MIDTARSAL KINEMATICS DEFINED USING FINITE HELICAL AXES ANALYSIS

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INTRODUCTION

The midtarsal joint of the normal foot has been observed to display bimodal behavior during the stance phase of walking. The forefoot is reasonably flexible during weight acceptance to conform to terrain; upon heel rise and thereafter it increases stiffness to propel the body forward. This changeover from a flexible to a stiff construct is often referred to as the midtarsal joint locking mechanism, and the most logical and frequent explanation for its existence is non-synchronous migration of talonavicular and calcaneocuboid joint axes [1].

Recently Okita et al. [2] observed increased excursion of the midtarsal joints in concert with subtalar inversion and rapidly increasing forces in the plantarflexors during the last 40% of the stance phase, suggesting the existence of transverse tarsal joint locking mechanism.

The purpose of the current study was to characterize the internal midtarsal kinematics during simulations of normal gait using finite helical axes.

METHODS

Ten normal fresh frozen donated cadaver extremities (5M/5F, 59.2 ± 14.2 years) were evaluated. Dynamic simulations of the stance of gait were conducted by employing a robotic dynamic activity simulator at 1/20th the velocity of typical walking [3]. Tibia, talus, calcaneus, navicular, and cuboid were instrumented with marker clusters composed of four retro-reflective markers (6 mm dia.) connected by carbon fiber rods (0.16 mm dia.). Marker trajectories were recorded at 100 Hz using a seven-camera passive 3D photogrammetry system (Motion Analysis Corp, Santa Rosa, CA) with a typical 3D reconstruction residual of 0.3 mm. For each specimen, the simulation parameters were optimized by adjusting sagittal plane tibia kinematics and six muscle actuations (TA:Tibialis Anterior, TP:Tibialis posterior, PER:Peroneus longus, FHL:Flexor hallucis longus, FDL:Flexor digitorum longus, and TS:Triceps Surae) until target ground reaction forces (AMTI, Newton, MA) were attained. Data collection trials were repeated three times.

The marker data were smoothed using a dual-pass 4th-order Butterworth filter at 2 Hz cutoff frequency, and a least squares method [4] was employed to obtain homogeneous coordinate transformation matrices for each bone.

Finite helical axis parameters were obtained using the relative transformation of the distal bone with respect to the proximal bone [5]. Average unit vectors ($\underline{\mathbf{n}}$) along the helical axis between two bones for each specimen were obtained by dividing the ensemble average of the joint angles ($\varphi\underline{\mathbf{n}}$) with the angle of rotation (φ) about the helical axis. The across specimen average was obtained in similar manner.

RESULTS AND DISCUSSION

Qualitatively, bimodal behavior of the foot was observed. Figure 1 shows the superior, posterior, and medial view of the time progression of the unit vectrors of the helical axes for the a) transverse tarsal joints and b) calcaneotalar and cubonavicular joints.

In general, the orientation of the helixal axes changed throughout the stance phase. Prior to the foot flat at approximately 35% of stance phase, the joint axes, especially calcaneocuboid (Figure 1a), were rather randomly orientated in all planes, indicating the flexibility (laxity) of the joints, thereafter all unit vectors became more organized as the foot stiffened. The rotation axes between the given pair were non-parallel in at least in one plane at a given instant. Inflection of the axis orientation can be seen in most of profiles at approximately 25% and 65%, and 80%.

The correlation between the changes in helical axes directions and muscle and ground reaction force profiles are clearly seen in this study. Joints were loose during weight acceptance without plantarflexor muscle activity and with most of the ground reaction forces concentrated in the hindfoot. Inflections of the axes orientations at 25%, and 65% seem to be a delayed response to the first TS and TP activations at 20% and second TP activation at 60%, respectively. The inflection at 80% (especially in the cubonavicular joint) corresponded to the second ground reaction force peaks and peaks of all muscles except for the TA at 80%.

The foot is under considerable loading in late stance due to high ground reaction and muscle forces, resulting in a change of joint axes orientations resulting in increased geometrical constraint. Even with this increased constraint, some joints had notable excursions [2].

CONCLUSIONS

The orientations of the helical axes were seen to correspond well to externally applied forces.

