

**THRESHOLD PROPERTIES OF LATERAL PTERYGOID MOTOR UNITS IN
CLINICAL PAIN**

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ABSTRACT

TMD-related chronic pain is a major health problem that affects the contemporary society and could cause severe economical, social and personal problems. Chronic TMD pain is associated with parafunctional activity of different masticatory muscles. The Lateral pterygoid (LP) muscle has been frequently implicated in TMD and a number of studies have suggested that its activity is different between asymptomatic individuals and patients with TMDs. A disturbance to the normal role of the muscle in the control or stabilisation of the temporomandibular joint was suggested as possible cause. Other theories, including muscle hyperactivity, muscle hypoactivity and poor coordination between the Inferior Head and the Superior Head of the Lateral Pterygoid (IHLP and SHLP), have also been proposed. The IHLP was proven to be a heterogeneous muscle due to its Single Motor Units (SMUs) distribution. However, none of the studies have tested its heterogeneity in TMDs. The aim of this study is to investigate the effect of clinical TMD pain on the activity of the IHLP during standardised horizontal jaw movement, with special reference to the relation between CT-verified location of recording electrodes and the threshold values of SMU, to test the heterogeneity of the IHLP already proposed in previous studies.

KEYWORDS: Orofacial pain, Muscle activity, Lateral pterygoid muscle, IHLP, TMD, EMG.**INTRODUCTION**

Due to the complexity of the jaw muscles' internal architectures, the study of the masticatory system's function in health and disease has proven to be difficult. Electromyography (EMG) is a useful tool that has been used extensively for investigating muscle activity in the masticatory system as well as the body's other muscular systems.

There are numerous studies in the literature that have used the recording of EMG muscle activity and its relations with force generation and movement control. In the masticatory system, most of the studies have demonstrated functional heterogeneity of most of the jaw muscles.^[1,2,3,4,5] Accordingly, every muscle is divided into different anatomical and functional compartments, with each compartment able to generate different force levels and vectors.^[2] This enables a jaw muscle the ability to grade its magnitude and direction of force and undertake a large range of motor tasks.

Some studies have analysed the EMG activity of the lateral pterygoid (LP) muscle motor units in both the inferior and superior head (IHLP and SHLP).^[6,7,8,9,10] They studied the single motor units' (SMU) activity of the LP in healthy subjects during horizontal jaw movements using fine wire electrodes. In each subject, the electrode position within each muscle head was

verified by a set of CT scans, to validate lateral pterygoid activity. Some of these studies found that the lateral pterygoid SMUs may have different physiological properties than those in other jaw muscles and functional heterogeneity has been demonstrated in both the superior and inferior head.^[7,9,10] The SHLP as an example has shown to be involved in many jaw movements, including opening, contralateral and protrusive jaw movements, in addition to its classical role in retrusion, ipsilateral and closing movements. In addition, the data suggested that some parts of the SHLP were acting differently than other parts, according to the direction of the jaw movement.^[9]

In the IHLP, the study of SMU recruitment thresholds suggests a level of functional "complexity" inside these muscles which further supports the notion of functional heterogeneity. By dividing the IHLP into four different parts, superomedial, inferomedial, inferolateral and superolateral, it was shown that SMUs recruited from different parts have different recruitment thresholds.^[7] The data suggested that the IHLP SMUs thresholds' variation was associated with the electrode location, the jaw movement direction and velocity.^[7]

The LP has been frequently implicated in temporomandibular disorders (TMD). A number of studies have suggested that the activity of the lateral

pterygoid muscle is different between asymptomatic individuals and patients with TMDs.^[11,12,13,14,15,16,17,18,19] A disturbance to the normal role of the muscle in the control or stabilisation of the temporomandibular joint was suggested as possible cause. Other theories, including muscle hyperactivity, muscle hypoactivity and poor coordination between its two bellies, the IHLP and the SHLP, have also been proposed.^[20,21,22,23,24,25,26] However, none of these studies have tried to investigate the heterogeneity of the LP in patients with TMD. The aim of this study is to investigate the effect of clinical TMD pain on the activity of the IHLP during standardised horizontal jaw movement, with special reference to the relation between CT-verified location of recording electrodes and the threshold values of IHLP SMUs, to test the heterogeneity of the IHLP already proposed in previous study, using the same materials and methodology.^[7]

