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WHEN ESTIMATING BONE POSE USING PROCRUSTES SUPERIMPOSITION, ONLY THE RIGID COMPONENT OF THE SOFT TISSUE ARTIFACT IMPACTS ON END RESULTS

T. Bonci^{1,2,3,4,5}, V. Camomilla^{4,5}, R. Dumas^{1,2,3,5}, L. Chèze^{1,2,3,5}, A. Cappozzo^{4,5}

Institutions:

¹ Université de Lyon, F-69622, Lyon, France

² Université Claude Bernard Lyon 1, Villeurbanne, France

³ IFSTTAR, UMR_T9406, Laboratoire de Biomécanique et Mécanique des Chocs (LBMC), F-69675, Bron, France

⁴ Department of Movement, Human and Health Sciences, Università degli Studi di Roma "Foro Italico", Rome, Italy

⁵ Interuniversity Centre of Bioengineering of the Human Neuromusculoskeletal System, Università degli Studi di Roma "Foro Italico", Rome, Italy

Introduction and Objectives: To reconstruct the pose of a bone in the 3D space, stereophotogrammetry and a skin-marker cluster are used. The movement between skin-markers and the underlying bone is regarded as an artefact (soft tissue artefact, STA) having devastating effects on end results. This STA can be described at marker-cluster level by a series of geometrical transformations, such as rotations and translations (cluster rigid motion: CRM), homotheties and stretches (cluster non-rigid motion: CNRM). Recent studies quantified these STA components [1]–[4], showing that CRM is normally predominant with respect to CNRM. Based on this observation, it is concluded, either explicitly or implicitly, that CNRM has a limited impact on bone pose estimation (BPE) and that STA compensation should concentrate on CRM. This study disputes the message carried by this statement and demonstrates that CNRM does not have a limited effect on BPE accuracy, but, rather, it has no effect whatsoever and that this is the case independently from its magnitude relative to CRM. For this reason, the only STA component to be compensated for is CRM.

Methods: The data obtained in [5] and relative to the trajectories of both skin and pin thigh markers recorded during 5 trials of each of 3 running subjects (S1, S2, S3) were used. For each trial and subject, a bone anatomical frame (AF) was defined, based on the pin markers, and the movement of four skin-markers reconstructed in the AF. Relevant displacement vectors were represented, in each k -th sample, as an STA vector field $V(k)$, ($k=1:n$) [6]. This field was decomposed into modes, by projecting it onto an orthogonal base of unit vectors chosen so that the first six modes represent rotations and translations (CRM), and the further six homotheties and stretches (CNRM) [6]:

$$V(k) = \sum_{l=1}^{12} a^l(k) \Phi^l$$

The energies associated with CRM and CNRM were calculated as

$$E_{\text{CRM}} = \sum_{l=1}^6 \left(\frac{1}{n} \sum_{k=1}^n (a^l(k))^2 \right)$$

and

$$E_{\text{CNRM}} = \sum_{l=7}^{12} \left(\frac{1}{n} \sum_{k=1}^n (a^l(k))^2 \right),$$

respectively.

The ratio between the former and the latter energy (R) was determined.

To assess the impact that CNRM has on BPE, a Monte Carlo Simulation was used to generate a set of one thousand STA fields that have the same CRM and amplified CNRMs:

$$V_S(k) = \sum_{l=1}^6 a^l(k) \Phi^l + r \sum_{l=7}^{12} a^l(k) \Phi^l$$

The amplification factor r was randomly generated in the range from 1 to $2\sqrt{R}$ so that the mean CNRM energy of this set was equal the CRM counterpart. Then, the CRM components were removed from both the measured and the amplified STA fields, generating STA fields affected only by the real,

