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SENSITIVITY ANALYSIS OF A SUBJECT-SPECIFIC GAIT MODEL TO JOINT AND SEGMENT PARAMETERS USING LIFEMOD™ AS A KINEMATIC MODELING TOOL

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SUMMARY

This study systematically modified lower extremity joint degrees of freedom and segment mass parameters to quantify the sensitivity of an inverse dynamics kinematic model generated using LifeMOD™.

INTRODUCTION

There is an inherent challenge in evaluating the accuracy of a kinematic model of the human body. It is limited by error from marker-based measures of position, as representations body segment kinematics during movement, and also by its sensitivity to user-controlled assumptions about segment parameters and model complexity [1,2,3]. Although subject-specific model simulation studies have allowed systematic testing of hypotheses to elucidate physiological phenomena that are difficult to test via experimentation, the sensitivity of results to specific user-controlled parameters remain crucial to interpretation. Often, these processes are poorly documented or overlooked [1,2,3,4]. The purpose of this study was to determine the sensitivity user-controlled parameters on ground reaction forces (GRF) simulated during gait using a 3D kinematic model of the body (LifeMOD™, Lifemodeler, San Clemente, CA). Sensitivity of results to user-controlled parameters was assessed by comparing experimentally measured GRFs to GRFs calculated using different levels of model complexity (e.g. joint degrees of freedom (DOF)) and subject-specific body segment parameter estimation.

METHODS

Kinematic and kinetic data during gait (N=1, female, 65.45kg, 1.7m) were captured using a motion analysis system (120 Hz, Vicon Motion System, Inc. Centennial, CO), and two force plates (1,200 Hz, AMTI, Boston, MA). Kinematic data were imported into LifeMOD™, a model was created, and inverse dynamics analysis was performed using built-in LifeMOD™ routines that scaled the model and calculated segment trajectories based on the plug-in gait marker data. During the model building routine, knee and ankle joint DOF were systematically modified to create 8 models (Table 1) while the hip and other upper extremity joints were passive 3DOF joints. Segment center of mass displacements were exported to MATLAB® and were smoothed using Woltring's Generalized Cross-Variance natural B-Spline filter with a cutoff frequency of 6Hz [5].

To test sensitivity of each model to segment mass parameters, the sum of each segment's mass-acceleration terms were computed using GeBOD [6] segment parameters of LifeMOD™ and body segment mass parameters described by Zatsiorsky et al. [7]. Figure 1 outlines the processing procedures.

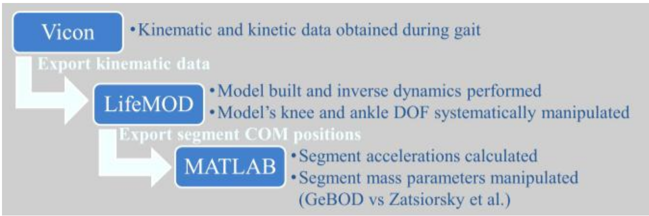

Figure 1: Summary of processing procedures

The definition $\sum F = \sum_{j=1}^{k} m_j a_j$ (where k is the number of body segments) was used with measured ground reaction force (GRF) and bodyweight (BW) to compare the measured sum of forces ($\sum F_{exp}$) to the sum of the model's mass-acceleration terms ($\sum ma$) at each time sample for each segment in the vertical and horizontal directions. The performance index used to quantify agreement between measured and calculated GRFs in each direction was root mean square error (RMSe) $RMSe = \sqrt{\sum_{i=1}^{N} \left|\sum F_i - \sum ma_i\right|^2 / N}$ (where N is the number of samples) during a portion of the gait cycle from estimated single limb stance to second double-limb support through second single limb stance. The RMSe was normalized to the subject's BW [1].

RESULTS AND DISCUSSION

The patterns of the $\sum ma$ were similar between the two mass parameter databases and followed that of the measured $\sum F_{exp}$ (Figure 2). However, the magnitudes of the $\sum ma$ were notably different than that of the $\sum F_{exp}$ during the double stance phase (Figure 2, t=0.5-0.65 s). The peak GRFs measured during this phase were due to the impact force experienced when the left foot contacted the force plate. Therefore, RMSe during the impact phase and non-impact phase were analyzed separately [8].

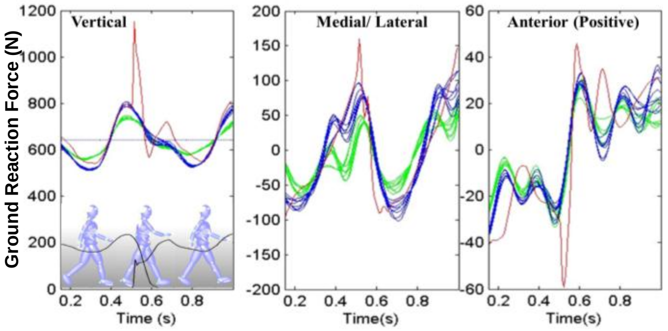

Figure 2: $\sum F_{exp}$ (red) and model- calculated $\sum ma$ for the models using GeBOD (green) [6] and the Zatsiorsky et al. (blue) mass parameters [7]. In the vertical direction, bodyweight was added to the $\sum ma$ to be compared to the measured vertical GRF. Additional illustration of kinematic and kinetic context (not to scale) displayed.

