Reliability of a Method to Measure Neck Surface Electromyography, Kinematics, and Pain Occurrence in Participants With Neck Pain

Ion Lascurain-Aguirrebeña, MSc,[a,b] Di J. Newham, PhD,[c] Jon Irazusta, PhD,[b] Jesús Seco, PhD,[d] and Duncan J. Critchley, PhD[e]

Abstract

Objective: To investigate the reliability of a novel method to measure neck surface electromyography (SEMG), kinematics, and pain during active movements in participants with neck pain.

Methods: This test-retest study evaluated 23 participants with chronic neck pain. Each was measured twice within a single session. Three-dimensional kinematics and SEMG were recorded in 10° increments during forward and side flexion, extension, and rotation of the neck. Neck position during pain occurrence was also measured.

Results: Intraclass correlation coefficients were >0.80 for 96% and 100% of SEMG and kinematic data, respectively. The percentage of standard error of the measurement (SEM) values were <25% for 91% of all SEMG measures; most were <15%, and some were <10%. For ranges of motion in the primary plane, percentage of SEM values were all <6% (SEM 1°-3°). Intraclass correlation coefficients for neck position during pain occurrence were all >0.60, except for right rotation (0.48) (SEM values 2°-8°). Pain occurred approximately 59% to 75% into the total range of motion and persisted to its end.

Conclusions: This methodology showed good reliability. It may be suitable for neck pain subclassification to evaluate the effects of treatment on pain, kinematics, and muscle activity during functional neck movements. The point of pain occurrence suggests increasing mechanical load on tissues may be one of the causative factors for movement-associated neck pain. (J Manipulative Physiol Ther 2018;41:413-424)

Key Indexing Terms: *Neck Pain; Electromyography; Movement*

[a] School of Population Sciences and Health Services Research, King's College London, London, United Kingdom.
[b] Department of Physiology, University of the Basque Country, Leioa, Spain.
[c] Centre of Human & Aerospace Physiological Sciences, King's College London, London, United Kingdom.
[d] Institute of Biomedicine (IBIOMED), University of León, León, Spain.
[e] School of Population Sciences and Health Services Research, King's College London, London, United Kingdom.
Corresponding author: Ion Lascurain-Aguirrebeña, MSc, Department of Physiology, University of the Basque Country, Barrio Sarriena s/n 48940, Leioa, Spain. Tel.: +34 664094455. (e-mail: Ion.lascurain@ehu.eus).
Paper submitted February 21, 2017; in revised form August 11, 2017; accepted October 19, 2017.
0161-4754

https://doi.org/10.1016/j.jmpt.2017.10.013

Introduction

Neck pain is widespread with a point prevalence of 14% and a 1-year prevalence of 26%.[1] Chronicity and recurrence are common; 37% of individuals with neck pain continue to experience neck pain 1 year after a first episode, and 22% experience recurrent episodes.[2,3] It is the fourth greatest contributor to global disability.[4]

Neck pain is associated with altered neck muscle activity[5,6] and impaired neck kinematics.[7,8] Successful management strategies incorporate various types of neck muscle and movement retraining and restoration; however, the optimum type and dose is poorly understood.[9] Greater knowledge of muscle and kinematic neck function in those with and without pain is required to understand the etiology of neck pain and develop more effective treatments. To date, neck surface electromyography (SEMG) in people with neck pain has been largely recorded during isometric contractions,[10-12] keyboard work,[13-15] the craniocervical flexion test,[16-18] balance tasks or postural perturbations,[19-21] and the test of the flexion-relaxation phenomenon.[22-24]

Few studies have assessed muscle activity during functional neck movements (ie, flexion-extension, side flexion and rotation), which are often associated with symptom occurrence. Analysis has been limited to 1 or 2 movement planes, and only the average muscle activity for the entire range of motion (ROM) has been measured.[22,25,26] However, studies on the directional specificity of neck muscles have demonstrated that activity is modulated for better biomechanical efficiency according to the position of the neck within the ROM[27-29]; therefore, different muscle activation levels may be expected in different parts of the range. Hence, the assessment of the average activity in the entire movement may not detect or reflect muscle dysfunction in people with neck pain. There is a need for a method that reliably assesses neck SEMG in discrete sections of the entire ROM.

Previous studies of neck kinematics have had participants either seated or with movement constrained by inclinometers or electromagnetic devices.[30-32] Flexible measurement methods that allow the free movement of the participant are required. Understanding of neck pain etiology and the development of more effective treatments requires better knowledge of neck symptoms, and, as far as we are aware, no study has previously assessed the point in the ROM at which pain occurs.

A tool for the reliable measurement of neck kinematics, SEMG, and pain occurrence during unconstrained movements of the neck throughout full available ROM is needed. Technical errors, learning effect, and biological variance can all contribute to measurement error,[33] and for any new measures to be meaningful, they must demonstrate sufficient consistency so that any differences or changes in the measures may be interpreted as real findings.[34] Once reliability is established, these measures may be used to track rehabilitation progress, assess the relevance of different causative factors, or assess the effectiveness of different therapeutic interventions for neck pain.

The aim of this study was to investigate the within-session reliability of a novel method to measure neck kinematics, pain occurrence during neck movement, and SEMG in each part of the ROM during all active physiological neck movements (frontal, sagittal, and transverse planes) in participants with chronic neck pain.

Methods

The study received the approval of the University of the Basque Country Research Ethics Committee (CEISH/243R/2014). Written informed consent was obtained from all participants.

Participants

Participants with chronic neck pain of >3 months' duration with no identifiable etiology were recruited from an outpatient clinic and posters placed in the area. Potential participants were excluded if they had previous cervical spine surgery, neurologic symptoms, participated in a neck exercise program in the past 12 months, or received any form of manual therapy in the 2 months prior to testing.[35]

Kinematics

A 10-camera Vicon motion capture system (Vicon Motion Systems Ltd, Oxford, United Kingdom) was used to capture 3-dimensional motion of the participant's head and thorax. Reflective markers (14 mm diameter) were attached with double-sided adhesive tape to the bridge of the nose, chin midpoint, right and left tragus, xiphoid process, suprasternal notch, external occipital protuberance, and spinous processes of the first and eighth thoracic vertebrae (Fig 1). To avoid jaw movements registering as head movements, a virtual chin midpoint marker was generated based on the position of this marker relative to the bridge of the nose and both tragus markers during a static recording. The same method was applied for the external occipital protuberance to avoid hair interfering with the markers. Local coordinate systems for the head and thorax were defined according to Koerhuis et al[36] and Guo et al,[37] with the exception of use of the spinous process of the first thoracic vertebra instead of the seventh cervical vertebra to reduce the effect of skin movement during flexion and extension. A further marker was placed on the left thumb, which participants were asked to raise when pain occurred during neck movements and to lower when pain disappeared. Motion was captured at a sampling rate of 100 Hz. All kinematic data were filtered with a fourth-order low-pass filter with a cutoff frequency of 6 Hz.[38]

