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Contribution of calcaneal and leg segment rotations to ankle joint dorsiflexion in a weight-bearing task

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ABSTRACT

Joint angle is the relative rotation between two segments where one is a reference and assumed to be non-moving. However, rotation of the reference segment will influence the system's spatial orientation and joint angle. The purpose of this investigation was to determine the contribution of leg and calcaneal rotations to ankle rotation in a weight-bearing task. Forty-eight individuals performed partial squats recorded using a 3D motion capture system. Markers on the calcaneus and leg were used to model leg and calcaneal segment, and ankle joint rotations. Multiple linear regression was used to determine the contribution of leg and calcaneal segment rotations to ankle joint dorsiflexion. Regression models for left ($R^2 = 0.97$) and right ($R^2 = 0.97$) ankle dorsiflexion were significant. Sagittal plane leg rotation had a positive influence (left: $\beta = 1.411$; right: $\beta = 1.418$) while sagittal plane calcaneal rotation had a negative influence (left: $\beta = -0.573$; right: $\beta = -0.650$) on ankle dorsiflexion. Sagittal plane rotations of the leg and calcaneus were positively correlated (left: $r = 0.84$, $P < 0.001$; right: $r = 0.80$, $P < 0.001$). During a partial squat, the calcaneus rotates forward. Simultaneous forward calcaneal rotation with ankle dorsiflexion reduces total ankle dorsiflexion angle. Rearfoot posture is reoriented during a partial squat, allowing greater leg rotation in the sagittal plane. Segment rotations may provide greater insight into movement mechanics that cannot be explained via joint rotations alone.

1. Introduction

Ankle dorsiflexion is important in a variety of activities of daily living. During gait and running, ankle dorsiflexion eccentrically loads the triceps surae from which energy is used for propulsion [1,2]. Dorsiflexion also affects more proximal musculature, where increased range of motion is associated with loading of the knee extensor apparatus [3,4]. Anatomically, ankle dorsiflexion occurs at the talocrural joint and is the relative motion between the leg and the talus in the sagittal plane [5]. Due to widening of the anterior aspect of the talus, dorsiflexion range of motion is limited to 20–30° in normal individuals.

Although the bony limitation to ankle dorsiflexion range of motion is well known, there are reports of ankle dorsiflexion up to 45° [6]. During squatting and jumping, performance is associated with a large range of motion at the ankle [3,4]. Specifically, as ankle dorsiflexion increases, forward inclination of the leg increases. These mechanics allow the trunk to remain upright while employing the knee extensors [3], the primary muscle group in squat-type motions [7]. These highlight the importance of understanding the mechanics of the foot and ankle as there are greater implications to the correct kinematic description and control of human movement.

Dorsiflexion is rotation of the foot relative to the leg, or vice versa, from a neutral position. However, different definitions of and techniques to measure dorsiflexion are used [8–12]. A primary limitation in research is segmental position of the foot is difficult to determine due to inter-segmental motion between bones in the foot. Classically, the foot is modeled in biomechanics as the straight-line distance between the ankle joint center and a point between the first and fifth metatarsal heads [13]. However, this definition assumes the foot is a rigid structure. Inter-segmental motion between the tarsals and metatarsals may alter the orientation of the talus and talocrural joint [5].

The calcaneus rotates in the transition from non-weight-bearing to weight-bearing [10,11]. The calcaneal motions described most in the literature are eversion and inversion. In the transition from non-weight-bearing to weight-bearing the medial longitudinal arch decreases in height. The bony motions contributing to arch decrease are not well understood, however, it is believed that calcaneal eversion occurs [14]. Increased arch collapse may be associated with excess calcaneal eversion [15], in turn leading to internal rotation of the leg [16]. Although rearfoot motion has been investigated, it is not known how

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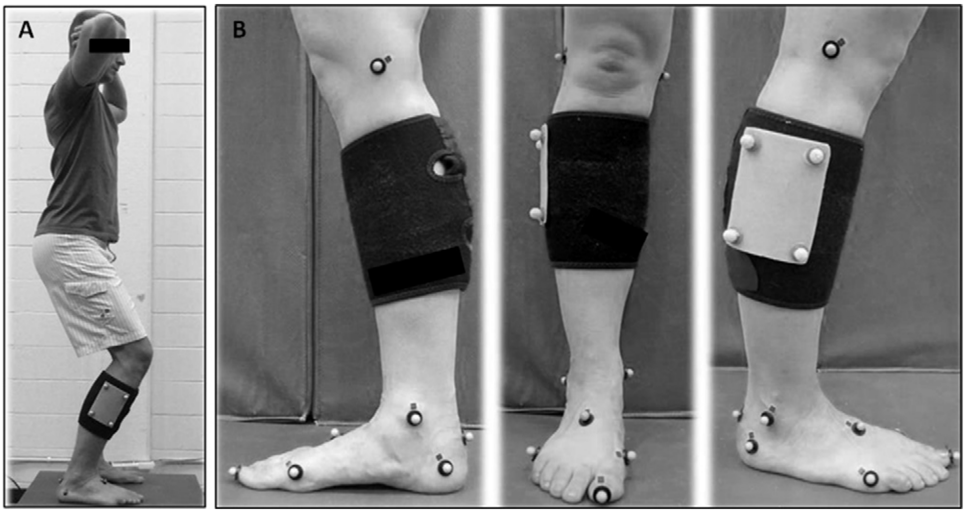

Fig. 1. Maximum ankle dorsiflexion partial squat task (A) and retro-reflective marker placement (B). Markers on first and fifth metatarsal heads, cuneiform and distal foot were not used for analysis in the current investigation.

calcaneal motion influences ankle motion during weight-bearing tasks. The purpose of this investigation was to determine the contribution of leg and calcaneal rotations to ankle dorsiflexion during a weight-bearing task.

