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Representation of planar motion of complex joints by means of rolling pairs. Application to neck motion.

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Abstract

We propose to model planar movements between two human segments by means of rolling-without-slipping kinematic pairs. We compute the path traced by the instantaneous center of rotation (ICR) as seen from the proximal and distal segments, thus obtaining the fixed and moving centrodes, respectively. The joint motion is then represented by the rolling-without-slipping of one centrode on the other. The resulting joint kinematic model is based on the real movement and accounts for nonfixed axes of rotation; therefore it could improve current models based on revolute pairs in those cases where joint movement implies displacement of the ICR. Previous authors have used the ICR to characterize human joint motion, but they only considered the fixed centrode. Such an approach is not adequate for reproducing motion because the fixed centrode by itself does not convey information about body position. The combination of the fixed and moving centrodes gathers the kinematic information needed to reproduce the position and velocities of moving bodies. To illustrate our method, we applied it to the flexion-extension movement of the head relative to the thorax. The model provides a good estimation of motion both for position variables (mean R_{pos}=0.995) and for velocities (mean R_{vel}=0.958). This approach is more realistic than other models of neck motion based on revolute pairs,such as the dual-pivot model. The geometry of the centrodes can provide some information about the nature of the movement. For instance, the ascending and descending curve of the fixed centrode suggests a sequential movement of the cervical vertebrae.

1. Introduction

The modeling of human motion is relevant for its applications in clinical and ergonomic fields. In whole-body models, even complex joints such as the lumbar spine, shoulder complex or neck are usually simplified to just one or two lower pairs whose axes pass through a fixed point (Goossens and Snijders, 1995; Petuskey et al., 2007; Willinger, 2005). However, several studies have shown that complex joints have a moving axis of rotation even in simple motions, such as flexion-extension (Woltring et al., 1994, Page et al., 2009a, Page et al., 2010). This limitation can be avoided by modeling complex articulations with a higher number of lower pairs (Van der Helm et al., 1992), or including all vertebrae as segments of the model (Himmetoglu et al., 2007; de Zee et al. 2008). Such models improve realism at the expense of introducing kinematic redundancy and complexity, which limits their usefulness for clinical routine or ergonomic applications.

A different approach uses the instantaneous helical axis (IHA) to characterize joint movements (Leardini et al.,1999; Wolf and Degani 2007; Grip et al., 2008). Nevertheless, the IHA does not actually provide a joint model because the IHA by itself does not represent relative position and orientation. These features need to be evaluated by a separate finite displacement analysis. The equivalent of the IHA in planar motion is the instantaneous center of rotation (ICR).

In this paper, we use both finite and instantaneous displacements to provide a geometrical model of planar motions. This model is obtained as a higher kinematic pair constituted by the proximal and distal centrodes as the one rolls without slipping on the other (Reuleaux, 1876), thus being compatible with a nonfixed ICR. The fixed and moving centrodes are the curves traced by the ICR as seen from the proximal and distal segments, respectively.

The rolling-without-slipping pair (subsequently called "rolling pair") is a one degree-of-freedom (DOF) model. The theoretical basis for modeling a complex joint as a one-DOF pair is provided by the concept of functional DOFs (fDOF) (Li, 2006). A human movement is said to have one fDOF when all degrees of freedom are coordinated such that all the kinematic variables can be expressed as functions of only one independent DOF.

The model is illustrated with an experimental study of neck flexion-extension movement. We tested the goodness of the rolling pair model and compared it with a model based on two revolute pairs (Woltring et al., 1994).

