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Detailed characterization of physiological EMG activations and directional tuning of upper-limb and trunk muscles in point-to-point reaching movements

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ABSTRACT

In recent years, several studies have investigated upper-limb motion in a variety of scenarios including motor control, physiology, rehabilitation and industry. Such applications assess people's kinematics and muscular performances, focusing on typical movements that simulate daily-life tasks. However, often only a limited interpretation of the EMG patterns is provided. In fact, rarely the assessments separate phasic (movement-related) and tonic (postural) EMG components, as well as the EMG in the acceleration and deceleration phases. With this paper, we provide a comprehensive and detailed characterization of the activity of upper-limb and trunk muscles in healthy people point-to-point upper limb movements. Our analysis includes in-depth muscle activation magnitude assessment, separation of phasic (movement-related) and tonic (postural) EMG activations, directional tuning, distinction between activations in the acceleration and deceleration phases. Results from our study highlight a predominant postural activity with respect to movement related muscular activity. The analysis based on the acceleration phase sheds light on finer motor control strategies, highlighting the role of each muscle in the acceleration and deceleration phase. The results of this study are applicable to several research fields, including physiology, rehabilitation, design of robots and assistive solutions, exoskeletons.

1. Introduction

In recent years, several applications have been developed to investigate upper-limb motion in a variety of scenarios including motor control (d'Avella et al., 2006), (Scano et al., 2019) physiology (Duprey et al., 2017), (Heming et al., 2016), (Kaplanis et al., 2009) rehabilitation (Samuel et al., 2018) and industry (Bi and Guan, 2019), (Pacifico et al., 2020). Typical assessments of people movement are performed with kinematics and EMG.

In this scenario, we noted that often the interpretation of EMG patterns is constrained to the standard-analysis of EMG time series within each task (or movement phase). On the contrary, a restricted number of preliminary works already emphasized the impact on results provided by more refined segmentation of movements. It is the case of the separation of tonic (postural/gravitational) and phasic (movement-related) EMG components. In fact, a pioneristic study on upper-limb motor control provided a mapping on 9 upper-limb muscles (Flanders et al., 1996), showing that the two EMG components (phasic and tonic) play different roles in limb dynamics and may have different directional tuning in the upper-limb operational workspace. Other studies characterized the differences between the components of the EMG from the movement related patterns (Flanders and Herrmann, 1992), and have tied the tuning of these complementary components to task execution time, movement speed and distance from the target, showing that phasic contribution scales up with movement speed (Flanders and Herrmann, 1992). Thus, in order to achieve higher movement velocity, a higher phasic EMG is needed. The relationship between EMG activation and movement distance and movement time has also been investigated (Buneo et al., 1994), concluding that the execution time impacts the intensity of the EMG. Other more recent studies shifted the analysis on muscle torques (Olesh et al., 2017), proposing an alternative separation between anti-gravitational activity and movement-related activity based on the shoulder joint torque. The concept of phasic and tonic activations was furtherly analyzed in the framework of motor control, physiology (Ostry et al., 1997) and muscle synergies (d'Avella et al., 2006), (Scano et al., 2019), (d'Avella et al., 2008), highlighting the relevance of separating phasic and tonic components for a more detailed data analysis.

Interestingly, the study of EMG is also gaining more and more

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visibility in the evaluation of assistive devices and exoskeletons (Bi and Guan, 2019), (Pacifico et al., 2020), (Kim et al., 2018), (Scano et al., 2015) where EMG patterns are evaluated mainly on tonic EMG in static or quasi-static set-ups. However, authors are progressively acknowledging the relevance of point-to-point movements and dynamics while wearing such devices. In this view, we noted how generally phasic and tonic EMG are considered together and, in addition, muscle physiological role is only partially distinguished. In particular, we observe that, in previous literature, it is suggested that acceleration and deceleration may be due to different muscle groups (Jobe et al., 1984), (Vandenberghe et al., 2010), (Vandenberghe et al., 2012). Nonetheless, very few studies have characterized in detail EMG activity from this perspective. In example, recently phasic and tonic components were separated in a context of point-to-point movements exploring a wide range of the upper limb's available workspace, including the frontal plane (Scano et al., 2019), and upper plane, which has been rarely assessed earlier (Chopp et al., 2010).

Following this rationale, in this study we provide a comprehensive and detailed characterization of upper-limb and trunk EMG activity in point-to-point upper limb movements with a set-up similar to the ones used in reference studies of the field (d'Avella et al., 2006), (Flanders et al., 1996). Our analysis includes in-depth muscle activation magnitude assessment, separation of phasic (movement-related) and tonic (postural) EMG activations, directional tuning, distinction between activations in the acceleration and deceleration phases. Our results target several research fields, including rehabilitation, the design and evaluation of robots and assistive solutions, and represent benchmark data and methodological suggestions for future analyses in the above-mentioned fields.

2. Materials and methods

2.1. Participants

The study took place in the Human Motion Analysis Laboratory, at the Consiglio Nazionale delle Ricerche (CNR - Italy), UOS Lecco. The study was reviewed and approved by the CNR Ethical Committee (Rome, Italy). All subjects signed a written informed consent before the experiment, which was conducted in accordance with the Declaration of Helsinki.

Sixteen healthy individuals were originally recruited; four of them were discarded from the analysis to uniform age ranges. The data considered for this study were thus from 12 "young adults" volunteers (3 F 9 M, age range 25–35, weight 69.1 kg $\pm$ 11.5, height 1.74 $\pm$ 0.08 m), neurologically and orthopedically intact. The subjects who participated to the study were recruited within an experimental protocol previously reported to analyze EMG and kinematics in variable movements of the upper-limb (Scano et al., 2019).

2.2. Experimental set-up

Subjects stood in the area tracked with the motion capture system (Vicon 8 TVC system, Oxford, United Kingdom). A support held a target board, with 8 targets indicated by markers placed on a circle of diameter 0.6 m at the cardinal points for movement directions (N, NE, E, SE, S, SW, W, NW), as in previous similar protocols (Scano et al., 2019). A further marker ("O") was placed at the center of the circle. The distance between each of the peripheral markers and the central marker was of 0.30 m (as in (d'Avella et al., 2006)). The support was designed so that the set of targets could be freely positioned and oriented in space with respect to the subject. The target board was used to map the upper portion of the workspace of the upper-limb. Lastly, a further marker (Reference, "R") indicated the starting position located at the subject's hip level, and was selected by the user in a comfortable position. The requirement for positioning R was not to interfere with movement and being at a lower height than the elbow vertical position.

