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REPRESENTATION OF SHOULDER KINEMATICS DURING MULTIPLANE TASKS PERFORMED BY MANUAL WHEELCHAIR USERS

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SUMMARY

To develop evidence-based strategies for preserving shoulder function in manual wheelchair (WC) users, approaches for comparing upper extremity 3D kinematics across a variety of activities of daily living require further development. In this study, Euler and quaternion based methods for parameterizing shoulder kinematics were quantified and compared for decoupled shoulder motions and more complex, multiplane tasks (e.g. car transfer). A 3D vector representation of shoulder joint angular velocity throughout the movement was found to be an effective tool for characterizing an individual's functional joint axis, throughout the course of multiplane movements. This quaternion based approach complement the ISB standards yet overcomes mathematical challenges often encountered when using Euler angle sequences for complex movements.

INTRODUCTION

Analysis of the kinetics of the human body requires knowledge of both the external forces applied to the body, as well as, the dynamic motion of body segment kinematics. With advances in motion capture, there is an increasing need to develop protocols that facilitate comparison of 3D shoulder kinematics and kinetics across tasks and between studies. Choice of marker sets, joint axes, segment reference systems, functional coordinate references systems of clinical relevance as well as computational methods are known to affect the kinematics reported[1-15]. Some consensus[8] was reached by the ISB–ISG[15] regarding anatomical landmarks most helpful for characterizing upper extremity kinematics using a shoulder model. Currently, the description of shoulder-motion relies on Euler angle notation that decouples any given rotation into three consecutive rotations applied about one Cartesian axis at a time. Such a representation is particularly useful when describing motion in robotics, since each actuator produces a pure, decoupled rotation about one of these axes; however, human movements are often multiplanar and are controlled by selective activation of 3D muscle forces. In addition, the preferred sequence of Euler angles needs to be modified for different movements to avoid singularities at times when the intermediate rotations approach 90 and 180 degrees, depending on the type of Euler rotation sequence. Note, this does not mean that there is a singularity in the physical motion of the segment, merely a singularity in the mathematical representation

In this study, we evaluated the utility of computational approaches and kinematic parameterizations for use with multiplane tasks (e.g. transfer of a WC into and out of the backseat of an automobile). Four different Euler rotations sequences of shoulder kinematics were compared with functional joint axis defined by the shoulder joint angular velocity vector, calculated from quaternion representation.

METHODS

The shoulder kinematic model was based on UE segment kinematic reference systems derived using 20 markers[14]. Data was acquired using a 3-D motion capture systems (AMASS, C-Motion). The shoulder was considered an ideal ball and socket joint and the elbow motion was modeled as a hinge (Fig1). The 3D model consists of seven rigid bodies: the trunk, three segments for each side: upper arm, forearm and hand (Fig. 1) with an embedded Local Coordinate System at the proximal end (Y' axis pointing from posterior to anterior and Z' axis oriented longitudinally towards the proximal direction).

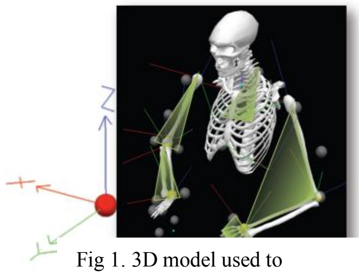

Fig 1. 3D model used to characterize shoulder kinematics.

Euler rotation sequences compared included 1) XYZ flex/ext as first rotation, axial direction as last (ISB recommended rotation sequence for most joints[15]), 2) ZYZ, ISB recommendation for shoulder, using the axial direction as first rotation[15], 3) YXZ[4,7], 4) XZY with flex/ext as the first rotation, axial direction as second rotation. To avoid potential singularities, a quaternion-based parameterization of attitude is proposed.[11] The four-parameter quaternion representation of the attitude prevents using logic statements to avoid singularities and provides a unique representation throughout the entire movement. A quaternion is an extension of the notion of complex numbers. Its application to describe 3D rotations employs Euler Theorem that states that every rotation can be expressed by a rotation angle ϕ about an axis $\hat{n}$. A quaternion $\bar{\mathbf{q}}$ is given by the four parameters $\bar{\mathbf{q}} = \begin{bmatrix} \mathbf{q} \\ q_4 \end{bmatrix}$, where $\mathbf{q}$ and q_4 are vector and scalar components parts of the quaternion, respectively. When describing rotation $\boldsymbol{q} = \hat{\boldsymbol{n}} sin\varphi$ and $q_4 = cos\varphi$. Then,

$\bar{v}_2 = \bar{q} \otimes \bar{v}_1 \otimes q^*,\ q^* = \begin{bmatrix} -\bar{q} \\ q_4 \end{bmatrix}$, represents a rotation of vector v_1 by angle $\phi = 2\varphi$ about the axis $\hat{\boldsymbol{n}}$. Here the symbol $\otimes$ indicates quaternion multiplication, which is defined as:

$$\bar{\mathbf{p}} \otimes \bar{\mathbf{q}} = \begin{bmatrix} q_4\mathbf{p} + p_4\mathbf{q} - \mathbf{p} \times \mathbf{q} \\ q_4 p_4 - \mathbf{p} \cdot \mathbf{q} \end{bmatrix}$$