2. Methods

2.1. Kinematc model

A planar motion can have up to three DOFs: a rotation angle, θ, and the two components of the displacement of a given point G, $\Delta\mathbf{R}_G$, on the plane of motion. However, natural movements are coordinated, so these variables do not vary independently. In the theoretical case that the condition of having one fDOF is satisfied, it is possible to express the kinematic variables as a function of the joint angle $\theta(t)$ and its time derivative $\dot{\theta}(t)$ (Page et al., 2010):

$$\Delta\mathbf{R}_G = \Delta\mathbf{R}_G(\theta) \tag{1}$$

$$\mathbf{w} = \dot{\theta}\,\mathbf{u} = w\,\mathbf{u} \tag{2}$$

$$\mathbf{v}_G = \frac{d\mathbf{R}_G}{d\theta}\,\dot{\theta} = \mathbf{v}_S(\theta)\,w \tag{3}$$

where $\mathbf{w}$ and $\mathbf{v}_G$ are the angular and linear velocities respectively, $\mathbf{u}$ is the unit vector perpendicular to the plane of motion and $\mathbf{v}_S$ is a standardized velocity representing

the displacement of G per unit of joint rotation. The location of ICR, H is given by (Figure 1a):

$$\mathbf{GH}(\theta) = \frac{\mathbf{w} \times \mathbf{v}_G}{w^2} = \frac{\dot{\theta}\mathbf{u} \times \dot{\theta}\mathbf{v}_S}{\dot{\theta}^2} = \mathbf{u} \times \mathbf{v}_S(\theta) \quad (4)$$

As the motion occurs, point H traces a planar curve called the fixed centrode. The moving centrode is the curve traced by the ICR of the relative motion of the proximal segment as seen from the distal one, H_1. This curve can be computed by applying the finite displacement $\{-\theta\mathbf{u}, -\Delta\mathbf{R}_G\}$ to the distal body at the current position (Figure 1b). Point H therefore moves "backwards" to H_1 (Page et al 2009b):

$$\mathbf{HH}_1 = -\Delta\mathbf{R}_G - \sin\theta\ \mathbf{u} \times \mathbf{GH} + (1 - \cos\theta)\ \mathbf{u} \times (\mathbf{u} \times \mathbf{GH}) \quad (5)$$

The movement can be reproduced exactly as the rolling-without-slipping motion of the moving centrode on the fixed one.

In practice, the relation between $\Delta\mathbf{R}_G$ and θ is not completely single-valued due to variability across repetitions of the same motion. For this reason, it is necessary to obtain an average motion that represents the typical motion performed by a subject when repeating the same movement a number of times (Page et al., 2010). The rolling pair is thus obtained from this averaged movement.

2.2. Experiment

The model has been applied to the neck flexion-extension movement in order to illustrate its usefulness. Twelve healthy volunteers participated in the study (6 male, 6 female) aged between 25 and 65 (mean=43.6 years old, SD=13.3 years old). All subjects signed an informed consent form.

Subjects sat on a chair with their back upright and firmly held against the backrest by means of straps (Baydal-Bertomeu et al., 2007). Each subject performed several cycles of flexion-extension at a self-selected speeed for 30s, starting from a neutral posture.

Head position and movements were recorded using stereophotogrammetry (Kinescan©, Page et al., 2009b) with passive markers fixed onto a helmet. Three additional markers were placed in the ears and at the C7 apophysis in order to have anatomical references.

A 3D kinematic analysis was performed by using the procedures described in Page et al. (2009b). From these 3D variables we checked the hypothesis of one fDOF and planar motion and then computed the centrodes that represented the averaged movement across cycles (Page et al., 2010). The centrodes were computed from this averaged movement.

The rolling pair model was compared with the dual pivot model, which represents the neck joint by means of two revolute pairs, one at the level of the center of C7-T1 and the other at the C1 level (Woltring et al. 1994). The instantaneous values of joint angles were computed from photogrammetric measures.

3. Results

Table 1 summarizes the results of the experiment. The adjustment between measured and fitted kinematic variables is good ($R_{pos} = 0.995$; $R_{vel} = 0.958$). The results confirm the hypothesis of a single fDOF.

With regard to the planar motion hypothesis, the deviation between $\mathbf{w}(t)$ and $\mathbf{u}$ was small in all subjects $(p95(\alpha) = 3.9^{o})$. Moreover, linear and angular velocities were perpendicular throughout the range of movement in all cases $(p95(\beta) = 2.1^{o})$.

