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NEW INSIGHTS INTO PAIN-RELATED CHANGES IN MUSCLE ACTIVATION REVEALED BY HIGH-DENSITY SURFACE ELECTROMYOGRAPHY

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Abstract

High-density surface electromyography (HDEMG) is an electrophysiological technique that can be used to quantify the spatial distribution of activity within muscles. When pain-free individuals perform sustained or repetitive tasks, different regions within a muscle become progressively more active; this is thought to reflect a strategy to redistribute the load to different regions, thus limiting localised muscle fatigue. The use of HDEMG has revealed that when people with musculoskeletal pain perform the same tasks, the distribution of activity within the same muscle is usually different, and the same muscle region tends to be active throughout the whole task without progressive activation of different muscle regions. This potentially results in a focal overload of a muscle region, and may contribute to fatigue, localised muscle pain and potentially pain persistence and/or recurrence over time. Interestingly, not all patients with musculoskeletal pain present with this regional alteration in muscle activation, reflecting the heterogeneity of patient presentations. This article will briefly review the technique of HDEMG followed by a review of studies demonstrating spatial redistribution of muscle activity in asymptomatic people during both isometric and dynamic conditions, including functional tasks. Lastly, the article will provide a review of HDEMG studies with a focus on changes in the behaviour of the lumbar erector spine and upper trapezius in people with spinal pain. These studies have revealed subtle changes in the distribution of muscle activity in people with spinal pain, which may have relevance for onset, persistence or recurrence of symptoms and could become a target of novel therapeutic approaches.

Keywords: musculoskeletal pain; experimental pain; chronic pain; EMG; trapezius; erector spinae

High-Density Surface Electromyography

Given the association between the neural input a muscle receives and the electrical voltage it generates, muscle activation and neuromuscular control strategies are commonly assessed using electromyography (EMG). Traditional bipolar surface EMG recordings are obtained using a pair of large electrodes, spaced 20-30mm, placed on the skin above the muscle of interest. While conventional EMG can appropriately describe the global activation of muscles, its fairly large detection volume makes it generally unsuitable to detect differences in the activation patterns of regions within a muscle, or of multiple muscles clustered in a relatively small region. This can be an issue when investigating the activation of some muscles because of the poor selectivity of conventional bipolar EMG techniques: for instance, differentiating the activation of the lumbar erector spinae at different spinal levels, or of regions within the divisions of the trapezius. Alternatively, intramuscular electromyography can be used to obtain highly selective recordings of the electrical activity of the fibers in close proximity of the wire electrode. While this technique is currently the only option to record EMG from deep muscles (e.g.: deep multifidus), its invasive nature makes it difficult to use in large clinical studies, or in clinical practice. Instead, when the muscles of interest are superficially-located, HDEMG offers a number of advantages compared to both conventional bipolar and indwelling EMG recordings (for a review, see (Merletti et al., 2010)). HDEMG consists of placing a large number of small surface electrodes, organized in a bidimensional "grid" over the muscle (region) of interest (Figure 1). The small electrode size (usually <3mm) and the small distance between the electrodes (usually 10mm or less) increases the selectivity of the recording (Vieira et al., 2017), such that the EMG signal recorded by each electrode is mainly representative of the activation of the surrounding muscle fibers. Unlike traditional bipolar surface EMG applications, HDEMG

provides a topographical representation of the EMG amplitude, allowing relative adaptations in the intensity of activity within regions of the muscle to be evaluated. Changes or differences in regional activation are usually described using the centroid of the EMG amplitude distribution. If the EMG amplitude values of a group of electrodes located in a region of the grid increases, the centroid will shift in that direction. It should be noted however that the amount of shift depends on how the barycenter is calculated, hence shifts of only a few millimeters may describe relatively large changes in EMG amplitude distribution (Figure 2). Importantly, as the characteristics of the surface EMG signal collected at each electrode depend on muscle anatomy, interpretation of changes in the HDEMG spatial distribution critically depend on whether the shift of the centroid occurs along or across the fiber direction (Gallina et al., 2013), or if the muscle architecture is pennate (Mesin et al., 2011). Since HDEMG provides more selective recordings than conventional surface EMG, and it can be used to describe the activation of muscle regions over different spinal levels and at different distances from the spine, HDEMG is an ideal technique to investigate the normal distribution of activation between regions of superficial muscle groups such as the erector spinae and how this is modified when people have pain.

