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Muscle pain induces a shift of the spatial distribution of upper trapezius muscle activity during a repetitive task

A mechanism for perpetuation of pain with repetitive activity?

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MUSCLE PAIN INDUCES A SHIFT OF THE SPATIAL DISTRIBUTION OF UPPER TRAPEZIUS MUSCLE ACTIVITY DURING A REPETITIVE TASK: A MECHANISM FOR PERPETUATION OF PAIN WITH REPETITIVE ACTIVITY?

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ABSTRACT

Objective: An association exists between repetitive movements and neck-shoulder muscle pain. The mechanisms underlying this association remain unclear. This observational study investigated the effect of upper trapezius muscle pain on the distribution of upper trapezius activity during repetitive lifting. It was hypothesized that nociception would change the distribution of activity resulting in activation of muscle regions which would not normally be active during the task.

Methods: Healthy men repeatedly lifted a box with a cycle time of 3s for 50 cycles, at baseline, following injection of isotonic and hypertonic saline into the upper trapezius muscle and 15 mins after the last injection. High-density surface electromyography (EMG) was recorded from the upper trapezius using a grid of 64 electrodes. The EMG amplitude was computed for each location to form a map of the EMG amplitude distribution.

Results: During the painful condition, the overall EMG amplitude was lower compared to all other conditions ($p<0.05$) and in addition, the center of activity of upper trapezius was shifted towards the caudal region of the muscle ($p<0.01$), a region not normally active during the task. The described alterations of muscle activity likely play an important role in the perpetuation of pain during repetitive activity.

Discussion: Novel mapping of the spatial distribution of upper trapezius muscle activity showed that nociception induced a redistribution of activity during repetitive lifting. This knowledge provides new insights into the mechanisms underlying the perpetuation of pain with repetitive activity.

Keywords. Muscle pain, repetitive work, work-related musculoskeletal disorders, high-density EMG

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INTRODUCTION

Pain localized to the neck-shoulder region is an increasing problem in both general and working populations [1]. Muscle pain frequently affects the upper division of the trapezius muscle, and patients typically complain of dull pain and stiffness. A prospective study among healthy female packers indicated that within the first year of employment more than 50% of workers develop trapezius myalgia [2]. Similarly an investigation among both blue- and white-collar workers with pain symptoms in the upper quadrant reported the highest prevalence of myofascial trigger points in the upper trapezius muscle [3]. Epidemiological reviews provide strong evidence for an association between repetitive movements, awkward posture, and the development of neck-shoulder muscle pain [4-7]. However the mechanisms underlying these associations remain unclear. One likely mechanism could be pain induced changes in neuromuscular control during repetitive movements, for instance to protect the painful region, which could eventually perpetuate the painful condition.

Pain within the region of the trapezius muscle is known to limit maximal voluntary contraction, reduce endurance, and induce adaptive changes in muscle coordination during complex tasks [8-11]. Additionally, studies using high-density surface electromyography (EMG) have shown a change in the spatial distribution of trapezius muscle activity during sustained isometric contractions following noxious stimulation of the upper trapezius muscle via injection of hypertonic saline [12-14]. Furthermore, high-density EMG investigations revealed a different distribution of muscle activity in people with fibromyalgia [15-16] and that pain prevents the redistribution of muscle activity to different regions of the upper trapezius during sustained shoulder abduction in this patient group [17]. These findings suggest that nociception induces a change in the distribution of upper trapezius muscle activity during isometric tasks leading to suboptimal production of force and potential overload on specific muscle regions. However, whether or not nociception induces a change in the distribution of upper trapezius muscle activity during repetitive tasks is unknown. Such knowledge would further our understanding of the mechanisms contributing to ongoing pain with repetitive work activity.

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Here we investigate the effect of experimentally induced upper trapezius muscle pain on the distribution of upper trapezius muscle activity during a repetitive dynamic task. High-density surface EMG was utilized to provide topographical representations of the EMG amplitude, and relative adaptations in the intensity of activity within regions of the upper trapezius muscle were quantified. It was hypothesized that nociception would change the distribution of upper trapezius muscle activity resulting in activation of muscle regions which would not normally be active during the task.

MATERIAL AND METHODS

Subjects

Ten healthy male (age: 26.2 ± 3.1 years, height: 178.2 ± 6.3 cm, weight: 71.3 ± 9.2 kg) volunteers participated in this observational study after providing written informed consent. All participants were free of shoulder and neck pain, had no past history of orthopedic disorders affecting the shoulder or neck region and no history of neurological disorders. All subjects were right hand dominant. Ethical approval for the study was granted by the local Ethics Committee (200538) and all procedures were conducted according to the Declaration of Helsinki. All subjects completed the study.

Experimental procedure

Subjects attended a single laboratory session were required to lift a 1 kg box between shelves positioned at hip and shoulder height with a cycle time of 3 s for 50 cycles. Subjects were asked to sit tall on an angled cushion positioned on a table, in order to have both legs suspended and avoid possible compensation from leg muscles. An acoustic signal from a digital metronome was provided to the subjects during the task to standardize the duration of cycles. Subjects repeated the task four times: 1. baseline, 2. following injection of isotonic saline into the right upper trapezius muscle, 3. following injection of hypertonic saline into the right upper trapezius muscle and 4. 15 mins after the last injection (recovery). The rest interval between the repetitions was set to 15

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minutes starting from the moment when the pain caused by the injections disappeared. Subjects practiced the movement sequence for ~1 min without the weight prior to data recording.

Experimental Muscle Pain

Experimental muscle pain was induced by injection (27G cannula) of 0.4 ml sterile hypertonic saline (5.8%) into the upper division of the trapezius on the right side. Isotonic saline (0.4 ml, 0.9 %) was used as a control injection in a similar location. For both injections, subjects were positioned in comfortable sitting. The location of the injection was defined as 15 mm cranial to the line between the acromion and the spinous process of the seventh cervical vertebra. The bolus was injected over a 10-s period. The isotonic saline injection was given first however participants were blinded to each injection and were told that one or both might be painful.

Measures of Perceived Pain Intensity and Area

Participants were asked to verbally rate their level of perceived pain intensity on an 11 point numerical rating scale (NRS) anchored with “no pain” and “the worst possible pain imaginable”. Pain intensity ratings were obtained immediately following the injection and every 30 s until pain was no longer reported. Peak pain intensity and duration of pain were extracted. Participants documented their area of pain on a simple body chart illustrating an outline of a body. Pain drawings were subsequently digitized (ACECAD D9000 + Taiwan) and pain areas measured in arbitrary units.

