Open access • Journal Article • DOI:10.1097/AJP.0B013E31823E9378

The change in deep cervical flexor activity after training is associated with the degree of pain reduction in patients with chronic neck pain. — Source link

Deborah Falla, Shaun O'Leary, Dario Farina, Gwendolen Jull

Published on: 01 Sep 2012 - The Clinical Journal of Pain (Lippincott Williams & Wilkins)

Topics: Neck pain, Chronic pain and Longus Colli

THE CHANGE IN DEEP CERVICAL FLEXOR ACTIVITY FOLLOWING TRAINING IS ASSOCIATED WITH THE DEGREE OF PAIN REDUCTION IN PATIENTS WITH CHRONIC NECK PAIN

Deborah Falla[1,2], Shaun O'Leary[3], Dario Farina[2], Gwendolen Jull[3]

1. Pain Clinic, Center for Anesthesiology, Emergency and Intensive Care Medicine, University Hospital Göttingen, Göttingen, Germany

2. Department of Neurorehabilitation Engineering, Bernstein Center for Computational Neuroscience, University Medical Center Göttingen, Georg-August University, Göttingen, Germany

3. Division of Physiotherapy, School of Health and Rehabilitation Sciences, University of Queensland, Australia

Acknowledgements: Shaun O'Leary is supported by an NHMRC of Australia Post-Doctoral Research Training Fellowship.

Address for correspondence:
Deborah Falla, Ph.D.
Pain Clinic, Center for Anesthesiology, Emergency and Intensive Care Medicine
University Hospital Göttingen,
Robert-Koch-Str. 40
37075, Göttingen, Germany
T: + 49 (0) 551 3920109
F: + 49 (0) 551 3920110
E: deborah.falla@bccn.uni-goettingen.de

ABSTRACT

Objectives: Altered activation of the deep cervical flexors (longus colli and longus capitis) has been found in individuals with neck pain disorders but the response to training has been variable. Therefore, this study investigated the relationship between change in deep cervical flexor muscle activity and symptoms in response to specific training.

Methods: Fourteen women with chronic neck pain undertook a 6 week program of specific training which consisted of a cranio-cervical flexion exercise performed twice per day (10-20 min) for the duration of the trial. The exercise targets the deep flexor muscles of the upper cervical region. At baseline and follow-up, measures were taken of neck pain intensity (visual analogue scale; 0-10), perceived disability (Neck Disability Index; 0-50) and deep cervical flexor EMG amplitude (via a nasopharyngeal electrode suctioned over the posterior oropharyngeal wall) during performance of cranio-cervical flexion.

Results: Following training, the activation of the deep cervical flexors increased ($P<0.0001$) with the greatest change occurring in subjects with the lowest values of deep cervical flexor EMG amplitude at baseline ($R^2=0.68$; $P<0.001$). There was a significant relationship between initial pain intensity, change in pain level with training, and change in EMG amplitude for the deep cervical flexors during cranio-cervical flexion ($R^2=0.34$, $P<0.05$).

Discussion: Specific training of the deep cervical flexor muscles in women with chronic neck pain reduces pain and improves the activation of these muscles, especially in those with the least activation of their deep cervical flexors prior to training. This finding suggests that the selection of exercise based on a precise assessment of the patients' neuromuscular control and targeted exercise interventions

INTRODUCTION

Neck pain is a common complaint which affects ~70% of individuals at some time in their lives.[1] The course of neck pain is best described as episodes occurring over a lifetime with variable degrees of recovery in between.[2] This tendency for recurrence and chronicity is partly attributed to persistent alterations of cervical neuromuscular control which has been well documented in patients with neck pain.[3]

The function of the deep cervical muscles, longus colli and longus capitis, that envelope and provide physical support to the cervical vertebral column is considered an important element of neuromuscular control of the cervical spine in neck pain.[4] Altered activation of the deep cervical flexor muscles is a feature of some neck pain disorders, including whiplash-induced neck pain [5], idiopathic neck pain [6, 7], work-related neck pain [8], and headache.[9, 10] Despite general agreement across studies on a reduced level of activity of these muscles, the range of degree of impairment observed between patients is wide. This variability may partly explain the variable symptomatic benefit experienced by patients from exercise programs designed to train deep cervical flexor function with responses ranging from an excellent outcome to no relevant benefit. [11, 12]

Although the mechanisms underlying the symptomatic benefits observed in patients performing exercise may be multifactorial, we hypothesize that the degree of muscle impairment present in the individual before the commencement of training is one of the important determinants of symptom relief. The purpose of this study was to test this hypothesis by investigating the relationship between deep cervical flexor muscle activity before training and symptoms in response to a 6 week exercise program specifically aimed at training the function of the deep cervical flexor muscles in patients with neck pain.

based on this assessment are likely to be the most beneficial to patients with neck pain.

Key Words: neck pain, longus colli, longus capitis, cranio-cervical flexion, training

METHODS

Subjects

Fourteen women (age, 39.5 ± 12.1 yrs) with a history of neck pain greater than 6 months (10.4 ± 11.5 yrs) participated in the study. The study was a single group design since the aim was to investigate the relationship between change in deep cervical flexor muscle activity and symptoms in response to specific training. Earlier studies have demonstrated the efficacy of the training intervention in randomized controlled trials.[11, 13]

Subjects were recruited by advertisements in the local press. Participants were included if they were between the ages of 18-60 years, reported a history of idiopathic neck pain of greater than 6 months duration, scored 5 points or greater out of a possible 50 points on the Neck Disability Index (NDI)[14], and demonstrated positive findings on a physical examination of the cervical spine (altered joint motion and painful reactivity to palpation). Patients were excluded if they had undergone cervical spine surgery, complained of any neurological signs in the upper limb or had participated in a neck exercise program in the past 12 months. The patients' average score for the Neck Disability Index (range, 0-50) was 10.2 ± 2.7 and their average pain intensity rated on a visual analogue scale (0-10) was 4.1 ± 1.7.