Non-uniform spatial distribution of muscle activity revealed by HDEMG

One of the necessary prerequisites for regional activation is that most of the muscle fibers innervated by an individual motor neuron are clustered in a region of the muscle, as opposed of being equally spread across the whole muscle volume. For instance, in a recent study Abboud and colleagues (Abboud et al., 2020), demonstrated the existence of localized motor unit territories within the human longissimus muscle, which allows the preferential activation of

cranial (L1-L3) and caudal (L4-L5) regions of the longissimus thoracis pars lumborum during voluntary movements. As the amplitude of the motor unit action potential measured on the skin decays sharply in space with the distance from its source (Roeleveld et al., 1997), the activation of muscle units clustered in a muscle region will be observed in the HDEMG as an uneven amplitude distribution; specifically, the peak of the EMG amplitude distribution will be located above the active muscle fibers (Gallina et al., 2016; Gallina and Vieira, 2015; Vieira et al., 2011). The use of HDEMG to investigate regional activation within a muscle was supported by showing that the cranial shift of EMG amplitude distribution during sustained contractions of the upper trapezius is positively correlated with the number of recruited motor units in the cranial muscle region, identified using selective intramuscular electrodes (Falla and Farina, 2008). Similarly, the caudal shift in EMG amplitude distribution induced by injecting hypertonic saline solution in the trapezius muscle is accompanied by decreased firing rate of motor units located in the cranial region of the muscle (Dideriksen et al., 2016). The fact that individuals are able to volitionally shift the activation between cranial and caudal regions within the trapezius when prompted to move the scapula in different directions (Gaffney et al., 2014) or when provided with biofeedback from HDEMG (Arvanitidis et al., 2019; Gaffney et al., 2016) further supports the use of HDEMG to describe the distribution of activity within a muscle. Preliminary results suggest that by combining intramuscular and HDEMG recordings, also the activation of individual lumbar extensor muscles (superficial multifidus at L4; longissimus at L1 and L4) can be observed as spatially-localized amplitude distributions during isometric activation of the trunk extensors (Abboud et al., 2019) and in response to electrically-elicited vestibular perturbations (Gallina et al., 2019).

When using HDEMG it should be remembered that a non-uniform spatial distribution of EMG amplitude can also be explained by factors other than neuromuscular activation. In the upper trapezius for instance, differences in the EMG amplitude distribution along the medio-lateral axis (along the fiber direction) will mainly be associated to anatomical factors such as the presence of an innervation zone or musculo-tendinous junction within the detection volume of the electrodes (Gallina et al., 2013). Instead, the activation of different regions within the trapezius will mainly be observed along the columns of electrodes (cranio-caudally) (Dideriksen et al., 2016; Falla et al., 2017, 2010, 2009, 2008; Falla and Farina, 2008, 2007).

Collectively these studies support investigating the spatial distribution of the EMG amplitude, estimated with HDEMG, to evaluate regional activation within muscles and how this is modified in various states including the influence of pain. Importantly for longitudinal studies, moderate to good between-day reliability has been established for parameters of the amplitude distribution measured with HDEMG (Abboud et al., 2015; Afsharipour et al., 2016).

