



PILOT STUDY

# Onset and maximum values of electromyographic amplitude during prone hip extension after neurodynamic technique in patients with lumbosciatic pain: A pilot study



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## KEYWORDS

Electromyography;  
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Prone hip extension

**Summary Objective:** The mechanisms underlying the effects of neurodynamic techniques are still unknown. Therefore, the aim of this study was to provide a starting point for future research on explaining why neurodynamic techniques affect muscular activities in patients with sciatic pain.

**Methods:** A double-blind trial was conducted in 12 patients with lumbosciatica. Surface electromyography activity was assessed for different muscles during prone hip extension. Pre- and post-intervention values for muscle activity onset and maximal amplitude signals were determined.

**Results:** There was a significant reduction in the surface electromyography activity of maximal amplitude in the erector spinae and contralateral erector spinae ( $p < 0.05$ ). Additionally, gluteus maximus ( $p < 0.05$ ) activity onset was delayed post-intervention.

**Conclusions:** Self-neurodynamic sliding techniques modify muscular activity and onset during

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prone hip extension, possibly reducing unnecessary adaptations for protecting injured components. Future work will analyze the effects of self-neurodynamic sliding techniques during other physical tasks.

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## Introduction

To move normally, the nervous system needs to freely perform three mechanical functions – tension, sliding, and compression, with most complex mechanical tasks being performed through a combination of these three functions (Shacklock, 2005). Due to these mechanisms, neural tissue is able to adapt to different body movements. Furthermore, the onset of muscle activity and pain are related. Nevertheless, the means by which muscular responses are mediated remain unclear (Van der Heide et al., 2001). In turn, neural tension was first used to describe dysfunction in the peripheral nervous system (Butler, 2009). During neurodynamic (ND) assessments of the lower limbs, mechanosensitivity of the nervous system occurred as a normal protective mechanism to control symptomatic responses (e.g. pain), increase muscle tone and, subsequently, reduce the range of motion (Boyd et al., 2009). To overcome this limitation, neural tissue mobilization techniques using passive or active movements can be applied to restore tolerance of the nervous system to normal compressive, frictional, and tensile forces associated with daily and sporting activities (Nee and Butler, 2006). Furthermore, during neural tissue mobilization, both high and low-pressure zones are produced, resulting in noxious flux distribution derived from adverse neural tension (Ellis and Hing, 2008).

Much of the initial evidence supporting the use of neural mobilization was anecdotal (Medina and Yancosek, 2008). Indeed, early studies examining the influence of neural mobilization on nerve movement were conducted in cadavers (Butler and Coppieters, 2007; Coppieters et al., 2006). However, cadaveric models limited the ability of these studies to provide support for theoretical concepts regarding nerve mechanics. While advancements have been made, to date many of the perceived benefits of neural mobilization are founded in theory only and have not been directly supported with research evidence (Beneciuk et al., 2009; Ellis et al., 2012).

Highly related to neural mobilization is the study of ND, or investigation on the mechanics and physiology of the nervous system and how these relate to each other (Shacklock, 1995; Pitt-Brooke, 1997). Hypotheses for the effects of ND in manual therapy techniques have historically been biomechanics-based (Butler, 2009), but there has been a recent shift away from purely mechanical rationale towards including physiological concepts, such as the structure and function of the nervous system (Ellis and Hing, 2008). For example, a recent study in rats with severe peripheral nerve injury showed that passive ND exercises reduce nociceptive behavior, in addition to normalizing satellite glial cell responses in the dorsal root ganglion and astrocyte responses in the spinal cord (Santos et al., 2012).

Moreover, the application of ND techniques on different pathologies related to normal nervous system movements appears to result in increased motion range, both passive and active; augmented grip and pinch forces; reduced disability and dysfunction; less pain; smaller symptom area; and lowered pressure pain (Ellis and Hing, 2008); however, the authors did not mention the effects of ND techniques on the central nervous system.

Restoration of restricted nerve movement is unlikely to be the main therapeutic effect of ND sliding exercises, and alternative consequences should be considered (Coppieters and Butler, 2008). For example, hamstring flexibility in male soccer players can be increased through ND sliding techniques (Castellote-Caballero et al., 2013). Moreover, normal protective muscle activity induced by the nervous system to avoid overstretching in healthy individuals should be taken into consideration when assessing the resistance felt during straight leg raise testing and when prescribing muscle and soft tissue stretches (Boyd et al., 2009).