The acquisition protocol included a comprehensive variety of movement trajectories, considering the target board orientation with respect to the subject. The target was oriented frontally to the subjects in a set-up typical for EMG analysis of the upper limb (d'Avella et al., 2006), (Scano et al., 2019), (Pirondini et al., 2016), and in a horizontal up position (Scano et al., 2019). The set-up is portrayed if Fig. 1.

The set of upper-limb movements was chosen taking inspiration from standard motor control literature (frontal plane) and overhead tasks (upper plane), with the goal of simulating several activities of daily living (ADL) and of frequently analyzed scenarios (Mehrholz et al., 2018), (Chen et al., 2015), (Hewett et al., 2007).

The protocol considered Point-to-Point reaching tasks (PtP), including movements from marker R to each cardinal direction (starting with NE) and to the O marker and movements back to the marker R. After each movement, the subject had to wait for about a second before going back to the starting position (R), and a further pause second before proceeding to the next target in clockwise direction. Furthermore, each subject was asked to perform ten trials of acquisitions (repetitions). Subjects were required to move in natural, quite fast way, in order to promote the emergency of physiological EMG related to phasic (dynamic) EMG activity. Following this instruction, subjects were expected to complete PtP trials in no more than 1.2 s. However, tolerance in execution time was accepted. To prevent fatigue, after each trial, a pause of 30 s was introduced. These movements are the basis of almost any motor task involving the upper limb, and are found in rehabilitation, physical training, and industry. Here, reaching towards an object was simulated trough paradigmatic point-to-point movements (Schwarz et al., 2020). Subjects performed the movements with their dominant limb.

During the trials, subjects wore a set of five markers, positioned on D5 and C7 vertebras, acromion (representing shoulder – S), lateral elbow epicondyle (E), styloid process of the ulna (W). Subjects held a 20-cm long pointer, simulating a tool or an end effector, which was identified by two markers (EE1 and EE2). The recordings were made with the Vicon System (Oxford, United Kingdom). The cameras recorded at a fixed sampling frequency of 100 Hz. Subjects were instrumented with 16 s-EMG electrodes (Cometa, Italy) positioned according to the SENIAM guidelines (Hermens, Freriks, Disselhorst-Klug, Rau) to map trunk and upper-limb muscles: Erector spinae (ES), Teres Major (TM), Infraspinatus (IF), Lower Trapezius (LT), Middle Trapezius (MT), Upper Trapezius (UT), Deltoid Anterior (DA), Deltoid Middle (DM), Deltoid Posterior (DP), Pectoralis (PT), Triceps Long Head (TL), Triceps Lateral Head (TLa), Biceps Long Head (BL), Biceps Short Head (BS), Pronator Teres and (PR), Brachioradialis (BR). The EMG probes sampled the muscle activity at 1000 Hz. A detailed representation of the probes and their position is provided in Fig. 2.

2.3. Data analysis

The first step of the data analysis consisted in pre-processing all the kinematics data with a custom upper-limb model and target model implemented in the Nexus Software. The second step consisted in data elaboration and was performed with Matlab 2019, with ad-hoc software.

First of all, kinematic recordings were used to separate movement phases. Each acquisition was thus segmented in 9 phases for PtP movements. The segmentation was achieved by computing the 3D Euclidean distance (3Ed) of the pointing marker from the O marker. Then, the velocity profile associated to 3Ed was computed, and used as signal for detecting movement onsets and offsets.

The kinematics of the upper-limb was computed in intrinsic articular coordinates. Two relevant angles were considered: shoulder flexion and elbow flexion, according to the protocol proposed in a previous study (Scano et al., 2019). Then, in order to compare the data, all the movements were aligned by considering the EMGs in the interval $[-0.5; +1.5]$ seconds with respect to the movement onset and resampled to have the same length. This procedure ensured to capture the complete EMG waveforms which could begin before movement kinematic onset and

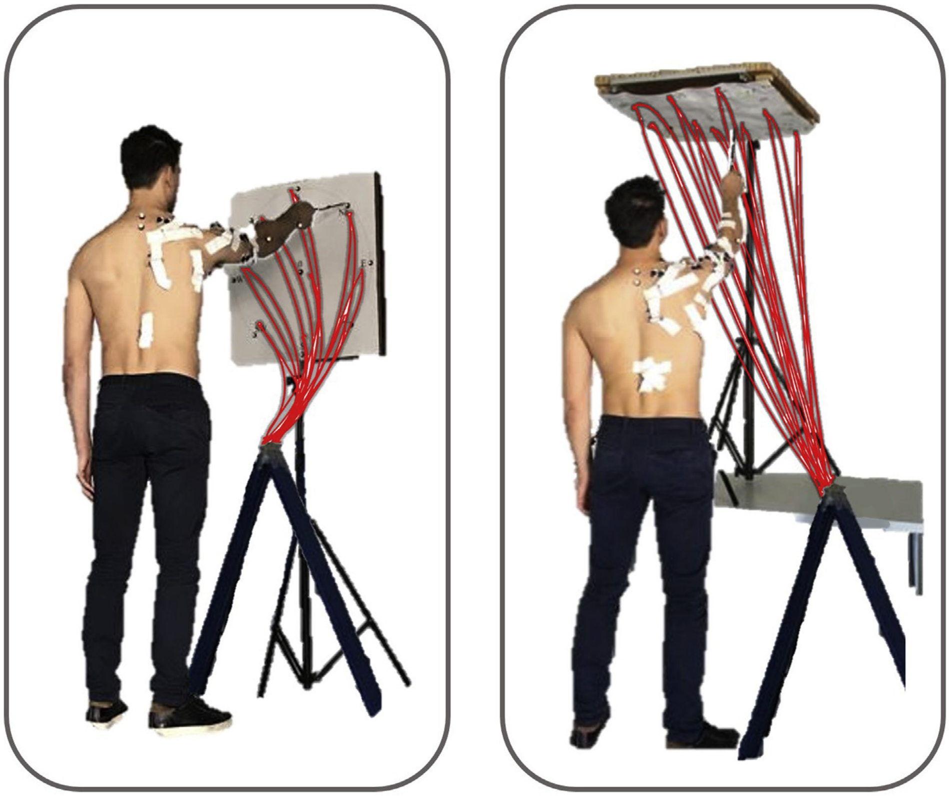

Fig. 1. A picture of the experimental set-up and of the considered movements: Point-to-point (PtP) in the frontal and up orientations of the target boards.