Spatial redistribution of muscle activity in asymptomatic people

Uniquely, HDEMG studies have revealed that the distribution of activity within muscles changes during both isometric and dynamic contractions, including functional tasks and in response to mechanical perturbations. This redistribution of activity is thought to have the physiological significance of redistributing load, minimising muscle fatigue and prolonging endurance, possibly by preventing overload on the muscle fibres active at the beginning of the task. This variation in activation within regions of the same muscle appears to be of particular relevance for muscles commonly exposed to repetitive or sustained activation, such as the upper trapezius muscle (Falla et al., 2017, 2007; Falla and Farina, 2007; Farina et al., 2008; Gallina et

al., 2013) and the lumbar erector spinae (Abboud et al., 2015; Falla et al., 2014; Martinez-Valdes et al., 2019; Sanderson et al., 2019b, 2019a; Tucker et al., 2009). For instance, Abboud and colleagues (Abboud et al., 2016) observed that the variability in the spatial location of the activation of the lumbar erector spinae is reduced in response to sudden trunk mechanical perturbations during the presence of fatigue.

Changes in the EMG amplitude distribution over the trapezius muscle have been observed in asymptomatic people during isometric contractions at different efforts in most (Falla and Farina., 2007; Gallina et al., 2013; Holtermann and Roeleveld, 2006; Kleine et al., 2000), but not all studies (Troiano et al., 2008). Differences between studies may be explained by different position and size of the electrode grid; specifically, by placing the longer dimension of the electrode grid along the muscle fiber, Troiano et al. (Troiano et al., 2008) may have been unable to capture regionalized muscle activation since only few electrodes (5 spanning 40mm) were placed in the cranio-caudal direction. In contrast, a caudal shift of the EMG amplitude distribution was observed during isometric shoulder elevation when contraction intensity increased from 5% to 25% of the maximal voluntary effort (Gallina et al., 2013), while a cranial shift of trapezius activation was noted between 50% and 100% of the maximal shoulder elevation voluntary effort (Kleine et al., 2000). A cranial shift of activation was also observed with repeated practice of an isometric scapular elevation task (Gallina et al., 2013). A redistribution in regional activation with varying contraction intensity and with repeated practice may be interpreted as a way for the central nervous system to redistribute load between muscle regions. Instead, shifts in the distribution of muscle activation at different contraction intensities have not been observed in the erector spinae (Tucker et al., 2009).

Alterations in the distribution of upper trapezius muscle activity are also observed when an isometric contraction is sustained for a long time period, resulting in fatigue. Consider the example provided in Figure 3 which shows a progressive shift of activity within the upper trapezius muscle during a task of sustained isometric shoulder abduction in an asymptomatic person (Falla and Farina, 2008) or Figure 4 which shows a change in the distribution of activity over the lumbar erector spinae muscle during a fatiguing sustained lumbar flexion contraction (Tucker et al., 2009). Similar observations have been made in other studies (e.g. Abboud et al., 2015, 2014; Sanderson et al., 2019). Importantly, an association between endurance time and the extent of redistribution of muscle activity in the trapezius was shown in asymptomatic participants (Farina et al., 2008)(Figure 5). Likewise, a study which investigated the spatial distribution of lumbar erector spinae activity and redistribution of activity during a trunk extension endurance task, showed that those who displayed a larger redistribution of activity were able to sustain the contraction for longer (Sanderson et al., 2019b)(Figure 6). Similar findings of positive association between the variability in the spatial distribution of EMG amplitude and fatigue were reported during a prolonged sitting task, where participants with larger spatial variability reported less perceived exertion (Ringheim et al., 2014). Taken together, these studies suggest an association between the extent of adaptation of muscle activation under load and functional performance in pain-free individuals, confirming the physiological significance of such findings.

A redistribution of muscle activity is also commonly observed in pain-free individuals during dynamic contractions. Consider Figure 7 which demonstrates a shift of activity towards more cranial regions of the trapezius muscle when lifting a 1 kg box between shelves positioned at hip and shoulder height (Falla et al., 2007). A further example was described in a study which

examined the spatial distribution of activity within the lumbar erector spinae during a repeated lifting task performed for three minutes (Falla et al., 2014). Similar to what has been observed in isometric and standardized dynamic tasks, localized regional activation of spinal muscles has been documented during activities such as playing string instruments (Afsharipour et al., 2016; Cattarello et al., 2018) and during rowing (Readi et al., 2015). Interestingly, large redistributions in cranio-caudal activation within the lumbar extensors were also described in elite rowers during progressive exercise bouts performed on a rowing ergometer (Readi et al., 2015). Overall, these studies show that regional activation can be observed in spinal muscles during isometric, dynamic and functional tasks. Critical to this current review, recent work has shown that this physiological phenomenon of spatially re-distributing activity within a muscle or muscle region can be altered in people with neck or low back pain (LBP).

