A modal approach for the soft tissue artefact mathematical representation in optimal joint kinematics estimators

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A modal approach for the soft tissue artefact mathematical representation in optimal joint kinematics estimators

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Abstract- Soft tissue artefact (STA) compensation is the main problem when aiming at optimal bone-pose estimate. Given the complexity and specificity of this phenomenon, its compensation can only rely on its general features. This study aims at investigating the effect on joint kinematics estimation of different STA mathematical representations and related degrees of approximation. A modal approach and three different STA definitions (individual marker displacements, MD; marker-cluster geometrical transformations, GT; skin envelope shape variations, SV) were used. Direct measure of thigh and shank STAs from running volunteers, with both skin and pin markers, were used to test which representation and approximation allowed the best improvement of knee kinematics estimate. For both GT and SV definitions, rms errors in knee kinematics were reduced to below 10% of reference rms values, when eleven and fourteen modes were used to approximate thigh and shank STA, respectively.

Keywords- stereophotogrammetry; mathematical models; knee kinematics.

1. Introduction

Optimal bone pose estimators (and therefore joint kinematics estimators), that use data obtained through stereophotogrammetry and skin markers, aim at compensating for the so-named soft tissue artefact (STA). They should rely on a mathematical representation of the STA that adequately approximates it and embeds a sustainable number of parameters. Few models have been proposed, based on observable task-specific biomechanical features, such as joint angles; nevertheless, they either model STA in a simplistic fashion [1], or require the identification of too large a number of parameters [2]. In a model perspective, the number of these parameters should decrease while approximating the whole STA phenomenon taking into account its main features. For this purpose, STA time histories can be represented using a modal approach, allowing to split the STA field into additive components (or modes), associated with an STA definition: individual marker displacements (MD), marker-cluster geometrical transformations (GT), or skin envelope shape variations (SV) [3]. These modes can be ranked, according to their relative contribution to the whole phenomenon, and selected, leading to different degrees of approximation of the STA reconstruction [3]. From *in-vivo* running data [4], using both skin and pin markers, modes were defined and ranked for the three STA above-listed definitions. To find the most appropriate STA mathematical representation for embedment in a pose estimator, this study investigates how, for each STA definition, removing an increasing number of modes from STA, i.e. improving the STA approximation to be embedded in pose estimation, improves accuracy of joint kinematics estimates.

2. Material and Methods

Experimental data

Experimental data were collected from three male volunteers [4] (age 27.7 ± 2.1 years, mass 85.5 ± 9.6 kg, stature 186 ± 10 cm), who carried intracortical pins inserted into lateral tibial condyle and lateral femoral condyle with three markers on each pin. Five skin markers were glued on the thigh and four on the shank. A system of three video-cameras was used to track marker trajectories (sampling frequency: 200 frames/s). Five running stance phase trials were acquired for each volunteer and an additional static trial was captured in the upright posture. Intracortical pin marker-clusters and calibrated anatomical landmarks were used to define relevant anatomical reference frames (AFs) [5].

STA mathematical representations

For each segment *i*, reference STA vectors were reconstructed for the m_i skin markers in the corresponding relevant AF as function of time ($k = 1{:}n$) and used to build STA fields $\boldsymbol{V}_i(k)$. To split $\boldsymbol{V}_i(k)$ into additive components (modes: amplitude $a_i^l(k)$ and direction $\mathbf{\Phi}_i^l$), a modal approach was used considering the three STA definitions [3] (i.e., basis of vectors $\{\mathbf{\Phi}_i^l\}$) mentioned earlier: MD, GT, and SV. For each definition, in order to model STA with a sustainable number of parameters, STA fields must be represented with some approximation. This approximation can be performed limiting the number of modes used to model STA with the proposed mathematical representation. When a selected number of modes is embedded in a bone-pose estimator, the estimate is, thereafter, affected only by the residual portion of the phenomenon, not embedded in the model, and the accuracy of the relevant joint kinematics increases. This is assumed to be equivalent to removing the modeled portion of STA from skin marker trajectories ($\boldsymbol{V}_i(k)$).