Quaternion algebra allows for a much more efficient computation as compared to Euler rotations representation. A successive rotation rule is also well defined and computationally less expensive. Two successive rotations q_1 and q_2 can be represented by a quaternion $\bar{q}_T$ given by $\bar{q}_T = \bar{q}_2 \otimes \bar{q}_1$. Quaternion algebra also allows calculation of the clinically relevant joint angular velocity $\boldsymbol{\omega}$ vector as follows:

$$\begin{bmatrix} \boldsymbol{\omega} \\ 0 \end{bmatrix} = 2\frac{d\boldsymbol{q}}{dt} \otimes \boldsymbol{q}^*, \qquad \boldsymbol{\omega} = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T$$

In this project, the quaternion indicates an orientation change of the arm-plane (AP) with respect to the trunk reference frame, expressed in trunk frame coordinates. The quaternion is thus defined, and the angular velocity vector of the arm-plane with respect to the trunk is calculated. Note, the three terms of the angular velocity vector indicate the x, y, and z components of the angular velocity, effectively describing the flexion/extension, abduction/adduction, and internal/external rotations, respectively. Angular velocity representations of these typical decoupled actions, along with an example of a more complex motion (Fig. 2,3).

RESULTS AND DISCUSSION

The shoulder functional joint axis was well represented by the direction of the joint angular velocity vector during each task (Fig 2). During the performance of the shoulder flexion/extension task, the individual's functional joint axis was aligned primarily with the Flex/Ext and Abd/Add axes. During shoulder abduction/adduction task, the functional joint axis more aligned with the Abd/Add axis than the Flex/Ext axis, particularly when rotating at greater angular velocities (length of vector). During shoulder internal and external rotation task, the shoulder angular velocity was aligned with the internal/external axis throughout the movement.

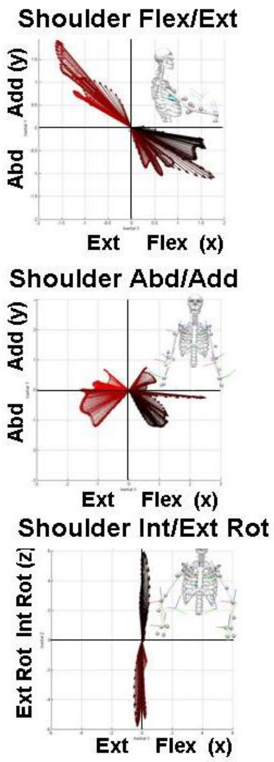

Fig 2. Joint angular velocity vectors during decoupled motions.

Euler representation of shoulder motion in the sagittal and frontal plane (Flex/Ext and Add/Abd) were similar for the rotation sequence XYZ[2,11,14]. The XZY rotation yielded the same excursion, but with a 20° to 30° shift in the sagittal plane and a 10° to 15° shift in the frontal plane. The rotation ZYZ gave satisfactory results for the sagittal plane, but not reliable results in the frontal or transverse planes.

Unlike the Euler angle representations of the same movements, the functional joint representation of upper arm motion relative to the trunk segment throughout the movement did not encounter mathematical challenges, common to Euler angle representations of shoulder motion. During the transfer of the WC to the backseat of the car, the functional joint axis representation of 3D shoulder kinematics allowed us to track how the primary axis of movement shifts between phases (Fig 3). Shifts in functional axes between movement phases will clarify the control logic when studying neuromuscular control of joint motion.

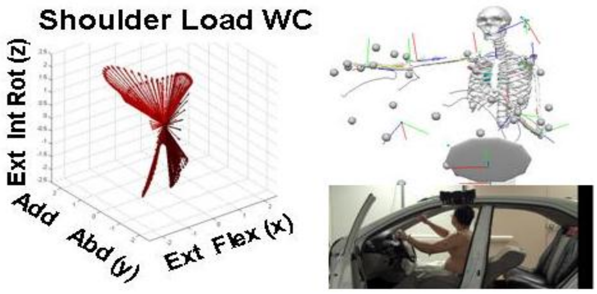

Fig 3. Angular velocity vectors illustrate the shoulder joint functional joint axis throughout the multiplane car transfer motion (color changes with time, black to red).

CONCLUSIONS

The quaternion approach and use of the angular velocity vector provides a consistent movement-base representation of an individual's functional joint axis throughout multiplane movements. The graphical representation of the angular velocity vector provides a visual understanding of both magnitude and direction through out both decoupled and multiplane movements. With a standardized movement-base for describing functional shoulder motion, evidence-based strategies for preserving shoulder function in manual wheelchair (WC) users can be more fully developed across a variety of activities of daily living.

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