KINEMATIC ANALYSIS OF REACHING TO EXTRACT COMMAND SIGNALS FOR FES CONTROL

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Abstract

We are testing the hypothesis that rotational and translational shoulder movements provide sufficient cues about reach and grasp movements to be used as command signals for FES control of the distal joints, which are commonly paralyzed in spinal injuries. Repeated reaching movements to various targets by able-bodied volunteers were recorded and analyzed using a motion tracking system and modeling software package from Vicon (Oxford Metrics Inc, UK). We created a 5-segment, 10 degree-of-freedom (DOF) kinematic model to process the 3D positions of reflective markers attached to anatomical landmarks on the arm. Using the limb geometry of the subjects, the model calculated shoulder, elbow, and wrist joint trajectories. Model segment coordinate frames match the conventions of forward dynamic models developed in SIMM (Musculographics Inc., USA), which will be used to analyze FES controllers. The SIMM model was successfully animated using the recorded kinematics. Analysis of the predictability of target location, grasp orientation and closure from the natural kinematics of the shoulder is underway.

Introduction

One of the difficulties in achieving FES control of reach and grasp is to obtain complete and reliable command signals from quadriplegic patients due to their limited residual capacity for voluntary movements. Contralateral voluntary shoulder movements have been used in the FreeHand™ system [1] for controlling hand opening and closing motions. An FES system that integrates reach and grasp tasks in a natural sequence using ipsilateral shoulder movements as control signals does not exist yet. One key requirement is a source of command signals that has sufficient dimensionality and precision to specify the desired actions and is simple enough to be controlled by the patient during movement. Behavioral analysis of 3D reaching movements has shown that the human sensorimotor control system tends to reduce kinematic redundancy in the arm with kinematic synergies among its many degrees of freedom [2]. It has also been shown that, for every reaching endpoint, there is a specific preferred final configuration of the arm joints [3]. Because of these kinematic properties, we hypothesize that it is possible to guide the had to specific targets in extrapersonal space (3 DOF) with three rotational angles of the shoulder joint complex by predicting the desired distal elbow and wrist angles from the shoulder angles. Thus, it would be possible to use residual shoulder movements in a paralyzed patient to drive an FES system that controls the distal arm in a natural manner [4].

This paper describes the development of a kinematic model of the arm and the experimental procedure for collecting 3D reach and grasp data using the Vicon motion analysis system. Preliminary results from two subjects indicate that the model produces reliable and consistent shoulder motion outputs that can control distal arm movements. A more extensive study is underway to collect and analyze a more complete set of reach and grasp data for FES command control.

Methods

***Experiments Procedures*:** 3D reaching motion was recorded with a 6-camera Vicon optical motion tracking system. A total of 11 markers were attached to anatomical landmarks on the trunk, right arm and right hand of two healthy adult male volunteers. Subjects sat in a chair, and a cylindrical target handle was mounted on a pole in front of the subject. The handle could be turned to be in either a vertical orientation (like a drink cup on a table), or a horizontal orientation (like a pencil on a table). The target was placed at the same height as the head, and in two positions around the body: 1) directly in front of the right shoulder, and 2) at an angle of approximately 45° to the right of the subject. In the initial experiments to develop and validate the model, the starting position was with the arm relaxed and hanging at the subject's side. For FES control, we are analyzing reaches from a lap table to similarly oriented targets in more locations. To normalize the distance to the target between subjects, each subject was asked to fully extend his arm toward the target without leaning or translating the shoulder. The target was then positioned 2 cm proximal to the wrist, where it could be reached without leaning or locking the elbow. This is expected to minimize the trunk motion during the reach. Subjects were instructed to perform 10 consecutive reaching movements at normal speed and the 3-D position of the markers were recorded by the motion tracking system.

Each reaching motion consisted of a reach phase followed by a brief grasping phase and ending with a returning motion. Sessions were kept under two hours per subject, and long rests were permitted between reaching sets to minimize the effects of fatigue. All trials were recorded at a sampling rate of 60 Hz. Obvious artifacts in the data, such as 1-4 frame jumps in marker position, were removed, and any confused markers were manually relabeled prior to data processing. Short (≤ 1/6 sec) gaps in marker trajectories were interpolated, and all trajectories were filtered with either 5 or 7 point weighted average filters (0.083 sec and .117 sec windows, respectively) using BodyBuilder's internal processing functions. These methods produced clean, complete, and usable data for 9 out of 10 reaches.