$$\mathbf{V}_N(k) = \mathbf{V}(k) - \sum_{l=1}^6 a^l(k) \Phi^l,$$

and simulated CNRM,

$$\mathbf{V}_{SN}(k) = \mathbf{V}_S(k) - \sum_{l=1}^6 a^l(k) \Phi^l$$

Results

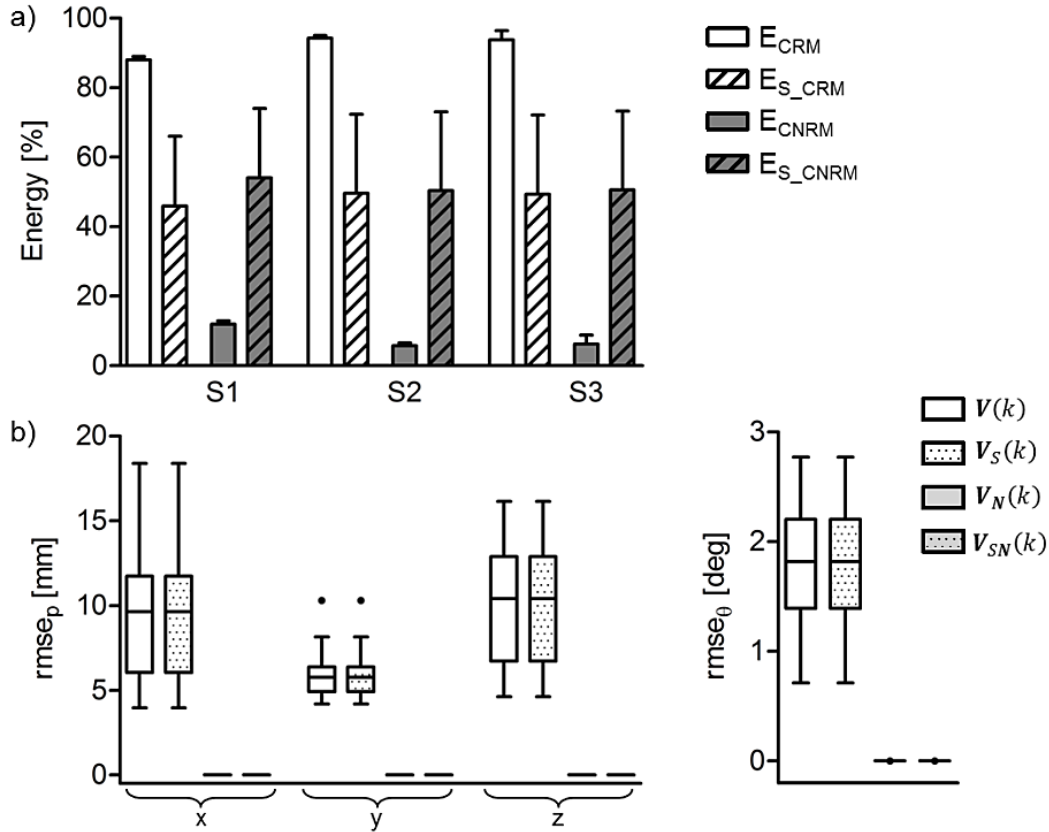


Figure – a) Mean values of the CRM and CNRM energy in percentage of the total energy, for the measured (E_{CRM} and E_{CNRM}) and simulated STA (E_{S_CRM} and E_{S_CNRM}). Statistics performed over all trials and subjects (S1, S2, S3). b) Box-plots (minimum, lower quartile, median, upper quartile, and maximum) of the BPE errors, for position and orientation, relative to all the STA fields available.

Discussion: Skin-marker trajectories were generated from the reference AF pose and the STA fields available ($V(k)$, $V_S(k)$, $V_N(k)$, $V_{SN}(k)$). These trajectories were used to estimate the artefact-affected pose of the AF in the global reference frame with a Procrustes Superimposition (PS) approach. The root mean square difference between the artefact-affected and reference AF pose was calculated and considered as an error (rmse_θ, and rmse_{px}, rmse_{py}, rmse_{pz}, for orientation (attitude angle) and position components, respectively).

The median (inter-quartile range) values of the R factors were 7(1), 18(4), and 14(15), for S1, S2 and S3, respectively. Obviously, the CNRM amplification caused an increase in the energy percentage of this component with respect to the total energy: mean (\pm standard deviation) values went from $8\pm 3\%$ ($V(k)$) to $52\pm 22\%$ ($V_S(k)$) (Fig. a).

Before and after the amplification of CNRM, errors in pose estimation were exactly the same (although the total STA energy increased) (Fig. b). In all cases, after removing CRM, not altered throughout the simulation, the error was null.

The results empirically showed that, using a PS approach, only CRM has an impact on the accuracy of the BPE, independently of the amplitude of CNRM. Moreover, after removing CRM, the real p was obtained. It

must be acknowledged that a reference pose obtained with pin markers was used to compute the modes and to remove CRM from skin-marker trajectories. In the present context, this choice does not constitute a limitation, but does simply show that the CNRM has no effect on BPE. Results suggest that, in a STA compensation perspective, future work should be focused on modelling and removing only CRM.

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