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Cervical helical axis characteristics and its center of rotation during active head and upper arm movements—comparisons of whiplash-associated disorders, non-specific neck pain and asymptomatic individuals

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ABSTRACT

The helical axis model can be used to describe translation and rotation of spine segments. The aim of this study was to investigate the cervical helical axis and its center of rotation during fast head movements (side rotation and flexion/extension) and ball catching in patients with non-specific neck pain or pain due to whiplash injury as compared with matched controls. The aim was also to investigate correlations with neck pain intensity. A finite helical axis model with a time-varying window was used. The intersection point of the axis during different movement conditions was calculated. A repeated-measures ANOVA model was used to investigate the cervical helical axis and its rotation center for consecutive levels of 15° during head movement. Irregularities in axis movement were derived using a zero-crossing approach. In addition, head, arm and upper body range of motion and velocity were observed. A general increase of axis irregularity that correlated to pain intensity was observed in the whiplash group. The rotation center was superiorly displaced in the non-specific neck pain group during side rotation, with the same tendency for the whiplash group. During ball catching, an anterior displacement (and a tendency to an inferior displacement) of the center of rotation and slower and more restricted upper body movements implied a changed movement strategy in neck pain patients, possibly as an attempt to stabilize the cervical spine during head movement.

1. Introduction

The helical axis model, defines a movement as the angle of rotation around a moving helical axis (Spoor and Veldpaus, 1980). It is an accurate method to describe translation and rotation of e.g. shoulder joints and spine segments (Woltring et al., 1985; Stokdijk et al., 2000; Baeyens et al., 2001). When modeling head movement, the helical axis describes the global movement of the cervical spine. The axis moves during head movement, and neck pain may effect its position (Milne, 1993; Winters et al., 1993; Woltring et al., 1994; Moore et al., 2005). The center of rotation of finite helical axes, defined as the intersection point of the axes, could give further information about restrictions in spine mobility. To our knowledge, this has not been studied previously.

Jerky and irregular cervical movements in patients with neck pain may indicate sensorimotor disturbances (Feipel et al., 1999; Sjölander et al., 2008). This should be reflected in the helical axis behaviour. In a previous study, we found signs on an increased variation in axis movement in a group of neck pain patients as compared with a control group (Grip et al., 2007). The variation was defined as the total trajectory of the axis and the standard deviation of its angle with a reference direction vector. One limitation is that the length of the trajectory probably also depends on the range of movement, which often is significantly decreased in individuals with neck pain. A different approach to detect irregularities is the zero-crossing rate, i.e. the rate at which the second derivative (acceleration) crosses zero (Novak et al., 2000).

Two tasks were chosen in the present study. The first consisted of standardized, repetitive head rotations in four movement directions. The second task was ball catching, chosen in order to study a complex, externally triggered task involving head and arm coordination, without causing excessive neck pain. Helical axis characteristics during such a task have to our knowledge not been studied previously. Our hypothesis was that neck pain leads to changes in head movement strategy, manifested as a displaced

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helical axis and center of rotation. We also expected increased irregularity in axis movement.

The first aim of this study was to investigate the helical axis and its center of rotation in patients with non-specific neck pain or pain due to whiplash injury as compared with matched controls. The second aim was to investigate correlations with neck pain intensity.

2. Methods

2.1. Subjects

The subjects also participated in our earlier study (Grip et al., 2007). Informed consent was obtained from each subject, and the local ethics committee of Umeå University approved the study. The non-specific neck pain group (NP) consisted of 21 subjects with persistent pain. Their symptoms were muscular without paraesthesia according to clinical assessment. The whiplash group (WAD) consisted of 22 subjects with persistent symptoms of grade 1–2 according to the Quebec Task Force (Spitzer et al., 1995). All patients were recruited via physiotherapists at rehabilitation clinics and medical centers. The control group (CON) was recruited through advertisements and consisted of 24 healthy subjects. Occasional neck or back pain was accepted as long as they were free from symptoms in the past 3 months. All subjects initially completed visual analogue scales (VAS) for pain intensity in the neck region (Carlsson, 1983) concerning the day of measurement. No group differences were found in cervical height or age (Table 1).

