35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Study of Variation in Human Upper Body Parameters and Motion for Use in Robotics Based Simulation

Derek J. Lura, Stephanie L. Carey, Rajiv V. Dubey, *Member, IEEE*

Abstract— **This paper reviews the variations in human upper body motion of subjects completing activities of daily living. This study was completed to serve as a reference to evaluate the quality of simulated of human motion. In this paper we define the variation in motion as the variation in subjects' parameters (link lengths), joint angles, and hand positions, for a given task. All of these variations are related by forward kinematic equations. Motion data from eight healthy right hand dominant adults performing three activities of daily living (brushing hair, drinking from a cup, and opening a door) were collected using an eight camera Vicon motion analysis system. Subject parameters were calculated using relative positions of functional joint center locations between segments. Joint angles were calculated by Euler angle rotations between body segments. Hand position was defined as the origin of the hand frame relative to the pelvis frame.**

The variance of recorded human motion was analyzed based on the standard deviations of subject parameters, joint angles, and hand positions. Variances in joint angles were found to be similar in magnitude to root mean squared error of kinematics based motion simulation. To evaluate the relative variance, the forward kinematic solutions of the trials were found after removing subject parameter variance and reducing joint angle variance. The variance in the forward kinematic solution was then compared to the recorded hand position variance. Reductions in subject parameter and joint angle variance produced a proportionally much smaller reduction in the calculated hand position variance. Using the average instead of individual subject parameters had only a small impact on hand position variance. Modifying joint angles to reduce variance had a greater impact on the calculated hand position variance than using average subject parameters, but was still a relatively small change. Future work will focus on using these results to create formalized procedures for quantifying the human likeness of artificial human motions, to serve as a basis for performance comparison between different methods.

I. INTRODUCTION

Developing a human like inverse kinematic solution for an upper body model is difficult for a variety of reasons. The upper body is a highly redundant system, resulting in an infinite number of potential solutions to the direct inverse kinematics. Each joint of the human body has a different range of motion. And there is a wide range of variability between persons. To investigate the motion of the human body it is necessary to simplify the geometry and kinematics. The robotic human body model (RHBM) used in this study is a bilateral upper body model with 25 revolute degrees of freedom (DoF) [1]. The investigations of various methods for solving the inverse kinematics of the RHBM have been tested [2]. These methods, used in previous studies by the authors [2-4], are based on the manipulator Jacobian which represents the mapping between joint angles and end effector velocities. Similar methods have been used to optimize the inverse kinematics of redundant manipulators [5-10], and have been used to avoid obstacles, joint limits, velocity limits, and minimize jerk. Recent studies have also proposed various methods for optimizing the pose of the upper arm, analyzing the arm as a 7 degree of freedom system and optimizing the swivel and angle to resolve the redundancy [11, 12]. Zacharias et al. have optimized the pose of a robot with two 7 degree of freedom arms based on a series of ergonomic conditions [13]. The forward and inverse dynamics of the human musculoskeletal system has been analyzed by several research groups [14-16]. Despite the wide variety of research investigating methods to produce humanlike robotic motions, there has been little effort focused on how best to define and evaluate the quality of simulated human motion. A good deal of research has been done on the perception of human motion [17] and factors that impact it [18-20], but these studies often do not consider the task resolving redundant kinematics of the body. As a result it is difficult to translate the knowledge from these studies into algorithms for creating or analyzing the performance of artificial motion algorithms.

This paper focuses on analyzing variance in subjects performing activities of daily living in terms of the standard deviation of the subject parameters, joint angles, and hand positions, as shown in Fig. 1. This method was selected because it is similar to the root mean squared error methods used by the authors to evaluate the performance of motion simulations in previous studies. While the root mean squared error allows for a direct quantitative comparison of methods, the values of the error did not have a qualitative reference. This allowed the authors to determine which algorithms were better than others, but the practical significance of subsequent decreases in error was unknown. It was therefore difficult to tell which algorithms produced sufficiently accurate results. Previous studies have shown that the weighted least norm solution with joint limit criteria [3] which resolves redundancy by controlling the relative rate of each joint based on anatomical joint limits, and the gradient projection

---

*This research and development project was conducted by University of South Florida and is made possible by a research grant that was awarded and administered by the U.S. Army Medical Research & Materiel Command (USAMRMC) and the Telemedicine & Advanced Technology Research Center (TATRC), at Fort Detrick, MD, under Contract Number: W81XWH-10-1-0601.The views, opinions and/or findings contained in this publication are those of the authors and do not necessarily reflect the views of the Department of Defense and should not be construed as an official DoD/Army position, policy or decision unless so designated by other documentation. No official endorsement should be made.

