

Variability of the helical axis during active cervical movements in people with chronic neck pain

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DOI:

[10.1016/j.clinbiomech.2019.01.004](https://doi.org/10.1016/j.clinbiomech.2019.01.004)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Alsultan, F, Cescon, C, De Nunzio, AM, Barbero, M, Heneghan, NR, Rushton, A & Falla, D 2019, 'Variability of the helical axis during active cervical movements in people with chronic neck pain', *Clinical Biomechanics*, vol. 62, pp. 50-57. <https://doi.org/10.1016/j.clinbiomech.2019.01.004>

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

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20 **Highlights**

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

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28 **Article Type:** Original article

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30 **Keywords:** Chronic neck pain; Movement variability; Helical axis

31
32 **Declarations of interest:** None

33
34
35 **Word count main text:** 4141

36 **Word count abstract:** 247

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46 **ABSTRACT**

47

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

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

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

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

68

69 INTRODUCTION

70 Chronic neck pain (CNP) is one of the most common musculoskeletal disorders affecting
71 adults, with reported prevalence ranging between 16.7% and 75.1% each year (Genebra et al.,
72 2017). In addition to the individual physical, social, and psychological impact, CNP contributes
73 greatly to health service costs (Coppieters et al., 2017; Genebra et al., 2017).

74 Besides pain, individuals with CNP may present with a number of disturbances in
75 physical function including reduced proprioception, neuromuscular impairments, and difficulties
76 with head-eye movement control (De Pauw et al., 2017; Della Casa et al., 2014; Ischebeck et al.,
77 2017). Furthermore, people with CNP may experience fear of movement, symptoms of dizziness,
78 a decrease of physical activity, and usually complain of disability during performance of daily
79 activities (Cheng et al., 2015; Soderlund et al., 2017; Sremakaew et al., 2018; Yalcinkaya et al.,
80 2017). A number of studies have examined neck movement characteristics in people with CNP
81 with reduced active neck range of motion (RoM) a common observation regardless of the
82 etiology of the neck pain disorder (Alricsson et al., 2001; Lee et al., 2005; Peolsson et al., 2007).
83 Yet, most studies have focused on the quantity of movement and typically static variables of
84 planar cervical motion. The quality or variability of movement may be a better indicator of
85 ongoing neuromuscular dysfunction in people with CNP (Anderst et al., 2017; Baydal-Bertomeu
86 et al., 2011; Edmondston et al., 2005; Preatoni et al., 2013). Furthermore, investigating kinematic
87 variables across multiple axes can provide more precise information regarding changes during
88 active movements (Ellingson et al., 2013).

89 Measures of the helical axis (HA) can be used to describe three-dimensional motion in
90 the cervical region. Recently, novel parameters were proposed to describe the behavior of the
91 helical axis during active neck movements in healthy volunteers and the reliability of these

92 parameters was established (intra and inter-session reliability (ICC) ≥ 0.80) (Barbero et al.,
93 2017). The distribution in space of the HA and the mean angle of the HA measurements
94 (Barbero et al., 2017; Cescon et al., 2014) demonstrated potential for investigating the variability
95 of neck movement. HA parameters could therefore provide novel information regarding
96 movement behaviour in people with CNP (Barbero et al., 2017; Lomond and Cote, 2010).

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

103

104 **METHODS**

105 *Design*

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

114

115 *Participants*

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

123

124 *Inclusion criteria*

125 Participants with neck pain were included in the study if they presented with painful
126 symptoms for at least three months. In the case of those with whiplash-associated disorder
127 (WAD), only grades I, II, or III according to the Quebec Task Force Classification (Spitzer,
128 1995) were included. In addition, the participants had to report their neck pain intensity over the
129 last four weeks as at least 4 (mild pain) out of 10 on a Numerical Rating Scale (NRS) with two
130 anchor points: 0 = “no pain” and 10 = “worst pain imaginable” (Boonstra et al., 2016; Kamper et
131 al., 2015). The NRS is a valid and reliable instrument for self-reported pain intensity
132 (Williamson and Hoggart, 2005). Asymptomatic participants were recruited to act as a control
133 group. To be included they must have had no history of a neck injury or neck pain in the last two
134 years that required treatment from a health care practitioner.

135

136 *Exclusion criteria*

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

142

143 *Questionnaires*

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

156

157 *Cervical Kinematics*

158 An optoelectronic system (BTS Bioengineering, Milan, Italy) was used to record cervical
159 kinematics following system calibration. The kinematic data was acquired at a standard

160 frequency of 250fps. The system consists of eight infrared cameras with a resolution of 2,2
161 Mpixels (2048x1088pxs). The cameras tracked the 3D motion of retroreflective markers attached
162 to the subject's skin over the following body landmarks: two markers on the sternum, superior at
163 the jugular notch and inferior at the xiphoid process, 7th cervical vertebra, 5th thoracic vertebrae,
164 9th thoracic vertebrae. In addition, a helmet was placed on the subject's head, with four reflective
165 markers as follows: on the head apex, the front, and right and left sides of the helmet (Cescon et
166 al., 2015). The helmet also contained a laser pointer.

