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A comparison of multi-segment foot kinematics during level overground and treadmill walking

Kirsten Tulchin *, Michael Orendurff, Lori Karol

Texas Scottish Rite Hospital for Children, Movement Science Laboratory, 2222 Welborn Street, Dallas, TX 75219, United States

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ABSTRACT

Previous work comparing treadmill and overground walking has focused on lower extremity motion and kinetics, with few identified differences. However, a comparison of multi-segment foot kinematics between these conditions has not been previously reported. Sagittal ankle motion using a single rigid body foot model and three-dimensional hindfoot and forefoot kinematics were compared during barefoot, level, overground walking at a self-selected speed and treadmill walking at a similar speed for 20 healthy adults. Slight differences were seen in ankle plantarflexion and hindfoot plantarflexion during first rocker, as well as peak forefoot eversion and abduction, however all changes were less than 3°, and most were within the day-to-day repeatability. These results indicate that foot mechanics as determined using a multi-segment foot model were similar between overground and treadmill walking at similar speeds in healthy adults. Treadmill protocols may provide a controlled method to analyze a patient's ability to adapt to walking at different speeds and surface slopes, which are encountered often during ambulation of daily living.

1. Introduction

Instrumented lower extremity gait analysis in the clinical setting typically focuses on overground walking at a self-selected speed. Ambulation of daily living in the community however often requires more demanding tasks such as speed variation, turning and negotiating uneven terrain [1,2]. The use of a treadmill provides clinicians a means to design controlled protocols to evaluate a patient's ability to adapt to changes in speed and surface slope. The advantages of gait analysis using a treadmill protocol also include the ability to collect multiple, consecutive strides within a small capture volume, which allows data collection to occur within a shorter period of time and with less variability in speed between trials [3].

Previous work comparing overground level walking and treadmill walking has focused on differences in lower extremity kinematics and kinetics. Alton et al. [4] found greater hip range of motion, greater maximal hip flexion angle and higher cadence during treadmill walking. They also observed a slightly decreased stance time compared to overground walking. Similar findings of a higher cadence during treadmill walking was also reported by Murray et al. [5]; however these results were not duplicated by Riley et al. [6]. In their study, Riley et al. reported on both kinematic and kinetic changes using a forceplate instrumented treadmill. In evaluating the minima and maxima values of each kinematic variable, they found that differences between conditions were less than 3°. In addition all differences seen were within the coefficients of repeatability of overground walking tests, with similar findings seen in the kinetic variables. Of particular interest to this study, they found no significant differences in maximum ankle dorsiflexion or plantarflexion motion, moments or power [6].

The use of multi-segment foot models to evaluate the pathological foot has expanded greatly over the last decade. These models provide a means to assess foot mechanics in more detail compared to the traditional lower extremity single rigid body foot model. By dividing the foot into multiple 'rigid' segments, three-dimensional intersegmental motion can be assessed for the hindfoot and forefoot, for example. Benedetti et al. [7] stated that approximately 16 studies utilizing multi-segment foot models were reported in literature between 1999 and 2008, on topics ranging from posterior tibialis dysfunction to talipes equinovarus deformity. Further analysis of this literature indicates that 13 of these 16 studies were published between 2004 and 2008, illustrating the emerging interest in the use of multi-segment foot models as an outcome tool in pathological gait evaluations. Fifteen of the 16 studies were conducted during overground ambulation at subjects' self-selected walking speed [8–21]. Rao et al. [22] conducted testing with all subjects walking overground at a speed of 0.89 m/s, and only three reported monitoring speed to within ±5% of each subject's self-selected velocity [11,14,19].

* Corresponding author. Tel.: +1 214 559 7580.
E-mail address: kirsten.tulchin@tsrh.org (K. Tulchin).
URL: http://www.tsrhc.org

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Tulchin et al. [23] have recently reported that walking speed can significantly affect sagittal plane multi-segment foot kinematics in healthy adults. Changes in inter-segment foot kinematics were similar to that seen at the ankle, with a shift towards plantarflexion and reduced stance duration as a percent of the gait cycle at faster speeds. The treadmill can provide a structured protocol to assess patients with pathological foot conditions at various speeds and inclines, which these patients may be subjected to during ambulation of daily living. However, it is important to first determine if there are any underlying differences in foot biomechanics, as measured using a multi-segment foot model, between overground and treadmill walking at similar speeds. The hypothesis of the current study was there would be no differences seen in multi-segment foot kinematics during level overground walking at a self-selected speed and level treadmill ambulation at a similar speed in a group of healthy adult subjects.