The Kinematic Model: A kinematic model of the right arm was created using BodyBuilder software package to calculate the motion of the joints and joint centers from the Cartesian coordinates of the markers. The model has 5 segments including trunk, Humerus, Ulna, Radius, and Hand.

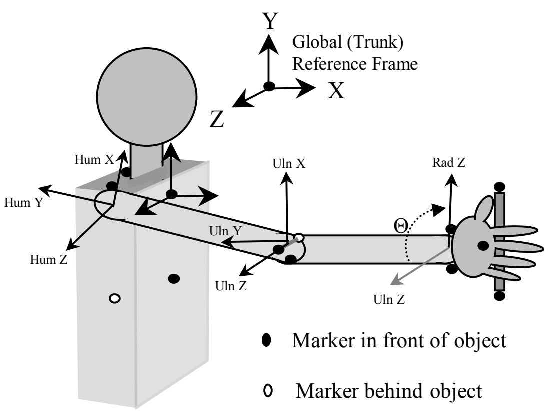

Figure 1. Marker set, target, and coordinate frames attached to the segments. When the arm in anatomical position, all segment axes are aligned with the trunk (global) axes. Some axes have been omitted for clarity.

In the kinematic model, each segment is specified by an orthogonal coordinate frame attached in the proximal joint center. The motion of the frame's origin and the relative orientation of the frames specify the motion of the segments. At least 3 points (recorded or calculated) are required to specify one segment's coordinate frame (origin and unit vectors). The trunk's frame is defined using 3 markers attached to the Jugular notch, C7 (neck), and T7 or T8 (back). The Humerus frame is defined by the approximate shoulder and elbow joint centers, and markers attached to the wrist and/or the humeral epicondyles. The elbow joint center is approximated using three markers on the elbow, and an approximate center of shoulder rotation is found by adding an offset vector to the acromion marker position. Shoulder translation is determined by the motion of the shoulder joint center relative to the trunk. This method does not account for scapular "winging," but has been used previously [5]. Other shoulder modeling methods exist and some [6] are being adapted for this model.

The ulna's reference frame is defined by the elbow joint center, wrist joint center, and the markers on the humeral epicondyles or on the shoulder. The proximal markers are used to define the ulna's z-axis (elbow flexion axis). The elbow joint center and two markers on the styloid processes of the wrist specify the radius frame. Radial rotation is calculated as the relative rotation of the radius frame about the longitudinal axis of the ulnar frame. The hand frame is modeled by the wrist joint center, the epicondylar markers on the wrist, and the center of grip, which is calculated from a marker on the 3rd metacarpophalangeal joint of the dorsal hand when the target is grasped in a static trial.

The model calculates angles and translations for 10 degrees of freedom in the arm and shoulder: shoulder pro/retraction, elevation/depression, ab/adduction, rotation, flexion/extension, elbow flexion/extension, radioulnar pro/supination, wrist flexion/extension, and wrist radial/ulnar deviation. In addition, translation of the shoulder radially from the midline was calculated, as a diagnostic tool and to provide necessary input for forward dynamic models that will use these data.

Results

Trajectories for a given task were consistent for all trials and both subjects. Trajectories of the joints for a typical reach to a horizontally oriented target are shown in Figure 2. The graphs show data for the complete motion, including reach, grasp, and return. Grasp occurs at about 1.5 sec. The shoulder angles are Euler rotations between the trunk and humerus reference frames. They are calculated as sequential rotations about the axes of the humerus-embedded reference frame in the order X,Z,Y, or (loosely) abduction, flexion, longitudinal rotation. Calculated segment lengths all varied by 1.6 cm or less. Low segment length variability is one measure of the accuracy of joint-center estimations and model accuracy. Recorded outward motion of the shoulder joint center is not zero, as might be expected. This is due to circular motion of the acromion, with the clavicle as its radius.