For each STA definition, the contribution of each STA mode was evaluated. The modes were ranked according to their relative contribution (i.e., deformation energy) to the whole phenomenon. For each segment *i*, the deformation energy of each mode *l* was calculated as:

$$\lambda_i^l = \frac{1}{n}\sum_{k=1}^{n}\left(a_i^k(k)\right)^2 \qquad (1).$$

The total deformation energy (i.e., the energy due to all $3{*}m_i$ modes) of each segment *i*, was normalized by the relative number of markers, m_i. This normalization allowed to perform a single ranking in a decreasing order of both thigh and shank modes and the normalized deformation energies (λ_i^l/m_i) were summed one by one (i.e. cumulative representation). Ranked modes were sequentially removed from the respective thigh or shank STA field, mode by mode, according to the relative contribution to the whole phenomenon. For each definition, residual STA fields were obtained in an iterative way

$$\begin{gathered}\widetilde{\boldsymbol{V}}_i^1(k) = \boldsymbol{V}_i(k) - a_i^1(k)\,\mathbf{\Phi}_i^1\\ \widetilde{\boldsymbol{V}}_i^2(k) = \widetilde{\boldsymbol{V}}_i^1(k) - a_i^2(k)\,\mathbf{\Phi}_i^2\\ \vdots\\ \widetilde{\boldsymbol{V}}_i^{3*m_i}(k) = \widetilde{\boldsymbol{V}}_i^{(3*m_i)-1}(k) - a_i^{3*m_i}(k)\,\mathbf{\Phi}_i^{3*m_i}\end{gathered} \qquad (2),$$

thus representing an STA residual field with decreasing energy content.

Knee joint kinematics

Knee reference joint angles (flexion/extension, FE; abduction/adduction, AA; internal/external rotation, IER) were calculated at each frame of the trial using the relevant AFs and the Cardan convention [6]. Reference knee displacement components (lateral/medial, LM; anterior/posterior, AP; proximal/distal, PD) were calculated with a non-orthonormal projection on the joint coordinate system (i.e. the axes about which the joint angles were computed) of the vector going from the center of the epicondyles, as calibrated in the reference posture with respect to the femoral AF, to the same point calibrated with respect to the shank AF [7].

Knee kinematics were computed from raw data (i.e. from $\boldsymbol{V}_i(k)$) and for each STA definition (MD, GT, SV) for STA models with increasing level of approximation, i.e. for residual STA field with a decreased energy content, as obtained with (2). Using an SVD approach, technical reference frames were obtained from skin marker-clusters ($\boldsymbol{V}_i(k)$ or $\widetilde{\boldsymbol{V}}_i(k)$). To define AFs affected by residual STA fields, calibrated anatomical landmarks and technical reference frames were used to calculate knee kinematics [5]. For each of the kinematics estimates thus obtained, the rms distance from the reference kinematics was calculated. The effect of the STA field reduction was represented normalizing the rms distance of the STA propagation to knee kinematics with the rms value of the reference one (RMSE%).

Statistical analysis

Descriptive statistics were obtained representing the five-number summary statistics (minimum, lower quartile, median, upper quartile, and maximum) using box-plots. Inter-quartile ranges (IQR) were calculated as difference between upper and lower quartiles. Statistics were performed over all trials and volunteers.

3. RESULTS

Cumulative deformation energy values of the ranked thigh and shank modes for the mentioned STA definitions are shown in Fig. 1.

RMSE% median values, for knee kinematics calculated using raw data (i.e., from $\boldsymbol{V}_i(k)$), were 11% (IQR: 7%), 79% (IQR: 60%), 51% (IQR: 14%), for FE, AA, IER knee angles, respectively; for the same angles, reference median rms values were 22, 4 and 5 deg, respectively. Concerning LM, AP, PD knee displacements, RMSE% median values were 114% (IQR: 347%), 118% (IQR: 124%), 238% (IQR: 567%), and reference median rms values were 4, 5 and 5mm, respectively.

RMSE% values obtained for the knee kinematics using the proposed STA definitions and increasing levels of STA approximation are shown in Fig. 2-4. Results are shown only in the range from 0% to 100%, assuming that higher RMSE% values would in any case lead to totally unreliable kinematic estimates.