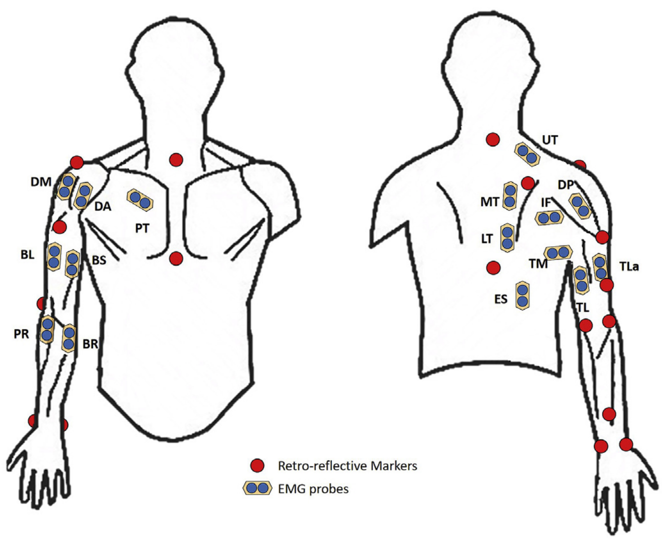

Fig. 2. Positioning of EMG electrodes in the analyzed data. EMG probes were positioned on Erector spinae (ES), Teres Major (TM) Infraspinatus (IF), Lower Trapezius (LT), Middle Trapezius (MT), Upper Trapezius (UT), Deltoid Anterior (DA), Deltoid Middle (DM), Deltoid Posterior (DP), Pectoralis (PT), Triceps Long Head (TL), Triceps Lateral Head (TLa), Biceps Long Head (BL), Biceps Short Head (BS), Pronator Teres (PR) and Brachioradialis (BR).

finish after having reached the target. The data from 16 sEMG channels were high-pass filtered at 20 Hz (Butterworth filter, 3rd order) to remove motion artifacts, rectified, low-pass filtered with a cut-off frequency of 5 Hz (Butterworth filter, 3rd order) to extract the EMG envelope. Data from each movement type were intra-subject averaged to characterize a mean pattern, which we labeled “filtered and averaged EMG.” Afterwards, the mean EMG data were further analyzed to extract the phasic component of the EMG, removing the postural (tonic) EMG activity from the original signal (Flanders et al., 1996), following the approach used in previous works (d’Avella et al., 2006), (Scano et al., 2019).

We than integrated the phasic and tonic EMG activity of each muscle within each phase (Pacifico et al., 2020), direction and repetition, and computed mean integrals and standard deviations for each subject, for each muscle, and for each movement direction. Lastly, a normalization procedure was performed in order to allow inter-subject comparisons. Thus, for each subject, the normalization of the data was performed on the maximum integral EMG (tonic or phasic) achieved for each muscle in the complete dataset referred to that subject, so that all the integrated activations were rescaled in a range between 0 and 1 for **tonic and phasic integrals**.

Then, we used the peak of the velocity profile of the limb end-effector to separate the acceleration phase of each movement from the deceleration phase. We then computed the mean and standard deviations of the integrated phasic acceleration and phasic deceleration EMG activity of each muscle within each phase, direction and repetition. Lastly, a normalization procedure was performed in order to allow inter-subject comparisons of segmented phasic waveforms. Thus, for each subject, the normalization of the data was performed by dividing each integrated EMG by the maximum integral EMG (phasic acceleration plus phasic deceleration) achieved for each muscle in the complete dataset referred to that subject. In this way, we achieved a rescaling of the integrated activations in a range between 0 and 1 for **segmented phasic waveforms**.

The aligned, filtered, averaged, tonic and phasic separated, integrated and normalized EMG envelopes within each phase and repetition were organized as follows (for the frontal and up sector separately). Denoting *nM* as the number of muscles, *nD* as the number of directions, *nS* as the number of subjects, we created (*nM* x *nD*) couples of data vectors, each one having *nS* number of samples; each of them was the mean integrated **tonic and phasic** EMG for each subject (*T-P* matrix). Moreover, the aligned, filtered, averaged, phasic acceleration and deceleration separated, integrated and normalized EMG envelopes within each phase and repetition were organized as follows (for the frontal and up sectors separately). Denoting *nM* as the number of muscles, *nD* as the number of directions, *nS* as the number of subjects; we created (*nM* x *nD*) couples of data vectors, each one having a *nS* number of subjects, which were the mean integrated **phasic acceleration and phasic deceleration** EMG for each subject (*A-D* matrix).

2.4. Kinematic analysis

Two articular angles were chosen to describe the reaching movement: the shoulder flexion angle (SF) and the elbow extension angle (EE). The SE was 0° when the arm rested along the body and 90° when the arm was fully extended at shoulder height. The EE was 0° when the arm and forearm were aligned and 90° when they were perpendicular one in respect to the other.

The results regarding the kinematics were expressed in terms of articular ranges of motion (ROM, computed as the average peak value minus the average starting value).

2.5. Data analysis: outcome measures and statistics

In this paragraph, we report the methods for statistical analysis and the defined outcome measures. First, we described the variability found on tonic/phasic activations for each muscle and direction: i.e., we tested for every muscle whether it showed more tonic or phasic activity and along which directions. In order to do so, we used (*nD* x *nM*) One-Way ANOVA tests (on the coupled EMG integrals – phasic and tonic, *T-P* matrix) with phasic and tonic muscle activations as factors. The level of significance was set to 0.05.

Similarly, we investigated the variability of activation between muscles in acceleration and deceleration phase i.e., showing which muscles showed differences between the phasic acceleration and phasic deceleration and along which directions. In order to do so, we used (*nD* x *nM*) One-Way ANOVA tests (on the coupled EMG integrals – phasic acceleration and deceleration, *A-D* matrix) with phasic acceleration and phasic deceleration activations as factors. The level of significance was set to 0.05.

We also coupled EMG measures with kinematics, testing whether there were directions in which kinematics angles were different. We grouped shoulder elevation and elbow flexion ranges of motion along directions and performed two separated One-Way ANOVA tests (shoulder flexion and elbow extension) with directions as factor. The level of significance was set to 0.05.

All the statistical analyses were performed separately for the Frontal and Up sectors.

3. Results

3.1. Articular kinematics

Fig. 3 shows the kinematics expressed in articular coordinates. In the frontal direction, the highest range of motion was found in the N direction (mean 64.42°). It was higher than the ranges of motion in the SE, S, SW directions ($p < 0.001$). It was also higher in respect the E direction ($p < 0.01$) and in the O and W directions ($p < 0.05$). The tests could not find any differences between the N, NE and NW directions. Similarly, the S direction had the smallest ROM (mean = 31.05°). It resulted lower than the N, NE and NW directions ($p < 0.001$) and than the O and W directions, ($p < 0.05$). Also, NW ROM resulted higher than in the SW and SE directions ($p < 0.001$). Similarly, the NE ROM was higher than the one in the SE and SW directions ($p < 0.001$). The test could not find any differences based on the direction of the movement in any of the ranges of motion of the elbow extension angle ($p > 0.9$).