Electromyography

A Myon 320 wireless system (Myon AG, Schwarzenberg, Switzerland) was used to collect SEMG data. With the participant seated upright, skin was lightly abraded and swabbed with alcohol,[39] and 25 × 25 mm silver or silver chloride electrodes (Biopac Systems Inc, Goleta, California) were applied bilaterally over the sternocleidomastoid (SCM), scalene, upper trapezius (UT), and erector spinae (ES) muscles (Fig 1). An interelectrode distance of 20 mm was used with the aim of obtaining a relatively large SEMG signal and a high signal-to-noise ratio.[40]

Sternocleidomastoid electrodes were placed adjacent to a point 30% of the distance from the sternal notch to the mastoid process and over the muscle belly of the sternal head. Scalene electrodes were placed parallel to the direction of the muscle fibers running to the lateral border of the clavicular portion of the muscle. These locations have good SEMG repeatability[41] and offer the best signal quality, being away from both the innervation zone and tendon.[42] For UT, electrodes were placed midway between C6 spinous process and the lateral acromion, on the anterior

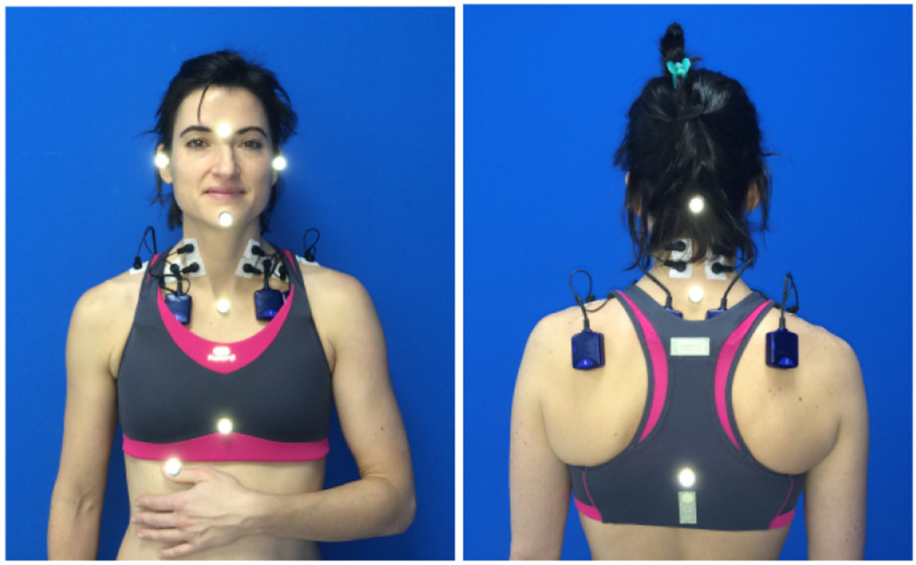

Fig 1. *Placement of reflective markers and surface electromyography electrodes.*

border of the muscle bulk.[43] Erector spinae electrodes were placed 2 cm lateral to the C4 to C5 spinous processes.[22,44]

Signals were differentially amplified at the transmitter (common mode rejection 110 dB, input impedance 100 MΩ, gain ±1.25 mV), and filtered with a 30 Hz high-pass[45,46] and 450 Hz low pass[39,47] fourth-order Butterworth filter. Electromyography signals were then full-wave rectified[21,46] and smoothed using a 20 ms linear envelope.[48] Surface electromyography and kinematic data were synchronized through a Giganet using Nexus 2 software (Vicon Motion Systems Ltd).

Procedure

Age, sex, height and body mass, handedness, and area of symptoms were recorded using a body chart, and participants were asked to complete the Neck Disability Index questionnaire.[49] The Neck Disability Index is the most commonly used, reliable, and validated self-report instrument to evaluate neck disability.[50] It consists of 10 questions, with total scores of 0 to 50, in which higher scores represent greater disability.[51]

Following electrode and marker placement, participants performed 4 repetitions each of neck left and right rotation, extension, flexion, and left and right side flexion movements, as far as they felt able, at their usual speed, in random order while standing still. All movements were repeated after a 20-minute rest period. Submaximal isometric contractions were used for SEMG normalization to reduce the possible confounding effects of pain and fear of movement and the risk of injury.[14,52,53] For SCM, SA, and ES, the participants sat with their back fully supported and secured with a strap around the thorax to avoid compensatory movements. They were asked to perform neck flexion, extension, side flexion right,

Table 1. *Participant Characteristics*

Variable	Mean ± SD [a]
Age (y)	46 ± 12
Height (m)	1.64 ± 8
Weight (kg)	64 ± 12
Sex (M/F)	4/19
Handedness (R/L)	23/0
Duration of neck pain (y)	9 ± 8
NDI score	12 ± 6
Area of pain (bilateral/right/left)	13/9/1

F, female; *L*, left; *M*, male; *NDI*, Neck Disability Index; *R*, right; *SD*, standard deviation.
[a] Values are mean ± SD unless stated otherwise.

and side flexion left isometric contractions equivalent to a force of 30 N, measured with a hand-held dynamometer (Lafayette Instrument Co, Lafayette, Indiana) that resisted movement. For UT, they were asked to maintain a 90° bilateral arm abduction position. All contractions were maintained for 5 seconds and repeated 3 times with 10 seconds of rest between trials.[54]

Data Analysis

The second to fourth movement repetitions were used for analysis. The smoothed and rectified SEMG signal (SRE) obtained during neck movements was expressed as a percentage SRE of the average signal obtained during the

Table 2. *Pain During Neck Movement*

	Flexion	Extension	R Rotation	L Rotation	R SF	L SF
Participants with pain during movement (%)	9	30	39	26	35	43
Point of pain during movement (degrees), mean ± SD	29 ± 15	33 ± 21	42 ± 10	34 ± 18	27 ± 13	24 ± 10
Point of pain during movement (% of total ROM), mean ± SD	67 ± 1	72 ± 32	73 ± 13	65 ± 32	80 ± 24	72 ± 23

Values are mean ± SD.
L, left; *R*, right; *ROM*, range of motion; *SF*, side flexion; *SD*, standard deviation.

