

# Variation in the spatial distribution of erector spinae activity during a lumbar endurance task in people with low back pain

Sanderson, Andy; Martinez-Valdes, Eduardo; Heneghan, Nicola R.; Murillo, Carlos; Rushton, Alison; Falla, Deborah

DOI:  
[10.1111/joa.12935](https://doi.org/10.1111/joa.12935)

License:  
Other (please specify with Rights Statement)

*Document Version*  
Peer reviewed version

*Citation for published version (Harvard):*  
Sanderson, A, Martinez-Valdes, E, Heneghan, NR, Murillo, C, Rushton, A & Falla, D 2019, 'Variation in the spatial distribution of erector spinae activity during a lumbar endurance task in people with low back pain', *Journal of Anatomy*, vol. 234, no. 4, pp. 532-542. <https://doi.org/10.1111/joa.12935>

[Link to publication on Research at Birmingham portal](#)

## **Publisher Rights Statement:**

This is the peer reviewed version of the following article: Sanderson, A. , Martinez-Valdes, E. , Heneghan, N. R., Murillo, C. , Rushton, A. and Falla, D. (2019), Variation in the spatial distribution of erector spinae activity during a lumbar endurance task in people with low back pain. *J. Anat.*. doi:10.1111/joa.12935, which has been published in final form at <https://doi.org/10.1111/joa.12935> . This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Self-Archiving

## **General rights**

Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

## **Take down policy**

While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact [UBIRA@lists.bham.ac.uk](mailto:UBIRA@lists.bham.ac.uk) providing details and we will remove access to the work immediately and investigate.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26

**Variation in the spatial distribution of erector spinae activity during a lumbar endurance task in people with low back pain**

Andrew Sanderson, Eduardo Martinez-Valdes, Nicola R. Heneghan, Carlos Murillo, Alison Rushton, 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, UK

Corresponding Author – Deborah Falla  
[d.falla@bham.ac.uk](mailto:d.falla@bham.ac.uk)  
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, UK

27 **Abstract**

28 This study aimed to investigate the spatial distribution and redistribution of lumbar erector  
29 spinae (ES) activity during a lumbar extension endurance task in pain-free participants and  
30 how this is modified in people with low back pain (LBP). High density surface  
31 electromyography (HDEMG) was recorded using 13x5 electrode grids placed over the  
32 lumbar ES in 13 LBP and 13 control participants while completing an Ito test to task failure.  
33 The root mean square of the HDEMG signals was computed, a topographical map of the  
34 EMG amplitude generated and the centre of the activity (centroid) determined throughout the  
35 task. The centroid of the EMG amplitude map was systematically more cranial ( $F = 6.09$ ,  $P =$   
36  $0.022$ ) for the LBP participants compared to the control subjects. Regression analysis showed  
37 that the extent of redistribution of ES activity was associated with longer endurance. These  
38 results show that LBP participants utilised a different motor strategy to perform the  
39 endurance task, characterised by greater activation of more cranial regions of the ES and less  
40 redistribution of ES activity throughout the task. This study provides new insight into the  
41 functional activation of the lumbar ES and how it is modified when people have pain.

42 **Keywords** – High density EMG, Ito Test, Erector Spinae, Functional Muscle Activity

43

44 **Funding Sources** - This research did not receive any specific grant from funding agencies in  
45 the public, commercial, or not-for-profit sectors.

46 **Competing Interests** – There are no competing interests to declare.

47

48

49

50

51

<b>Abbreviation</b>	<b>Meaning</b>
LBP	Low Back Pain
EMG	Electromyography
HDEMG	High Density Electromyography
ES	Erector Spinae
MVC	Maximum Voluntary Contraction
ODI	Oswestry Disability Index
TSK	Tampa Scale for Kinesiophobia
PNRS	Pain Numeric Rating Scale
RPE	Rate of Perceived Exertion
RMS	Root Mean Squared Amplitude
MNF	Mean Spectral Power Frequency
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
CON	Control Participant
SE	Standard Error of the Mean

## 52        **1. INTRODUCTION**

53            Previous anatomical and biomechanical research on the lumbar erector spinae (ES)  
54 has focussed on the relationship and the structure of different portions of this muscle group  
55 (Christophy et al., 2012, Bogduk, 1980, Bogduk, 2005). Bogduk (2005), via several  
56 dissection studies, described the origins, insertions and functions of the portions of the  
57 lumbar ES, work which was adapted by Christophy and colleagues to produce a  
58 biomechanical model of the lumbar musculature (Christophy et al., 2012, Bogduk, 1980).  
59 These descriptions concurred that while the portions of the muscle group have different  
60 origins and insertions, all play important roles in extending the lumbar spine during  
61 functional movements. The structures described for the portions of the ES indicate a broad  
62 bilateral muscular region lateral to the lumbar spine extending from L5 into the thoracic  
63 region (Bogduk, 2005, Christophy et al., 2012). To extend the lumbar spine, the most  
64 effective motor strategy would be to recruit fibres especially from the caudal portions of the  
65 ES, creating a longer lever arm and conferring a biomechanical advantage to the movement  
66 (Bogduk, 2005).

67            Surface electromyography (EMG) is used to measure muscle activity and can be  
68 applied as a means to understand variations in neuromuscular control in individuals with  
69 musculoskeletal pain (Abboud et al., 2014, Fabian et al., 2005, Falla et al., 2017, Falla et al.,  
70 2014, Gallina et al., 2011, Gizzi et al., 2015). More recently, high-density surface  
71 electromyography (HDEMG) has been utilised to understand and quantify changes in the  
72 spatial distribution of muscle activity which was not previously possible with classic bipolar  
73 surface EMG. Existing research utilising HDEMG has also commonly evaluated changes in  
74 the distribution of muscle activity during either sustained or dynamic contractions by  
75 quantifying a shift in the centroid of the HDEMG amplitude map, the point which defines the  
76 barycentre of muscle activation (Falla et al., 2014, Madeleine et al., 2006, Farina et al., 2008,

77 Falla et al., 2017, Gallina et al., 2013). HDEMG studies on healthy asymptomatic volunteers  
78 have shown that the centre of muscle activity shifts during contraction (Falla and Farina,  
79 2008b, Farina et al., 2008, Tucker et al., 2009) and that this redistribution of muscle activity  
80 has the physiological significance of minimising muscle fatigue and prolonging endurance  
81 (Farina et al., 2008, Gallina et al., 2013, Falla et al., 2014), possibly by preventing overload  
82 on the muscle fibres active at the beginning of the task.

