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Automated marker registration improves OpenSim joint angle and moment estimates of a humanoid robot.

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INTRODUCTION

Inverse kinematics (IK) [1] requires accurate scaling of a 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. Since the joint angles are dependent on virtual marker‘s tracking the positions of experimental markers, the virtual markers need to be correctly positioned in the model's local segment coordinate systems. We define this as marker registration. With regard to performing IK within OpenSim [2], the operator manually, and subjectively, registers the virtual markers on the model segments to match the experimental marker locations. However, errors in this registration process likely cause errors in the joint motion and moments estimated by IK.

The purpose of this paper was to assess the accuracy of joint motion and moments estimated from IK using 'operator' registration and 'automated' registration of virtual markers. To achieve this we conducted a gait analysis on a bipedal humanoid robot, with known parameters. A geometrically-accurate model of the robot was used to evaluate the effect of poor marker registration on the model's joint angle estimates and marker tracking.

METHODS

We performed a motion capture experiment on a fully actuated bipedal walking humanoid robot. This robot is subject to patent and freedom of information restrictions; therefore, only differences between the onboard sensor and model results are reported. The technical specifications of the robot were used to build a geometrical replica in OpenSim having 14 degrees of freedom (Dof); Hip flex/ext, abd/add and int/ext rotation; Knee flex/ext; and Ankle flex/ext, and inv/ever.

An eight-camera Vicon system (Oxford Metrics, Oxford, UK) and 2 Bertec forceplates (Bertec, Columbus, OH) were used to collect motion data (200Hz) and ground reaction forces (GRFs) (2000Hz), respectively. Marker and GRF data were filtered using a 4th order low pass Butterworth filter with a cut-off frequency of 6Hz. Twenty-seven retro-reflective markers were placed on the robot; three on each foot, shank and thigh segments, four on the pelvis, one on each shoulder and three on the head. A static trial and 8 strides of right foot forceplate contact were collected and used for analysis.

Five experienced OpenSim testers used the OpenSim 2.4 GUI to register the virtual markers from pictures showing the experimental marker locations. Using the static pose data, a single frame IK solution established the best fit between model joint configuration and virtual marker placement. These five tester models (TESTER) are representative of the manual registration method.

Two additional models were created using an automated registration method. The automated method constrained model joint angles to calculated angles from the static trial data. Using direct kinematics to calculate and constrain the model angles prior to single frame IK, the best-fit between the static trial and model was achieved by allowing re-positioning of only the virtual markers.

The first of these automated techniques constrained the model using the kinematics derived from the robot's onboard sensors during the experimental static trial (ROBOT). The second model used marker clusters and joint axes positions to calculate joint angles, analogous to the CAST [3] technique.

All seven models (Tester (5), Robot, CAST) were used in OpenSim 2.4 to run IK analysis of the selected strides. Joint kinematics were normalized from midswing to midswing. Joint moments were normalized to single right foot stance. Root mean square error (RMSE) was calculated between the robot's onboard sensors and the IK and ID from each of the seven models (Tester(5), Robot, CAST). Two ANOVA's were performed, the first was a between group ANOVA (ROBOT, CAST, TESTER) comparing RMSE values across each DoF between groups, with Tukey's post-hoc assessment. The second ANOVA was performed on the TESTER group to assess inter-tester difference. RMSE values between the virtual and experimental marker positions were also calculated with paired-t-tests to compare marker error between groups (ROBOT, CAST, TESTER).

RESULTS AND DISCUSSION

Tester models resulted in greater joint angle and moment errors compared to automated registration methods across all DoF's (ROBOT and CAST, $p<0.05$) and had significant inter-tester differences for all DoF's ($p<0.05$, Table 1). The ROBOT model estimated joint angle and moments most accurately with the lowest RMSE across all DoFs (Figure 1). The CAST model was an improvement over Tester models showing significantly lower ($p<0.05$) error across all DoF's

Manual registration of virtual marker positions was shown to be a significant source of error in joint angle and joint moment calculations. Although automated registration reduced this source of error, the method was dependent on the accuracy and repeatability of joint angle calculation during the static trial. This distinguishes the differences between ROBOT and CAST results. CAST angle calculation errors from misplacement of marker clusters on the pelvis and foot resulted in joint angle and moment errors throughout the dynamic trials. The use of marker placement rigs [4] and functional techniques [5] are still necessary to improve accuracy and repeatability of static joint angle calculations.

