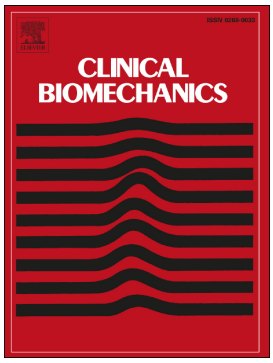
# Lumbar extensor muscle force control is associated with disability in people with chronic low back pain

Pranata, Adrian; Perraton, Luke; El-Ansary, Doa; et.al.



Pranata, A., Perraton, L., El-Ansary, D., Clark, R., Fortin, K., Dettman, T., & Bryant, A. (2017). Lumbar extensor muscle force control is associated with disability in people with chronic low back pain. Clinical Biomechanics, 46, 46–51. https://doi.org/10.1016/j.clinbiomech.2017.05.004
Document Type: Accepted Version

Link to Published Version: https://doi.org/10.1016/j.clinbiomech.2017.05.004




# Lumbar extensor muscle force control is associated with disability in people with chronic low back pain

Adrian Pranata, Luke Perraton, Doa El-Ansary, Ross Clark, Karine Fortin, Tim Dettmann, Adam Bryant

PII: S0268-0033(17)30116-X
DOI: doi: 10.1016/j.clinbiomech.2017.05.004
Reference: JCLB 4325

To appear in: *Clinical Biomechanics*

Received date: 14 February 2017
Revised date: ###REVISEDDATE###
Accepted date: 9 May 2017

Please cite this article as: Adrian Pranata, Luke Perraton, Doa El-Ansary, Ross Clark, Karine Fortin, Tim Dettmann, Adam Bryant , Lumbar extensor muscle force control is associated with disability in people with chronic low back pain, *Clinical Biomechanics* (2017), doi: 10.1016/j.clinbiomech.2017.05.004

# Lumbar extensor muscle force control is associated with disability in people with chronic low back pain

**Adrian Pranata[a], Luke Perraton[a], Doa El-Ansary[a], Ross Clark[b]**

**Karine Fortin[a], Tim Dettmann[c], Adam Bryant[a]**

Address: [a]Centre of Health, Exercise and Sports Medicine, The University of Melbourne, Melbourne, Australia, [b]University of the Sunshine Coast, Queensland, Australia, [c]Kieser, Melbourne, Australia

**Corresponding author:** Adrian Pranata

**Corresponding email:** a.pranata@student.unimelb.edu.au

**Conflict of interest:** none

**Acknowledgement:** the authors would like to thank the staff members at Kieser Brighton and South Melbourne, namely: Brett Long, Georghia Considine, Jess Hiew, Ben Enser, Steven Ooi, Jessica Falduto, Xavier Stevens and Todd Scarce.

Abstract word count: 243 words

Manuscript word count: 4000 words

**Abstract**

*Background*

The ability to control lumbar extensor force output is necessary for daily activities. However, it is unknown whether this ability is impaired in chronic low back pain patients. Similarly, it is unknown whether lumbar extensor force control is related to the disability levels of chronic low back pain patients.

*Methods*

Thirty-three chronic low back pain and 20 healthy people performed lumbar extension force-matching task where they increased and decreased their force output to match a variable target force within 20%-50% maximal voluntary isometric contraction. Force control was quantified as the root-mean-square-error between participants' force output and target force across the entire, during the increasing and decreasing portions of the force curve. Within- and between-group differences in force-matching error and the relationship between back pain group's force-matching results and their Oswestry Disability Index scores were assessed using ANCOVA and linear regression respectively.

*Findings*

Back pain group demonstrated more overall force-matching error (mean difference = 1.60 [0.78, 2.43], $P<0.01$) and more force-matching error while increasing force output (mean difference = 2.19 [1.01, 3.37], $P<0.01$) than control group. The back pain group demonstrated more force-matching error while increasing than decreasing force output (mean difference = 1.74, $P<0.001$, 95%CI [0.87, 2.61]). A unit increase in force-matching error while decreasing force output is associated with a 47% increase in Oswestry score in back pain group ($R^2$ = 0.19, $P=0.006$).

*Interpretation*

Lumbar extensor muscle force control is compromised in chronic low back pain patients. Force-matching error predicts disability, confirming the validity of our force control protocol for chronic low back pain patients.

## 1. Introduction

It is well established that impairments in trunk muscle function are a characteristic of chronic low back pain (CLBP) (van Dieen et al., 2003). Traditional tests of muscle function including lumbar extensor strength (maximal voluntary isometric contraction; MVIC) assessment are commonly performed in people with CLBP (Steele et al., 2014). People with CLBP demonstrate less lumbar extension strength compared to healthy people (Steele et al., 2014). Additionally, impairment in trunk muscle function can also be caused by changes in motor planning, spinal reflexes (Hodges, 2001) and the mechanical properties of passive structures such as the ligaments and intervertebral discs (Sjolander et al., 2002). Collectively, these changes may impact on the ability of people with CLBP to control lumbar extensor muscle force output.

Muscle force control is defined as the ability of the neuromuscular system to produce coordinated, accurate and/or smooth (i.e., less variable) force output (Enoka, 2002). Muscle force control can determined by calculating sub-maximal muscle force *accuracy* – by measuring the difference between sub-maximal force output generated by a participant and a target force; with larger difference suggests lesser accuracy (Rice et al., 2015).