83         Previous HDEMG investigations have described an association between endurance  
84 time and the redistribution of muscle activity in the trapezius in asymptomatic participants  
85 (Farina et al., 2008). More Recently HDEMG was applied to evaluate changes in lumbar ES  
86 activity in a LBP population (Abboud et al., 2014). Participants completed a force-matching  
87 modified Sørensen test (lifting of the unsupported upper body with the legs affixed to a  
88 plinth), resisting a load cell around their shoulders which simulated 30% of their maximum  
89 voluntary contraction (MVC). Increased variability in the position of the centroid of the EMG  
90 amplitude map was observed in the healthy controls compared to the LBP group.

91         Despite these observations, the functional relevance of a change in the distribution of  
92 muscular activity remains unclear. We hypothesised that people with LBP would engage  
93 different regions of the lumbar ES during isometric back extension, reflecting less efficient  
94 activation of the ES and, that people with LBP would show less redistribution of ES activity  
95 which would be associated with significantly lower endurance in this group.

96         Thus, the aim of this study was to investigate the spatial distribution of lumbar ES  
97 activity and redistribution of activity during an endurance task in participants with chronic  
98 LBP and pain-free controls. Moreover, we evaluate the relationship between the extent of  
99 redistribution of activity and endurance time, with the hypothesis that those who display a  
100 larger redistribution of activity would be able to sustain the contraction for longer. This study

- 101 stands to provide new insight into the functional activation of the lumbar ES and how it is
- 102 modified when people have pain.

103 **2 - METHODS**

104 This study was an observational, cross-sectional case-control study using a  
105 convenience sample of participants from the staff, students and community of the University  
106 of Birmingham, UK. Data collection took place in a laboratory within the Centre of Precision  
107 Rehabilitation for Spinal Pain, University of Birmingham.

108 2.1 - Participants

109 LBP participants aged 20-55 were recruited via posters and social media accounts  
110 related to the University of Birmingham. Due to the nature of the fatiguing task, it was  
111 decided that 55 would be the maximum age of participants eligible for this study. Eligibility  
112 criteria included non-specific LBP which had persisted for at least half the days of the  
113 previous six months, exceeding the minimum definition for LBP (Dionne et al., 2008).  
114 Consistent with previous studies, age and gender matched control participants (CON) were  
115 recruited in the same way and were included if they had no history of LBP or lower limb  
116 disorders. Exclusion criteria for both groups comprised concurrent systemic issues including  
117 rheumatic and neuromuscular disorders, a history of chronic respiratory or neurological  
118 problems, spinal deformity or surgery, cardiovascular conditions, pregnancy, and healthcare  
119 management for LBP in the previous 6 months (a requirement of the University ethical  
120 committee). To support a normal distribution for statistical analysis, a planned sample size of  
121 30 participants (15 LBP and 15 CON) was chosen, consistent with previous HDEMG studies  
122 comparing symptomatic and asymptomatic participants.

123 Ethical approval was granted by the University of Birmingham ethics committee  
124 (ERN\_17-0782). Participants gave written informed consent prior to data collection and all  
125 procedures were completed in accordance with the Declaration of Helsinki.



## 126 2.2 - Questionnaires

127 Prior to testing, participants from both groups were required to complete several  
128 questionnaires to gather population statistics; including the level of disability, intensity of  
129 pain, and current level of activity. Participants were asked to complete the Oswestry  
130 Disability Index (ODI), as it has previously been shown to be a reliable measure of disability  
131 relating to spinal pain (Fairbank and Pynsent, 2000). The Tampa Scale for Kinesiophobia was  
132 used to assess any fear surrounding movement related to pain (Miller et al., 1991). A Pain  
133 Numeric Rating Scale (0-10) (PNRS) was used to assess current pain at the time of testing,  
134 and pain over the prior week (Breivik et al., 2008). Information on the general health of  
135 participants at the time of testing was collected using the RAND 36 item health survey, which  
136 has been shown to be effective and reliable as a measure of health across cultures and gender  
137 (Hays et al., 1993, VanderZee et al., 1996). Throughout the endurance task (see below), the  
138 rate of perceived exertion (RPE) was recorded at 30 s intervals and immediately following  
139 task failure using the Borg RPE scale (Borg, 1998). This measure was used to assess the  
140 perceived exertion of the participants throughout the task and ensure that the task was  
141 appropriate for LBP participants.

## 142 2.3 - Experimental Set-Up

143 Surface EMG signals were recorded from the lumbar ES using 13x5 semi-disposable  
144 2D electrode grids (OT Bioelettronica, Italy). Electrodes were spaced evenly with a 1 mm  
145 diameter and an 8 mm inter-electrode distance; one corner electrode was missing in each grid  
146 to provide directional reference. Electrodes were positioned over the lumbar ES on the right-  
147 hand side in control participants and the most painful side in the LBP group. Where equal  
148 pain was reported bilaterally, participants were randomly allocated a side (Figure 1).

149 Prior to the application of electrodes, the skin in the region lateral to the lumbar spine  
150 was prepared by firstly shaving the area if needed and then applying an abrasive paste (SPES  
151 Medica, Italy), and finally washing and drying the region. The electrodes were prepared by  
152 applying a thin custom double-sided adhesive foam pad to the electrode grid (SPES Medica,  
153 Genova, Italy). The cavities of the electrode grids were then filled with an electroconductive  
154 paste (SPES Medica, Genova, Italy). As there is no way of differentiating different portions  
155 of the ES in-vivo, the electrode was placed on the ES in accordance with EMG guidelines  
156 and previous studies (Barbero et al., 2012, Falla et al., 2014). The grids were then applied to  
157 the skin approximately 2cm lateral to the lumbar spinous processes, starting at the level of the  
158 L5 and extending to approximately the level of L3, as described previously (Falla et al.,  
159 2014). Reference electrodes were placed on prepared skin over the right anterior superior  
160 iliac spine and on the spinous process of the vertebra prominens.

