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Methodological analysis of finite helical axis behavior in cervical kinematics

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ABSTRACT

Although a far more stable approach compared to the six degrees of freedom analysis, the finite helical axis (FHA) struggles with interpretational difficulties among health professionals. The analysis of the 3D-motion axis has been used in clinical studies, but mostly limited to qualitative analysis. The aim of this study is to introduce a novel approach for the quantification of the FHA behavior and to investigate the effect of noise and angle intervals on the estimation of FHA parameters. A simulation of body movement has been performed introducing Gaussian noise on position and orientation of a virtual sensor showing linear relation between the simulated noise and the error in the corresponding parameter.

FHA axis behavior was determined by calculating the intersection points of the FHA with a number of planes perpendicular to the FHA using the Convex Hull (CH) technique. The angle between the FHA and each of the IHA was also computed and its distribution was also analyzed.

Input noise has an inversely proportional relationship with the angle steps of FHA estimation. The proposed FHA quantification approach can be useful to provide new approaches to researchers and to improve insight for the clinician in order to better understand joint kinematics.

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1. Introduction

The complexity of three-dimensional joint motion analysis has resulted in an extensive amount of methodologies for the analysis of the kinematics.

At each moment in time, a continuously moving rigid body may be viewed as having a translation velocity and a rotation velocity about a directed line in space (see Fig. 1a). The position of this instantaneous helical axis (IHA) will generally vary during the movement, and the movement is completely known once the translation and rotation velocities and the position of the helical axis are known over time.

The helical axis approach defines a movement as a rotation angle, Θ, around the axis, described by a direction vector, $\mathbf{n}$, the point $\mathbf{c}$ on the axis closer to the origin, and the translation $\mathbf{t}$ along the axis (Söderkvist et al., 1993; Spoor and Veldpaus, 1980) (see Appendix A for details).

The most common method used to describe joint motion is the use of a six degrees of freedom (6DoF) approach, which consists in the decomposition of the movements into three translation along the corresponding Cartesian axis, and three rotation angles around them. The coordinate system generally used for the study of the spine spans the frontal, sagittal and transverse planes (Kettler et al., 2004). The three Euler angles (angles describing the orientation of a rigid body) can therefore be called lateral bending, flexion–extension and axial rotation angles (Wu et al., 2002) see (Fig. 1b–d).

In the clinical field, computation of movement axis is considered to be a determinant parameter for analyzing the quantity of motion (Dugailly et al., 2010). Some authors have reported aberrant location of instantaneous axis in the sagittal plane for patients with cervical complaints, and alterations of axis location and orientation were observed in whiplash patients (Grip et al., 2008, Woltring et al., 1994). Thus, the relationship between neck pain and irregularities of kinematic patterns could characterize movement impairments in patients.

Although the description of spinal motion by the use of Euler angles is readily understood, the respective predefined axes mostly do not reflect the actual rotary axes of the joint. Furthermore, variations in the localization of the axes reduce the reproducibility of results and may lead to an over- or underestimation of angle values, called "crosstalk effect" (Chao, 1980). For this reason, the Euler angles often require a predefined anatomical coordinate

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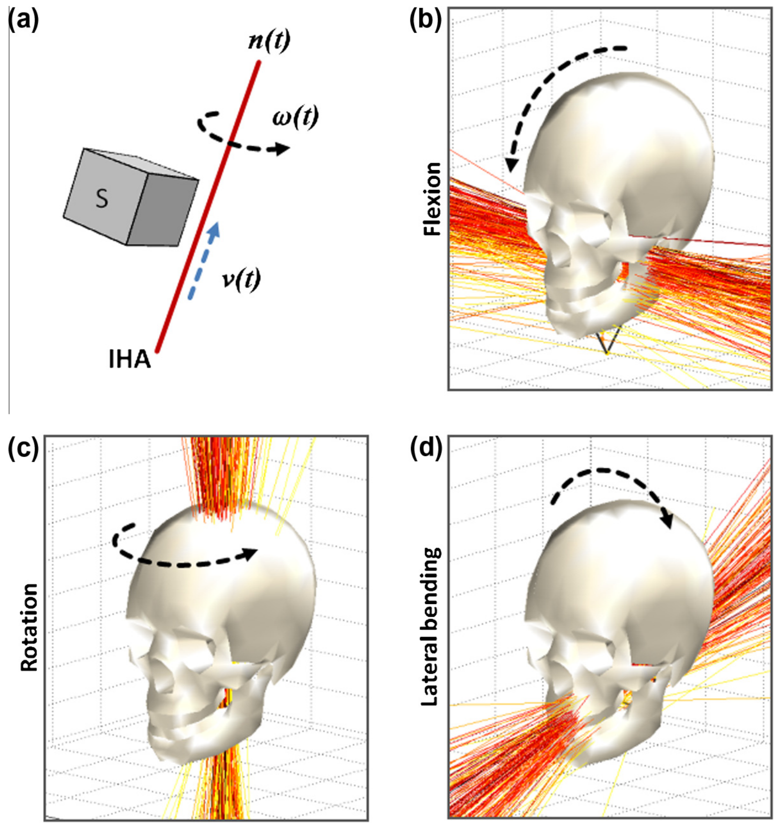