However, in most functional daily tasks (e.g., lifting, pushing, pulling), the lumbar extensor muscles are required to produce variable amounts of sub-maximal force accurately to prevent injuries (Marras, 2008). Hence, one may question the external validity of assessing lumbar extensor force control using a constant force target. In this context, incorporation of a variable

or fluctuating sub-maximal force target may be more appropriate when assessing lumbar muscle force control. Moreover, utilising a fluctuating force target allows for the assessment of force production accuracy during the ramp-up (i.e., increasing force production) or ramp-down (i.e., decreasing force production) phases of the test. The ability to accurately control lumbar extensor muscle force output could be an important risk factor in the development of work-related musculoskeletal disorders such as CLBP (Srinivasan and Mathiassen, 2012).

A novel method for assessing muscle force control utilising a variable force target has recently been developed to assess patients following anterior cruciate ligament reconstruction (ACLR) (Telianidis et al., 2014). With visual feedback, ACLR and healthy control participants were instructed to contract their quadriceps, increasing and decreasing force output between 5% and 30% MVIC at a frequency of 0.128 Hz. Compared to the control group, the ACLR group demonstrated 23% more force matching error (Telianidis et al., 2014) which was associated with greater odds (odds ratio 4.4) of performing poorly in a hop test (Perraton et al., 2016). At the knee, these findings may indicate a link between impairments in muscle force control and functional limitations, or disability level.

In CLBP, disability is most commonly measured using the Oswestry Disability Index (ODI) (Chapman et al., 2011). The ODI is a 10-domain questionnaire that assesses CLBP-related ADL limitations (i.e., pain intensity, personal care, lifting capacity, walking, sitting, standing, sleeping, sexual activity, social life and travelling capacity) (Fairbank and Pynsent, 2000). The ODI has been demonstrated to be valid, reliable and responsive to changes in back pain status (Davidson and Keating, 2002) and is therefore potentially useful in evaluating the validity of lumbar extensor force matching error in participants with CLBP. This means CLBP participants with higher ODI score could demonstrate more force-matching error (i.e., poorer muscle force control) than those with lower ODI score.

To our knowledge, no previous studies have examined lumbar extensor force matching error utilising a fluctuating, sub-maximal force target in CLBP people and healthy controls. Clearly, it is unknown as to whether lumbar extensor force control deficits in CLBP are associated with disability level. Thus, the aims of this study were to compare lumbar extensor force-matching error between CLBP and healthy controls and to investigate the relationship between lumbar extensor force-matching error and disability level in people with CLBP. We hypothesised that CLBP participants will display significantly more error compared to healthy controls ($H_1$). In addition, we also hypothesised that significant positive associations will exist between force-matching error and disability level in people with CLBP ($H_2$).

## 2. Methods

### *2.1. Participants*

Thirty-three participants (76% of the total participants approached, $n_{female}$ = 18) aged 25-60 years with CLBP were recruited from a large physiotherapy clinic in Melbourne, Australia. To be included, participants needed to be new patients of the clinic, report pain between the level of the twelfth thoracic vertebra (T12) and the gluteal fold >3 months as per the diagnosis of non-specific CLBP (Von Korff et al., 1993) during their initial physiotherapy assessment session. Physiotherapists screened and excluded participants if they presented with overt neurological signs such as muscle weakness, previous spinal surgery, systemic or inflammatory conditions such as rheumatoid arthritis, malignancy, unstable spondylolisthesis (i.e., specific diagnosis of CLBP; physical assessment of CLBP patients has been described in detail previously (Maitland et al., 2005)) or inability to understand written or spoken English. In addition, a control group of 20 participants (age, gender and BMI-matched) with no history of CLBP were recruited from the community. Ethics approval was obtained from The University of Melbourne's Behavioural and Social Sciences Human Ethics Committee (ethics

ID: 1340715). All participants provided written informed consent prior to entering the study. A moderate effect size (a Cohen's d of 0.64), with significance level, $\alpha = 0.05$ and power, $\beta = 0.80$ were chosen. Using this criteria, 20 participants per group were required.

*2.2. Experimental Procedure*

Pain and disability: All participants completed the ODI immediately prior to testing. Participants were also asked to rate their pain out of 10 using the Numerical Rating Scale before and after testing.

Isometric lumbar extensor strength: Lumbar extensor MVIC was measured to derive submaximal values for the target-matching task in a supported seated position using a lumbar extensor dynamometer (MedX, Ocala, Florida USA). The MedX has demonstrated validity (Pollock et al., 1991) and reliability in assessing isometric strength and range of motion in healthy (r = 0.81-0.97, SEE = 24.0 Nm) (Graves et al., 1990) and CLBP (r = 0.57-0.93, SEE = 12.0 – 44.5 Nm) (Robinson et al., 1992) populations.

The MedX stabilises the pelvis via a restraint system which prevents pelvic rotation – critical in isolating the lumbar extensor muscle group during assessment (Graves et al., 1994). MVIC measurement was preceded by a 30-second warm-up involving assisted lumbar flexion and extension throughout pain free range of motion. Participants were then locked in a neutral spine position ($12^o$ flexion, $0^o$ being full extension) with their back supported by the backrest (Fig. 1). In this position, participants were instructed to press their back against the backrest increasing isometric force to MVIC over a 4-second period. Only 1 MVIC trial was performed so as to minimise the risk of neuromuscular fatigue and muscle cramps (as per our pilot testing, see section below) which could impede lumbar extensor force matching testing.