Electromyography

Surface EMG signals were detected with a semi-disposable adhesive grid of electrodes (OT Bioelettronica, Torino, Italy). The grid consists of 13 rows and 5 columns of electrodes (1-mm diameter, 8-mm inter-electrode distance in both directions) with one absent electrode at the upper right corner (Figure 1). The position corresponding to the missing electrode was used as the origin of the coordinate system to define the electrode location. Prior to electrode placement, the main innervation zone location of the right upper trapezius was identified between the seventh cervical vertebra (C7) and the lateral edge of the acromion line with an array of 8 electrodes (silver bars, 5-

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mm long, 1-mm diameter, 5-mm inter-electrode distance). The electrode grid was placed with the 4th row along the line between C7 and the lateral edge of the acromion with the lateral electrode column 10-mm distant from the innervation zone location (Figure 1). The injections were performed lateral to the electrode grid (~ 10 mm) and corresponded to the 4th row of the grid.

The subject's skin was prepared by gentle local abrasion (Medic-Every, Parma, Italy) and cleaned with water. 30 µl of conductive gel was inserted into each cavity of the grid to provide electrode-skin contact. A ground electrode was placed around the right wrist.

The bipolar EMG signals were amplified (128-channel surface EMG amplifier, OT Bioelettronica, Torino, Italy; -3dB bandwidth 10-500 Hz) by a factor of 2000, sampled at 2048 Hz, and converted to digital form by a 12-bit analog-to-digital converter.

Signal Analysis

Surface EMG signals were off-line band-pass filtered (second order Butterworth filter; -3 dB bandwidth, 10-400Hz). 51 bipolar EMG signals along the direction of the muscle fibers were obtained from the grid (13 x 4 bipolar recordings with one absent electrode). Root mean square (RMS) values were computed from each bipolar recording from adjacent, non-overlapping signal epochs of 1-s duration. For graphical representation, the 51 values were linearly interpolated by a factor of 8 but only the original values were used for data processing and statistical analysis. To characterize the spatial distribution of muscle activity, the following variables were extracted from the 51 bipolar signals: RMS averaged over the 51 signals, entropy, and the two coordinates of the centroid of the RMS map (*x* and *y*-axis coordinates for the medial-lateral and cranial-caudal direction, respectively) [13,18]. The centroid of the amplitude map is the mathematical barycenter of the map. Entropy indicates the degree of homogeneity in activation, with higher values corresponding to more uniform distribution of the RMS values over the grid.

Four uniaxial accelerometers (two parallel and two perpendicular to the horizontal plane) were mounted on the box to obtain the start and end points of the cyclic movement. The signals from the accelerometers were rectified, averaged and low pass filtered (Butterworth 2nd order filter,

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anticausal, 10 Hz cut-off) in order to identify the instant of contact of the box with the shelf. A simple threshold on the resulting signal was sufficient to identify the contact instants of the box with each of the two shelves. This operation was necessary to extract the correct timing of the cycles and to compensate possible errors with respect to the timing provided by the metronome.

Each cycle was divided in 10 epochs of equal length and the EMG signals were analyzed separately for each epoch of each cycle. The epochs are indicated in the following paragraphs as percentages with respect to the cycle duration (e.g. 30% cycle indicates the third of the 10 epochs of a cycle). The EMG variables were then averaged across the 50 cycles for each epoch of the cycle.

Statistical analysis

One-way ANOVAs were applied to the duration, area and intensity of pain with condition (hypertonic, isotonic) as a factor. Repeated measures ANOVAs were applied to RMS, entropy and *x* and *y*-axis coordinates with condition (baseline, isotonic, hypertonic, post) and stage of cycle (10% intervals of the cycle) as factors.

Significant differences revealed by ANOVA were followed by post-hoc Student-Newman-Keuls (SNK) pair-wise comparisons. Results are reported as mean and standard deviation (SD) in the text and standard error (SE) in the figures. Statistical analyses were performed with SPSS Version 22.0 (IBM Corp., Armonk, NY, USA). Statistical significance was set at $p<0.05$.

RESULTS

Sensory characteristics

Peak pain intensity was greater following the injection of hypertonic (5.5 ± 1.8) compared to isotonic saline (0.9 ± 0.8, $p<0.00001$; Figure 2). Pain duration and area were significantly greater following hypertonic compared to isotonic saline injection (both $p<0.00001$). Total mapped pain areas were 0.25 ± 0.18 and 0.02 ± 0.05 (arbitrary units) for the hypertonic and isotonic saline injections respectively.

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Electromyography

Figure 3 illustrates the average EMG amplitude (averaged across the entire grid of electrodes) for each of the four conditions. An overall reduction in the amplitude of upper trapezius activity is evident in the painful condition compared to the other conditions. Consistent with this observation, the mean RMS was dependent on the interaction between condition and stage of the cyclic movement ($F=8.5$, $p<0.00001$). The mean RMS was lower during the painful condition compared to baseline, post and recovery during stages 30-70% of the cyclic movement (SNK: all $p<0.05$; Figure 3), stages when the muscle should have been most active.

The y-axis coordinate of the centroid of the EMG map was also significantly dependent on condition ($F=7.5$, $p<0.001$) with higher values observed during the painful condition compared to all other conditions (SNK: all $p<0.01$; Figure 4). This indicates that center of activity was shifted in the caudal direction in the painful condition. No differences were observed between the baseline, isotonic or recovery conditions ($p>0.05$).

Figure 5 provides representative EMG amplitude maps from a single subject extracted at 60% of the cycle for the four conditions. Note the overall reduced EMG amplitude and shift of activity away from the cranial direction in the painful condition. On the contrary the x-axis coordinate of the centroid of the EMG map did not differ between conditions ($p>0.05$; Figure 6).

Figure 7 illustrates the entropy measured from the EMG amplitude maps recorded for each cycle of the task from a single representative subject for all four conditions. Note that the EMG amplitude becomes more uniform in the painful condition. Accordingly, the entropy of the EMG amplitude was dependent on the interaction between condition and stage of the cyclic movement ($F=2.5$, $p<0.001$) with a higher percentage of entropy observed during the painful condition compared to all other conditions at stages 30-80% of the cyclic movement (SNK: all $p<0.01$; Figure 8). Entropy was also higher for the painful condition at stage 20% of the cycle compared to the isotonic and recovery conditions (SNK: both $p<0.05$).

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DISCUSSION

Noxious stimulation of the upper trapezius resulted in a shift of the distribution of activity towards the caudal region of the muscle during performance of a repetitive lifting task. This change in the distribution of activity to different regions of the muscle may have important implications for the perpetuation and worsening of neck-shoulder pain during repetitive tasks.