Increased afferent discharge from abnormal impulse generation sites and sensitized nerve fibers are thought to mediate the symptom response associated with ND assessments (Butler, 2000; Devor and Seltzer, 1999; Hall and Elvey, 1999). Symptomatic complaints during nerve palpation do not necessarily result in the identification of the neural tissue injury site since the entire neural tissue tract can become mechanically sensitive after injury to a particular nerve segment (Butler, 2009; Hall and Elvey, 1999). Furthermore, pain catastrophizing seems to be an important factor to consider when evaluating evoked pain intensity reports during upper-extremity ND testing (Beneciuk et al., 2010). Research on participants believing muscle to be the pain source resulted in no changes in pain with provocative ND tests, whereas participants that believed pain was due to 'nerve irritation' experienced significant changes during straight leg raises and variations of this test. Interestingly, pain increased or decreased according to patient expectations (Coppieters et al., 2005).

Likewise, a number of studies have demonstrated altered activation patterns of the lumbo-pelvic muscles during various tasks in patients who suffer from lower back pain (LBP) (Arab et al., 2011). In patients with chronic LBP, there is an alteration in the hip extensors that affects pelvic stability in automatic responses (Bullock-Saxton et al., 1993). One way of automatically examining activity of hip extensor and spinal column musculature is through active prone hip extension (PHE) (Hungerford et al., 2003). However, PHE presents a comparatively variable pattern of activation, whereas gluteus maximus activation is the weakest and/or substantially delayed when the erector spinae on the ipsilateral side or even the shoulder girdle muscles initiate movement (Janda, 1983; Liebenson, 2006).

Muscle firing order during active PHE is extremely variable at both the individual and group levels (Nygren Pierce and Lee, 1990); however, LBP disorders are likely associated with changes in the hip extensor recruitment pattern (Vogt et al., 2003). Moreover, subjects with a clinical diagnosis of sacroiliac joint pain show a delayed onset of surface electromyography (SEMG) activity of the internal oblique abdominis muscle, multifidus, and gluteus maximus in comparison with control subjects (Hungerford et al., 2003). In a later study, subjects with lumbo-sacral instability presented significantly greater muscle activity in the back and hip extensors, and significantly less hip extension force than controls during PHE (Jung et al., 2015). Patients with chronic LBP have higher maximal amplitudes of normalized electrical activity for the ipsilateral and contralateral erector spinae than in patients without LBP. Interestingly, the normalized electrical activity of the gluteus maximus and hamstring, although not statistically significant, is greater in women with LBP than in healthy subjects (Arab et al., 2011). The nervous system has a range of options to achieve protection, and these may involve increased, decreased, or redistributed activities (Hodges and Tucker, 2011). Therefore, it could be important to determine changes in patients with sciatic pain, changes that can be found in the way that muscles are activated during PHE.

In this sense, SEMG is an experimental technique that allows for studying and recording the electrical muscle activity of muscle function through the linear, spatial, and temporary addition of action potentials during muscle contraction. This method allows the electrical activity of each muscle to be studied and recorded in a general articular motion (Hug, 2011). Therefore, it is possible to measure the relationship between ND techniques and muscle coordination during PHE. This test is usually required during lumbopelvic assessments (Lehman et al., 2004), and the regional muscle firing patterns during this test are similar to those that occur during walking.

Since ND techniques restore the tolerance of the nervous system to normal compressive, frictional, and tensile forces (Nee and Butler, 2006). This mechanism could be useful in modifying the automatic hip extension pattern and addressing physiological changes related to radicular symptoms in sciatic pain.

The aim of this study was to assess whether SEMG activity changes during PHE after the self-application of an ND technique in patients with lumbosciatic pain. The results supported the application of ND techniques in physical therapy interventions.

## Methods

### Study participants

Twelve participants (8 women with a mean age of  $51.1 \pm 9.1$  years and 4 men with a mean age of  $44.5 \pm 16.4$  years) were included in this study. Participants were selected from patients under treatment at the Eloisa Diaz and Cruz Melo Health Centers due to lumbosciatic pain. The cluster established by Smart et al. (2012) was used to predict neuropathic pain. The inclusion criteria were based on a history of nerve injury assessed by Magnetic Resonance

Imaging (MRI), dermatomal distribution, and nerve movement tests (positive straight leg raise test) (Cook and Hegedus, 2013; Majlesi et al., 2008). Patients were excluded if they showed sensitivity or motor compromise of other nerves, had previous surgery in the lower limbs, underwent recent trauma (<6 months), were being treated with corticosteroids, were pregnant, had cauda equine syndrome, had spinal cord injury, suffered progressive neurological compromise, or had range of motion restrictions that would interfere with test performance.