D. J. Lura, S. L. Carey and R. V. Dubey are with the Center for Assistive, Rehabilitation and Robotics Technologies (CARRT), at the University of South Florida (USF), Tampa, FL, 33620. (phone: 813-974-9651; e-mail: dlura@mail.usf.edu).

978-1-4577-0216-7/13/$26.00 ©2013 IEEE

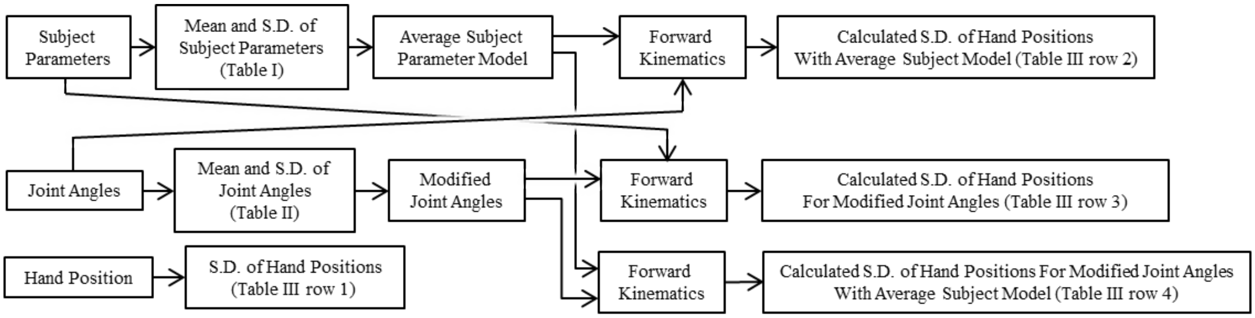

Figure 1. Diagram of Study Flow

method with probability density criteria [4] which uses the null space of the manipulator to optimize the joint angle probability relative to recorded data, both produce reasonably accurate predictions of upper body inverse kinematics. The difference in error between these methods and others may be small enough that other factors, including complexity and computation time, are more important than their accuracy. The goal of this paper is to refine the quantitative methods for determining humanlike motion so that better comparisons between methods for simulating human motions can be made. This goal can be achieved by first establishing a normal range of variation, based on recorded subject data. Simulated motion that is within this normal range of variation can be considered acceptable. Secondly a priority of constraint can be established by the relative form of variation. For instance, if a task exhibits a large variation in hand position then hand position should not be tightly constrained in simulation. Conversely a task may have a large variance in joint angles, but a small variance in hand position, in this case the task should have a tightly constrained hand position.

II. METHODS

This study uses data collected from 8 healthy adult subjects. All procedures were reviewed and approved by the University of South Florida Institutional Review Board, and informed consent was received from each subject before they participated. Motion data were collected using an 8 camera Vicon (OMG plc, Oxford, UK) motion analysis system. Subject specific Robotic Human Body Models (RHBMs) were created based on segment properties calculated from the motion data [1], using the relative position of the functional center of rotation of each joint and imposing the rigid body constraint. Subjects completed a series of range of motion tasks, and activities of daily living. For brevity and to allow for a greater depth of analysis, only the unilateral tasks such as brushing hair, drinking from a cup, and opening a door for the right handed subjects were included. Future work will analyze the motions of the bilateral tasks and include data from left hand dominant subjects.

The primary issue addressed in the paper is the variation in performance of a task. Since a human performer will not be able to recreate the same performance twice and no two people will be able to perform the identical motion, the variations in motion within subjects and between subjects should be evaluated. This study considered three factors of variation, subject parameters (segment geometry and length as calculated from functional joint center locations), joint angles, and hand positions. These factors are interdependent in human motion as defined by the forward kinematic solution. To evaluate the relative impact on each, the subject parameters and joint angles were normalized and forward kinematics were used to find the modified hand positions. The change in variation of the normalized motions was then used to assess the relative impact of each factor.

A. Variation in Subject Parameters:

The mean and standard deviation of the subject parameters were calculated. The mean subject parameters were then used to create an artificial average subject model. The forward kinematic solution of the average subject model and the recorded joint angles were used to find the hand position for comparison to recorded hand position variance and joint angle variance.

