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Alsultan, Feras; Cescon, Corrado; De Nunzio, Alessandro Marco; Barbero, Marco; Heneghan, Nicola R.; Rushton, Alison; Falla, Deborah

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VARIABILITY OF THE HELICAL AXIS DURING ACTIVE CERVICAL MOVEMENTS IN PEOPLE WITH CHRONIC NECK PAIN

Feras Alsultan,[a,b] Corrado Cescon [c], Alessandro Marco De Nunzio [a], Marco Barbero,[c] Nicola R Heneghan [a], Alison Rushton,[a] Deborah Falla[a]

[a] *Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, UK.*

[b] *Physical Therapy Department, College of Medical Rehabilitation, Qassim University, Buraidah, Saudi Arabia.*

[c] *Rehabilitation Research Laboratory, Department of Business Economics, Health and Social Care, University of Applied Sciences and Arts of Southern Switzerland, Manno, Switzerland.*

Highlights

- Examines movement variability in people with neck pain via parameters of the helical axis
- Decreased movement variability was observed in people with chronic neck pain
- Movement variability decreased with higher levels of fear of movement

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Corresponding Author: Professor Deborah Falla
Centre of Precision Rehabilitation for Spinal Pain (CPR Spine),
School of Sport, Exercise and Rehabilitation Sciences,
College of Life and Environmental Sciences,
University of Birmingham,
Birmingham, B15 2TT, UK.
Email: d.falla@bham.ac.uk

ABSTRACT

Background: Recent work described parameters of the helical axis in asymptomatic people with potential for investigating kinematic changes in the cervical region. This approach could provide novel information on movement variability in people with neck pain, however this has never been investigated. This study aimed to investigate movement variability during active neck movements performed at different speeds in people with and without chronic neck pain.

Methods: This observational case-control study examined 18 participants with chronic neck pain of either idiopathic or traumatic origin and 18 gender-matched asymptomatic participants. Cervical kinematics were captured with 3D motion capture as people with and without chronic neck pain performed flexion-extension, bilateral lateral flexion and bilateral rotation at different speeds (natural, slow, and fast). The mean distance and mean angle parameters of the helical axis were extracted to describe 3D motion and quantify movement variability.

Findings: A smaller mean distance was observed in those with neck pain compared to asymptomatic participants during flexion-extension (P=0.019) and rotation movements (p=0.007). The neck pain group displayed smaller values for the mean angle during rotation movements with different speeds (P=0.01). These findings indicate less variable movement for those with neck pain relative to the asymptomatic control participants. No difference in the mean angle was observed between groups for flexion-extension and lateral flexion.

Interpretation: The findings reiterate the importance of data derived from kinematic measures, and its potential for providing clinicians with further insight into the quality of active neck movements in people with chronic neck pain.

INTRODUCTION

Chronic neck pain (CNP) is one of the most common musculoskeletal disorders affecting adults, with reported prevalence ranging between 16.7% and 75.1% each year (Genebra et al., 2017). In addition to the individual physical, social, and psychological impact, CNP contributes greatly to health service costs (Coppieters et al., 2017; Genebra et al., 2017).

Besides pain, individuals with CNP may present with a number of disturbances in physical function including reduced proprioception, neuromuscular impairments, and difficulties with head-eye movement control (De Pauw et al., 2017; Della Casa et al., 2014; Ischebeck et al., 2017). Furthermore, people with CNP may experience fear of movement, symptoms of dizziness, a decrease of physical activity, and usually complain of disability during performance of daily activities (Cheng et al., 2015; Soderlund et al., 2017; Sremakaew et al., 2018; Yalcinkaya et al., 2017). A number of studies have examined neck movement characteristics in people with CNP with reduced active neck range of motion (RoM) a common observation regardless of the etiology of the neck pain disorder (Alricsson et al., 2001; Lee et al., 2005; Peolsson et al., 2007). Yet, most studies have focused on the quantity of movement and typically static variables of planar cervical motion. The quality or variability of movement may be a better indicator of ongoing neuromuscular dysfunction in people with CNP (Anderst et al., 2017; Baydal-Bertomeu et al., 2011; Edmondston et al., 2005; Preatoni et al., 2013). Furthermore, investigating kinematic variables across multiple axes can provide more precise information regarding changes during active movements (Ellingson et al., 2013).