2. Methods

Twenty adults, six males and 14 females, underwent gait analysis with IRB informed consent (Table 1). Subjects were excluded if they had a history of lower extremity surgery, or recent lower extremity injury within the last 6 months. Subjects were instrumented with a modified Helen Hayes marker set [24], as well as a multi-segment foot marker set bilaterally [23,25]. For the foot model, two of the Helen Hayes markers placed on the foot (toe and heel) were used in conjunction with five additional markers to model the hindfoot and forefoot. Marker trajectories were collected using a 12 camera VICON Mx motion capture system operating at 120 Hz (VICON, Denver, CO). All data were filtered with a smoothing spline (Woltring) routine using a mean square error of 10 [26]. Subjects performed level, overground barefoot walking at a self-selected speed. Multiple trials were collected for each leg, however a single side was randomly chosen for analysis for each subject, which resulted in equal distribution between right and left legs across all subjects. Subjects were then asked to complete a treadmill protocol, walking at speeds beginning at 0.89 m/s and increasing in increments of 0.23 m/s up to 1.79 m/s. The speed which most closely matched their self-selected walking speed during the overground condition was used for comparison. A single representative trial was chosen for each condition for comparison. Maximum and minimum values of sagittal plane ankle and three-dimensional hindfoot and forefoot motion were determined for each subject. Sagittal plane ankle motion as defined using a single rigid body foot model (Plug-In Gait, VICON) was determined. Hindfoot and forefoot angles were calculated using a custom written multi-segment foot kinematic model (Bodybuilder for Biomechanics, VICON). Sagittal plane motion of ankle and hindfoot motion were examined specifically during each of the three ankle rockers: (1) plantarflexion during weight acceptance, (2) dorsiflexion during single limb stance, and (3) plantarflexion at terminal stance [27]. The mean differences between conditions for all variables were determined for each individual subject, and one sample *t*-tests were conducted for the group with a hypothesized mean of zero, indicating that no differences between conditions were expected. In addition, mean differences between overground and treadmill walking were compared to the day-to-day repeatability of each variable based on previous work comparing two sessions of data collected 2 weeks apart on 10 healthy adults [25].

2.1. Multi-segment foot model

The multi-segment foot model employed for this work was a three segment model of the shank, hindfoot, and forefoot [23,25]. Marker placement on the foot is shown in Fig. 1. A marker was also placed on the medial malleoli during the static trial. For the shank segment: the origin was located at the midpoint of the lateral and medial malleoli (ankle joint center); the *X*-axis was defined as the line joining the lateral and medial malleoli; the *Y*-axis was perpendicular to a line joining the knee and ankle joint centers, and the *X*-axis; and the long axis, *Z*, was therefore defined as being orthogonal to the *X* and *Y* axes. The shank segment was offset in the coronal plane to be parallel to the plane of the floor during the static trial, thus eliminating offsets in hindfoot motion based on bimalleolar axis variations.

Individual markers were placed on the posterior, medial and lateral calcaneus to define the hindfoot segment The foot was marked non-weight bearing such that, with the subject lying prone, the clinician palpated the medial and lateral borders of the calcaneus and drew a midline bisection along the posterior calcaneus. During quiet standing, a custom hindfoot alignment device with a cross-hair laser, based on the novel device described by Wervey and Schwartz [28], was used to ensure proper placement of the medial and lateral calcaneus markers in the coronal plane, so that they were perpendicular to the posterior midline of the calcaneus. This method was used to assure accurate measurement of hindfoot inversion/eversion. The third marker was placed along the midline of the posterior calcaneus. Calipers were then used to ensure that the distances from the medial and lateral calcaneal markers to the posterior calcaneal marker were equal, decreasing erroneous hindfoot rotation. For the hindfoot: the origin was the midpoint of the lateral and medial calcaneal markers (mid-calcaneus); The *X*-axis was defined as the line joining the medial and lateral calcaneal markers; the *Z*-axis was defined perpendicular to the line joining the posterior calcaneus marker and the mid-calcaneus, and the *X*-axis; and the *Y*-axis was defined as orthogonal to the *X* and *Z* axes. The hindfoot segment was offset in the sagittal plane to be parallel to the plane of the floor when the foot was plantigrade.