B. Variation in Joint Angles:

All trials were normalized to percent of task completion to decrease the impact of time variations. Then the average joint angles were found as functions of the percentage of task completion. The variation in joint angle was quantified by the root mean squared difference, or standard deviation between the recorded motions and the average motion. For each trial the mean of the difference between the recorded joint angles and the average joint angles motion was calculated and subtracted from the joint angle vector, as given in Equation 1 where $\theta_{modified}$, $\theta_{original}$, $\theta_{average}$ are 1 by 100 vectors of the modified, recorded, and average angles of a joint normalized to percent of tasks completion.

$$\theta_{modified} = \theta_{original} - mean(\theta_{original} - \theta_{average}) \quad (1)$$

This effectively removes an ideal offset between the mean joint angle, and trial joint angles for each trial. These new joint angles are referred to hereafter as the modified joint angles. The standard deviation of the modified joint angles was then found to determine the portion of variance that is due to static differences in the joint angles between trials. The forward kinematic solutions of the modified joint angles were then found for comparison to variation in hand position and subject parameters. The solution was found using both the individual subject parameters and the average subject model.

C. Variation in Hand Position

The variance in hand position was evaluated by the calculating the standard deviation of the hand's path for each task. The variation of the original path was evaluated relative to the variation of the path produced by forward kinematics of the average subject model, by the modified joint angles, and by the average subject model with the modified joint angles. The relative impact of subject parameter variation was evaluated based on the difference between the variation in hand position and the variation of the forward kinematic of the average subject model. Relative impact of joint angle variation was evaluated by the difference between variation in hand position and variation in forward kinematics of the modified joint angles. Relative impact of hand position variation was evaluated by the remaining variation when solving for the forward kinematics of the average subject model using the modified joint angles.

III. RESULTS

A. Variation in Subject Parameters

The largest variation in the subject parameters was found in the torso height. Since the segment lengths are calculated using the functional joint centers, and the spine is a series of joints that was simplified into a single approximate center of rotation, variation in relative motion of vertebrae between subjects likely led to increase variation in torso parameters. The average subject parameters and their standard deviations are given in Table 1. Definitions of the segments in the RHBM's neutral position are shown in Fig. 2. Segment lengths were also tested for correlation to subject height. Torso height and width had poor correlations (Pearson's r = -0.17 and r = 0.39), but significant correlations were found for Shoulder Width (r = 0.76), upper arm length (r = 0.62), and forearm length (r = 0.91). All subjects were included in the segment parameter averages, and correlations. Arm length was assumed to be independent of side and handedness, giving a sample size of 20. The right and left arms of the mean parameters were assumed to be of equal length when used in the average subject parameter model.

TABLE I. VARIATION IN SUBJECT PARAMETERS

Link	**Mean Upper Body Segment Lengths (mm)**		
	Description	***Mean***	***S.D.***
TORY	Torso Height	294 mm	±42 mm
TORX	Torso Width	74 mm	±10 mm
SHO	Shoulder Width	128 mm	±16 mm
UPA	Upper Arm Length	255 mm	±17 mm
FRA	Forearm Length	262 mm	±21 mm

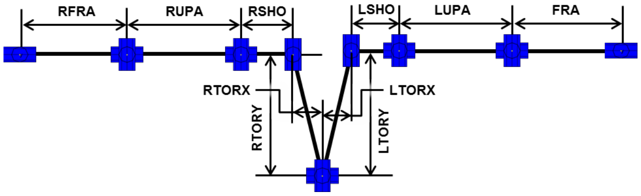

Figure 2. Diagram of Robotic Human Body Model Segments

B. Variation in Joint Angles

The variation in joint angles was the greatest for the brushing task, and the least for the drinking task. The standard deviation presented in this study is similar to the root mean squared error of previous studies [2-4]. Table II shows the standard deviation of the joint angles for each task, given the original joint angles, modified joint angles, and the difference between them (portion of the variance due to static difference in joint angles between trials).

TABLE II. VARIATION IN JOINT ANGLES

Standard Deviation in Joint Angle (degrees)				
Method	***Brushing***	***Drinking***	***Opening***	***Average***
Original	14.3°	12.1°	14.0°	13.5°
Modified	10.9°	6.5°	10.1°	9.2°

Fig. 3 shows the distribution of the shoulder elevation joint angle of the brushing hair task. The standard deviation of this joint angle for this task is 14.0° for the original joint angles (shown in blue) and 7.3° for the modified joint angles (shown in red). Data is contained in an array of 1 through 100 points, so there is no data at 0%.

