Journal of Biomechanics 46 (2013) 2619–2625

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Propagation of soft tissue artifacts to the center of rotation: A model for the correction of functional calibration techniques

Helios De Rosario [a,c,*], Álvaro Page [b,c], Antonio Besa [d], Ángel Valera [e]

[a] Instituto de Biomecánica de Valencia, Valencia, Spain
[b] Departamento de Física Aplicada, Universitat Politècnica de València, Valencia, Spain
[c] CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Spain
[d] Departamento de Ingeniería Mecánica y de Materiales, Universitat Politècnica de València, Valencia, Spain
[e] Instituto de Automática e Informática Industrial, Universitat Politècnica de València, Valencia, Spain

ARTICLE INFO

Article history:
Accepted 14 August 2013

Keywords:
Soft tissue artifacts
Functional calibration
Center of rotation
Gleno-humeral joint

ABSTRACT

This paper presents a mathematical model for the propagation of errors in body segment kinematics to the location of the center of rotation. Three functional calibration techniques, usually employed for the gleno-humeral joint, are studied: the methods based on the pivot of the instantaneous helical axis (PIHA) or the finite helical axis (PFHA), and the "symmetrical center of rotation estimation" (SCoRE). A procedure for correcting the effect of soft tissue artifacts is also proposed, based on the equations of those techniques and a model of the artifact, like the one that can be obtained by double calibration. An experiment with a mechanical analog was performed to validate the procedure and compare the performance of each technique. The raw error (between 57 and 68 mm) was reduced by a proportion of between 1:6 and less than 1:15, depending on the artifact model and the mathematical method. The best corrections were obtained by the SCoRE method. Some recommendations about the experimental setup for functional calibration techniques and the choice of a mathematical method are derived from theoretical considerations about the formulas and the results of the experiment.

1. Introduction

The correct location of joints is crucial in many kinematic and kinetic analyses of human motion. This problem may be solved by predictive methods, based on the position of visible anatomical landmarks and regression equations, or by functional calibration techniques (FCT) that infer the joint position by analyzing a set of planned gestures (Della Croce et al., 2005). FCT are often preferred when the kinematic model chosen for the joint is a good approximation to reality and the range of motion is wide enough to ensure high accuracy. These two conditions are met by some human joints, most notably the hip and gleno-humeral joints, which may be modeled as "ball-and-socket" articulations and have the greatest ranges of motion (Cereatti et al., 2010; Karduna et al., 1996).

There is, however, controversy about the optimal mathematical approach to FCT. For the gleno-humeral joint in particular (GHJ), the International Society of Biomechanics (ISB) recommended calculating the pivot point of the instantaneous helical axes (Wu et al., 2005). A variation based on finite helical axes, to avoid inaccuracies and other problems in the derivation of velocities, has also been suggested (Halvorsen et al., 1999; Monnet et al., 2007). But in their comprehensive review, Ehrig et al. (2006) recommended the SCoRE method for estimating centers of rotation (CoR), on the basis of their results with numerical simulations. After that, others have compared the accuracy and repeatability of these methods applied to the GHJ, with diverging results (Lempereur et al., 2010; Monnet et al., 2007; Nikooyan et al., 2011).

This apparent inconsistency suggests that no method is generally superior, so it is necessary to take into account the nature of potential errors that may affect the calculation of CoR, and how they are propagated by each method, before choosing a specific procedure. Many evaluations of FCT have been done with simulations that added random noise to a theoretical motion (Camomilla et al., 2006; Ehrig et al., 2006, 2011), but such simulations do not provide an adequate representation of actual errors in FCTs (Sangeux et al., 2011). Such errors are chiefly due to soft tissue artifacts (STA), which are simulated in some cases as "continuous noise" signals, with sinusoidal or Gaussian motions added to marker positions (Begon and Lacouture, 2005; Begon et al., 2007), although STA do not generally follow those patterns (Cerveri et al., 2005). Other simulations use real motion patterns of individual markers that have been observed in previous studies (Halvorsen et al., 1999), or measured

* Correspondence to: Instituto de Biomecánica de Valencia, Universitat Politècnica de Valencia, Edificio 9C, Camino de Vera s/n, E-46022 Valencia, Spain. Tel.: +34 963879160; fax: +34 963879169.
E-mail address: helios.derosario@ibv.upv.es (H. De Rosario).

