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The SCoRE residual: A quality index to assess the accuracy of joint estimations

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ABSTRACT

The determination of an accurate centre of rotation (CoR) from skin markers is essential for the assessment of abnormal gait patterns in clinical gait analysis. Despite the many functional approaches to estimate CoRs, no non-invasive analytical determination of the error in the reconstructed joint location is currently available. The purpose of this study was therefore to verify the residual of the symmetrical centre of rotation estimation (SCoRE) as a reliable indirect measure of the error of the computed joint centre.

To evaluate the SCoRE residual, numerical simulations were performed to evaluate CoR estimations at different ranges of joint motion. A statistical model was developed and used to determine the theoretical relationships among the SCoRE residual, the magnitude of the skin marker artefact, the corrections to the marker positions, and the error of the CoR estimations to the known centre of rotation. We found that the equation $err=0.5r_s$ provides a reliable relationship among the CoR error, err, and the scaled SCoRE residual, r_s, providing that any skin marker artefact is first minimised using the optimal common shape technique (OCST). Measurements on six healthy volunteers showed a reduction of SCoRE residual from 11 to below 6 mm and therefore demonstrated consistency of the theoretical considerations and numerical simulations with the *in vivo* data.

This study also demonstrates the significant benefit of the OCST for reducing skin marker artefact and thus for predicting the accuracy of determining joint centre positions in functional gait analysis. For the first time, this understanding of the SCoRE residual allows a measure of error in the non-invasive assessment of joint centres. This measure now enables a rapid assessment of the accuracy of the CoR as well as an estimation of the reproducibility and repeatability of skeletal motion patterns.

1. Introduction

The accurate quantification of skeletal motion is not only important for the assessment of abnormal gait patterns caused by skeletal disorders such as cerebral palsy (Röhrle et al., 1987; Bowsher et al., 1993), but also plays a key role in predicting musculoskeletal loading (Heller et al., 2001, 2003; Taylor et al., 2004, 2006) and the functional evaluation of therapy outcomes (Cappozzo, 1983). Marker-based motion capture has therefore become a common approach for the collection of kinematic data (Leardini et al., 1999), with clinical applications focused on using skin markers to derive internal bone motion (Benoit et al., 2005; Stagni et al., 2005). The reconstruction of skeletal kinematics, however, is limited by the relative motion of the skin markers over the underlying bones (Cappozzo et al., 1990), an error referred to as soft tissue artefact (STA).

In order to reduce the errors in determining skeletal kinematics caused by this soft tissue artefact, a number of numerical approaches have been presented (Andriacchi et al., 1998; Lu and O'Connor, 1998; Cappello et al., 2005). By generating a rigid marker configuration from the complete segment marker data, the optimal common shape technique (OCST) (Taylor et al., 2005) removes any motion of the markers relative to one another—an artefact generally associated with muscle firing and skin elasticity. The advantages of this approach have been demonstrated directly against skeletal motion using bone pin data in sheep, but how these findings relate to the conditions in humans remains unknown because the assessment of segment and skeletal motion in sheep was restricted by the limited range of joint motion during normal gait and the magnitude of skin marker artefact. Whether, and to what extent, application of the OCST improves

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identification of the human hip joint centre (HJC) and thus the assessment of skeletal motion, however, has not been investigated in detail (Kornaropoulos et al., 2010; Taylor et al., 2010).

In combination with techniques for reducing skin marker artefact, functional approaches that identify joint centres and axes using the motion of one segment relative to the other, have been proposed as a key element for increasing the accuracy in the non-invasive determination of skeletal motion (Cappozzo, 1984; Leardini et al., 1999; Piazza et al., 2001; Halvorsen, 2003; Schwartz and Rozumalski, 2005). Although sphere fitting approaches may be the most accurate in determining CoRs if one segment is fixed in space or no STAs are present (Ehrig et al., 2006; MacWilliams, 2008; Cereatti et al., 2009), the use of the symmetrical centre of rotation estimation (SCoRE) (Ehrig et al., 2006) has been demonstrated to be the most accurate technique when both segments move simultaneously. First applications *in vivo* demonstrate that the SCoRE method can also be successfully applied for the functional determination of the glenohumeral joint (Monnet et al., 2007). Furthermore this specific numerical approach has also been shown to work significantly faster than other CoR approaches (Rozumalski and Schwartz, 2008).

One severe limitation of analyses to determine skeletal kinematics is the ability to evaluate their accuracy *in vivo* (Rettig et al., 2009). Since anatomical data is generally not available, gait analyses do not commonly include subject specific anatomical reference information (Kirkwood et al., 1999; Peters et al., 2010), and are therefore reliant upon the marker data alone. A rapid evaluation of the accuracy of the position of a spherical joint from captured skin marker motion data alone could offer benefits such as improved interpretation of the functional data, the early recognition of measurement errors, and a quantification of the quality of the reconstructed joint in post-processing applications. Such a quality measure could therefore offer additional reliability to ensure that any differences found in clinical longitudinal studies are indeed due to changes in patient functional outcome rather than differences in the evaluation set-up, including marker placement or system calibration.

As a result of the minimisation task to optimally determine joint centres using SCoRE, it is possible to calculate a residual value, and therefore an assessment of the divergence of the joint motion compared to a joint that moves in a perfectly spherical manner. In this study, we tested the hypothesis that this SCoRE residual can provide a reliable quantitative assessment of joint quality, and further, that application of the OCST to reduce skin marker artefact is able to improve the identification of the hip joint centre using the SCoRE residual as a quality measure.