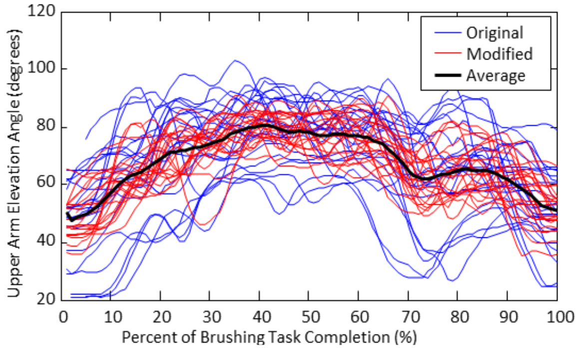

Figure 3. Original and Modified Joint Angles for all Brushing Trials

The variance of each joint (proximal to distal) is presented in Fig. 4. It is important to note differences in variation between joints since it may be beneficial to place stricter constraints on joints that have a naturally small variance. For instance, elbow flexion (joint 10) has a larger variance in all tasks than lateral torso flexion (joint 2). This indicates that error of simulated motion in elbow flexion would be preferable to error in lateral torso flexion for these tasks.

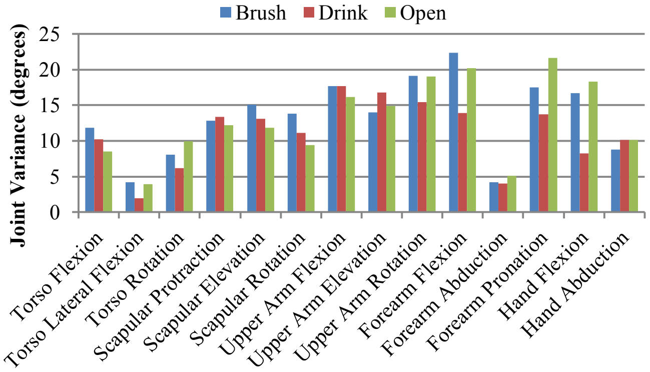

Figure 4. Variance of Each Joint for the Studied Tasks

C. Variance in Hand Position

Similar to the joint angle variance, the brushing task was found to have the highest variance in hand position, and the drinking task was found to have the least variance. The variance in the forward kinematic solution of the average subject model was only slightly reduced relative to the recorded hand positions. The forward kinematic solution of the modified joint angles had a greater impact, but still did not drastically reduce the variation. Using the modified joint angles with the average subject parameters produced another small reduction in hand position variance, but the majority of the variance remained regardless of the modifications considered in this study. The standard deviations of the hand positions are given in Table III.

TABLE III. VARIATION IN HAND POSITION

Standard Deviation of Hand Position (mm)				
Method	***Brushing***	***Drinking***	***Opening***	***Average***
Original	125 mm	77 mm	119 mm	107 mm
Avg Parameters	123 mm	72 mm	114 mm	103 mm
Mod. Angles	117 mm	69 mm	104 mm	97 mm
Avg Parameters + Modified Angles	112 mm	61 mm	97 mm	90 mm

IV. DISCUSSION

The use of the average subject parameter model and the modified joint angles produced an unintuitively small change in the variation of hand positions. Using the mean subject parameters had a much less significant impact of hand path than expected, and therefore the accuracy of subject model might not be as significant as expected. The variation in joint angles were higher than expected, with even the modified joint angle variations exceeding the root mean squared errors of the majority of algorithms tested in previous studies. However, since the inverse kinematics algorithms tested in previous studies used the hand path and orientation from the recorded data, variations in hand path does not have a significant impact on the root mean squared error of the algorithms.

Future work will focus on addressing additional limitations of the root mean squared error methods for evaluating human motion, and incorporating results from this study in to quantitative procedures. The root mean squared error could be modified to weight joints based on variation in recorded joint angles and/or the available range of motion of each joint. This study also provides a baseline for what can be considered an acceptable error for the selected tasks. Analysis of additional tasks will give a broader base for comparison and assessment of generalized performance. Analysis of variation in joint angles could also be more accurately performed if data were collected while subjects performed tasks with a constrained hand position. The assessment of perception of movement error in each joint should also be considered. This study assumes that a correlation between natural variations and perceived human likeness of motion exist, this could be evaluated using surveys of motions with abnormal movement variations.

V. CONCLUSIONS

This study provided a baseline for the evaluation of simulated upper body motion, based on inter-subject variations. The joint angle error of previously developed methods for creating simulated human upper body motion is within the observed variance between subjects. An unintuitive relationship between subject parameter, joint angle, and hand position variations exist, since reductions in subject parameter and joint angle variances did not produce proportional reductions in hand position variance. Additional analysis of variation in human motion would likely further increase our ability to quantitatively classify humanlike motion and better understand the fundamental concepts of human motion. Future work will focus on studying additional tasks, constrained motions, and evaluation of the perceived human likeness of simulated human motion.