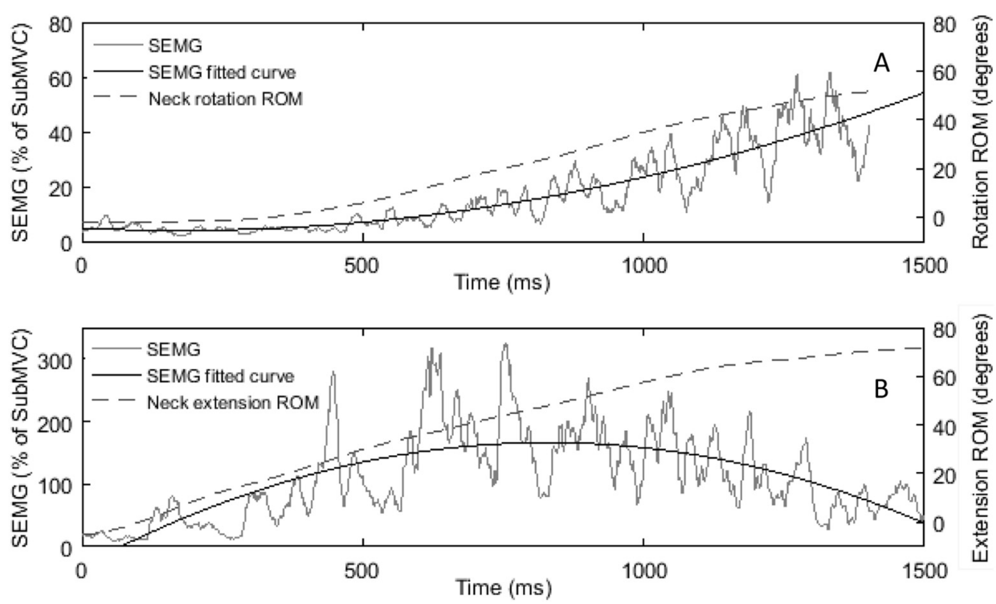

Fig 2. *Neck ROM and left sternocleidomastoid SEMG during right rotation (A) and extension (B). A curve has been fitted to SEMG data.* ROM, *range of motion;* SEMG, *surface electromyography;* SubMVC, *submaximal voluntary contraction.*

submaximal normalization contractions.[55] Average percentage SRE was then calculated for each 10° section of each movement (0°-10°, 10°-20°, etc). Maximum ROM values in each movement plane (transverse, frontal, and sagittal) and neck position during pain occurrence were also calculated. Processing was performed with a custom-written program in MATLAB software (MathWorks, Natick, Massachusetts).

To assess reliability the intraclass correlation coefficient (ICC), standard error of the measurement (SEM), and percentage SEM (%SEM) values were calculated for each measure. When the aim of the measurement is to assess the differences between participants, reliability can be established by measuring the ratio of the between-participant versus the within-participant variance. This ratio can be expressed with an ICC, where a high ICC (≈1) denotes a small within-participant variance relative to the between-participant variance.[56] Intraclass correlation coefficient values were interpreted as poor (<0.20), fair (0.21-0.40), moderate (0.41-0.60), good (0.61-0.80), and very good (0.81-1.00).[57]

The SEM is the most appropriate statistic to assess the precision and absolute error of a measurement.[33] It is a measure of the typical error or variation of recorded values between measurements and allows the calculation of a confidence interval about which a value is expected to vary.[58,59] The SEM is especially useful to determine if observed preintervention to postintervention differences are larger than the measurement error.[59] The SEM is defined as the standard deviation multiplied by the square root of 1 minus the ICC.[57] To better interpret the magnitude and importance of the error and allow comparison with other measurements, the SEM can be expressed as a percentage of the grand mean (%SEM).[60] However, where the mean is close to 0, %SEM has the disadvantage of giving large values; therefore, its use in conjunction with the SEM is recommended.[59] A specific threshold for a %SEM value that denotes good reliability is yet to be agreed upon, but a %SEM of <25% in conjunction with a high ICC has been suggested to demonstrate good to excellent reliability.[46]

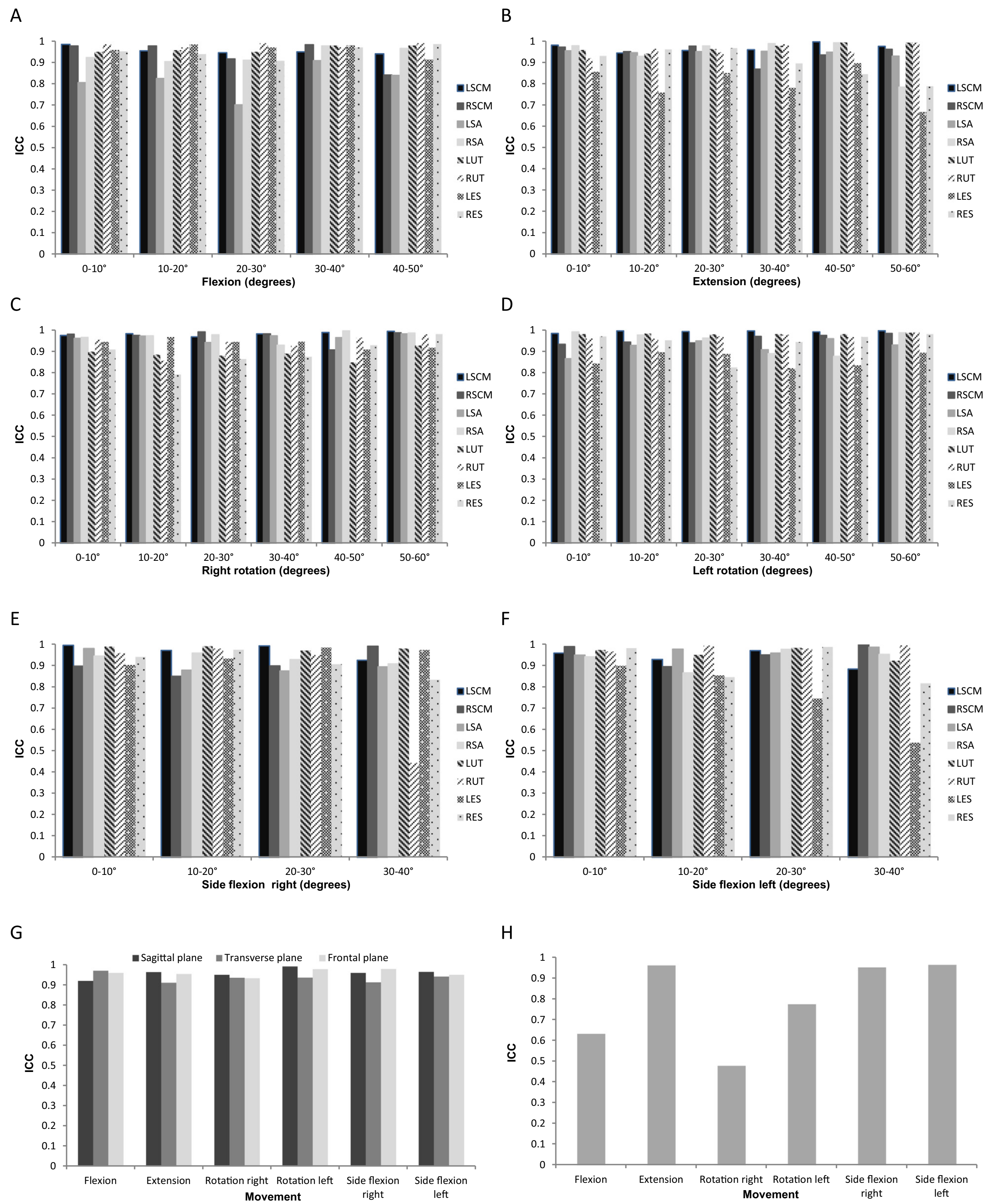

Fig 3. *Intraclass correlation coefficient for SEMG (A, B, C, D, E, F), ROM (G), and neck position during pain occurrence (H).* ICC, *intraclass correlation coefficient;* LES, *left erector spinae;* LSA, *left scalene;* LSCM, *left sternocleidomastoid;* LUT, *left upper trapezius;* RES, *right erector spinae;* ROM, *range of motion;* RSA, *right scalene;* RSCM, *right sternocleidomastoid;* RUT, *right upper trapezius;* SEMG, *surface electromyography.*