161 A twin-axis SG150B digital goniometer (Biometrics Ltd., Gwent, UK) was applied to  
162 the right mid-axillary line of the participant. Only one axis (sagittal plane) was used for  
163 analysis. The lower sensor was attached to the centre of the iliac crest, with the midline of the  
164 sensor in line with the greater trochanter of the femur. With the participant positioned in  
165 prone on the plinth, the resting angle was calibrated as 0°, with trunk deviation measured  
166 from this point. EMG signals and angular data were sampled at 2048Hz and amplified (400-  
167 channel EMG amplifier Quattrocento, OT Bioelettronica, Torino, Italy; -3dB, bandwidth 10-  
168 500 Hz)) by a factor of 150 and converted to digital form by a 16-bit analogue-to-digital  
169 converter. Collected signals were stored on a computer hard drive and later analysed using a  
170 custom code on MATLAB (The Mathworks Inc., USA).

171 As described previously by Falla et al. (2014), each grid of electrodes recorded 64  
172 monopolar signals. These signals were then processed offline to form horizontal derivatives  
173 across the grids. This was achieved by first filtering the monopolar signals using a 20-350 Hz

174 band-pass filter and then adjacent signals were processed to produce 59 bipolar EMG signals.  
175 The amplitude (RMS) and mean spectral power frequency (MNF) for each bipolar derivation  
176 were then calculated. The individual RMS and MNF values for each bipolar signal were  
177 averaged to produce the mean RMS and MNF values across the grid. The RMS values for  
178 each bipolar signal were used to create a topographical map of ES activity. This map was  
179 used to determine the location of the x- and y-coordinates of the centroid as described  
180 previously (Abboud et al., 2014, Falla et al., 2017, Falla et al., 2014, Farina et al., 2008,  
181 Madeleine et al., 2006, Tucker et al., 2009). The location of the centroid was averaged across  
182 the 10s or 10% epochs for further use in analysis.

183         The values for the x- and y- coordinates of the centroid were analysed as an absolute  
184 shift in mm from the start point quantified in the first 10% epoch (Falla et al., 2014). As  
185 movement of the centroid was both cranial and caudal in both groups, to allow for  
186 comparison between groups of the absolute shift in the y-coordinate of the centroid, both  
187 positive and negative movements were made positive.

#### 188 2.4 - Experimental Procedure

189         To complete the endurance task, participants were required to maintain an Ito test, as  
190 described by Ito et al. (1996) and Muller et al. (2010) until task failure or until 300s.  
191 Participants were first asked to lie prone on a plinth, with a firm semi-circular foam pad (18  
192 cm diameter) centred below the anterior superior iliac spines. To complete the endurance  
193 task, participants were asked to lift their sternum from the plinth, raising their upper body by  
194  $\sim 15^\circ$ . While maintaining this position, participants were asked to keep their arms in line with  
195 the body axis and not in contact with the plinth; participants were also required to contract  
196 their gluteal muscles and retain a neutral neck position. Prior to beginning the task, an

197 investigator demonstrated the correct position for completion of the Ito test, and participants  
198 were permitted to complete a short 5 s contraction to ensure they had the correct technique.

199           Throughout the task, the angle of the body axis was monitored visually and  
200 participants were alerted if their body axis was approaching the upper or lower acceptable  
201 limits ( $\pm 10^\circ$ ) (Demoulin et al., 2007). Task failure was determined by a drop in the angle of  
202 trunk of greater than  $10^\circ$  at any point. While completing the contraction, participants were  
203 timed using a stopwatch, the time was recorded until task failure or until the maximum  
204 contraction duration was reached (300 s). Throughout the task, participants were given verbal  
205 encouragement and at 30s increments were provided with feedback for how long they had  
206 sustained the contraction.

## 207 2.5 - Statistical Analysis

208           Statistical analysis was performed using SPSS 24 (IBM, USA) with an alpha level set  
209 at 0.05. Regression analysis and analysis of covariance (ANCOVA) tests were performed  
210 using Prism (GraphPad, USA). Where P-values were reported on SPSS as 0.000, they have  
211 been stated as  $P < 0.001$  herein. Effect sizes have been reported where appropriate with  
212 ANOVA results, based on guidance by Lakens (2013) in the format of generalised  $\eta^2$  ( $\eta_g^2$ ),  
213 alongside  $\eta^2$  values. For interpretation of these values, effect sizes are defined as small ( $\eta^2 / \eta_g^2$   
214 = 0.01), medium ( $\eta^2 / \eta_g^2 = 0.06$ ), or large ( $\eta^2 / \eta_g^2 = 0.14$ ) (Lakens, 2013, Cohen, 1988).

215           A student t-test was performed in order to identify any differences in endurance times  
216 between groups. The questionnaires used to gather sample characteristics were interpreted  
217 according to their respective guidelines (Childs et al., 2005, Fairbank and Pynsent, 2000,  
218 Hays et al., 1993, Miller et al., 1991). Student t-tests were performed for each group to  
219 identify differences between the samples at baseline. To determine if the failure of the task

220 was influenced by fear of movement, the endurance time for each participant was correlated  
221 to their respective TSK score.

222 No direct comparison of the values reported for perceived exertion could be made  
223 between groups, as the time to task failure varied between groups. Therefore, the initial value  
224 after 30 s, the value at the mid-point of endurance, and the level of exertion at task failure  
225 were determined for each participant. Significant differences between groups were  
226 investigated using a repeated measures analysis of variance (ANOVA).

227 In order to make comparisons between groups with different times to task failure, the  
228 total contraction time for each participant was normalised into 10% epochs of the total  
229 endurance time (Farina et al., 2008). Repeated measures ANOVA, with factors of group  
230 (CON and LBP) and time (10 epochs) were used to compare differences in EMG variables  
231 between groups. Newman-Keuls post-hoc tests were also conducted where appropriate.

232 To identify trends in the displacement of the y-coordinate of the centroid between  
233 groups, a linear regression was performed. To ensure that the results were not affected by the  
234 normalisation of time, this regression was performed using absolute endurance times and y-  
235 coordinate displacement values calculated from the position of the centroid in the first 10 s  
236 epoch. The regression lines for the CON and LBP groups were compared for statistical  
237 significance using an ANCOVA.

