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Comparison of anatomical, functional and regression methods for estimating the rotation axes of the forearm

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ABSTRACT

Numerous methods exist to estimate the pose of the axes of rotation of the forearm. These include anatomical definitions, such as the conventions proposed by the ISB, and functional methods based on instantaneous helical axes, which are commonly accepted as the modelling gold standard for non-invasive, *in-vivo* studies. We investigated the validity of a third method, based on regression equations, to estimate the rotation axes of the forearm. We also assessed the accuracy of both ISB methods. Axes obtained from a functional method were considered as the reference.

Results indicate a large inter-subject variability in the axes positions, in accordance with previous studies. Both ISB methods gave the same level of accuracy in axes position estimations. Regression equations seem to improve estimation of the flexion–extension axis but not the pronation–supination axis. Overall, given the large inter-subject variability, the use of regression equations cannot be recommended.

1. Introduction

Accurate estimation of the rotation axes of the forearm, flexion–extension (FE) and pronation–supination (PS), is important for clinical assessment of function and prosthesis design (London, 1981). One common approach is to define these axes directly from the positions of palpable anatomical landmarks (Schmidt et al., 1999). Such an *anatomical* approach is used in the ISB recommendations (Wu et al., 2005), with two possible definitions for the upper arm. In the first one (ISB1), the Coordinate System (CS) of the upper arm is based solely on landmarks belonging to the humerus, whereas in the second one (ISB2) landmarks from the forearm are also used. The ISB approaches offer a simple and easily implemented solution for describing elbow kinematics.

The other approach, referred to as *functional*, estimates the rotation axes by computing the instantaneous helical axes of rotation (IHAs) of the forearm relative to the upper arm. Subjects perform elbow flexion–extension and pronation–supination movements. The corresponding IHAs are then computed for each motion, with the average calculated to obtain a single functional axis of rotation for each degree of freedom (FE and PS). Functional methods have been used both *ex vivo* (Morrey and Chao, 1976; Veeger et al., 1997; Veeger and Yu, 1996; Hollister et al., 1994) and *in vivo* using non-invasive methods (Biryukova et al., 2000; Stokdijk et al., 1999, 2000; Chin et al., 2010; Fohanno et al., 2013) or medical imaging (Youm et al., 1979; Nakamura et al., 1999; Tay et al., 2010). Using a functional method reduces kinematic cross-talk (Chin et al., 2010) and reduces marker residuals after reconstruction (Fohanno et al., 2013), and overall, gives a better estimate of the true physiological axes than anatomical methods. However, functional methods require experimental protocol modifications, which increase the duration of data collection sessions. Moreover, the algorithms used to compute functional axes are not straightforward and require a good knowledge of the underlying theory. In comparison, anatomical methods are much easier to use.

Functional axes studies have shown that, qualitatively, the position of the functional axes relative to anatomical landmarks is consistent among individuals. For instance, the FE axis is offset anteriorly and distally from the axis of the humeral epicondyles, and the PS axis is offset medially from the lateral humeral epicondyle (at the elbow) and from the ulnar styloid (at the wrist) (Youm et al., 1979; Veeger and Yu, 1996; Veeger et al., 1997; Stokdijk et al., 1999) The actual values of the offsets vary among individuals, but the relative positions are consistent. Anatomical methods, such as the ISB definitions, do not take these offsets into account. By doing so, it may be possible to improve on axes estimation while keeping the method as simple as the anatomical one.

This type of approach is commonly used for estimating the position of the hip joint centre (HJC). It is very common to

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estimate HJC location as a function of the distance between anatomical landmarks of the pelvis, such as the iliac spines. These relations are given in the form of regression equations, such as the ones provided by Bell et al. (1989) or Harrington et al. (2007), have been shown to give reliable estimates of the HJC positions and are widely used nowadays. Such methods will be further referred to as *regression methods*. Compared to functional methods, regression methods do not require additional experimental data collection, while offering improved joint parameters estimates compared to anatomical methods.

The primary objective of this study was to investigate the feasibility of a *regression method* to estimate the FE and PS axes positions from the positions of anatomical landmarks of the upper arm and forearm. To achieve this, two groups of subjects were used. In the first group, the functional FE and PS axes were computed for each subject, then normalised and averaged over all subjects. The average positions were used to build the regression equations. In the second group of subjects, joint angles obtained using these regressions were compared to those obtained from functional and anatomical methods. As a secondary goal, the results from the two ISB methods were also compared. Results from the functional method were considered as the reference.

2. Methods

2.1. Experiment

Thirty one ($n=31$) healthy, right-handed subjects (17 male, 14 female, mean age = 28 y.o. SD = 7, mean height = 1.78 m SD = 0.10, mean weight = 76.0 kg SD = 17.1) took part in the experiment. All participants were free from any upper limb musculoskeletal disease and chronic pain. The study was approved by University of South Australia Human Research Ethics Committee (protocol no. 0000026539). Written, informed consent was obtained before data collection. Participants were divided in two groups. Group A ($n=21$) was used to develop the predictive regression equations, while Group B ($n=10$) was used to test the accuracy of these equations and compare them to the ISB and functional methods.