MATERIALS AND METHODS

A total of 30 subjects were included in this study (age range 21-52 yrs). 16 of them were classified as chronic painful temporomandibular disorder (TMD) patients (age range: 23-52 yrs; 6 males, 13 females) and were recruited from the Orofacial Pain Clinic, Westmead Centre for Oral Health, Westmead Hospital. The Research Diagnostic Criteria for Temporomandibular Disorders (RDC/TMD) were used to verify the presence or absence of a chronic TMD pain diagnosis.^[27] Chronic

pain here defined as pain lasting for more than 6 months.^[28] All data recording sessions were conducted in the Jaw Function and Orofacial Pain research unit, Westmead Centre for Oral Health, Westmead Hospital. Experimental procedures were approved by the Sydney West Area Health Service Ethics Committee of Westmead Hospital and the Human Ethics Committee of the University of Sydney.

The activities of the IHLP during the prescribed jaw movements were recorded with fine wire electrodes. The detailed insertion method for electrode placement within the IHLP was described by Salame and his colleagues.^[29] In brief, to place the electrode within the IHLP, bipolar fine-wire electrodes were prepared by passing two Teflon-insulated stainless-steel fine wires (Medwire®, New York, USA; 75 µ dia., total dia. with Teflon coating 110 µ) through a disposable spinal needle (51-mm long, 25 gauge, Becton-Dickson, USA) and following a standardised intraoral approach. To be able to hook in the muscle, the end of the wires outside the needle were bent and the needle was inserted in an upward, medial and posterior direction towards the external auditory meatus for about 29 mm. In this way, the hub of the 51mm needle ended adjacent to the interdental space between the maxillary second premolar and first molar. The needle, then, was carefully retracted, leaving the wires within the IHLP (Fig. 1).

B, Pair of Teflon-insulated stainless-steel fine electrodes inserted into the needle prior to muscle insertion, and bent for 2-3mm to hook into the muscle during the retraction of the needle from the muscle.

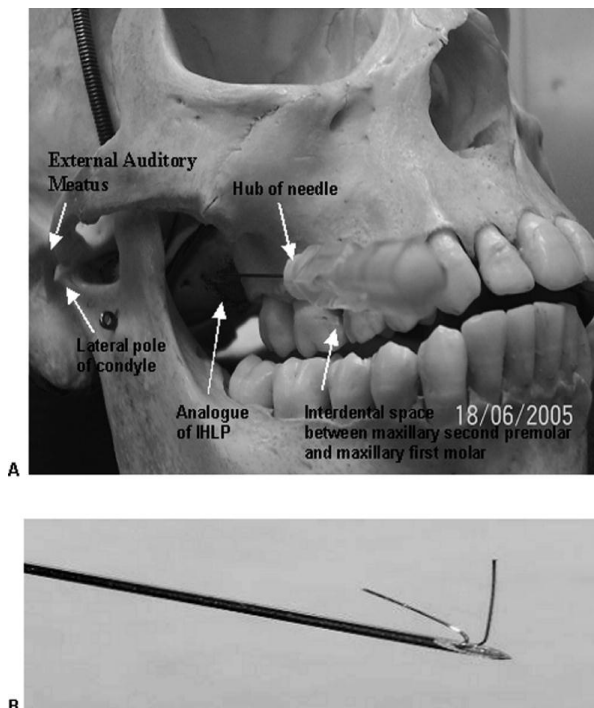


Fig. 1. A, representation of the insertion of the electrodes in the IHLP. A 51 mm Electrode-carrying needle inserted into an analogue IHLP attached to a dried skull.

The experiments protocol, materials and methodology replicated that used by phanachet et al.^[7] Three-dimensional movement of the jaw was obtained in six degrees of freedom with an optoelectronic system (JAWS3D, Metropoly, Switzerland) during standardized laterotrusive jaw movements with a sampling rate of 67 samples/s. A target frame with 3 light-emitting diodes (LEDs) was attached to the anterior maxillary teeth and another similar target frame was attached to the mandibular teeth, using prefabricated titanium clutches and cyanoacrylate adhesive (Supa Glue, Selleys Pty Ltd, Padstow, Australia). The clutches were free from dental occlusal contact and interfered minimally with lip movement. The frames were positioned at the side of the face, parallel to the Frankfort horizontal and the mid-sagittal planes. The movements of the LEDs were recorded with three charged-couple device cameras, and the JAWS3D system computed, according to rigid body dynamics, the movement of the mandibular mid-incisor point (MIPT) in real time (Fig. 2). The mid-incisor point is the point between the incisor edges of the lower central incisors. The lateral pole of the condyle was palpated and designated as a secondary reference point.