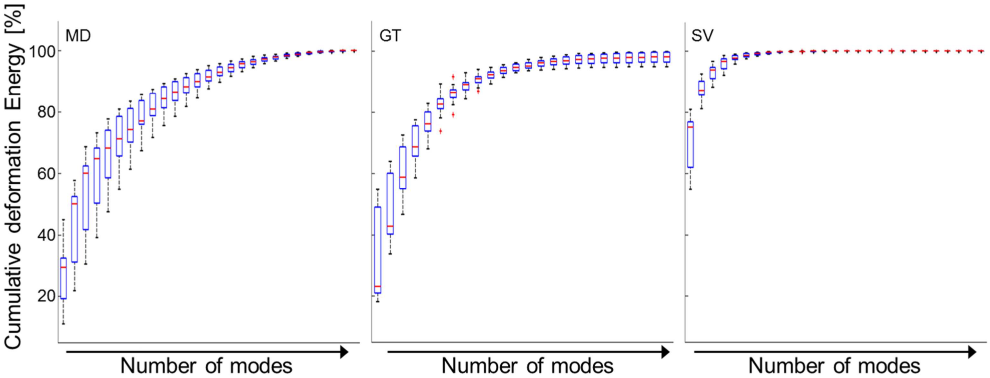

Figure 1. Box-plots of cumulative deformation energy, in percentage, normalized by the number of markers and the total deformation energy, for the thigh and shank segments, for the ranked modes (for each trial and volunteer) using the MD, GT and SV definition.

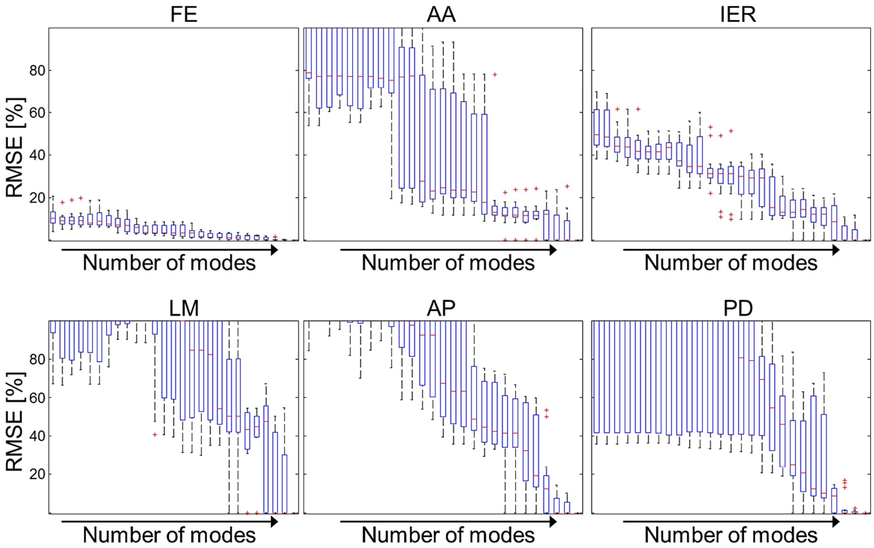

Figure 2. Box-plots of RMSE% values for the knee kinematics using the MD definition, removing from $\boldsymbol{V}_i(k)$ the ranked thigh and shank modes.