During the baseline and control conditions, there was a general increase in the amplitude of upper trapezius activity during the lifting phase of the task (stages ~30-70%). This was expected and is in line with the anatomical action of the muscle. Activation of the upper trapezius is essential for normal scapulohumeral rhythm during arm elevation [19]. Normal scapulohumeral rhythm requires upward rotation of the scapula which is provided by the force couple of the trapezius and serratus anterior, in order to prevent the rotator cuff tendon from impinging against the anterolateral acromion [19,20]. Moreover, the results revealed a shift in the distribution of activity towards the cranial region of the muscle during the elevation phase of the task. The relative adaptations in the intensity of activity within muscle regions may be attributed to variation in peripheral properties or in the control of motor units within a muscle. For example, since muscle fibers within the upper trapezius have non-uniform morphological and histological properties [21], an increase in the neural drive to the muscle would result in preferential activation of specific muscle regions. Most likely, motor unit recruitment or the discharge rate of the active motor units varied within the different regions of the muscle [22,23]. The cranial shift in the distribution of upper trapezius activity likely reflects a shift in activation towards the muscle fibers which have a better mechanical advantage to generate the upward rotation and elevation of the scapula with arm elevation. This pattern of upper trapezius muscle activation during the repetitive task was consistent between the baseline and control conditions and is in agreement with the characteristic increase in surface EMG amplitude towards the cranial region of the upper trapezius muscle with increasing force [24].

An overall reduction of upper trapezius activity was observed following noxious stimulation of the upper trapezius muscle. This observation is line with several studies which demonstrated that

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injection of hypertonic saline (experimental muscle pain), which excites nociceptive muscle afferents (group III and IV), reduces the activation of the painful muscle [13,25-27]. Reduced muscle activation implies that the nociceptive input reduced the net excitatory input to the population of motor neurons [28,29] which is likely due to decreased descending drive to the muscle or to pure spinal mechanisms, or more likely, a combination of both.

Novel to this study, we also observed a shift of the distribution of upper trapezius activity during performance of the repetitive task. Specifically, the center of trapezius muscle activity was shifted more caudally in the painful condition. This implies that regions of the muscle which would not normally be as active, became active in the painful condition and that regions which would normally be active (based on their anatomical action) became less active. This change resulted in more uniform activation of the upper trapezius muscle as seen from the entropy data. This new motor strategy may be seen as effective mechanism to "protect" the painful region [30,31]. However, based on anatomical considerations, the "new" pattern of trapezius muscle activation in the painful condition can be seen as inefficient motor strategy. Previous investigations of the distribution of upper trapezius muscle activity using high-density EMG have observed a shift in the distribution of activation towards the caudal region of the muscle during painful conditions, albeit during isometric shoulder abduction [12-14]. Additionally, people with fibromyalgia display activation of their upper trapezius which is centered more caudally compared to pain-free participants during sustained shoulder abduction [17]. Moreover, a recent study of people with low back pain showed that patients performed a repetitive task with a different distribution of lumbar erector spinae muscle activity compared to pain-free volunteers [32]. Although there may be a short term benefit of such an adaption as it allows the person to complete the motor task, the long term consequence of these altered motor strategies may be overload of muscle fibers and as a further consequence, perpetuation or recurrence of pain.

Hodges and Tucker [31] proposed a theory of motor adaptation to pain, which explained a large number of findings that were not fully explained by previous theories such as the Pain

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Adaptation [33] or Vicious Cycle [34] theories. One element of this new theory is that muscle activity is redistributed to minimize activity of the painful region with the aim of "protecting" the painful area. The current results support this theory since the shift of activity was away from the site of local noxious stimulation. However, other work has shown a shift of the distribution of muscle activity towards the caudal (painful) region of the upper trapezius during isometric shoulder abduction even when the site of noxious stimulation is in the caudal region [13]. Motor units in the caudal region of the upper trapezius have greater discharge rates during sustained shoulder abduction than motor units in cranial regions [22-23] which suggests that motor units in the caudal region have lower recruitment thresholds than those in the cranial region. Since nociception decreases the net excitatory drive to the motor neurons [28,29], the presence of pain in the upper trapezius is expected to reduce muscle activity predominantly in the cranial region, where motor units have higher threshold for activation. Thus when the upper trapezius muscle is painful, regardless of the location of pain, the adaptation of the upper trapezius aims preferentially to minimize activation of the cranial region; possibly because this region has higher pain sensitivity [35].

Clinical considerations

Repetitive movement is a physical risk for work-related musculoskeletal disorders including those of the neck-shoulder region [36]. The proportion of workers exposed to repetitive arm movement continues to increase [37]. Needless to say, musculoskeletal disorders located in the neck–shoulder region are associated with substantial socio-economic consequences [36]. Changes in the activation of upper trapezius have been observed in people with neck-shoulder disorders and include altered activation during repetitive tasks [38-40] and computer work [41], reduced ability to relax the upper trapezius following voluntary activation [39] and reduced rest periods of the upper trapezius during repetitive tasks [42]. Given the common complaint of upper trapezius muscle pain and the alterations of upper trapezius activity which have been frequently documented in people with neck-shoulder disorders, further studies investigating the basic effect of nociception on the activation of the trapezius muscle have been needed to better understand the potential associations between

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repetitive movement, pain and altered motor control. By applying state of the art, high-density surface EMG, the current work revealed a change in the distribution of upper trapezius activity during repetitive work when pain is present. These findings may be relevant for interpreting changes in trapezius activity in clinical pain conditions and offer further insight into the hypothesis of overload of muscle regions and overexertion of low-threshold motor units in the presence of upper trapezius pain [43].

Methodological considerations

It is likely that the noxious stimulation of the upper trapezius induced a reorganization of the activation of other neck, shoulder and/or scapular muscles [25,45]. However, we preferred to have more channels placed over the trapezius muscle in order to generate a larger mapping of trapezius muscle activity rather than having a reduced number of electrodes spread over multiple muscles. Since upper trapezius activity changed in the painful condition, it is also possible that scapular motion was altered during the lifting task. Motion analysis of the upper quadrant may have strengthened the current observations. The lack of kinematic analysis of task performance does not allow us to conclude that the task was performed in exactly the same way in the painful condition i.e. that the subjects were doing the same movements, although using different muscle patterns. Even though the general posture and performance of the subjects were monitored throughout by investigators to ensure consistency, we cannot exclude subtle variations in movement between conditions. Nonetheless, other studies using more constrained tasks have confirmed that the kinematics of the task can remain the same in painful and control conditions despite reorganization of muscle activation [25,45].

The electrode grid was positioned in order to be within the region of the upper trapezius and achieve coverage of a large proportion of the upper trapezius in the longitudinal direction. In some cases the electrode grid may have covered a portion of the middle division of trapezius. However this would not affect the main conclusion of the study, as the middle fibers of the trapezius are not anatomically suited to provide scapular elevation with arm elevation.

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Experimental muscle pain provides a means to explore the effect of nociception on motor control in the absence of pathological changes within the muscle and joint. Thus for the purposes of the current study, this approach allowed us to specifically evaluate the effect of nociception on the distribution of upper trapezius muscle activity. However, different results may be seen in people with work-related neck-shoulder pain, especially in people with high levels of kinesiophobia where their motor strategy may be altered in a different way due to fear of pain provocation with movement. Although the sample size was small it is in line with previous experimental pain studies however, it should be noted that the subjects were young men and the results cannot necessarily be generalized to women or older persons. This is a limitation of the study especially considering the higher prevalence of trapezius myalgia in women [5]. Finally, a potential further limitation of the study is that the order of the injections was not randomized although, the participants were advised that one or both could be painful. Moreover a recovery condition was included.

