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Short communication

A hip joint kinematics driven model for the generation of realistic thigh soft tissue artefacts

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ABSTRACT

In human movement analysis, accuracy and robustness of the algorithms used to determine the location of centres of rotation from stereophotogrametric data depend mainly on their capacity to deal with the artefacts due to soft tissue deformation (STA). While evaluating these algorithms using a mathematical simulation approach, effectual realizations of STAs are needed. This study aimed at accomplishing this objective by modelling STAs, in twelve selected areas of the thigh, as a linear function of the hip angles, assuming no knee joint movement. The proposed model was calibrated and assessed using *ex-vivo* experiments. This entailed that only the component of the STA due to skin stretching was accounted for. Photogrammetric data of markers placed on the skin and on hip-bone and femur pins were recorded during passive flexion-extension, ab-adduction, rotation and circumduction of the hip joint. Artefact skin marker displacements were represented in a femur embedded anatomical frame. Model parameters were estimated by minimizing the least squares difference between measured and modelled STAs. The STA affecting a skin marker placed in a given thigh location of a given subject could be modelled with a high accuracy (median root mean square difference over 4 subjects × 3 trials × 12 markers × 3 coordinates: 0.8 mm—inter quartile range 1.0 mm). This was also true for a hip joint movement different from the one used to calibrate the model. High inter-subject variability of the model parameters confirmed the subject-dependency of the phenomenon.

1. Introduction

In physiological conditions, the relative movement between femur and the hip-bone can be assumed as a pure rotation (Cereatti et al., 2010), thus, reference may be made to a hip joint rotation centre (HJC). The HJC location can be estimated using a functional approach that consists in measuring, through stereophotogrammetry, the global trajectories of skin markers located on pelvis and thigh while the subject performs an *ad hoc* selected hip joint movement, HJM, (Begon et al., 2007; Camomilla et al., 2006). To this purpose, different algorithms have been proposed (Cappozzo, 1984; Cereatti et al., 2004; Cerveri et al., 2005; Chang and Pollard, 2007; De Momi et al., 2009; De Momi et al., 2012; Ehrig et al., 2006; Gamage and Lasenby, 2002; Halvorsen, 2003; Leardini et al., 1999; Marin et al., 2003; Piazza et al., 2004; Schwartz and Rozumalski, 2005; Siston and Delp, 2006; Stoddart et al., 1999). Despite the resources invested, the accuracy of HJC location estimates based on the functional method and non-invasive experimental set-ups is in the order of 20–30 mm (Cereatti et al., 2009; Hicks and Richards, 2005; Leardini et al., 1999; Sangeux et al., 2011). These values are regarded as unsatisfactory in most applications (Della Croce et al., 2005, Lenaerts et al., 2009; Stagni et al., 2000).

The accuracy of the HJC location estimate is jeopardized by many factors:

(a) instrumental errors;
(b) relative movement of the skin markers and the underlying bones (soft tissue artefact: STA) the characteristics of which vary depending on the markers location and on the HJM performed;
(c) marker cluster geometry;
(d) bi-directionality and amplitude of the trajectories of the thigh markers over the quasi spherical caps explored during the HJM and the density of their sampled positions on it;
(e) algorithm used.

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The identification and comparative validation of optimally performing experimental protocols and estimation algorithms must cope with all of these factors and is a complex endeavour that may be effectively approached using simulation (Camomilla et al., 2006; Chang and Pollard, 2007; Ehrig et al., 2006; Gamage and Lasenby, 2002; Halvorsen et al., 1999; Heller et al., 2011; Hicks and Richards, 2005; Siston and Delp, 2006). This approach requires the development of a model of the femur-pelvic bone system to generate error-free pelvis and thigh marker trajectories for a selected HJM and marker set. Realistic errors and artefacts are thereafter added to the ideal trajectories. By generating different data sets, accuracy and precision of the algorithms can be evaluated under different conditions. Within this scenario, the problem of producing realistic STAs arises (Camomilla et al., 2009). So far two simulation studies embedded realistic STAs (Gamage and Lasenby, 2002; Halvorsen, 2003), but they used data relative to 2D HJMs (Cappozzo et al., 1996). The objective of the present study was to devise and assess a mathematical model to generate these realistic STAs during a HJM of choice, for skin markers located in selected areas of the thigh. The proposed model was calibrated and assessed using experimental data obtained in a previous *ex-vivo* study (Cereatti et al., 2009).

2. STA model

2.1. Model architecture

Previous investigations of STAs concluded that the relationship between marker artefact and hip angular displacements is quasi-linear (Akbarshahi et al., 2010; Cappozzo et al., 1996). Based on this observation, the displacement vector components, relative to a reference position in a femur anatomical frame (AF: *x*, *y*, *z*), of a selected marker at time j was modelled as a linear function of the hip joint angles ($\alpha_j,\beta_j,\gamma_j$: flexion-extension, abduction-adduction and internal-external rotation, respectively):

$$\tilde{a}_{c,j}\left(\alpha_j,\beta_j,\gamma_j\right) = h_c^{\alpha}\alpha_j + h_c^{\beta}\beta_j + h_c^{\gamma}\gamma_j + h_c^{0} \quad c = x, y, z \quad j = 1..N \qquad (1)$$

where $h_c^{\alpha}, h_c^{\beta}, h_c^{\gamma}, h_c^{0}$ (in the following indicated as vector $\mathbf{h}_c$) are the 12 model parameters. The parameters h_c^{0} are determined so that the STA vector has a zero value when the subject assumes a reference posture (α_0, β_0, γ_0).