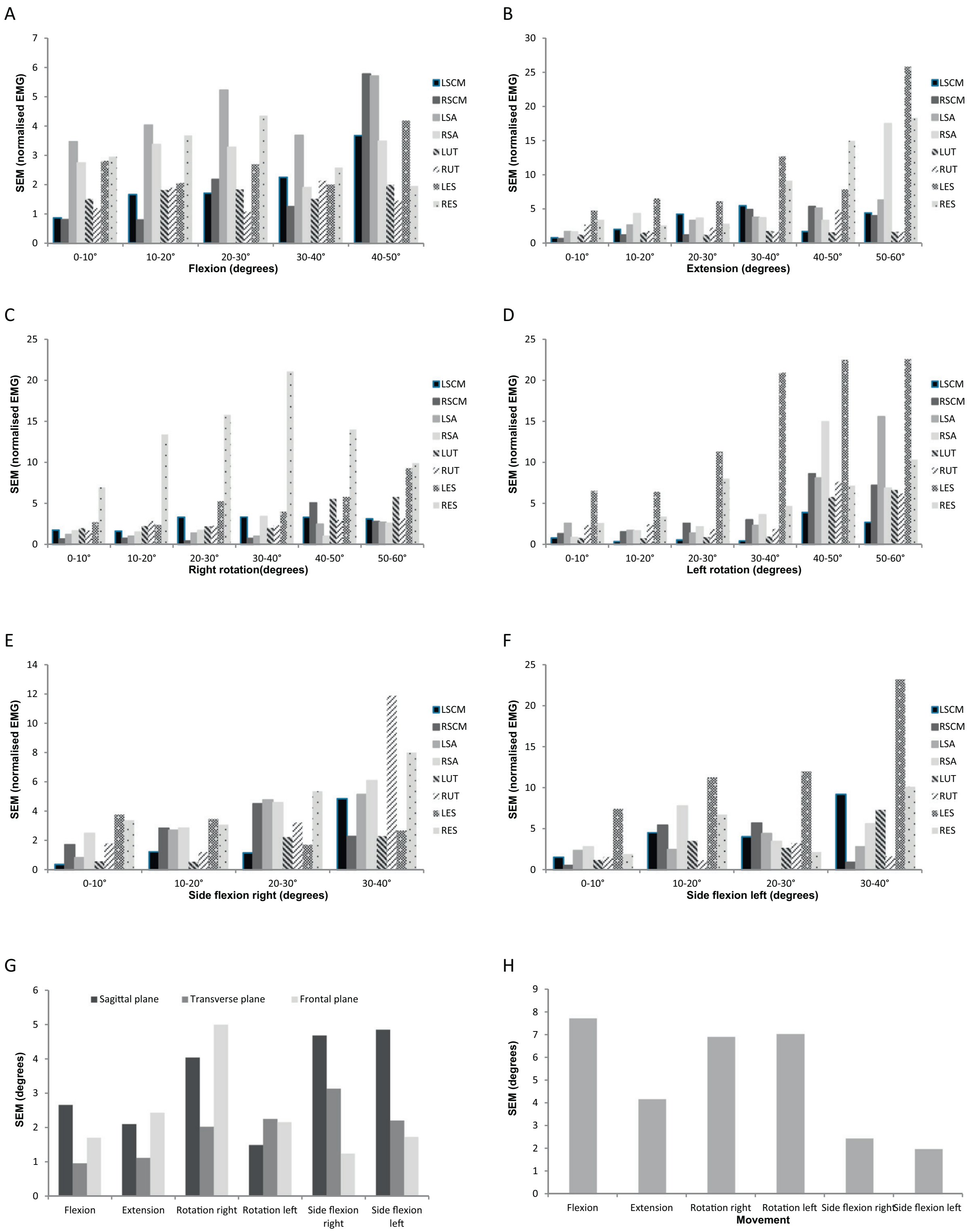

Fig 4. *Standard error of the measurement for SEMG (A, B, C, D, E, F) (normalized SEMG), ROM (G) (degrees), and neck position during pain occurrence (H) (degrees).* EMG, *electromyography;* LES, *left erector spinae;* LSA, *left scalene;* LSCM, *left sternocleidomastoid;* LUT, *left upper trapezius;* RES, *right erector spinae;* ROM, *range of motion;* RSA, *right scalene;* RSCM, *right sternocleidomastoid;* RUT, *right upper trapezius;* SEM, *standard error of measurement;* SEMG, *surface electromyography.*