238 Finally, in order to assess myoelectric manifestations of muscle fatigue, linear  
239 regressions were performed on RMS and MNF variables (Larivière et al., 2002). For each  
240 participant, the relationships between RMS and time to task failure, and MNF and time to  
241 task failure were computed. In this analysis both absolute values for RMS and MNF across  
242 time, and normalised values (using the using the first 10s epoch as a reference) were  
243 considered and the resulting slopes extracted. Independent samples t-tests were then

244 performed on the slopes for each condition to identify the mean slope for each group and  
245 identify any differences between these means (Pagé and Descarreaux, 2012, Roy et al., 1995).

## 246 3 - RESULTS

### 247 3.1 - Participants

248 13 LBP and 13 CON participants successfully completed data collection, population  
249 characteristics are reported in Table 1. No significant anthropometric differences were found  
250 between groups for BMI, height or weight and the BMI for both groups was within the  
251 'normal weight' range (Stenholm et al., 2017). However, as anticipated the LBP group  
252 presented with higher levels of disability (ODI -13.16%) and lower general and emotional  
253 health (RAND 36 item health survey). Prior to data collection, LBP participants reported a  
254 current pain level of 1.92 out of 10, but a usual pain of 2.92, characterising the pain within  
255 the group as mild or low severity (Breivik et al., 2008). No significant correlation was found  
256 between scores on the TSK and the endurance time ( $R = -0.281$ ,  $P = 0.165$ ).

### 257 3.2 - Endurance

258 Significantly lower endurance times were recorded for the LBP group ( $F = 8.4$ ,  $P <$   
259  $0.001$ ) compared to the control group ( $186.3 \pm 72.3$ s and  $283.0 \pm 33.0$ s respectively). With  
260 96.7s difference, this equates to the LBP group maintaining the contraction for 65.8% of the  
261 total time for the CON group on average. The mean values for initial, middle and final  
262 perceived exertion are shown in Figure 2. No significant differences were found between  
263 groups for exertion at any point ( $F = 1.42$ ,  $P = 0.216$ ).

### 264 3.3 – Electromyographical Changes

#### 265 3.3.1 – EMG amplitude and mean frequency of the EMG signal

266 Across the duration of the contraction, the RMS was found to be systematically higher  
267 for CON than LBP participants (main effect of group;  $F = 6.09$ ,  $P = 0.022$ ,  $\eta_g^2 = 0.18$ ,  $\eta^2 =$   
268  $0.18$ ) (Figure 3). This higher activation of the ES was visible in the topographical maps of the

269 EMG amplitude (Figure 4). On average, the CON participants showed a larger distribution of  
270 the activity throughout the entire muscle, whereas LBP participants showed a less diffused  
271 activation which tended to be more cranial. When this was quantified, an even distribution  
272 across the entire grid was observed in 11 CON and 4 LBP participants. Distribution was  
273 weighted cranially in 1 CON and 8 LBP participants and distribution was focussed in the  
274 middle of the grid for 1 Con and 1 LBP participant.

275         There were no significant differences between groups for the change in RMS  
276 throughout the task ( $F = 1.42$ ,  $P = 0.216$ ). There was also no significant increases or  
277 decreases in the mean RMS recorded for either group at any point during the endurance task  
278 ( $F = 0.929$ ,  $P = 0.344$ ). No significant differences between groups were observed for the  
279 mean MNF at any point during the contraction ( $F = 1.118$ ,  $P = 0.334$ ).

### 280 3.3.2 – Centroid of the EMG RMS map

281         No significant differences were found between groups for the position of the x-  
282 coordinate of the centroid (medial-lateral direction) throughout the task (initial position –  $F =$   
283  $2.27$ ,  $P = 0.77$ ; shift over the duration of the contraction –  $F = 2.27$ ,  $P = 0.77$ ).

284         The y-coordinate of the centroid (cranial-caudal direction) in CON participants was  
285 found to be systematically more caudal than the LBP group (main effect for group;  $F = 44.00$ ,  
286  $P < 0.001$ ,  $\eta_g^2 = 0.64$ ,  $\eta^2 = 0.65$ ). The y-coordinate in CON participants was found to be  
287 approximately 42.0 mm ( $\pm 4.99$  mm) cranial of the reference electrode, whereas for the LBP  
288 participants, the y-coordinate was approximately 53.6 mm ( $\pm 3.64$  mm) cranial of the  
289 reference electrode. Throughout the endurance task there was a mean difference between the  
290 LBP and CON in the y-coordinate position of 11.6mm (Figure 5).



291 Using the location of the y-coordinate of the centroid in the 1<sup>st</sup> epoch as a reference  
292 point, the displacement was calculated for each 10% epoch. To achieve this, the shift in mm  
293 was measured from the position of the y-coordinate in the first epoch, this could be either a  
294 positive (cranial movement) or negative (caudal) value. No clear direction of shift was found  
295 (cranially or caudally) as groups showed both cranial and caudal movements (CON – 6  
296 cranial, 7 caudal; LBP – 9 cranial, 4 caudal). To better understand the movement of the  
297 centroid, all values for displacement were therefore made positive and so net displacement is  
298 used for all y-coordinate shift results. At task failure, the mean y-coordinate displacement for  
299 the CON group was 2.10±0.45mm whereas for the LBP group it was 1.40±0.29mm. Both  
300 groups showed a significant displacement of the centroid in the y-axis over time (F=2.5,  
301 P=0.004,  $\eta_g^2 = 0.22$ ,  $\eta^2 = 0.30$ ) and a significant displacement within each group (F=9.9,  
302 P=0.01) (Figure 6). There was no interaction between groups for the displacement of the y-  
303 coordinate in the data which had been normalised to task failure (F = 1.709, P = 0.134).

304 The regression analysis performed using absolute values for time showed a significant  
305 relationship between the shift in the y-coordinate of the centroid and the time to task failure  
306 (Figure 7) for both groups (CON -  $r^2 = 0.142$ , P < 0.0001; LBP -  $r^2 = 0.053$ , P = 0.0004).  
307 Additionally, ANCOVA analysis showed that there was a significant difference between the  
308 regression lines for each group (F=5.597, P=0.0183) indicating that the relationship between  
309 y-coordinate shift and time was significantly different between groups (LBP/CON) (Zar,  
310 2010).

