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EFFECTS OF DIFFERENT SCALING METHODS ON OPENSIM MODEL FIDELITY

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INTRODUCTION

Methods commonly used in clinical gait analysis [1] are obsolete. Modern methods employ computational techniques such as CAST [2], SVD-based marker clusters [3], and functionally determined joints [4] to help control soft tissue artifact and improve the reliability of gait data. These modern computational methods direct [5] or inverse kinematics[6] approaches determine gait kinematics.

Direct kinematics is a purely mathematical approach to describe motion, and does not use an underlying musculoskeletal model of the human subject. Direct kinematics uses retroreflective marker trajectories to define segment dimension, position and orientation. Joint angles are then determined by computing the transformation between adjacent segments. Direct kinematics is computationally fast, but can cause joints to distract or interpenetrate, or segments to change length because segments are directly defined by noisy marker trajectories. The direct kinematics approach also lacks *direct* extensibility to neuromusculoskeletal modeling and forward simulation tools.

Inverse kinematics (IK) [6] employs a multi-segment model with joints of pre-defined degrees of freedom and fixed segment lengths. IK requires accurate scaling of this multi-segment model to closely represent a tested participant. IK potentially reduces soft tissue artifact by using a weighted least-squares adjustment of the model's generalized coordinates (i.e. joint angles) to minimize the distance between the virtual markers and the experimental marker positions.

A common musculoskeletal modeling platform that uses IK for motion analysis and dynamic simulation of movement has emerged: OpenSim [6]. Implementing dynamic simulations of human motion in OpenSim requires several user-dependent processes such as virtual marker configuration and model scaling. Virtual marker configuration involves the user placing virtual markers onto the model at locations which are intended to replicate experimental markers on the human subject. The effect of this user-dependent virtual marker configuration has been studied using a humanoid robotic [7]. The conclusions were: 1) user-dependent virtual marker configurations result in inaccurate model kinematics, and 2) automated virtual marker registration results in accurate model kinematics.

Model kinematics can also be influenced by the model scaling process, which is also a user-dependent process. Researchers use medical imaging, marker-based regression, and functional methods to scale generic models to subject-specific values. The user must select the markers which determine scale factors, the target bodies and dimensions for scaling. The effect of different scaling methods on model mechanics has not previously been investigated.

Motion analysis model fidelity is commonly assessed using several error metrics. These error metrics are static and dynamic marker fitting error, knee kinematic cross-talk, and pelvic residual forces and moments. The aim of this study is to examine the effect of different virtual marker configuration and model scaling methods on measures of model fidelity.

METHODS

Data were collected at the University of Western Australia with ethics approval. One subject walked at a constant speed (0.75 m/s) on an instrumented split-belt treadmill (Bertec, USA) sampling ground reaction forces at 2000 Hz. An 8-camera Vicon motion analysis system (Vicon, UK) sampled motion data at 100 Hz. Subsequently, both marker and ground reaction force data were filtered using a low-pass zero lag 4th order Butterworth filter with a 6 Hz optimal cut-off frequency that was selected using a custom residual analysis algorithm (MATLAB, USA).

Subjects performed functional trials to determine joint centres and axes for the hip and knee joints [4]. We used OpenSim v2.0.2 and a modified Hamner multi-segment model [9].

Three methods were selected to evaluate the effect of different virtual marker configuration and scaling on gait mechanics. The first approach relied entirely on user-defined anatomically relevant markers (uANAT). The model was scaled using only marker pairs placed over prominent anatomical landmarks. The second scaling method used both anatomical markers and functional joint centres (uFUNC). In both uANAT and uFUNC the virtual markers were posited by the user to match the experimental setup. The third method used the same combination of functional and anatomical markers as used in uFUNC to scale the model, but used an automated registration procedure to set the initial model pose and virtual marker positions (aREG). The automated registration procedure involved determining a set of joint angles and virtual marker positions using direct kinematics and registering these angles and positions to a scaled OpenSim model through MATLAB algorithms. To account for errors in the direct kinematic values, virtual markers were permitted to move to best fit (in a least squares sense) the experimental data.