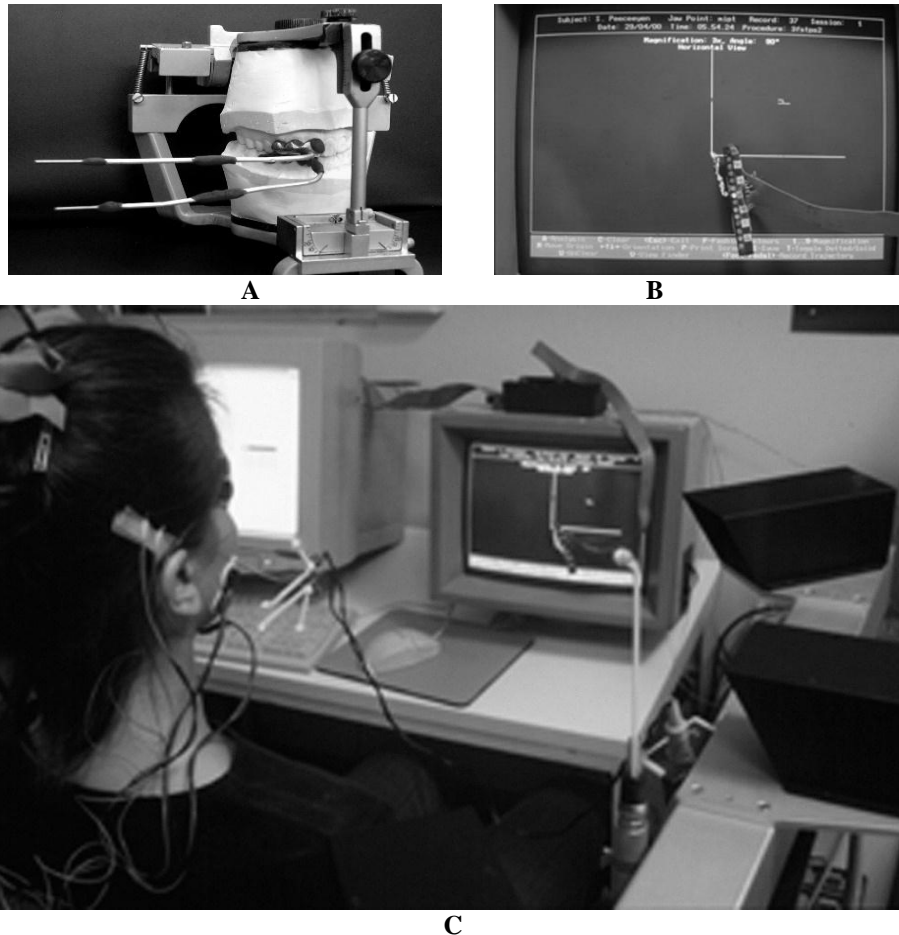


Fig. 2. Experimental set-up: The metallic clutches (A) are attached to the anterior upper and lower teeth to connect the target frames with the LEDs to the maxilla and mandible. Target LEDs attached to the computer screen before the subject (B) are detected. To standardise movements, an LED target bank is placed over the real-time video display of jaw movement in front of the subject (B and C). The subject tracks her/his jaw movement to these LED targets. Jaw movement is detected by the JAWS3D tracking system (C: black cameras on the right) which monitors the spatial position of the LEDs during jaw movement.

As in Phanachet et al. paper, tasks standardised for velocity, displacement and direction were performed in the laterotrusive directions. Subjects were asked to move the mandible to the side by tracking a computer-controlled target consisting of a linear bank of 15 LEDs (Fig. 2, B) attached on a computer screen in front of the subject. Jaw movements were standardised by asking the subject to move their mid-incisal point (MIPT), represented as a small marker on the computer display, in line with direction and speed of the sequentially illuminated LEDs, which were controlled by Spike 2[®] software (Cambridge Electronic Design Limited, Cambridge, UK). To investigate the effect of rate of jaw movement on single motor units (SMUs) firing onset during muscle contraction, the target was set at fast (6.5 mm/s) and slow (1.3 mm/s) jaw velocity. Muscle activity was analysed with software to collect and display motor unit activity and discriminate single motor units (Spike 2, CED, Cambridge Electronic Design Limited, Cambridge, UK).

The lateral jaw movement task started with the subject in the postural jaw rest position for 2-4 seconds and then

the mandible was moved laterally (contralateral to the side of the worst pain for pain subjects) to a maximal comfortable displacement where the discrimination of SMUs was still possible. The subject then held the jaw at this lateral position for about 5 seconds and returned the mandible to postural jaw position by tracking the LED target.