In the up sector, the statistical test could not identify differences between movements directionalities for the ranges of motion of the shoulder elevation angle ($p > 0.9$ for all cases). The analysis of the elbow extension angle highlighted that the highest range of motion was found in the S direction (57.61°). The test also underlined that the ROM in this direction was higher than the ROM in the O, NE, NW and N directions ($p < 0.001$), and in the E direction ($p < 0.05$). Both SE and SW, with respective means 55.52° and 56.1°, were lower than the NW, N and NE directions ($p < 0.001$), and in respect to the E and O directions ($p < 0.05$). In all other cases, the test could not detect a statistical difference between directions.

3.2. EMG waveforms (phasic vs tonic)

In Fig. 4, a typical example of Phasic and Tonic Components in the frontal sector after signal processing was reported. Tonic activations were modelled as linear ramps, while phasic activations have a single or multi-peak profile. The sum of phasic and tonic components was the original EMG envelope.

3.3. Muscle directional tuning (phasic vs tonic)

3.3.1. Frontal sector

Fig. 5 and reports a polar representation of phasic and tonic EMG activations muscles in the frontal sector. Fig. 6 summarizes the same results with histograms. In almost every considered case, the tonic activity was higher than the phasic activity. As can be noted from the figures, only in three cases (specifically, the DA muscle in the O, NE and E directions) statistically significant difference was not found. Instead, tonic activity was higher than phasic on the DA muscle, in the NW and N directions ($p < 0.05$); for the PT in the NW, NE and N directions ($p < 0.01$); for DA in the SE and S directions ($p < 0.01$), and in all other tests ($p < 0.001$).

3.3.2. Up sector

The results related to the Up sector are summarized in Fig. 7 and Fig. 8. The first figure illustrates the directional tuning of muscle activity, tonic in red and phasic in purple. Fig. 8 portrays the results in the form of a histograms, highlighting the tests in which significant difference was found.

The statistical analysis showed that the tonic activation of the Erector Spinae (ES), Teres Major (TM), Infraspinatus (IF), Lower Trapezius (LT), Middle Trapezius (MT), Deltoid Middle (DM), Deltoid Posterior (DP), Triceps long head (TL), Triceps Lateral head (TLa), Brachioradialis (BR), is higher than the phasic activity in all directions ($p < 0.001$). Statistically significant difference was observed for the Upper trapezius (UT) in the W direction, for the Pectoralis (PT) in the NE and E direction, for Biceps long head (BL) in the E, SE, S, SE and W directions and for the Pronator Teres (PR) in the E, SE and S directions ($p < 0.001$).

Statistically significant difference was observed for the UT in the SE, S, SW and NW directions ($p < 0.01$); for the PT in the SE, SW and N directions, for the BL in O and NE directions, for the Biceps Short head (BS) in the E direction and for the PR in the NE, SW and W directions ($p < 0.01$); in UT, E and N directions ($p < 0.05$); in PT in the O, S, W and NE directions ($p < 0.05$), for the BL in the NW directions ($p < 0.05$), for the BS in the O, NE, SE, S and SE directions ($p < 0.05$), in PR in the O and NW directions ($p < 0.05$).

In all other cases, statistical difference between the activities was not found ($p > 0.05$). In is interesting to note that for Deltoid Anterior, no differences were found.

3.4. EMG waveforms (phasic acceleration vs deceleration)

Fig. 9 illustrates the decomposition of the EMG signal in the acceleratory phasic phase and the deceleration phasic phase in the up sector.

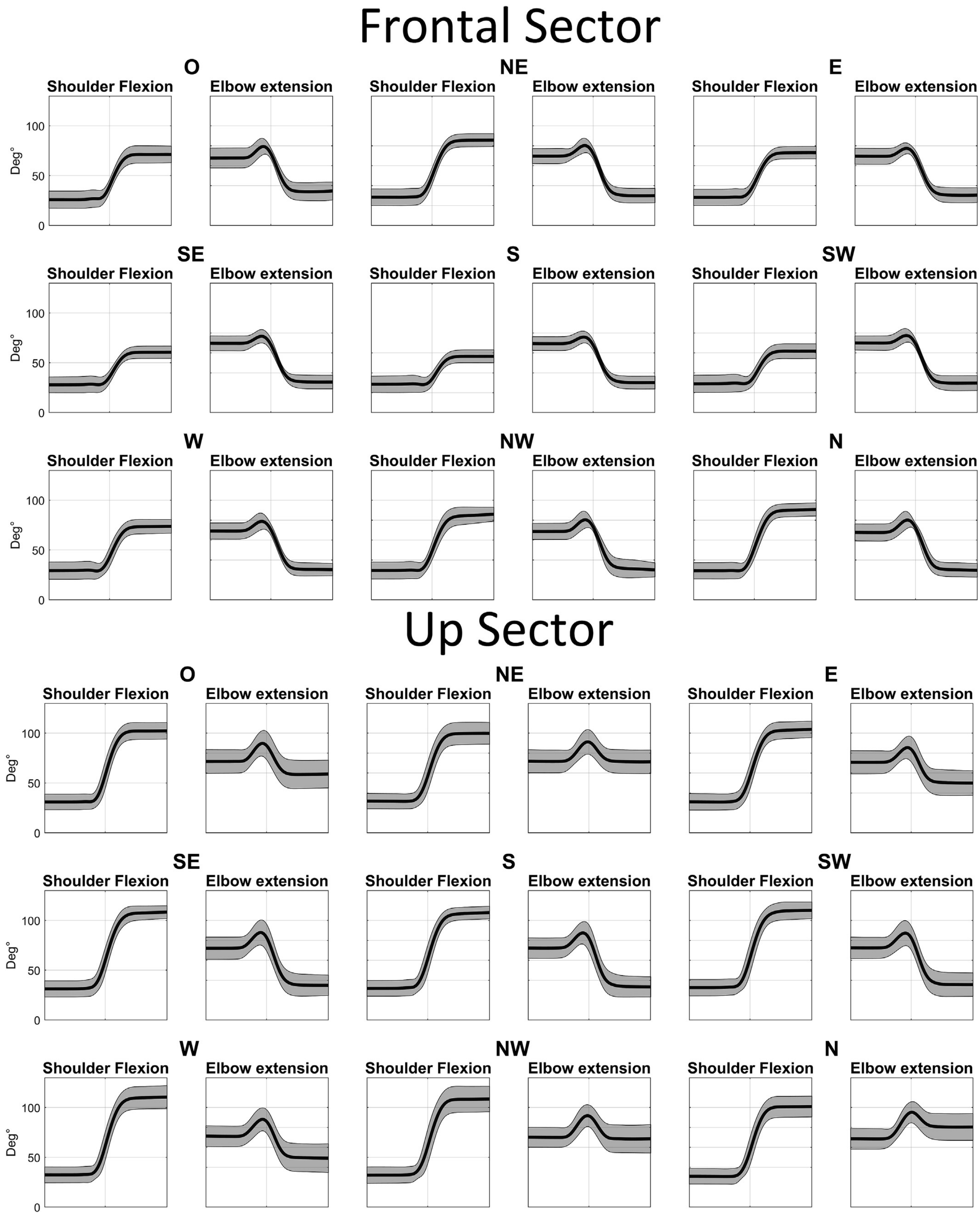

Fig. 3. The mean ranges of motion and standard deviation are reported for shoulder elevation and elbow extension in the Frontal and Up sectors, for each of the considered directions.

