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Short communication

Assessment of anatomical frame variation effect on joint angles: A linear perturbation approach

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ABSTRACT

Although the interpretability and reliability of joint kinematics depends strongly on the accuracy and precision of determining the anatomical frame (AF) orientation, the exact dependency of joint angle error on AF misalignment is still not clear. To fully understand the behavior, this study uses linear perturbations to quantify joint angle error due to known modifications of the AFs, where the joint angles are calculated according to the Cardanic convention. The result is a functional representation of joint angle error with dependence on nominal joint angles and on the orientations of the alternative AFs relative to the nominal AFs. The results are validated using numerical analysis on knee joint angle data during walking. The derived relationship elucidates results from previous work studying this effect and allows AF differences to be inferred by joint angle curves when multiple sets of joint angle curves are collected simultaneously.

1. Introduction

Accurate quantification of three-dimensional joint orientation is a fundamental concern in kinematic studies related to orthopaedics and rehabilitative medicine. In biomechanics, joint rotations can be quantified by comparing the relative orientation between anatomical frames (AFs) established in body segments immediately distal and proximal to the joint. Axes of AFs are often defined from body-surface anatomical marker positions through various anatomical calibration procedures (Cappozzo et al., 1995; Ferrari et al., 2008; Della Croce et al., 2003; Donati et al., 2007). However, determination of their positions with high accuracy and precision through palpation has been recognized as a difficult problem (Della Croce et al., 2005; Donati et al., 2007). The inaccuracies in the identified anatomical landmarks will propagate to the orientation of the corresponding AFs. As axes from the AFs are often used as the rotational axes of the joint involved, the inaccuracy in the AF determination will introduce distortions of the joint angles (kinematic crosstalk), hindering the repeatability and interpretability of the joint kinematics. Recognizing the importance of AF determination on reliable joint kinematics assessment, a number of studies have investigated the joint angle sensitivity to AF orientation variations (Kadaba et al., 1990; Ramakrishnan and Kadaba, 1991; Fioretti et al., 1997; Della Croce et al., 1999; Piazza and Cavanagh, 2000; Della Croce et al., 2005; Chéze, 2000; Most et al., 2004).

These studies experimentally or numerically considered how joint angle waveforms are sensitive to either changes to rotational axes or to marker uncertainty. The mathematical tools for describing errors in both the 3-D attitudes and Eulerian conventions were developed by Woltring (1994), but were only applied to find the magnitude of errors, not their direct effect on joint angle waveforms. A complete description of joint angle error dependence on AF determination under the Cardanic convention still does not exist. The present study uses linear perturbation techniques with numerical validation to mathematically describe the error propagation to joint angles due to all possible anatomical frame orientation variations.

2. Methods

The description of the proximal and distal AFs that follow is for the right knee (Fig. 1) and can be easily applied to other joints. Let T and F denote the nominal AFs for the tibia and femur segments. Let $\tilde{T}$ and $\tilde{F}$ be a second system of AFs, which could differ from T and F due to differing conventions for defining anatomical frames or the difficulty in precisely identifying AFs from manually palpated anatomical landmarks. The four frames and their relationships are shown in Fig. 1. Three nominal joint angles (flexion/extension (γ), abduction/adduction (α), and internal/external rotation (β)) can be determined from the AFs F and T through a Cardan sequence of rotations (Cappozzo et al., 2005). The alternative joint angles $\tilde{\gamma}, \tilde{\alpha}$, and $\tilde{\beta}$ can be determined similarly from $\tilde{F}$ and $\tilde{T}$.

2.1. Perturbations of anatomical frame definitions

The nominal and alternate AFs are related by rotation matrices $R_{T\tilde{T}}$ and $R_{F\tilde{F}}$. Following the results of Woltring et al. (1985), these matrices can be approximated by the sum of the identity matrix and a skew-symmetric matrix. A standard

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