Table 1
Subject demographics, including age, height and weight.

Subjects	*N*	Age (years)	Height (cm)	Weight (kg)
Female	14	25.0 ± 4.3	166.8 ± 4.3	62.3 ± 10.0
Male	6	25.3 ± 6.2	182.0 ± 7.2	84.9 ± 16.6
All subjects	20	25.1 ± 4.8	171.4 ± 8.8	69.1 ± 15.9

Mean (standard deviation).

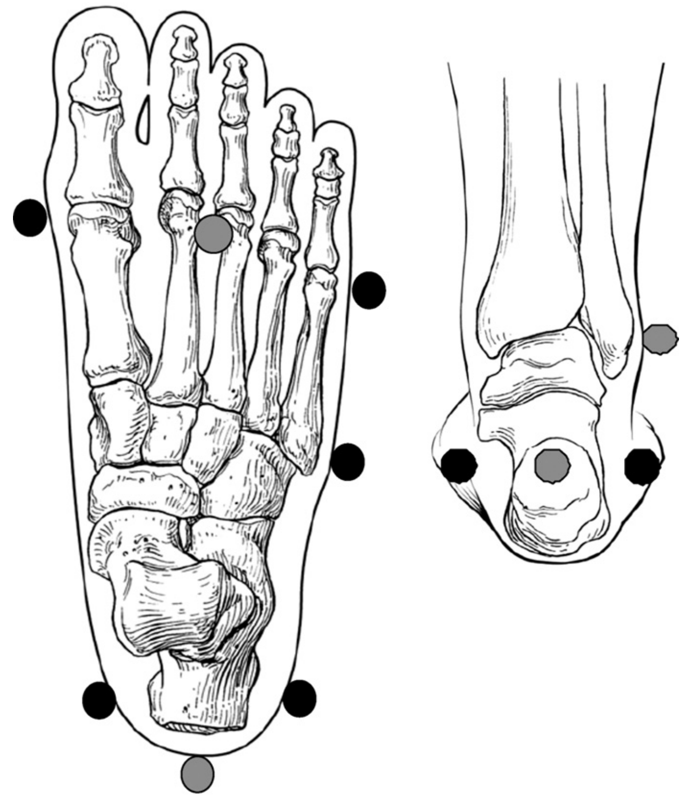

Fig. 1. Skin marker placement for the TSRH multi-segment foot model. Markers on the second/third metatarsal, lateral malleolus and posterior calcaneus, shown in gray, are used for the single rigid body foot model, as well as the multi-segment foot model. Markers on the heads of the first and fifth metatarsals, the fifth metatarsal base, medial and lateral calcaneus markers, shown in black, in addition to the posterior calcaneus marker, are used to define the hindfoot and forefoot segments in the multi-segment foot model.

Palpation was used to place markers on the first and fifth metatarsal heads and the fifth metatarsal base. For the forefoot: the origin was defined as a point at the perpendicular bisector of the fifth metatarsal base to a line joining the second/third metatarsal heads to the posterior calcaneus (long axis of the foot); the *X* axis joined the heads of the first and fifth metatarsals; the *Z* axis was perpendicular to a line joining the fifth metatarsal base and the fifth metatarsal head, and the *X* axis; and the *Y* axis was orthogonal to the *X* and *Z* axes.

Relative inter-segmental motion of the following segments were examined: hindfoot relative to the shank (termed hindfoot motion) and forefoot relative to the hindfoot (forefoot motion). Hindfoot motion represented motion at the ankle mortise and the subtalar joint. Forefoot motion included the Chopart and Lisfranc joints. All angles were described by Euler rotations about the proximal segment axes, using a *XYZ* (sagittal, coronal, transverse) rotation order.

3. Results

The 1.12 m/s (2.5 mph) treadmill speed was selected for 11 subjects (average overground speed 1.17 ± 0.05 m/s) and 1.34 m/s (3.0 mph) was used for the nine remaining subjects (average overground speed 1.31 ± 0.07 m/s). Mean differences between