Fig. 1. (a) Representation of the instantaneous helical axis (IHA) of an object with an instantaneous angular velocity $\omega(t)$ and linear velocity $\boldsymbol{v}(t)$. The inclination of the IHA is represented by vector $\boldsymbol{n}(t)$ (b–d) representation of the movements of the head around the Euler axis: flexion extension, rotation and lateral bending respectively. The IHA superimposed are the results of the analysis of a representative subject.

system according to the joint they describe and the three angles are sequence dependent. This problem is most evident in the case of large, coupled vertebral motions.

On the other hand, most studies exploring the IHA tend to produce good qualitative results, but quantitative results are often lacking (Blankevoort et al., 1990; Baillargeon and Anderst, 2013). Graphical representations of the IHA have been used in many different studies and add to an easier interpretation. The location of the knee axis of motion has been extensively discussed from a clinical and orthopedic point of view (Asano et al., 2005; Mannel et al., 2004a,b; Marin et al., 2003; Sheehan, 2007; Van Sint Jan et al., 2002; Wismans et al., 1980; Woltring et al., 1985). Spine motion analysis using the IHA has shown to provide a useful method for the analysis of complex segmental and regional 3D-motions (Cripton et al., 2001; Dugailly et al., 2010; Kettler et al., 2004; Milne, 1993).

The dispersion of the 3D-motion axis has been used to express the stability of the motion in cervical spine and in knee and ankle joint analysis (Graf and Stefanyshyn, 2012; Grip and Häger, 2013; Osterbauer et al., 1992; Panjabi, 1979; Woltring et al., 1994). The position and orientation in space of the IHA can be defined by a number of parameters, and the dispersion of each of the parameters has been recently used to compare different movements (Grip and Häger, 2013). Most of the studies investigated the intersections of IHA with predefined planes or their inclination with respect to anatomical landmarks (Asano et al., 2005; Baillargeon and Anderst, 2013; Cripton et al., 2001). To date there is no attempt to describe the localization of a group of IHA in space during a movement without the need of a 3D reconstruction of the bones of the joint.

Since the helical axis is a differential quantity (measuring infinitely small change in a variable), most users have approximated the IHA with the so called finite helical axis (FHA) which is estimated from a single finite displacement (Blankevoort et al., 1990) (Fig. 2a).

The main drawback in the use of FHA is the sensitivity to noise, since the errors in FHA estimation are inversely proportional to the magnitude of displacement. On the other hand, small increments are necessary to approximate finite displacements with continuous movements. A simplified theoretical analysis of error propagation was proposed by Spoor and collaborators (1980) on a subset of data obtained with stereophotogrammetry, but no indications were provided about the intervals for optimal FHA estimation.

The aim of this study is to evaluate the effect of measurement noise and intervals between frames on FHA parameters and to propose two parameters for the analysis of FHA which are not dependent on the anatomical landmarks and on the type of movement, and that could have direct application in the analysis of cervical spine kinematics.

2. Methods

This study is divided in three parts:

(a) Evaluation of the effect of noise and angle intervals on the estimation of FHA parameters.
(b) Quantification of FHA behavior.
(c) Application of FHA parameters to cervical kinematics.

For the analysis, an orthogonal dextral coordinate system was used with anterior, superior and right being positive (**x**, **y** and **z**-directions, respectively), as recommended by the International Society of Biomechanics (Wu et al., 2002).

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