Ethical approval for the study was granted by the Institutional Ethics Committee and the procedures were conducted according to the Declaration of Helsinki.

Measurements

The outcome measurements for the study were the EMG amplitude of the longus colli/longus capitis during five stages of an isometric cranio-cervical flexion task and the patient reported levels of pain and disability. All were assessed at baseline and in the week immediately after the 6-week intervention period (week 7).

Electromyography

Electromyography was acquired from the longus colli/longus capitis muscles unilaterally on the side of greatest pain, which was the right side for 7 patients. The apparatus consisted of bipolar silver wire electrode contacts (2 mm × 0.6 mm, 10-mm inter-electrode distance) attached to a suction catheter (size 10FG), with a heat sealed distal end, which was inserted via the nose to the posterior oropharyngeal wall (Fig. 1A,B). The validity and reliability of this technique has been established in previous studies.[15, 16] The electrode location was confirmed by inspection through the mouth ~1cm lateral to the midline at the level of the uvula (approximately the level of the C2–3 intervertebral disc) which is the level at which the longus colli muscle has its greatest cross-sectional area.[17] The electrode contacts were fixed to the mucosal wall with a suction pressure of 30 mmHg via a portal between the two contacts. Before insertion, the nose and pharynx were anaesthetized with three metered doses of 2% Xylocaine ® spray (lidocaine, Astra Pharmaceuticals, Sweden) administered via the nostril and to the posterior oropharyngeal wall, via the mouth. A ground electrode was placed on the upper thoracic spine.

EMG signals were amplified with gain 1000, band-pass filtered between 20Hz – 1kHz, and sampled at 2kHz. Data were sampled with Spike software using a micro1401 data acquisition system (Cambridge Electronic Design, Cambridge, UK) and converted to digital form by a 12-bit analog-to-digital converter.

Insert Figure 1 here

Cranio-cervical Flexion Task

Subjects were comfortably positioned in supine, crook lying with the head and neck in a mid-position and were instructed to perform a cranio-cervical action (anatomical action of the deep cervical flexors) (Fig. 1C). The task consisted of five incremental movements of increasing cranio-cervical flexion range of motion. Performance was guided by visual feedback from an air-filled pressure sensor (Stabilizer™, Chattanooga Group Inc. USA) which was placed sub-occipitally behind the subject's neck and inflated to 20 mmHg. During the test, subjects were required to perform gentle nodding motions of cranio-cervical flexion that progressed in range to increase the pressure by five incremental levels, with each increment representing 2 mm Hg. Subjects practiced targeting the five test levels (22-30 mmHg; increments of 2 mmHg) in two practice trials before the electrodes were applied. The repeatability of normalized EMG amplitude of the deep cervical flexor muscles for the five stages of this cranio-cervical flexion task has been established previously.[15]

Both pre and post training, EMG data were first collected for 10 s during a standardized manoeuvre for EMG normalization. The task involved cervical and cranio-cervical flexion to lift and hold the head just clear of the bed (reference voluntary contraction). Subjects then performed the five incremental stages (22-30 mmHg) of the cranio-cervical flexion task, maintaining the pressure steady on each target for 10 s and resting for 30 s between stages. Data collection commenced when the subject reached the pressure target.

The root mean square (RMS) of the EMG was calculated over a 1 s sliding window and presented as an average across the 10-s contractions. The values of RMS were expressed as a percentage of the maximum RMS value during the reference voluntary contraction (head lift).

Patient Reported Levels of Pain and Disability

At both laboratory sessions the participants' reported levels of pain were measured with a Visual Analogue Scale (VAS). Participants were asked to indicate their average neck pain intensity over the previous week by placing a mark on a 100mm line bordered at one end by the words "no pain" and the other end by the words "worst pain ever". Participants also completed a Neck Disability Index (NDI)[14] which is a 10 item questionnaire relating to daily activities and cervical spine related pain. Each item is scored from 0 to 5, and the total score out of 50 points is summated.

Training Intervention

The training intervention commenced within one week of the initial assessment and lasted 6 weeks. The patients received personal instruction and supervision by a physiotherapist once per week. No exercise sessions were longer than 30 min. Subjects were asked not to seek other interventions for neck pain although usual medication was not withheld. Subjects received an exercise diary and were requested to practice the cranio-cervical flexion exercise twice per day (10-20 min) for the duration of the trial, without provoking neck pain and with attention to performance of smooth uniplanar movements. Cranio-cervical flexion training followed the protocol described by Jull et al.[18] The exercise targets the deep flexor muscles of the upper cervical region (longus capitis and longus colli), rather than the superficial flexor muscles, which flex the neck but not the head.