2. Methods

Men (n = 23) and women (n = 25) were recruited for this investigation. All participants provided written informed consent as approved by a Research Ethics Board at the authors' institution. Participants were not excluded if they had pes planus, pes cavus or dynamic flexible flatfoot. Men were 25.1 ± 5.4 years old, 1.79 ± 0.06 m tall and weighed 85.3 ± 17.8 kg. Women were 25.2 ± 5.3 years old, 1.66 ± 0.06 m tall and weighed 63.4 ± 10.5 kg.

Participants performed a partial squat task, where they were instructed to reach maximum dorsiflexion without allowing their trunk to flex forward (Fig. 1). Participants practiced the task until they were comfortable with the procedures before data collection. The distance between the femoral greater trochanters was measured and foot width was standardized by having the feet pointing forward with the 2nd ray of each foot at this distance. For each trial, participants stood motionless for a minimum of 2 s (baseline position), then squatted to their maximum dorsiflexion and held this position for 3–4 s (squat position). Three trials were recorded. Retro-reflective markers (9 mm diameter) were placed on the participant's lower extremity and recorded at 120 Hz using a six-camera optoelectronic motion capture system (Qualisys ProReflex MCU240; Qualisys, Sweden).

To model the leg, proximal markers were placed on the medial and lateral tibial condyles and distal markers on the medial and lateral malleoli (Fig. 1). The longitudinal axis (Z) of the leg was defined as running through the mid-point between the proximal and distal markers. The transverse axis (X) and sagittal axes were orthogonal to each other and the longitudinal axis, running through the mid-point between the proximal markers. A cluster of four markers fixed to a thermoplastic plate was used for tracking the leg.

The calcaneus was modeled by three markers placed on medial, lateral and posterior aspects of the calcaneus (Fig. 1). The coordinate system for the calcaneus was established using virtual markers. The medial and lateral calcaneal markers represented the proximal end of the calcaneus. The distal end of the calcaneus was calculated by projecting the medial and lateral calcaneal markers vertically, thus creating virtual markers at the height of the laboratory floor. The longitudinal axis (Z) of the calcaneus was defined as running through the mid-point between the lateral and medial calcaneal markers and between the two virtual markers. The transverse (X) and sagittal (Y) axes were orthogonal to each other and the longitudinal axis and centered at the mid-point between the proximal markers. All data processing was performed with Visual 3D (version 4.75.36; C-Motion, Inc., Germantown, MD, USA).

Segment rotations were determined for the leg and calcaneus using a ZYX Cardan sequence relative to the laboratory reference frame [17]. The ankle joint was operationally defined as the relative motion between the leg and calcaneus [18]. Ankle joint angle was determined using an XYZ Cardan sequence with the calcaneus as the reference segment. All coordinate systems on the right limb conformed to the right-hand rule. On the left limb, data were processed in right-hand rule coordinate systems; however, for presentation of segment and joint angles, the signs were reversed for rotations about Y- and Z-axes to conform to the right limbs. Excursion of the segments and joints was determined as the average value in the squat position minus the average value in the baseline position.

2.1. Statistical analyses

Gender differences in leg, calcaneus and ankle rotations were tested using independent sample t-tests. To determine contribution of leg and calcaneus segment rotations to ankle joint dorsiflexion, multiple regression models were developed using ankle dorsiflexion excursion as the independent variable. Separate models were developed for the left and right limbs. Pearson product moment correlations were run generating a correlation matrix for leg, calcaneal and ankle excursions in three planes. Variables that were significantly related to ankle dorsiflexion excursion were inputted into linear multiple regression models. Statistical calculations were performed in SPSS (version 11.0; SPSS Inc., Chicago, USA).

3. Results

No gender differences ($P > 0.05$) were found for leg, calcaneus or ankle rotations, thus men and women were grouped together for correlation and regression analyses (Table 1). For the right limb, the rotation of the leg and calcaneus in the sagittal plane and leg in the frontal plane contributed significantly to predicting ankle dorsiflexion excursion ($R^2 = 0.97$; Table 2). The standardized β scores indicated a positive effect of forward leg inclination on ankle dorsiflexion whereas anterior rotation of the calcaneus had a negative effect. The effect of frontal plane leg rotation was trivial. For the left limb, only rotation of the leg and calcaneus in the

Table 1
Calcaneus, leg and ankle excursions during weight-bearing partial squat.

Segment/joint	Plane	Left	Right
Calcaneus	X (sagittal)	10° (5°; 15°)	10° (5°; 18°)
	Y (frontal)	−5° (−13°; 1°)	−6° (−12°; 0°)
	Z (transverse)	−1° (−6°; 6°)	−2° (−5°; 0°)
Leg	X (sagittal)	30° (17°; 43°)	29° (15°; 42°)
	Y (frontal)	1° (−6°; 19°)	−1° (−7°; 4°)
	Z (transverse)	1° (−6°; 8°)	0° (−15°; 12°)
Ankle	X (sagittal)	19° (12°; 29°)	18° (9°; 27°)
	Y (frontal)	4° (−4°; 10°)	4° (−1°; 13°)
	Z (transverse)	2° (−6°; 9°)	2° (−13°; 13°)

Data are: mean (minimum; maximum). Positive values indicate: calcaneus – anterior rotation (X), inversion (Y), adduction (Z); leg – anterior rotation/inclination (X), eversion (Y), internal rotation (Z); ankle – dorsiflexion (X), eversion (Y), abduction (Z).