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Plantar-flexion of the ankle joint complex in terminal stance is initiated by subtalar plantar-flexion: A bi-planar fluoroscopy study

Seungbum Koo [a,*], Kyoung Min Lee [b], Young Joo Cha [c]

[a] Department of Mechanical Engineering, Chung-Ang University, 84 Heukseokro, Dongjak-gu, Seoul 156-756, Republic of Korea
[b] Department of Orthopedic Surgery, Seoul National University Bundang Hospital, Seongnam, Republic of Korea
[c] Department of Laboratory Medicine and Medical Device Clinical Trials Center, Chung-Ang University Hospital, Seoul, Republic of Korea

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ABSTRACT

Gross motion of the ankle joint complex (AJC) is a summation of the ankle and subtalar joints. Although AJC kinematics have been widely used to evaluate the function of the AJC, the coordinated movements of the ankle and subtalar joints are not well understood. The purpose of this study was to accurately quantify the individual kinematics of the ankle and subtalar joints in the intact foot during ground walking by using a bi-planar fluoroscopic system. Bi-planar fluoroscopic images of the foot and ankle during walking and standing were acquired from 10 healthy subjects. The three-dimensional movements of the tibia, talus, and calcaneus were calculated with a three-dimensional/two-dimensional registration method. The skeletal kinematics were quantified from 9% to 86% of the full stance phase because of the limited camera speed of the X-ray system. At the beginning of terminal stance, plantar-flexion of the AJC was initiated in the subtalar joint on average at 75% ranging from 62% to 76% of the stance phase, and plantar-flexion of the ankle joint did not start until 86% of the stance phase. The earlier change to plantar-flexion in the AJC than the ankle joint due to the early plantar-flexion in the subtalar joint was observed in 8 of the 10 subjects. This phenomenon could be explained by the absence of direct muscle insertion on the talus. Preceding subtalar plantar-flexion could contribute to efficient and stable ankle plantar-flexion by locking the midtarsal joint, but this explanation needs further investigation.

1. Introduction

The ankle joint complex (AJC) supports a large mechanical load during heel strike and push off of the stance phase of walking [1,2]. The tibia, talus, and calcaneus form the ankle (talocrural) and subtalar (talocalcaneal) joints in the AJC; thus, the kinematics of the AJC consists of the combined kinematics of the ankle and subtalar joints [3–5]. The talus in particular is surrounded by ligaments and muscles, so its motion is difficult to measure with skin markers. Previous studies on AJC kinematics based on skin markers assumed a single functional joint in the AJC [6–8]. While multi-segment foot models with a single functional joint in the AJC provide apparent ankle motion and have been widely used to evaluate pathological symptoms in the AJC, they lack information on the delicate and coordinated movements of the ankle and subtalar joints.

Two joint models with geometrical constraints in the AJC have been investigated along with skin markers to predict the separate kinematics of the ankle and subtalar joints [5,9–11]. Scott and Winter [9] calculated talus motion using 10 skin markers on the leg and foot during walking by assuming monocentric single-degree-of-freedom hinge joints in the ankle and subtalar joints. MacWilliams et al. [5] used a nine-segment foot model and 19 skin markers on the shank and foot to calculate joint kinematics of the foot, including the ankle and subtalar joints. However, these methods cannot evaluate bone and joint movement directly, and they may involve measurement errors due to inadvertent skin movement unrelated to true joint motion [10].

Skeletal kinematics of the bones in the AJC have been directly measured, although they necessitate invasive treatments of the foot prior to testing. Intracortical pins were inserted in the bones of the shank and foot of subjects under local anesthesia [3,11–13]. The three-dimensional (3D) movements of individual bones were then calculated with multiple reflective markers attached to each intracortical pin during walking trials. Rotations in the ankle and subtalar joints were quantified from the 3D bone movements. While these studies reported that the kinematics of the ankle were

* Corresponding author. Tel.: +82 2 820 5876; fax: +82 2 814 9476.
E-mail address: skoo@cau.ac.kr (S. Koo).

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repeatable between subjects and played a major role in AJC motion during walking [12], they could not observe repeatable kinematics between subjects in the subtalar joint, whose subtle kinematics might have been affected by local anesthesia and invasive treatments.

Recently, non-invasive bi-planar radiographs and bi-planar fluoroscopy-based methods [14] have been used to measure the skeletal movements of the foot and ankle. Lundberg et al. [15] inserted 0.8-mm tantalum markers in the foot bones, including the tibia, talus, and calcaneus, and captured bi-planar radiographs while subjects performed quasi-static dorsiflexion–plantar flexion, inversion–eversion, and abduction–adduction on a platform. Rotational axes and ranges of motion of the individual joints in the AJC were quantified, but only for non-ambulatory motions. De Asla et al. [16] measured the 3D poses of the tibia, talus, and calcaneus with bi-planar fluoroscopy using a model-based 3D/2D registration without beads in the bones for three time points of walking: heel strike, mid-stance, and toe off.