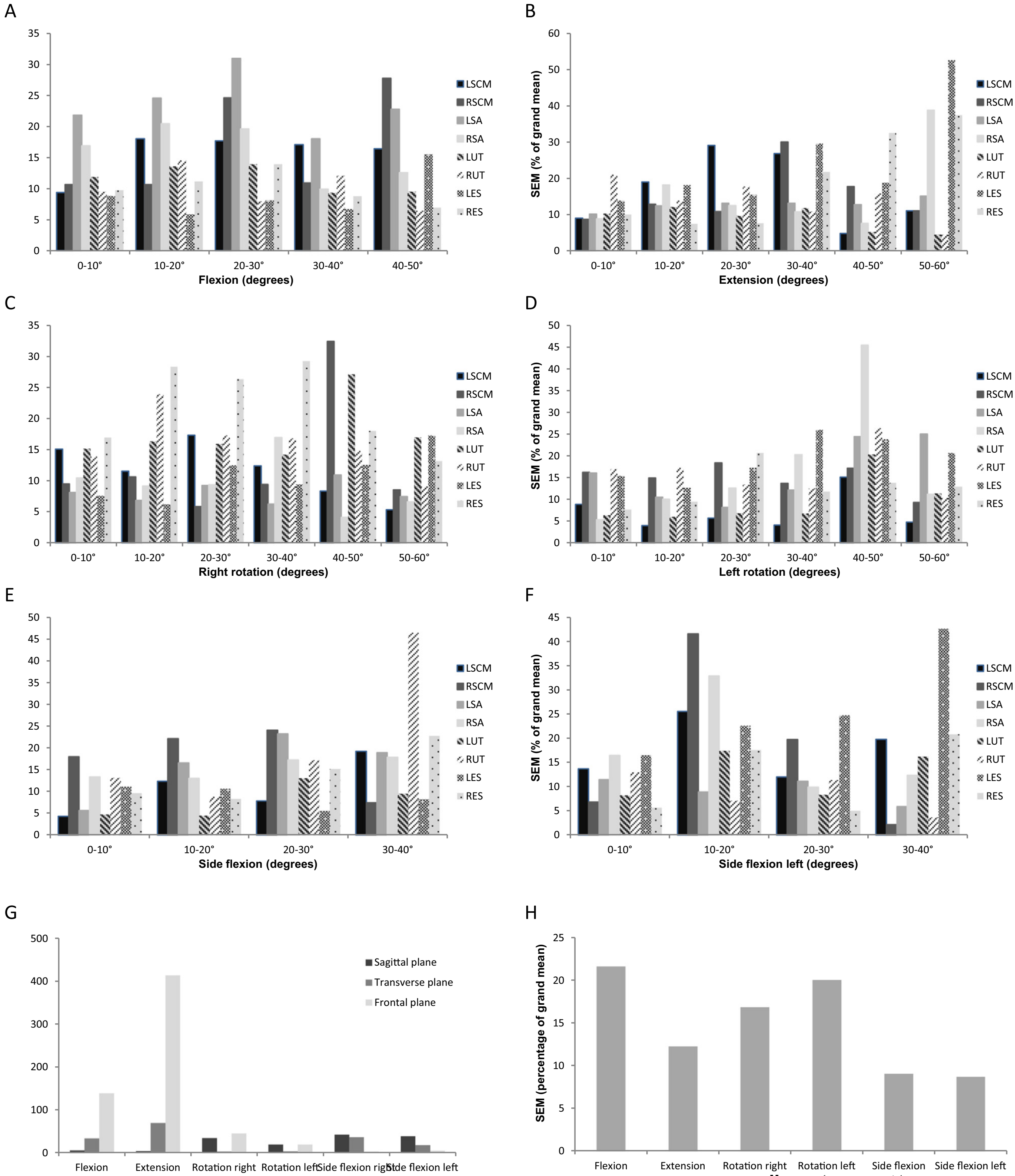

Fig 5. *Standard error of the measurement (% of grand mean), for SEMG (A, B, C, D, E, F), ROM (G), and neck position during pain occurrence (H).* LES, *left erector spinae;* LSA, *left scalene;* LSCM, *left sternocleidomastoid;* LUT, *left upper trapezius;* RES, *right erector spinae;* ROM, *range of motion;* RSA, *right scalene;* RSCM, *right sternocleidomastoid;* RUT, *right upper trapezius;* SEM, *standard error of measurement;* SEMG, *surface electromyography.*

Results

Twenty-three participants took part in the study; their characteristics are shown in Table 1. The mean (standard deviation) ROM was 46 (10°) and 47 (11°) for flexion and extension, 56 (8°) and 57 (9°) for right and left rotation, and 35 (9°) and 31 (8°) for right and left side flexion, respectively. Sixty-one percent of participants had pain during at least 1 neck movement. Table 2 shows the percentage of participants in the neck pain group who reported pain during each movement and the point in the ROM at which it occurred; in all participants, pain continued to the end of the ROM.

Figure 2 shows SEMG of the left SCM during right rotation and extension in a participant, representative of the SEMG and movement patterns observed in the study. Left SCMs demonstrated increasing SEMG through the ROM of rotation, showing a 10-fold increase in SEMG at the end of ROM (Fig 2A). In contrast, greatest activity of the left SCM was observed at midrange during extension, with similar levels of activity at the beginning and end of ROM (Fig 2B). Intraclass correlation coefficient, SEM, and %SEM values for SEMG, ROM, and pain occurrence are shown in Figures 2 to 4, respectively. Ninety-six percent of all SEMG ICCs were above 0.80, and only 1% (2 measures) were below 0.6 (right UT activity during 30°-40° right side flexion and left ES activity during 30°-40° left side flexion had only 6 and 3 cases, respectively, because most participants did not reach 40° of side flexion). All ROM ICCs were >0.90, whereas for neck position during pain occurrence, 3 out of 6 measures were >0.90, 2 were between 0.60 and 0.80, and 1 was <0.60. Ninety-one percent of all SEMG measures demonstrated %SEM values <25%, and 53% and 33% of SEMG measures had %SEM values of <15% and 10%, respectively (Fig 5).

No specific movements or muscles were identified as having superior reliability, although it is of note that for the 30° to 60° extension range, 4 out of 6 ES measures had %SEM values >25%. For ROM taking place in the primary movement plane of flexion extension (sagittal), rotation (transverse) and side flexion (frontal), %SEM were all <6% (SEM ranging 1°-3°). For other movement planes, %SEM was 18% to 414%; although SEM was low (1°-5°).

Intraclass correlation coefficients varied for neck position during pain occurrence; they were above 0.90 for extension and both-side flexions and 0.63, 0.48, and 0.77 for flexion, right rotation, and left rotation, respectively. Standard error of the measurement for neck position during pain occurrence was 8° and 4° for flexion and extension, 2° for left and right-side flexion, and 7° for left and right rotation (%SEM 9-22).

Discussion

This novel method of simultaneously recording 3-dimensional kinematics and neck muscle SEMG in 10° increments and neck position at pain onset has good reliability for all 3 measures. Ninety-six percent of SEMG measures had ICC values >0.80, which denotes very good reliability. Two measures had ICCs <0.61, indicating moderate reliability; however, in these, the number of values was small (3 and 6), making ICCs susceptible to a single participant's data. Ninety-one percent of SEMG measures had a %SEM lower than the 25% threshold, 53% had <15%, and 33% <10%; in conjunction with the observed high ICCs, these findings support the present methodology as being reliable for the assessment of neck SEMG during neck movements.

Muscle activity was modulated by neck position, supporting the need to analyze SEMG in discrete sections of the ROM. The method used previously,[25,26] in which an average SEMG for the entire movement was reported, was a less complete representation of muscle function during neck movements and therefore less helpful to unravel the complexities of muscle dysfunction in neck pain and the effect of therapeutic interventions on neck dysfunction.

Intraclass correlation coefficients for SEMG are similar to those reported previously for isometric neck contractions[61] and the craniocervical flexion test.[62,63] The %SEM for SCM has been reported as 2 to 5 during the craniocervical flexion test,[62,63] which is lower than in this study; however, that test involves a small neck movement compared to the full-range movements reported here. Other studies investigated reliability of neck SEMG during isometric contractions[41] and the craniocervical flexion test[64]; however, they used the standard error of the mean rather than the SEM to assess measurement precision. Therefore comparison is not possible.