167

168 *Procedure*

169 Following placement of the reflective markers, the participant was seated upright on a
170 chair with their head in a neutral position and they were instructed to avoid shoulder movements
171 and to relax their arms. The participant was seated 220 cm in front of a wall and with the head in
172 neutral, the point of the laser was marked on the wall to define the starting reference position
173 (0°). Using a goniometer, the subjects head was then rotated 45° to the left and right and these
174 positions were marked (*Fig. 1*). Flexion and extension to 45° was also performed and these
175 positions were marked on the ceiling and floor. The participants performed the following neck
176 movements: flexion-extension, bilateral lateral flexion, and bilateral rotation. Each movement
177 was performed in three conditions: at a natural self-selected speed, slow speed (30 beats per
178 second (bps)) and fast speed (60 bps) (*Table 1*). The movement speed was controlled using a
179 metronome beats mobile application and the conditions were randomized in order to minimize
180 the risk of order as a confounding variable.

181 Participants were instructed to start every movement from the reference point at 0° and
182 then perform continuous neck movements without stopping in the midline. The subjects were

183 instructed to maintain the laser at 0° while performing lateral flexion, move between the 45°
184 reference points while performing rotation, and move up and down between the 45° reference
185 points while performing flexion-extension. The range of motion was limited since performing
186 functional tasks and activities of daily living does not usually require the full active range of
187 motion (Bennett et al., 2002; Bible et al., 2010). In addition, the position and the orientation of
188 the HA depends on the range of motion (Barbero et al., 2017).

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

194

195 *Data analysis*

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

204 Data from eight repetition movement cycles were analysed following exclusion of the
205 first and last cycle in order to avoid artefacts or alterations in angular velocity (Cescon et al.,

206 2014). The degree of variability of neck movements across the whole movement cycle was
207 measured by calculating the standard deviation (SD) of the mean.

208

209 *Statistical analysis*

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

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

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

226

227 **RESULTS**

228 A total of 36 participants completed the study with 8 men and 10 women in each group.
229 Those with CNP had a mean (SD) age of 32.2 (13.4) years, while the mean (SD) age of the
230 control group was 25.8 (7.3) years which was not significantly different ($U = 109.500$, $z = -$
231 1.664 , $P = .097$).

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

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

243

244 **Mean distance (MD)**

245 Flexion-extension

246 The CNP group displayed a smaller MD for the flexion-extension movements regardless
247 of the condition (main effect for group: $F=5.7$, $P=0.019$). Despite a trend, the MD did not vary
248 across flexion-extension movement conditions ($F=3.0$, $P=0.051$) and was not dependent on the
249 interaction between group and condition ($F=0.7$, $P=0.47$). The MD decreased in the CNP group
250 as compared to control group for the flexion-extension movements. The mean (SD) of CNP

251 group were as follows; natural speed condition 1.46 cm (0.33cm), slow condition 1.39 cm (0.25
252 cm), fast condition 1.65 cm (0.39 cm); whereas in the control group the values for the natural
253 speed condition were 1.61 cm (0.28 cm), slow condition 1.63 cm (0.31 cm), and fast condition
254 1.71 cm (0.31 cm).

255 Lateral flexion

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

262 Rotation

263 Consistent with the results for flexion-extension, the CNP group displayed smaller MD
264 values for the rotation movements regardless of condition (main effect for group: $F=7.48$,
265 $P=0.007$). The MD did not vary across rotation movement conditions ($F=0.19$, $P=0.82$) and was
266 not dependent on the interaction between group and condition ($F=1.53$, $P=0.22$).

267 The MD for the rotation movements decreased in the CNP group as compared to the
268 control group. The mean (SD) of the CNP group were as follows: natural speed condition 0.83
269 cm (0.15 cm), slow condition 0.90 cm (0.29 cm), and fast condition 0.84 cm (0.15 cm). The
270 control group mean (SD) were: 1.07 cm (0.33 cm) in the natural speed condition, slow condition
271 0.93 cm (0.22 cm), and fast condition 0.99 cm (0.35 cm).

272

273 ***Mean angle (MA)***

274 Flexion-extension

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

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

286 Lateral flexion

287 The MA did not vary across groups ($F=1.5$, $P=0.21$) or condition ($F=0.3$, $P=0.68$) for the
288 lateral flexion movements, and was not dependent on the interaction between group and
289 condition ($F=0.2$, $P=0.82$). The mean (SD) of the CNP group were as follows: natural speed
290 condition 8.96° (1.62°), slow condition 8.61° (1.92°), and fast condition 9.04° (2.07°); while for
291 the control group, the values were natural speed condition 9.70° (2.16°), slow condition 9.21°
292 (2.42°), and fast condition 9.20° (2.11°).

293 Rotation

294 The MA during the rotation movements was dependent on group ($F=9.30$, $p=0.003$) and
295 condition ($F=4.82$, $P=0.010$), but not the interaction between group and condition ($F=1.34$,

296 $P=0.26$). The post-hoc analysis revealed that the CNP group displayed smaller values for the MA
297 during rotation movements with different speeds (SNK: $P<0.01$) (*Table 3*).