In the first phase of training the physiotherapist taught the subject to perform a slow and controlled cranio-cervical flexion action in the supine position. The subject concentrated on feeling the back of the head slide in cephalad and caudad directions on the supporting surface to ensure a sagittal rotation rather than a retraction movement. Once the correct cranio-cervical action was achieved, subjects began the second phase of training in which they trained to hold progressively increasing ranges of cranio-cervical flexion using feedback from the air-filled pressure sensor placed behind the neck. The feedback dial displayed the amount of pressure change as the cervical lordosis progressively flattened during cranio-cervical flexion. The subject initially performed cranio-cervical flexion to sequentially reach five pressure targets in 2 mmHg increments from a baseline of 20 mmHg to the final level of 30 mmHg. The physiotherapist identified the target level that the subject could hold steadily for 5 s without resorting to retraction, without dominant use of the superficial neck flexor muscles, and without a quick, jerky cranio-cervical flexion movement. Contribution from the superficial muscles was monitored by the physiotherapist by palpation. Training was commenced at the target level that the subject could achieve with a correct cranio-cervical flexion movement and without dominant use of the superficial muscles. They then trained to be able to sustain progressively greater ranges of cranio-cervical flexion using feedback from the pressure sensor progressing through the stages of the task (22 mmHg – 30 mmHg) from their baseline level. For each target level, the contraction duration was increased to 10-s, and the subject trained to perform 10 repetitions with brief rest periods between each contraction (~3-5s). Once a stage was achieved, the exercise was progressed to train at the next target level up to the final target of 30 mmHg.

Statistical Analysis

Two-way analysis of variance (ANOVA) was used to analyze the normalized RMS of the deep cervical flexors, with time (pre and post intervention) and stage (20 mmHg – 30 mmHg) as repeated measures. Further, a one-way ANOVA was used to evaluate differences in the average pain intensity and perceived disability (NDI) following training, with time (pre and post intervention) as the repeated measure.

Significant differences revealed by ANOVA were followed by post-hoc Student-Newman-Keuls (SNK) pair-wise comparisons.

Linear correlation analysis was used to determine the association between changes in normalized RMS and changes in pain and NDI induced by the training program. Finally, a multiple regression analysis was performed with change in pain intensity as the dependent variable and initial pain and percent change in RMS across the five stages of the cranio-cervical flexion test as independent variables. Results are reported as mean and SD in the text and SE in the figures. Statistical significance was set at $P < 0.05$.

RESULTS

All patients returned for the follow-up assessment. The patients attended 5.8 ± 0.4 of the 6 sessions and none reported receiving any other treatments in the intervention period. Exercise compliance was 94.3 ± 5.9 % completion of suggested exercise prescription, as recorded in the exercise diary. The average neck pain intensity decreased from 4.1 ± 1.7 to 2.3 ± 2.3 following the 6 week intervention period ($P<0.01$). The perceived disability reduced from 10.2 ± 2.7 to 5.5 ± 4.4 following training ($P<0.001$). Forty-three percent of patients indicated an average intensity of neck pain less than 0.5 out of 10 post training, of which 21% of patients reported complete relief of pain. Two patients reported an increase of their neck pain (from 4.4 to 6.2 and from 6 to 7).

The EMG amplitude recorded during the reference voluntary contraction was 208.5 ± 123.1 μV and 191.5 ± 113.3 μV pre and post training respectively. Analysis of the group data showed that the activation of the deep cervical flexors increased following training across all stages of the cranio-cervical flexion test (main effect for time; P<0.0001; Fig 2).

Insert Figure 2 here

Fig. 3 presents representative raw EMG data for the deep cervical flexors in two patients performing the cranio-cervical flexion task and head lift maneuver. Patient A showed similar levels of activation of the deep cervical flexor muscles during the cranio-cervical flexion task relative to the head lift post training as compared to baseline whereas patient B showed lower amplitude of deep cervical flexor activity at baseline and a greater increase in activation post training compared to patient A. Accordingly, the group data showed that patients with the greatest change in the activation of deep cervical flexors (% increase) following training were those with the lowest values of deep cervical flexor RMS at baseline (R^2=0.68; P<0.001; Fig 4*A*). When the change in deep cervical flexor activation post training was averaged across all stages of the cranio-cervical flexion test, there was no correlation between the amount of change in activation and change in pain intensity (R^2=0.04) or NDI (R^2=0.002). However, a greater increase in activation of the deep cervical flexors across the final two stages of the test (28 and 30 mm Hg) correlated with a greater reduction in average neck pain intensity (R^2=0.30; P<0.05; Fig. 4*B*) but not NDI (R^2=0.07). In accordance, a multiple regression between change in pain level (dependent variable) and initial pain and change in EMG RMS for the deep cervical flexors for the five stages was significant (R^2=0.34, P<0.05), with a correlation identified between change in pain post training and change in activation of the deep cervical flexors at stages 28 mmHg and 30 mmHg (P<0.05).

Insert Figures 3 and 4 here

DISCUSSION

Following 6 weeks of training, the patients with the greatest percent change in activation of their deep cervical flexor muscles on a task of cranio-cervical flexion showed the greatest pain relief from training. Furthermore, patients with the least activation of their deep cervical flexors at baseline showed the greatest change in activation post training. These findings suggest that there is an association between the level of pain perceived by the patients and the degree of function of their deep cervical flexor muscles and supports the prescription of this form of exercise to patients with neck pain, particularly those who demonstrate poor performance on specific tests of deep cervical flexor muscle function.