311 Myoelectric manifestations of muscle fatigue showed no differences under any  
312 condition. There were no differences in the slopes between groups for absolute RMS (P =  
313 0.71), normalised RMS (P = 0.37), absolute MNF (P = 0.48) or normalised MNF (P = 0.79).

## 314 4 – DISCUSSION

315 This is the first study to assess muscle activation behaviour using HDEMG during a  
316 functional position-matching lumbar endurance task in people with and without LBP. The  
317 results revealed an altered motor control strategy to a standardised endurance task in people  
318 with LBP with evidence of activation of more cranial regions of the lumbar ES with respect  
319 to asymptomatic people. Moreover, a relationship was also demonstrated between the extent  
320 of redistribution of muscle activity and endurance time which has important implications for  
321 the understanding of the neurophysiological responses to fatigue.

### 322 4.1 –Distribution of Activity

323 Throughout the endurance contraction, the RMS was found to be significantly higher  
324 in the CON group than the LBP group. One possible explanation for this disparity in  
325 amplitude could be quantified from the systematic differences in the position of the centroid  
326 along the y-axis. Throughout the task the y-coordinate of the centroid for the CON group was  
327 12mm caudal to that of the LBP group. Previous studies which have induced pain via  
328 injection of hypertonic saline, have shown that areas with greater pain show reduced activity  
329 and that in an acute painful condition, the muscle activation can shift outside of the painful  
330 region (Falla et al., 2017, Falla and Farina, 2008a, Madeleine et al., 2006). Although  
331 somewhat speculative, it is likely that a more caudal centre of contraction could indicate a  
332 more biomechanically favourable contraction through activating a greater number of fibres.  
333 In this instance, those with pain appear to have shifted the activity in the ES more cranially.  
334 A more caudal contraction, which is distributed over a larger area of the muscle would be  
335 able to utilise the larger volume of muscles from lower lumbar vertebrae and spread the load  
336 more effectively across a greater number of muscle fibres creating a longer lever arm  
337 (Bogduk, 2005). The longer lever arm would act to minimise the force needed to sustain the

338 contraction and the diffuse activation would reduce localised fatigue, facilitating sustained  
339 endurance.

#### 340 4.2 - Redistribution of lumbar ES activity

341 During the Ito test, the CON participants showed a greater shift of the centroid of the  
342 EMG amplitude map indicating a greater redistribution of lumbar ES activity than the LBP  
343 group. It was also shown that the amount of redistribution increased progressively over the  
344 duration of the task and that there was an association between the extent of redistribution of  
345 activity and endurance time. As previously described by Falla et al. (2014), a redistribution of  
346 activity likely prevents localised muscle fatigue through the build-up of metabolic factors and  
347 overload on specific regions of the muscle. The task used in Falla et al (2014) was dynamic  
348 and consisted of periodic contractions, whereas the contraction used here is static and so the  
349 tissue would be under further strain due to decreased blood flow and ischemia (Masuda et al.,  
350 1999).

351 The results of this study do not support a direction of shift for this task as there was no  
352 clear preference for a direction in either group. However, this study differs from previous  
353 studies which used HDEMG to examine the lumbar muscles as it does not involve an external  
354 force. Gallina et al. (2013) investigated the significance of the shift in the trapezius muscle  
355 and determined that the direction of shift was task dependant. Russ et al. (2018) and Thomas  
356 et al. (2011) showed that there were specific differences in lumbar endurance between force-  
357 and position-matching tasks, the reasons for which they were unable to describe. The lack of  
358 a clear direction of shift seen in this study, may imply a focus of muscle activity in a more  
359 biomechanically favourable point for each participant. As there was no specific point to  
360 'push' against, the centre of activity for each participant was likely determined by individual  
361 anthropomorphic features, for example a greater trunk length to leg length ratio. In this study,

362 it is speculated that as participants were not secured to the plinth or pushing against a point,  
363 the impact of the relative size and weight of the legs compared to the upper body would  
364 impact on the stability of the participant while contracting. Thus the participant might be  
365 likely to sustain a contraction which affords them the optimal stability for their individual  
366 anthropomorphic characteristics.

#### 367 4.3 – Muscular Activity

368 Biomechanical and anatomical models of the lumbar musculature indicate that the  
369 shared insertions of portions the ES cause a diagonal slight overlapping of successive  
370 superficial fibres (Bogduk, 2005, Bogduk, 1980). According to anatomical studies, the  
371 portions of the ES which are likely to be muscular in the region beginning 2cm lateral to L5  
372 include the *iliocostalis lumborum pars lumborum* and the *iliocostalis lumborum pars*  
373 *thoracis*, with the muscular portions of the longissimus being too medial or too cranial to be  
374 covered by the electrode grid. In the *pars lumborum*, most deep and lateral fibres are from  
375 L5, the most superficial and medial fibres are from L1; each successive lamina of fibres  
376 slightly overlaps the previous layer (Bogduk, 2005, Christophy et al., 2012). The Ito test used  
377 in this study is designed to gain relative isolation of the lumbar musculature, so the  
378 distribution and redistribution of activity in this portion of the muscle is thought to be key to  
379 understanding endurance in this task (Muller et al., 2010). It is therefore suspected and  
380 proposed that due to pain in the lumbar region, LBP participants utilised a motor control  
381 strategy which preferentially activated different portions of the muscle, such as the more  
382 cranial *iliocostalis lumborum pars thoracis* and thus led to a shorter time to task failure than  
383 the CON group. As no imaging was used in this study, the exact distribution of activity  
384 among portions of the ES, and what effect any individual variations in muscle architecture or  
385 fibre distribution could have on the activation pattern remains unknown (Mannion et al.,  
386 1997, Mannion et al., 2000).