The participants were randomly allocated to the intervention group or the control group, using randomization software ([www.randomization.com](http://www.randomization.com)). In both groups, SEMG activity was measured during a hip extension test.

This study was approved by the Ethics Committee of the Northern Metropolitan Area Health Service on August 12th, 2013. All participants were provided with written and verbal information concerning the testing procedures, and an informed consent form was signed by all participants. Finally, this was a double-blind pre-test/post-test controlled trial. The sampling was non-probabilistic by convenience.

### Measurement protocol

The patients were placed in a prone position on a bench with disc-shaped surface electrodes (Ag/AgCl) with a recording area of  $0.5 \text{ cm}^2$ . These discs were placed in pairs parallel to muscle fiber directions of the semitendinosus, gluteus maximus, and the contralateral and ipsilateral erector spinae. To ensure good contact and low electrical interference, skin preparation included shaving and rubbing and cleaning with alcohol (Sakamoto et al., 2009). For the gluteus maximus, the electrodes were placed at the midpoint of a line running from the last sacral vertebrae to the greater trochanter. For the semitendinosus muscle, the electrodes were placed medially on the mid-distance between the gluteal fold and the knee joint. For the erector spinae muscles, the electrodes were placed at the L3 level, bilaterally 2 cm lateral to the spinal processes and parallel to the lumbar spine (Sakamoto et al., 2009). Additionally, a marker was installed on the fibula at the ankle level to determine initiation of movement (Sakamoto et al., 2009).

With the subject in a prone position, hip extension with knee straightening was performed. The bench had a stop device to control extension, thereby preventing extension beyond  $20^\circ$ . Motion speed was regulated with a metronome at 72 Hz, and all patients received training to adjust motion speed to this rhythm. Six repetitions were performed and averaged for a representative sample. Five repetitions have been shown enough to obtain a low variability pattern (Hug, 2011).

### Intervention group protocol

The patients (3 males, 3 females) received training on self-ND sliding techniques in the sitting position, with motion involved in three areas. First, the patient sits in a slump position and performs a neck extension, knee extension, and dorsal flexion of the ankle (Butler, 2000). Next, the patient performs neck flexion, knee flexion, and plantar ankle flexion (Fig. 1). These motions were repeated five



**Figure 1** Experimental set-up for self-sliding neurodynamic technique.

times for 60 s each (Castellote-Caballero et al., 2013; Butler, 2000).

### Control group protocol

The patients (5 females, 1 male) rested for 60 s in a prone position on a bench with short wave equipment, with the electrode near the rear thigh. All short-wave parameters were at zero during the evaluated minute. Short wave detuned (placebo) has been used in some researches about physical therapy and manual therapy in chronic low back pain (Costa et al., 2009; Ferreira et al., 2002).

### SEMG processing

SEMG values were measured with an 8-channel BTS FREEEMG (BTS Bioengineering, Milan, Italy) at the Motion Analysis Laboratory of the Department of Physical Therapy at the University of Chile. Signal collection was performed with the SMART-D and SMART CAPTURE v1.10.427.0 software. Signal processing was performed using Matlab software (2013a, MathWorks Inc, Natick, Massachusetts), wherein an automatic algorithm was used to detect the onset and maximum amplitudes of muscle activity. The signal was filtered in base to empirical mode decomposition, with a soft-threshold of the mean added with two standard deviations of the baseline signal (Kopsinis and McLaughlin, 2009). This was later smoothed by a root mean square with a window of 250 ms. Movement onset was assumed when the marker speed reached 5% of the peak PHE value. As a result, selective muscle latency was calculated as the difference between the values of movement and muscle activation onset points.

### Data analysis

The Windows SPSS v21.0 (IBM Corp., Armonk, New York, United States) software was used to calculate normality and descriptive statistics for each of the variables. The Shapiro–Wilks test for normality was used to determine normal value distribution. Then, the t-student parametric test was used to compare measures between related and non-dependent variables, with significant values obtained for each figure.