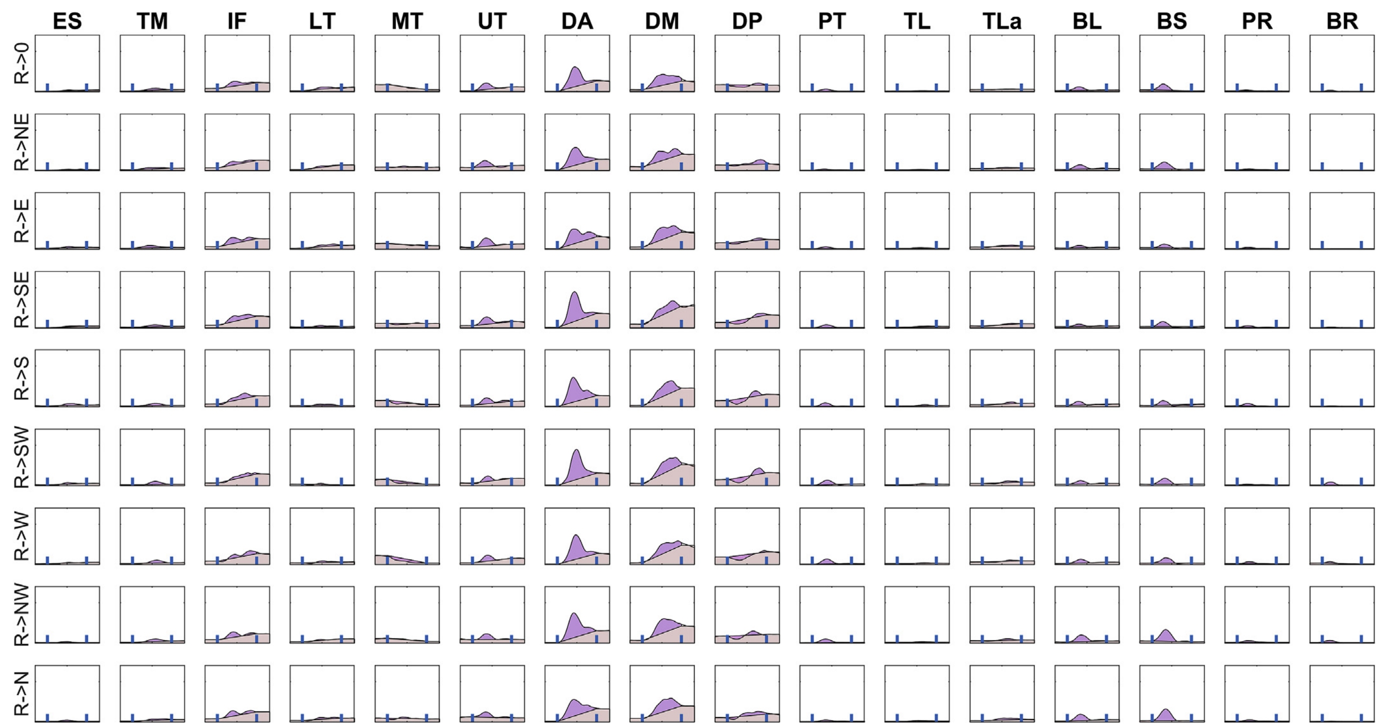

Fig. 4. Phasic (violet) and Tonic (light red) EMG envelopes in frontal sector in a representative subject.

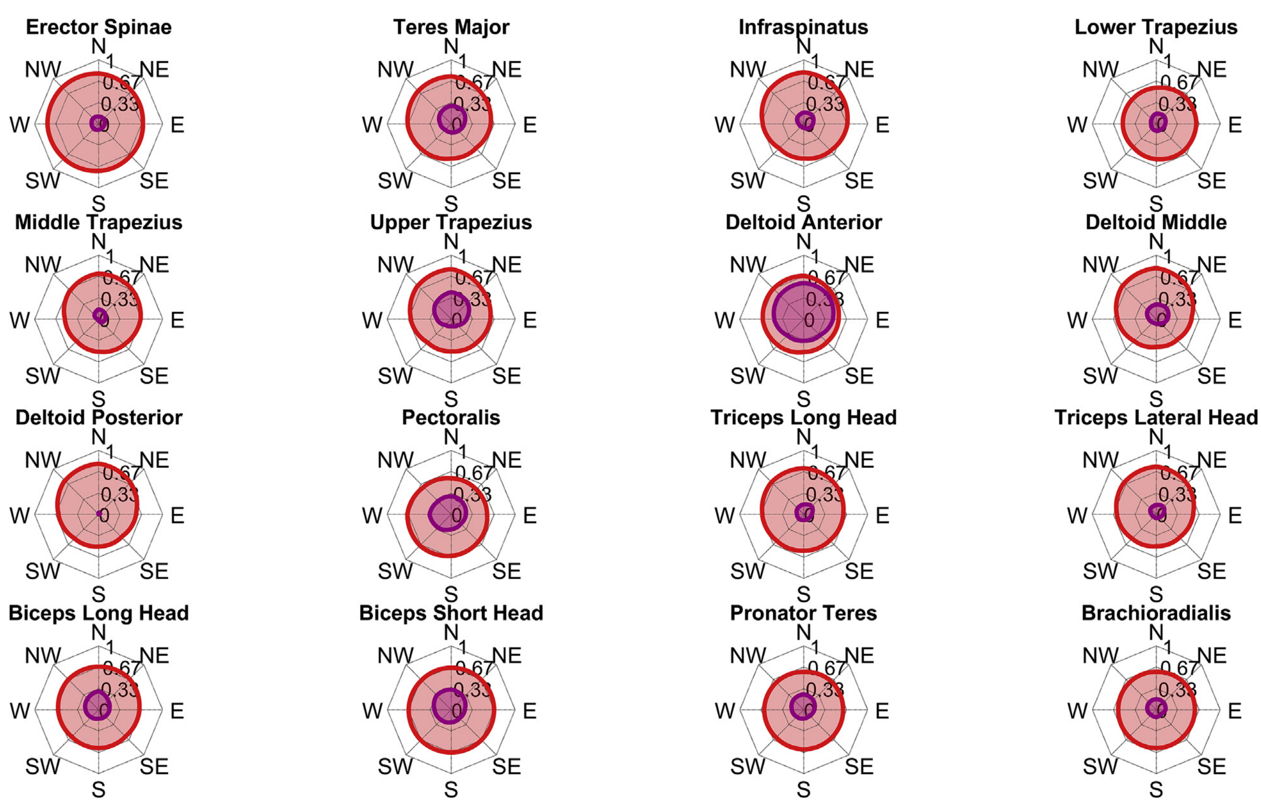

Fig. 5. Frontal sector: Radar-plot with phasic (purple) and tonic (red) directional tuning (mean of all subjects).

