DIRECT MEASURES OF PROSTHESIS INERTIA INFLUENCE JOINT KINETICS DURING SWING

[1]Jeremy D. Smith, [1]Abbie E. Ferris, [1]Gary D. Heise, [2]Richard N. Hinrichs, and [3]Philip E. Martin

[1]School of Sport & Exercise Science, University of Northern Colorado, Greeley, CO
[2]Kinesiology Program, Arizona State University, Phoenix, AZ
[3]Department of Kinesiology, Iowa State University, Ames, IA
Email: jeremy.smith@unco.edu; website: http://www.unco.edu/nhs/ses/

INTRODUCTION

Modern lower limb prostheses are fabricated using lightweight materials resulting in prosthetic limbs that are often much lighter than the limbs they replace. One consequence of this fabrication practice is that an inertial asymmetry between the prosthetic limb and intact limb is created. Compared with a typical intact shank and foot, the mass of a below-knee prosthesis and residual limb is approximately 35% less and has a center of mass located approximately 35% closer to the knee joint [1]. The lower and more proximally distributed mass produce a much lower (~60%) moment of inertia relative to the knee joint compared to the intact shank and foot. Although Miller [2] previously suggested that using intact inertia estimates for the prosthetic limb have little effect on joint kinetic estimates, her comparisons were limited to resultant joint moments during stance, where the ground reaction force strongly influences lower extremity moments. During swing, it is unclear whether lower inertial properties of the prosthesis influence resultant joint moments. Thus, the purpose of this study was to contrast the effects of using direct measures of the prosthesis inertia versus using estimates of intact limb inertial properties on ankle, knee, and hip resultant joint moments during walking in unilateral, transtibial amputees.

METHODS

Six amputees (5 males; 1 female; age = 46±16 yrs, mass = 104.7±9.7, height = 1.8±0.1) participated in this study. Five of six amputees had amputations due to traumatic injuries with the other due to congenital bone disease. All amputees used a lock and pin type suspension system and a dynamic elastic response prosthetic foot. Participant recruitment focused on amputees who were fully ambulatory, had used a prosthesis for at least one year, and maintained some degree of physical activity. The protocol was reviewed and approved by the University's Institutional Review Board. Informed consent was obtained from each participant.

Participants completed five overground walking trials at preferred speed ($1.2 \pm 0.1\ m \cdot s^{-1}$) while ground reaction forces (480 Hz) from two force plates and motion data (60 Hz) from a six camera motion analysis system were collected. Retro-reflective markers were placed bilaterally on the greater trochanter, lateral femoral condyle, lateral malleolus, lateral aspect of the heel, and the head of the fifth metatarsal prior to data collection. A three-segment sagittal plane inverse dynamics model was used to compute resultant joint forces and moments. Segment inertial properties for intact body segments were predicted using regression equations from de Leva [3]. Inertial properties of the prosthesis and residual limb were measured directly using oscillation and reaction board techniques [1]. To determine the effect that inertia values (direct measures vs. estimates based on intact segment inertia properties) had on joint moments, a single factor, repeated measures MANOVA was used with a Bonferroni adjustment. Peak resultant joint moments at the ankle, knee, and hip during stance and swing served as primary dependent variables. Significance differences were considered at $p < .05$.

RESULTS

Averaged across participants, prosthetic side mass was 39% less, moment of inertia about a transverse axis through the knee was 52% less, and the center of mass location was 24% closer to the knee compared with values for the intact leg. Peak resultant knee and hip joint moments (Figure 1) during swing were lower when direct measures of prosthesis inertial were used in inverse dynamics assessments compared with use of predicted inertial properties for intact anatomy. Effect sizes suggest these differences were large (Table 1). During stance, several significant differences in moment magnitudes were observed at the ankle and knee (Table 1), but effect sizes for all differences during stance were less than or equal to 0.1.

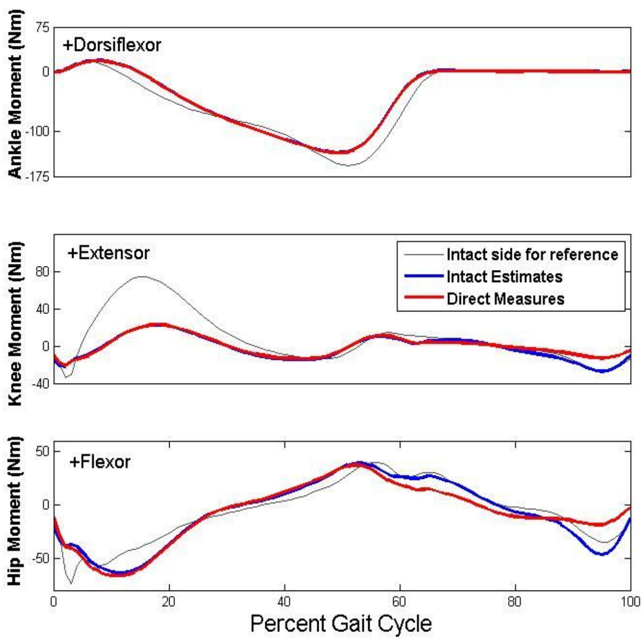

Figure 1: Resultant joint moments about a transverse axis through the ankle, knee, and hip. Foot contacts occur at 0 and 100%, whereas toe-off occurs at ~60% of the gait cycle.

Table 1: Peak resultant joint moments averaged across subjects and statistical comparisons between the two inertial models.

Variable	Inertial Model: Direct Measures	Inertial Model: Intact Estimates	*p* value	Cohen's d (Effect Size)
Ankle				
Early Stance	20.0(5.6)	20.5(5.6)	0.001	0.10
Terminal Stance	-141.5(37.4)	-140.9(37.3)	<0.001	0.01
Knee				
Mid-Stance	27.0(31.8)	26.1(31.4)	0.053	0.03
Terminal Stance	-21.4(21.9)	-22.3(21.2)	0.033	0.04
Initial Swing	4.4(3.3)	8.7(3.4)	0.015	1.26
Terminal Swing	-13.7(3.)	-28.4(4.9)	0.001	3.64
Hip				
Initial Swing	20.6(13.0)	32.7(11.4)	0.002	1.00
Terminal Swing	-19.8(5.2)	-48.4(9.4)	<0.001	3.78

Notes. Mean data are presented as mean(SD).

DISCUSSION

In absolute terms, the largest magnitude difference during stance was less than 1 N·m, which is slightly less than the average moment magnitude difference of 3 N·m Miller [2] reported for the stance phase of running. Moment magnitudes during running are generally larger than during walking, which likely contributed to larger differences reported by Miller. However, Miller concluded that even the 3 N·m difference was unlikely to influence overall conclusions of the study. Thus, although we observed significant differences during stance, it is unlikely these differences have physiological relevance.

In the absence of ground reaction force influences during swing, the motion of the limb is more dependent on system inertia and segment interactions. When using intact segment inertial properties in the model, resultant joint moment magnitudes at the hip and knee were artificially high. This illustrates a limitation of interpreting resultant joint moments as an indicator of muscular demand during swing. Using intact segment inertial properties to model the prosthetic side during swing would suggest a higher muscular demand to control the limb that was actually more comparable to the control utilized in the intact limb. Thus, one might be lead to interpret that prosthetic side joint function during swing as similar to that of an intact leg.

In conclusion, when focusing on swing phase mechanics, researchers should use direct measures of prosthesis inertia in inverse dynamics models, but during stance the inertia parameters seem to have little impact on study outcomes.

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