All ICCs for neck ROM were >0.9, indicating very good reliability, and SEM in the primary movement planes were low, all <4°. Although the %SEM for other movement planes was often >25, this was a result of the small magnitude of the grand means because SEM values were low, ranging 1° to 5°. Intraclass correlation coefficients for ROM obtained in this study are in line with those previously reported for measurement with a Cybex electronic digital inclinometer[30] and the cervical ROM device (Performance Attainment Associates, Roseville, Minnesota)[31] and higher than those reported when measuring with a Flock of Birds system of motion analysis and standard inclinometers (Ascension Technology Corp, Burlington, Vermont).[32] This suggests equal or better reliability than with the methodologies reported previously. Our methodology allows the free, unconstrained movement of the participant and the measurement of movement in secondary movement planes, which was not measured with these devices.

To our knowledge, this is the first study that has assessed neck position during pain occurrence. Sixty-one percent of participants reported pain during at least 1 neck movement, demonstrating the importance of the movements assessed in the current study. All movements, except right rotation (moderate reliability), showed good to very good reliability (ICCs 0.63-0.96) with SEMs of only 2° to 8°. Pain occurred at a point equivalent to 65% to 80% of the total ROM and, in all cases, persisted to the end of the range. No participant reported only midrange pain. The increasing mechanical load on tissues as the neck approaches the end of ROM may be a causative factor for movement-associated neck pain. Patients with neck pain may show greater loading of spinal tissues; increased activity of neck muscles, and hence greater loading, has already been reported in participants with neck pain during resisted contractions,[28] the craniocervical flexion test,[17] and the test of the flexion-relaxation phenomenon.[23]

This novel method has shown high reliability for the measurement of SEMG, kinematics, and neck position during pain occurrence, as evidenced by the high ICCs and low SEMs and %SEMs. The former indicates that within-participant variability is low compared with between-participant variability and may be confidently used for comparison between participants. Higher ICCs reduce the risk of type 2 error.[65] Standard error of the measurement data as provided in this study should be used to determine the minimal difference between 2 measures of a single participant that can be considered a real difference (ie, minimal detectable change), which indicates the degree (interval) to which scores fluctuate in the absence of actual change. The proposed method may be used to help the study of the subclassification of patients with neck pain according to their muscle dysfunction, the occurrence of pain at specific points in the ROM, or the effects of treatment techniques on neck pain occurrence and neck muscle activity during functional movements. This method is sensitive to dysfunctions occurring only in some parts of the ROM and allows the accurate measurement of specific parts of the ROM, where the intervention may be targeted. The relationship between pain occurrence and muscle activity at those specific points in the ROM may also be explored.

Two electrode positions for UT have been described previously. Several groups have used a line between the spinous process of C7 and the acromion[55,66,67]; however, a cadaveric study by Mercer[68] revealed that this location records the activity of middle, rather than upper, fibers. Consequently, Wegner et al[43] proposed placing the electrodes midway between C6 spinous process and the lateral acromion, as used in this study.

Limitations

Surface electromyography signals were high-pass filtered with a 30 Hz filter, as recommended by Drake and Callaghan[45] and Schinkel-Ivy et al[46] for the removal of movement artifact and electrocardiographic contamination. This may have removed or attenuated some low-frequency SEMG signal, but after testing with 10 to 30 Hz filters, this frequency offered the best compromise, reducing artifact while minimizing the removal of the SEMG signal.

Speed of movement was not controlled, and it is possible that subtle differences in speed between test and retest movements may have existed, thus affecting reliability because neck SEMG has been shown to correlate with movement speed.[69] Although the point at which participants lifted their thumb to report pain during neck movement showed good reliability, it is possible that there was a delay between the participant experiencing neck pain and moving the thumb, which may have underestimated the proportion of the ROM that was painful.

Conclusion

Muscle activity is modulated by the position of the neck in the ROM; therefore, neck muscle SEMG should be analyzed in relation to the position of the neck during movement. The novel method described here has high reliability for the measurement of neck kinematics, SEMG, and point of pain occurrence in the ROM, as evidenced by the high ICCs, low SEMs, and %SEMs. The reported SEM and %SEM values should be used in the future to interpret differences between participants or changes secondary to interventions. The point of pain occurrence suggests that increasing mechanical load on tissues as the neck advances closer to the end of ROM may be one of the causative factors for movement-associated neck pain. Further research is required to assess whether the presence of movement-associated pain and its location in the range is associated with impaired neck kinematics and neck muscle activity.

Acknowledgments

The authors acknowledge Professor Roger Woledge for his assistance with data analysis.

Funding Sources and Conflicts of Interest

Ion Lascurain-Aguirrebeña received a grant from the University of the Basque Country. No conflicts of interest were reported for this study.

Contributorship Information

Concept development (provided idea for the research): I.L.-A., D.J.N., J.I., J.S., D.J.C.
Design (planned the methods to generate the results): I.L.-A., D.J.N., J.I., J.S., D.J.C.
Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): I.L.-A., D.J.N., J.I., J.S., D.J.C.
Data collection/processing (responsible for experiments, patient management, organization, or reporting data): I.L.-A., D.J.N., J.I., J.S., D.J.C.
Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): I.L.-A., D.J.N., J.I., J.S., D.J.C.

Literature search (performed the literature search): I.L.-A., D.J.N., J.I., J.S., D.J.C.
Writing (responsible for writing a substantive part of the manuscript): I.L.-A., D.J.N., J.I., J.S., D.J.C.
Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): I.L.-A., D.J.N., J.I., J.S., D.J.C.

Practical Applications

- Muscle activity is modulated by the position of the neck in the ROM; hence, neck muscle SEMG should be analyzed in relation to the position of the neck during movement.
- The novel method described here has high reliability for the measurement of neck kinematics, SEMG, and point of pain occurrence in the ROM.
- The point of pain occurrence suggests that increasing mechanical load on tissues as the neck advances closer to the end of ROM may be one of the causative factors for movement-associated neck pain.