Reduced redistribution of muscle activity in people with spinal pain

For many of the examples given above which describe redistribution of muscle activation throughout isometric or dynamic contractions, or during functional tasks, studies have also confirmed that the observed phenomenon was not present or was at least reduced in a cohort of participants with chronic pain. For instance, work showed significantly less redistribution of trapezius muscle activity during sustained shoulder abduction in people with chronic neck symptoms (Falla et al., 2010)(Figure 8). Similarly, HDEMG recordings revealed that individuals with fibromyalgia have an impaired ability to redistribute the activation between cranial and caudal regions within the upper trapezius during isometric contractions (Gerdle et al., 2010), and that this lack of redistribution is moderately associated to pain intensity (Holtermann et al., 2011). Finally, differences in regional activation were also reported between people with and

without myofascial trigger points, with symptomatic individuals preferentially activating a more caudal region of the upper trapezius compared to pain-free controls (Barbero et al., 2016). Compared to pain-free participants, people with LBP were shown to engage different regions of the lumbar erector spinae during sustained back extension, reflecting less efficient activation of their muscles (Sanderson et al., 2019b). Specifically, those with LBP showed relatively greater activation of cranial regions of the lumbar erector spinae which contrasted to the pain-free participants, which displayed a more even activation of their erector spinae (Sanderson et al., 2019b) (Figure 9). In addition, the LBP participants displayed less redistribution of lumbar erector spinae activity across the sustained task. This reduced ability to redistribute muscle activation was associated with significantly lower endurance in this group (Controls: 283.0 ± 33.0s versus LBP: 186.2 ± 72.3s). A further example is illustrated in Figure 10 which demonstrates reduced task-induced variations in the distribution of activity across back muscle regions in individuals with LBP during a repeated lifting task (Falla et al., 2014). Specifically, in contrast to the pain-free participants which demonstrated a caudal shift of lumbar erector spinae over the duration of the 3-min lifting task, the LBP group displayed an unaltered distribution of muscle activity despite an overall increase in EMG amplitude over the task duration. Interestingly, this lack of variability in the distribution of muscle activity observed for the participants with LBP occurred concomitantly with an increase in LBP, reduced lumbar movement and was associated with increased pressure pain sensitivity of the lumbar region immediately following the task. Decreased redistribution of activation within the low back extensor muscles has also been identified in individuals with LBP performing a modified version of the Sorensen test (Abboud et al., 2014); furthermore, those without LBP were able to increase the variability of the location of activation throughout the test to a much larger extent than

symptomatic individuals. In this study, altered redistribution of activation also tended to be associated to clinical outcomes, including disability and pain. Altered regional activation of the lumbar erector spinae were also identified when comparing competitive rowers with and without a history of LBP during progressive exercise bouts performed on a rowing ergometer (Martinez-Valdes et al., 2019); more cranial regions of the lumbar erector spinae were recruited by asymptomatic rowers at higher loads, whereas more caudally-located regions were progressively recruited by rowers with a history of LBP. One study demonstrated that altered regional activation was not present when people with LBP performed a sustained sitting task (Ringheim et al., 2019) suggesting that the altered regional activation seen in other studies is task-specific.

