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Innervation zone locations distribute medially within the pectoralis major muscle during bench press exercise

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ABSTRACT

Changes in innervation zone (IZ) position may affect the amplitude of surface electromyograms (EMGs). If not accounted for, these changes may lead to equivocal interpretation on the degree of muscle activity from EMG amplitude. In this study we ask how much the IZ position changes within different regions of the pectoralis major (PM) during the bench press exercise. If expressive, changes in IZ position may explain the conflictual results reported on PM activation during bench press. Single-differential surface EMGs were collected from 15 regions along the PM cranial, centro-cranial, centro-caudal and caudal fibres, while 11 healthy participants gently, isometrically contracted their muscle. IZs were identified visually, from EMGs collected with the glenohumeral joint at extreme bench press positions; 20° and 110° of abduction in the horizontal plane. Except for 3 out of 88 acquisitions (4 detection sites × 2 glenohumeral angles × 11 participants), for which no phase opposition and action potential propagation were observed, IZs could be well identified. Group results revealed the IZ moved medially from 110° to 20° of glenohumeral joint abduction in the horizontal plane, regardless of the PM region from where EMGs were detected ($P < 0.01$). IZs were confined medially within PM, from ~20% to ~40% of the muscle-tendon unit length, and their position changed up to 13.3%. These results suggest that changes in the amplitude of EMGs detected mainly medially from PM may be not associated with changes in the degree of PM activity during bench press.

1. Introduction

Surface electromyography has been extensively used to investigate the pattern of pectoralis major (PM) activation in resistance training studies. Attention is often focused on the effect of exercise variants on PM activation, such as trunk inclination, hand grip distance on the barbell and different training methods (Barnett et al., 1995; Glass and Armstrong, 1997; Gomo and Van Den Tillaar, 2016; Keogh et al., 1999; Lauver et al., 2016; Lehman, 2005; Mookerjee and Ratamess, 1999; Sakamoto and Sinclair, 2012; Snyder and Fry, 2012; Trebs et al., 2010). Notwithstanding such well-conducted research, contradictory findings on the pattern of PM activation have been reported. For example, while Glass and Armstrong (1997) did not observe a significant effect of bench press inclination on the degree of activation of the PM clavicular region, Trebs et al. (2010) observed greater activation of this region for more inclined bench press positions. Whether such discrepancies indicate different patterns of PM activation between individuals or are possibly attributable to a broad spectrum of well-described limitations in surface electromyography remains an open issue.

Inferences on the pattern of PM activation are usually drawn from variations in the amplitude of surface electromyograms (EMGs). There is however a number of factors limiting the interpretation of changes in EMG amplitude in terms of variations in the degree and timing of muscle activation (Farina, 2006; Vigotsky et al., 2018). Muscle fibre orientation, thickness of subcutaneous tissues and the proximity of electrodes to tendon regions and to the innervation zone (IZ) location are some examples of non-physiological sources affecting the amplitude of EMGs (Farina et al., 2004). In particular, studies using arrays of electrodes have consistently reported spurious decreases in the amplitude of bipolar EMGs when detected nearby the muscle IZ (Nishihara

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et al., 2013; Rainoldi et al., 2004). This issue is especially critical in dynamic contractions or when comparing the amplitude of EMGs collected for different joint angles, given the relative position between IZ and electrodes changes with changes in joint angle (Farina et al., 2001). Innervation zone displacement has been indeed quantified for the neck muscles (Falla et al., 2002), facial muscles (Lapatki et al., 2006) and muscles in the lower and upper limbs (De Souza et al., 2017; Martin and MacIsaac, 2006; Nishihara et al., 2013). Similar quantifications seem nevertheless undocumented for the PM muscles.

Here we therefore investigate how much the IZ position changes in the PM muscle during bench press exercise. We specifically collect EMGs from multiple PM regions to quantify i) the IZ position in different cranio-caudal regions and ii) how much IZ position changes during the bench press exercise. Given the wide range of glenohumeral joint motion reported during bench press execution, and in agreement with previous reports on other muscles (Martin and MacIsaac, 2006; Nishihara et al., 2013; Rainoldi el al., 2000), we expect to observe IZ shifts of at least half a centimeter. In addition to enlightening researchers and practitioners on the validity of previous EMG results, addressing this issue would potentially assist in the acquisition and interpretation of EMGs collected from PM.