Kinematic differences exist despite little to no difference in marker tracking errors between models (Table 1). As an isolated measure, low RMSE marker error should not be used as a surrogate measure of accurately modeled joint kinematics during dynamic tasks.

CONCLUSIONS

Inaccurate manual registration of virtual markers was seen as an additional source of error when using the inverse kinematic method. The described automated marker registration methods improved estimates of joint angles and moments when compared to the manual methods. However this is dependent on the accuracy of the joint angles calculated during the static pose. CAST modeling of the robot showed that the automated method only addressed errors caused by manual marker registration and not experimental marker placement.

Methods which improve the repeatability of experimental marker placement should be employed, along with automated marker registration, to improve IK calculations in human subjects. Error between experimental and virtual marker positions should not be used to assess the accuracy of joint kinematics derived from IK.

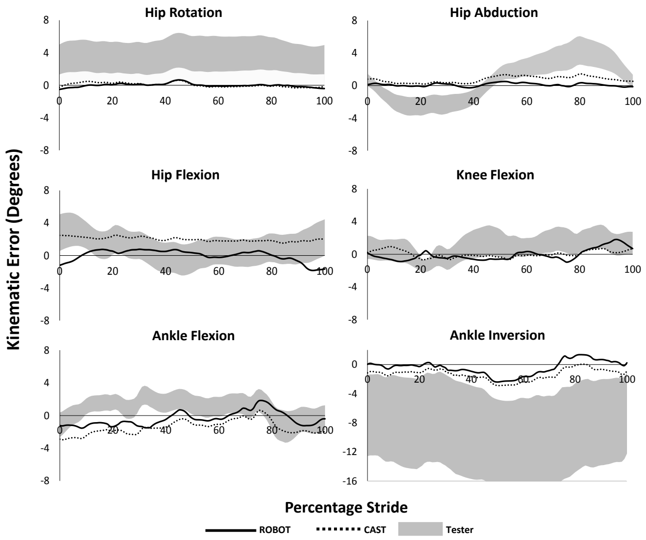

Figure 1: Typical stride error between experimental and ROBOT, CAST and Tester group data respectively.

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Table 1: Root Mean Square Errors (RMSE) between experimental robot and Tester, CAST and ROBOT models, respectively. Joint angles (degrees), Joint moments (Nm) and distance between experimental and virtual markers (mm) are presented.

RMSE	Robot	CAST	Tester
Angle (degrees)			
Hip Rotation	0.27 ± 0.09	0.25 ± 0.09	3.52 ± 1.92
Hip Adduction	0.25 ± 0.03	0.71 ± 0.07	2.43 ± 1.00
Hip Flexion	0.55 ± 0.21	1.84 ± 0.14	2.08 ± 0.56
Knee Flexion	0.80 ± 0.43	0.81 ± 0.45	2.07 ± 0.57
Ankle Flexion	1.19 ± 0.54	1.72 ± 0.21	1.99 ± 0.74
Ankle Inversion	0.97 ± 0.18	1.20 ± 0.30	8.39 ± 6.13
Moment (Nm)			
Hip Rotation	0.06 ± 0.03	1.15 ± 0.08	1.69 ± 0.83
Hip Adduction	0.18 ± 0.14	0.83 ± 0.43	2.23 ± 0.85
Hip Flexion	0.31 ± 0.15	0.30 ± 0.24	7.00 ± 3.05
Knee Flexion	0.20 ± 0.23	0.45 ± 0.19	1.49 ± 0.65
Ankle Flexion	0.32 ± 0.28	1.02 ± 0.35	3.28 ± 1.83
Ankle Inversion	0.66 ± 0.22	1.53 ± 0.34	3.92 ± 3.45
Marker Distance (mm)	0.031 ± 0.11	0.035 ± 0.11	0.035 ± 0.10

[a] CAST significantly different to ROBOT ($p<0.05$)
[b] Tester significantly different to ROBOT ($p<0.05$)
[c] Tester significantly different to CAST ($p<0.05$)
[d] Inter-Tester significantly differences ($p<0.05$)