As a component of the neuromuscular control changes observed in people with neck pain, a relatively consistent observation is a change in the behavior of the deep cervical flexor muscles. Altered activity of the deep cervical flexors has been observed during the task of cranio-cervical flexion [6, 7, 10], during postural perturbations [19], and deficits in their strength and endurance have been observed at different contraction intensities.[20] Furthermore, these changes in neuromuscular control occur early after the onset of the disorder as observed in persons with acute whiplash measured within 4 weeks of injury.[5]

Training interventions that aim to address the impairment in the deep cervical flexors in patients with neck pain have been evaluated previously in randomized controlled trials.[11-13, 21] As observed in this study, activation of the deep cervical flexors has been previously shown to increase following specific and repeated training of the deep cervical flexors in patients with neck pain.[11] The approach involves training the activation of the deep cervical flexor muscles independently of the more superficial flexor muscles. The rationale for this training approach is based on the principle of motor learning, which places emphasis initially on the practice of movement components rather than practicing the whole movement.[22] This principle has also been applied successfully to train muscles in other musculoskeletal conditions.[23-26] The basis for this approach is that repeated activation of the deep cervical flexor muscles may induce neuroplastic changes which in turn will lead to improved recruitment of the trained muscle during complex functional tasks.[26]

The main contribution of this study is the analysis of the relation between the amount of activation of the deep cervical flexors prior to training and the amount of improvement post training, and their association to perceived pain. The hypothesis that patients with the greatest impairment in the deep cervical flexor function would show the greatest improvement in the activation of these muscles following the intervention was verified. Furthermore, those who showed the greatest improvement in the activation of the deep cervical flexor muscles also showed the greatest amount of pain relief from the training intervention. A correlation between the reduction in average neck pain intensity and change in deep cervical flexor activity post training existed only when the change in activation was averaged across the final two stages of the cranio-cervical flexion test (28 and 30 mm Hg) and not when it was averaged across all stages of the test. This finding is not surprising considering that significantly reduced activation of the deep cervical flexor muscles was observed in patients with neck pain at the stages of 28 and 30 mm Hg only in the original study investigating differences between patients with neck pain and controls. [27] The finding of an association between the pain perceived by the patients and the level of motor impairment strongly supports the inclusion of training in the treatment of neck pain patients. Further, selection of exercises based on a precise assessment of the patients' neuromuscular control and targeted exercise interventions based on this assessment are likely to be the most beneficial to patients.

Training the deep cervical flexors is achieved by having the patient perform cranio-cervical flexion in supine as an active movement at a slow speed with an emphasis on precision and control and without provocation of pain [18], as implemented in this study. Formal practice of the movement should be undertaken twice a day (10-20 min). Training endurance of the deep cervical flexors is commenced as soon as the patient can perform the cranio-cervical flexion movement correctly. Training is commenced at the pressure level that the patient has been assessed to be able to achieve and hold steadily with a good movement pattern. This is often at the lowest levels of the test (22 or 24 mmHg). The movement is facilitated with eye movement into the flexion direction and emphasis is always on precision and control. For each pressure level, the holding time is built up to 10 seconds, and 10 repetitions are performed. Once the holding contractions at a certain pressure level are achieved, the exercise is progressed to train endurance at the next pressure level. Studies have shown that most asymptomatic subjects can achieve pressure levels between 26 and 30 mmHg and can hold the pressure steady for 10 seconds with 10 repetitions. [7, 9, 28, 29] The aim for neck pain patients is to train the muscles towards an optimal performance (30 mmHg) and most neck pain patients are capable of achieving these higher levels.[12] The time taken to achieve and hold the five levels of the cranio-cervical task is variable but can usually be achieved in four to six weeks.

The increased activation of the deep cervical flexor muscles post training may reflect both central and peripheral adaptations. Some studies have reported early peripheral changes (i.e., after 6.5 to 14 weeks), such as increased fiber cross sectional area and fiber pennation angle [30-32] in response to high-intensity strength training paradigms. However, given that the training protocol in this study involved low loads applied for only 6 weeks, changes in muscle activation were presumably induced by neural adaptations, as has been shown previously.[33-35]

Changes at many levels of the nervous system may explain the changes observed for the deep cervical flexor muscles following the exercise intervention in this study. Although not yet examined in patients with neck pain, reorganization of deep trunk muscle representation at the motor cortex has been observed in individuals with recurrent low back pain.[36] Changes in the excitability of the motor neurons and motor cortex have been shown to occur with repeated voluntary contractions.[37-40] Furthermore, animal studies have revealed that increased task proficiency is correlated with increased synaptic efficacy of the primary motor area [41] through processes such as strengthening of horizontal cortical connections in layers II/III [42] and increased synapses per neuron in layer V [43]. It is now well appreciated that the primary motor cortex of both humans and animals is specifically engaged during the acquisition phase of novel motor skills and that the associated neuroplasticity is not the result of increased muscle or nerve excitability.[40, 44] These changes can take place rapidly within minutes to hours following motor practice [37], especially in novel tasks. The task used in the present study for training is also relatively novel since it is not a common voluntary activity, thus the training protocol can be associated to learning a novel task. The ability to target a specific component of movement requires greater skill and increased levels of attention and precision than contraction of all muscles (e.g., strength training). Therefore, it is likely that changes at the cortical level may have occurred following the training program in this study. Accordingly, the type of training used in this study has been reported to invoke superior plastic changes in central motor control pathways compared to unskilled or non-isolated training.[45]

A control group was not included in this study since the aim was to investigate the relation between the amount of activation of the deep cervical flexors prior to training and the amount of improvement post training, and their association to perceived pain. Previous randomized controlled trials have confirmed that training the deep cervical flexors in patients with neck pain is effective at reducing neck pain, headache and perceived disability. [12, 11, 13] Likewise this study did not include a long term follow-up since previous trials have shown that the pain relief gained from this training approach is maintained at a 12 month follow-up.[12] The main limitation of the study is the small sample size. A large sample was difficult to achieve due to the invasiveness of the procedure. Despite the small sample, the findings yielded significant results.