Twelve reflective markers were placed on the right upper arm and forearm. Markers were placed on the following anatomical landmarks (Fig. 1A): forward-most tip of the acromion (ACRO); medial and lateral humeral epicondyles (MHE, LHE); radial and ulnar styloid processes (RS, US), according to the guidelines established by Van Sint Jan (2007). Additionally, four tracking markers were placed laterally on the right upper arm (UARM1-4) and three markers near the distal end of the forearm (FARM1-3). Only tracking markers were used for reconstruction.

Subjects were sitting on an adjustable chair, with their right elbow resting on the edge of a table. First a static trial was captured with the subjects maintaining an elbow angle of 90° and a neutral pronation–supination position (right thumb pointing to the shoulder). The subjects then performed elbow flexion–extensions at a rate of 0.25 Hz while maintaining a neutral pronation–supination angle (palm of the hand facing left) as best as they could through a 100° range of motion (40°–140° of elbow flexion). Then the subjects performed full range of motion forearm pronation–supination at a rate of 0.2 Hz while trying to maintain a fixed elbow flexion angle of 90°. The rate of the movement was controlled with a metronome. Five cycles were recorded per task.

Additionally, subjects from Group B were asked to perform two more tasks representing Activities of Daily Living (ADL) and involving large amplitudes of FE and PS motion. In the first task (REACH), subjects were standing in an upright, relaxed posture, arms hanging along the torso. At the experimenter's signal they touched the back of their neck with their right hand in a naturally paced motion, then brought their right arm back along the torso (Fig. 1B and C). In the second task (FLIP), subjects were sitting in front of a table and were asked to grasp a plastic card (10 × 7 cm) placed at the bottom left corner of the table, flip it over and place it at the top right corner (Fig. 1D, E, F). Five trials were recorded for each activity.

Kinematic data were recorded at 100 Hz using a 12-camera optoelectronic motion capture system (Optitrack®, Natural Point, USA). Marker trajectories were low-pass filtered at 5 Hz using a 4th order, zero-lag Butterworth filter.

2.2. Data processing

Joint kinematics were computed using four different methods: two anatomical methods (ISB1 and ISB2), a functional method (FUNC) and the proposed regression method (REG).

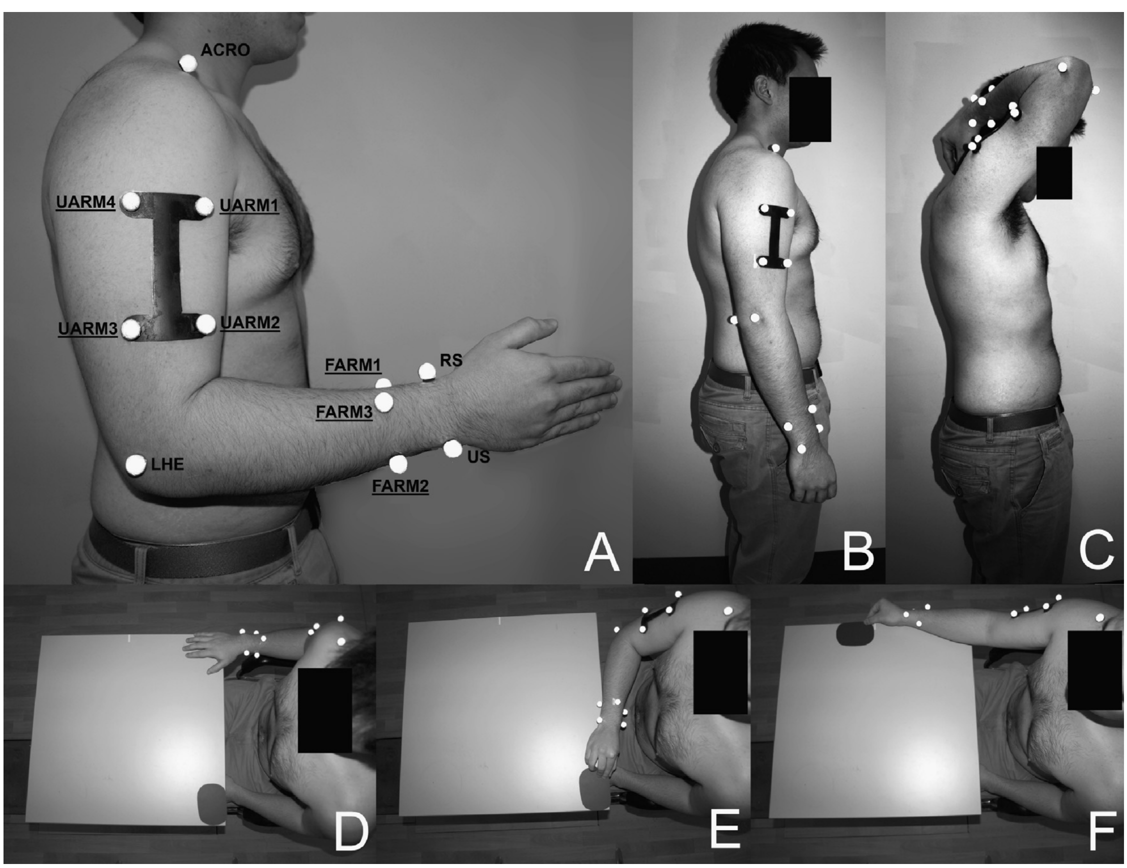

Fig. 1. Marker set used in the study (A). Technical markers used for reconstruction are underlined. REACH movement: initial posture (B) and posture during reach (C). FLIP movement: initial posture (D), grabbing the card (E), and flipping the card (F).