3.5. Muscle directional tuning (phasic acceleration vs deceleration)

3.5.1. Frontal sector

Fig. 10 portrays the directional tuning of phasic components during the acceleration and deceleration phases. Fig. 11 illustrates the results in form of histograms and shows statistical differences found between datasets. The portrayed results for the frontal sector highlight that the muscles can be divided in 3 groups based on their main EMG contributions. The first group included BR, PR, BS, BL, TLa, PT, DP, DM, UT and MT; these muscles were more active in the acceleration phase. The

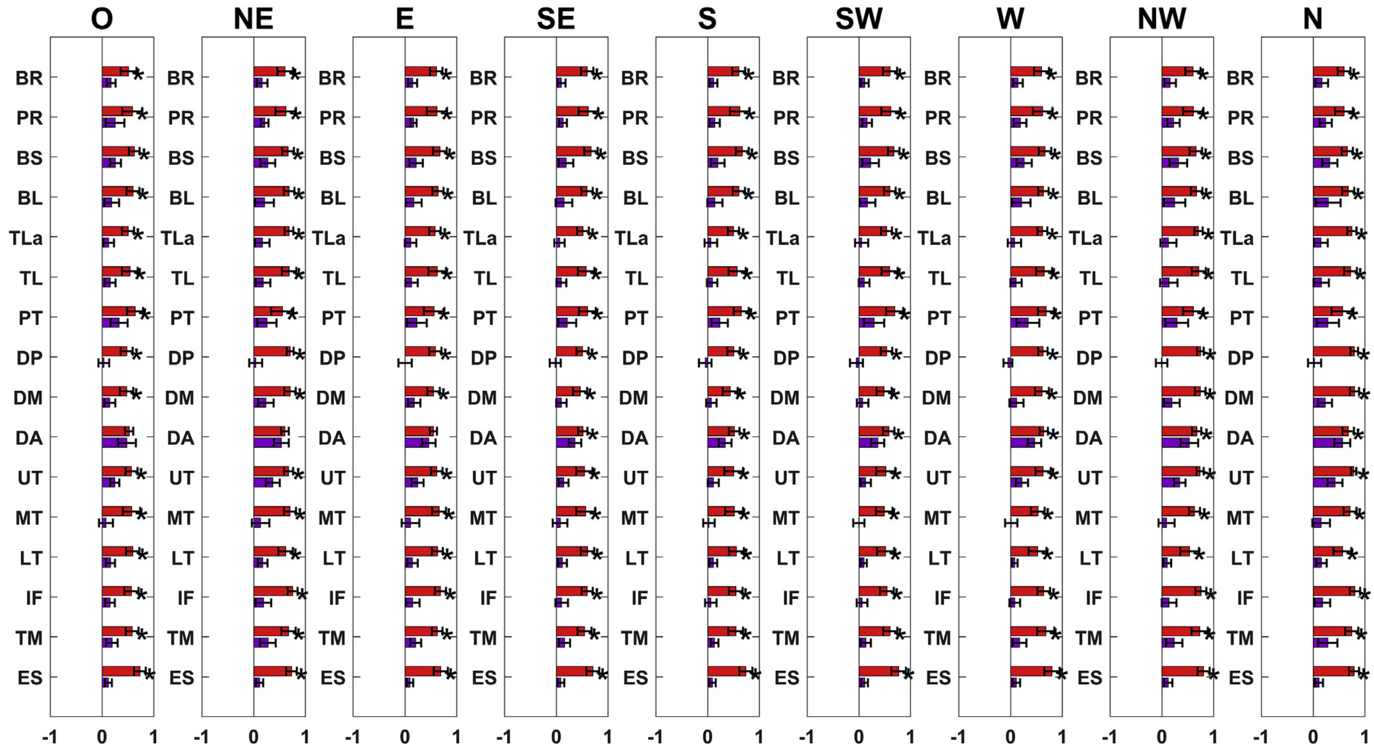

Fig. 6. Frontal sector: bar-plot with phasic (purple) and tonic (red) directional tuning (mean of all subjects). Asterisks indicate statistically significant difference ($p < 0.05$).