0021-9290/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jbiomech.2013.08.006

Nomenclature

$\mathbf{a}^T$	transpose of vector $\mathbf{a}$ (row vector)
$\mathbf{d}_{Xt}$	displacement of point X
$\mathbf{e}_t$	direction of the finite helical axis (unit vector)
$\mathbf{g}_t$	position vector of the marker cluster center
$\mathbf{I}$	identity matrix
$\mathbf{n}_t$	direction of angular velocity/instantaneous helical axis (unit vector)
$\mathbf{P}\{\cdot\}$, $\mathbf{S}\{\cdot\}$, $\mathbf{T}\{\cdot\}$	matrix operators—see definitions in (2), (3), and (9)
$\boldsymbol{q}_t = q_{wt} + \mathbf{q}_{vt}$	quaternion (scalar and complex vector components)
$\mathbf{R}_t$	rotation matrix
$\mathbf{r}_C$	position vector of the center of rotation
t	instant of time
$\mathbf{w}_t$	angular velocity
$\mathbf{u}_{Xt}$	normalized velocity at point X (divided by $\lvert\mathbf{w}_t\rvert$)
$\mathbf{v}_{Xt}$	velocity at point X
$\delta\mathbf{a}$	error (artifact) of the variable $\mathbf{a}$
θ_t	rotation angle
$\boldsymbol{\theta}_t$	orientation vector ($=\theta_t\mathbf{e}_t$)
ξ	phase variable
$\boldsymbol{\Omega}_t$	Rodrigues vector ($=\tan(\theta_t/2)\mathbf{e}_t$)

in a deformable mechanical analog (MacWilliams, 2008). However, real STA patterns can be modeled with fewer variables and independently of specific marker configurations, taking into account that the kinematic calculations are only affected by the rigid motion component, which is usually a function of the motion cycle (De Rosario et al., 2012).

The possibility of modeling STA as a function of joint kinematics (Camomilla et al., 2013) provides the opportunity of attempting their correction. This idea is the basis of techniques like the double calibration, whereby the motion of markers in the bone frame is linearly interpolated between previously measured positions at the ends of the motion cycle (Cappello et al., 2005; Brochard et al., 2011). The objective of this paper is to apply that idea to FCT, disentangling the underlying mathematics and defining formulas to correct CoR errors from STA models. Those formulas, validated with real data from a mechanical analog, are presented as the basis for informed decisions about what method may be more adequate in different situations, and strategies to reduce it.

2. Material and methods

2.1. Mathematical methods

Three different ways of calculating the CoR were considered. The supplementary material contains some mathematical proofs of the statements that are succinctly presented in this section.

To simplify the calculations, the proximal segment was considered to be fixed, so that all the kinematic variables represent the relative motion of the distal segment, as seen in the proximal reference frame. Quaternions were preferred to other ways of representing rotations like matrices, Euler angles or orientation vectors, because they allowed more compact mathematical models of CoR errors, although it would be possible to derive such models from any other representation. For any unit quaternion, its complex vector and real scalar components, $\mathbf{q}_{vt} = q_x\mathbf{i} + q_y\mathbf{j} + q_z\mathbf{k}$ and q_{wt} respectively, were defined by the rotation angle θ_t and the direction of the helical axis $\mathbf{e}_t$ as follows (Chou, 1992):

$$\mathbf{q}_{vt} = \sin\left(\frac{\theta_t}{2}\right)\mathbf{e}_t, \quad q_w = \cos\left(\frac{\theta_t}{2}\right) \tag{1}$$

The formulas for calculating the CoR presented in the following subsections include two special matrices. The skew-symmetric matrix $\mathbf{S}\{\mathbf{a}\}$ and the symmetric matrix $\mathbf{P}\{\mathbf{a}\}$ (where $\mathbf{a}$ is any column vector), which respectively define the cross product of $\mathbf{a}$ with another column vector, and the orthogonal projection on the plane normal to $\mathbf{a}$, scaled by the squared norm of that vector:

$$\mathbf{S}\{\mathbf{a}\} = \begin{pmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{pmatrix} \quad : \quad \mathbf{S}\{\mathbf{a}\}\mathbf{b} = \mathbf{a} \times \mathbf{b} \tag{2}$$

$$\mathbf{P}\{\mathbf{a}\} = \begin{pmatrix} a_y^2 + a_z^2 & -a_x a_y & -a_x a_z \\ -a_x a_y & a_x^2 + a_z^2 & -a_y a_z \\ -a_x a_z & -a_y a_z & a_x^2 + a_y^2 \end{pmatrix} = \lvert\mathbf{a}\rvert^2\mathbf{I} - \mathbf{a}\mathbf{a}^T \quad : \quad \mathbf{P}\{\mathbf{a}\}\mathbf{b} = -\mathbf{a} \times (\mathbf{a} \times \mathbf{b}) \tag{3}$$