Measures of the helical axis (HA) can be used to describe three-dimensional motion in the cervical region. Recently, novel parameters were proposed to describe the behavior of the helical axis during active neck movements in healthy volunteers and the reliability of these parameters was established (intra and inter-session reliability (ICC) ≥ 0.80) (Barbero et al., 2017). The distribution in space of the HA and the mean angle of the HA measurements (Barbero et al., 2017; Cescon et al., 2014) demonstrated potential for investigating the variability of neck movement. HA parameters could therefore provide novel information regarding movement behaviour in people with CNP (Barbero et al., 2017; Lomond and Cote, 2010).

The objective of this study was to investigate movement variability during active neck movements inclusive of flexion-extension, lateral flexion and rotation performed at different speeds in people with and without neck pain. People with CNP of either idiopathic or traumatic origin were included. The secondary objective was to assess correlations between HA parameters and levels of pain, disability, fear of movement, physical activity and dizziness in the participants with neck pain.

METHODS

Design

An observational case-control study was conducted from May to November 2017. Ethical approval for the study was granted by the Ethics Committee of the University of Birmingham, UK (CM06/03/17-1) and the study was conducted according to the Declaration of Helsinki. Convenience sampling was used to recruit participants from among students and staff of the University of Birmingham. The main purpose of the study and the methods that would be used were explained to participants before they were asked to give written informed consent. The guidelines of the STROBE statement (Strengthening the Reporting of Observational Studies in Epidemiology) were adhered to (Von Elm et al., 2014).

Participants

The sample size included 36 male and female gender-matched participants, including 18 asymptomatic people and 18 people with CNP of either idiopathic or traumatic origin. Participants attended a single laboratory session. An *a priori* sample size could not be determined, since no previous study had evaluated parameters of the HA in people with CNP and therefore no data were available for sample size calculation. Thus, sample size was estimated based on a previous study evaluating cervical kinematics in people with and without CNP (Vogt et al., 2007).

Inclusion criteria

Participants with neck pain were included in the study if they presented with painful symptoms for at least three months. In the case of those with whiplash-associated disorder (WAD), only grades I, II, or III according to the Quebec Task Force Classification (Spitzer, 1995) were included. In addition, the participants had to report their neck pain intensity over the last four weeks as at least 4 (mild pain) out of 10 on a Numerical Rating Scale (NRS) with two anchor points: 0 = "no pain" and 10 = "worst pain imaginable" (Boonstra et al., 2016; Kamper et al., 2015). The NRS is a valid and reliable instrument for self-reported pain intensity (Williamson and Hoggart, 2005). Asymptomatic participants were recruited to act as a control group. To be included they must have had no history of a neck injury or neck pain in the last two years that required treatment from a health care practitioner.

Exclusion criteria

Participants were excluded from either group if they presented with any of the following: previous spinal surgery, rheumatic condition, current or chronic respiratory condition, having an ongoing compensation claim related to an injury. Additional exclusion criteria for the CNP group included currently receiving active management, and neck injury that resulted in a spinal fracture.

Questionnaires

All participants were required to complete the International Physical Activity Questionnaire (IPAQ), which was used to characterise the sample with respect to their physical activity levels (Craig et al., 2003). Additionally, for the participants with CNP, their average pain level over the last four weeks was recorded using the NRS (Kamper et al., 2015) and their perceived neck disability was assessed using the Neck Disability Index (NDI), with a possible score range of 0–50 (Vernon, 2008; Vernon and Mior, 1991). The Dizziness Handicap Inventory (DHI) was used to determine self-reported levels of dizziness (Jaco and Graig, 1990). Additionally, self-reported dizziness intensity at rest and during activity was measured following testing, using an NRS from 0 to 10, where 0 was “no symptoms” and 10 was “worst symptoms” (Kammerlind et al., 2005; Kamper et al., 2015). Finally, the Tampa Scale for Kinesiophobia (TSK), a 17-item questionnaire, was employed to evaluate fear of movement and related behavioural problems, including avoidance and disability (Miller et al., 1991).