Conclusion

Repetitive tasks are an important risk factor for initiation, maintenance and recurrence of neck-shoulder pain. This study revealed a different distribution of upper trapezius activity when a repetitive lifting task was performed in the presence of pain. This knowledge provides new insights into the mechanisms underlying the perpetuation of pain with repetitive activity.

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Contributors: DF, CC, RL contributed to the conception and design of the study. CC and RL collected the data. CC, DF and MB analysed the data. DF and MB wrote the first draft of the paper. All authors contributed to the interpretation of findings, revising the manuscript for important intellectual content, and approved the final version to be published. All authors had full access to all of the data (including statistical reports and tables) in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

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FIGURE LEGENDS

Figure 1: High-density surface EMG signals were detected using a semi-disposable adhesive grid of electrodes over the right upper trapezius muscle. The grid consists of 13 rows and 5 columns of electrodes with one electrode absent at the upper right corner. The electrode grid was placed with the 4th row along the C7-acromion line. The injection was performed lateral to the electrode grid (~ 10 mm) 15 mm cranial to the line between the acromion and the spinous process of the seventh cervical vertebra.

Figure 2: Mean (+ SE) pain intensity scores following injection of 0.4 ml of hypertonic saline and 0.4 ml of isotonic saline into the cranial of the upper trapezius.

Figure 3: Mean (± SE) of the average root mean square (RMS) estimated for each stage of the repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the EMG signals were analyzed separately for each epoch of each cycle. The EMG variables were then averaged across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-100%) with respect to the cycle duration. Significant difference between hypertonic saline condition compared to baseline: * $p<0.05$; significant difference between hypertonic saline condition compared to isotonic saline condition: # $p<0.05$; significant difference between hypertonic saline condition compared to recover condition: ‡ $p<0.05$.

Figure 4: Mean (± SE) of the *y*-axis coordinate of the centroid of the RMS map estimated for each stage of the repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the EMG signals were analyzed separately for each epoch of each cycle. The EMG variables were then averaged across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-100%) with respect to the cycle duration. Significant difference between hypertonic saline condition compared to baseline: * $p<0.01$; significant difference between hypertonic saline condition compared to isotonic saline condition: # $p<0.01$; significant difference between hypertonic saline condition compared to recover condition: ‡ $p<0.01$.

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Figure 5: Representative topographical maps (interpolation by a factor 8) of the EMG root mean square (RMS) value recorded for one subject during the stage 60% of the repetitive lifting task at baseline, following the injection of isotonic saline and hypertonic saline into the cranial region of the upper trapezius and following 15 min of rest after the last injection (recovery). Colors are scaled between the minimum and maximum RMS values. Areas of dark blue correspond to areas of low EMG amplitude and dark red to areas of high EMG amplitude. Note the overall decrease of EMG amplitude in the painful condition (hypertonic) and the general shift of activity towards the caudal region of the muscle.

Figure 6: Mean (± SE) of the *x*-axis coordinate of the centroid of the RMS map estimated for each stage of the repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the EMG signals were analyzed separately for each epoch of each cycle. The EMG variables were then averaged across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-100%) with respect to the cycle duration. No significant differences were identified.

Figure 7: Representation of entropy of EMG amplitude maps during each portion of each cycle in the four conditions of a representative subject. Each pixel of the map represents the entropy of the RMS map. Each column corresponds to each of the lifting cycles while each row represents a portion of the cycle. Each cycle was divided in 20 epochs of equal length for graphical reasons. Baseline, Isotonic and Recovery conditions show similar patterns of entropy with lower values between 30% and 60% of each cycle while the Hypertonic conditions shows higher values and a different distribution of values.

Figure 8: Mean (± SE) of the entropy (%) of the RMS map estimated for each stage of the repetitive lifting task. Each cycle was divided in 10 epochs of equal length and the EMG signals were analyzed separately for each epoch of each cycle. The EMG variables were then averaged across the 50 cycles for each epoch of the cycle. Data are expressed in percentages (0-100%) with respect to the cycle duration.