2.1.1. Pivot of instantaneous helical axis (PIHA)

The method recommended by the ISB consists of calculating all the locations of the instantaneous helical axis during the calibration movements and finding the nearest point to them (Woltring, 1990). This is equivalent to solving the following matrix equation:

$$\left(\sum_t \mathbf{P}\{\mathbf{n}_t\}\right)\mathbf{r}_C = \sum_t \mathbf{S}\{\mathbf{n}_t\}\mathbf{u}_{Ot}, \tag{4}$$

where $\mathbf{r}_C$ is the position of the CoR, $\mathbf{n}_t$ is the unit vector of the angular velocity $\mathbf{w}_t$, and $\mathbf{u}_{Ot}$ is the velocity at the origin "normalized" by the amount of angular velocity, i.e:

$$\mathbf{n}_t = \frac{\mathbf{w}_t}{\lvert\mathbf{w}_t\rvert} \tag{5}$$

$$\mathbf{u}_{Ot} = \frac{\mathbf{v}_{Ot}}{\lvert\mathbf{w}_t\rvert} \tag{6}$$

Since errors are very sensitive for low angular velocities, the frames where $\lvert\mathbf{w}_t\rvert$ is lower than 0.25 rad/s are usually discarded (Monnet et al., 2007; Stokdijk et al., 2000).

2.1.2. Pivot of finite helical axes (PFHA)

The second method is a variant of the former, where the target point is the pivot of the finite helical axis (FHA), calculated from the displacement of skin markers with respect to a fixed, reference position (Woltring, 1985). It is often used to calibrate the hip joint center, but has also been applied to the GHJ (Lempereur et al., 2010). A weighting factor equal to $\sin^2(\theta_t/2)$ may be used for an optimal compensation of small rotation errors (Ehrig et al., 2006). Using quaternions and the translation of the origin $\mathbf{d}_{Ot}$, the PFHA equation with this weighting factor is similar to (4):

$$\left(\sum_t \mathbf{P}\{\mathbf{q}_{vt}\}\right)\mathbf{r}_C = \sum_t (q_{wt}\mathbf{S}\{\mathbf{q}_{vt}\} + \mathbf{P}\{\mathbf{q}_{vt}\})\frac{\mathbf{d}_{Ot}}{2}, \tag{7}$$

2.1.3. SCoRE

The SCoRE method does not look for a fixed point, but a pair of points, one of each linked segment, that keep a minimal distance during the motion, such that the CoR is defined as the midpoint between them. The original equation defined by Ehrig et al. (2006) may be rewritten as a function of the vectors and matrices described above:

$$\left(\sum_t \begin{pmatrix} \mathbf{P}\{\mathbf{q}_{vt}\} & -\mathbf{q}_{wt}\mathbf{S}\{\mathbf{q}_{vt}\} \\ q_{wt}\mathbf{S}\{\mathbf{q}_{vt}\} & \mathbf{T}\{\mathbf{q}_t\} \end{pmatrix}\right)\begin{pmatrix} \mathbf{r}_C \\ \Delta_C \end{pmatrix} = \sum_t \begin{pmatrix} q_{wt}\mathbf{S}\{\mathbf{q}_{vt}\} + \mathbf{P}\{\mathbf{q}_{vt}\} \\ q_{wt}\mathbf{S}\{\mathbf{q}_{vt}\} - \mathbf{T}\{\mathbf{q}_t\} \end{pmatrix}\frac{\mathbf{d}_{Ot}}{2} \tag{8}$$

where Δ_C is the vector that defines the distance between the two points, and $\mathbf{T}\{\boldsymbol{q}_t\}$ is defined for the quaternion $\boldsymbol{q}_t$ as:

$$\mathbf{T}\{\mathbf{q}_t\} = \mathbf{I} - \mathbf{P}\{\mathbf{q}_{vt}\} = q_{wt}^2\mathbf{I} + \mathbf{q}_{vt}\,\mathbf{q}_{vt}^T \tag{9}$$

2.1.4. Error estimation

If the CoR position were known beforehand, and the origin of coordinates were located at that point, $\mathbf{r}_C$, $\mathbf{u}_{Ot}$, and $\mathbf{d}_{Ot}$ would ideally be null. Thus, in the presence of