## Results

### Study participants

Twelve subjects volunteered for this study. Eight were women with an average age of  $51.1 \pm 9.1$  years and a Body Mass Index (BMI) of  $25.3 \pm 2.7$ . Four were men with an average age of  $44.5 \pm 16.4$  years and a BMI of  $24.1 \pm 0.8$ . A comparison between latency and maximal amplitude values was performed before starting the intervention to assure that the groups were homogenous. Values obtained showed non-significant differences between the groups for all variables considered.

### Maximal amplitude

In the control group, maximal amplitude increased in all tested muscles after the sham intervention, with the exception of semitendinosus muscle, which showed the least activity. However, statistically significant changes were found for only the increase in maximum amplitude of the contralateral erector spinae ( $p = 0.01$ ), where pre-test electrical activity was  $53.34 \pm 18.81 \mu\text{V}$ , while the post-test value was  $63.34 \pm 17.67 \mu\text{V}$ .

In the experimental group, the maximal amplitude of the semitendinosus and gluteus maximus muscles increased after the ND technique. Additionally, there was a decreasing tendency in amplitude for the erector spinae after the ND method. Significant changes were obtained for the ipsilateral erector spinae ( $p = 0.036$ ) and contralateral erector spinae ( $p = 0.005$ ). Pre-test electrical activity of the contralateral erector spinae was  $80.59 \pm 10.01 \mu\text{V}$ , and the post-test value was  $57.70 \pm 17.85 \mu\text{V}$ . The pre-test electrical activity of the ipsilateral erector spinae was  $71.48 \pm 17.58 \mu\text{V}$ , and the post-test value was  $53.3 \pm 13.3 \mu\text{V}$ . All data regarding maximal amplitude variation are displayed as percentages in Table 1 and Fig. 2.

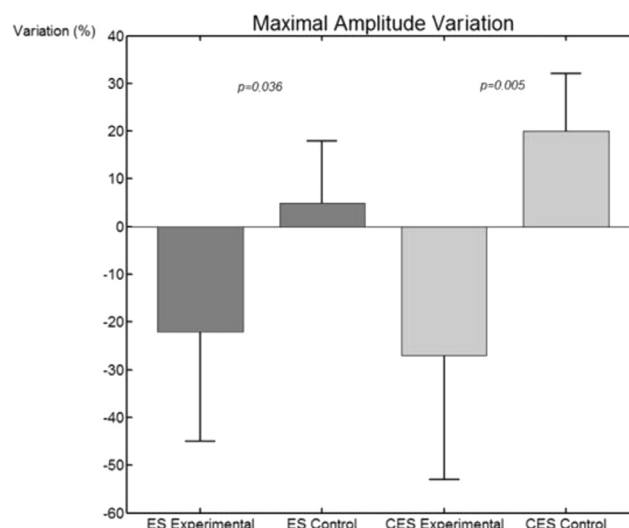
### Muscle onset

In the experimental group, the results showed a tendency of delayed onset for all muscles after application of the ND technique. Statistically significant changes were found only for the onset delay of the gluteus maximus ( $p = 0.01$ ), where the pre-test value was  $0.06 \pm 0.14 \text{ s}$ , and the post-test value was  $0.26 \pm 0.23 \text{ s}$ . In the control group, there were no statistically significant changes. All data regarding activity onset are displayed in Table 2 and Fig. 3.

### Discussion

The aim of this study was to determine whether SEMG activity of muscles involved in PHE changes after a self-applied ND technique. The results showed significant changes in the maximal amplitude signals of the ipsilateral and contralateral erector spinae muscles ( $p < 0.05$ ). However, there were no changes in any other evaluated muscles. Additionally, significant differences were observed for activity onset of the gluteus maximus (202 ms;  $p < 0.01$ ). These results are indicative of changes in protective muscle activities, which may reduce unnecessary adaptations for the protection of injured components (Hodges, 2011).

Based on the present findings, modifications produced by the sliding of neural structures during mobilization in the slump position likely reduce erector spinae muscle activity and improve muscle activity of the gluteus maximus, thereby bettering motion performance. For future studies, the performance of motion kinematics and changes in symptoms pre- and post-intervention must be



**Figure 2** Mean maximal amplitude variation values in the Erector Spinae (ES) and Contralateral Erector Spinae (CES) pre- and post-intervention for the control and experimental groups.

considered to determine the influence on motion mechanics.