Discussion

The data appear symmetrical for reaching and returning. Little forearm rotation occurs for this subject while reaching to the horizontal target, indicating his preference to orient his hand with shoulder rotations and elbow flexion. The other subject demonstrated more forearm rotation for this same reach, indicating a different preferred strategy. Presumably FES patients could learn to use either strategy if one provides better command information or more stability.

When the computed joint angles were applied to SIMM to create an animation of the reach and grasp movements, the animated skeletal motion appeared similar to the subject's observed limb motion and to the Vicon marker and segment displays. Quantitative validation studies are underway. The model is being used at USC's biokinesiology lab for their own studies, and enhancements are being added to improve clinical interpretability of model outputs and to simplify clinical usage. There is great demand in the biomechanics field for a simple, accurate, and well-documented model of the upper extremity for motion capture and analysis. This model may satisfy that demand.

Data from a more complete set of reach and grasp tasks are being analyzed to address two key questions:

1) Are the kinematics of the distal arm specified unambiguously by the independent shoulder DOF?
2) Can shoulder motion be recorded from wearable or implantable sensors be used as command signals for FES control of the ipsilateral distal joints?

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Acknowledgments: The authors wish to thank Dr. Chris Powers, Emily Wang, and Matt Sandusky at the USC Biokinesiology Lab for assistance with the Vicon hardware and software.

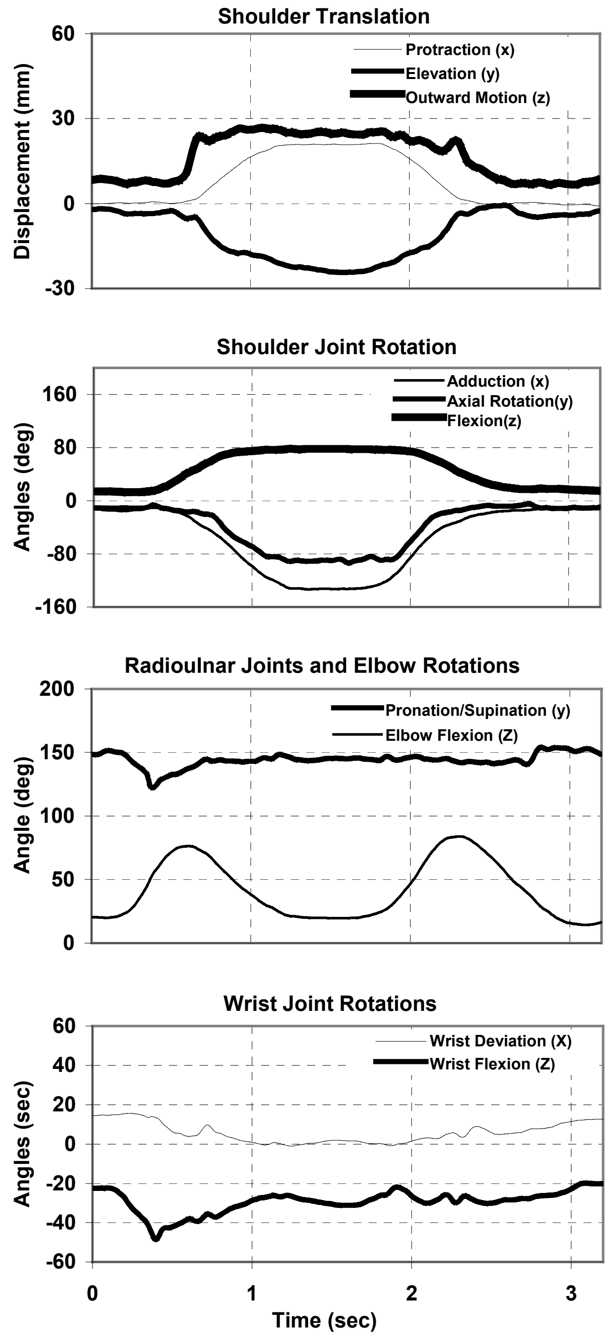

Figure 2. Translation of the shoulder joint center, and angular motion of joints for a typical reach-return to a horizontally oriented target in front of the subject. Elbow and wrist angles are positive for flexion. The elbow flexes during movement initiation, and extends again as the subject reaches out. Pronation produces positive radioulnar angles. Ulnar wrist deviation is positive.