2. Methods

2.1. Participants

Eleven healthy, male subjects (mean ± S.D.: 27.2 ± 5.0 years; 174.2 ± 7.8 cm; 77.5 ± 5.4 kg) were recruited to participate in the study after providing written informed consent. Previous experience with bench press exercise (at least 1 year) and lack of injuries in elbow and shoulder joints at the occasion of experiments were inclusion criteria. The study was conducted in accordance with the latest revision of the *Declaration of Helsinki* and approved by our University Hospital Ethics Committee (HUCFF/UFRJ – 204/17).

2.2. Experimental protocol

While laying comfortably on a flat bench in supine position, participants were instructed to perform four gentle isometric contractions against a fixed barbell in two different glenoumeral joint conditions (Fig. 1A): (i) 110° of abduction in the horizontal plane; (ii) 20° of abduction in the horizontal plane (with elbow joint slightly flexed). These joint angles have been shown to roughly define the range of motion during the bench press exercise (~90°; Chou et al., 2012). Even though we could not measure the intensity of isometric contractions, visual inspection of EMGs revealed the contraction intensity was sufficiently high, likely greater than 10% of the maximal (Nishihara et al., 2013), to allow the appreciation of action potentials of different motor units in the surface EMGs. During contractions, the barbell grip was defined as 200% of the biacromial distance (Lehman, 2005). The barbell was aligned to the midpoint of the sternum and the glenohumeral joint was abducted by 80° (frontal plane). Each contraction lasted 10 s with a rest period of 3 min and a goniometer was used to ensure the joint angles were consistent across trials.

2.3. Electrode placement and EMG recordings

Surface EMGs were collected with a dry array of sixteen silver-bar electrodes (10 mm inter-electrode distance; LISiN-Politecnico di Torino, Turin, Italy). Since PM covers a broad area, EMGs were detected from four, cranio-caudal PM regions (Fig. 1B). First, the PM insertion into the intertubercular sulcus of the humerus bone was marked on the skin with the aid of ultrasound imaging (10 MHz B mode linear probe with 40 mm width, 70% gain and 7 cm depth view; Logiq-e; GE Healthcare, USA). The manubrium and the xiphoid processes were identified by palpation and the distance between them was considered to define the sternum length. *Reference lines* (RL) connecting four equally spaced sites along the sternum length (*cranial*, *centro-cranial*, *centro-caudal*, *caudal*) to the PM muscle insertion were drawn on the skin (Fig. 1B). The dry array was then centred at and aligned parallel to the *caudal reference line*, with the first electrode placed as close as possible to the sternum. Subjects were asked to isometrically contract their PM muscles and EMGs were visually inspected. While keeping the centre of the array over the RL, its orientation was changed slightly until the propagation of action potentials could be clearly observed across electrodes (Cabral et al., 2018). This orientation was deemed parallel to the PM fibres. Finally, EMGs were detected with the dry array held at this location while the participant performed isometric contractions for 10 s. This