Lumbar extensor force matching task: The assessment protocol of lumbar extensor force control was adapted from a previously published isometric quadriceps protocol (Perraton et al., 2016; Telianidis et al., 2014). Participants were instructed to match the force target as

accurately as possible by increasing and decreasing isometric force production from 20-50% MVIC at a frequency of 0.16 Hz (Fig. 2) determined from our pilot data ($n_{CLBP}$ = 5, $n_{control}$ = 10). A test frequency higher than 0.16 Hz resulted in lower back discomfort post-testing in both groups. Conversely, a frequency lower than 0.16 Hz resulted in a ceiling effect (i.e., both CLBP and healthy participants performed well on the test). The lower and upper force target limits (i.e., 20% and 50% MVIC, respectively) were selected based on lumbar extensor contraction intensities utilised during activities of daily living (Lee et al., 2012). This test frequency is equivalent to 10 sinusoidal cycles per minute; or 5 ascending and 5 descending cycles. Participants completed 2 trials (the first serving as a familiarisation) of 60 seconds duration with a 30-second rest period between trials. Visual feedback was provided via a computer monitor placed one meter in front of the seated participant at eye level. No verbal encouragement was provided and the testing environment was kept silent. Previous testing in our laboratory has shown this force matching protocol to be reliable in both healthy (n = 16, ICC = 0.88, SEM = 0.05) and CLBP participants (n = 17, ICC = 0.88, SEM = 0.04).

*2.3. Data analysis*

Lumbar extensor isometric strength data were obtained from the MedX, filtered using a low-pass Symlet-8 undecimated wavelet filter (62.5 Hz) and converted to torque in Newton meters (Nm) using a customised LabVIEW software (National Instruments U.S.A.). Calibration for the custom data acquisition system was performed by applying a series of loads to the machine, recording the results from the MedX software and the raw data from the data acquisition system and creating a calibration factor for the raw data with the MedX results as the criterion reference using linear regression.

Participants' force matching error relative to the force target throughout the session was quantified by using the root-mean-square-error (RMSE) of the torque output data relative to the target torque. To account for potential errors caused by participants adjusting their sitting

position, the results of the first and last repetition of the sine wave were not used for calculation and the average value for the remaining 4 repetitions was obtained (i.e., total average RMSE; $RMSE_T$). In addition to the measurement of $RMSE_T$, sub-regional analyses were also performed to measure the average RMSE during the ascending (ramp up; $RMSE_A$) phase of the test (between 20%-50% lumbar extensor MVIC) and the average RMSE during the descending (ramp down; $RMSE_D$) phase of the test (between 50%-20% lumbar extensor MVIC). This approach was implemented to quantify the phase of the test at which the force error is the greatest.

*2.4. Statistical analysis*

Normality and equality of variance of the variables were analysed using Shapiro-Wilk and Levene median tests, respectively. Means and standard deviations (SD) were calculated for participant's characteristics (age, weight, height, BMI, CLBP duration, NRS and ODI scores), lumbar extensor MVIC and RMSE variables. Chi-squared ( $\chi^2$) test was used to compare the number of males and females in control and CLBP groups.

As there were significant age differences between the groups, group (CLBP and control) x RMSE ($RMSE_T$, $RMSE_A$ and $RMSE_D$) factorial analysis of covariance (ANCOVA) was performed. Within-group RMSE analyses were conducted using one-way ANCOVA. The effect size of significant ANCOVA test results were quantified using partial eta-squared ($\eta^2_p$). Normality, homoscedasticity and linearity of residual for ANCOVA tests were assessed using Levene's test and scatter graphs (Osborne and Waters, 2002). Pairwise comparisons were conducted using Fisher's Least Significant Difference test.

Linearity and strength of bivariate relationships between candidate predictors (i.e., RMSE and MVIC variables) and dependent variable (i.e., ODI) were analysed using Pearson product-moment correlation coefficient and scatter graphs. Neuromuscular variables that exhibited a significant correlation with the ODI were included within the multivariate linear regression

model as candidate predictor variables. The strength of the linear regression between ODI and the neuromuscular variables was quantified using an $R^2$ value. Collinearity of the model predictors was assessed using variance inflation factor and tolerance level (Osborne and Waters, 2002). All analyses were conducted with an alpha level of 0.05 using SPSS Version 21.0 (IBM, Inc., Chicago, IL).

## 3. Results

Descriptive data (mean (SD)) pertaining to participant characteristics of CLBP and control groups is outlined in Table 1. There were no reported adverse events or increase in pain during or following testing.

Descriptive data (mean (SD)) for the force control variables together with the results of statistical comparisons for CLBP and control groups are presented in Table 2. There were no significant differences in lumbar extension MVIC between the CLBP (180.00 (12.61) Nm) and control (182.03 (16.42) Nm, $F_{1,50}$ = 0.009, $P$ = 0.93) groups. Controlling for age, there were significant main effects of group ($F_{1,152}$ = 11.2, $\eta^2_p$ = 0.07, $P$ = 0.001) and RMSE ($F_{2,152}$ = 3.3, $\eta^2_p$ = 0.04, $P$ = 0.039). There was no group x RMSE interaction ($F_{2,152}$ = 2.7, $\eta^2_p$ = 0.03, $P$ = 0.069). The CLBP group produced significantly more $RMSE_T$ than the control group (% difference = 30, $P$ = 0.022, 95% CI [0.18, 2.21]). Similarly, the CLBP group produced significantly more $RMSE_A$ than the control group (% difference = 45, $P$ = 0.001, 95% CI [0.76, 2.80]). However, there were no significant differences in $RMSE_D$ between groups ($P$ = 0.80). A sample muscle force control test outcome for participants with good and impaired ability to control force output is illustrated in Fig. 3.

Within-group RMSE comparison demonstrated that in the CLBP group, there was a main effect of RMSE ($F_{2,95}$ = 5.83, $P$ = 0.004). There were large and statistically significant differences between $RMSE_D$ and $RMSE_A$ (mean difference = 1.74, % difference = 43, $P$ <

0.001, 95% CI [0.87, 2.61]) and between $RMSE_D$ and $RMSE_T$ (mean difference = 1.08, % difference = 21, $P$ = 0.015, 95% CI [0.21, 1.95]); however, the difference between $RMSE_A$ and $RMSE_T$ did not reach significance ($P$ = 0.14). There were no significant within group differences between any RMSE variables in the control group ($P$ = 0.87 - 0.98). Between- and within-group RMSE variables of CLBP and control groups are shown in Fig. 4.