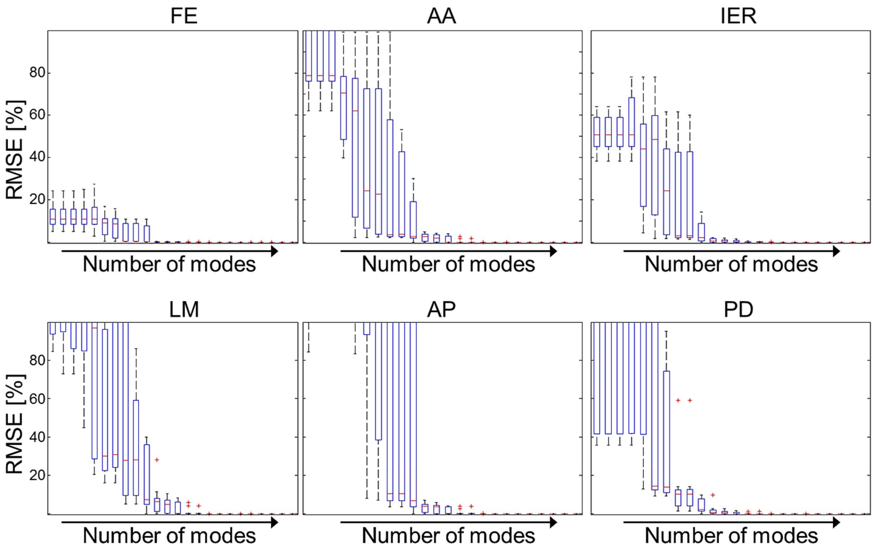

Figure 3. Box-plots of RMSE% values for the knee kinematics using the GT definition, removing from $\boldsymbol{V}_i(k)$ the ranked thigh and shank modes.

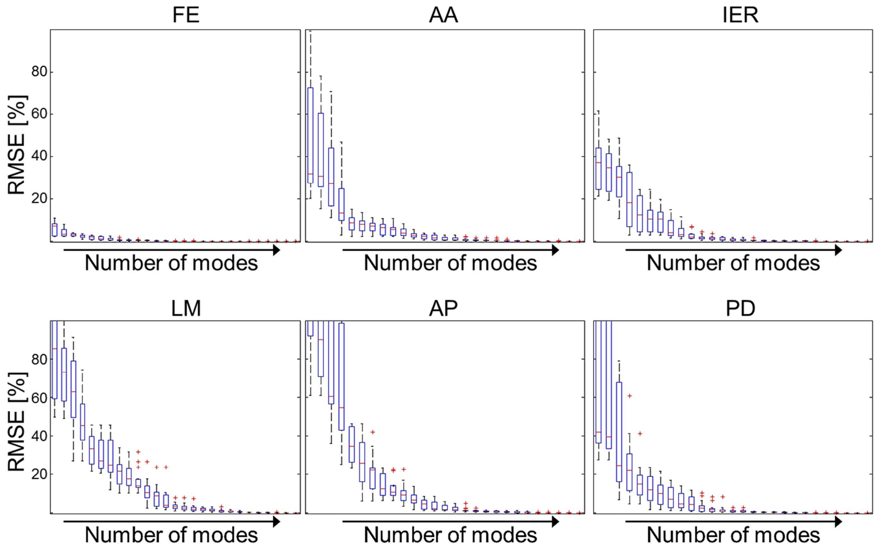

Figure 4. Box-plots of RMSE% values for the knee kinematics using the SV definition, removing from $\boldsymbol{V}_i(k)$ the ranked thigh and shank modes.

4. DISCUSSION

The aim of this study was to identify a STA definition and approximation able to grant reasonable joint kinematics accuracy while using a feasible number of parameters. For this purpose, the propagation to knee kinematics of STA residual fields with decreasing energy content was evaluated for three STA definitions. The RMSE% values of the knee kinematics have been shown to improve, when removing an increasing number of modes from $\boldsymbol{V}_i(k)$, for all the proposed definitions, but with different decreasing patterns.

Current results suggest that an appropriate number and type of modes could be selected by setting a threshold for the knee kinematics error reduction. To obtain a RMSE% value lower than 10%, all modes (27) are necessary for the MD definition (Fig. 2), whereas eleven modes for GT (Fig. 3) and fourteen modes for SV (Fig. 4) are sufficient. These modes represent 100%, 94% and 99% of the total STA deformation energy, for MD, GT and SV definition, respectively (Fig. 1). Therefore, MD definition does not seem to be the most appropriate modal approach to be embedded in bone pose estimators, exhibiting slower trend and moderate RMSE% value reduction as the number of modes increases, as compared to the other two definitions. The latters , instead, allow for an acceptable trade-off between STA compensation effectiveness and number of modes, relative to knee kinematics accuracy and the number of parameters. This opens an interesting scenario for further work to be performed by using the latter STA definitions in STA models for bone-pose estimators.

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