2.2. Movement registration

Movements were registered with an optical motion capture system (Qualisys Medical AB®, Gothenburg, Sweden), consisting of five 120 Hz cameras and 21 reflective markers. Markers were placed on the head and upper body (Fig. 1A). Markers on mandibular fossa were used to estimate the cervical height and were removed before further movement registration. The chosen camera setup was evaluated using two markers placed on a wand (distance 750.4 mm). The accuracy and precision were estimated by the mean and standard deviation of the error of the calculated distance (0.8 ± 1.73 mm). Angle precision and accuracy were estimated by a simulation where the head cluster was affected with Gaussian white noise, and then rotated 1°, 5° and 45°. The standard deviation of the noise in the simulation was set to the estimated system precision (1.73 mm). This gave mean angles $1.3\pm0.4^\circ$, $5.0\pm0.4^\circ$ and $45.0\pm0.4^\circ$ (Grip et al., 2007; Öhberg, 2008).

2.3. Movement tasks

Fast head rotations: The subject sat on a chair with the head in a neutral, straight-ahead target position. A board with arrows was placed 1 m in front of the subject. The subject was instructed to perform a fast maximal movement immediately after an arrow on the board was illuminated. The movement should be performed as fast and far as possible under the restriction that the movement was painless. A signal was given for each new movement, to instruct the subject when and in which direction the movement should be performed. Each subject did five repetitions in each movement direction (flexion, extension, and left rotation, right rotation) in a random order.

Ball catching: The subject sat on a chair with head in a neutral straight-ahead target position with both hands resting in the lap. Two tubes (1.7 m long) was placed 1 m in front of the subject, with an inclination of 35°, tilted approximately 15° to left or right (Fig. 1B). A ball was rolled through one of the tubes (mean velocity 1.8 m/s). The ball passed close to the right or left shoulder of the catcher, and the subject had about 1 s to catch the ball with both hands. The trial was considered as completed when both upper arms had reached their angular maximum (relative to upper body). The subject practiced 10 times (five balls on each side) before the ball was rolled 10 times in random order. Earplugs were used to minimize the sound from the ball rolling inside the tube, as it could guide the test subject. The test leader registered whether the subject managed to catch the ball. The subject was excluded if less than 2 out of 10 trials were successful.

Table 1
Age, cervical height and pain intensity in neck and shoulders for CON, NP and WAD groups

	CON	NP	WAD
Age (year)	50 ± 18	49 ± 16	49 ± 15
Female/male	16/8	14/7	17/8
Cervical height[a] (cm)	20.0 ± 1.4	19.4 ± 2.1	19.4 ± 1.5
Neck pain intensity (VAS)	0.5 ± 2.1	49.2 ± 20.8	66.1 ± 18.8

These demographic data have also been described in Grip et al. (2007).

[a] From the level of suprasternal notch to the level of mandibular fossa.

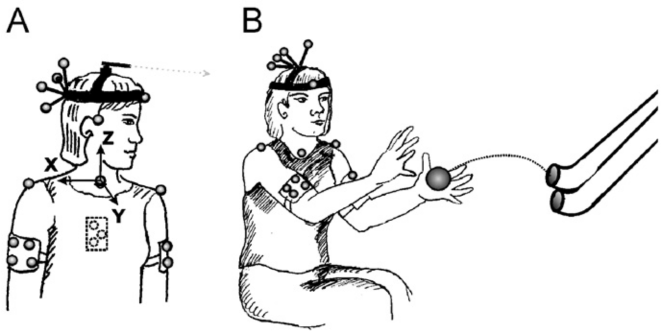

Fig. 1. (A) Markers positions are illustrated: five in a rigid cluster configuration on the head, one on the suprasternal notch, three on a rigid plate on the back, one on each shoulder, one on each mandibular fossa, and four on a rigid plate on each upper arm. The subject was seated relative to the lab coordinate frame so that the *X*-axis was transverse, the *Y*-axis was anterior–posterior and the *Z*-axis was vertical (Cole et al., 1993). The dashed marker plate with three markers is placed on the back, approximately level with T6–T8. (B) The ball catching task is illustrated: The subject catches a ball that passes on either the right or the left side of the subject, approximately level with the subject's shoulders.