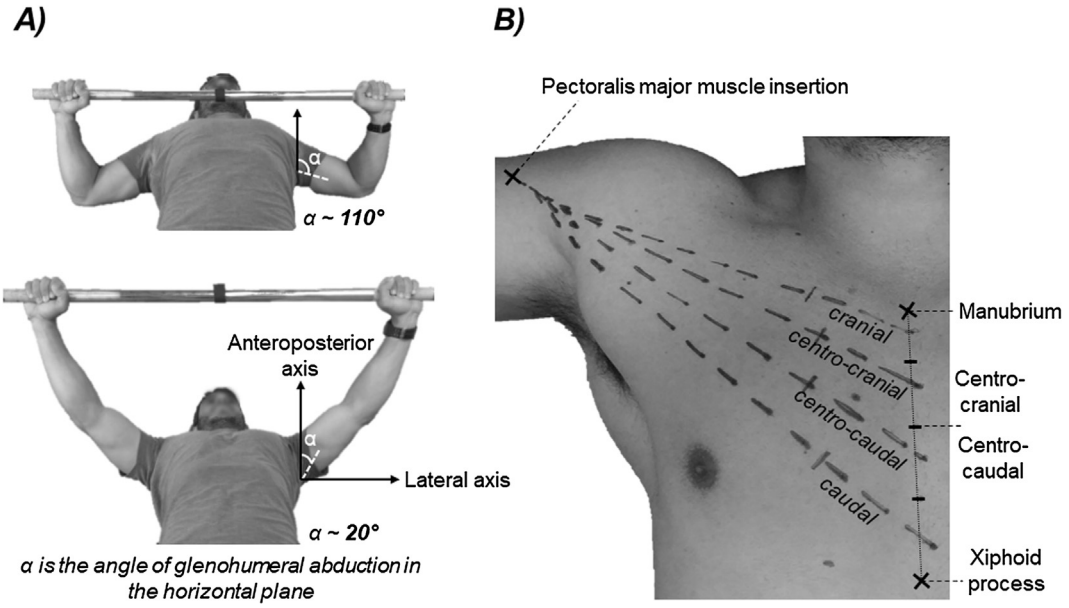

Fig. 1. Subjects' and electrodes' positioning. *A*, shows the two postures at which isometric conditions were applied. Glenohumeral joint abduction of 0° in the horizontal plane verifies when arms are aligned parallel to each other. *B*, shows the four reference lines of the Pectoralis Major (PM) muscle along which the surface array of electrodes was positioned. As illustrated in the panel, each line spanned a different, cranio-caudal PM region.

procedure was repeated for the other three detection sites (Fig. 1B) and for the two glenohumeral joint angles in random order; the array was centered over the RL for each region and its orientation was specifically set for each region. In 5 out of 11 participants, as we often did not observe propagation in PM *caudal* region, we used ultrasound to identify the orientation of PM *caudal* fascicles and then guide array positioning. The reference electrode was positioned at the olecranon process of the ulna and the skin was cleaned with abrasive paste and slightly bathed with water before positioning the dry array.

Surface EMGs were acquired in single-differential derivation and amplified by a variable factor, ranging from 5000 to 10,000 (10–900 Hz bandwidth amplifier; CMRR > 100 dB; EMG-USB2, OTBioelettronica, Turin, Italy). EMGs were digitised at 2048 samples/s using a 12-bit A/D converter (5 V dynamic range).

2.4. Calculating the innervation relative zone position

For each of the four detection sites (Fig. 1B), innervation zone location was identified through visual inspection of surface EMGs, after they were band-pass filtered with a fourth-order Butterworth filter (15–350 Hz cut-off frequencies). First, the IZ position was identified by inspecting EMGs over short epochs (~250 ms) throughout the 10 s contractions, with the glenohumeral joint at 20° of abduction in the horizontal plane. The IZ location was defined as the position of the channel (pair of electrodes) located between channels providing EMGs with clear phase opposition and after which propagation could be well appreciated (Fig. 2A; de Souza et al., 2017; Ullah et al., 2014), providing a resolution of half an inter-electrode distance (i.e., 5 mm) for the identification of IZ position (Rainoldi et al., 2004). This procedure was then repeated for the 110° of glenohumeral joint abduction in the horizontal plane, whereby a new IZ position was identified (Fig. 2B). Shifts in IZ position were computed as the difference between the IZ position identified for both glenohumeral joint angles (Fig. 2) and for each of the four detection sites (Fig. 1A). To compensate for inter-individual differences in PM size, both the IZ position from the sternum and its shift between glenohumeral angles were normalized with respect to the length of the *reference line* over which the array was centered.

2.5. Statistics

After ensuring the data normality (D'Agostino-Pearson normality test; $P > 0.07$) and homoscedasticity (Levene's test; $P = 0.62$), parametric analysis was considered for inferential statistics. The two-way repeated measures ANOVA was applied to compare main and interaction effect of the two glenohumeral joint positions (110° and 20° of abduction in the horizontal plane) and the four PM sites tested (*cranial*, *centro-cranial*, *centro-caudal* and *caudal*) on the IZ position. The Tukey's post-hoc test was used for paired comparisons. All analyses were carried out with Statistica (Version 10, StatSoft Inc., Tulsa, USA) and the level of significance was set at 5%.

