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Rigid and non-rigid geometrical transformations of a marker-cluster and their impact on bone-pose estimation

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ABSTRACT

When stereophotogrammetry and skin-markers are used, bone-pose estimation is jeopardised by the soft tissue artefact (STA). At marker-cluster level, this can be represented using a modal series of rigid (RT; translation and rotation) and non-rigid (NRT; homothety and scaling) geometrical transformations. The NRT has been found to be smaller than the RT and claimed to have a limited impact on bone-pose estimation. This study aims to investigate this matter and comparatively assessing the propagation of both STA components to bone-pose estimate, using different numbers of markers.

Twelve skin-markers distributed over the anterior aspect of a thigh were considered and STA time functions were generated for each of them, as plausibly occurs during walking, using an *ad hoc* model and represented through the geometrical transformations. Using marker-clusters made of four to 12 markers affected by these STAs, and a Procrustes superimposition approach, bone-pose and the relevant accuracy were estimated. This was done also for a selected four marker-cluster affected by STAs randomly simulated by modifying the original STA NRT component, so that its energy fell in the range 30–90% of total STA energy.

The pose error, which slightly decreased while increasing the number of markers in the marker-cluster, was independent from the NRT amplitude, and was always null when the RT component was removed. It was thus demonstrated that only the RT component impacts pose estimation accuracy and should thus be accounted for when designing algorithms aimed at compensating for STA.

1. Introduction

When bone-pose is estimated using non-invasive stereophotogrammetry, skin markers move with respect to the underlying bone, generating the soft tissue artefact (STA). This source of error is regarded as a major issue in movement analysis (Leardini et al., 2005; Peters et al., 2010).

Given four or more markers arranged in a cluster, a sequence of four independent geometrical transformations (GTs) can be used to describe the STA that affects it (Benoit et al., 2015; Dumas et al., 2014; Grimpampi et al., 2014): a translation and a rotation, representing the rigid transformation (RT), and a change of size and shape, representing the non-rigid transformation (NRT). These components were quantified on humans while performing various motor tasks (Andersen et al., 2012; Barré et al., 2013; Grimpampi et al., 2014; Benoit et al., 2015; de Rosario et al., 2012; Dumas et al., 2015) and on a sheep (Taylor et al., 2005), showing that the magnitude of the RT is most often greater than that of the NRT. Based on this observation it has been concluded, either explicitly or implicitly, that the STA NRT component has a limited impact on bone-pose estimation and that STA compensation should concentrate on the marker-cluster RT.

Bone-pose estimators described in the past do not reduce the propagation of the cluster RT to their end results (Alexander and Andriacchi, 2001; Andriacchi et al., 1998; Challis, 1995; Chèze et al., 1995; Dryden and Mardia, 1998; Heller et al., 2011; Taylor et al., 2005; Veldpaus et al., 1988), and are considered totally unsatisfactory for reconstructing all bone displacements that occur during function (Carman and Milburn, 2006; Cereatti et al., 2006; de Rosario et al., 2013). For this reason, using plate-mounted

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markers that remove the NRT component while enhancing applicability, would not improve accuracy (Garling et al., 2007).

In order to solve these issues, advanced bone-pose estimators must be designed that embed mathematical models to estimate the STA during the motor act being analysed (Bonci et al., 2014; Camomilla et al., 2009, 2013, 2015). This estimate of the STA would be used to correct the recorded marker trajectories. In the perspective of designing these bone-poses, so that the inherent optimisation problem converges to the correct solution, it is important to mathematically represent the STA using the minimum number of parameters. This complexity reduction entails accounting only for that portion of the artefact which has a major impact on the end results (Dumas et al., 2015). In addition, since it may be supposed that a redundancy in the number of markers forming the cluster would be beneficial, the question arises as to whether and to what extent increasing this number affects mathematical complexity.

Dumas et al. (2014) showed that a modal approach mathematically represents the STA at marker-cluster level as a series of twelve independent modes, six of which describe the RT and six the NRT. The STA is fully described by this series only when the cluster is formed by four markers. The present study tackles the hypothesis that the loss of information caused by this mathematical representation of the STA with clusters of more than four markers would have a minimal impact on STA-compensated bone-pose estimation, and is thus sustainable.