RESULTS AND DISCUSSION

Static RMS static and dynamic marker error increased from uANAT to uFUNC to aREG methods (Table 1). Knee flexion and adduction curves during stance were influenced by the scaling method (Figures 1 and 2). None of the scaling methods produced strong correlations between knee flexion and adduction. Regardless of the scaling method the joint range of motion and absolute values were within reported physiologic boundaries. The vertical, medial/lateral and anterior/posterior pelvic residual forces remained stable across scaling methods, while the pelvic tilt, list and rotation residual moments varied slightly between methods but did not substantially decrease using aREG.

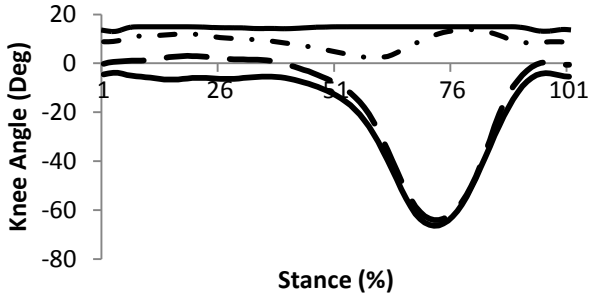

Figure 1: Right knee extension and adduction derived from 5 averaged gait cycles using uANAT and uFUNC scaling methods. uANAT knee extension (solid) and adduction (long-short dash). uFUNC knee extension (long dash) and adduction (bullet).

All three scaling methods resulted in error metrics within limits recommended by OpenSim's developers [9]. Unfortunately, none of these individual error metrics are sufficient indicators of model fidelity. For example, low marker fitting error is not indicative of accurate model kinematics [7]. As well, pelvic residuals can be reduced through optimization [10], but may alter model kinematics such they substantially deviate from experimental data. An automated registration procedure combined with functional scaling is advantageous because it is a systematic approach to remove the user-dependent process of initial model pose and virtual marker configuration. It should be noted that the automated registration method cannot control for errors in experimental data collection, such as human operator marker misplacement, inaccurate instrument calibration, or systematic errors in motion capture.

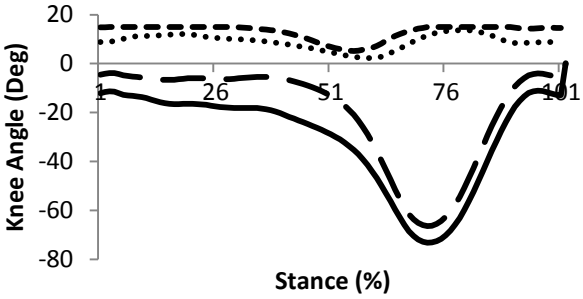

Figure 2: Right knee extension and adduction derived from 5 gait averaged cycles using uANAT and aREG scaling methods. uANAT knee extension (long dash) and adduction (bullet). aREG knee extension (solid) and adduction (short dash).

CONCLUSIONS

The aREG method uses a validated and automated method to calibrate OpenSim models providing a systematic approach to configure virtual markers and establish model pose. Our preliminary results suggest that the incorporation of aREG does not necessarily result in improvements in model fidelity assessed by standard error metrics. Expansion of this study to a larger data set is planned.

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Table 1: Summary of model criteria.

Scale Method	RMS Static Marker Error (m)	RMS Dynamic Marker Error (m)	Mean ± Std Vertical Pelvic Residual Force (N)	Mean ± Std Pelvic Tilt Residual Moment (Nm)
uANAT	0.0232	0.0206	5.89 ± 32.53	31.04 ± 21.13
uFUNC	0.0272	0.0305	5.87 ± 33.58	-24.66 ± 21.27
aREG	NA*	0.0325	5.87 ± 34.26	-27.12 ± 21.43

*Markers were not involved in the objective function in the IK fit for the static trial.