Data analysis

Electromyographic signals were amplified by an isolated bioelectric amplifier (SA Instrumentation Co., San Diego, USA), digitally acquired (micro1401, CED; Cambridge) and initially analysed with integrated software (Spike2, CED; Cambridge), which displayed motor unit activity and discriminated single motor units. The sampling rate was 10,000 or 20,000 samples/s, and bandwidth 100Hz – 10 kHz to help eliminate low frequency noise associated with mains electrical instruments and machinery whilst acquiring single motor unit activity.

Single motor units from the IHLP were discriminated with the Spike2[®] software. The discrimination was done

manually based on the shape and amplitude of the trace. The waveforms that were similar in shapes and amplitude were considered to belong to the same motor unit. The motor units that could be visualised at the beginning of a movement were discriminated. IHLP units were characterised for threshold properties (see below) during standardised tasks from 16 pain subjects and 14 non-pain subjects for different speeds during laterotrusive movement.

The threshold values of the same SMU were calculated for all trials of the same movement and speed and averaged (Fig. 3). In some subjects, only one trial was

considered for discrimination, due to increasing pain and inadequate jaw movement, where muscle activity was very sporadic and the SMU discrimination was impossible. Thresholds of each SMU at different rates were compared (Linear Mixed Effects Model) between different speeds and between pain and non-pain subjects. The threshold values were log transformed to approximate normality prior to analysis. The statistical software package S-PLUS Version 6.2 (TIBCO Software Inc., California, USA) was used to analyse the data. Two-tailed tests with a significance level of 5% were used throughout.

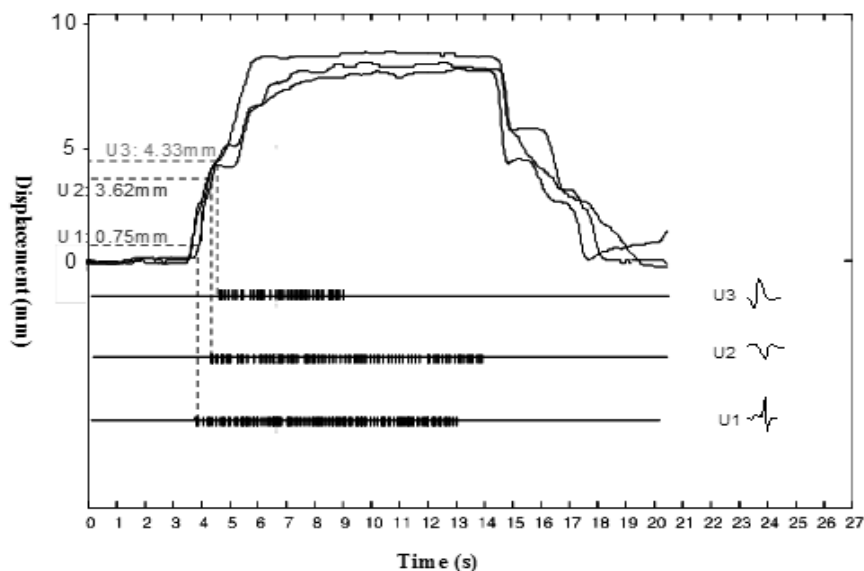


Fig. 3. Displacement-time graph demonstrating the trajectory of the mid-incisor point of a pain subject during 3 consecutive trials of the same lateral movement and at the same speed, with 3 different motor units recruited at a threshold of 0.75mm (U1), 3.62mm (U2) and 4.33mm (U3) from these trials. The same units were discriminated from every trial and their values were averaged by summing them and dividing by the number of trials. The lower right traces show the different shapes of the three different units discriminated. The upper graph represents the movement of the MIPt during laterotrusion. The first flat line (0 to 4/X axis) represents the rest position before the start of the trial. The ascending line represents the outgoing phase, then the holding phase (upper flat line), ending by the return phase (descending line).

The effect of electrode location

Virtually, the IHLP was divided mediolaterally into medial and lateral regions and superior-inferiorly into superior and inferior regions. These muscle divisions were selected to facilitate analysis with previous studies using this method.^[7] The regions were designated as 1, 2, 3 and 4 for lateral superior (LS), medial superior (MS), medial inferior (MI) and lateral inferior (LI) respectively. The electrode location was indicated accordingly and the linear mixed effect model was used as a statistical method to investigate the effect of electrode location on the firing threshold of IHLP single motor.