Conclusion

Repetitive specific training of the deep cervical flexor muscles in women with chronic neck pain reduces pain and increases the activation of these muscles, especially in patients with the least activation of their deep cervical flexors prior to training.

REFERENCES

1. Cote P, Cassidy JP, Carroll LJ et al. The annual incidence and course of neck, and shoulder pain in the general population: a population based cohort study. *Pain* 2004;112:267-273

2. Haldeman S, Carroll L, Cassidy JD et al. The Bone and Joint Decade 2000-2010 Task Force on Neck Pain and Its Associated Disorders: Executive Summary. *Spine* 2008;33:S5-S7

3. Falla D, Farina D. Neural and Muscular Factors Associated with Motor Impairment in Neck Pain. *Curr Rheumatol Rep* 2007;9:497-502

4. Mayoux-Benhamou MA, Revel M, Vallee C et al. Longus Colli has a postural function on cervical curvature. *Surg Radiol Anat* 1994;16:367-371

5. Sterling M, Jull G, Vicenzino B et al. Development of motor dysfunction following whiplash injury. *Pain* 2003;103:65-73

6. Falla D, Jull G, Hodges PW. Patients with neck pain demonstrate reduced electromyographic activity of the deep cervical flexor muscles during performance of the craniocervical flexion test. *Spine* 2004;29:2108-2114

7. Chiu TT, Law E, Chiu TH. Performance of the craniocervical flexion test in subjects with and without chronic neck pain. *JOSPT* 2005;35:567-571

8. Johnston V, Jull G, Souvlis T et al. Neck movement and muscle activity characteristics in female office workers with neck pain. *Spine* 2008;33:555-563

9. Jull G, Barrett C, Magee R et al. Further clinical clarification of the muscle dysfunction in cervical headache. *Cephalalgia* 1999;19:179-85

10. Fernandez-de-las-Penas C, Perez-de-Heredia M, Molero-Sanchez A et al. Performance of the craniocervical flexion test, forward head posture, and headache

clinical parameters in patients with chronic tension-type headache: a pilot study. *J Orthop Sports Phys Ther* 2007;37:33-39

11. Jull G, Falla D, Vicenzino B et al. The effect of therapeutic exercise on activation of the deep cervical flexor muscles in people with chronic neck pain. *Man Ther* 2009;14:696-701

12. Jull G, Trott P, Potter H et al. A randomized controlled trial of exercise and manipulative therapy for cervicogenic headache. *Spine* 2002;27:1835-1843

13. Jull G, Falla D, Treleaven J et al. Retraining cervical joint position sense: The effect of two exercise regimes. *J Orthop Res* 2007;25:404-412

14. Vernon H, Mior S. The Neck Disability Index: A study of reliability and validity. *J Manipulative Physiol Ther* 1991;14:409-15

15. Falla D, Jull G, Dall'Alba P et al. An electromyographic analysis of the deep cervical flexor muscles in performance of craniocervical flexion. *Phys Ther* 2003;83:899-906

16. Falla D, Jull G, O'Leary S et al. Further evaluation of an EMG technique for assessment of the deep cervical flexor muscles. *J Electromyogr Kinesiol* 2006;16:621-628

17. Lang J. *Clinical anatomy of the cervical spine*. New York. Thieme Medical Publishers. 1993

18. Jull G, Sterling M, Falla D et al. *Whiplash, Headache and Neck Pain: Research Based Directions for Physical Therapies*. Edinburgh. Elsevier, Churchill Livingstone. 2008

19. Falla D, Jull G, Hodges PW. Feedforward activity of the cervical flexor muscles during voluntary arm movements is delayed in chronic neck pain. *Exp Brain Res* 2004;157:43-48

20. O'Leary S, Jull G, Kim M et al. Cranio-cervical flexor muscle impairment at maximal, moderate, and low loads is a feature of neck pain. *Man Ther* 2007;12:34-39

21. Falla D, Jull G, Russell T et al. Effect of neck exercise on sitting posture in patients with chronic neck pain. *Phys Ther* 2007;87:408-417

22. Fitts PM, Posner MI. *Human Performance*. USA. Wadsworth. 1967

23. O'Sullivan PB, Phyty GD, Twomey LT et al. Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. *Spine* 1997;22:2959-2967

24. Richardson C, Jull G, Hodges P et al. *Therapeutic Exercise for Spinal Segmental Stabilization in Low Back Pain: Scientific basis and clinical approach*. United Kingdom. Churchill Livingstone. 1998

25. Cowan SM, Bennell KL, Hodges PW et al. Simultaneous feedforward recruitment of the vasti in untrained postural tasks can be restored by physical therapy. *J Orthop Res* 2003;21:553-558

26. Tsao H, Hodges PW. Persistence of improvements in postural strategies following motor control training in people with recurrent low back pain. *J Electromyogr Kinesiol* 2008;18:559-567

27. Falla D, Bilenkij G, Jull G. Patients with chronic neck pain demonstrate altered patterns of muscle activation during performance of a functional upper limb task. *Spine* 2004;29:1436-1440

28. Jull G, Kristjansson E, Dall'Alba P. Impairment in the cervical flexors: a comparison of whiplash and insidious onset neck pain patients. *Man Ther* 2004;9:89-94