2.2. Model calibration

For a given subject *s*, trial *t*, and marker *k*, the model parameters are determined by minimizing a cost function based on the root mean square difference ($\mathrm{rmsd}_{s,t,k,c}$) between measured ($a_{s,t,k,c}$) and estimated STA ($\tilde{a}_{s,t,k,c}$) components

$$f(\mathbf{h}_{s,t,k,c}) = \begin{cases} \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left[a_{s,t,k,c,j} - \tilde{a}_{s,t,k,c,j}\left(\alpha_j,\beta_j,\gamma_j\right)\right]^2} & r_{s,t,k,c} > 0 \\ \infty & r_{s,t,k,c} < 0 \end{cases} \qquad (2)$$

where the correlation coefficient between these components ($r_{s,t,k,c}$) acts as penalty factor to exclude solutions resulting in STA displacements in a direction opposite to that of the real artefact.

If the data sets provided by *M* trials are used to calibrate the model, then the following objective function is used:

$$f(\mathbf{h}_{s,k,c}) = \sum_{t=1}^{M} f(\mathbf{h}_{s,t,k,c}) \qquad (3)$$

The optimization problem was solved using a global optimization algorithm (PatternSearch, Matlab®, MathWorks, Natick, MA).

3. Model validation

3.1. Experimental method

Experiments were carried out on four intact fresh adult cadaver subjects positioned supine (Table 1). Steel pins, equipped with four-marker clusters, were implanted into tibia, femur and hip-bones. In addition, 12 markers were glued on the thigh skin (Fig. 1). Details concerning the marker locations can be found in the supplementary material (Table 1s).

The markers instantaneous position in a global frame was reconstructed using a 9-camera stereophotogrammetric system (VICON MX—120 frames/second).

After performing anatomical landmark calibration (Fig. 1), three HJM trials were recorded for each subject. An operator slowly made the hip joint move as depicted in Fig. 2.

3.2. Data analysis

Tibia, femur and pelvis AF poses and knee and hip joint kinematics were determined consistent with the ISB convention (Wu et al., 2000) using the pin marker trajectories. STA vectors of the skin markers were reconstructed in the femoral AF as functions of time, and each peak-to-peak value determined and represented using box-plots with a five-number summary.

Table 1
Diameters of the proximal (S_p), median (S_m), and distal (S_d) sections of the thigh as indicated in Fig. 1. The length of the thigh (L_t) was measured as the distance between the centre of the femoral head (HJC) and the midpoint between the femoral epicondyles. Data in mm.

	Subj1	Subj2	Subj3	Subj4
S_p	161	132	114	190
S_m	123	111	96	151
S_d	105	106	101	123
L_t	396	360	411	364

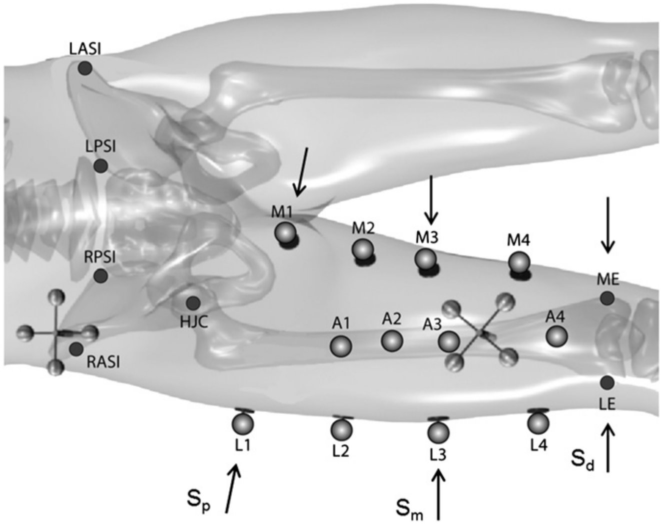

Fig. 1. Marker set-up along three longitudinal lines in antero-lateral (*L*), anterior (*A*), and antero-medial (*M*) positions. The following anatomical landmarks (dark circles) were calibrated using a pointer equipped with a cluster of four markers: right and left anterior superior iliac spines (RASI, LASI), right and left posterior superior spines (RPSI, LPSI), and lateral and medial femoral epicondyles (LE, ME). Diameters of the proximal (S_p), median (S_m), and distal (S_d) sections of the thigh are indicated (Table 1). The HJC was determined using a functional approach as described in Cereatti et al. (2009) and the pin markers.