Only $RMSE_D$ was significantly correlated (moderately and positively) with ODI in CLBP participants (r = 0.47, $P$ = 0.006). The other neuromuscular variables including $RMSE_A$, $RMSE_T$ and lumbar extensor MVIC were not significantly correlated with self-reported disability ($P$ > 0.05). $RMSE_D$ significantly predicted 19% of the variance in self-reported disability (adjusted $R^2$ = 0.19, standardised β = 0.47, $P$ = 0.006).

## 4. Discussion

To our knowledge, this is the first study to evaluate lumbar extensor muscle force control utilising a variable force target. Our results demonstrated that people with CLBP exhibit an impaired ability to control lumbar extensor force with an overall diffierence of 30% when compoared to healthy controls. In particular, during the ramp-up phase of the test a difference of 45% was demonstrated compared to control group. Interestingly, differences in force-matching error exist despite groups exhibiting similar levels of lumbar extensor strength. Furthermore, the ability to accurately decrease lumbar extensor force was positively associated with disability level; that is, CLBP participants with higher disability display more force matching error than those who are less disabled. These findings confirm the face validity of our lumbar extensor muscle force control protocol for people with CLBP.

Compared to healthy controls, results demonstrated that people with CLBP are less able to control variable, submaximal lumbar extensor force output (accepted $H_1$). In particular, CLBP participants demonstrated elevated $RMSE_T$ and $RMSE_A$ but not $RMSE_D$ compared to controls.

Interestingly, the between-group differences in force control error in this study were considerably larger than those reported in a previous study (Miura and Sakuraba, 2014) (i.e., 24%-28% vs. 30%-45%) which used a non-variable, sub-maximal force target.

The higher amount of $RMSE_T$ in this study could be explained by a several factors. Firstly, the central nervous system increases the level of agonist (i.e., the lumbar extensors) muscle activity as task demand increases (Reeves et al., 2013); in this case, as the force requirement increases from 20% to 50% MVIC. As the force target decreases from 50% to 20% MVIC, activation of antagonist muscles (i.e., lumbar flexors) (Reeves et al., 2013) and/or a proportional decrease in lumbar extensor muscle activity is required to decrease force output to maintain accurate target matching. There is evidence to suggest that the ability of the central nervous system to regulate agonist-antagonist muscle activity is impaired in people with CLBP (D'Hooge et al., 2013). This impairment could be explained by the 'motor adaptation to pain theory' (Hodges and Tucker, 2011) whereby pain tends to increase net trunk muscle activation and, in turn, the stiffness of trunk musculature (i.e., trunk muscle co-contraction) (van Dieën et al., 2003) – adaptations that may persist well after the resolution/attenuation of symptoms (Hodges et al., 2009). Increased trunk muscle stiffness has been associated with decreased anticipatory lumbar movement in response to perturbations (Mok et al., 2007) and delayed anticipatory trunk muscle agonist-antagonist coordination time in response to changes in external loads (Radebold et al., 2000). Therefore, it is not surprising that augmented force-matching error is observed when the target force is constantly varied in people with CLBP.

Secondly, increased total error could be attributed to the isolation of lumbar extensor muscles during testing. In order to maximise lumbar extensor muscle activity, adequate pelvic restraint is required to minimise the involvement of larger and more powerful hip extensors during lumbar extension (Smidt et al., 1983). This study replicated the set-up suggested by Graves et

al. (1994) where a restraint system at $12^{o}$ lumbar flexion (pelvic, femur, thigh restraints and a foot board) was used to stabilise the pelvis and a counterweight was utilised to neutralise the gravitational effects of upper body mass. This set-up has been demonstrated to minimise gluteal muscle activation during isometric sub-maximal muscle testing (Udermann et al., 1999). Moreover, in a previous study, when the lumbar extensor muscles became fatigued, the hamstring musculature was recruited as a compensation strategy which could confound lumbar extensor muscle force assessment (San Juan et al., 2005). In this study, lumbar extensor fatigue was minimised by utilising a single MVIC and force-matching trials combined with frequent rest periods. Therefore, possible compensatory strategies adopted by the hip extensors were minimised by our study protocol. Isolated lumbar extensor assessment may also contribute to more error during our force-matching task compared to past studies where lower limb contributions during testing were not adequately controlled for.

Interestingly, in this study people with CLBP demonstrated more impairment in force control during the ramp-up phase than during the ramp-down phase of the test. In contrast, control participants demonstrated almost identical amount of errors during both test phases. Although it is difficult to generalise this finding to previous studies due to the novelty of this study's methodology, Descarreaux et al. (2004) reported slower rate of isometric force production (i.e., ramp-up rate) compared to healthy controls which could result in increased error in the ramp-up phase in the CLBP group in the present study. During the isometric force-matching test, participants increased and decreased muscle force output in a cyclical fashion. Increased error during the ramp-up phase is supported by the findings of MacDonald et al. (2011) who reported over-recruitment of multifidus (superficial and deep fibers) muscles – denoted by increased muscle thickness on ultrasonography, during gentle leg lifting activity in people with recurrent LBP. Over-recruitment of lumbar extensor muscles could result in CLBP

participants to overshoot resulting in augmented error in the ramp-up phase of the force-matching test.