To confirm the location of the electrodes inside the IHLP, at the end of the recording session several computer tomographic images (CT-axial slices; 1-3 mm thick; General Electric High Speed Advantage CT scanner, Milwaukee, USA) were obtained from each subject (Fig. 4). The locations of the CT-axial slices were inferior to and parallel with the clinically approximated Frankfort Horizontal Plane, with the most superior slice at this plane and the most inferior below the electrode's intraoral insertion point.

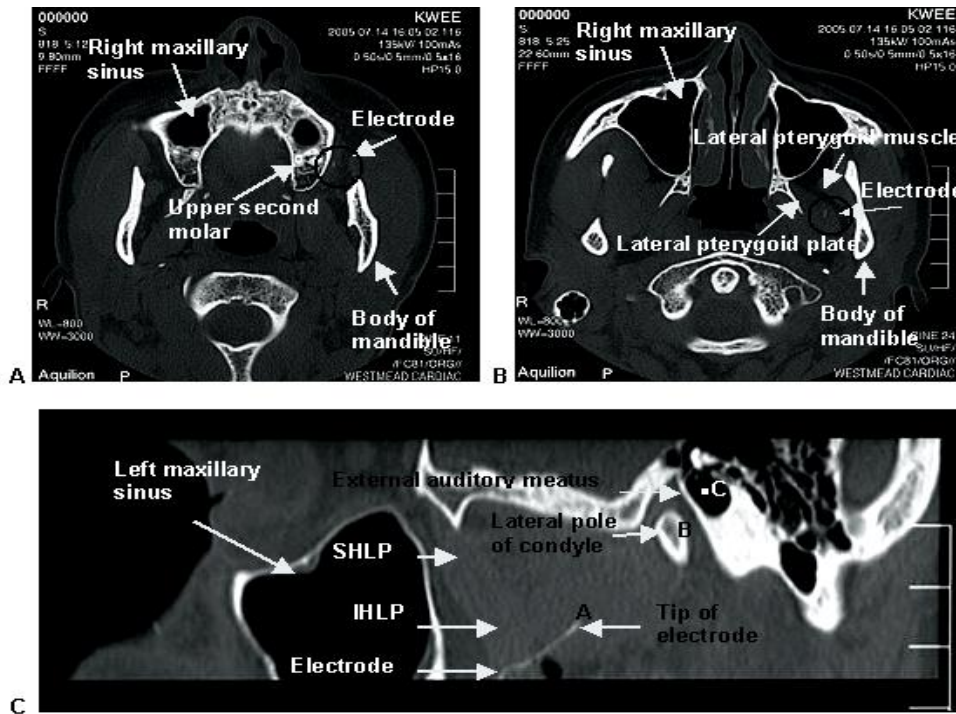


Fig. 4. Three CT scan images of one subject after lateral pterygoid electrode insertion showing the insertion point, the placement site, and the trajectory of the insertion. Figure A is an axial view at the level of maxillary alveolar process showing the insertion point of the electrode adjacent to the distal root of the second maxillary molar. Figure B is an axial view at the level of the lateral pterygoid muscle, showing the tip of the electrode located in the middle of the muscle. Figure C is a reformatted parasagittal view parallel to the long axis of the LP muscle, showing the trajectory of the electrode from the insertion to the placement point (A) at the centre of the muscle. Note that the placement point (A), the lateral pole of the condyle (B) and the centre of the external auditory meatus (C) all lie along the same line.

RESULTS

Threshold characteristics of the SMUs activity of the IHLP

Between 2 and 6 SMUs could be discriminated from each subject. Unit 1 has to be the same for all trials, unit 2 as well and so for all the units. A total of 75 SMUs were discriminated.

Effect of electrode location on SMUs threshold values during contra-lateral movement

The location of the electrodes after insertion into the IHLP of all the 16 pain subjects was derived from the CT

scans. Three of the insertions were located in region 1 (i.e. LS or lateral superior, see methods), five of them were in region 2 (MS or medial superior), six in region 3 (MI or medial inferior) and 2 in the fourth region (LI or lateral inferior). As for the contralateral movement, 3 out of the thirty-nine SMUs were found in region 1, eleven were found in region 2, 18 in region 3 and 7 in region 4 (Table 1).

There was no significant effect of the electrode location on the threshold value of the IHLP SMUs of all 4 regions (P> 0.05).