29. Jull GA. Deep cervical flexor muscle dysfunction in whiplash. *Journal of Musculoskeletal Pain* 2000;8:143-154

30. Kosek DJ, Kim JS, Petrella JK et al. Efficacy of 3 days/wk resistance training on myofiber hypertrophy and myogenic mechanisms in young vs. older adults. *J Appl Physiol* 2006;101:531-544

31. Blazevich AJ, Cannavan D, Coleman DR et al. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol* 2007;103:1575

32. Seynnes OR, de Boer M, Narici MV. Early skeletal muscle hypertrophy and architectural changes in response to high-intensity resistance training. *J Appl Physiol* 2007;102:368-373

33. Costill DL, Coyle EF, Fink WF et al. Adaptations in skeletal muscle following strength training. *J Appl Physiol* 1979;46:96-99

34. Sale DG. Neural adaptation to resistance training. *Med Sci Sports Exerc* 1988;20:S135-145

35. Folland JP, Williams AG. The adaptations to strength training : morphological and neurological contributions to increased strength. *Sports Med* 2007;37:145-168

36. Tsao H, Galea MP, Hodges PW. Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain* 2008;131:2161-2171

37. Pascual-Leone A, Nguyet D, Cohen LG et al. Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *J Neurophysiol* 1995;74:1037-1045

38. Ziemann U, Mullbacher W, Hallet M et al. Modulation of practice-dependent plasticity in human motor cortex. *Brain* 2001;124:1171-1181

39. Svensson P, Romaniello A, Wang K et al. One hour of tongue-task training is associated with plasticity in corticomotor control of the human tongue musculature. *Exp Brain Res* 2006;173:165-173

40. Koeneke S, Lutz K, Herwig U et al. Extensive training of elementary finger tapping movements changes the pattern of motor cortex excitability. *Exp Brain Res* 2006;174:199-209

41. Monfils MH, Teskey GC. Skilled-learning-induced potentiation in rat sensorimotor cortex: a transient form of behavioural long-term potentiation. *Neuroscience* 2004;125:329-336

42. Rioult-Pedotti MS, Friedmann D, Hess G et al. Strengthening of horizontal connections following skill learning. *Nat Neurosci* 1998;3:230-234

43. Kleim JA, Barbay S, Cooper NR et al. Motor learning-dependent synaptogensis is localized to functionally reorganized motor cortex. *Neurobiol Learn Memory* 2002;77:63-77

44. Mullebacher W, Ziemann U, Boroojerdi B et al. Role of the human motor cortex in rapid motor learning. *Exp Brain Res* 2001;136:431-438

45. Kleim JA, Barbay S, Nudo RJ. Functional reorganization of the rat motor cortex following motor skill learning. *J Neurophysiol* 1988;80:3321-3325

FIGURE LEGENDS

Figure 1. A. disposable bipolar surface electrodes for detection of deep cervical flexor (longus colli and longus capitis) EMG activity. B. Using a nasopharyngeal application, surface electrodes, attached to a catheter, are positioned over the posterior oropharyngeal wall. The deep cervical flexor muscles lie directly posterior to the oropharyngeal wall. C. Motion characteristics of the cranio-cervical flexion task and exercise protocol. The figure shows the starting position (left) and end range cranio-cervical flexion position (right) of the exercise. The cranio-cervical flexion action involves a nodding 'yes' movement of the head such that it remains in contact with the supporting surface, flexion motion occurring predominantly about the upper cervical motion segments.

Figure 2. Normalized root mean square (RMS) values (mean and standard deviation) for the deep cervical flexor muscles for each stage of the cranio-cervical flexion task pre and post intervention. * indicates significant difference between pre and post intervention data ($P < 0.05$).

Figure 3. Representative raw EMG data for the deep cervical flexor (DCF) obtained both pre and post training for two representative patients. (A) In this example note the similar amount of DCF muscle activation post training compared to baseline values. (B) In this representative example the patient shows lower amplitude of DCF activity relative to the head lift at baseline and a much greater increase in EMG amplitude relative to the head lift post training.

Figure 4. (A) Scatter plot of pre-training normalized deep cervical flexor (DCF) root mean square (RMS) values and the percentage change in DCF RMS values post training. (B) Scatter plot of post-training normalized DCF RMS (averaged over 28 and 30 mmHg only) and change in average neck pain intensity rated on a visual analogue scale (VAS) post training.