Of relevance, studies using experimentally induced pain in healthy volunteers (i.e. intramuscular injection of hypertonic saline), have confirmed that nociception induces an alteration in the distribution of muscle activity, similar to what is seen in people with LBP or neck pain. For instance, when hypertonic saline is injected into the upper trapezius muscle, the normal re-distribution of muscle activity seen for the trapezius during dynamic or sustained contractions before pain induction, becomes substantially reduced or even absent during acute pain, similar to what is seen in people with chronic pain (Dideriksen et al., 2016; Falla et al., 2017, 2009, 2008; Liew et al., 2019). Interestingly, these pain-induced adjustments can be observed irrespective of the location of noxious stimulation (Dideriksen et al., 2016). Importantly, such observations indicate that nociception is likely the initial trigger for the reduction or lack of redistribution of muscle activity noted in people with chronic pain when performing sustained or repetitive tasks.

Clinical relevance

In each of the studies that found differences between people with and without spinal pain, participants performed repetitive tasks or sustained task by maintaining the same type of activation of their muscles across the duration of the task. The long-term consequence of this strategy could be an overload of some muscle fibers and as a further consequence, possibly a perpetuation or recurrence of LBP. Repetitive tasks are indeed considered an important risk factor for initiation, maintenance and recurrence of pain (Wai et al., 2010). The less focal activation observed in asymptomatic people, and their ability to redistribute activity to different regions within the muscle during sustained or repetitive tasks, indicates a biomechanically more favourable contraction by distributing the load over a larger muscle volume. Collectively these findings prompt exploration of HDEMG biofeedback as a tool to induce variability in muscle activity and this should be explored further for people with chronic musculoskeletal pain.

It should be noted however, that not all the participants with chronic pain behaved in the same way reflecting the very common observation of heterogeneity of presentation in people with chronic musculoskeletal pain. In one of the studies reviewed above, 36% of LBP patients demonstrated what was considered to be a relevant caudal shift of the centroid of the EMG amplitude map during the lifting phase of the repetitive task, reflecting the muscle strategy observed in asymptomatic people (Falla et al., 2014).

Conclusion

By describing the regional activation within muscles, HDEMG provides unique information on the neuromuscular adaptations that can occur in people with spinal pain. Studies have shown that most individuals with chronic neck or back pain do not vary the activity of their

muscles during sustained or repetitive contractions. This suggests that specific regions within muscles or muscle groups may become overloaded potentially contributing to earlier fatigue and persistence of their symptoms. Clinical studies are needed to determine whether exercise interventions and HDEMG biofeedback can be used to modify the pattern of muscle activation in patients with chronic pain, and whether this results in improved clinical outcomes. Methodological studies, such as the identification of the minimal number of electrodes needed to identify altered regional activation in patients with spinal pain, are needed to facilitate the application of HDEMG in clinical settings.

FIGURE CAPTIONS:

Figure 1: Example of regional activation within the trapezius muscle. Left: position of the high-density electrode grid with an 8mm inter-electrode distance. Middle: EMG signals collected by the different electrodes. Right: EMG amplitude distribution calculated as the root mean square calculated from single differential signals. The amplitude value (root mean square) of each channel is color-coded according to the bar on the right; the red/orange pixels in the middle rows of the grid indicate that the EMG amplitude is higher for the trapezius fibers under those electrodes compared to those in other muscle regions.

Figure 2: The colormaps (monopolar root mean square amplitude distributions, 10mm inter-electrode distance) represent the distribution of EMG amplitude over the lumbar erector spinae in different participants performing a lumbar extension task in a seated position. Clear differences in amplitude distribution can be observed between participants, with preferential activation of different regions along the cranial-caudal and the medio-lateral direction. The circles represent the centroid which is calculated from all channels of the HDEMG grid. The crosses represent the centroid calculated from channels above 70% of the peak EMG amplitude values of each map, as described in (Vieira et al., 2010). The distance between the centroid calculated on channels above 70% of the peak and the center of the colormap is in the order of centimeters, resulting in centroids located closer to the region where large activation can be observed visually. Instead, centroids calculated on the same distributions but on all the channels are generally only few millimeters distant from the center of the colormap. Despite large differences in the amount of shift, the coordinates of the centroids calculated using the two methods are highly correlated (R=0.96 for both medio-lateral and cranio-caudal directions).