Table 1. The location of the electrode inserted within the IHLP of 16 pain subjects, as determined in the CT scans performed at the end of each experimental session. The IHLP was divided virtually into 4 different regions: Medial-Inferior (MI), Lateral-Superior (LS), Medial-Superior (MS) and Lateral-Inferior (LI). 6 of the insertions were located in MI, 3 in LS, 5 in MS and 2 in LI.

Subjects	Medial	Lateral	Superior	Inferior	Location
S1	x			x	MI
S2		x	x		LS
S3	x			x	MI
S4	x			x	MI
S5	x		x		MS
S6		x		x	LI
S7		x	x		LS
S8	x		x		MS
S9	x		x		MS

S10	x		x		MS
S11		x	x		LS
S12	x		x		MS
S13	x			x	MI
S14		x		x	LI
S15	x			x	MI
S16	x			x	MI

Effects of rate of movement on IHLP' SMUs threshold values in pain subjects

Linear mixed effects (LME) models were used to statistically assess the effects of pain and speed on the log transformed thresholds for each motor unit. These models allow for the dependence between multiple observations made on the same patient. In the LME

models, speed and pain were considered as both fixed and random factors each with two levels. The patient identifier was fitted as a random effect. The interaction between the fixed effects of pain and speed was not significant for any motor unit. Neither were the fixed main effects for pain alone and for speed alone (Fig. 5).

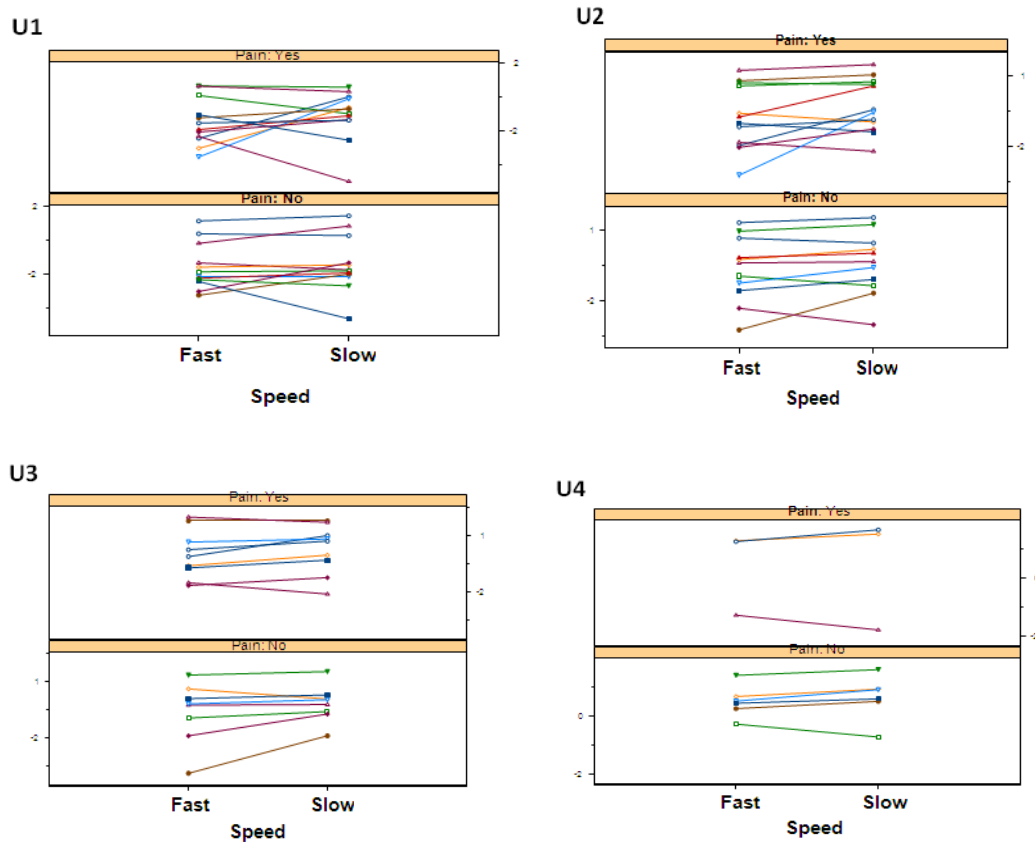


Fig. 5. The effect of jaw movement speed (fast and slow) on threshold values of the first four motor units (U1, U2, U3 and U4), discriminated from all pain subjects during contralateral movement, as shown from the statistically analysed data. There was no statistically significant effect of pain or speed, neither was there any statistically significant combined effect of pain and speed, on the threshold values of any of the units studied.