For both body segment parameter databases, the RMSe values were less than 10%BW with exception of RMSe in the vertical direction during the impact phase. The lowest RMSe was in the medio-lateral (ML) direction, followed by the antero-posterior (AP) direction, and vertical (V) direction. Large RMSe values indicated that the kinematic models were unable to successfully simulate the GRFs experienced during the impact phase without implementing model modifications specific to the impact phase [8].

Comparison between two body segment mass parameter databases yielded significantly greater RMSe for the models using GoBOD [6] segment masses than those using Zatsiorsky's [7] (Table 1). These results suggest that body segment parameters influence outcomes of the simulation and must be selected to appropriately fit the subject. Further, using proper body segment geometry has also been known to influence the outcomes of a kinematic model [9].

The model with ML and AP direction DOF at the ankle, and ML DOF at the knee (Table 1, M1) had the lowest RMSe in all directions, particularly during the non-impact phase. These results are consistent with the ankle and knee DOFs previously used in a model to simulate straight-line gait [4]. When DOF were added to the ankle and knee, the RMSe in the AP direction noticeably increased while it did not seem to affect the RMSe in the vertical direction. Although the model with limited DOFs at the ankle and knee (M1) performs well during straight-line walking, its performance in other tasks such as turning-while-walking needs further evaluation.

A major limitation with the model building routine using imported plug-in gait marker data is that, with few foot markers, LifeMOD™ created foot segments to simulate the complex foot-floor interaction. Additionally, the high frequency kinetic foot-floor interaction typically found in gait during impact [10] was not accounted for in the $\sum ma$ of the kinematic model (Figure 2, Table 1) possibly due to the low sampling frequency of the kinematic data. Implementation of kinematic foot-floor model with more foot markers, foot segments, and DOFs to the kinematic model may help predict high frequency foot-floor kinetics [8]. Future work includes systematically modifying the marker weights that LifeMOD™ uses during the inverse dynamics simulation to determine how well segment trajectory matches each marker's trajectory.

CONCLUSIONS

This study documented the start of model calibration for subject-specific modeling using LifeMOD™. Comparison between measured and model kinematically-calculated total GRF in each direction generally corroborated the importance of evaluating model complexity and use of appropriate body segment parameters.

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Table 1: Model definition based on knee and ankle joint degrees of freedom (DOF) and root- mean-square-error (RMSe) normalized to %BW between kinematic model calculated and measured ground reaction force in medio-lateral (ML), antero-posterior (AP), and vertical (V) directions using segment mass parameters provided by GeBOD [6] and Zatsiorsky et al.(Z) [7].

	Knee DOF			Ankle DOF			GeBOD Impact #,^			GeBOD Non-Impact #,^			Z Impact #,^			Z Non-Impact #,^		
Model	**ML**	**AP**	**V**	**ML**	**AP**	**V**	**ML**	**AP**	**V**	**ML**	**AP**	**V**	**ML**	**AP**	**V**	**ML**	**AP**	**V**
M1	x	x		x			3.42	7.82	24.11	2.05	5.36	7.67	1.80	4.73	22.03	1.82	2.91	5.82
M2	x	x	x	x			3.23	9.44	24.09	2.21	7.30	8.34	1.71	6.33	21.72	1.92	5.26	6.71
M3	x	x		x	x		3.29	8.26	24.00	2.21	4.94	7.61	1.80	5.62	21.91	2.01	3.61	5.86
M4	x	x		x		x	3.44	9.30	24.08	2.12	6.48	7.87	1.86	6.31	21.92	1.85	4.78	6.00
M5	x	x		x	x	x	3.24	9.06	24.16	2.29	5.78	8.00	1.79	6.35	22.10	2.12	4.56	6.37
M6	x	x	x	x	x		3.12	8.85	24.02	2.39	6.58	8.53	1.69	5.78	21.91	2.28	4.58	7.20
M7	x	x	x	x		x	3.31	9.60	24.09	2.18	7.29	8.33	1.73	6.7	22.05	1.92	5.42	6.74
M8	x	x	x	x	x	x	3.12	9.39	24.16	2.41	6.59	8.54	1.68	6.58	22.11	2.32	5.04	7.26
Average (Standard Deviation) RMSe							24.09 (0.06)	8.97 (0.63)	3.27 (0.12)	8.11 (0.37)	6.29 (0.86)	2.23 (0.12)	3.27 (0.12)	6.05 (0.65)	24.09 (0.06)	2.23 (0.12)	4.52 (0.86)	8.11 (0.37)

and ^ indicate significant differences between two phases within database and two databases within phase, respectively ($P<0.05$).