Lumbar extensor force control was moderately and positively correlated with self-reported disability of CLBP participants (accepted $H_2$). In this study, a unit increase in $RMSE_D$ is associated with an increase in the ODI score of 47%; that is, less-accurate lumbar extensor force output was significantly associated with increasing disability. Trunk flexor (e.g., rectus abdominis) and extensor (e.g., erector spinae) muscle co-contraction is a common feature of CLBP and could alter functional performance (Reeves et al., 2008). In people with CLBP, increased trunk muscle co-contraction (i.e., dyskinesia) may be mal-adaptive by reducing quality of movement and increasing compressive load on the spine (Marras et al., 2001). This could be reflected in impaired trunk muscle force control which, in turn, was associated with disability in CLBP participants.

Streiner et al. (2014) suggest that in order for two outcome measures to quantify the same underlying construct, they should demonstrate a bivariate correlation coefficient between 0.40 and 0.80. Similarly, correlation coefficients ranging from 0.40 to 0.60 have also been observed between physical function tests such as walking and sit-to-stand and self-reported disability (Novy et al., 2002; Simmonds et al., 1998). Thus, the finding of this study (i.e., $r = 0.47$ between $RMSE_D$ and ODI) confirmed the face validity of the lumbar extensor muscle force control assessment in people with CLBP.

Albeit novel, our study has several limitations. Firstly, our results only pertain to a relatively younger CLBP cohort (mean age 41.7 (11.5)) and as back pain prevalence peaks at the age of 80 (Hoy et al., 2014), our results may not be generalidable to older CLBP population. Secondly, our CLBP group were mostly people of lower disability level therefore may not be representative of the wider CLBP population. That said, our variable force target protocol still detected significant force control impairment in this cohort. Thirdly, as there was no

superficial or in-dwelling electromyography (EMG) utilised in this study, the existence of trunk muscle co-contraction of superficial trunk muscles (e.g., rectus abdominis and erector spinae) or deep trunk muscles (e.g., transversus abdominis and deep lumbar multifidus) (van Dieën et al., 2003) as a contributing factor to impairment trunk muscle force control in people with CLBP could not be confirmed. Indeed, EMG assessment of the lumbar extensors could provide insight into the mechanism of trunk muscle force control; that is, accuracy of trunk muscle force production in people with CLBP may occur as a result of trunk muscle co-contraction. Lastly, as we only performed one trial for force control assessment, we could not account for the within-subject variability.

## 5. Conclusions

Our study demonstrated that people with CLBP exhibit more error during a lumbar extensor force-matching task than healthy individuals. These findings indicate that lumbar extensor muscle force control is impaired in people with CLBP. Moreover, in our CLBP group, the inability to accurately control decreasing muscle force production alone explained 19% of the variance of self-reported disability. This study provides evidence that the ability to control lumbar extensor muscle force is a significant predictor of self-reported disability in people with CLBP. Future reaserch is warranted to investigate the effects of incorporating training in muscle force control into rehabilitation.

**References**

Chapman, J.R., Norvell, D.C., Hermsmeyer, J.T., Bransford, R.J., DeVine, J., McGirt, M.J., Lee, M.J., 2011. Evaluating common outcomes for measuring treatment success for chronic low back pain. Spine (Phila Pa 1976) 36, S54-68.

D'Hooge, R., Hodges, P., Tsao, H., Hall, L., Macdonald, D., Danneels, L., 2013. Altered trunk muscle coordination during rapid trunk flexion in people in remission of recurrent low back pain. J Electromyogr Kinesiol 23, 173-181.

Davidson, M., Keating, J.L., 2002. A comparison of five low back disability questionnaires: reliability and responsiveness. Phys Ther 82, 8-24.

Enoka, R.M., 2002. Neuromechanics of human movement, 3rd ed. Human Kinetics, Champaign, IL.

Fairbank, J.C., Pynsent, P.B., 2000. The Oswestry Disability Index. Spine (Phila Pa 1976) 25, 2940-2952; discussion 2952.

Graves, J.E., Pollock, M.L., Carpenter, D.M., Leggett, S.H., Jones, A., MacMillan, M., Fulton, M., 1990. Quantitative assessment of full range-of-motion isometric lumbar extension strength. Spine (Phila Pa 1976) 15, 289-294.

Graves, J.E., Webb, D.C., Pollock, M.L., Matkozich, J., Leggett, S.H., Carpenter, D.M., Foster, D.N., Cirulli, J., 1994. Pelvic stabilization during resistance training: its effect on the development of lumbar extension strength. Arch Phys Med Rehabil 75, 210-215.

Hodges, P., van den Hoorn, W., Dawson, A., Cholewicki, J., 2009. Changes in the mechanical properties of the trunk in low back pain may be associated with recurrence. J Biomech 42, 61-66.

Hodges, P.W., 2001. Changes in motor planning of feedforward postural responses of the trunk muscles in low back pain. Exp Brain Res 141, 261-266.

Hodges, P.W., Tucker, K., 2011. Moving differently in pain: a new theory to explain the adaptation to pain. Pain 152, S90-98.

Hoy, D., March, L., Brooks, P., Blyth, F., Woolf, A., Bain, C., Williams, G., Smith, E., Vos, T., Barendregt, J., Murray, C., Burstein, R., Buchbinder, R., 2014. The global burden of low back pain: estimates from the Global Burden of Disease 2010 study. Ann Rheum Dis 73, 968-974.

Lee, Y.J., Hoozemans, M.J., van Dieën, J.H., 2012. Trunk muscle control in response to (un)expected turns in cart pushing. Gait Posture 36, 133-138.

Maitland, G., Hengeveld, E., Banks, K., English, K., 2005. Maitland's Vertebral Manipulation, 7th ed. Elsevier Butterworth Heinemann, Philadelphia.

Marras, W.S., 2008. The working back: A systems view. Wiley-Interscience, Hoboken, NJ.

Marras, W.S., Davis, K.G., Ferguson, S.A., Lucas, B.R., Gupta, P., 2001. Spine loading characteristics of patients with low back pain compared with asymptomatic individuals. Spine 26, 2566-2574.