IHLP activity at rest

No activity in the IHLP was observed during the rest position before the start of each trial or between the trials in any of the subjects investigated.

DISCUSSION

Many studies demonstrated that the IHLP is active during protrusive, contralateral and jaw-opening movements.^[21,30,31] Single motor unit (SMU) studies suggested that the IHLP plays an important role in the generation and fine control of the jaw during

contralaterally directed horizontal isometric forces.^[7,32] They suggested that a possible alteration in the activity of the IHLP could be correlated with the alteration of the jaw function during some tasks such as mastication and jaw parafunction (tooth clenching and grinding) which is observed frequently in TMD patients. Other studies found that parameters such as conduction velocity, power frequency and root mean square were altered in painful, when compared to non-painful, muscles.^[33,34,35] Phanachet and colleagues suggested that the fine control ability of the IHLP may be further enhanced by

functional heterogeneity of the muscle where there can be activation of specific regions of the IHLP.^[7] They have shown that different threshold values of SMUs exist in different regions of the IHLP. There is also evidence that the masticatory muscles histo-anatomical composition is heterogeneous. This means that different regions in the same muscle activate differently according to the specific jaw task.^[36,37] In effect, these muscles consist of a number of different functional units. The lateral pterygoid muscle is no exception. It has been suggested that the IHLP is a multipennate muscle.^[38] This means that different muscle fibres are aligned in different directions to enable the application of different force vectors required for different movement directions.^[32] In addition, some studies suggested that, within the IHLP, there are different muscle tendons that separate the muscle into different histological compartments. Also, the type of muscle fibres within the IHLP varies throughout the muscle, with the middle part of the muscle being rich in muscle spindle composition in comparison to the extremities.^[39,40] All of the above support the idea of heterogeneous activation of the IHLP which could explain the association of different regions with different threshold values of SMUs as found by Phanachet and coworkers.^[7]

Our results contradicted the results of Phanachet study. The SMUs threshold values in pain subjects were not affected by different electrode location within the IHLP. This puts the notion of the IHLP heterogeneity in pain patients into question. The explanation for this could be consistent with the notion proposed by Lund's pain adaptation model about reducing the entire agonistic muscle activity to prevent further damage.^[41] It is known that the CNS has the freedom to regulate the activity of motor units through the "central pattern generator" to conform to the direction of a desired movement.^[42,43] It is also known that a muscle can act as a principal agonist for certain directions and as a supportive one to other muscles for other movement directions.^[44] The principal role of the IHLP is suggested to be for horizontal movements such as contralaterotrusion and protrusion.^[45] Although this muscle head has been shown to be active in mouth open movements according to some studies, this muscle would be supportive to other opening muscles rather than as the principal muscle. In this instance, it is possible that the CNS regulation of the IHLP activity stops the motor units of this muscle head being active during synergistic movements in order to preserve their activity in more principal movements.

The Phanachet study showed that the rate at which the movement was executed (i.e. fast or slow) significantly affected the threshold values of discriminated motor-units in a non-pain population.^[7] This was consistent with Freund's observations about the effect of speed of movement on the recruitment of motor units, where he found that the threshold values of motor units firing at a fast rate of movement were significantly lower than the values of those firing at a slow rate of movement.^[46] In

our study there was no significant effect of speed on motor units' threshold values in pain patients. And this could suggest another alteration of EMG muscle activity in TMD pain patients that could be conformed to the pain adaptation model. The fast movement suggested in Desmedt and Godaux studies was supposed to be brisk or ballistic.^[47,48] Their conclusion was that, although there was a decreased threshold value of SMUs with increased rate of movement, but the difference in these threshold values between different rates of movement was significant only when the speed reached the ballistic level. If the subjects in Phanachet study were able to execute a ballistic movement during fast rate movement, and that could explain the different IHLP SMU thresholds values, It could be possible that due to pain, the TMD subjects in our study were not able to perform a ballistic movement in order to prevent the muscle from more pain and further damage as suggested by the PAM.

