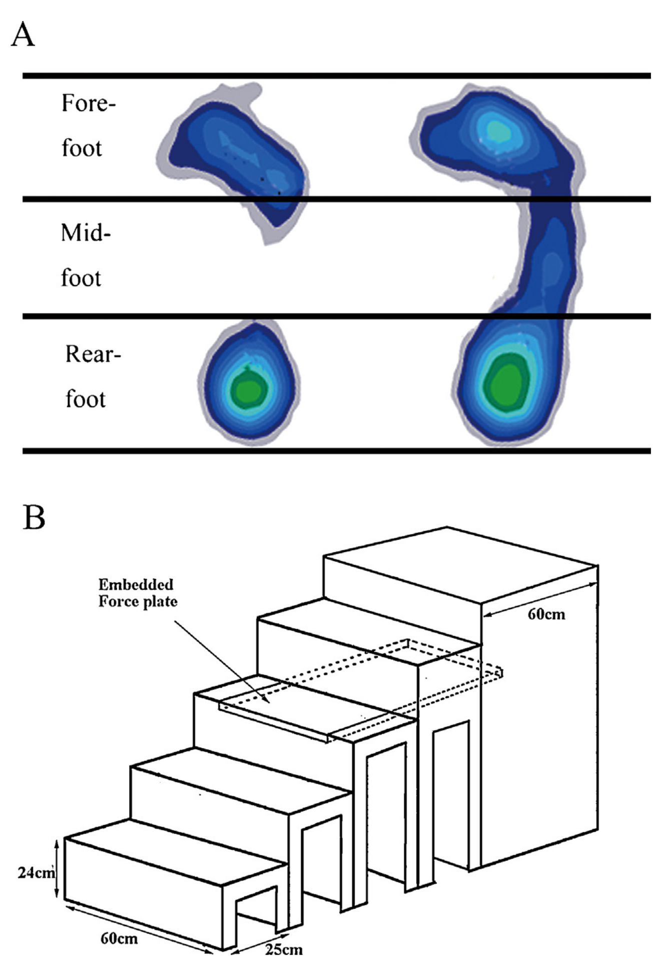

Fig. 1. (A) Foot was divided into three equal parts using static foot pressure distribution: fore-foot; mid-foot; rear-foot. Low MFCA ratio foot (left) and high MFCA ratio foot (right) are classified by the ratio of mid-foot-contact-area relative to the total foot area. (B) A five-step (height = 24 cm, depth = 25 cm, width = 60 cm) staircase was used. The force plate was embedded below the third step.

2. Methods

Twenty-two healthy women (age: 22.3 ± 2.2 years; height: 1.63 ± 0.05 m; mass: 56.1 ± 1.6 kg) participated in the study after providing written informed consent approved by our University's Institutional Review Board. The subjects with clinical sign of high arched foot were excluded. All analyses were completed bare foot and on the dominant limb, defined as the preferred limb when kicking a ball.

To classify the foot type objectively, static foot pressure was measured with the participants standing on a pressure plate (FDM-S; Zebris Medical GmbH, Germany). The participants were instructed to stand for 10 s with their weight evenly distributed on both feet. The participants faced a front wall with arms hanging down naturally. The sampling frequency was 100 Hz. Using the static foot pressure distribution, the foot area was divided into three areas referred to as the fore-foot, mid-foot, and rear-foot (Fig. 1A) using arch index methods [19]. MFCA ratio was defined as the ratio of the mid-foot contact area relative to the total area of the foot contact, excluding the toes [19]. Using this procedure, foot types were objectively classified into the following two groups [2]: a low MFCA ratio(similar to normal arched foot) group was defined as having an MFCA ratio less than or equal to 0.15 ($\leq$0.15) and a high MFCA ratio (similar to low arched foot) group with an MFCA ratio greater than 0.15 ($>$0.15) [4]. The dominant foot was analyzed for each participant and the same side was used in the kinetic and kinematic analyses. To test the reproducibility of the measurement, one examiner repeatedly measured the MFCA ratio of five subjects nine times throughout two weeks. To determine between-trial reproducibility of the MFCA for each participant, intraclass correlation coefficient (ICC) was calculated.

Three-dimensional lower extremity kinematics and kinetics of the dominant limb were recorded for each participant during stair descent. The marker set defined a three-segment rigid body (thigh, shank, and foot) model of the lower extremities, and kinematics of lower extremities was captured at 200 Hz using six cameras (Motion Analysis Corp., Santa Rosa, CA, USA). GRFs were obtained from the force plate at 1200 Hz. Before the experiments, the motion cameras and force plates were calibrated on the basis of the manufacturers' recommendation; kinematics data were synchronized with the GRF data. Eighteen retroreflective markers (12.5 mm) were placed on bony landmarks (posterior superior iliac spines, right/left anterior superior iliac spine, bilateral greater trochanter, thigh, medial/lateral femoral epicondyles, medial/lateral edges of the tibial plateau, shank, medial/lateral malleoli, medial/lateral calcaneus, medial navicular, head of the first metatarsal, head of the fifth metatarsal, and top of proximal phalange) according to a modified Helen Hayes marker set and the conventional Cleveland Clinic lower extremity marker set [19,20]. The joint work was calculated as the scalar product of the joint moment and the joint angular velocity during stance time. All kinematic movements were calculated by subtracting the static value from the dynamic value. Approach velocities were calculated

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