Journal of Biomechanics 42 (2009) 1527–1532

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

MRI development and validation of two new predictive methods of glenohumeral joint centre location identification and comparison with established techniques

A.C. Campbell, D.G. Lloyd *, J.A. Alderson, B.C. Elliott

School of Sport Science, Exercise and Health, The University of Western Australia, M408, 35 Stirling Highway, Crawley, WA 6009, Australia

ARTICLE INFO

Article history:
Accepted 23 March 2009

Keywords:
Shoulder kinematics
Glenohumeral joint
Rotation centre
Linear regression

ABSTRACT

Identification of the centre of the glenohumeral joint (GHJ) is essential for three-dimensional (3D) upper limb motion analysis. A number of convenient, yet un-validated methods are routinely used to estimate the GHJ location in preference to the International Society of Biomechanics (ISB) recommended methods. The current study developed a new regression model, and simple 3D offset method for GHJ location estimation, employing easy to administer measures, and compared the estimates with the known GHJ location measured with magnetic resonance imaging (MRI). The accuracy and reliability of the new regression and simple 3D offset techniques were compared with six established predictive methods. Twenty subjects wore a 3D motion analysis marker set that was also visible in MRI. Immediately following imaging, they underwent 3D motion analysis acquisition. The GHJ and anatomical landmark positions of 15 participants were used to determine the new regression and simple 3D generic offset methods. These were compared for accuracy with six established methods using 10 subject's data. A cross validation on 5 participants not used for regression model development was also performed. Finally, 10 participants underwent a further two MRI's and subsequent 3D motion analysis analyses for inter-tester and intra-tester reliability quantification. When compared with any of the other established methods, our newly developed regression model found an average GHJ location closer to the actual MRI location, having an GHJ location error of 13 ± 2 mm, and had significantly lower inter-tester reliability error, 6 ± 4 mm ($p < 0.01$).

1. Introduction

Three-dimensional (3D) motion analysis with surface markers requires the accurate and repeatable identification of anatomical landmarks. These are essential in the definition of bone-embedded anatomical coordinate systems (ACS), and errors in their locations will significantly alter the derived kinematic and kinetic variables (Della Croce et al., 1999; Stagni et al., 2000; Van Sint Jan and Della Croce, 2005). A number of anatomical landmarks can be identified by palpation. However, this is not possible for the estimation of the glenohumeral joint centre (GHJ) location.

A review of the recent upper limb biomechanics literature demonstrates a number of predictive methods of GHJ location being performed that largely lack thorough validation (Anglin and Wyss, 2000a, b; Cutti et al., 2006; Hingtgen et al., 2006; Klopcar and Lenarcic, 2006; Mackey et al., 2005; Rab et al., 2002; Requejo et al., 2005). These can be categorised as multiple linear regression models (Harrington et al., 2007; Meskers et al., 1998), two-dimensional (2D) offset methods (Schmidt et al., 1999), or 3D offset methods (Anglin and Wyss, 2000a, b). Despite the suggestion that 2D methods are not sophisticated enough for the 3D environment (Harrington et al., 2007), these have been implemented in a number of investigations (Anglin and Wyss, 2000a, b; Henmi et al., 2006; Schmidt et al., 1999). The International Society of Biomechanics (ISB) recommend a predictive 'multiple linear regression' model that is based on scapula landmarks and was developed and validated on cadavers (Meskers et al., 1998), which has recently been rewritten based on different scapula anatomical landmarks and has been suggested for use by the International Shoulder Group (Meskers et al., 1998) rewritten version available at http://trac.assembla.com/isgcode/browser/kinematics, accessed 19/03/09). Importantly, the cadaveric validation of Meskers et al. (1998) may not be representative of error margins expected during *in vivo* analyses (Graichen et al., 2000).

The *in vivo* accuracy assessment of the two ISB recommended predictive methods and a representative sample of other previously used methods will help clarify the most valid method. For

* Corresponding author. Tel.: +61 8 6488 3919; fax: +61 8 6488 1039.
E-mail address: David.Lloyd@uwa.edu.au (D.G. Lloyd).

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doi:10.1016/j.jbiomech.2009.03.039

this purpose, a suitable gold standard measure of GHJ location is required. Magnetic resonance imaging (MRI) is an accurate medical imaging tool, which has been used as a gold standard approach for the identification of the hip joint centre (Harrington et al., 2007).

This investigation has four aims. (1) To determine the reliability of the MRI digitising protocol for identifying the head of the humerus. (2) To determine the accuracy of the original and rewritten version of the ISB recommended predictive method (Meskers et al., 1998), and four other established predictive methods; the UWA method (Lloyd et al., 2000), two versions of the Vicon standard method (Vicon Metrics), and a 7 cm drop method (Schmidt et al., 1999). (3) To develop and cross validate two new predictive methods, namely, a new regression model and a simple 3D offset method. (4) To compare the inter-tester and intra-tester reliability of all these predictive methods of GHJ identification.

2. Methods

Twenty healthy males provided their written informed consent and participated in this study following approval by the Ethics in Human Research Committee of the University of Western Australia. The participants' age, height, and mass were 24 years ($\pm$2), 177.6 cm ($\pm$7.2), and 76 kg ($\pm$10), respectively. All subjects underwent an MRI scan followed directly by a 3D motion analysis. This analysis was necessary to determine the location of the scapula landmarks, which was not possible in the MRI given that the field of view was primarily focused on ensuring the accurate reconstruction of the GHJ.