References

1. Hoy DG, Protani M, De R, Buchbinder R. The epidemiology of neck pain. *Best Pract Res Clin Rheumatol.* 2010;24: 783-792.
2. Côté P, Cassidy D, Carroll L, Kristman V. The annual incidence and course of neck pain in the general population: a population-based cohort study. *Pain.* 2004;112:267-273.
3. Vasseljen O, Woodhouse A, Bjorngaard JH, Leivseth L. Natural course of acute neck and low back pain in the general population: the HUNT study. *Pain.* 2013;154:1237-1244.
4. Hoy D, March L, Woolf A, et al. The global burden of neck pain: estimates from the global burden of disease 2010 study. *Ann Rheum Dis.* 2014;73:1309-1315.
5. Juul-Kristensen B, Clausen B, Ris I, et al. Increased neck muscle activity and impaired balance among females with whiplash-related chronic neck pain: a cross-sectional study. *J Rehabil Med.* 2013;45:376-384.
6. Izquierdo TG, Pecos-Martin D, Girbés EL, et al. Comparison of cranio-cervical flexion training versus cervical proprioception training in patients with chronic neck pain: a randomized controlled clinical trial. *J Rehabil Med.* 2016;48:48-55.
7. Treleaven J, Chen X, Sarig Bahat H. Factors associated with cervical kinematic impairments in patients with neck pain. *Man Ther.* 2016;22:109-115.
8. Meisingset I, Stensdotter AK, Woodhouse A, Vasseljen O. Neck motion, motor control, pain and disability: a longitudinal study of associations in neck pain patients in physiotherapy treatment. *Man Ther.* 2016;22:94-100.
9. Gross A, Kay TM, Paquin JP, et al. Exercises for mechanical neck disorders. *Cochrane Database Syst Rev.* 2015;1CD004250.
10. Edmondston S, Björnsdóttir G, Pálsson T, Solgård H, Ussing K, Allison G. Endurance and fatigue characteristics of the neck flexor and extensor muscles during isometric tests in patients with postural neck pain. *Man Ther.* 2011;16:332-338.
11. Kumar S, Narayan Y, Prasad N, Shuaib A, Siddiqi ZA. Cervical electromyogram profile differences between patients of neck pain and control. *Spine (Phila Pa 1976).* 2007;32: E246-E253.
12. Stapley PJ, Beretta MV, Dalla Toffola E, Schieppati M. Neck muscle fatigue and postural control in patients with whiplash injury. *Clin Neurophysiol.* 2006;117:610-622.
13. Nakphet N, Chaikumarn M, Janwantanakul P. Effect of different types of rest-break interventions on neck and shoulder muscle activity, perceived discomfort and productivity in symptomatic VDU operators: a randomized controlled trial. *Int J Occup Saf Ergon.* 2014;20:339-353.
14. Johnston V, Jull G, Darnell R, Jimmieson NL, Souvlis T. Alterations in cervical muscle activity in functional and stressful tasks in female office workers with neck pain. *Eur J Appl Physiol.* 2008;103:253-264.
15. Szeto GPY, Straker LM, O'Sullivan PB. A comparison of symptomatic and asymptomatic office workers performing monotonous keyboard work–1: neck and shoulder muscle recruitment patterns. *Man Ther.* 2005;10:270-280.
16. Steinmetz A, Claus A, Hodges PW, Jull GA. Neck muscle function in violinists/violists with and without neck pain. *Clin Rheumatol.* 2016;35(4):1045-1051.
17. O'Leary S, Falla D, Jull G. The relationship between superficial muscle activity during the cranio-cervical flexion test and clinical features in patients with chronic neck pain. *Man Ther.* 2011;16:452-455.
18. Park J, Hur J, Ko T. Influence of pressure changes on recruitment pattern and neck muscle activities during Cranio-Cervical Flexion Tests (CCFTs). *J Back Musculoskelet Rehabil.* 2015;28:255-259.
19. Jull G, Falla D, Vicenzino B, Hodges PW. 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.
20. Cheng CH, Chien A, Hsu WL, Yen LW, Lin YH, Cheng HY. Changes of postural control and muscle activation pattern in response to external perturbations after neck flexor fatigue in young subjects with and without chronic neck pain. *Gait Posture.* 2015;41:801-807.
21. Boudreau S, Falla D. Chronic neck pain alters muscle activation patterns to sudden movements. *Exp Brain Res.* 2014;232:2011-2020.
22. Zabihhosseinian M, Holmes M, Ferguson B, Murphy B. Neck muscle fatigue alters the cervical flexion relaxation ratio in subclinical neck pain patients. *Clin Biomech.* 2015;30:397-404.
23. Maroufi N, Ahmadi A, Mousavi Khatir S. A comparative investigation of flexion relaxation phenomenon in healthy and chronic neck pain subjects. *Eur Spine J.* 2013;22:162-168.
24. Murphy BA, Marshall PW, Taylor HH. The cervical flexion-relaxation ratio: reproducibility and comparison between chronic neck pain patients and controls. *Spine.* 2010;35:2103-2108.
25. Cheng CH, Cheng HYK, Chen CPC, et al. Altered co-contraction of cervical muscles in young adults with chronic neck pain during voluntary neck motions. *J Phys Ther Sci.* 2014;26:587-590.
26. Cheng CH, Lin KH, Wang JL. Co-contraction of cervical muscles during sagittal and coronal neck motions at different movement speeds. *Eur J Appl Physiol.* 2008;103:647-654.
27. Lindstrøm R, Schomacher J, Farina D, Rechter L, Falla D. Association between neck muscle coactivation, pain, and strength in women with neck pain. *Man Ther.* 2011;16:80-86.