Cervical Kinematics

An optoelectronic system (BTS Bioengineering, Milan, Italy) was used to record cervical kinematics following system calibration. The kinematic data was acquired at a standard frequency of 250fps. The system consists of eight infrared cameras with a resolution of 2,2 Mpixels (2048x1088pxs). The cameras tracked the 3D motion of retroreflective markers attached to the subject's skin over the following body landmarks: two markers on the sternum, superior at the jugular notch and inferior at the xiphoid process, 7^{th} cervical vertebra, 5^{th} thoracic vertebrae, 9^{th} thoracic vertebrae. In addition, a helmet was placed on the subject's head, with four reflective markers as follows: on the head apex, the front, and right and left sides of the helmet (Cescon et al., 2015). The helmet also contained a laser pointer.

Procedure

Following placement of the reflective markers, the participant was seated upright on a chair with their head in a neutral position and they were instructed to avoid shoulder movements and to relax their arms. The participant was seated 220 cm in front of a wall and with the head in neutral, the point of the laser was marked on the wall to define the starting reference position (0°). Using a goniometer, the subjects head was then rotated 45° to the left and right and these positions were marked (*Fig. 1*). Flexion and extension to 45° was also performed and these positions were marked on the ceiling and floor. The participants performed the following neck movements: flexion-extension, bilateral lateral flexion, and bilateral rotation. Each movement was performed in three conditions: at a natural self-selected speed, slow speed (30 beats per second (bps)) and fast speed (60 bps) (*Table 1*). The movement speed was controlled using a metronome beats mobile application and the conditions were randomized in order to minimize the risk of order as a confounding variable.

Participants were instructed to start every movement from the reference point at 0° and then perform continuous neck movements without stopping in the midline. The subjects were instructed to maintain the laser at 0° while performing lateral flexion, move between the 45° reference points while performing rotation, and move up and down between the 45° reference points while performing flexion-extension. The range of motion was limited since performing functional tasks and activities of daily living does not usually require the full active range of motion (Bennett et al., 2002; Bible et al., 2010). In addition, the position and the orientation of the HA depends on the range of motion (Barbero et al., 2017).

Kinematic data were acquired for 10 repetitions of each condition following the protocol described by Barbero and colleagues (Barbero et al., 2017). Familiarisation with each test condition preceded data acquisition. A rest period of 30 seconds was given between each condition to prevent fatigue and ensure that the participant returned to the neutral position between conditions (Miura and Sakuraba, 2014).

Data analysis

The mean distance (MD) of the HA and mean angle (MA) of the HA were calculated as defined previously (Barbero et al., 2017). The MD represents the distance between all intersection points between the HA and a transversal plane from their barycenter, while the MA is defined by calculating the MA of each axis and the total average (*Fig. 2*). Lower values of the MD and MA imply that the movement is less variable. The RoM was quantified by calculating the mean difference between the maximal flexion and extension movements, while the mean difference of neck rotation and lateral flexion were computed between the left and right movements (Barbero et al., 2017).

Data from eight repetition movement cycles were analysed following exclusion of the first and last cycle in order to avoid artefacts or alterations in angular velocity (Cescon et al., 2014). The degree of variability of neck movements across the whole movement cycle was measured by calculating the standard deviation (SD) of the mean.

