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A comparison of subtalar joint motion during anticipated medial cutting turns and level walking using a multi-segment foot model

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ABSTRACT

The weight-bearing in-vivo kinematics and kinetics of the talocrural joint, subtalar joint and joints of the foot were quantified using optical motion analysis. Twelve healthy subjects were studied during level walking and anticipated medial turns at self-selected pace. A multi-segment model of the foot using skin-mounted marker triads tracked four foot segments: the hindfoot, midfoot, lateral and medial forefoot. The lower leg and thigh were also tracked. Motion between each of the segments could occur in three degrees of rotational freedom, but only six inter-segmental motions were reported in this study: (1) talocrural dorsi-plantar-flexion, (2) subtalar inversion–eversion, (3) frontal plane hindfoot motion, (4) transverse plane hindfoot motion, (5) forefoot supination–pronation twisting and (6) the height-to-length ratio of the medial longitudinal arch.

The motion at the subtalar joint during stance phase of walking (eversion then inversion) was reversed during a turning task (inversion then eversion). The external subtalar joint moment was also changed from a moderate eversion moment during walking to a larger inversion moment during the turn. The kinematics of the talocrural joint and the joints of the foot were similar between these two tasks.

During a medial turn, the subtalar joint may act to maintain the motions in the foot and talocrural joint that occur during level walking. This is occurring despite the conspicuously different trajectory of the centre of mass of the body. This may allow the foot complex to maintain its function of energy absorption followed by energy return during stance phase that is best suited to level walking.

1. Introduction

The ankle–foot complex is functionally composed of the talocrural and subtalar joints between the leg and foot, the joints of the foot itself and the longitudinal and transverse arches. During stance phase, these structures give the lower leg a great range of rotational freedom with respect to the planted foot [1,2] and are loaded to many times body-weight [3]. Sprain of the lateral ankle ligaments accounts for approximately 75% of injuries to the ankle–foot complex [4], which often occur during sporting activities when the ankle–foot musculoskeletal system is over-loaded and fails [5,6]. The most common activity associated with lateral ankle injury is medial cutting turns [7–9] (Fig. 1), which can cause rapid over-inversion of the foot, particularly when the foot is in a plantar-flexed position [5,10,11]. Stacoff et al. [12] studied ankle kinematics during medial turning tasks in barefoot and shoed conditions. This group conducted a video analysis of the ankle–foot complex (treating the foot as a single segment) in the frontal plane and was able to examine relative motion between the foot and shoe. This group concluded that lateral stability of the subtalar joint could be improved with more appropriate shoe design.

However, the influence of the joints of the foot, which may play a significant role in lateral ankle sprain, has not been examined during medial cutting turns (Fig. 1). Measurement of foot joint motion requires that multiple foot segments be tracked independently. Several groups have tracked various configurations of multi-segment foot models with skin-mounted markers [13–16] and markers attached to bone pins [17]. These studies each defined foot segments differently, but common segments have been the hindfoot (rearfoot), forefoot and phalanges. These models have added great insight into the normal and pathological function of

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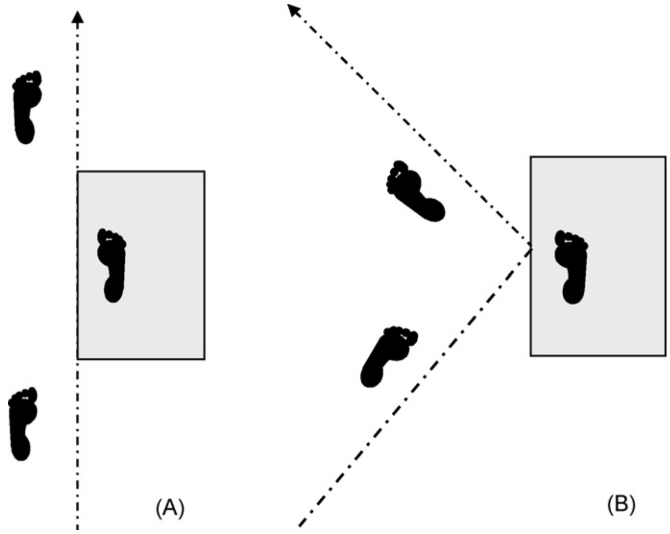

Fig. 1. Subject paths for the (A) level walking and (B) medial turning task showing the sequence of foot falls approaching and leaving the force plate. Only the right leg and foot kinematics were studied.

the foot. However, none have examined the interaction of the joints of the foot with the talocrural and subtalar joints during medial turning tasks, instead looking only at level walking.

Most of the multi-segment foot models described in the literature do not define a midfoot segment [14,16,17]. While making them simpler than the model in the current study [18] and therefore easier to use in a clinical setting, these models possess two shortcomings. The first is to treat the forefoot as a rigid segment when functionally it is quite flexible. Therefore no supination–pronation twisting of the forefoot can be quantified. The second shortcoming is the inability to simultaneously measure subtalar joint, hindfoot and forefoot motions. Without a midfoot segment there are only enough degrees of freedom to resolve two of these three motions.

This study used a four-segment kinematic model of the foot that included a midfoot segment [18]. Six inter-segmental motions were examined, including the talocrural and subtalar joints, during level walking and anticipated medial cutting turns. The study was performed on normal subjects with no history of ankle or foot injury. It was hypothesized that motion in all six degrees of freedom would be significantly different between the two tasks. Specifically it was hypothesized that the frontal plane hindfoot and forefoot motions (with respect to the midfoot segment) would tend to be more inverted along with the subtalar joint.

