Journal of Biomechanics 48 (2015) 2019–2025

Contents lists available at ScienceDirect

Journal of Biomechanics

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

Can optimal marker weightings improve thoracohumeral kinematics accuracy?

Mickaël Begon [a,*], Fabien Dal Maso [a], Anton Arndt [b], Tony Monnet [c]

[a] Laboratoire de Simulation et Modélisation du Mouvement, Département de Kinésiologie, Université de Montréal, Laval, QC, Canada
[b] Karolinska Institutet and Swedish School of Sport and Health Sciences, Stockholm, Sweden
[c] Université de Poitiers, Institut Pprime, UPR 3346, CNRS Bvd M&PCurie, BP30179, Futuroscope Cedex 86962, France

ARTICLE INFO

Article history:
Accepted 25 March 2015

Keywords:
Arm
Local optimization
Skin markers
Kinematics
Intracortical pins

ABSTRACT

Local and global optimization algorithms have been developed to estimate joint kinematics to reducing soft movement artifact (STA). Such algorithms can include weightings to account for different STA occur at each marker. The objective was to quantify the benefit of optimal weighting and determine if optimal marker weightings can improve humerus kinematics accuracy. A pin with five reflective markers was inserted into the humerus of four subjects. Seven markers were put on the skin of the arm. Subjects performed 38 different tasks including arm elevation, rotation, daily-living tasks, and sport activities. In each movement, mean and peak errors in skin- *vs.* pins-orientation were reported. Then, optimal marker weightings were found to best match skin- and pin-based orientation. Without weighting, the error of the arm orientation ranged from 1.9° to 17.9°. With weighting, 100% of the trials were improved and the average error was halved. The mid-arm markers weights were close to 0 for three subjects. Weights of a subject applied to the others for a given movement, and weights of a movement applied to others for a given subject did not systematically increased accuracy of arm orientation. Without weighting, a redundant set of marker and least square algorithm improved accuracy to estimate arm orientation compared to data of the literature using electromagnetic sensor. Weightings were subject- and movement-specific, which reinforces that STA are subject- and movement-specific. However, markers on the deltoid insertion and on lateral and medial epicondyles may be preferred if a limited number of markers is used.

1. Introduction

Human movement kinematics is commonly assessed using stereophotogrammetry and skin-markers placed above bony landmarks. When skeleton kinematics is the subject of interest, the primary source of error in joint angles comes from the displacement of the skin-markers with respect to their underlying bones. This occurrence, termed soft tissue artifact (STA), is the consequence of muscle contraction, skin elasticity, impacts, etc. (Peters et al., 2010). Efforts have been made to reduce errors due to STA, which are usually assessed using invasive methods: *e.g.* intracortical pins (Andersen et al., 2010; Reinschmidt et al., 1997b) or fluoroscopy (Stagni et al., 2005), for a review see Leardini et al. (2005). Such method have been used to investigate the lower-limb STA (Akbarshahi et al., 2010; Cappozzo et al., 1996; Reinschmidt et al., 1997b; Tsai et al., 2009), but few investigations focused on upper-limb (Hamming et al., 2012b; Matsui et al., 2006). Since STA are different between segments, *e.g.* thigh *vs* shank (Benoit et al., 2006; Camomilla et al., 2009; Reinschmidt et al., 1997a; Stagni et al., 2005), further investigations are needed to identify suitable methods for reducing STA propagation to the upper-limb kinematics.

While marker sets exist for upper-limb use in conjunction with optoelectronics systems (Butler et al., 2010; Jackson et al., 2012), electromagnetic sensors are preferred in clinical studies for reasons of space and cost (Finley and Lee, 2003; Hamming et al., 2012a; Meskers et al., 1998; Stokdijk et al., 2003). Efforts have already been made to better track the scapula which slides under the skin (Lempereur et al., 2014). Regarding the humerus, errors up to 30° were reported in axial rotation due to STA (Hamming et al., 2012a) when using cuff mounted electromagnetic sensors. This error cannot be compensated for since one sensor on each segment does not provide any redundancy.