Statistical analysis

Mean and SD were calculated to describe MD and MA parameters. In addition, mean and SD were used to demonstrate the range and distribution of participant demographics and questionnaire responses. Two-way analysis of variance (ANOVA) was applied to evaluate the MD, MA and RoM during the flexion-extension movements, lateral flexion movements and rotation movements, with group (control, CNP) and condition (slow, natural and fast speed) as factors. Significant differences revealed by ANOVA were followed up by post-hoc Student-Newman-Keuls (SNK) pair-wise comparisons.

Pearson or Spearman correlations (depending on the distribution of each questionnaire data) were performed to assess the relationship between MA and MD of the neck movements and the following six variables: NDI, DHI and self-reported dizziness intensity (NRS), level of average pain intensity (NRS), TSK, and IPAQ. The strength of the correlation was interpreted as: small correlation <0.3, moderate correlation between 0.3 and 0.5, and strong correlation >0.5 (Cohen, 1988).

Results are reported as mean and SD in the text and figures. Statistical analyses were performed with SPSS Version 22.0 (IBM Corp., Armonk, NY, USA). Statistical significance was set at $p<0.05$.

RESULTS

A total of 36 participants completed the study with 8 men and 10 women in each group. Those with CNP had a mean (SD) age of 32.2 (13.4) years, while the mean (SD) age of the control group was 25.8 (7.3) years which was not significantly different (U = 109.500, z = -1.664, *P* = .097.).

There were 6 CNP participants who had experienced a whiplash injury: two with grade I, three with grade II, and one with grade III. Participant demographics for both groups are presented in *Table 2*. One participant in the CNP group did not complete the TSK questionnaire. There were 7 missing values across all kinematic variables: 2 values of RoM for flexion-extension at fast speed and lateral flexion at slow speed in the control group, and 5 values of MD for two conditions for lateral flexion at slow and fast speed, one condition for rotation slow speed in the control group, and two conditions for flexion-extension slow and lateral flexion natural speed in the CNP group. These occurred due to artefacts in data acquisition.

Fig. 3 presents representative data from a control subject and person with CNP acquired during rotation at a natural speed. The observations from this representative example were confirmed at the group level as presented in Fig. 4 and detailed below.

Mean distance (*MD)*

<u>*Flexion-extension*</u>

The CNP group displayed a smaller MD for the flexion-extension movements regardless of the condition (main effect for group: F=5.7, *P* =0.019). Despite a trend, the MD did not vary across flexion-extension movement conditions (F=3.0, *P*=0.051) and was not dependent on the interaction between group and condition (F=0.7, *P*=0.47). The MD decreased in the CNP group as compared to control group for the flexion-extension movements. The mean (SD) of CNP group were as follows; natural speed condition 1.46 cm (0.33cm), slow condition 1.39 cm (0.25 cm), fast condition 1.65 cm (0.39 cm); whereas in the control group the values for the natural speed condition were 1.61 cm (0.28 cm), slow condition 1.63 cm (0.31 cm), and fast condition 1.71 cm (0.31 cm).

Lateral flexion

The MD did not vary across groups (F=1.1, *P*=0.28) or condition (F=0.2, *P*=0.82) for the lateral flexion movements, and was not dependent on the interaction between group and condition (F=0.2, *P*=0.83). The mean (SD) of the CNP group were: natural speed condition 0.91 cm (0.23 cm), slow condition 0.90 cm (0.23 cm), and fast condition 0.91 cm (0.25 cm); while for the control group, natural speed condition values were 1.02 cm (0.44 cm), slow condition 0.93 cm (0.34 cm), and fast condition 0.97 cm (0.31 cm).

Rotation

Consistent with the results for flexion-extension, the CNP group displayed smaller MD values for the rotation movements regardless of condition (main effect for group: F=7.48, *P*=0.007). The MD did not vary across rotation movement conditions (F=0.19, *P*=0.82) and was not dependent on the interaction between group and condition (F=1.53, *P*=0.22).