298 The MA or the rotation movements decreased in the CNP group as compared to the
299 control group. The mean (SD) for the CNP group were as follows: natural speed condition 4.98°
300 (0.85°), slow condition 4.89° (0.71°), and fast condition 3.98° (0.42°). The control group values
301 were: natural speed condition 5.21° (1.04°), slow condition 5.44° (1.64°), and fast condition
302 4.99° (1.02°) (*Table 4*).

303

304 ***RoM***

305 The RoM for flexion-extension movements was consistent across conditions ($F=0.4$,
306 $P=0.62$) and groups ($F=1.9$, $P=0.16$), with no interactions present ($F=0.4$, $P=0.66$). The same
307 was true for lateral flexion, with no differences between conditions ($F=2.4$, $P=0.09$) and groups
308 ($F=2.0$, $P=0.15$) and no interactions present ($F=0.0$, $P=0.98$). For rotation, there were no effect of
309 conditions ($F=2.60$, $P=0.07$), no effect of group ($F=0.74$, $P=0.39$), and no interaction present
310 ($F=1.07$, $P=0.34$). The results of the RoM confirmed that all neck movement conditions were
311 performed within the range of movement required by the experimental protocol.

312

313 ***Correlations between kinematic variables and subjective descriptors***

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

317 ***Mean distance (MD)***

318 There was a moderate positive correlation between NDI and the MD measured during
319 flexion-extension neck movements at the fast speed ($r = .490, P=.039$). A strong positive
320 correlation was found between the average pain intensity (NRS) and the MD measured during
321 flexion-extension neck movement at the fast speed ($r = .514, P=.029$). Furthermore, a moderate
322 negative correlation was documented between the TSK score and MD during lateral flexion
323 performed and at the fast speed ($r = -.481, P=.044$). A moderate negative correlation was found
324 between the IPAQ score and the MD during lateral flexion performed at the fast speed ($r = -.346,$
325 $P=.042$).

326

327 Mean angle (MA)

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

332

333 **DISCUSSION**

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

340

341 *Movement variability*

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

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

364 strategy by people with neck pain, presumably employed as a protective method to decrease or
365 potentially avoid neck pain.

366 Even though the level of pain reported in this study was low in the CNP group,
367 differences in movement behaviour and movement variability were observed between groups.
368 This is congruent with other research and with current theories about the impact of pain on
369 movement and motor control. Some people may continue to display less variability in
370 movements even when they are free from pain (Moseley and Hodges, 2006). Moreover, an
371 association may exist between motor variability and learning in pain disorders (Moseley and
372 Hodges, 2006). This association could be controlled by evaluative processes that play a role in
373 motor variability: when a movement is associated with pain, the patient performs that movement
374 differently, and over a period of time this change in movement becomes ingrained (Moseley and
375 Hodges, 2006). Furthermore, motor adaptations to pain could lead to protection from
376 vulnerability to pain or injury, and contribute to changes in mechanical behaviour (Hodges and
377 Tucker, 2011). For example, a protective movement strategy was employed by healthy people
378 when they anticipated that a movement could cause harm to their back (Moseley and Hodges,
379 2006). Thus, the lower movement variability identified in the CNP group in the current study
380 could reflect an adapted behaviour due to pain.

381

382 *The influence of movement speed*

383 In the current study, reduced movement variability was observed in the CNP group as
384 compared to the control group for flexion-extension as revealed by differences in the MD.
385 Furthermore, decreased movement variability during flexion-extension was seen via the MA
386 when performed at the faster speed than when performed at the slower and self-selected speeds,

387 and this was the case for both groups. Vikne et al. (2013) also observed a significant reduction in
388 movement speed and displacement during flexion-extension movements when performed at a
389 faster speed compared to the preferred or slower speed. In addition to the observed reduction of
390 movement variability during flexion-extension at the faster speed, positive correlations were also
391 found between the MD during flexion-extension performed at the faster speed, and the level of
392 disability (NDI), and the level of average pain intensity (NRS). Based on the current and on
393 previous observations, faster movements could be emphasised during the clinical examination of
394 people with CNP especially since people with neck pain often complain of difficulty performing
395 rapid movement of their head (Bahat et al., 2010).

396

397 *Correlation between movement parameters and clinical features*

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

402

403 *Clinical implications*

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

409 implemented in a clinical setting, are capable of detecting such changes in movement quality in
410 people with CNP.

411

412 *Methodological considerations*

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

422

423 *Conclusion*

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

428

429 **Funding Acknowledgements**

430 This study was funded by a Ph.D. scholarship awarded to the first author by Qassim
431 University in Saudi Arabia.

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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 |

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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) |

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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).

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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 |

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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 (°) | |
|------------------|----------------------|----------------------|------------------|------------------|
| | 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° (0.73°) |
| 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° (1.91°) |
| LatFlex fast | 0.97 cm (0.31 cm) | 0.91 cm (0.25 cm) | 9.20° (2.11°) | 9.04° (2.01°) |
| Rotation natural | 1.07 cm (0.33 cm) | 0.83 cm (0.15 cm) | 5.21° (1.04°) | 4.98° (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°) | 3.98° (0.43°) |

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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 |

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* 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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