On the lower-limb, markers undergo different STA according to their location. On each marker, STA is composed of a rigid (or in-unison) component and a deformation (or own) component

---

[*] Corresponding author at: Laboratoire de Simulation et Modélisation du Mouvement, Département de Kinésiologie, Université de Montréal, 1700, rue Jacques Tétreault, Laval, QC, Canada H7N 0B6. Tel.: +1 514 343 6111x44017; fax: +1 514 343 2181.
E-mail address: mickael.begon@umontreal.ca (M. Begon).

http://dx.doi.org/10.1016/j.jbiomech.2015.03.023
0021-9290/

(Andersen et al., 2012; Grimpampi et al., 2014; Leardini et al., 2005). Some authors have proposed mathematical models representing STA (Camomilla et al., 2013; Dumas et al., 2014) and others used least squares algorithms to reduce STA (Cheze et al., 1995), especially the deformation component, in so-called local optimization algorithms. To reduce the rigid component and avoid joint dislocation problems, chain models with set degrees of freedom in combination with nonlinear least squares algorithms (Begon et al., 2009; Laitenberger et al., 2014; Lu and O'Connor, 1999) or extended Kalman filters (Fohanno et al., 2014; Halvorsen et al., 2004) (termed as global optimization) have emerged.

Since STA is not uniform within and between the body segments, these algorithms were improved by introducing weightings, in both global (Alonso et al., 2007; Ausejo et al., 2011; Begon et al., 2008) and local optimization (Andriacchi et al., 1998). Each marker weight can manually be adjusted in the musculoskeletal OpenSim software (Delp et al., 2007). Lu and O'Connor (1999) introduced a weighting matrix to reflect the error distribution among the markers. For simplicity, they chose equal weightings for all the markers at the same segments but smaller weightings to the thigh than the pelvis and shank. Indeed skin movement artefact is bigger on the thigh (Cappozzo et al., 1996). In their application to the upper-limb, Roux et al. (2002) refined the weightings with segmental residual errors given by the algorithm of Söderkvist and Wedin (1994). Unfortunately, to the best of our knowledge, weighting values, methods for their identification, and assessment of the gain in accuracy have never been provided for lower-limb or upper-limb.

The objective of this study was to assess the effect of skin marker weightings in a local optimization algorithm on arm orientation accuracy. First, optimal weightings for each skin marker were obtained based on a gold standard humeral orientation. Then optimal weightings obtained for each movement and each subject were applied to other movements and other subjects to determine if weightings are subject- and/or movement-specific.

2. Method

2.1. Experiment

Four male subjects (age: 32, 41, 44 and 27 years, height: 1.72, 1.82, 1.77 and 1.65 m, mass: 80, 115, 82 and 57 kg, and BMI 27, 35, 26 and 21 kg m^{-2}, for $S1$ to $S4$ respectively) volunteered after giving their informed consent. The protocol was approved by the ethic committees of both University of Montreal and Karolinska Institutet, where the experiment took place. As fully described in Dal Maso et al. (2014), an orthopaedic surgeon inserted a pin into the humerus under sterile surgery conditions. Five markers were secured on the pin (Fig. 1) to locate the humerus using an optoelectronic system (18 cameras, 2 and 4 Mpx at 300 Hz). The uncertainties of the segment position and orientation were estimated at 0.15 mm and 0.2°, respectively (Dal Maso et al., 2014). In addition, seven markers were put on the skin located as follows (Fig. 1B and C): (M_1) deltoid insertion, arm lateral (M_2) and medial (M_3) faces, on the middle arm over the triceps (M_4), under the insertion of the triceps tendon (M_5) and on the lateral (M_6) and medial (M_7) humeral epicondyles.

Each subject was instructed to hold a relaxed posture and to perform a series of (1) maximal arm elevations (elbow extended) with the arm in internal, neutral, and external rotation, as well as rotations (elbow flexed at 90°) at 30°, 60°, and 90° in ad-abduction and flexion–extension, (2) six daily living tasks, and (3) four sports activities. A total of 38 different movements were recorded. Ten trials were acquired during flexion, abduction, and rotation with the arm abducted at 0° and 90°, and during each daily-living task and sport activities. Only two trials for each movement were used for the subsequent analysis. Refer to the Supplementary materials for an enumeration (Table 3) and illustrations (Figs. 5 and 6) of movements performed in series 1.