The MD for the rotation movements decreased in the CNP group as compared to the control group. The mean (SD) of the CNP group were as follows: natural speed condition 0.83 cm (0.15 cm), slow condition 0.90 cm (0.29 cm), and fast condition 0.84 cm (0.15 cm). The control group mean (SD) were: 1.07 cm (0.33 cm) in the natural speed condition, slow condition 0.93 cm (0.22 cm), and fast condition 0.99 cm (0.35 cm).

Mean angle (MA)

Flexion-extension

No difference was observed between groups for the MA during the flexion-extension movements (F=0.1, *P*=0.92), and no interaction between group and condition was observed (F=5.2, *P*=0.59). However, the MA did vary across conditions (F=4.0, *P*=0.02), with smaller MA observed during the fast speed condition compared to the slow and natural speed conditions (both SNK: *P*<0.05).

The MA for the flexion-extension movements was reduced in the fast speed condition as compared to other conditions. The mean (SD) values during the fast speed condition were as follows: CNP group 3.88° (0.75°) and control group 3.89° (0.92°); whereas for the CNP group the values were 4.51° (0.73°) for natural speed condition and 4.22° (0.57°) for slow condition; and for the control group, 4.29° (0.91°) for natural speed condition and 4.39° (0.99°) for slow condition.

Lateral flexion

The MA did not vary across groups (F=1.5, *P*=0.21) or condition (F=0.3, *P*=0.68) for the lateral flexion movements, and was not dependent on the interaction between group and condition (F=0.2, *P*=0.82). The mean (SD) of the CNP group were as follows: natural speed condition 8.96° (1.62°), slow condition 8.61° (1.92°), and fast condition 9.04° (2.07°); while for the control group, the values were natural speed condition 9.70° (2.16°), slow condition 9.21° (2.42°), and fast condition 9.20° (2.11°).

Rotation

The MA during the rotation movements was dependent on group (F=9.30, p=0.003) and condition (F=4.82, *P*=0.010), but not the interaction between group and condition (F=1.34, *P*=0.26). The post-hoc analysis revealed that the CNP group displayed smaller values for the MA during rotation movements with different speeds (SNK: *P*<0.01) (*Table 3)*.

The MA or the rotation movements decreased in the CNP group as compared to the control group. The mean (SD) for the CNP group were as follows: natural speed condition 4.98° (0.85°), slow condition 4.89° (0.71°), and fast condition 3.98° (0.42°). The control group values were: natural speed condition 5.21° (1.04°), slow condition 5.44° (1.64°), and fast condition 4.99° (1.02°) (*Table 4*).

RoM

The RoM for flexion-extension movements was consistent across conditions (F=0.4, *P*=0.62) and groups (F=1.9, *P*=0.16), with no interactions present (F=0.4, *P*=0.66). The same was true for lateral flexion, with no differences between conditions (F=2.4, *P*=0.09) and groups (F=2.0, *P*=0.15) and no interactions present (F=0.0, *P*=0.98). For rotation, there were no effect of conditions (F=2.60, *P*=0.07), no effect of group (F=0.74, *P*=0.39), and no interaction present (F=1.07, *P*=0.34). The results of the RoM confirmed that all neck movement conditions were performed within the range of movement required by the experimental protocol.

Correlations between kinematic variables and subjective descriptors

The correlation between the questionnaires scores and MA and MD variables are shown in *Table 5*. Significant correlations were found between MA and MD with the following variables: NDI, level of average pain intensity (NRS), TSK, and IPAQ.

<u>*Mean distance (MD)*</u>

There was a moderate positive correlation between NDI and the MD measured during flexion-extension neck movements at the fast speed (r = .490, *P*=.039). A strong positive correlation was found between the average pain intensity (NRS) and the MD measured during flexion-extension neck movement at the fast speed (r = .514, *P*=.029). Furthermore, a moderate negative correlation was documented between the TSK score and MD during lateral flexion performed and at the fast speed (r = -.481, *P*=.044). A moderate negative correlation was found between the IPAQ score and the MD during lateral flexion performed at the fast speed (r = -.346, *P*=.042).