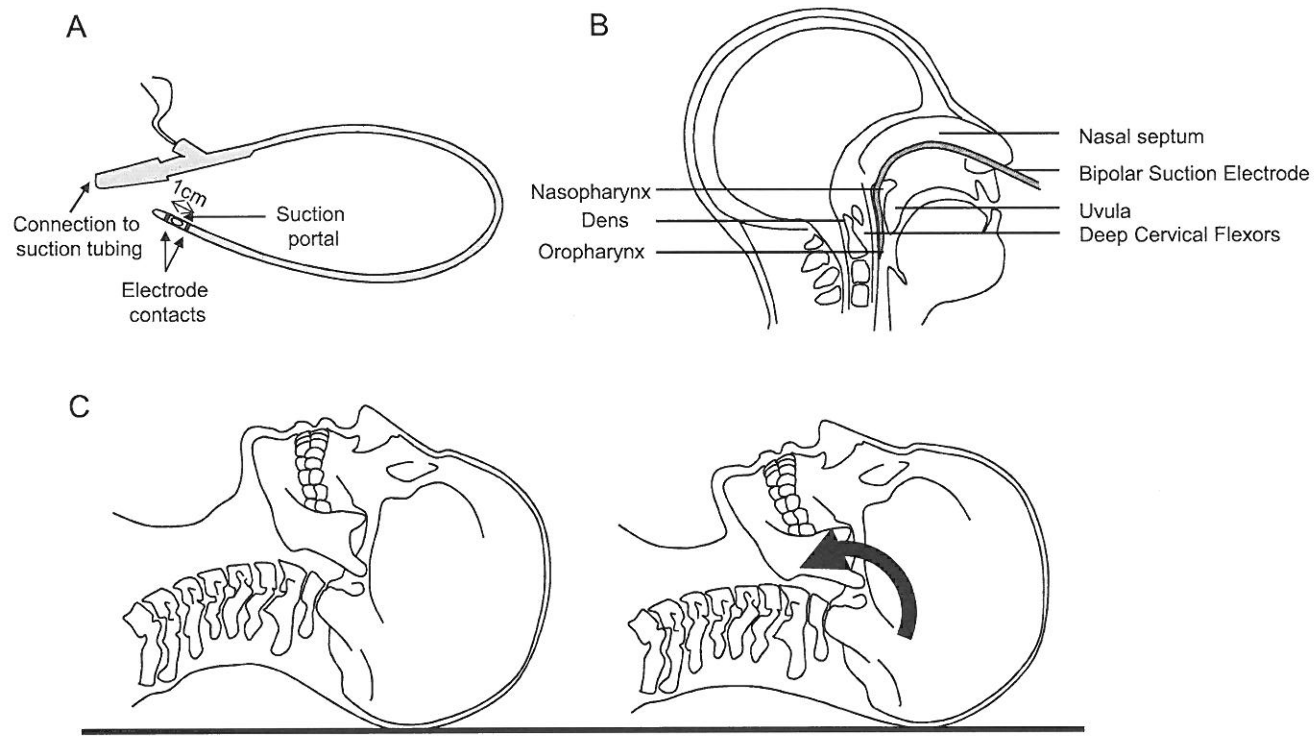
A
Connection to suction tubing
1cm
Suction portal
Electrode contacts
B
Nasal septum
Bipolar Suction Electrode
Nasopharynx
Dens
Oropharynx
Uvula
Deep Cervical Flexors
C

Figure 1

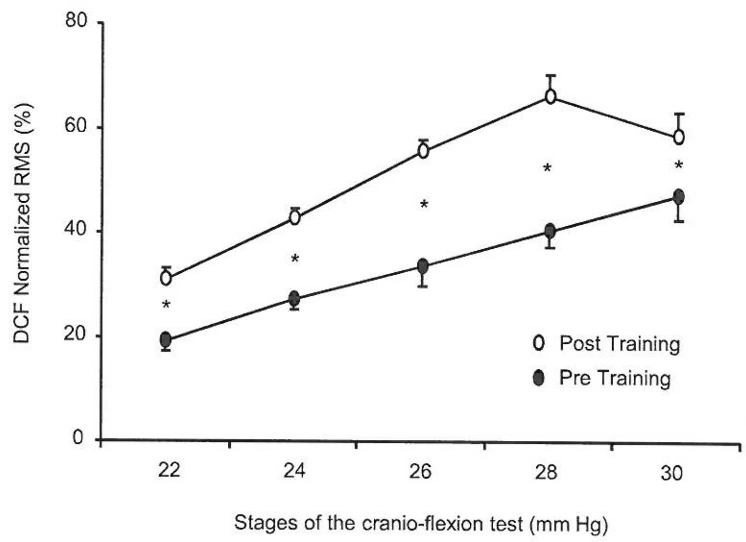
80
60
40
20
0
DCF Normalized RMS (%)
22
24
26
28
30
Stages of the cranio-flexion test (mm Hg)
Post Training
Pre Training
*