2.4. Movement analysis

Data analysis was performed off-line using MATLAB® (The MathWorks Inc., Natick, MA, USA). The coordinate data were filtered with a dual low-pass Butterworth filter (2nd order, 6 Hz). The movement of head, upper arms and upper body were calculated using a finite helical axis model (Spoor and Veldpaus, 1980; Söderkvist and Wedin, 1993). This model defines a movement as a positive rotation angle, θ, around a helical axis, described by a direction vector, $\mathbf{n}$, the points $\mathbf{c}$ on the axis closest to origin, and the slide s along the axis ($\mathbf{n}$ and $\mathbf{c}$ are three-dimensional vectors, s is a scalar). Head and upper arm movements were defined as the helical angle of rotation relative to the upper body, and upper body movement as the helical angle of rotation relative to the lab coordinate frame. Velocity and acceleration were calculated by differentiating the angular data. The marker placed on the suprasternal notch was used as a reference point for $\mathbf{c}$ for all calculations regarding the cervical helical axis. The finite helical axis was estimated for each time frame using a variable time window with a cut-off at $\Delta\theta = 4^\circ$ (Grip et al., 2007). $\mathbf{n}$ and $\mathbf{c}$ were filtered once more with the same filter as above.

2.5. Axis of motion parameters

The zero-crossing rate of the acceleration curves of $\|\mathbf{c}\|$, $\mathbf{n}(x)$, $\mathbf{n}(y)$ and $\mathbf{n}(z)$ was computed. Only zero crossings that occurred when velocity exceeded 10% of peak velocity were included. Zero crossings occurring at lower velocities were considered as noise. The maximum rate of $\mathbf{n}(x)$, $\mathbf{n}(y)$ and $\mathbf{n}(z)$ was used for $\mathbf{n}$. Reference direction ($\mathbf{n}_{\text{ref}}$) was calculated using the interval from movement initiation (velocity exceeded 10% of peak velocity) until reaching 80% of maximal range of movement, ROM. The 3D angle between each $\mathbf{n}_i$ (for time frame i) and $\mathbf{n}_{\text{ref}}$ was calculated from the dot product of $\mathbf{n}$ with $\mathbf{n}_{\text{ref}}$ and was denoted by ω.

Each axis can be described by a line $\boldsymbol{l}_i\,(\alpha_i) = [\mathbf{c}_i, \mathbf{c}_i{+}\alpha_i\mathbf{n}_i]$, where α_i is a scalar. If the movement occurs in a single, fixed joint, all axes would intersect in a point. The helical axis for the cervical spine consists of several joints. Due to this, and to measurement errors, the point of intersection of finite helical axes was computed as the solution to the overdetermined least squares problem

$$\min \sum_{i=1}^{n} (CR - \ell(\alpha_i))^2$$

where $\mathbf{CR}$ is the mean center of rotation and n is the number of helical axes. On matrix form, this becomes

$$\min \left\| \begin{bmatrix} \mathbf{n}_1 & & & & & \mathbf{I} \\ & \mathbf{n}_2 & & & & \mathbf{I} \\ & & \mathbf{n}_3 & & & \mathbf{I} \\ & & & \ddots & & \mathbf{I} \\ & & & & \mathbf{n}_n & \mathbf{I} \end{bmatrix} \cdot \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_n \\ \mathrm{CR}_x \\ \mathrm{CR}_y \\ \mathrm{CR}_z \end{bmatrix} - \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_n \end{bmatrix} \right\|$$