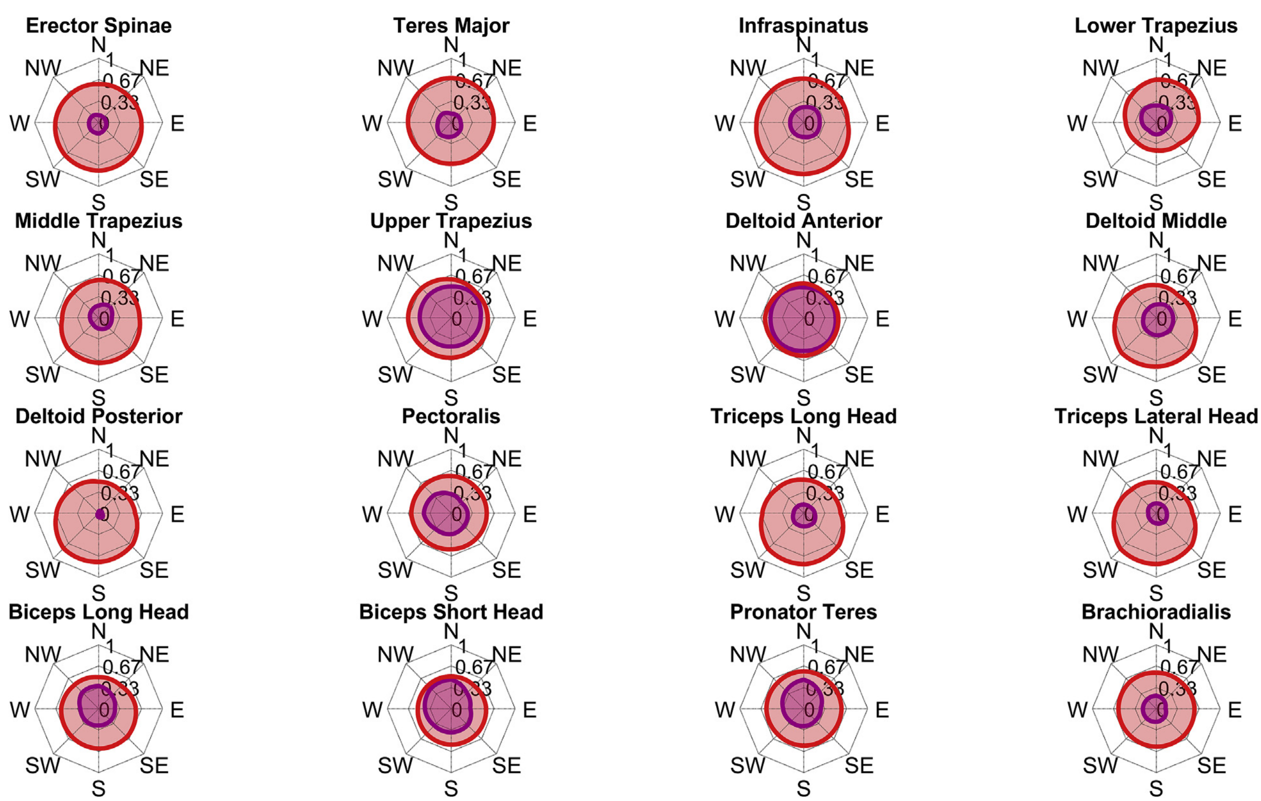

Fig. 7. Up sector: radar-plot with phasic (purple) and tonic (red) directional tuning (mean of all subjects).

second group was composed of muscles active prevalently in the deceleration phase, including TL, DA, IF and TM. The third group included muscles with main contributions that depended on the direction. These muscles were LT and ES. LT was mainly active in the acceleration phase in the S and SE directions, while in all other directions, it contributed mainly to the deceleration phase. ES contributed to the acceleration

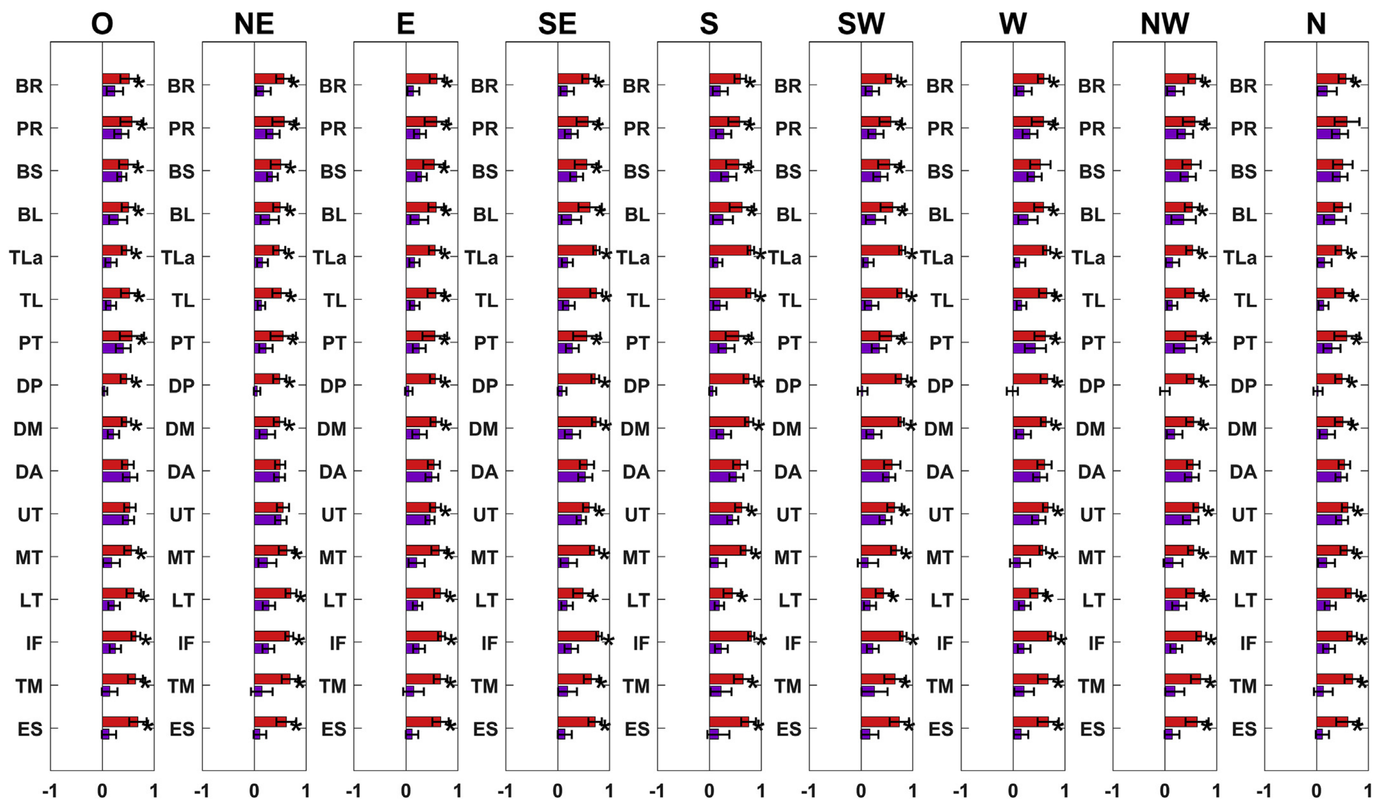

Fig. 8. Up sector: bar-plot with phasic (purple) and tonic (red) directional tuning (mean of all the subjects). Asterisks indicate statistically significant difference ($p < 0.05$).