113 Fig. 2 shows the centrodes for a subject, plotted at the reference posture. This
114 picture is animated in the electronic version in order to show the field of standardized
115 velocities at each position.

116 Fig. 3 shows the trajectories of anatomical point O (the midpoint of markers located
117 at ear canals) for the same subject as in Fig. 2. As seen in the plot, the dual pivot model
118 introduces some bias into the trajectory of point O. In contrast, the rolling pair model is an
119 unbiased model. The average error of the rolling pair model is approximately half of that of
120 the dual pivot model $(1.00\ vs\ 1.95\ cm)$.

121 **4. Discussion**

122 The proposed model is an extension of the analysis of movements based on the IHA.
123 Studies on the IHA have shown their potential in clinical applications but they have not
124 been oriented to modeling motion, since the IHA does not by itself convey information
125 about body position. However, the combination of the fixed and moving axodes (centrodes
126 in planar movement) gathers the kinematic information needed to reproduce the position
127 and velocities of moving bodies in any configuration.

128 The results show a good adjustment of both position and velocities variables, better
129 than provided by the dual pivot model, a representation of the neck by two revolute pairs
130 which is widely used in kinematic and dynamic applications (Woltring et al., 1994;
131 Willinger et al., 2005).

132 The rolling pair approach has previously been used for designing knee prostheses
133 (Freudenstein and Woo, 1969, Hobson and Torfason, 1975). Our method extends this
134 concept to model planar motions of complex joints under the hypothesis of a single fDOF.

135 The condition of planar motion has been verified in many studies of joint kinematics
136 based on IHA (Woltring et al., 1994, Page et al., 2009). Regarding the restriction of one

fDOF, there are several examples of movements of complex joints that exhibit only one fDOF (Leardini et al., 1999; Page et al., 2008; Page et al., 2010). In this paper we have verified that these hypotheses also apply to the flexion-extension neck movement.

In any case, both conditions are implicitly accepted in all models that represent human joints with revolute pairs. The proposed model does not introduce any additional restrictions but, on the contrary, accounts for nonfixed axes of rotation, and therefore can improve current models based on revolute pairs in those cases where the actual ICR moves over the range of movement.

Although the rolling pair does not provide detailed information about the motion of internal structures, it is possible to extract some information about the nature of the movement from the shape of the centrodes. For instance, the inverted U shape of the fixed axode (present for all measured subjects) suggests a sequential movement of the vertebrae starting with the higher vertebrae at the neutral position and following with the lower vertebrae at the positions of maximum extension and flexion. This fact is illustrated in Fig. 4 and it has been previously observed in lumbar flexion-extension (Page et al., 2009a).

The estimation of IHA (or ICR) location is very sensitive to soft tissue artifacts. Therefore, this model is useful in those cases in which artifacts are negligible or can be efficiently controlled, e.g. neck flexion-extension (Woltring et al., 1994), lumbar flexion-extension (Page et al., 2009a) or shoulder abduction-aduction (Page et al., 2010). Its application to knee or ankle joints will perhaps need kinematic data from in-vitro experiments (Leardini, et al., 1999; Wolf and Degani, 2007) or the use of other experimental techniques that can provide a good estimation of bone motion, e.g. intracortical pins or fluoroscopy (Dennis et al., 2005).

Conflict of interest statement

The authors have no conflicts of interest related to this work.

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FIGURE LEGENDS

Fig. 1. a) The position of the distal body with respect to a reference position is given by the joint angle θ and the displacement of a given point G, $\Delta\mathbf{R}_G(\theta)$. Infinitesimal displacements are described by means of angular and linear velocities, $\mathbf{w}$ and $\mathbf{v}_G$, respectively. b) The fixed centrode is the curve described by point H, H_0H. It depends on the instantaneous variables. We can obtain the moving centrode at the reference position, H_0H_1, by applying the finite displacement $-\{\theta\ ;\ \Delta\mathbf{R}_G\}$ to the distal segment. Then point H moves to H_1.