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Figure 1

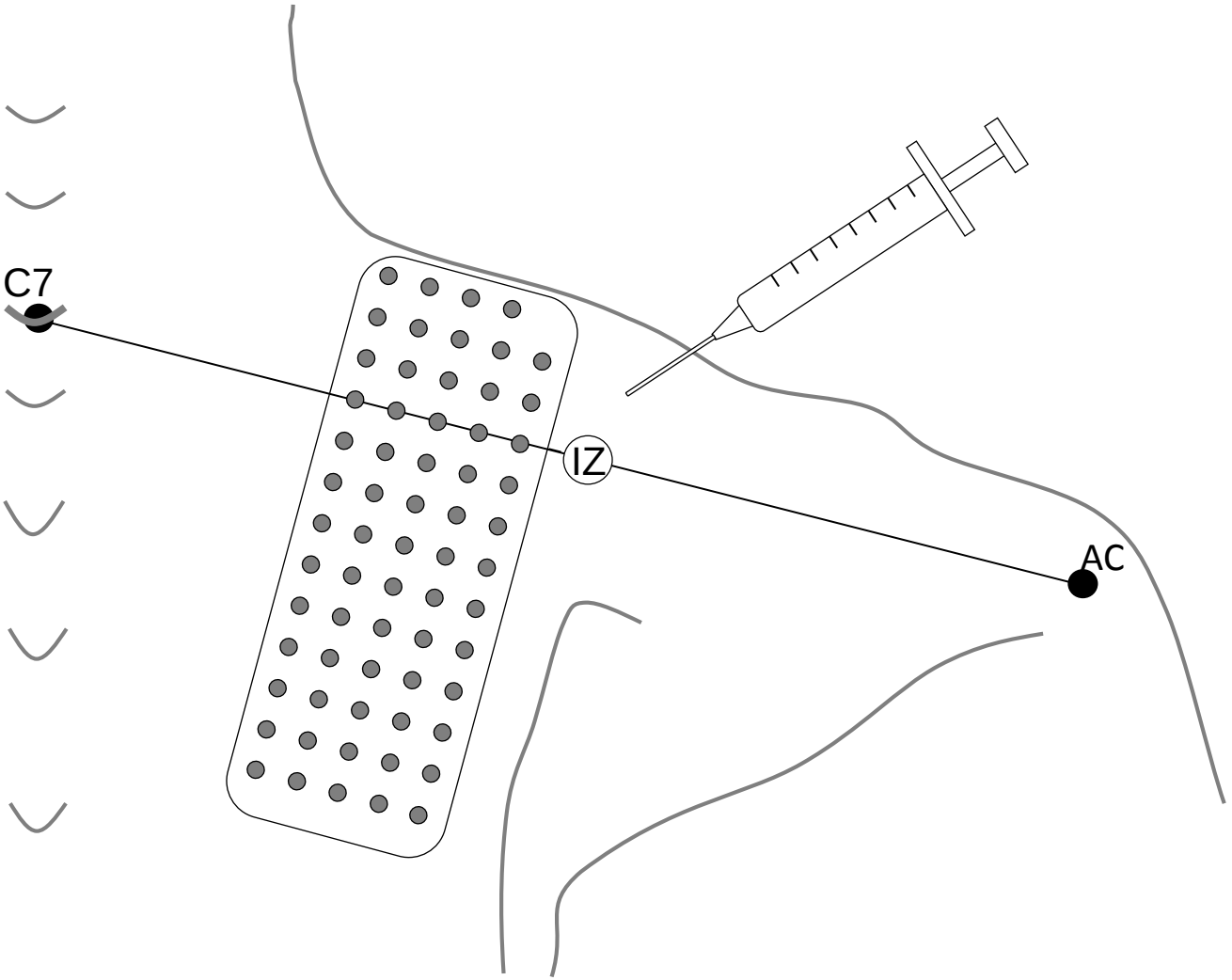

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Figure 2

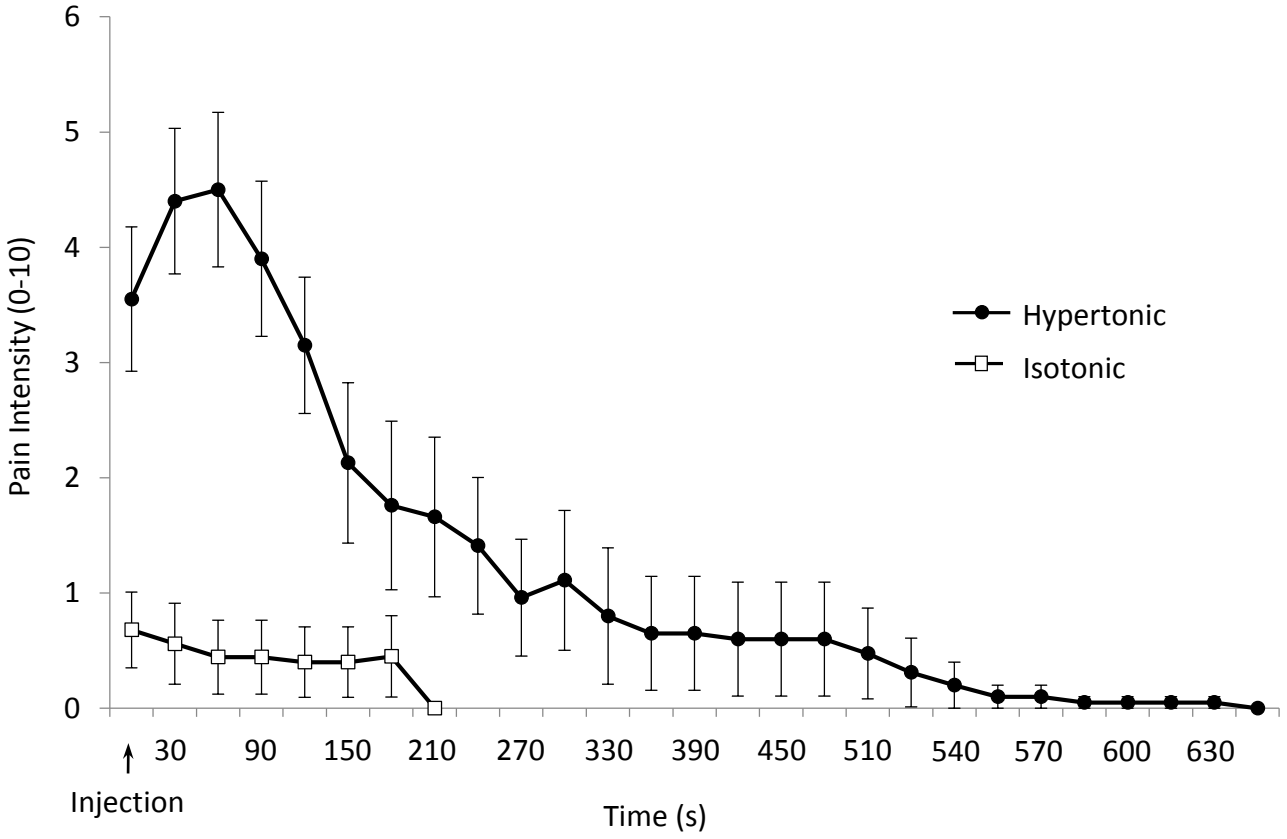