Miura, T., Sakuraba, K., 2014. Properties of Force Output and Spectral EMG in Young Patients with Nonspecific Low Back Pain during Isometric Trunk Extension. J Phys Ther Sci 26, 323-329.

Mok, N.W., Brauer, S.G., Hodges, P.W., 2007. Failure to use movement in postural strategies leads to increased spinal displacement in low back pain. Spine (Phila Pa 1976) 32, E537-543.

Novy, D.M., Simmonds, M.J., Lee, C.E., 2002. Physical performance tasks: what are the underlying constructs? Arch Phys Med Rehabil 83, 44-47.

Osborne, J.W., Waters, E., 2002. Four assumptions of multiple regression that researchers should always test. Pract Assess Res Eval 8, 1-5.

Perraton, L., Clark, R., Crossley, K., Pua, Y.H., Whitehead, T., Morris, H., Telianidis, S., Bryant, A., 2016. Impaired voluntary quadriceps force control following anterior cruciate ligament reconstruction: relationship with knee function. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA.

Pollock, M.L., Graves, J.E., Leggett, S.H., 1991. Accuracy of counter weighting to account for upper body mass in testing lumbar extension strength. Med Sci Sports Exerc 23, S66.

Radebold, A., Cholewicki, J., Panjabi, M.M., Patel, T.C., 2000. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. Spine (Phila Pa 1976) 25, 947-954.

Reeves, N.P., Cholewicki, J., Milner, T., Lee, A.S., 2008. Trunk antagonist co-activation is associated with impaired neuromuscular performance. Exp Brain Res 188, 457-463.

Reeves, N.P., Pathak, P., Popovich, J.M., Jr., Vijayanagar, V., 2013. Limits in motor control bandwidth during stick balancing. J Neurophysiol 109, 2523-2527.

Rice, D.A., McNair, P.J., Lewis, G.N., Mannion, J., 2015. Experimental knee pain impairs submaximal force steadiness in isometric, eccentric, and concentric muscle actions. Arthritis Res Ther 17, 259.

Robinson, M.E., Greene, A.F., O'Connor, P., Graves, J.E., MacMillan, M., 1992. Reliability of lumbar isometric torque in patients with chronic low back pain. Phys Ther 72, 186-190.

San Juan, J.G., Yaggie, J.A., Levy, S.S., Mooney, V., Udermann, B.E., Mayer, J.M., 2005. Effects of pelvic stabilization on lumbar muscle activity during dynamic exercise. J Strength Cond Res 19, 903-907.

Simmonds, M.J., Olson, S.L., Jones, S., Hussein, T., Lee, C.E., Novy, D., Radwan, H., 1998. Psychometric characteristics and clinical usefulness of physical performance tests in patients with low back pain. Spine 23, 2412-2421.

Sjolander, P., Johansson, H., Djupsjobacka, M., 2002. Spinal and supraspinal effects of activity in ligament afferents. J Electromyogr Kinesiol 12, 167-176.

Smidt, G., Herring, T., Amundsen, L., Rogers, M., Russell, A., Lehmann, T., 1983. Assessment of abdominal and back extensor function. A quantitative approach and results for chronic low-back patients. Spine (Phila Pa 1976) 8, 211-219.

Srinivasan, D., Mathiassen, S.E., 2012. Motor variability in occupational health and performance. Clin Biomech (Bristol, Avon) 27, 979-993.

Steele, J., Bruce-Low, S., Smith, D., 2014. A reappraisal of the deconditioning hypothesis in low back pain: review of evidence from a triumvirate of research methods on specific lumbar extensor deconditioning. Curr Med Res Opin 30, 865-911.

Streiner, D.L., Norman, G.R., Cairney, J., 2014. Health Measurement Scales: A Practical Guide to Their Development and Use, 5th ed. Oxford University Press, United Kingdom.

Telianidis, S., Perraton, L., Clark, R.A., Pua, Y.H., Fortin, K., Bryant, A.L., 2014. Diminished sub-maximal quadriceps force control in anterior cruciate ligament reconstructed patients is related to quadriceps and hamstring muscle dyskinesia. J Electromyogr Kinesiol 24, 513-519.

Udermann, B.E., Graves, J.E., Donelson, R.G., Ploutz-Snyder, L., Boucher, J.P., Iriso, J.H., 1999. Pelvic restraint effect on lumbar gluteal and hamstring muscle electromyographic activation. Arch Phys Med Rehabil 80, 428-431.

van Dieen, J.H., Cholewicki, J., Radebold, A., 2003. Trunk muscle recruitment patterns in patients with low back pain enhance the stability of the lumbar spine. Spine (Phila Pa 1976) 28, 834-841.

van Dieën, J.H., Selen, L.P., Cholewicki, J., 2003. Trunk muscle activation in low-back pain patients, an analysis of the literature. J Electromyogr Kinesiol 13, 333-351.

Von Korff, M., Deyo, R.A., Cherkin, D., Barlow, W., 1993. Back pain in primary care. Outcomes at 1 year. Spine (Phila Pa 1976) 18, 855-862.

**Fig. 1.** A participant is seated on MedX Lumbar Dynamometer at 12$^{o}$ lumbar flexion. Full extension is defined as 0$^{o}$ lumbar flexion and full flexion is 72$^{o}$ lumbar flexion.