Fig. 2. Centrodes of the neck flexion-extension movement of a subject, represented at the neutral position ($\theta = 0^o$) . The fixed centrode is plotted as the solid black curve; the moving centrode is the dotted black curve. As the head moves from the neutral position, the moving axode rolls without slipping over the fixed axode. The skull and spinal structures are figurative representations (no radiographs were taken), based on the locations of the anatomical markers.

Fig. 3. Measured and estimated path of anatomical point O (the midpoint of markers located at the ears). The rolling pair model (grey solid line) provides an unbiased estimation of the mean path, corresponding to the averaged trajectory obtained in the process of averaging across cycles. In contrast, the dual pivot model assumes a fixed axis of rotation at C7-T1 level, therefore the length of C7-O is constant. This introduces a bias in the estimation of the path of point O and increases the RMS error.

Fig. 4. Interpretation of the sequential movement of vertebrae from the shape of the centrodes. The motion of the head relative to the thorax can be decomposed into a set of small angular displacements of each vertebra with regard to the one below, the axes of which are approximately on the intervertebral discs. In the picture, we represent these angular vectors as circles with their radius proportional to the magnitude of the angle. The measured global motion is the sum of all intervertebral rotations, with a global ICR located at the centroid of that system (Page et al, 2009a). (a) In the neutral position the ICR is located at the top of the fixed centrode, H_N, near C1; therefore the global motion at this position is mainly caused by the contribution of the upper vertebrae. (b) As the neck flexes, the ICR moves down on the fixed axode to H_F; this implies a downwards sequential motion of vertebrae. The skull and spinal structures are figurative representations (no radiographs were made), based on the locations of the anatomical markers.

Figure 1
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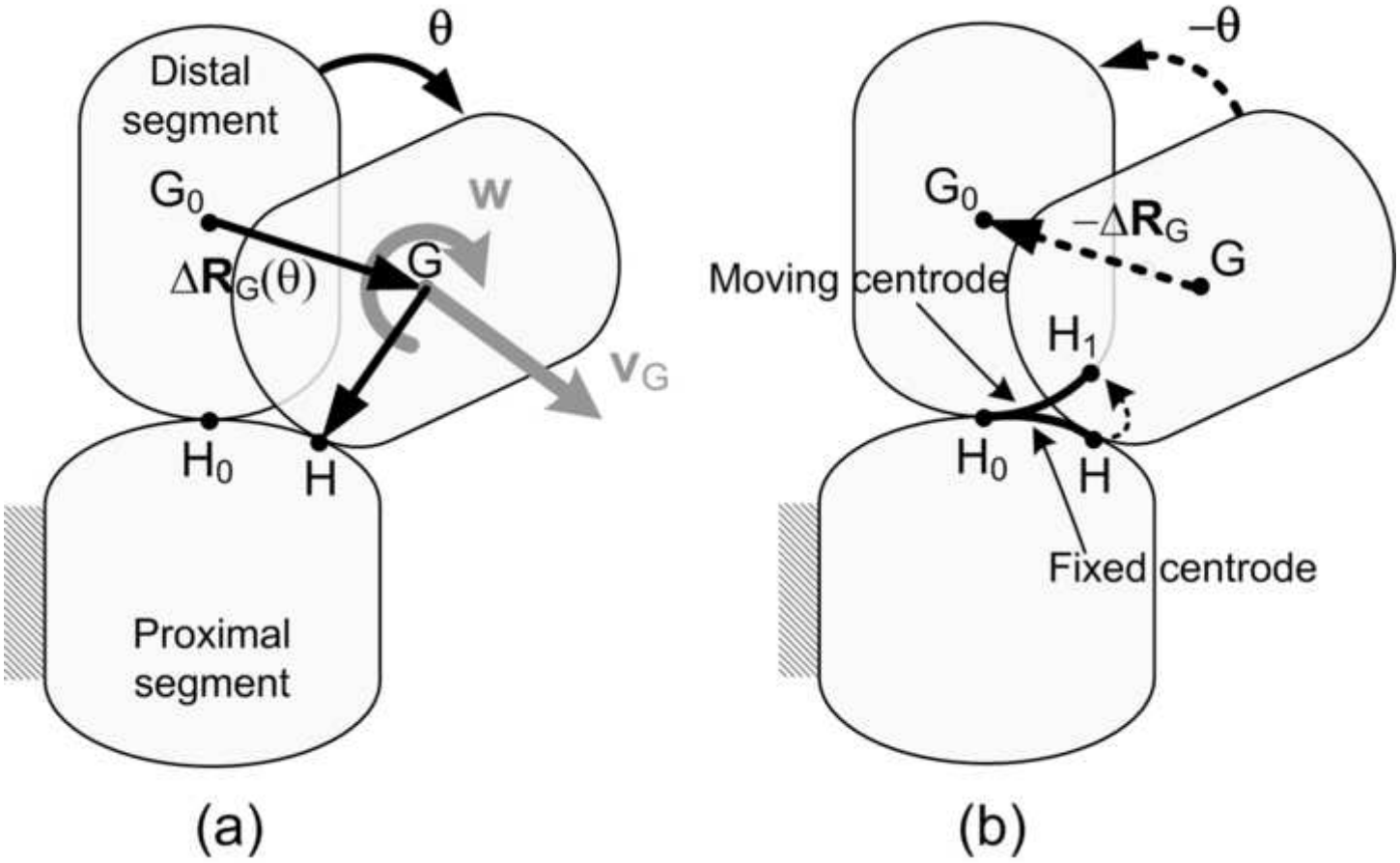