2.1. MRI data collection and digitisation

The participants had one marker set affixed to their upper body; with the markers covered in retro-reflective tape and filled with oil to permit visibility in both imaging systems. The shoulder girdle marker set (Table 1 and Fig. 1) was affixed to the participant's dominant shoulder prior to imaging in a MRI Sigma scanner at Perth Radiological Clinic (Subiaco, Western Australia). An axial T1 weighted fast spin echo-sequence with 5 mm slice thickness, spaced at 1 mm, and 384×256 matrix was implemented. The field of view was 28 cm, with a TR of 450 ms, and TE of 11 ms. This MRI configuration was implemented in consult with a radiologist, for the primary objective of manual digitisation of bone. The subject's laid supine with their upper arm secured to the midline of their torso.

The location of the shoulder girdle markers and the GHJ (defined as the centre of the humeral head) in each MRI were determined using medical imaging software, Mimics (Materialise Software Inc.). The digitisation process included manual segmentation of the humeral head and all the markers in each transverse plane slice in which they appeared. The border of each object was then defined using B-spline polynomial contour lines, which were collated and fit with a sphere by a Mimics function (CAD object fitting). The centre point of each sphere was then used to represent the 3D location of the GHJ and each marker.

2.2. Kinematic data collection

Immediately following MRI data collection, the participant's were transported to the biomechanics laboratory at the University of Western Australia. The following measures were recorded: the distance between the acromioclavicular joint (AC) and the visually estimated GHJ, the width of the shoulder at the level of the GHJ, and subject's height and mass. A 12 camera Vicon MX motion analysis system (Vicon Oxford Metrics Inc.) operating at 250 Hz was then used to collect the scapula landmark identification static trials, with the participant in the same humeral position achieved during the MRI data collection, i.e., with their upper arm secured to the midline of their torso. To allow 3D motion analysis marker visibility, the participant was standing, rather than lying. The tester then used a 'pointer wand' (Besier et al., 2003) to identify the 3D location of each of the scapula landmarks necessary for the implementation of the scapula regression model (Table 1).

2.3. Data processing

Using a custom Matlab program (Mathsworks Inc.), the 3D locations of the markers and the GHJ from the MRI, as well as the scapula landmarks from the 3D motion analysis, were transformed from their respective global coordinate systems, into a technical coordinate system (TCS) defined from the acromion triad, Acr1, Acr2, and Acr3 (Eq. (1)). These markers were visible and unmoved in both imaging systems. To position this marker triad, the midpoint between the most posterior and anterior points of the lateral ridge of the acromion process (AcrLR) was estimated and marked. The centre of the long bar of the marker triad was placed directly above this point (Fig. 1), which was also used as the origin of the acromion reference TCS (AcrCS). The AcrCS was defined as

$$x_{Acr} = \frac{Acr3 - Acr1}{|Acr3 - Acr1|},$$
$$y_{Acr} = x_{Acr} \times \frac{(Acr1 + Acr3)/2 - Acr2}{|(Acr1 + Acr3)/2 - Acr2|},$$
$$z_{Acr} = x_{Acr} \times y_{Acr}. \quad (1)$$

The known distance from the centre of each spherical acromion marker to the skin surface was removed in the AcrCS calculation allowing comparisons with alternate systems. The estimation of the GHJ location with each method, and all comparisons, were carried out with respect to the AcrCS.

2.3.1. GHJ calculation with established methods

The GHJ was estimated using six established methods drawn from the literature (Lloyd et al., 2000; Meskers et al., 1998; Schmidt et al., 1999). Two of these methods (Vicon M1, Vicon M2) were adopted from Vicon's motion analysis system generic model (Vicon Oxford Metrics, Inc.) (Table 2).

2.3.2. Development of a two new regression models

A new regression method to predict the location of the GHJ was developed. For this, the GHJ location, determined from the MRI images of 15 participants (a subset of the total cohort of 20 participants) were used in a stepwise linear regression analysis (SPSS) to create three regression equations to estimate the *x*, *y*, and *z* coordinates of the GHJ. Five possible independent variables were employed: (1) subject height, (2) subject mass, (3) the 3D distance between the incisura jugularis (IJ), and the 7th cervical vertebrae (C7) (IJ–C7), (4) the 3D distance between the midpoint of the lateral ridge of the acromial plateau and the centre point between the IJ and C7 markers (CP) (ACRLR–CP), and (5) the 3D distance between a marker

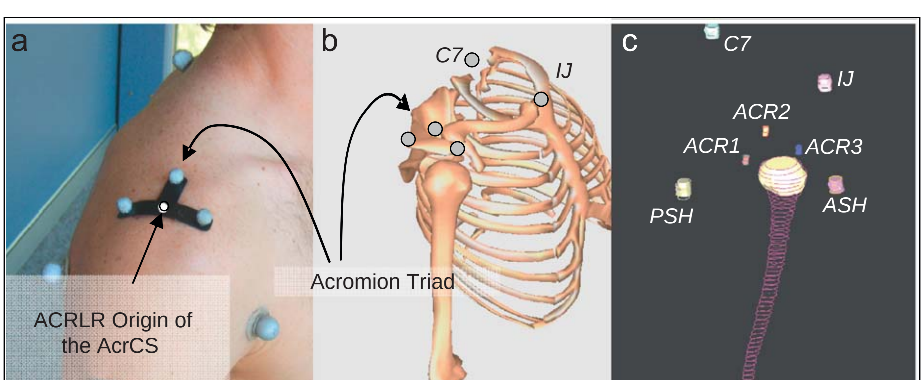

Fig. 1. (a) The upper limb marker set required by the GHJ identification methods, (b) representation of the acromion triad on a skeleton, and (c) reconstruction of the humerus and the markers following MRI digitisation.