2.2. Initial arm misorientation

No signal processing (smoothing or filtering) was applied to the marker trajectories. The humerus orientation in the global reference frame (${}^{G}R_h$) was obtained from pin-markers using a segmental optimization algorithm (Roosen et al., 2013, Appendix B) and previous recommendations (Monnet et al., 2010). Based on skin-markers, the arm orientation $\left({}^{G}R_a\right)$ was calculated using the said algorithm modified to include marker weightings as illustrated in Fig. 2. Initially the weightings were set to an equal value ($w_i = 0.378, \quad i = 1, \ldots, 7$ such that $\|\mathbf{w}\| = 1$).

In the relaxed posture, the humeral and arm orientations based on pin- and skin-markers respectively were mathematically superimposed and the markers' geometry served as a reference (t_0 in Fig. 2) for the segmental optimization algorithm. During the movements, the misorientation between ${}^{G}R_h$ and ${}^{G}R_a$ was calculated as the helical axis angle between skin and pin-based coordinates systems ${}^{h}R_a = \left({}^{G}R_h^{-1}\,{}^{G}R_a\right)$ (de Vries et al., 2010) as follows:

$$\theta = cos^{-1}\left(\frac{trace({}^{h}R_a) - 1}{2}\right), \qquad \theta \in [0, \pi] \tag{1}$$

The angle-time histories ($\theta_0(t)$) associated to the helical axis were calculated and the mean and peak error were reported.

2.3. Optimal weightings

Weightings ($\mathbf{w} = [w_1, \ldots, w_7]$) applied to markers ($M_i$ for $i = 1, \ldots, 7$) were optimized to minimize the error between the pin and skin-marker based matrices of rotation in the following constrained problem:

$$\min_{\mathbf{w}} J(\mathbf{w}) = \frac{1}{T}\sum_{t=1}^{T} {}^{G}R_h - {}^{G}R_a(\mathbf{w})_F$$

where for each frame t

$$\max_{R_a(\mathbf{w})^T R_a = I} tr\left[R_a \sum_{i=1}^{n} \left(\left(w_i\, p_i^t\right)\,\left(w_i\, p_i^{t_0}\right)^T\right)\right]$$

subject to

$$0 \le w_i \le 1, \qquad i = 1, \ldots, 7$$

$$\|\mathbf{w}\| = 1.$$

For computational efficiency, the Frobenius norm of the difference between the two rotation matrices ($\left\|{}^{G}R_h - {}^{G}R_a(\omega)_F\right\|$) was preferred to Eq. (1) in the fitness function. This problem with several local minima was solved using a hybrid optimization algorithm, which was run four times. The weightings associated to the fittest solution for each trial were retained. This two-step algorithm was

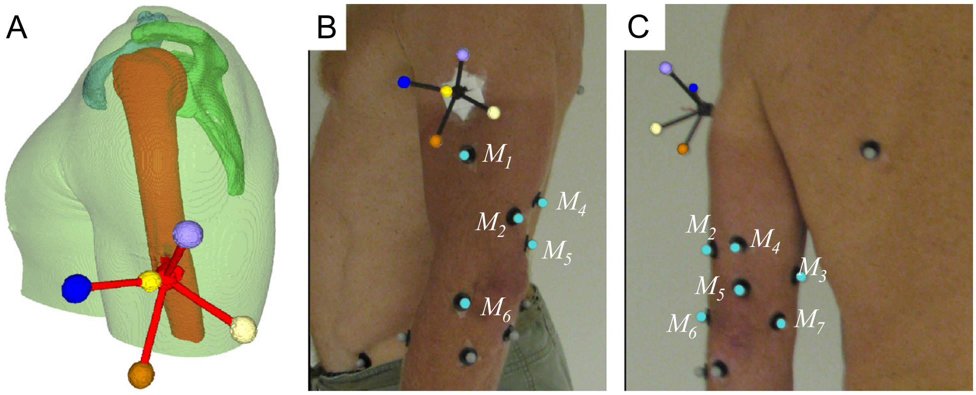

Fig. 1. Five markers are secured on a pin screwed in the humerus and seven markers (M_i) placed on the arm skin.