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Figure 3

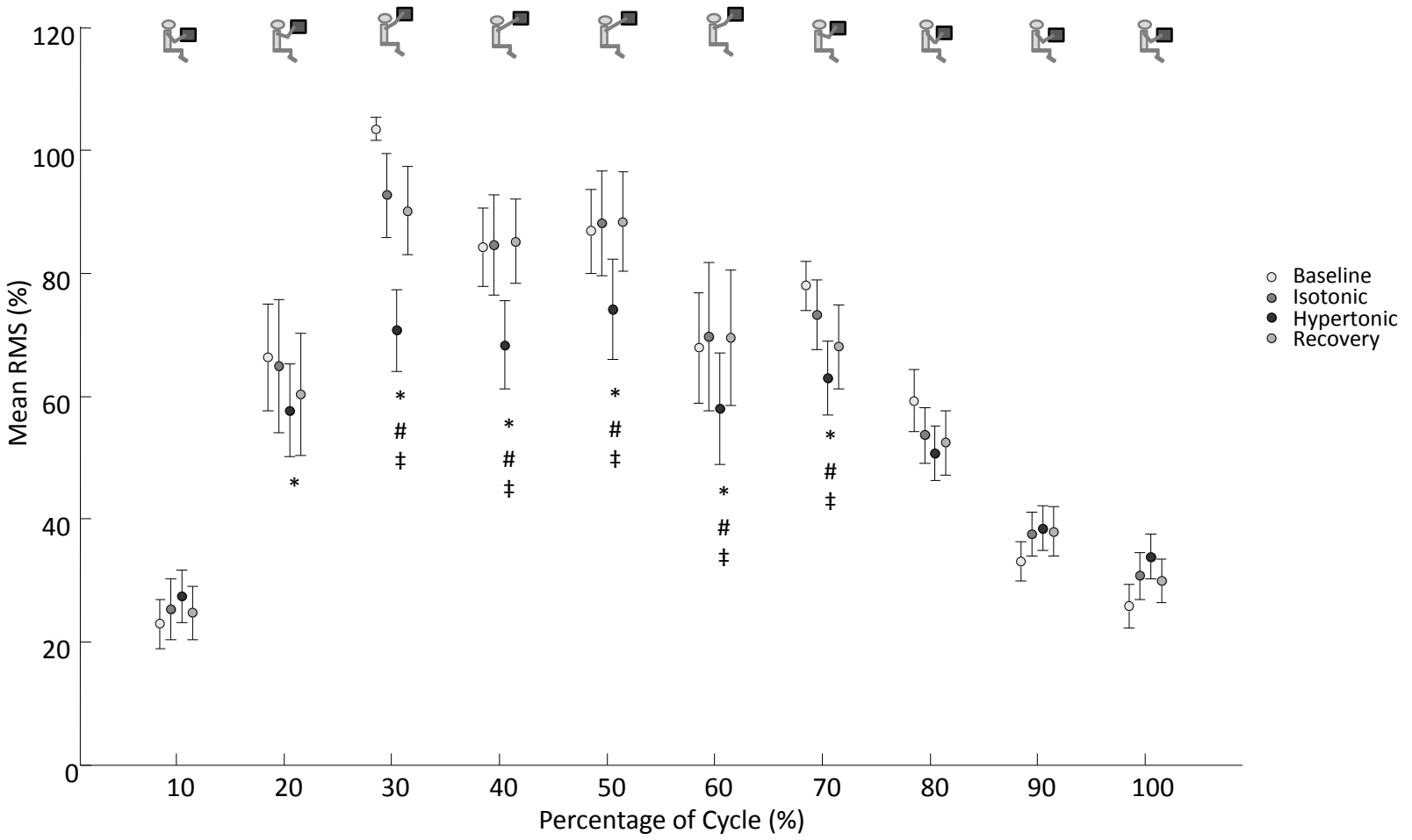

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Fig. 3

Figure 4

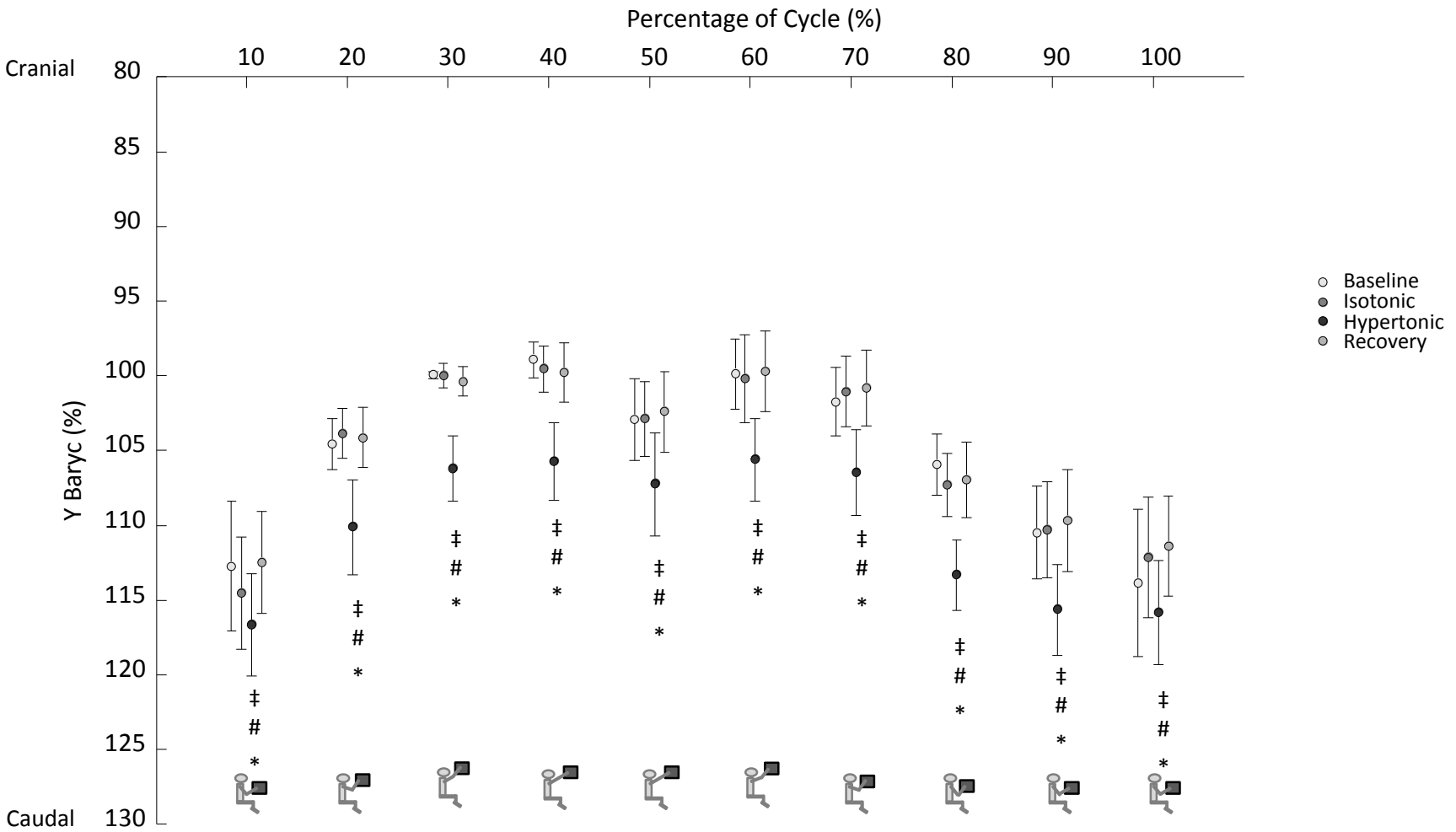