These data exemplify how the direction of the shift of the centroid can be used to represent different EMG amplitude distributions, although the amount of shift can be minimal depending on how the centroid is calculated.

Figure 3: Representative topographical maps of the EMG amplitude recorded from the upper trapezius muscle of an asymptomatic person (A). Maps (root mean square calculated on single differential signals, 8mm inter-electrode distance, interpolation by a factor 8) are shown for the first, middle and last 5 s of a 60 s sustained shoulder abduction contraction (B). Colors are scaled between the minimum and maximum amplitude values. Areas of dark blue correspond to low EMG amplitude and dark red to high EMG amplitude. Note the progressive shift of activity towards the cranial region of the muscle. Reprinted with permission from Falla & Farina. 2008

Figure 4: (A) An adhesive grid of 64 electrodes placed above the right paraspinal muscles between the level of the L5 and L2 spinal processes as pain-free participants performed a 6-min sustained contraction in standing with 20° forward flexion holding a weighted bar (7.5-kg load). B) Topographical maps (root mean square calculated on single differential signals, 8mm inter-electrode distance, interpolation by a factor 8) of the EMG amplitude obtained at the beginning and end of the 6 min sustained contraction. Note that the spatial distribution of activity changed over time during the sustained contraction with a shift toward the caudal direction of the lumbar region. Reprinted with permission from Tucker et al., 2009.

Figure 5: Significant correlation between the extent of the shift of the y-coordinate of the centre of upper trapezius muscle activity and the duration of a sustained shoulder abduction contraction in pain-free participants. Reprinted with permission from Farina et al., 2008.

Figure 6: Linear regression analysis confirmed a significant association between the extent of the shift of the y-coordinate of the centre of lumbar paraspinal muscle activity and the duration of the trunk extension endurance contraction in pain-free participants. Reprinted with permission from Sanderson et al., 2019.

Figure 7: Mean (± standard error) of the *y*-axis coordinate of the centroid of the upper trapezius EMG amplitude map estimated at 10% intervals of a task involving lifting and lowering of a 1 kg box between shelves positioned at hip and shoulder height. Note the shift of the centre of activity depending on the extent of arm elevation. Reprinted with permission from Falla et al., 2017.

Figure 8: Representative topographical maps (root mean square calculated on single differential signals, 8mm inter-electrode distance, interpolation by a factor 8) of the EMG amplitude recorded from the upper trapezius muscle of an asymptomatic person and person with neck pain. Maps are shown for the first and last 5 s of a 60 s sustained shoulder abduction contraction. Note the progressive shift of activity towards the cranial region of the muscle for the asymptomatic person but not the patient with neck pain. Reprinted with permission from Falla et al., 2010.

Figure 9: (A) Representative topographical maps (root mean square calculated on single differential signals, 8mm inter-electrode distance, interpolation by a factor 8) of the EMG amplitude recorded from the lumbar erector spinae of an asymptomatic person and person with low back pain (LBP) during isometric trunk extension. Note relatively greater activity of cranial regions of the lumbar erector spinae relative to more caudal regions in this person with LBP. This contrasted to the pain-free participants which displayed a more even activation of their erector spinae. (B) Displays the position of the center of lumbar paraspinal muscle activity along the longitudinal axis for people with chronic LBP and pain-free participants across the duration of a trunk extension endurance contraction. Note that the activity was concentrated more

cranially across the entire task for the LBP participants. Reprinted with permission from Sanderson et al., 2019

Figure 10: Representative topographical maps (root mean square calculated on single differential signals, 8mm inter-electrode distance, interpolation by a factor 8) of the EMG amplitude recorded from the right lumbar erector spinae for a person with low back pain (LBP) and control subject for the start, mid and end of a repetitive lifting task. Note the shift of activity in the caudal direction for the control subject only. Reprinted with permission from Falla et al., 2014

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