#### 387 4.4 – Endurance and Fatigue

388           The LBP group demonstrated endurance which fell significantly short of the CON  
389 group. Similar findings have been demonstrated in previous studies investigating lumbar  
390 endurance to task failure, however the absolute endurance times reported here were  
391 significantly higher than those reported following a Sørensen test (Abboud et al., 2014,  
392 Jubany et al., 2017). This difference could be attributed in part to the differences between  
393 force-matching tasks previously used, and position-matching such as the Ito test used here  
394 (Russ et al., 2018). However, Muller et al. (2010) reported lower endurance times for a  
395 position-matching Sørensen test when compared directly with an Ito test. In this instance it  
396 may also be relevant to consider the biomechanical and myoelectrical differences between the  
397 Ito and Sørensen positions. As discussed previously, muscle activation in the Ito test is  
398 focussed on the lumbar region while the Sørensen has shared activation between the lumbar  
399 and hip extensors, possibly contributing to differences in endurance time (Muller et al.,  
400 2010). Additionally though both tasks are measures of lumbar endurance, each requires a  
401 different position to be held; with the Ito test requiring spinal extension to be sustained and  
402 the Sørensen requiring an unsupported neutral spine maintained against gravity (Muller et al.,  
403 2010). Due to this, it is likely that the point at which the participant's centre of mass is  
404 supported may be lower in the Ito test, producing a lower moment.

405           At task failure, both LBP and CON participants reported a mean RPE of between 18.3  
406 – 18.5, indicating that both groups reached a similar level of exertion. Analysis of the MNF  
407 results and the indices measuring the myoelectric manifestations of fatigue revealed that there  
408 were no significant differences between the CON and LBP groups. Previous HDEMG studies  
409 evaluating fatigue of the lumbar ES have shown greater myoelectric manifestations of fatigue  
410 than these results suggest, however other studies also did not find significant differences  
411 between groups (Abboud et al., 2014, Tucker et al., 2009). This could be somewhat explained

412 by recent studies which have demonstrated that frequency variables, including MNF, do not  
413 accurately predict motor unit recruitment during contractions (Merletti and Farina, 2016,  
414 Vecchio et al., 2017). Additionally, it has been shown in the knee extensors that myoelectric  
415 manifestations of fatigue are only seen when the exertion exceeds 40% of the MVC (de  
416 Ruiten et al., 2012). Two exercises in a study by Plamondon et al. (2002) were similar in  
417 position and function to the Ito test, in that study these exercises were found to be between  
418 26-32% of a participant's MVC. As the current study did not assess the functional capacity of  
419 the participants, the results for MNF may be affected by the task being below 40% of an  
420 MVC for some participants.

421         The results of this study coalesce to indicate that the LBP participants utilise a  
422 different motor control strategy to complete the task. This strategy was characterised by a  
423 reduced activation of the ES which was focussed more cranially and throughout the task  
424 showed less redistribution of activity. It appears that participants used less favourable  
425 portions of the ES to complete the task which lead to shorter endurance times.

#### 426 4.5 - Strengths and Limitations

427         A strength of this study was its use of HDEMG to present a more comprehensive  
428 characterisation of ES activity during an endurance test, a test which can be easily replicated  
429 in a clinical environment. In addition, the Ito test presented here has previously been found to  
430 better isolate the lumbar musculature than the Sørensen test (Muller et al., 2010). As no  
431 significant differences were found in the RPE between groups, it is supported that the Ito test  
432 was a suitable test for this population. However, it should be considered that as no clear  
433 guidelines for task failure have been validated for the Ito test, the task failure criteria of  $\pm 10^\circ$   
434 could be perceived to affect the redistribution of activity during the task. However, as  
435 systematic differences were seen between groups for all values related to the RMS, we are

436 confident that the differences between groups are valid, but could hinder comparison to other  
437 lumbar endurance tasks. To mitigate this effect, where possible, generalised effect sizes have  
438 been reported with ANOVA results, which have been interpreted in line with the guidelines  
439 suggested by Cohen (1988), and reiterated by Lakens (2013), whereby effect sizes are  
440 defined as small ( $\eta^2 = 0.01$ ), medium ( $\eta^2 = 0.06$ ), or large ( $\eta^2 = 0.14$ ). However it has been  
441 suggested that these benchmarks for  $\eta^2$  may not be as accurate in repeated measures  
442 conditions. Therefore we also included the  $\eta_g^2$  values, which have been proposed to allow  
443 better comparisons between studies (Lakens, 2013).

444 Since participants could not be under current active management by a healthcare professional  
445 (a requirement of the University Ethical Committee), the LBP group presented with low  
446 levels of current pain and mild disability. Although the sample size was relatively small and  
447 the LBP participants presented with relatively mild LBP, significant group differences were  
448 revealed and even greater group differences may be expected when testing patients with even  
449 greater pain severity or longer pain duration (Arendt-Nielsen and Graven-Nielsen, 2008,  
450 Mannion et al., 2000). Finally, synergistic muscles were not covered by the HDEMG grid.  
451 This limitation was imposed in an attempt to reduce the effect of crosstalk between  
452 overlapping muscles of different architecture which may have confounded the results  
453 (Martinez-Valdes et al., 2018). Further studies using mixed methodologies, including  
454 intramuscular electrodes and motor unit decomposition, may provide clearer information  
455 about individual muscle contributions to this task.

456 **5 - CONCLUSION**

457           Asymptomatic people display a spatial redistribution of lumbar ES activity during an  
458 endurance task and this adaptation is reduced in people with LBP. Moreover, people with  
459 LBP engage more cranial regions of the lumbar ES during trunk extension; likely reflecting  
460 an inefficient motor strategy.

461

462

463 **The authors declare no conflict of interest.**

464

465



466 **Author Contributions**

467 AS, EMV and DF contributed to study conception and design. AS and CM acquired the data.

468 AS, EMV and DF performed the data analysis. All authors contributed to interpretation of the

469 data. Drafting of the manuscript was performed by AS, EMV and DF. All authors

470 participated in revising the manuscript and approving the final submission.