3. Results

A total of 88 EMG acquisitions were analysed (4 detection sites × 2 glenohumeral angles × 11 participants). IZ position could not be identified for three cases, as no phase opposition and action potential propagation were clearly observed in the EMGs. As shown for a representative participant in Fig. 3, the IZ position could be clearly identified for the 85 remaining cases. Inspection of single-differential EMGs collected for this participant indicates the IZ position shifted towards the sternum when the glenohumeral joint was moved from 110° to 20° of abduction in the horizontal plane. IZ shifts amounted to 2.5, 2.5, 1.5 and 1.5 cm from the *cranial* to the *caudal* detection sites, respectively (cf. grey rectangles in Fig. 3).

Group data revealed a significant effect of glenohumeral joint angle on the shift of IZ position during the bench press exercise. For all PM detection sites considered, the IZ moved medially when the glenohumeral joint moved from 110° to 20° of abduction in the horizontal plane (two-way repeated measures ANOVA main effect; $F = 161.43$, $P < 0.01$, $N = 85$ cases). Shifts in IZ position ranged from 0.5 cm to 4 cm across all subjects and detection sites. These shifts respectively amounted to 1.4% and 13.3% of the length of reference lines. Individually for each PM region, the mean values of IZ displacement were 6.88 ± 3.19%, 7.01 ± 3.36%, 6.57 ± 2.54% and 5.53 ± 3.83% from cranial to caudal and did not depend significantly on the detection site (Fig. 4; ANOVA interaction effect; $F = 0.45$, $P = 0.72$). Post-hoc analysis indicated the IZ position changed medially for all PM regions from which EMGs were detected (cf. asterisks in Fig. 4). Overall, IZs were confined medially within PM, from ~20% to ~40% of the PM muscle-tendon unit length, and their position changed up to 13.3% when the glenohumeral joint moved from 20° to 110° (Fig. 4).

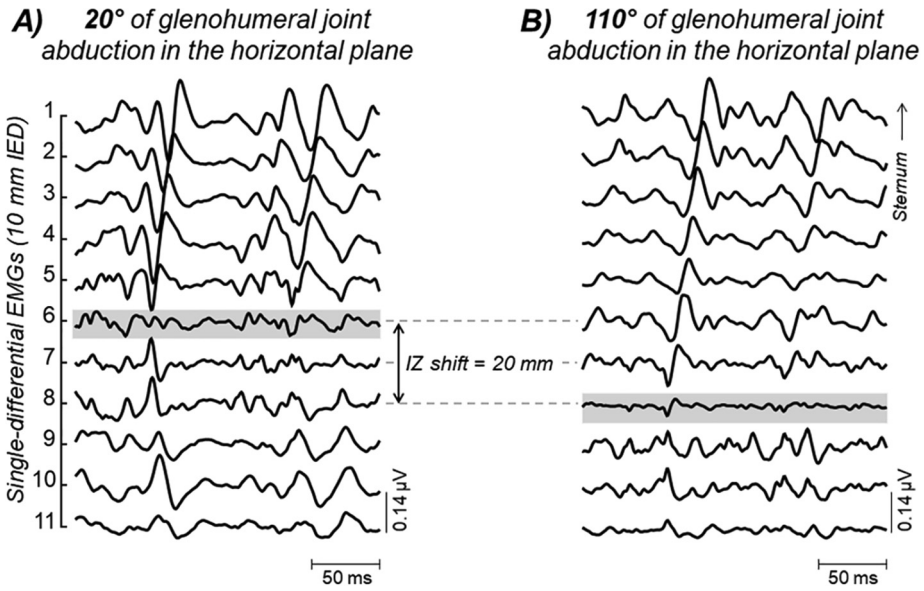

Fig. 2. Quantification of innervation zone (IZ) displacement. Single-differential EMGs detected from the cranial region of the PM muscle of a single participant are shown for the glenohumeral positions, 20° (A) and 110° (B) of abduction in the horizontal plane. Grey rectangles indicate the location of IZ identified for both glenohumeral positions (see text for information on the definition of IZ location). Displacement of the IZ was defined as the algebraic difference between its position identified at 20° and 110° of glenohumeral joint abduction in the horizontal plane. This representative example illustrates an IZ shift of 20 mm.