Mean angle (MA)

There was a moderate negative correlation between the IPAQ score and the MA during lateral flexion performed at the natural speed (r = -.346, *P* =.039). In addition, there was a strong negative correlation between the TSK score and the MA during neck rotation and at a natural speed (r = -.563, *P* =.015), slow speed (r = -.561, *P* =.015), and fast speed (r = -.805, *P* =.000).

DISCUSSION

This study is the first to evaluate the variability of active neck movement in people with CNP by utilising parameters of the HA. The findings revealed less variability of movement in people with CNP during flexion-extension and rotation movement compared to healthy controls as shown by the MD measurements. The results also showed reduced variability of movement during rotation in people with CNP as compared to asymptomatic people as seen in the MA measurements.

Movement variability

The results of the present study are congruent with previous research findings that people with pain may move with less variability. Madeleine et al. (2008) reported reduced variability of arm and trunk acceleration in people with chronic neck-shoulder pain as compared to asymptomatic people during a repetitive arm movement task. Reduced variability of transverse thoracic and lumbar rotations has also been observed in people with low back pain as compared to asymptomatic controls while participants were walking (Lamoth et al., 2006). However, some other studies suggest the opposite. For example, Vogt et al. (2007) found that movement variability was significantly higher in people with CNP when compared to an asymptomatic group. However, they examined movement variability only in the maximum oscillation amplitudes (Vogt et al., 2007), whereas the present study investigated a larger cycle of neck movement. Continuous cyclical movement trials are more likely to able to provide information regarding movement behaviour associated with CNP (Baydal-Bertomeu et al., 2011).

One previous study which investigated full active neck movements, found that motion patterns were characterised by less flexibility and slower movement in people with neck pain as compared to healthy controls. Reduced range of neck movement was observed for motion in the primary plane and the two correlated movement planes at the maximum of the RoM (conjunct motion) (Meisingset et al., 2015). The findings of the present study concur with these results even though the different procedures were used in both studies. In Meisingset, et al., (2015) participants were asked to move as far as possible while performing neck movements at a self-determined speed, whilst the participants in this study were requested to move between fixed points at both a natural speed as well as fixed speed. The findings from the present study, as in those of Meisingset, et al., (2015) could be interpreted as evidence of a more cautious movement strategy by people with neck pain, presumably employed as a protective method to decrease or potentially avoid neck pain.

Even though the level of pain reported in this study was low in the CNP group, differences in movement behaviour and movement variability were observed between groups. This is congruent with other research and with current theories about the impact of pain on movement and motor control. Some people may continue to display less variability in movements even when they are free from pain (Moseley and Hodges, 2006). Moreover, an association may exist between motor variability and learning in pain disorders (Moseley and Hodges, 2006). This association could be controlled by evaluative processes that play a role in motor variability: when a movement is associated with pain, the patient performs that movement differently, and over a period of time this change in movement becomes ingrained (Moseley and Hodges, 2006). Furthermore, motor adaptations to pain could lead to protection from vulnerability to pain or injury, and contribute to changes in mechanical behaviour (Hodges and Tucker, 2011). For example, a protective movement strategy was employed by healthy people when they anticipated that a movement could cause harm to their back (Moseley and Hodges, 2006). Thus, the lower movement variability identified in the CNP group in the current study could reflect an adapted behaviour due to pain.

The influence of movement speed

In the current study, reduced movement variability was observed in the CNP group as compared to the control group for flexion-extension as revealed by differences in the MD. Furthermore, decreased movement variability during flexion-extension was seen via the MA when performed at the faster speed than when performed at the slower and self-selected speeds, and this was the case for both groups. Vikne et al. (2013) also observed a significant reduction in movement speed and displacement during flexion-extension movements when performed at a faster speed compared to the preferred or slower speed. In addition to the observed reduction of movement variability during flexion-extension at the faster speed, positive correlations were also found between the MD during flexion-extension performed at the faster speed, and the level of disability (NDI), and the level of average pain intensity (NRS). Based on the current and on previous observations, faster movements could be emphasised during the clinical examination of people with CNP especially since people with neck pain often complain of difficulty performing rapid movement of their head (Bahat et al., 2010).