To the best of our knowledge, no previous studies have directly measured the continuous kinematics of the ankle and subtalar joints of the intact foot during normal walking using bi-planar fluoroscopy. Although the AJC supports the entire body weight during walking and its joint kinematics would determine the load distribution in articular surfaces and connective tissues, the delicate and coordinated movements of the ankle and subtalar joints have not been well investigated. Therefore, the purpose of this study was to quantify the kinematics of the ankle and subtalar joints during normal walking of the intact foot by direct X-ray imaging of skeletal movements using a bi-planar fluoroscopic system and a model-based 3D/2D registration method.

2. Methods

This study was approved by the Institutional Review Board of Chung-Ang University. Ten healthy young males (age, 21.5 ± 1.9 years; BMI, 21.7 ± 1.9 kg/m^2) participated after informed consent was obtained. The participants had no history of lower limb fractures or sprains, and they had no lower limb pain for the previous two years. Participants with a low and high arch foot were excluded by visual assessment of a clinician.

2.1. Bi-planar fluoroscopic system set-up

Our bi-planar fluoroscopic system (KMC-1400ST, Gemss Medical, Kyungki-do, Republic of Korea) was approved by the Korean Food and Drug Administration. The X-ray tubes of the system were operated at 55 kVp and 10 mA in continuous mode. Each X-ray image intensifier was equipped with a one-megapixel CCD sensor camera (1024×1024 pixels, 14-bit depth). The cameras acquired images synchronously at 27 frames per second with exposure time of 4 ms.

The locations and directions of the imaging systems were simulated with a graphical 3D design tool (SketchUp, Google, Mountain View, CA, USA) to avoid interference with the walkway and the subject walking (Fig. 1(a)). The walkway was made of high-density polystyrene foam with dimensions of 120 cm, 60 cm, and 360 cm in height, width, and length, respectively. The form blocks were firmly attached to each other for stability. The angle between the two imaging directions was 37° (Fig. 1). The best position for obtaining bi-planar images of the right foot on the walkway was marked with a circle.

2.2. Subject preparation and data acquisition

Two reflective markers were placed on the waist and tracked with a motion capture system (MX-T10, Vicon Motion Systems, Oxford, UK) to obtain walking speed. Bi-planar radiographs of the right foot in a static standing posture were also taken to determine the reference positions of the bones. Subjects practiced walking on the walkway for about 10 min until they felt comfortable with walking barefoot and their steps became stabilized. There were four hanging safety ropes on both sides of the walkway so that subjects could hold them in case they felt unstable. Subjects were instructed to hit the circle marked on the walkway with their right foot while keeping their normal walking pace. Bi-planar fluoroscopic images were taken for 2 s while the foot touched the target position, as shown in Fig. 1(b). The foot was in the field of view of the bi-planar fluoroscopic system for less than 1 s.

Bi-planar radiographs of a custom calibration phantom with 81 steel beads were obtained after testing each subject. In-house calibration software calculated the intrinsic and extrinsic parameters of the bi-planar imaging system [17]. An aluminum plate with grids of 3-mm holes was attached to the front panel of the image intensifiers to take radiographs. The images were used to calculate the distortions of the imaging system with custom software [18].

2.3. Bi-planar image data processing

All subjects underwent foot computed tomography (CT) imaging. Three-dimensional triangular mesh models of the tibia, talus, and calcaneus were obtained from the CT data using custom

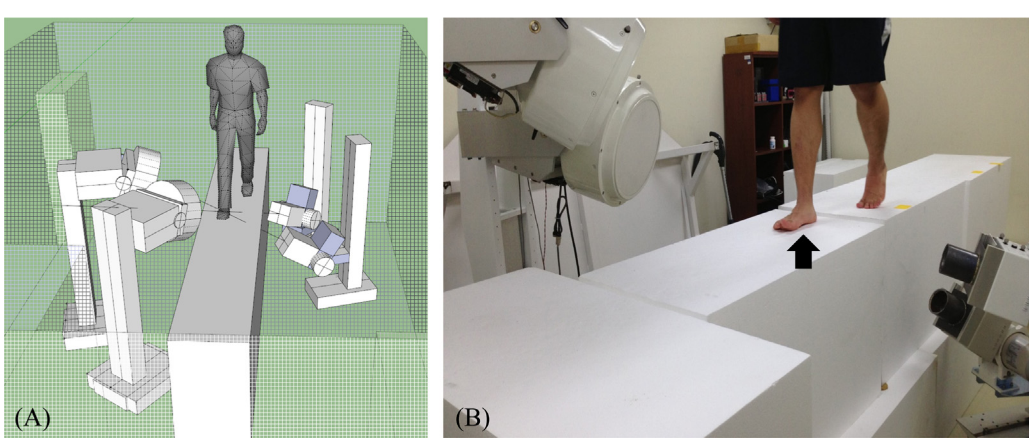

Fig. 1. Graphical simulation to determine the locations and directions of the bi-planar imaging systems (a). Bi-planar fluoroscopic imaging of the right foot during normal walking (b).