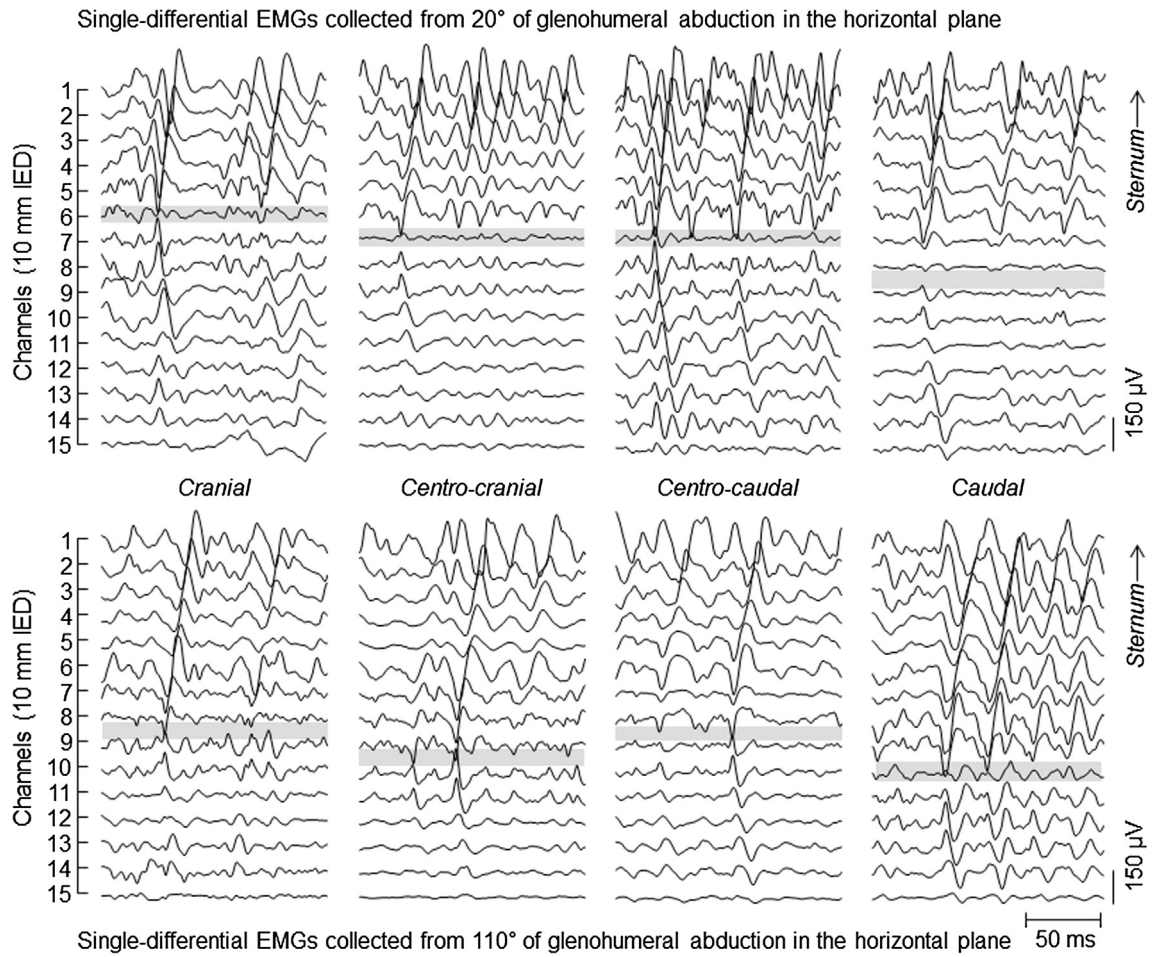

Fig. 3. Representative changes in IZ position. Raw single-differential EMGs (250 ms) and IZs (grey rectangles) are shown for a representative participant. Signals are shown separately for the four PM regions, from the cranial to the caudal (left to right) region, and for the two joint positions, 20° (top row) and 110° (bottom row) of glenohumeral joint abduction in the horizontal plane. For all PM regions, IZs displaced towards the sternum when the joint angle changed from 110° to 20°.