Methodological issues

Methodological factors could not be totally excluded from explaining this difference in results between the two studies. In Phanachet's study, the SMUs discriminated were those that fire tonically. Tonic firing was defined as continuous firing of motor units throughout the whole movement during a specified task. In our study we were not always able to discriminate the motor units continuously throughout the movement. Some studies on other skeletal muscles faced the same difficulties.^[49,50] Bigland and Lippold (51) found that the presence of different units that have similar shapes is not uncommon in normal muscles, and confusion between them is possible during discrimination.^[51] Erim and coworkers found an unstable firing property of SMUs at low force levels, specifically at the beginning of the movement, when motor units start firing, which affected the recruitment threshold calculation.^[52] Another study found that motor units displayed unstable firing patterns with increased level of contraction.^[53] In addition, the possible summation of multiple potentials that are discharging simultaneously during activity changes the shape of the motor units' signal and makes them not easy to discriminate.^[54] We cannot exclude also the change in the position of the electrode inside the muscle, due to repetitive muscle contraction during the experiment, which could cause changes in the shape of the EMG signal as well.

Adding to this, pain subjects in our study were not able to follow the same axis of displacement throughout one movement, and changes in movement direction was common while they were executing a specified task. It has been shown that various motor units are activated according to their mechanical action in a way that the neuromuscular system activates different motor units for different directions of movement.^[55] Thus, an interruption in one motor unit activity could occur, and the firing of another motor unit could have started, when the jaw changes direction during executing a specified task, which would make the discrimination of one

specific motor unit throughout the whole movement more difficult in pain subjects. All the above factors would explain the difficulty of discriminating the same motor unit throughout a specified task and suggest that, while our goal was to discriminate only tonic motor units to analyse their activity in pain subjects, it is possible that some motor units discriminated as tonic could be actually phasic and this could affect the threshold calculation of the overall number of tonic motor units.

The other methodological difference between the two studies is statistical. As an example, the statistical analysis chosen by Phanachet and colleagues in order to compare the firing thresholds difference between the fast and slow rates of movement was the Mann-Whitney test.^[7] While this test is a powerful non-parametric way for assessing whether two samples of observations come from the same distribution, the main condition for this test to be applied is the independency of the samples.^[56,57] However, in the present study, multiple motor units firing at fast rates and slow rates of movements and collected for statistical comparison belonged to the same subject and the use of this test is, hence, not adequate. When the data is characterized by the presence of a correlation between observations within the same group, the Mixed-effects model is the best-known and most flexible tool for the analysis of grouped data.^[58] Consequently this was the test chosen to analyse the data in our study.

Absence of activity at postural jaw position

Some studies on experimental and chronic muscle pain found a significant effect of pain on the activity of some masticatory muscles, namely the masseter and temporalis, at postural jaw position.^[59,60] Their findings suggested an increased activity in the painful muscle that is supporting the notion of pain-spasm-pain as in the Vicious Cycle Theory.^[61] Other scholars, however, suggested that the increase in the resting electromyographic muscle activity elicited by pain is not long-lasting and it is not significant enough to be considered as "hyperactivity".^[62] No activity in the IHLP was observed in our pain subjects when the jaw was in postural (rest) position before the start of any movement or between the trials. This is consistent with the Phanachet findings regarding the absence of resting activity of masticatory muscles in non-pain subjects and contradict the principle of increased activity in pain patients as proposed by the vicious cycle theory.

Our recorded muscle activity, however, was always accompanied by noise. This is a normal phenomenon and can be caused by the body of the subject acting as an aerial, inherent electrical noise from the recording equipment and/or surrounding electromagnetic signals from adjacent electrical sources. During processing, data should be filtered first to get rid of some of this noise. In the process, low amplitude, high frequency motor units that could be confused with the noise could be filtered as well and missed from discrimination. In some data,

activity could be seen, even after filtration, which could be considered as similar to a motor unit more than noise but was disregarded to eliminate confusion. Nonetheless this processing would have occurred in the control population as well and thus we are confident that the resting muscle activity in the pain population was not increased.

CONCLUSION

This study offered new insights on the effect of chronic pain on the single motor units' activity of the IHLP in patients with temporomandibular disorders. As far as the authors concerned, this is the first study that confirmed the absence of the IHLP functional heterogeneity in TMD patients. These results were suggested to be supporting the notion of the pain Adaptation Model, regarding the alteration of muscle activity in pain patients in order to prevent more pain and further damage. In addition, this study confirmed the absence of muscle activity at rest in pain patients which is contradicting to the principle of muscle hyperactivity earlier proposed by the Vicious Cycle Theory. Due to the lack of understanding of the effect of chronic pain on muscle activity in TMD patients, current treatment modalities proved to be random and not based on scientific evidence which could lead some times to inadequate treatment methods. We believe that these results could shed new lights on the effect of pain on muscle activity which could lead to more evidence based treatment techniques.

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