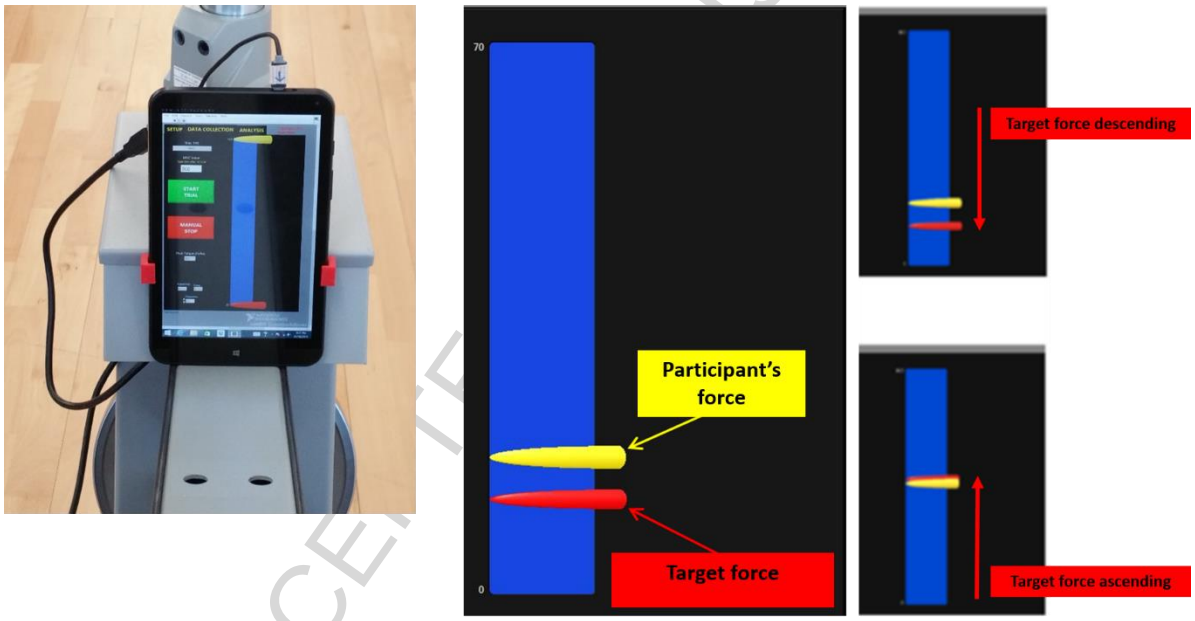



**Fig. 2.** Participant's view during lumbar extensor force control assessment (A). A screenshot of lumbar extensor muscle force control assessment process (B).

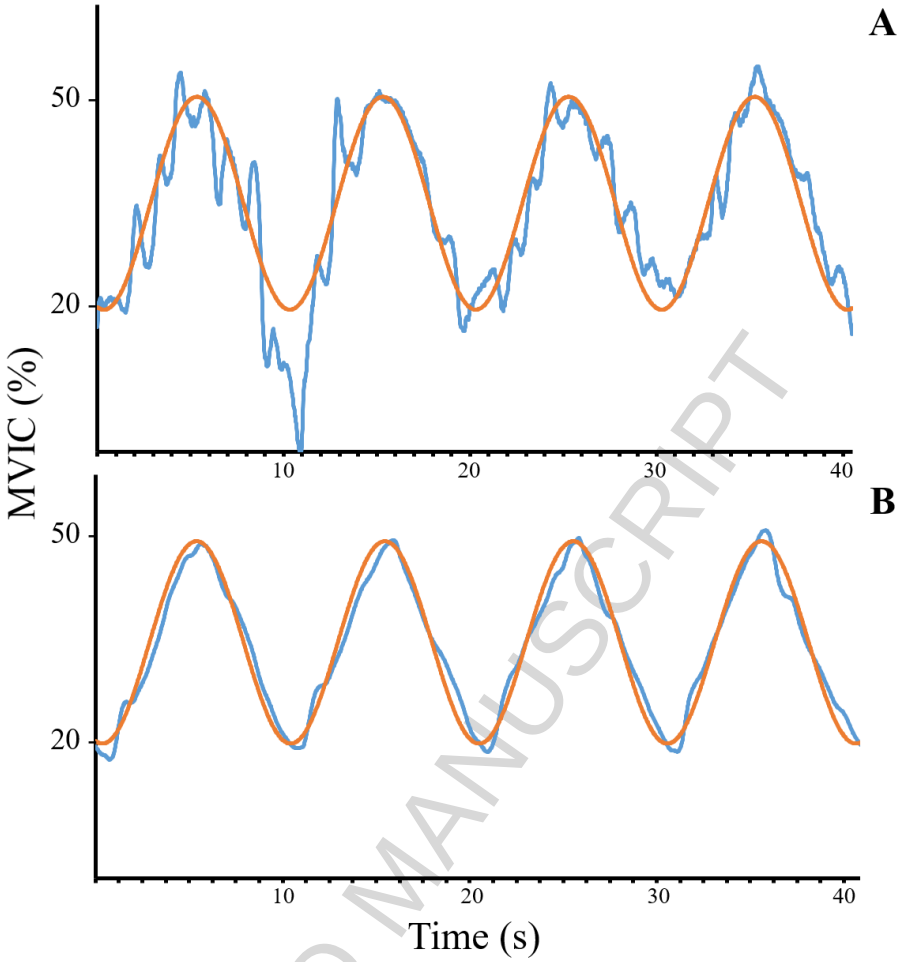



**Fig. 3.** A sample outcome of lumbar extensor muscle force control assessment for someone with good (i.e., a control participant) (A) and impaired (i.e., a CLBP participant) ability to control force output (B). Red trace = target force, blue trace = participant's force.

