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Bone orientation and position estimation errors using Cosserat point elements and least squares methods: Application to gait

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ABSTRACT

The aim of this study was to analyze the accuracy of bone pose estimation based on sub-clusters of three skin-markers characterized by triangular Cosserat point elements (TCPEs) and to evaluate the capability of four instantaneous physical parameters, which can be measured non-invasively *in vivo*, to identify the most accurate TCPEs. Moreover, TCPE pose estimations were compared with the estimations of two least squares minimization methods applied to the cluster of all markers, using rigid body (RBLS) and homogeneous deformation (HDLS) assumptions. Analysis was performed on previously collected *in vivo* treadmill gait data composed of simultaneous measurements of the gold-standard bone pose by bi-plane fluoroscopy tracking the subjects' knee prosthesis and a stereophotogrammetric system tracking skin-markers affected by soft tissue artifact. Femur orientation and position errors estimated from skin-marker clusters were computed for 18 subjects using clusters of up to 35 markers. Results based on gold-standard data revealed that instantaneous subsets of TCPEs exist which estimate the femur pose with reasonable accuracy (median root mean square error during stance/swing: 1.4/2.8 deg for orientation, 1.5/4.2 mm for position). A non-invasive and instantaneous criteria to select accurate TCPEs for pose estimation (4.8/7.3 deg, 5.8/12.3 mm), was compared with RBLS (4.3/6.6 deg, 6.9/16.6 mm) and HDLS (4.6/7.6 deg, 6.7/12.5 mm). Accounting for homogeneous deformation, using HDLS or selected TCPEs, yielded more accurate position estimations than RBLS method, which, conversely, yielded more accurate orientation estimations. Further investigation is required to devise effective criteria for cluster selection that could represent a significant improvement in bone pose estimation accuracy.

1. Introduction

In the process of the estimation of a bone orientation and position (pose) from a marker cluster attached to the skin using optoelectronic stereophotogrammetry, the accuracy is greatly compromised by the relative motion between the skin markers and the underlying bone, which is defined in the literature as the soft tissue artifact (STA) (Leardini et al., 2005). STA is caused by a combination of skin stretching and sliding, muscle contractions, gravity and inertial effects (Leardini et al., 2005; Peters et al., 2010). Commonly used bone pose estimators (BPEs) define an appropriate marker cluster model and match the model with the measured marker trajectories at each time step by solving a least squares (LS) minimization problem constraining the cluster transformation to a translation and a rotation, with or without uniform scaling (Cappello et al., 1996; Challis, 1995; Söderkvist and Wedin, 1993; Spoor and Veldpaus, 1980). This technique has been implemented in numerous studies according to the framework of Procrustes analysis, and will be referred to in this paper as rigid body least squares (RBLS). Alternatively, the transformation can be approximated by a translation and a general non-singular tensor, which permits homogeneous deformation (including stretching and shearing). This approach was implemented in several studies under the framework of affine mapping (Ball and Pierrynowski, 1998; Dumas and Chèze, 2009; Solav et al., 2014), and will be referred to in this paper as homogeneous deformation least squares (HDLS). RBLS and HDLS generally obtain different

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