Several studies suggest that varied types of LBP (Arab et al., 2011; Vogt et al., 2003; Hungerford et al., 2003; Jung et al., 2015) are related to functional changes in the muscle that promote further alterations in the musculoskeletal system. Normal muscle activity and central nervous system regulation (Sakamoto et al., 2009) strongly influence proper muscle coordination since normal spine motion is more complex than passive joint motion. For this reason, the peripheral and central nervous systems necessarily played primary roles in regulating the motor output observed in patients with radicular (sciatic) pain in the present study, thus allowing proper muscle control in terms of intensity and time for each motor task. Increased muscle activity, in addition to pain, likely impairs the muscle coordination necessary for common activities such as gait. To further elucidate this subject, clear data on objective muscle coordination should be investigated to develop novel therapeutic interventions.

Values recorded for the 12 patients in this study were used to establish the average onset time for each of the assessed muscles, thus providing a muscle pattern in patients with lumbosciatic pain. The first muscle activated was the semitendinosus, followed by the contralateral erector spinae, the ipsilateral erector spinae, and, finally, the gluteus maximus. These results are similar to those in patients presenting LBP (Guimaraes et al., 2010). This could be interesting because pain could promote changes in the motor performance of the lumbopelvic girdle in different groups of patients in pain. More research is needed to clarify the accuracy of these assumptions.

The present results showed that in 75% of individuals with lumbosciatic pain, the gluteus maximus was the last muscle to be activated. This muscle is important for maintaining stable gait and posture, and it has been associated with LBP in cases of deficient load absorption in the spine (Sakamoto et al., 2009). The current data showed a delay in gluteus maximus onset after application of the

**Table 1** Maximal amplitude variation (%) in the control and the experimental groups. Mean values and standard deviation were calculated for the following muscles: Erector Spinae (ES), Gluteus Maximus (GM), Semitendinosus (ST), and Contralateral Erector Spinae (CES). \* $p < 0.05$ .

Maximal amplitude variation (%)	Control group (n = 6)	Experimental group (n = 6)	p
ES	5.816 (13.662)	-22.043 (23.362)	0.036*
GM	21.219 (19.822)	3.947 (27.968)	0.248
ST	4.020 (12.518)	1.477 (28.012)	0.845
CES	20.929 (12.052)	-27.066 (26.841)	0.005*

**Table 2** Mean activity onset values and standard deviation were calculated in the control and experimental groups for the following muscles: Erector Spinae (ES), Gluteus Maximus (GM), Semitendinosus (ST), and Contralateral Erector Spinae (CES). Each group was divided into three columns that show the pre- and post-intervention quantities and their comparison results ( $p$  value). \* $p < 0.05$ .

Onset (ms)	Control group ( $n = 6$ )			Experimental group ( $n = 6$ )			
	Pre	Post	$p$	Pre	Post	$p$	$p$
ES	-9 (360)	-100 (430)	0.22	-173 (260)	-11 (170)	0.06	
GM	395 (570)	368 (270)	0.87	66 (140)	268 (230)	0.01*	
ST	-282 (110)	-266 (350)	0.88	-432 (230)	-401 (200)	0.84	
CES	-230 (960)	-290 (390)	0.61	-149 (130)	15 (270)	0.16	

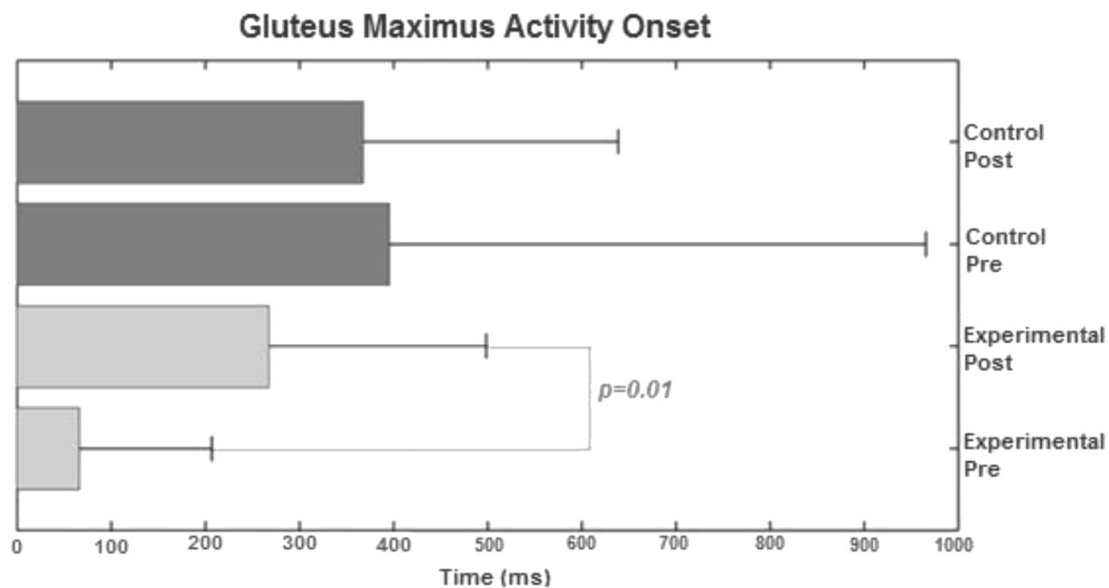
treatment technique. This could be the result of a modification in motor strategy after neural self-sliding, thus decreasing the anticipated activation of musculature to produce a lesser protective response and, therefore, better task execution (Hodges, 2011).