The other objective of this study was to prove the hypothesis that, when the pose estimator is based on a Procrustes superimposition approach (Dryden and Mardia, 1998; Söderkvist and Wedin, 1993; Spoor and Veldpaus, 1980), as is normally the case, the marker-cluster NRT does not have a limited effect on bone-pose accuracy, as claimed in the literature, but, rather, it has no effect whatsoever. This is the case independently from the number of markers included in the cluster and the relative magnitude between NRT and RT.

In order to demonstrate this hypotheses, the paradigmatic case of the thigh STA generated during walking was used in association with a simulation approach, to explore the impact on bone-pose estimation error caused by STAs characterized by RT and NRT in different proportions, and the use of marker-clusters formed by different numbers of markers.

2. Materials and method

2.1. Generation of reference and artefact-affected data

The time functions of pelvic-bone, femur and tibia anatomical frame (AFs; Fig. 1) pose, acquired during a level walking cycle of an able-bodied adult in a

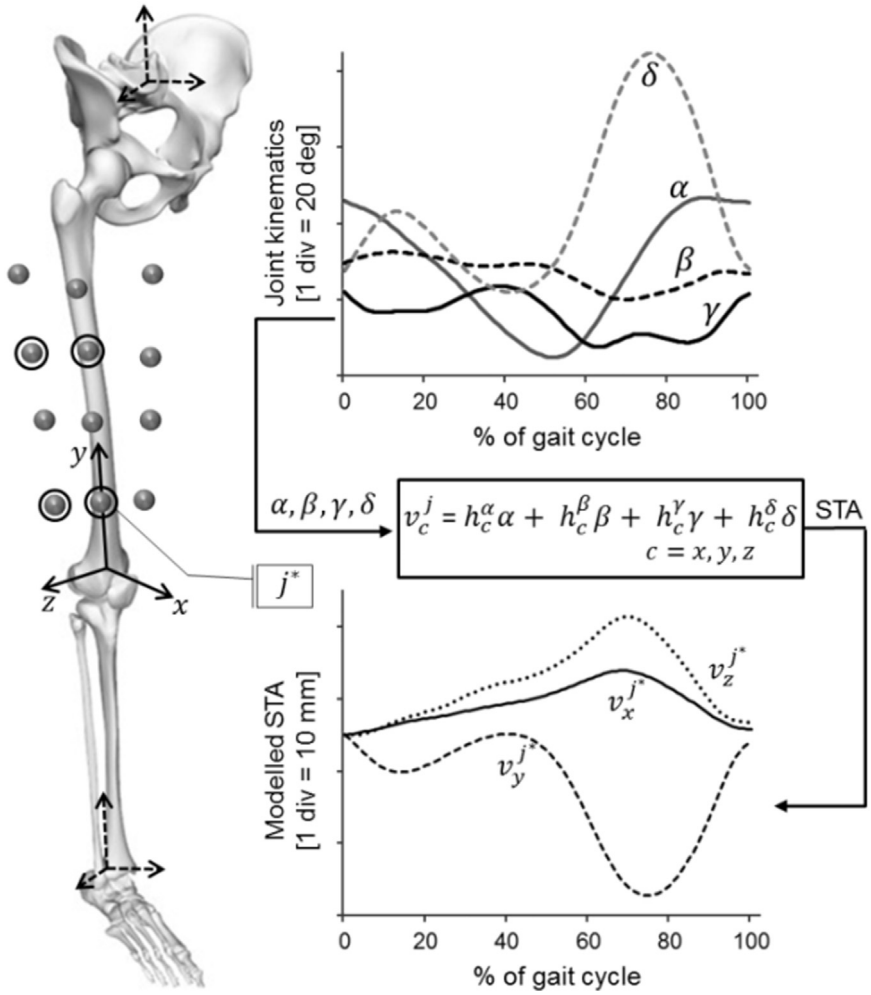

Fig. 1. Skin-marker locations on the thigh segment are shown. The pelvic-bone, femur and tibia anatomical frames are also indicated. The time-histories of hip (α – flexion/extension, β – ab/abduction, γ – internal/external rotation) and knee (δ – flexion/extension) angles, generated during gait and used as input for the soft tissue artefact model, are shown. The model used to estimate the STA for the skin marker indicated with j^* is also reported. The circled skin-markers are those used in the Monte Carlo simulation described in Section 2.4.