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Fig. 4

Figure 5

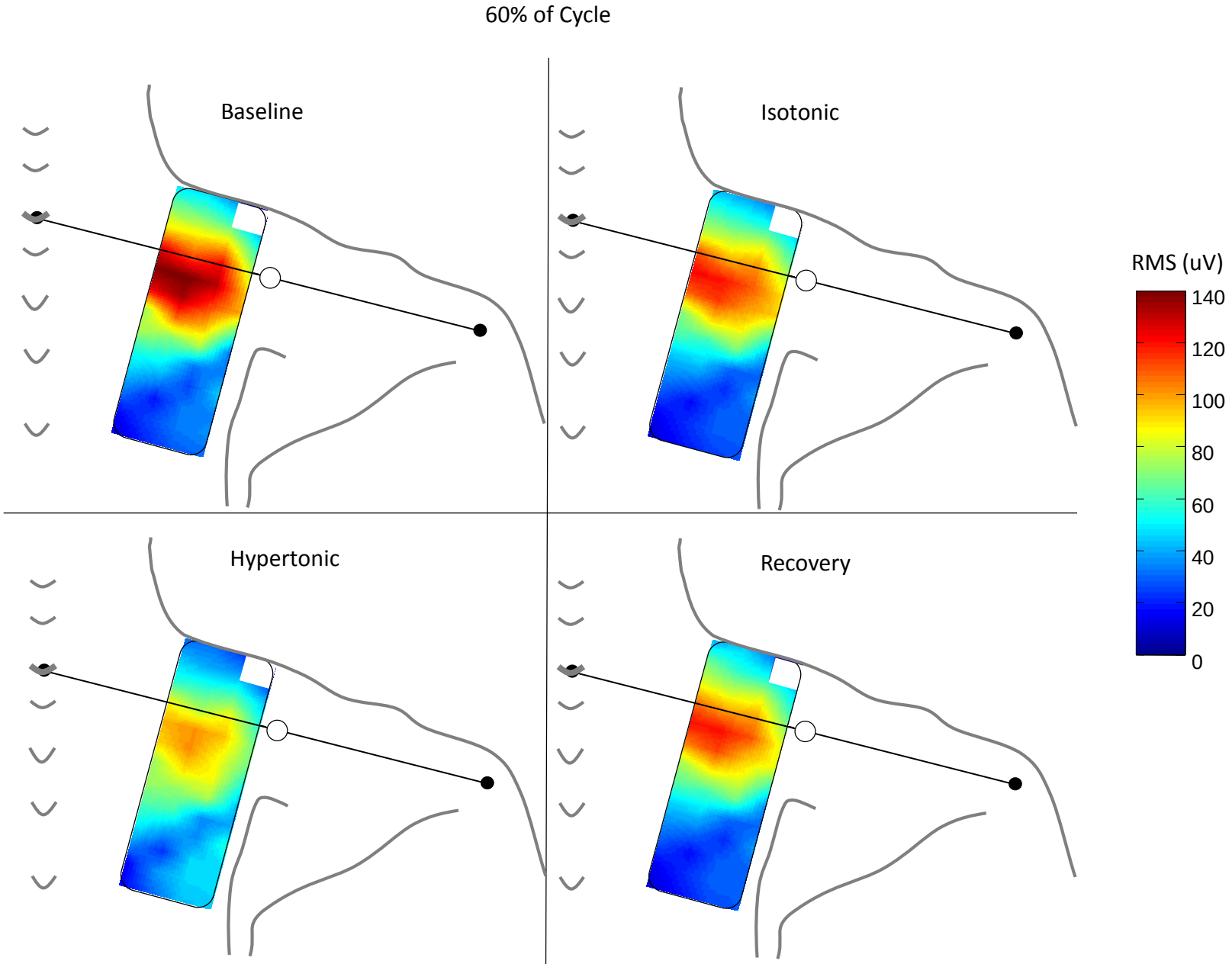

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Figure 6

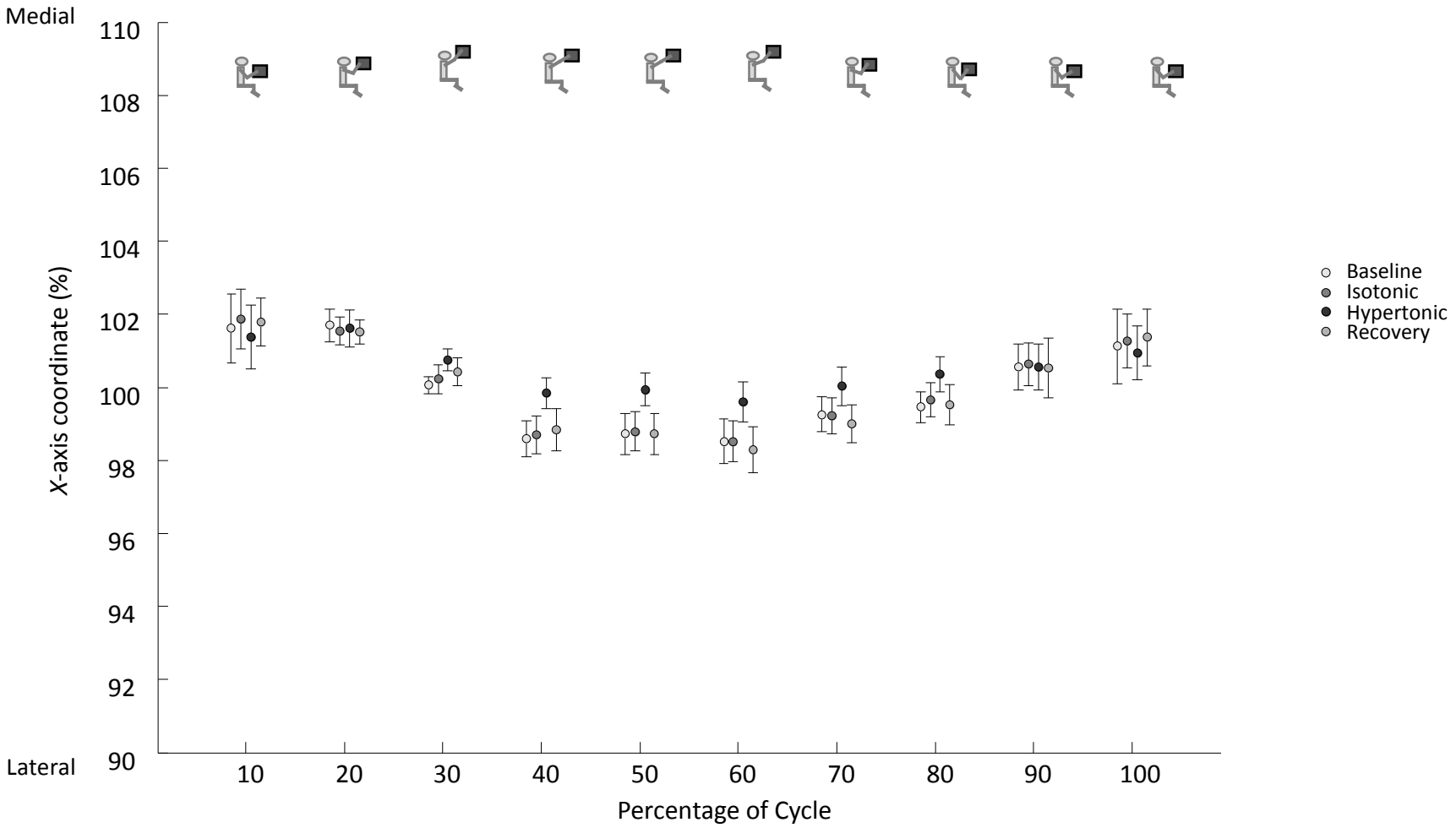

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Figure 7