Figure 2

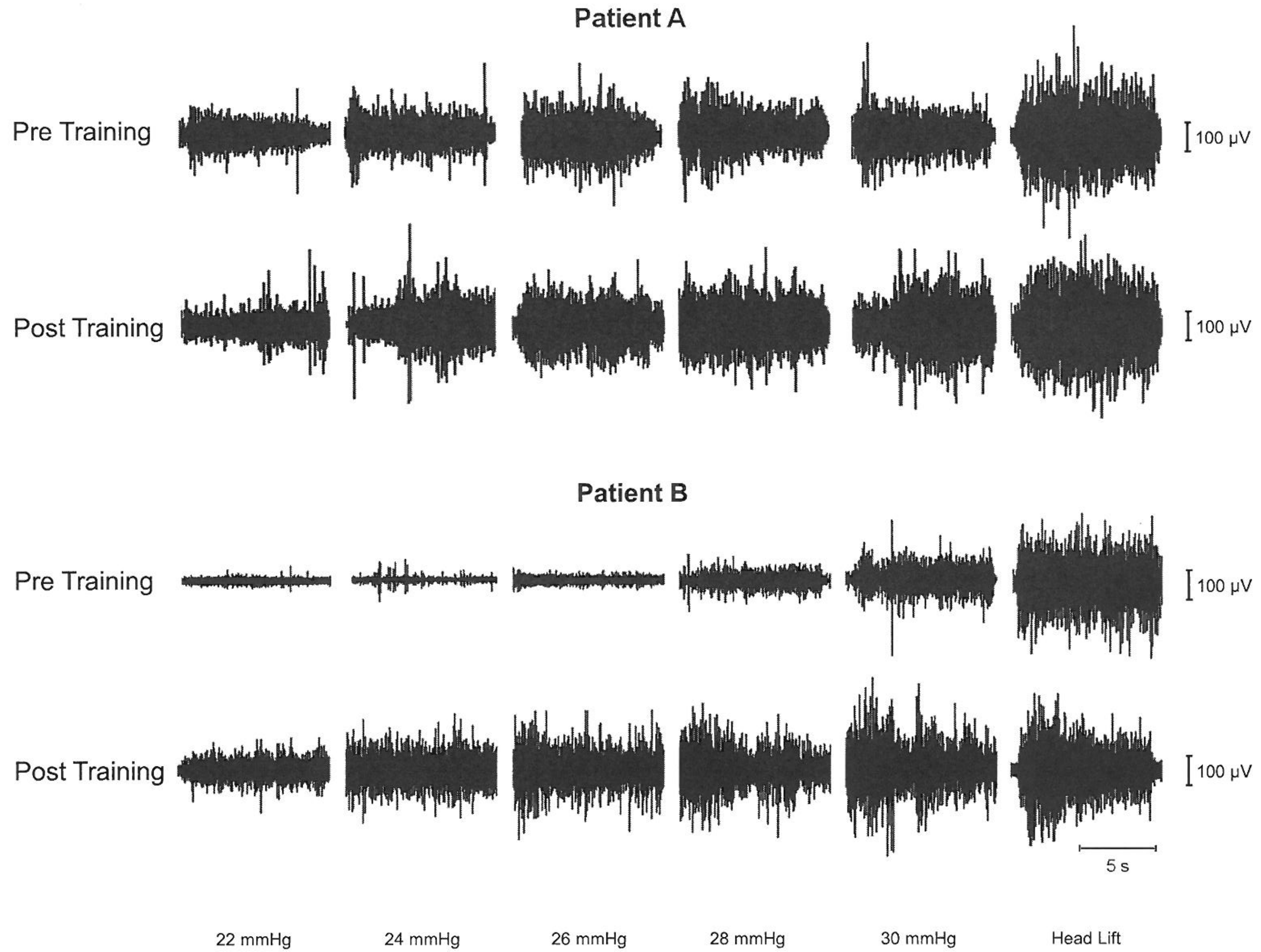
Patient A
Pre Training
100 µV
Post Training
100 µV
Patient B
Pre Training
100 µV
Post Training
100 µV
5 s
22 mmHg
24 mmHg
26 mmHg
28 mmHg
30 mmHg
Head Lift

Figure 3

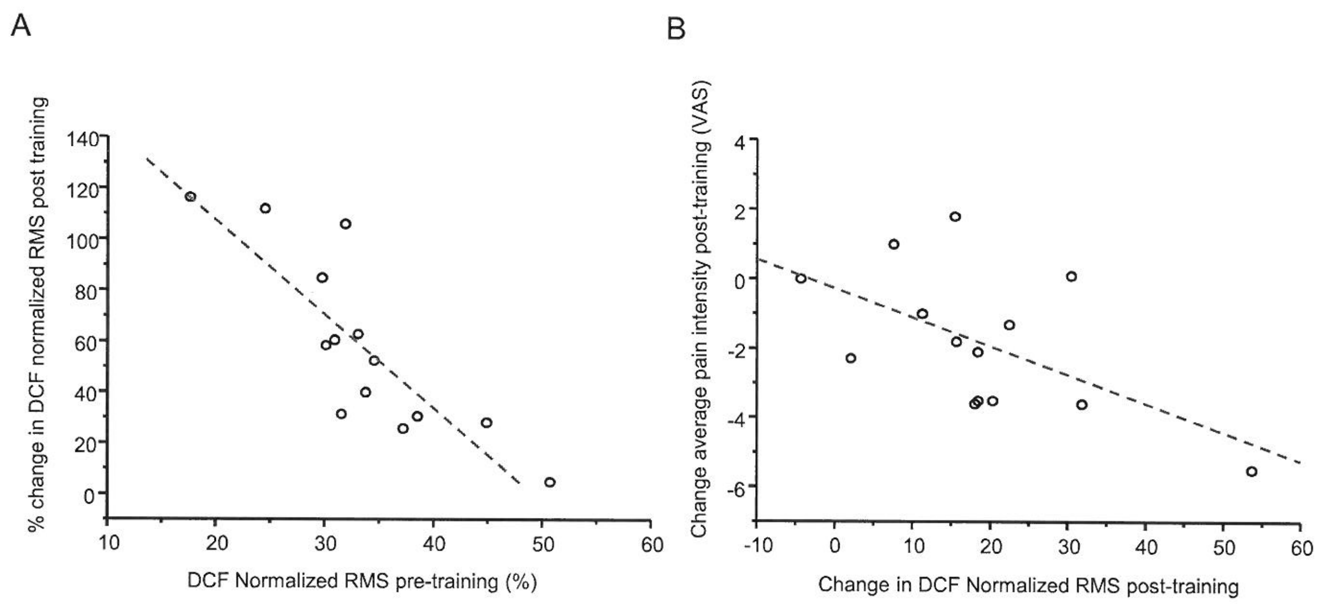
A
% change in DCF normalized RMS post training
140
120
100
80
60
40
20
0
10
20
30
40
50
60
DCF Normalized RMS pre-training (%)
B
Change average pain intensity post-training (VAS)
4
2
0
-2
-4
-6
-10
0
10
20
30
40
50
60
Change in DCF Normalized RMS post-training

Figure 4