471

472

473 **Reference List**

- 474 Abboud J, Nougrou F, Page I, Cantin V, Massicotte D, Descarreaux M (2014) Trunk motor variability  
 475 in patients with non-specific chronic low back pain. *Eur J Appl Physiol*, **114**, 2645-54.
- 476 Arendt-Nielsen L, Graven-Nielsen T (2008) Muscle pain: sensory implications and interaction with  
 477 motor control. *Clin J Pain*, **24**, 291-8.
- 478 Barbero M, Merletti R, Rainoldi A (2012) *Atlas of Muscle Innervation Zones*, Springer-Verlag Mailand.
- 479 Bogduk N (1980) A reappraisal of the anatomy of the human lumbar erector spinae. *J Anat*, **131**, 525-  
 480 40.
- 481 Bogduk N (2005) *Clinical anatomy of the lumbar spine and sacrum*, Elsevier/Churchill Livingstone,  
 482 Edinburgh.
- 483 Borg G (1998) *Borg's perceived exertion and pain scales*, Human kinetics.
- 484 Breivik H, Borchgrevink PC, Allen SM, et al. (2008) Assessment of pain. *Br J Anaesth*, **101**, 17-24.
- 485 Childs JD, Piva SR, Fritz JM (2005) Responsiveness of the numeric pain rating scale in patients with  
 486 low back pain. *Spine (Phila Pa 1976)*, **30**, 1331-4.
- 487 Christophy M, Faruk Senan NA, Lotz JC, O'Reilly OM (2012) A musculoskeletal model for the lumbar  
 488 spine. *Biomech Model Mechanobiol*, **11**, 19-34.
- 489 Cohen J (1988) *Statistical Power Analysis for the Behavioral Sciences*, Routledge Academic, New  
 490 York, NY.
- 491 de Ruiter CJ, Maas EA, Wesseling MG, de Haan A (2012) Knee extensor fatigue threshold is related to  
 492 whole-body VO<sub>2</sub>max. *Med Sci Sports Exerc*, **44**, 1366-74.
- 493 Demoulin C, Crielaard JM, Vanderthommen M (2007) Spinal muscle evaluation in healthy individuals  
 494 and low-back-pain patients: a literature review. *Joint Bone Spine*, **74**, 9-13.
- 495 Dionne CE, Dunn KM, Croft PR, et al. (2008) A consensus approach toward the standardization of  
 496 back pain definitions for use in prevalence studies. *Spine (Phila Pa 1976)*, **33**, 95-103.
- 497 Fabian S, Hesse H, Grassme R, Bradl I, Bernsdorf A (2005) Muscular activation patterns of healthy  
 498 persons and low back pain patients performing a functional capacity evaluation test.  
 499 *Pathophysiology*, **12**, 281-7.
- 500 Fairbank JC, Pynsent PB (2000) The Oswestry Disability Index. *Spine (Phila Pa 1976)*, **25**, 2940-52;  
 501 discussion 2952.
- 502 Falla D, Cescon C, Lindstroem R, Barbero M (2017) Muscle Pain Induces a Shift of the Spatial  
 503 Distribution of Upper Trapezius Muscle Activity During a Repetitive Task: A Mechanism for  
 504 Perpetuation of Pain With Repetitive Activity? *Clin J Pain*, **33**, 1006-1013.
- 505 Falla D, Farina D (2008a) Neuromuscular adaptation in experimental and clinical neck pain. *J*  
 506 *Electromyogr Kinesiol*, **18**, 255-61.
- 507 Falla D, Farina D (2008b) Non-uniform adaptation of motor unit discharge rates during sustained  
 508 static contraction of the upper trapezius muscle. *Exp Brain Res*, **191**, 363-70.
- 509 Falla D, Gizzi L, Tschapek M, Erlenwein J, Petzke F (2014) Reduced task-induced variations in the  
 510 distribution of activity across back muscle regions in individuals with low back pain. *Pain*,  
 511 **155**, 944-53.
- 512 Farina D, Leclerc F, Arendt-Nielsen L, Buttelli O, Madeleine P (2008) The change in spatial  
 513 distribution of upper trapezius muscle activity is correlated to contraction duration. *J*  
 514 *Electromyogr Kinesiol*, **18**, 16-25.
- 515 Gallina A, Merletti R, Gazzoni M (2013) Uneven spatial distribution of surface EMG: what does it  
 516 mean? *Eur J Appl Physiol*, **113**, 887-94.
- 517 Gallina A, Merletti R, Vieira TM (2011) Are the myoelectric manifestations of fatigue distributed  
 518 regionally in the human medial gastrocnemius muscle? *J Electromyogr Kinesiol*, **21**, 929-38.
- 519 Gizzi L, Muceli S, Petzke F, Falla D (2015) Experimental Muscle Pain Impairs the Synergistic Modular  
 520 Control of Neck Muscles. *PLoS One*, **10**, e0137844.
- 521 Hays RD, Sherbourne CD, Mazel RM (1993) The RAND 36-Item Health Survey 1.0. *Health Econ*, **2**,  
 522 217-27.

523 Ito T, Shirado O, Suzuki H, Takahashi M, Kaneda K, Strax TE (1996) Lumbar trunk muscle endurance  
524 testing: an inexpensive alternative to a machine for evaluation. *Arch Phys Med Rehabil*, **77**,  
525 75-9.

526 Jubany J, Marina M, Angulo-Barroso R (2017) Electromyographic and Kinematic Analysis of Trunk  
527 and Limb Muscles During a Holding Task in Individuals With Chronic Low Back Pain and  
528 Healthy Controls. *PM R*, **9**, 1106-1116.

529 Lakens D (2013) Calculating and reporting effect sizes to facilitate cumulative science: a practical  
530 primer for t-tests and ANOVAs. *Frontiers in psychology*, **4**, 863-863.

531 Larivière C, Arsenault AB, Gravel D, Gagnon D, Loisel P (2002) Evaluation of measurement strategies  
532 to increase the reliability of EMG indices to assess back muscle fatigue and recovery. *Journal  
533 of Electromyography and Kinesiology*, **12**, 91-102.

534 Madeleine P, Leclerc F, Arendt-Nielsen L, Ravier P, Farina D (2006) Experimental muscle pain  
535 changes the spatial distribution of upper trapezius muscle activity during sustained  
536 contraction. *Clin Neurophysiol*, **117**, 2436-45.

537 Mannion AF, Dumas GA, Cooper RG, Espinosa FJ, Faris MW, Stevenson JM (1997) Muscle fibre size  
538 and type distribution in thoracic and lumbar regions of erector spinae in healthy subjects  
539 without low back pain: Normal values and sex differences. *Journal of Anatomy*, **190**, 505-  
540 513.