2. Materials and methods

2.1. Overview of methodological strategy

To evaluate the SCoRE residual as an indirect measure of the quality of the computed joint position, a series of numerical simulations was performed at different ranges of joint motion (RoMs) using Gaussian distributions of skin marker artefact. An additional statistical model was developed and used to determine the theoretical relationships among the SCoRE residual, the magnitude of the skin marker artefact, the corrections to the marker positions, and the error of the CoR estimations to the known centre of rotation. Both the numerical simulations and the statistical model were then extended to consider the additional application of the OCST to the SCoRE determination of joint centres. Finally, a set of six *in vivo* measurements were performed to verify that the theoretical relationships fit into the framework of the experimental results. These steps are described more completely in the following sections.

2.2. The symmetrical centre of rotation estimation (SCoRE) residual

The SCoRE is an algorithm to determine the centre of rotation of spherical joints and is based on the fact that a joint centre is stationary in each segment's local coordinate system (Ehrig et al., 2006). In the following sections, we use the same terminology as introduced in that study. If the transformations, i.e. rotations and translations, (R_i,t_i), (S_i,d_i), $i=1,\ldots,n$, where n is the total number of time frames, from the local segment coordinates to a global system for each time frame are known, the optimal CoR can be obtained by solving the over-determined linear least squares problem

$$\begin{pmatrix} R_1 & -S_1 \\ \vdots & \vdots \\ R_n & -S_n \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} d_1 - t_1 \\ \vdots \\ d_n - t_n \end{pmatrix} \tag{1}$$

where c_1 and c_2 are the centres of rotation in the local coordinate systems. In the following we will abbreviate Eq. (1) as $Ac=b$. After transformation into an appropriate global system, both centre representations $c_{1,i}=R_ic_1+t_i$, $c_{2,i}=S_ic_2+d_i$ will coincide for all time frames i, as long as the motion of the segments perfectly describes spherical circumvention around a common centre. Thus the magnitude $r=(c_{1,1}-c_{2,1},\ldots,c_{1,n}-c_{2,n})^T=Ac-b$ should be a useful measure for the expected error of the result. In fact, mathematically, r is exactly the so-called residual of the underlying linear least squares problem. We therefore use the scaled residual $r_s=r/\sqrt{n}$, which is a measure of the deviation of the joint estimations from a perfectly joint (as described in Eq. (1)) per time frame.

2.3. Optimal common shape technique (OCST)

The OSCT is an approach to reduce the effect of soft tissue artefact (Taylor et al., 2005) that uses a so-called Procrustes analysis (Dryden and Mardia, 2002) to determine a common rigid marker configuration that fits optimally to the marker positions over all time frames. Its efficacy has been demonstrated *in vivo* in sheep studies (Taylor et al., 2005), but until recently (Kornaropoulos et al., 2010; Taylor et al., 2010) had little exposure for gait analysis in humans. A brief description of the approach is provided here: The OCST uses both the generalised and the ordinary (Veldpaus et al., 1988) Procrustes analyses to determine the optimal common configuration of the markers and to transform this configuration into each time frame, respectively. The ordinary Procrustes analysis fits one marker configuration $(p_1^1,\ldots,p_1^m)$, $p_1^k\in\mathbf{R}^3$, of m markers, into a second configuration $(p_2^1,\ldots,p_2^m)$ by a rotation matrix R and a translation t. This leads to the least squares problem

$$\min_{R\in SO(\mathrm{a}),t\in\mathbf{R}^3}\sum_{k=1}^{m}||Rp_1^k+t-p_2^k||^2$$

that can be solved using singular value decomposition (see e.g. Söderkvist and Wedin, 1993).

In an extension of this ordinary Procrustes analysis, the generalised Procrustes analysis or OCST is used to generate the mean configuration of the markers that fits optimally to all marker configurations $1,\ldots,n$ simultaneously. For this purpose the sum of the squared norms of all pair-wise differences of the appropriate transformed configurations is minimised

$$\min_{R_i,t_i}\sum_{i=1}^{n}\sum_{j=i+1}^{n}\sum_{k=1}^{m}||(R_ip_i^k+t_i)-(R_jp_j^k+t_j)||^2$$

For this task, there are no direct solution methods, but effective iterative algorithms can be employed (Dryden and Mardia, 2002). The resulting optimal mean configuration, defined by

$$\overline{p^k}=\frac{1}{n}\sum_{i=1}^{n}(R_ip_i^k+t_i)$$

which replaces the actual configurations of each frame using a back transformation with the ordinary Procrustes analysis.

2.4. Relationship between the SCoRE residual and the error of the estimated CoR

In this study, a statistical model has been developed to understand the theoretical relationships between the SCoRE residual, the absolute CoR error, the OCST marker corrections, and the magnitude of the STA. This model assumed a set of markers with an independent, isotropic, and identically distributed Gaussian noise. Using the probability distribution of the marker positions, it was possible to derive a distribution of induced marker errors, as well as an expected value for the magnitude of the OCST correction. While full details and derivation of the mathematical relationships can be found in the online supplementary material, only a brief summary is provided here: It is possible to yield a direct relationship between the mean CoR error in global coordinates and the SCoRE residual:

$$err=\frac{||r||}{2\sqrt{n}}\left(1+\frac{2}{\sqrt{6}}\sqrt{\sum_{i=1}^{6}\frac{1}{s_i^2}}\right)=\frac{||r_s||}{2}\left(1+\frac{2}{\sqrt{6}}\sqrt{\sum_{i=1}^{6}\frac{1}{s_i^2}}\right) \tag{2}$$

where $s_1,\ldots,s_6$ are the singular values of the matrix A in Eq. (1). In most situations, the second term in the brackets in Eq. (2) can be ignored, since the sum is