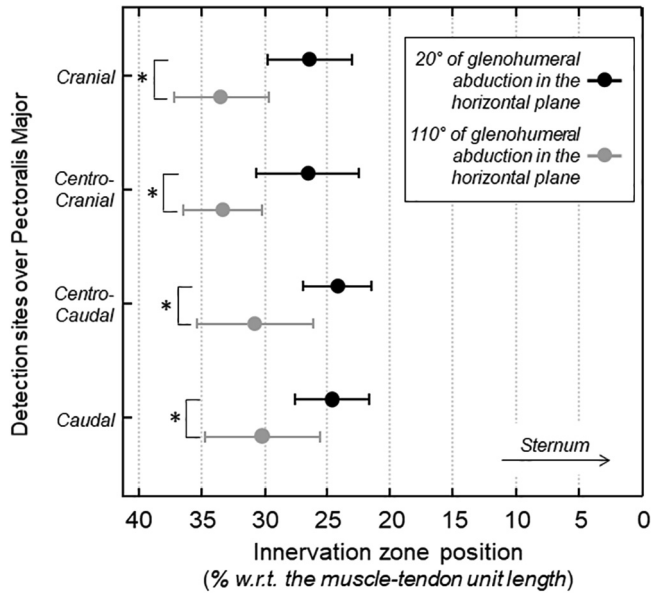

Fig. 4. Distribution of IZ positions across the PM muscle. The mean (circles) and standard deviation (whiskers) values of the normalized IZ position within each of the four PM regions are shown. Asterisks denote statistical significance at 5% between glenohumeral joint angles.

4. Discussion

The main purpose of the present study was to assess the shift in IZ location from multiple PM regions during the bench press exercise. Our results revealed the IZ position changed markedly (up to 4 cm) regardless of where EMGs were sampled from cranio-caudal regions in PM. Considering the attenuation of EMG amplitude when detected nearby the muscle IZ (Rainoldi et al., 2004), our results indicate equivocal inferences on PM activation may be drawn from surface EMGs if changes in IZ location are not accounted for during bench press exercise.

4.1. Why quantifying shifts in pectoralis major innervation zone with a linear array of electrodes?

The identification of the muscle innervation zone from surface EMGs demands the parallel alignment between surface electrodes and fibres. In fusiform muscles (e.g. biceps brachii) this condition is easily met (Martin and MacIsaac, 2006). In muscles with more complex architectures from an electromyographic perspective, this condition is either hardly verified (e.g., in in-depth pinnate muscles like gastrocnemius; Merletti et al., 2016) or demands the positioning of arrays of electrodes aligned in different directions across the muscle (e.g., in skin-parallel fibered muscles with a spectrum of fibre inclination like the vastii and trapezius; Gallina et al., 2013; Piccoli et al., 2014). Because of its pennate fibre architecture, the PM muscle falls in the latter case. One could therefore argue we could have used a bidimensional grid of

electrodes to map IZ location from the PM cranial to caudal region, as e.g. for the trapezius muscle (Barbero et al., 2013). We nevertheless decided to quantify shifts in IZ position with a linear array of electrodes for each of the four PM regions shown in Fig. 1. Given we did not find any evidence on where along the fibres the IZ could be located for different PM regions, positioning a single matrix of electrodes over PM could not reveal IZs along the whole cranio-caudal muscle region. This potential issue could be overcome by sampling EMGs from almost the whole PM fibre length. Indeed, with a long (15 cm) array of electrodes we were able to identify the IZ location for both glenohumeral joint angles and for the four muscle regions (Fig. 2), providing a representative indication of how much IZ position changed within PM during bench press exercise.