Correlation between movement parameters and clinical features

A negative correlation was found for the CNP group between TSK and MA measured for all neck rotation conditions. Thus, movement variability decreased with higher levels of fear of movement. These findings confirm the effect of avoidance behaviour on physical functioning (Bahat et al., 2014).

Clinical implications

Examining the variability of neck movement as done in this study is not trivial to perform in a clinical setting (Lamoth et al., 2006). However, our findings show that such data derived from kinematic measures has the potential to provide clinicians with important insights into active neck movement behaviour in people with CNP. Further research should evaluate whether simplified measures of movement e.g. with inertial sensors, which can be more easily implemented in a clinical setting, are capable of detecting such changes in movement quality in people with CNP.

Methodological considerations

Our current sample of CNP participants presented with relatively low levels of pain and disability (average pain intensity ~4/10 and NDI score ~13/50) and the study sample size was not calculated *a priori* thus the generalisability of study findings is likely reduced. The sample size also prevented comparisons between those with idiopathic neck pain versus trauma induced neck pain or a comparison between genders. This could be explored in future studies. Nevertheless, the kinematic variables in this study were able to detect differences in the quality of cervical motion between groups and provided information about the nature of these differences. This is one of very few studies examining whole-cycle movement at different speeds in people with CNP.

Conclusion

Through parameters of the HA we observed differences in movement variability during neck flexion-extension and rotation movements in people with CNP. These measurements may be useful in future studies to evaluate the effects of interventions, including exercise, to enhance movement control in people with CNP.

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TABLES

Table 1: *Overview of the movements and conditions measured.*

Movements	Conditions
Flexion-extension	**1.** Natural speed
	2. Slow speed
	3. Fast speed
Bilateral lateral flexion	**4.** Natural speed
	5. Slow speed
	6. Fast speed
Bilateral rotation	**7.** Natural speed
	8. Slow speed
	9. Fast speed

Table 2: *Participant demographics and self-report questionnaires. Standard deviations (SD) are reported in parentheses.*

		Control Group	CNP Group
Age	Mean (SD)	25.89 (7.34)	32.22 (13.41)
Height (cm)	Mean (SD)	168.80 cm (7.71 cm)	170.77 cm (10.34 cm)
Weight (kg)	Mean (SD)	64.67 kg (14.41 kg)	68.39 kg (14.69 kg)
Total IPAQ score	Mean (SD)	3940.97 (3163.72)	5175.61 (4569.36)
NDI	Mean (SD)	Not applicable	12.94 (6.84)
Average pain intensity	Mean (SD)	Not applicable	4.08 (1.89)
TSK	Mean (SD)	Not applicable	36.53 (6.58)
DHI	Mean (SD)	Not applicable	20.78 (17.32)
Dizziness NRS	Mean (SD)	Not applicable	1.65 (2.12)

Abbreviations: International Physical Activity Questionnaire (IPAQ), Neck Disability Index (NDI), Average pain level over the last four weeks was recorded using NRS (average pain), Tampa Scale for Kinesiophobia (TSK), Dizziness Handicap Inventory (DHI), self-reported dizziness NRS (dizziness NRS), Not applicable (NA).