Evaluations of PHE during physical exams are based on the belief that a "normal" muscle pattern is produced, but to date, the literature has failed to show that there is such a normal pattern in healthy subjects (Lehman et al., 2004). If muscle activation variability is high among this group of patients, the use of this test to determine dysfunction will be limited. Nevertheless, applying a transversal methodology to study PHE may result in the identification of muscle patterns in normal individuals and in patients with lumbosciatic pain. This proposal is supported by variations in SEMG data analyses depending on the method used to determine muscle onset, which could explain the differences for pattern determination (Staudte et al., 2001). The present methodology used empirical mode decomposition to filter the SEMG signal. This method acts as a noise filter without removing the frequency components of the muscle (Andrade et al., 2006). This is relevant since the selection method for the filter signal can influence the determination of muscle patterns.

For another hand, it is important to clarify that although the diagnosis by MRI can show nerve damage, this does not always correlate with clinical symptoms (Bertilson et al., 2010). Since the neural entrapment can occur at different levels of nerve trajectory (Dong et al., 2012), and this is where the neural mobilization can help restore the mechanical behavior of the nerve.

Regarding limitations of this study, the small sample size probably reduced the ability of analyses to determine significant difference in all of the evaluated muscles. Likewise, the small sample size did not permit for comparing intervention effects between genders. As this study was the first in a series of studies to be performed, acting as a benchmark assessment for methodologies, future evaluations will take into consideration larger sample groups to more efficiently assess statistical differences and gender variations.

Moreover, pain level could be an uncontrolled bias since this was measured only during patient selection, but not in relation to SEMG parameters. Additionally, some patients found it difficult to maintain the prone position due to severe symptoms. Either of these factors could have influenced the results when considering that discomfort could affect baseline muscle activity signals. In addition to this,



**Figure 3** Mean activity onset values for the Gluteus Maximus pre- and post-intervention for the control and experimental groups.

patient medication was not taken into account as a variable; some medications can affect muscle activation, such as muscle relaxants.

Finally, this study did not consider the lumbopelvic rhythm during the hip extension test in prone patients. This rhythm might explain the different activation strategies in cases where patients either rectified or augmented the curve of the lower back. For future studies, measurements should be taken of the lumbar curve and pelvis position during task execution, which will provide data to cross-check kinematic and SEMG results.

## Conclusions

In a sitting position, self-applied neurodynamic sliding techniques produced changes in muscular onset and activity during prone hip extension. These modifications may play a role in reducing unnecessary component adaptations to protect injured muscles. Future work will study the effects of self-neurodynamic sliding techniques during other physical tasks.