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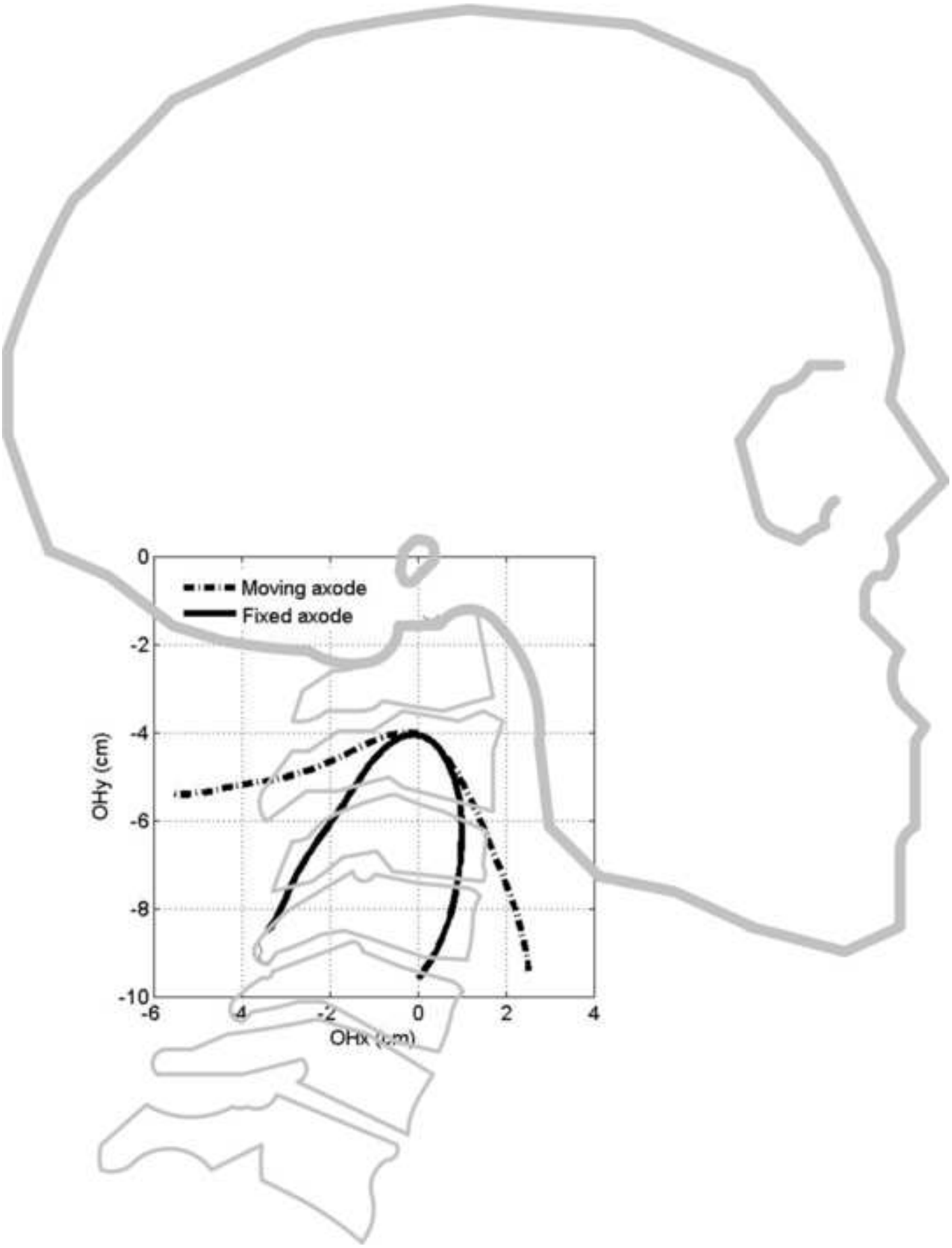