Joint stiffness is controlled by the combined effects of muscle, and ground reaction forces, ligaments, and anatomical/geometrical constraints. It appears that the foot is utilizing all of the above effectively, allowing for the gradual change and/or maintenance of stiffness during different phases of stance.

The current data partially support the idea of a transverse tarsal joint locking mechanism. The talonavicular and calcaneocuboid joint axes remained non-parallel after foot flat as the stiffness of the foot increased, matching the classic description as presented in the literature [1]. However, prior to this stiffening stage, joint axes were not parallel to each other; they were rather randomly oriented due to the minimal constraints posed at the joints.

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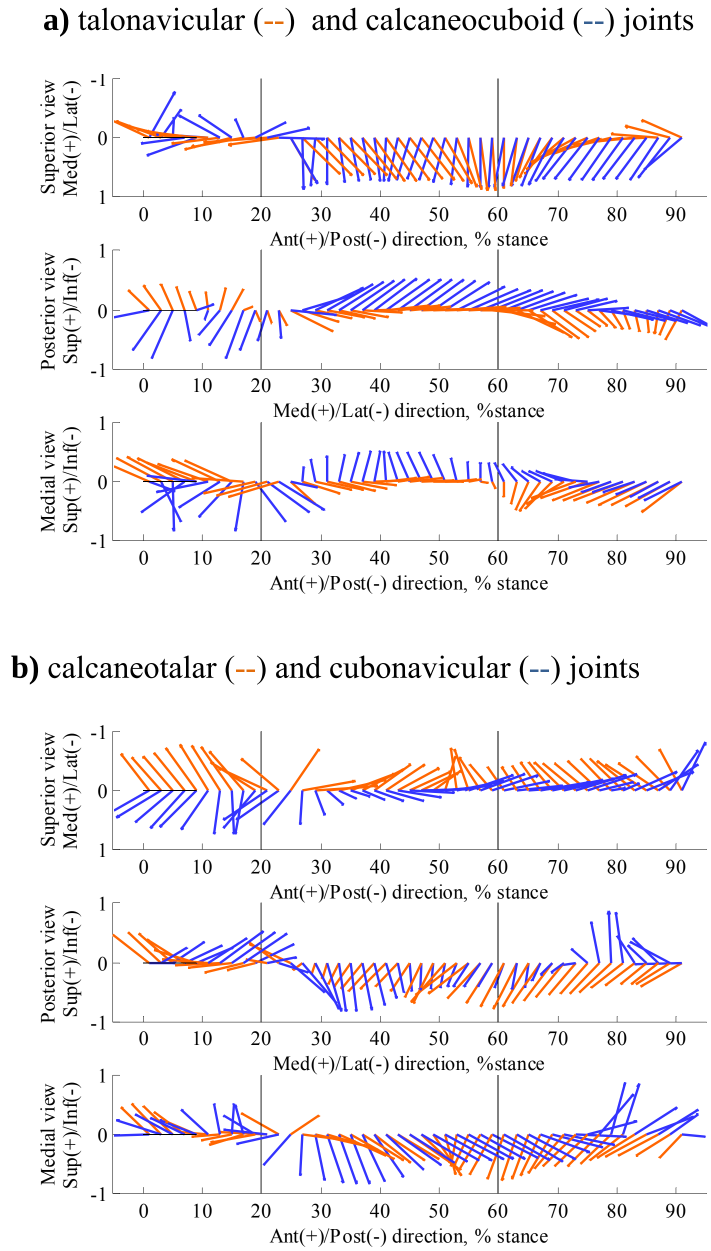

Figure 1: Progression of helical axis orientation during stance phase of gait for a) transverse tarsal joints, and b) calcaneotalar and cubonavicular joints. Mean profiles from ten specimens are shown. From the top to bottom in each group, superior, posterior, and medial views for a left foot is shown with the same scaling in all axes. Approximate muscle activations are indicated by the vertical lines at 20% for the TS and first TP activation, and at 60% for the second TP activation. Vertical ground reaction force and all muscles except for the TA peaked at 80% (in agreement with clinical data). Foot flat was observed between approximately 35~65% of stance.

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