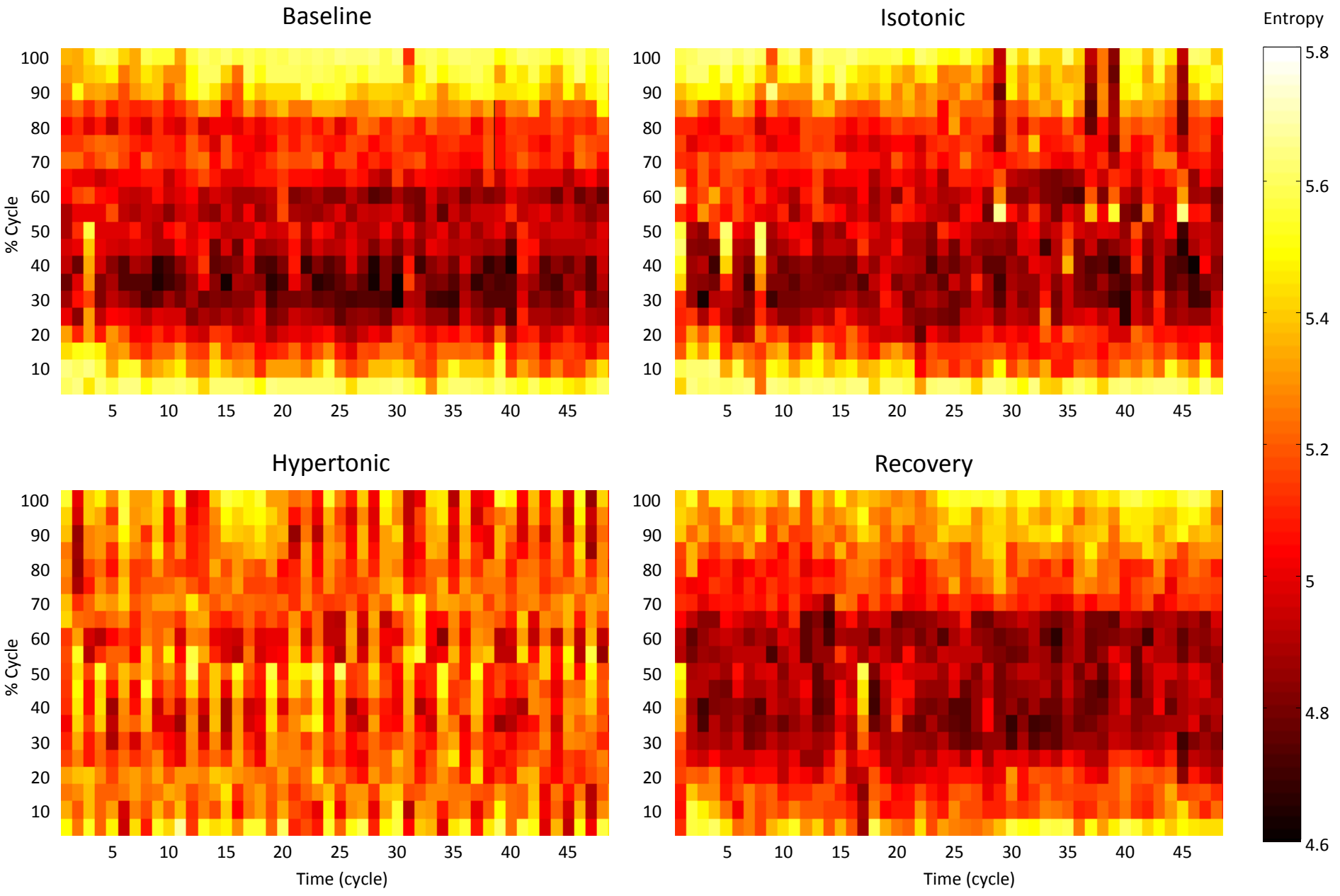

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Figure 8

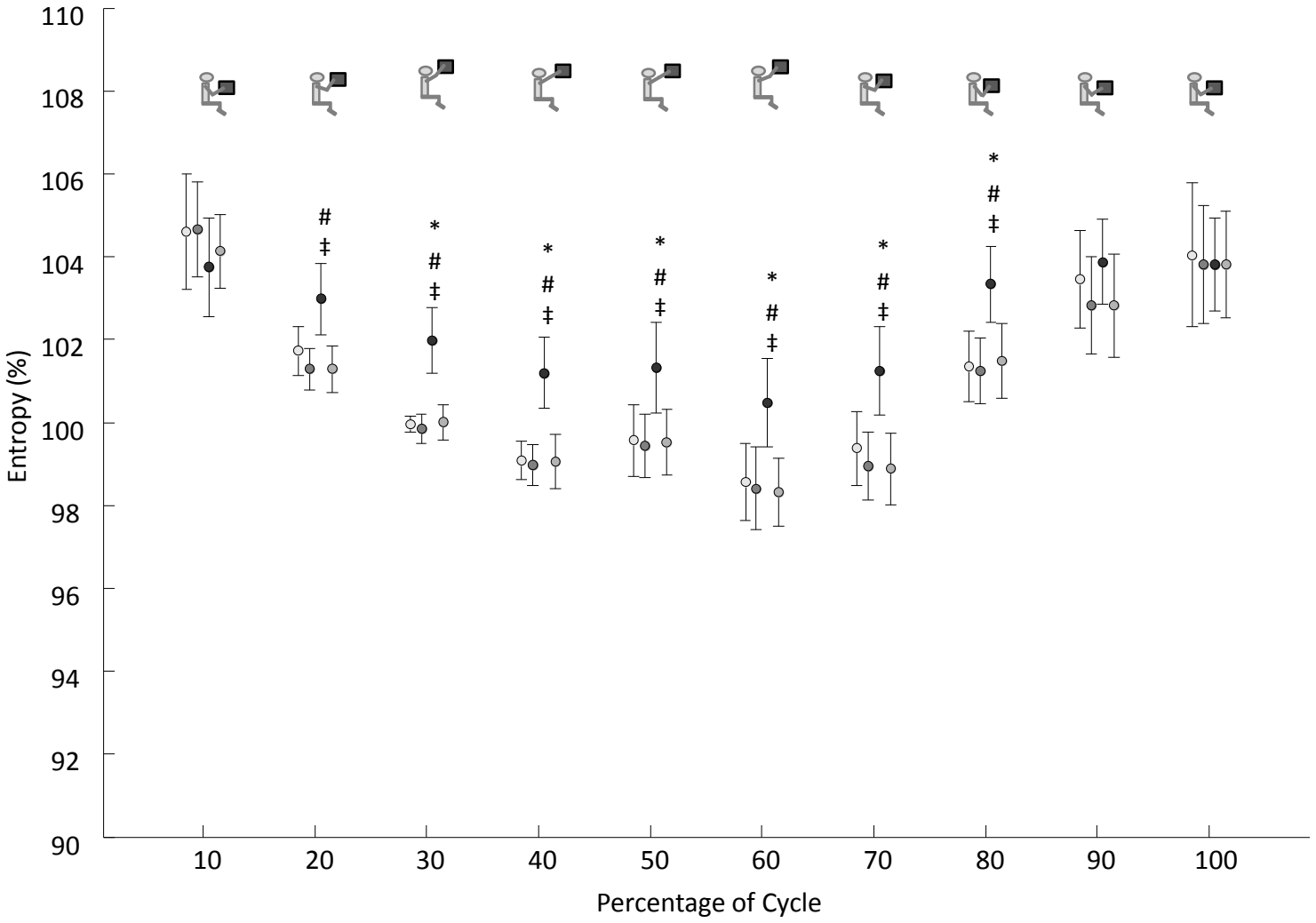

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Fig. 8