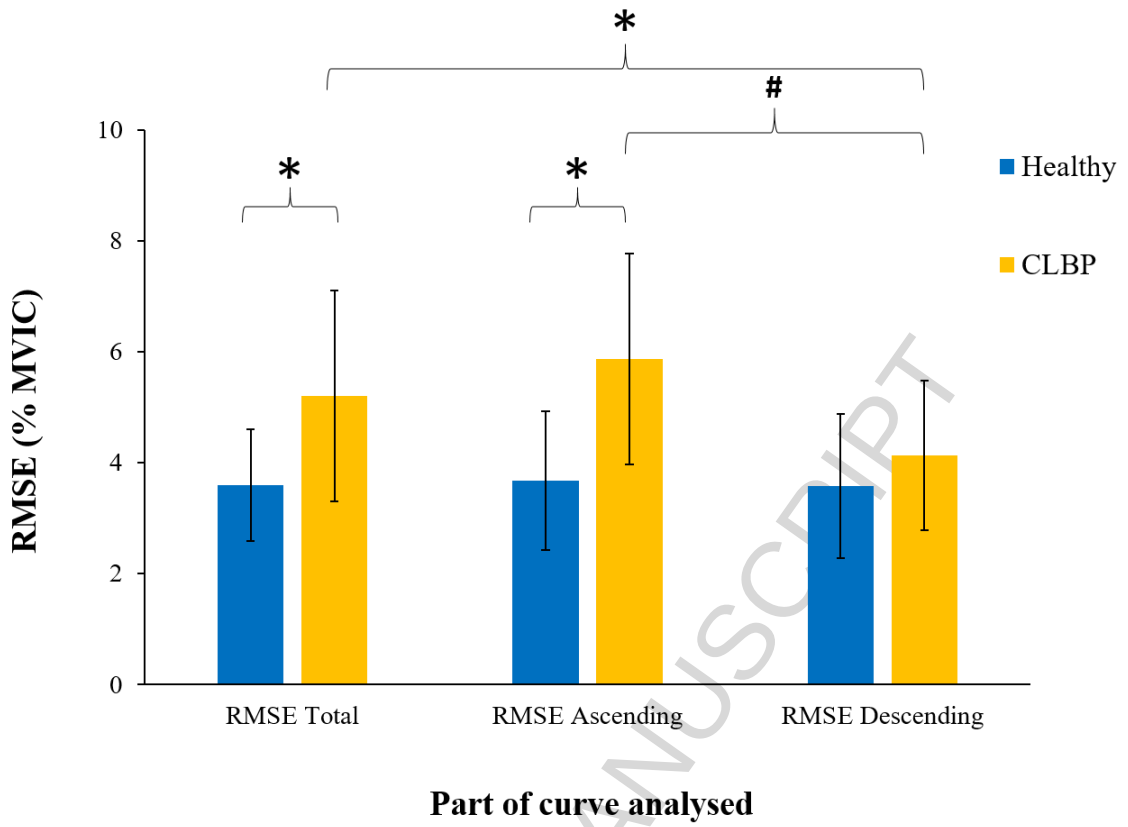



**Fig. 4.** Root mean squared error (RMSE) values in CLBP and control groups. In the CLBP group, $RMSE_A$ (ascending) is significantly larger than $RMSE_D$ (descending). No within group differences in RMSE values were found in healthy controls. $^{\#}P < 0.01$, $^{*}P < 0.05$. Error bars denote standard deviation.

**Table 1.** Descriptive data (mean (SD)) pertaining to participant characteristics of CLBP and control groups.

| Variables (units) | CLBP (n = 33) Mean (SD) | Control (n = 20) Mean (SD) | *P*-values |
|---|---|---|---|
| Age (years) | 41.8 (10.8) | 34.8 (8.8) | 0.01 |
| Gender (female, %) | 18 (54.5%) | 10 (50%) | 0.10 |
| Height (m) | 1.70 (0.1) | 1.66 (0.1) | 0.17 |
| Mass (kg) | 75.3 (17.7) | 76.6 (20.2) | 0.31 |
| BMI ($m/kg^2$) | 25.2 (4.7) | 27.0 (6.7) | 0.80 |
| CLBP duration (months) | 107.5 (119.0) | 0.0 (0.0) | <0.001 |
| ODI (%) | 20.7 (12.3) | 0.1 (0.4) | <0.001 |
| NRS (/10) | 3.30 (1.8) | 0.0 (0.0) | <0.001 |

Values indicate mean ± standard deviation, n = number of participants, BMI = Body Mass Index, ODI = Oswestry Disability Index, NRS = Numerical Rating Scale

**Table 1.** Descriptive data (mean (SD)) pertaining to neuromuscular variables together with results of statistical analyses in CLBP and control groups.

| Variables (units) | CLBP Mean (SD) | Control Mean (SD) | Mean Difference [95% CI] | *P*-values |
|---|---|---|---|---|
| LE strength (Nm) | 180.00 (12.61) | 182.03 (16.42) | 2.02 [-40.63, 44.67] | 0.93 |
| $RMSE_T$ | 5.21 (1.90) | 3.60 (1.01) | 1.60 [0.78, 2.43] | 0.00 |
| $RMSE_A$ | 5.87 (1.90) | 3.68 (1.25) | 2.19 [1.01, 3.37] | 0.001 |
| $RMSE_D$ | 4.13 (1.35) | 3.59 (1.30) | 0.54 [-0.22, 1.30] | 0.16 |

SD = Standard deviation, CI = Confidence interval, LE strength = Lumbar extensor strength, Nm = Newton.meter, $RMSE_T$ = Average total root mean square error, $RMSE_A$ = Average root mean square error of ascending phase, $RMSE_D$ = Average root mean square error of descending phase

**Highlights**

- Lumbar extensor muscle force control is impaired in people with chronic low back pain.
- The ability to accurately increase, but not decrease, force output is impaired in people with chronic low back pain.
- Impairment in lumbar extensor muscle force control is associated with disability in people with chronic low back pain.