Table 3: *Results of the ANOVA to evaluate differences in the mean distance (MD) and mean angle (MA) for each movement direction.*

Parameters	Conditions	Group * Conditions (Sig.)	Group (Sig.)	Conditions (Sig.)
MD (cm)	Rotation	0.22	0.007*	0.82
	Flexion-Extension	0.47	0.019*	0.051
	Lateral flexion	0.83	0.28	0.82
MA (°)	Rotation	0.26	0.003*	0.010*
	Flexion-Extension	0.59	0.92	0.02*
	Lateral flexion	0.82	0.21	0.68

Statistically significant difference; * $P < 0.05$

Table 4: *Mean and standard deviation of the mean distance (MD) and mean angle (MA) recorded during each movement direction and each condition for both the control and chronic neck pain (CNP) groups*

Parameter	MD (cm)		MA (°)	
Group	Control	CNP	Control	CNP
Movement	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Flex/Ext natural	1.61 cm (0.28 cm)	1.46 cm (0.33 cm)	4.29° (0.91°)	4.51° (0.73°)
Flex/Ext slow	1.63 cm (0.31 cm)	1.39 cm (0.25 cm)	4.39° (0.99°)	4.22° (0.57°)
Flex/Ext fast	1.71 cm (0.31 cm)	1.65 cm (0.39 cm)	3.89° (0.92°)	3.88° (0.75°)
LatFlex natural	1.02 cm (0.44 cm)	0.91 cm (0.23 cm)	9.70° (2.16°)	8.96° (1.62°)
LatFlex slow	0.93 cm (0.34 cm)	0.90 cm (0.23 cm)	9.21° (2.42°)	8.61° (1.92°)
LatFlex fast	0.97 cm (0.31 cm)	0.91 cm (0.25 cm)	9.20° (2.11°)	9.04° (2.07°)
Rotation natural	1.07 cm (0.33 cm)	0.83 cm (0.15 cm)	5.21° (1.04°)	4.94° (0.84°)
Rotation slow	0.93 cm (0.22 cm)	0.90 cm (0.29 cm)	5.44° (1.64°)	4.89° (0.71°)
Rotation fast	0.99 cm (0.35 cm)	0.84 cm (0.15 cm)	4.99° (1.02°)	3.95° (0.45°)

Abbreviations: Mean distance (MD), mean angle (MA), Standard Deviation (SD)

Table 5: *Correlations between questionnaire responses and helical axis parameters*

Questionnaires	Parameters	Neck movements	Correlation Coefficient	Sig. (2-tailed)
NDI	MD (cm)	Flexion-Extension with fast speed	.490*	.039
Pain (average)	MD (cm)	Flexion-Extension with fast speed	.514*	.029
TSK	MA (°)	Rotation Natural	-.563*	.015
		Rotation Slow	-.561*	.015

		Rotation Fast	-.805**	.000
	MD (cm)	Lateral Flexion Fast	-.481*	.044
IPAQ	MA (°)	Lateral Flexion Natural	-.346*	.039
	MD (cm)	Lateral Flexion Fast	-.346*	.042

* Correlation is significant at the 0.05 level (2-tailed), ** Correlation is significant at the 0.01 level (2-tailed). Abbreviations; Mean distance (MD), mean angle (MA), Neck Disability Index (NDI), Average pain level over the last four weeks was recorded using NRS (average pain), Tampa Scale for Kinesiophobia (TSK), International Physical Activity Questionnaire (IPAQ).

FIGURE LEGENDS

***Fig. 1** illustrates the experimental setup. Marks were placed on the wall in front of the subject to identify the starting position and, as illustrated here, 45° of right and left rotation. Markers were placed on a helmet and on the subject to track the movement of their head in 3D space.*

***Fig. 2** demonstrates the HA parameters that were used in the experimental protocol. Mean distance (MD) intersection points are represented in red, while mean angle (MA) angles of axis lines are represented in blue.*

***Fig. 3** representative data acquired from a patient and control subject during head rotation performed at a natural speed. Note the smaller mean distance (MD) and mean angle (MA) for the participant with chronic neck pain compared to the control subject.*

***Fig. 4** presents boxplots representing the descriptive results, mean and standard division of the mean distance (MD), and mean angle (MA) for all the neck movement conditions investigated.*
*Statistically significant difference between groups; ** $P < 0.05$*
*Statistically significant difference between conditions; * $P < 0.05$*

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