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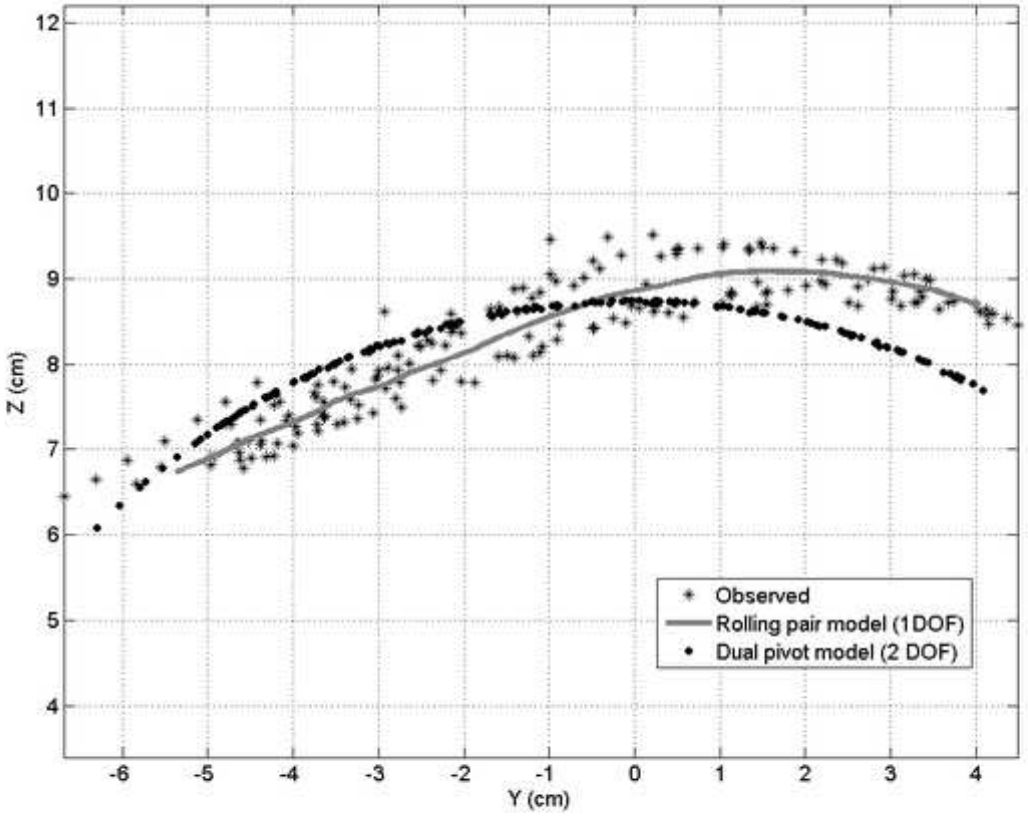