2. Methods

2.1. Subjects

Twelve normal subjects were selected from a cohort of convenience. The average age was 27 years (range from 22 to 40 years) with average body mass of 64 kg (range 53–78 kg). Subjects with any known gait abnormalities of neurological or orthopaedic nature were excluded, as were those with history of surgery or severe trauma to either lower leg or foot, including previous ankle sprain. Subjects who regularly wore orthotics for high arches or flat foot were also excluded. Subjects were barefoot and wore shorts and a short-sleeved shirt.

2.2. Experimental protocol

Subjects performed two movement tasks: level walking and a medially directed, anticipated turn. Both tasks were performed at self-selected pace with the right foot striking a force plate (Kistler Instrument Corp., Amherst, NY). For the turning task, the subject approached the force plate at 45° with respect to the walking approach then performed a 90° turn to the left at force plate contact (Fig. 1). The subject then left the force plate at 45° the path of walking. All trials were performed in barefoot. Each trial was repeated five times.

2.3. Experimental equipment

Kinematic data was collected with a six-camera optical motion capture system (Vicon, Oxfordmetrics, Oxford, UK) at a sample rate of 50 Hz. Kinetic data was collected at 1000 Hz (Kistler, Inc., Winterthur, Switzerland). Passive reflective markers were arranged in rigid clusters of three markers as described in Jenkyn and Nicol [18]. The markers were spherical foam beads of 10 mm diameter covered in self-adhesive reflective tape (3 M, Minneapolis, MN, USA). The cluster stalks were 3 mm diameter carbon fiber rods press-fit into a polyethylene base of 16 mm diameter. Cluster mass was approximately 100 g and the cluster was attached to the skin using medical, two-sided tape. An additional cluster was placed on the distal thigh segment. Due to the additional time required to apply, digitize and post-process the multi-segment cluster markers on the foot and leg, only the right foot and leg were examined in this study. Therefore it was not possible to control for the influence of side-dominance. A left-leg dominant subject may have had more difficulty performing the medial cutting turn with their right leg. Although none of the subjects complained about the difficulty of the turning task.

2.4. Multi-segment foot model

The multi-segment foot model used to track the kinematics of the joints of the foot is described in Jenkyn and Nicol [18]. The ankle and foot were functionally divided into four rigid segments that were tracked individually. These were the hindfoot (calcaneous), midfoot (tarsals), lateral forefoot (5th metatarsal) and medial forefoot (1st metatarsal) segments. The leg was also divided into the thigh and lower leg segments. Three bony landmarks were palpated on each segment (Table 1) and digitized in quiet standing with an instrumented stylus to establish segment-fixed reference frames. The initial quiet standing trial also established the weight-bearing neutral positions for each of the inter-segmental motion measures. Between each segment were three degrees of rotational freedom. In this study, only six inter-segmental motions are reported: the talocrural joint, the subtalar joint, hindfoot segment with respect to midfoot in the frontal plane and the transverse plane, the frontal plane twisting of the forefoot segments motion with respect to midfoot and the height-to-length ratio of the medial longitudinal arch (Fig. 2). The medial longitudinal arch was defined by three bony landmarks, each on a different segment: MiH on the medial forefoot, MNT on the midfoot and CAMT on the hindfoot segments (Table 1). Marker trajectories were post-processed in the commercial software accompanying the motion capture system (Polygon 1.0, Oxfordmetrics, Oxford, UK). All trajectories were low pass filtered with a fourth-order Butterworth filter with a cutoff of 6 Hz to remove vibration artifacts from the marker clusters and jitter from the marker positions. Inter-segmental joint measures were calculated using the trajectories and digitizations with custom-written software (Matlab, The Mathworks, Natick, MA). Five trials per condition were used for each subject. Two strides were taken before the force plate was struck. Only the stance phase occurring on the force plate and the subsequent swing phase were analyzed. Heel-strike and toe-off were identified as the first and last frames when vertical ground reaction force exceeded 3 N. The inter-segmental motions reported in the results section are the average of the five trials per subject per condition. External moments at the talocrural and subtalar joints were calculated during stance phase using the custom-written software in Matlab.

2.5. Analysis

To test whether inter-segmental kinematics differed between tasks, the magnitudes of the turning task measures and the walking task measures were

Table 1
Bony landmarks digitized on each segment (three per segment) used to define segment-fixed axes. Note that the medial and lateral forefoot segments share landmarks.

Segment	Tracked landmarks
Thigh	FLE: lateral epicondyle (most lateral point)
	FGT: greater trochanter (most lateral point)
	FME: medial epicondyle (most medial point)
Lower leg	LLM: lateral malleolus (most lateral point)
	LFH: fibular head (most lateral point)
	LMM: medial malleolus (most medial point)
Hindfoot	CAER: eminentia retrotrochlearis (greatest lateral elevation)
	CALT: lateral tuberosity (lateral to achilles tendon attachment)
	CAMT: medial tuberosity (medial to achilles tendon attachment)
Midfoot	MCI: first cuneiform (distal dorsal crest)
	MNT: navicular tuberosity (most medial point)
	MCU: cuboid (lateral dorsal edge at joint with calcaneus)
Medial forefoot	MIH: first metatarsal head (most dorsal point)
	MIB: first metatarsal base (most dorsal point)
Lateral forefoot	MVH: fifth metatarsal head (most dorsal point)
	MVB: fifth metatarsal base (most dorsal point)