

AN OBJECTIVE EVALUATION OF SEGMENTED FOOT MODELS USING A ROBOTIC DYNAMIC ACTIVITY SIMULATOR

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INTRODUCTION

Over the last several years investigators have proposed methods for measuring the motions of different regions of the foot to quantitatively assess foot function in health and disease. These methods consider the foot as a system of segments, whereby the tibia (TIB), hindfoot (HF), and forefoot (FF) are treated as separate rigid bodies that move relative to each other. The goal of the current study was to objectively verify the utility of this approach by comparing the multi-segment kinematic data calculated from skin- and bone-mounted markers. By using a high fidelity cadaveric Robotic Dynamic Activity Simulator:RDAS (Hoskins, 2006), comparisons were conducted under five simulated neuromuscular conditions.

METHODS AND PROCEDURES

A total of ten normal fresh frozen cadaver extremities (5M/5F, 59.2 ± 14.2 years) were evaluated. The RDAS was employed to conduct dynamic simulations of the stance of gait at 1/20th the velocity of typical walking. For each specimen, the baseline *Normal* simulation was achieved by adjusting sagittal plane tibia kinematics and six muscle actuations (Tibialis Anterior:TA, Tibialis Posterior:TP, Peroneus longus, Flexor hallucis longus, Flexor digitorum longus, Triceps Surae) until target ground reaction forces were attained. Four additional conditions simulating common neuromuscular pathologies were examined by altering specified muscle activation patterns while

holding other simulation parameters at normal values: *NoTP* (no TP activation during stance phase), and three hyperactive conditions set at 75% of the normal peak output through out stance phase: *ExtTA* (hyperactive TA), *ExtTP* (hyperactive TP), and *ExtTATP* (hyperactive TA and TP).

A seven-camera passive marker 3D photogrammetry system (Motion Analysis Corporation, Santa Rosa, CA) was employed to capture marker motion at 100 Hz with a typical 3D reconstruction residual of 0.3 mm. A three-segment foot and ankle model (TIB, HF, FF) was developed based on Buczek et al. (2003). The joint angles were obtained by taking ZYX Cardan decomposition of the distal segment with respect to the proximal segment.

The first marker configuration (referred to as “REAL markers”) utilized external skin markers (3/8” diameter) adhered with cyanoacrylate on the following 9 landmarks: medial and lateral malleoli; medial, posterior, and lateral calcaneus; bases and heads of Metatarsals 1 and 5, respectively.

Following successful collection of 15 trials (5 conditions × 3 repetitions each) with REAL markers, every bone of the foot except for the phalanges was instrumented with marker clusters (four 1/8”-dia. markers on carbonfiber rods), and another 15 trials were collected. The second marker configuration (referred to as “VIRTUAL markers”) was then calculated as the virtual skin markers from the collected motion of bone-mounted

markers and fixed local vectors in respective bones. The local vectors were determined by merging the static data with skin and bone markers. The static trials were extracted from normal walking trials when the tibia was aligned with vertical axis to reflect muscle action.

A General Linear Model ANOVA (Minitab, State College, PA) was used to examine the significance of interaction term “Condition × Marker type” with $\alpha=0.05$, and followed by post-hoc comparisons with Bonferroni correction ($\alpha=0.05$).

RESULTS

As listed in Table 1, significant Condition × Marker type interaction term was found in the Int/Ext rotation profiles of all joints. Only the hyperactive conditions resulted in significantly different means. Representative results for *ExtTA* are shown in Figure 1. The maximum difference between the REAL and VIRTUAL data in significantly different joint angles was approximately 2.5 degrees.

INT/EXT Axis	ANOVA	Bonferroni Group Comparison for REAL v.s. VIRTUAL				
		Normal	NoTP	ExtTA	ExtTP	ExtTATP
HF_TIB	0.000	0.280	1.000	0.000	0.100	0.000
FF_TIB	0.000	0.090	1.000	0.000	1.000	0.000
FF_HF	0.004	1.000	1.000	1.000	0.020	1.000

Table 1: Results of ANOVA and Bonferroni Comparisons. Significance level was set at $p<0.05$.

DISCUSSION

Based upon the current results, all joint angles calculated from REAL or VIRTUAL markers under *Normal* and *NoTP* resulted in statistically similar measured angles. Hyperactive conditions resulted in significantly different measurements but only in Int/Ext rotation angles. One possible explanation is that the foot was mostly constrained by the floor during 0~90% of stance, allowing transverse rotation of bones due to the imbalance caused by hyperactive muscle force, but constraining abnormal motions in the sagittal and frontal planes.

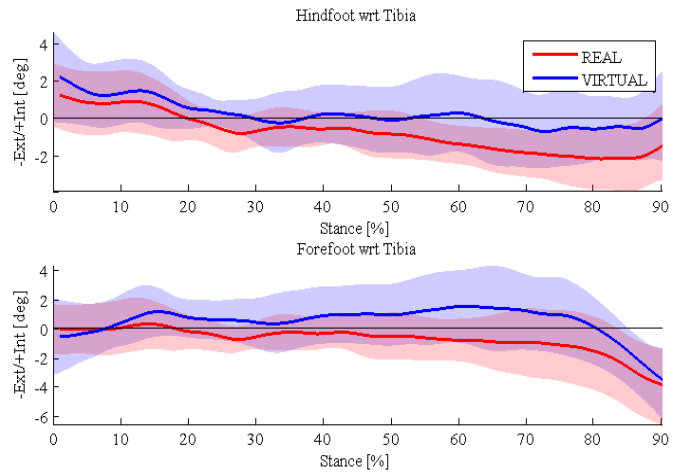


Figure 1: Int/Ext rotation of left HF_TIB and FF_TIB joints under ExtTA condition. Each shade represents \pm sd.

Overall, the REAL and VIRTUAL marker data agreed well (within 2.5° mean difference even in Int/Ext rotation). This good agreement between the REAL and VIRTUAL marker data may be due to the scaled speed (1/20) of the simulation. Reduced velocity would tend to minimize extraneous marker jiggle and skin motion artefact. On the other hand the reduced velocity of the simulations would tend to amplify viscoelastic effects, allowing the soft tissues to creep and bones to move more than at normal velocity.

SUMMARY

The current study suggests that a three segment foot model based on external skin markers provides a reliable means of assessing overall internal skeletal motion in the sagittal and frontal planes, although detectable inaccuracies exist in the transverse plane (Int/Ext rotation).

REFERENCES

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