REFERENCES

[1] D. J. Lura, S. L. Carey, and R. V. Dubey, "Automatic Generation of A Subject Specific Upper Body Model From Motion Data," in *ASME 2011 International Mechanical Engineering Congress & Exposition*, Denver, CO, 2011.

[2] D. J. Lura, "The Creation of a Robotics Based Human Upper Body Model for Predictive Simulation of Prostheses Performance," University of South Florida, 2012.

[3] D. Lura, S. Carey, and R. Dubey, "Joint Limit vs. Optimized Weighted Least Norm Methods in Predicting Upper Body Posture," in *Internation Conference on NeuroRehabilitation*, Toledo, Spain, 2012.

[4] D. Lura, M. Wernke, R. Alqasemi, S. Carey, and R. Dubey, "Probability Density Based Gradient Projection Method for Inverse Kinematics of a Robotic Human Body Model," in *34th Annual International Conference of the IEEE Engineering in Medicine & Biology Society*, San Diego, CA, 2012.

[5] P. H. Chang, "A Closed-Form Solution for Inverse Kinematics of Robot Manipulators with Redundancy," *IEEE Journal of Robotics and Automation,* vol. 3, pp. 393-403, Oct 1987.

[6] S. Khadem and R. Dubey, "A Global redundant robot control scheme for obstacle avoidance," in *IEEE Southeast Conference*, Knoxville, TN, 1988, pp. 397-402.

[7] Y. Nakamura, *Advanced Robotics: Redundancy and Optimization*, 1st ed. Boston, MA, USA: Addison-Wesley Longman Publishing Co., Inc. , 1990.

[8] S. McGhee, T. F. Chan, R. Dubey, and R. Kress, "Probability-based weighting of performance criteria for a redundant manipulator," in *IEEE International Conference on Robotics and Automation (ICRA)*, San Diego, CA, 1994, pp. 1887-1894.

[9] H. Zghal, R. Dubey, and J. Euler, "Efficient gradient projection optimization for manipulators with multiple degrees of redundancy," 1990, pp. 1006-1011 vol. 2.

[10] T. F. Chan and R. V. Dubey, "A weighted least-norm solution based scheme for avoiding joint limits for redundant joint manipulators," *Robotics and Automation, IEEE Transactions on,* vol. 11, pp. 286-292, 1995.

[11] B. Kashi, J. Rosen, M. Brand, and I. Avrahami, "Synthesizing two criteria for redundancy resolution of human arm in point tasks," 2011, pp. 63-68.

[12] H. Kim, L. Miller, N. Byl, G. Abrams, and J. Rosen, "Redundancy Resolution of the Human Arm and an Upper limb Exoskeleton," *IEEE transactions on bio-medical engineering,* 2012.

[13] F. Zacharias, C. Schlette, F. Schmidt, C. Borst, J. Rossmann, and G. Hirzinger, "Making planned paths look more humanlike in humanoid robot manipulation planning," 2011.

[14] K. Yamane and Y. Nakamura, "Robot kinematics and dynamics for modeling the human body," *Robotics Research,* pp. 49-60, 2011.

[15] O. Khatib, E. Demircan, V. De Sapio, L. Sentis, T. Besier, and S. Delp, "Robotics-based synthesis of human motion," *Journal of Physiology-Paris,* vol. 103, pp. 211-219, 2009.

[16] S. Lee, E. Sifakis, and D. Terzopoulos, "Comprehensive biomechanical modeling and simulation of the upper body," *ACM Trans. Graph,* vol. 28, pp. 1–17, 2009.

[17] J. C. Thompson, J. G. Trafton, and P. McKnight, "The perception of humanness from the movements of synthetic agents," *Perception-London,* vol. 40, p. 695, 2011.

[18] N. Sebanz and M. Shiffrar, "Detecting deception in a bluffing body: The role of expertise," *Psychon Bull Rev,* vol. 16, pp. 170-175, 2009.

[19] R. McDonnell, S. Jörg, J. K. Hodgins, F. Newell, and C. O'sullivan, "Evaluating the effect of motion and body shape on the perceived sex of virtual characters," *ACM Transactions on Applied Perception (TAP),* vol. 5, p. 20, 2009.

[20] R. McDonnell, S. Jörg, J. McHugh, F. Newell, and C. O'Sullivan, "Evaluating the emotional content of human motions on real and virtual characters," in *Proceedings of the 5th symposium on Applied perception in graphics and visualization*, 2008, pp. 67-74.