4.2. How much does the innervation zone position changes within the pectoralis major muscle?

The amount of IZ displacement depends mainly on how much the length of muscle fibres changes during movement. Two main factors account for the change in fibre length and thus in the IZ position with movement; the joint range of motion and muscle architecture. Overtly, the wider the joint moves the greater the fibres shorten/lengthen. Similarly, greater changes in fibre length are expected for muscles which fibres are less inclined with respect to the tendon. Indeed, for movements eliciting similar ranges of motion, the shift in IZ position reported for the fusiform biceps brachii muscle was on average 1 cm greater than that observed for the vastus medialis muscle (Martin and MacIsaac, 2006; Nishihara et al., 2013; Rainoldi el al., 2000). Although the ~90° range of glenohumeral motion considered in the current study was comparable to that considered in these previous studies and was fixed across subjects, representing well the range of motion often elicited during bench press (Chou et al., 2012), the range of IZ shifts we observed for the PM muscle was somewhat large (from 0.5 to 4 cm). Even after normalizing the IZ location with respect to the approximate length of PM fibres, measured with the glenohumeral joint at 110° of abduction in the horizontal plane, the relative range of shifts in IZ position was large (1.4–13.3%); inter-individual differences unlikely explain the differences in the amount of IZ displacement. The large range is presumably due to the pennate PM architecture. Given the glenohumeral movement during bench press is mostly within the horizontal plane, changes in fibre length are likely less expressive in the *caudal* than *cranial* PM region. Even though no interaction was observed between the amount of IZ shift and PM region, there was a tendency for smaller IZ displacements to be observed in the more caudal PM region (Fig. 4). Regardless of the variation in the amount of displacement, our results (Fig. 4) show the IZs reside from ~20% to ~40% of PM muscle-tendon unit length and their position may change up to 13.3% during bench press exercise.

4.3. Practical considerations

Before commenting on practical applications, we would like to make one relevant consideration concerning the generalization of results. In this study we did not control for the contraction intensity and did not quantify the IZ location for different PM regions concurrently. It is true that by having not controlled for the contraction intensity we are not able to state the results presented in Figs. 3 and 4 reflect the whole pool of motor units within each PM region. The IZ of motor units not recruited during the isometric contractions, because e.g. their recruitment threshold was above the contraction level, could be located in channels different from those where IZs were observed within each PM region and shifts by different amounts. On the other hand, it should be noted that, except for the external anal sphincter muscle (Enck et al., 2004), only one IZ is often observed when sampling surface EMGs along a single longitudinal skin region for different muscles (Nishihara et al., 2013; Gallina et al., 2013). Moreover, the potential existence of multiple IZs along each of the four PM regions would further highlight the importance of the issue we raise here: variations in the amplitude of EMGs collected from the PM muscle during the bench press exercise may be attributable to non-physiological sources.

There is an assortment of anatomical and geometrical factors accounting for the spurious changes in EMG amplitude (Farina et al., 2004; Vigotsky et al., 2018). In the current study we focused attention on the location and displacement of IZs in the PM muscle during bench press. When collected in proximity of the muscle IZ, the amplitude of bipolar EMGs is typically small and this small amplitude should be not regarded as necessarily indicative of low degree of activation (Rainoldi et al., 2004). Notwithstanding the sample of 11 subjects tested, here we show there is a considerably large skin region beneath which IZs may move and, thus, where variations in the amplitude of EMGs collected from the PM muscle may be mistakenly conceived as variations in the degree of activity. This possibly explains the controversial results on the pattern of PM activation during the bench press exercise. For instance, although positioning surface electrodes similarly (at 2nd intercostal space, midclavicular line), previous studies found distinct results on the effect of bench press inclination in upper PM portion activity (Glass and Armstrong, 1997; Trebs et al., 2010). Contributing to the initiatives aimed at providing recommendations for the good practice of bipolar surface EMG (Hermens et al., 2000; Barbero et al., 2012), our results seem to suggest EMGs sampled from the lateral half of the PM muscle would be less affected by changes in IZ position with glenohumeral movement. This indication is in agreement with the results from Barbero et al. (2012), who shown the IZ was located between 23% and 55% of a line traced between the xiphoid process and the acromion during isometric PM contraction at 30° glenohumeral abduction. Moreover, in the muscle lateral half the PM fibres span a smaller skin region. For a given inter-electrode distance, the number of fibres within the pick-up volume of a single pair of electrodes would therefore be greater (Vieira et al., 2017) if the pair was centred at more lateral PM regions; bipolar EMGs collected from the lateral PM half likely represents the activity of a greater population of motor units than EMGs collected medially. While the validity of this recommendation in different conditions urges further verification, our results suggest that surface EMGs may be more genuinely associated with changes in the degree of PM activity if detected from the muscle lateral half during the bench press exercise that moves glenohumeral joint angle from 110° to 20°.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jelekin.2019.03.002.

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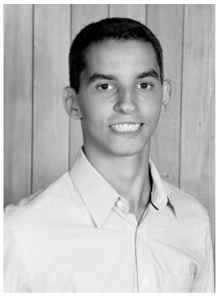

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