## References

- Andrade, A.O., Nasuto, S., Kyberd, P., Sweeney-Reed, C.M., Van Kanijn, F.R., 2006. EMG signal filtering based on empirical mode decomposition. *Biomed. Signal Process. Control* 1, 44–55.
- Arab, A.M., Ghamkhar, L., Emami, M., Nourbakhsh, M.R., 2011. Altered muscular activation during prone hip extension in women with and without low back pain. *Chiropr. Man. Ther.* 19, 18.
- Beneciuk, J.M., Bishop, M.D., George, S.Z., 2009. Effects of upper extremity neural mobilization on thermal pain sensitivity: a sham-controlled study in asymptomatic participants. *J. Orthop. Sports Phys. Ther.* 39 (6), 428–438.
- Beneciuk, J.M., Bishop, M.D., George, S.Z., 2010. Pain Catastrophizing predicts pain intensity during a neurodynamic test for the median nerve in healthy participants. *Man. Ther.* 15 (4), 370–375.
- Bertilson, B.C., Brosjo, E., Billing, H., Strender, L.E., 2010. Assessment of nerve involvement in the lumbar spine: agreement between magnetic resonance imaging, physical examination and pain drawing findings. *BMC Musculoskelet. Disord.* 11, 202.
- Boyd, B.S., Wanek, L., Gray, A.T., Topp, K.S., 2009. Mechano-sensitivity of the lower extremity nervous system during straight-leg raise neurodynamic testing in healthy individuals. *J. Orthop. Sports Phys. Ther.* 39 (11), 780–790.
- Bullock-Saxton, J.E., Janda, V., Bullock, M.I., 1993. Reflex activation of gluteal muscles in walking: an approach to restoration of muscle function for patients with low-back pain. *Spine* 18 (6), 704–708.
- Butler, D.S., 2000. *The Sensitive Nervous System*. Noigroup Publications, Adelaide.
- Butler, D.S., 2009. *Mobilización del Sistema Nervioso*. Paidotribo, Badalona.
- Butler, D.S., Coppiters, M.W., 2007. Neurodynamics in a broader perspective. *Man. Ther.* 12 (1), e7–e8.
- Castellote-Caballero, Y., Valenza, M.C., Martín-Martín, L., Cabrera-Martos, I., Puenteadura, E.J., Fernández-de-las-Peñas, C., 2013. Effects of a neurodynamic sliding technique on hamstring flexibility in healthy male soccer players. A pilot study. *Phys. Ther. Sport* 14 (3), 156–162.
- Cook, C., Hegedus, E., 2013. *Orthopedic Physical Examination Tests: an Evidence Based Approach*. Pearson.
- Coppiters, M.W., Alshami, A.M., Babri, A.S., Souvlis, T., Kippers, V., Hodges, P.W., 2006. Strain and excursion of the sciatic, tibial and plantar nerves during a modified straight leg raising test. *J. Orthop. Res.* 24, 1883–1889.
- Coppiters, M.W., Butler, D.S., 2008. Do “sliders” slide and “tensioners” tension? An analysis of neurodynamic techniques and considerations regarding their application. *Man. Ther.* 13 (3), 213–221.
- Coppiters, M.W., Ryan, L., Chan, K.Y., Soh, L.H., Chan, K.P., Hodges, P.W., 2005. Do patients’ expectations of test responses affect outcomes?. In: *Musculoskeletal Physiotherapy Australia 14th Biennial Conference*, p. 514.
- Costa, L.O., Maher, C.G., Latimer, J., Hodges, P.W., Herbert, R.D., Refshauge, K.M., McAuley, J.H., Jennings, M.D., 2009. Motor control exercise for chronic low back pain: a randomized placebo-controlled trial. *Phys. Ther.* 89, 1275–1286.
- Devor, M., Seltzer, Z., 1999. Pathophysiology of damaged nerves in relation to chronic pain. In: *Textbook of Pain*, pp. 129–164.
- Dong, Q., Jacobson, J.A., Jamadar, D.A., Gandikota, G., Brandon, C., Morag, Y., Fessell, D.P., Kim, S.M., 2012. Entrapment neuropathies in the upper and lower limbs: anatomy and MRI features. *Radiol. Res. Pract.* 2012, 230679.
- Ellis, R.F., Hing, W.A., 2008. Neural mobilization: a systematic review of randomized controlled trials with an analysis of therapeutic efficacy. *J. Man. Manip. Ther.* 16 (1), 8–22.
- Ellis, R.F., Hing, W.A., McNair, P.J., 2012. Comparison of longitudinal sciatic nerve movement with different mobilization exercises: an in vivo study utilizing ultrasound imaging. *J. Orthop. Sports Phys. Ther.* 42 (8), 667–675.
- Ferreira, M.L., Ferreira, P.H., Latimer, J., Herbert, R., Maher, C.G., 2002. Does spinal manipulative therapy help people with chronic low back pain? *Aust. J. Physiother.* 48, 277–284.
- Guimaraes, C.Q., Sakamoto, A.C., Laurentino, G.E., Teixeira-Salmeda, L.F., 2010. Electromyographic activity during active prone hip extension did not discriminate individuals with and without low back pain. *Rev. Bras. Fisioter.* 14 (4), 351–357.
- Hall, T.M., Elvey, R.L., 1999. Nerve trunk pain: physical diagnosis and treatment. *Man. Ther.* 4 (2), 63–73.
- Hodges, P.W., 2011. Pain and motor control: from the laboratory to rehabilitation. *J. Electromyogr. Kinesiol.* 21 (2), 220–228.
- Hodges, P.W., Tucker, K., 2011. Moving differently in pain: a new theory to explain the adaptation to pain. *Pain* 152 (Suppl. 3), S90–S98.
- Hug, F., 2011. Can muscle coordination be precisely studied by surface electromyography? *J. Electromyogr. Kinesiol.* 21 (1), 1–12.
- Hungerford, B., Gilleard, W., Hodges, P., 2003. Evidence of altered lumbopelvic muscle recruitment in the presence of sacroiliac joint pain. *Spine* 28 (14), 1593–1600.
- Janda, V., 1983. *Muscle Function Testing*. Butterworths, London.
- Jung, H.S., Kang, S.Y., Park, J.H., Cynn, H.S., Jeon, H.S., 2015. EMG activity and force during prone hip extension in individuals with lumbar segmental instability. *Man. Ther.* 20 (3), 440–444.
- Kopsinis, Y., McLaughlin, S., 2009. Development of EMD-based denoising methods inspired by wavelet thresholding. *IEEE Trans. Signal Process.* 57 (4), 1351–1362.
- Lehman, G.J., Lenno, D., Tresidder, B., Rayfield, B., Poschard, M., 2004. Muscle recruitment patterns during the prone leg extension. *BMC Musculoskelet. Disord.* 10 (5), 3.
- Liebenson, C., 2006. *Rehabilitation of the Spine: a Practitioner’s Manual*. Lippincott Williams & Wilkins.
- Majlesi, J., Togay, H., Ünalán, H., Toprak, S., 2008. The sensitivity and specificity of the slump and the straight leg raising tests in patients with lumbar disc herniation. *J. Clin. Rheumatol.* 14, 87–91.