28. Falla D, Lindstrom R, Rechter L, Farina D. Effect of pain on the modulation in discharge rate of sternocleidomastoid motor units with force direction. *Clin Neurophysiol.* 2010;121:744-753.
29. Schomacher J, Boudreau SA, Petzke F, Falla D. Localized pressure pain sensitivity is associated with lower activation of the semispinalis cervicis muscle in patients with chronic neck pain. *Clin J Pain.* 2013;29:898-906.
30. Hoving JL, Pool JJ, van Mameren H, et al. Reproducibility of cervical range of motion in patients with neck pain. *BMC Musculoskelet Disord.* 2005;6:59.
31. Fletcher JP, Bandy WD. Intrarater reliability of CROM measurement of cervical spine active range of motion in persons with and without neck pain. *J Orthop Sports Phys Ther.* 2008;38:640-645.
32. Gelalis I, DeFrate L, Stafilas K, Pakos EE, Kang JD, Gilbertson LG. Three-dimensional analysis of cervical spine motion: reliability of a computer assisted magnetic tracking device compared to inclinometer. *Eur Spine J.* 2009;18:276-281.
33. Ball N, Scurr J. An assessment of the reliability and standardisation of tests used to elicit reference muscular actions for electromyographical normalisation. *J Electromyogr Kinesiol.* 2010;20:81-88.
34. Smoliga JM, Myers JB, Redfern MS, Lephart SM. Reliability and precision of EMG in leg, torso, and arm muscles during running. *J Electromyogr Kinesiol.* 2010;20(1):e1-e9.
35. Falla D, Jull G, Hodges P. 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.
36. Koerhuis CL, Winters JC, van der Helm FC, Hof AL. Neck mobility measurement by means of the 'Flock of Birds' electromagnetic tracking system. *Clin Biomech.* 2003;18(1):14-18.
37. Guo LY, Lee SY, Lin CF, et al. Three-dimensional characteristics of neck movements in subjects with mechanical neck disorder. *J Back Musculoskelet Rehabil.* 2012;25:47-53.
38. Bagwell JJ, Fukuda TY, Powers CM. Sagittal plane pelvis motion influences transverse plane motion of the femur: kinematic coupling at the hip joint. *Gait Posture.* 2016;43: 120-124.
39. De Luca CJ, Gilmore LD, Kuznetsov M, Roy SH. Filtering the surface EMG signal: movement artifact and baseline noise contamination. *J Biomech.* 2010;43(8):1573-1579.
40. Hermens H, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *J Electromyogr Kinesiol.* 2000;10(5): 361-374.
41. Falla D, Dall'Alba P, Rainoldi A, Merletti R, Jull G. Repeatability of surface EMG variables in the sternocleidomastoid and anterior scalene muscles. *Eur J Appl Physiol.* 2002;87:542-549.
42. Falla D, Dall'Alba P, Rainoldi R, Merletti R, Jull G. Location of innervation zones of sternocleidomastoid and scalene muscles–a basis for clinical and research electromyography applications. *Clin Neurophysiol.* 2002;113(1):57-63.
43. Wegner S, Jull G, O'Leary S, Johnston V. The effect of a scapular postural correction strategy on trapezius activity in patients with neck pain. *Man Ther.* 2010;15(6):562-566.
44. Pialasse JP, Lafond D, Cantin V, Descarreaux M. Load and speed effects on the cervical flexion relaxation phenomenon. *BMC Musculoskelet Disord.* 2010;11:46.
45. Drake JDM, Callaghan JP. Elimination of electrocardiogram contamination from electromyogram signals: an evaluation of currently used removal techniques. *J Electromyogr Kinesiol.* 2006;16:175-187.
46. Schinkel-Ivy A, DiMonte S, Drake J. Repeatability of kinematic and electromyographical measures during standing and trunk motion: how many trials are sufficient? *J Electromyogr Kinesiol.* 2015;25:232-238.
47. Hibbs AE, Thompson KG, French DN, Hodgson D, Spears IR. Peak and average rectified EMG measures: Which method of data reduction should be used for assessing core training exercises? *J Electromyogr Kinesiol.* 2011;21(1):102-111.
48. Cesqui B, Tropea P, Micera S, Krebs HI. EMG-based pattern recognition approach in post stroke robot-aided rehabilitation: a feasibility study. *J Neuroeng Rehabil.* 2013;10:75.
49. Kovacs FM, Bagó J, Royuela A, et al. Psychometric characteristics of the Spanish version of instruments to measure neck pain disability. *BMC Musculoskelet Disord.* 2008;9:42.
50. MacDermid JC, Walton DM, Avery S, et al. Measurement properties of the neck disability index: a systematic review. *J Orthop Sports Phys Ther.* 2009;39(5):400-417.
51. Vernon H. The neck disability index: state of the art, 1991-2008. *J Manipulative Physiol Ther.* 2008;31(7):491-502.
52. Lindstroem R, Graven-Nielsen T, Falla D. Current pain and fear of pain contribute to reduced maximum voluntary contraction of neck muscles in patients with chronic neck pain. *Arch Phys Med Rehabil.* 2012;93(11):2042-2048.
53. Sommerich CM, Joines SM, Hermans V, Moon SD. Use of surface electromyography to estimate neck muscle activity. *J Electromyogr Kinesiol.* 2000;10:377-398.
54. Hidalgo-Lozano A, Calderon-Soto C, Domingo-Camara A, Fernández-de-Las-Peñas C, Madeleine P, Arroyo-Morales M. Elite swimmers with unilateral shoulder pain demonstrate altered pattern of cervical muscle activation during a functional upper-limb task. *J Orthop Sports Phys Ther.* 2012;42:552-558.
55. Nederhand M, Jzerman M, Hermens H, Baten CT, Zilvold G. Cervical muscle dysfunction in the chronic whiplash associated disorder grade II (WAD-II). *Spine.* 2000;25(15):1938-1943.
56. Dankaerts W, O'Sullivan PB, Burnett AF, Straker LM, Danneels LA. Reliability of EMG measurements for trunk muscles during maximal and sub-maximal voluntary isometric contractions in healthy controls and CLBP patients. *J Electromyogr Kinesiol.* 2004;14(3):333-342.
57. Seitz AL, Uhl TL. Reliability and minimal detectable change in scapulothoracic neuromuscular activity. *J Electromyogr Kinesiol.* 2012;22:968-974.
58. Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med.* 2000;30(1):1-15.
59. Delisle A, Lariviere C, Plamondon A, Salazar E. Reliability of different thresholds for defining muscular rest of the trapezius muscles in computer office workers. *Ergonomics.* 2009;52(7): 860-871.
60. de Araujo RC, Tucci HT, de Andrade R, Martins J, Bevilaqua-Grossi D, de Oliveira AS. Reliability of electromyographic amplitude values of the upper limb muscles during closed kinetic chain exercises with stable and unstable surfaces. *J Electromyogr Kinesiol.* 2009;19:685-694.
61. Oksanen A, Ylinen JJ, Poyhonen T, et al. Repeatability of electromyography and force measurements of the neck muscles in adolescents with and without headache. *J Electromyogr Kinesiol.* 2007;17(4):493-503.
62. Sterling M, Jull G, Wright A. Cervical mobilisation: concurrent effects on pain, sympathetic nervous system activity and motor activity. *Man Ther.* 2001;6:72-81.
63. Soon B, Schmid A, Fridriksson E, Gresslos E, Cheong P, Wright A. A crossover study on the effect of cervical mobilization on motor function and pressure pain threshold in pain-free individuals. *J Manipulative Physiol Ther.* 2010;33(9):652-658.
64. Falla D, Jull G, Dall'Alba P, Rainoldi A, Merletti R. An electromyographic analysis of the deep cervical flexor muscles in performance of craniocervical flexion. *Phys Ther.* 2003;83(10):899-906.

65. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *J Strength Cond Res.* 2005;19(1):231-240.
66. Ekstrom R, Donatelli R, Soderberg G. Surface electromyographic analysis of exercises for the trapezius and serratus anterior muscles. *J Orthop Sports Phys Ther.* 2003;33:247-258.
67. Farina D, Madeleine P, Graven-Nielsen T, Merletti R, Arendt-Nielsen L. Standardising surface electromyogram recordings for assessment of activity and fatigue in the human upper trapezius muscle. *Eur J Appl Physiol.* 2002;86:469-478.
68. Mercer S. Short communication: surface electrode placement and upper trapezius. *Adv Physiother.* 2002;4:50-53.
69. Tsang SMH, Szeto GPY, Lee RYW. Relationship between neck acceleration and muscle activation in people with chronic neck pain: implications for functional disability. *Clin Biomech.* 2016;35:27-36.