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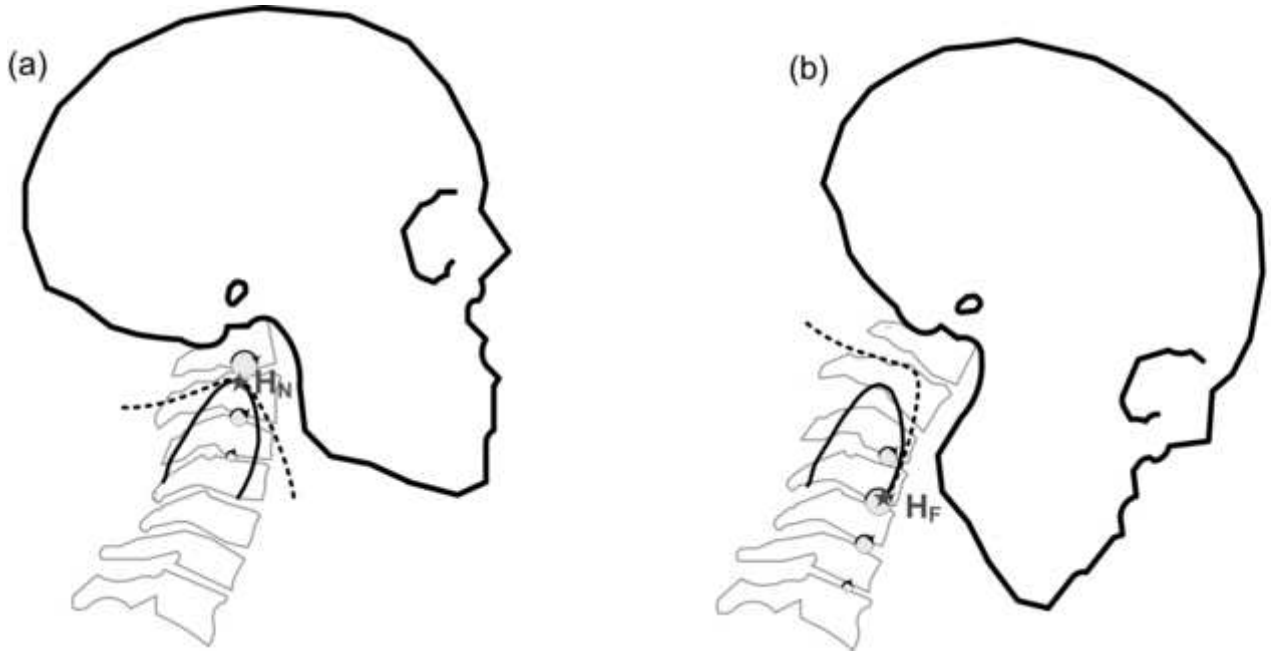

Table 1

Verification of the hypotheses of one functional degree of freedom (fDOF) and planar movement. Comparison between rolling pair and dual pivot model.

Variable	**Description**	**Mean** (n=12)	**SD** (n=12)
R_{pos}	Multiple correlation coefficient between measured and fitted coordinates of point G	0.995	0.005
R_{vel}	Multiple correlation coefficient between measured and fitted values of $\mathbf{v}_G$	0.958	0.025
p95 (α)	Percentile 95 of the angle between the average direction perpendicular to motion, **u**, and the measured **w**(t), for each subject (º)	3.9	1.0
p95(β)	Percentile 95 of the deviation from 90º of the angle between linear velocity, $\mathbf{v}_G$, and angular velocity, **w**(t), for each subject (º)	2.1	0.8
Error RP	RMS error of the distance between measured positions of point O and those estimated by the rolling-pair model (cm).	1.00	0.28
Error DP	RMS error of the distance between measured positions of point O and those estimated by the dual pivot model (cm)	1.95	1.00