541 Mannion AF, Kaser L, Weber E, Rhyner A, Dvorak J, Muntener M (2000) Influence of age and  
542 duration of symptoms on fibre type distribution and size of the back muscles in chronic low  
543 back pain patients. *Eur Spine J*, **9**, 273-81.

544 Martinez-Valdes E, Negro F, Falla D, De Nunzio AM, Farina D (2018) Surface electromyographic  
545 amplitude does not identify differences in neural drive to synergistic muscles. *J Appl Physiol  
546 (1985)*, **124**, 1071-1079.

547 Masuda K, Masuda T, Sadoyama T, Inaki M, Katsuta S (1999) Changes in surface EMG parameters  
548 during static and dynamic fatiguing contractions. *J Electromyogr Kinesiol*, **9**, 39-46.

549 Merletti R, Farina D (2016) *Surface Electromyography: Physiology, Engineering, and Applications*,  
550 John Wiley & Sons.

551 Miller RP, Kori SH, Todd DD (1991) The Tampa Scale: a Measure of Kinisophobia. *The Clinical Journal  
552 of pain*, **7**, 51.

553 Muller R, Strassle K, Wirth B (2010) Isometric back muscle endurance: an EMG study on the criterion  
554 validity of the Ito test. *J Electromyogr Kinesiol*, **20**, 845-50.

555 Pagé I, Descarreaux M (2012) Trunk muscle fatigue during a lateral isometric hold test: what are we  
556 evaluating? *Chiropr Man Therap*, **20**, 12.

557 Plamondon A, Serresse O, Boyd K, Ladouceur D, Desjardins P (2002) Estimated moments at L5/S1  
558 level and muscular activation of back extensors for six prone back extension exercises in  
559 healthy individuals. *Scand J Med Sci Sports*, **12**, 81-9.

560 Roy SH, De Luca CJ, Emley M, Buijs RJ (1995) Spectral electromyographic assessment of back muscles  
561 in patients with low back pain undergoing rehabilitation. *Spine (Phila Pa 1976)*, **20**, 38-48.

562 Russ DW, Ross AJ, Clark BC, Thomas JS (2018) The Effects of Task Type on Time to Task Failure During  
563 Fatigue: A Modified Sorensen Test. *J Mot Behav*, **50**, 96-103.

564 Stenholm S, Head J, Aalto V, et al. (2017) Body mass index as a predictor of healthy and disease-free  
565 life expectancy between ages 50 and 75: a multicohort study. *International Journal Of  
566 Obesity*, **41**, 769.

567 Thomas JS, Ross AJ, Russ DW, Clark BC (2011) Time to task failure of trunk extensor muscles differs  
568 with load type. *J Mot Behav*, **43**, 27-9.

569 Tucker K, Falla D, Graven-Nielsen T, Farina D (2009) Electromyographic mapping of the erector  
570 spinae muscle with varying load and during sustained contraction. *J Electromyogr Kinesiol*,  
571 **19**, 373-9.

- 572 VanderZee KI, Sanderman R, Heyink JW, de Haes H (1996) Psychometric qualities of the RAND 36-  
573 Item Health Survey 1.0: a multidimensional measure of general health status. *Int J Behav*  
574 *Med*, **3**, 104-22.
- 575 Vecchio AD, Negro F, Felici F, Farina D (2017) Associations between motor unit action potential  
576 parameters and surface EMG features. **123**, 835-843.
- 577 Zar JH (2010) *Biostatistical Analysis*, Prentice Hall.

578

579

Characteristic		LBP	Control	P-Value
Age (Years)		27.39 ±9.7	26.46 ±5.0	-
Gender (# Males)		6	7	-
Height (cm)		168.75 ±9.7	170.38 ±6.7	-
Weight (kg)		70.97 ±12.4	69.11 ±12.7	-
BMI		24.78	23.78	-
ODI (%) *		13.16% ±8%	0.00%	< 0.001
TSK		25.31 ±4.89	22.31 ±7.20	-
PNRS	Current Pain *	1.92 ±1.44	0	< 0.001
	Usual Pain *	2.92 ±1.98	0	< 0.001
RAND 36 Item Health Survey	Physical Functioning *	82.52 ±10.64	99.30 ±2.52	< 0.001
	Emotional Wellbeing *	69.85 ±17.33	82.46 ±7.58	0.024
	Pain *	68.46 ±16.79	95.00 ±8.6	< 0.001
	General Health *	64.62 ±20.15	82.31 ±10.53	0.010

581

582 **Table 1** – Mean participant characteristics separated by group, showing the standard deviation where  
583 appropriate. Where significant differences occur, the characteristic is marked with an asterisk and a P-value  
584 is displayed.

585

586 **Figures**

587 **Figure 1** – Depicting (A) the approximate positioning of the HDEMG grid 2cm lateral to the L5 Spinous  
588 process on the lumbar ES of the participant and (B) a schematic of the electrode grid showing the x- and y-  
589 axes, reference electrode and inter-electrode distance (not to scale).

590 **Figure 2** – The mean values for the initial, mid-point and final values (and SE) for the RPE as reported by  
591 participants during the endurance task. No significant differences were found between groups for exertion  
592 during the task.

593 **Figure 3** - Average RMS values for LBP and CON participants across the duration of the endurance  
594 contractions (and SE), shown in 10% epochs of the participants' total endurance times. No interactions or  
595 differences in shift were found between groups, but the CON group was found to be systematically higher  
596 throughout the contraction.

597 **Figure 4** - Representative RMS topographical maps for CON (A) and LBP (B) participants during the  
598 endurance task. The centroid is depicted by the crosshair and the scale is indicated in  $\mu\text{V}$ .

599 **Figure 5** - Absolute mean locations (and SE) of the y-coordinate of the centroid for CON and LBP group  
600 throughout the endurance contraction

601 **Figure 6** - Displacement of the y-coordinate of the centroid from the position in the first 10% epoch (and  
602 SE), showing a significant displacement of the y-coordinate for both the CON and LBP group.

603 **Figure 7** - Linear regression analysis on the shift in y-coordinate of the centroid, showing significant  
604 variation in the shift of the y-coordinate over the length of the endurance contraction ( $F=5.597$ ,  $P=0.0183$ ).  
605 Two CON points where shift was more than 6mm not shown.

606