- Medina, McKeon JM., Yancosek, K.E., 2008. Neural gliding techniques for the treatment of carpal tunnel syndrome: a systematic review. *J. Sport Rehabil.* 17 (3), 324–341.
- Nee, R.J., Butler, D., 2006. Management of peripheral neuropathic pain: integrating neurobiology, neurodynamics, and clinical evidence. *Phys. Ther. Sport* 7 (1), 36–49.
- Nygren Pierce, M., Lee, W.A., 1990. Muscle firing order during active prone hip extension. *J. Orthop. Sports Phys. Ther.* 12 (1), 2–9.
- Pitt-Brooke, J., 1997. *Rehabilitation of Movement: Theoretical Basis of Clinical Practice.* Bailliere Tindall.
- Sakamoto, A.C., Teixeira-Salmela, L.F., Rodrigues de Paula, F., de Moraes Faria, C.D., Guimaraes, C.Q., 2009. Muscular activation patterns during active prone hip extension exercises. *J. Electromyogr. Kinesiol.* 19, 105–112.
- Santos, F.M., Silva, J.T., Giardini, A.C., Rocha, P.A., Achermann, A.P., Alves, A.S., Brito, L.R., Chacur, M., 2012. Neural mobilization reverses behavioral and cellular changes that characterize neuropathic pain in rats. *Mol. Pain* 8, 57.
- Shacklock, M., 2005. *Clinical Neurodynamics: a New System of Musculoskeletal Treatment.* Elsevier, Oxford.
- Shacklock, M., 1995. Neurodynamics. *Physiotherapy* 81 (1), 9–16.
- Smart, K.M., Blake, C., Staines, A., Thacker, M., Doody, C., 2012. Mechanisms-based classifications of musculoskeletal pain: part 2 of 3: symptoms and signs of peripheral neuropathic pain in patients with low back ( $\pm$  leg) pain. *Man. Ther.* 17 (4), 345–351.
- Staud, G., Flachenecker, C., Daumer, M., Wolf, W., 2001. Onset detection in surface electromyographic signals: a systematic comparison of methods. *J. Appl. Signal Process.* 1, 67–81.
- Van der Heide, B., Allison, G.T., Zusman, M., 2001. Pain and muscular responses to a neural tissue provocation test in the upper limb. *Man. Ther.* 6 (3), 154–162.
- Vogt, L., Pfeifer, K., Banzer, W., 2003. Neuromuscular control of walking with chronic low-back pain. *Man. Ther.* 8 (1), 21–28.