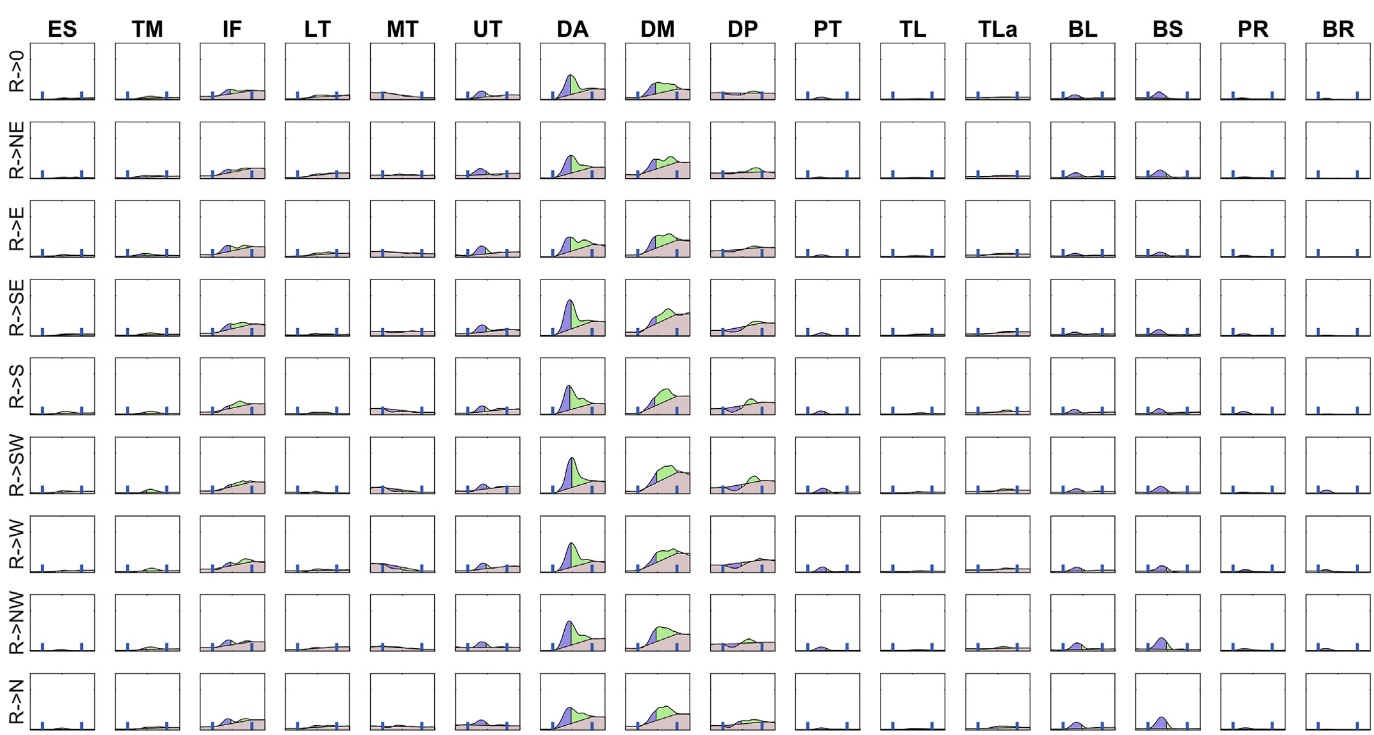

Fig. 9. Phasic acceleration (blue) and deceleration (green) and Tonic (light red) EMG envelopes in the up sector in a typical subject.

phase in the NE, E and SE directions.

In detail, we found that the previous findings were found with the following levels of significativity: TM in all directions ($p < 0.001$); IF in O, NE, W, NW and N directions ($p < 0.001$); MT in NE, E, W, NW and N directions ($p < 0.001$); MT in all directions but S ($p < 0.001$); UT in all directions but O ($p < 0.001$); DM in all directions ($p < 0.001$); DP in all directions ($p < 0.001$); PR in all directions but O, E and SE ($p < 0.001$); BR in all directions ($p < 0.001$), IF in the E direction ($p < 0.01$); MT in the

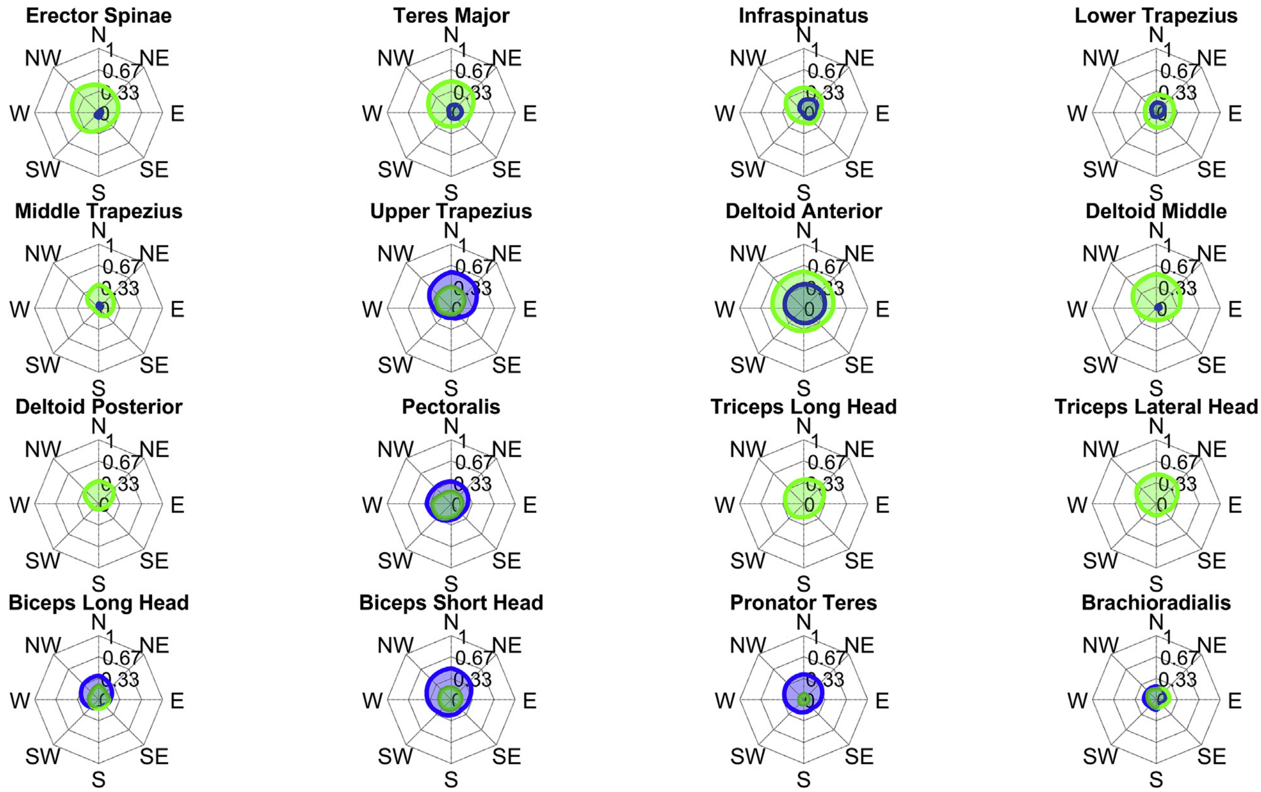

Fig. 10. Frontal sector: Radar-plot with acceleration (blue) and deceleration (green) directional tuning (mean of all subjects).

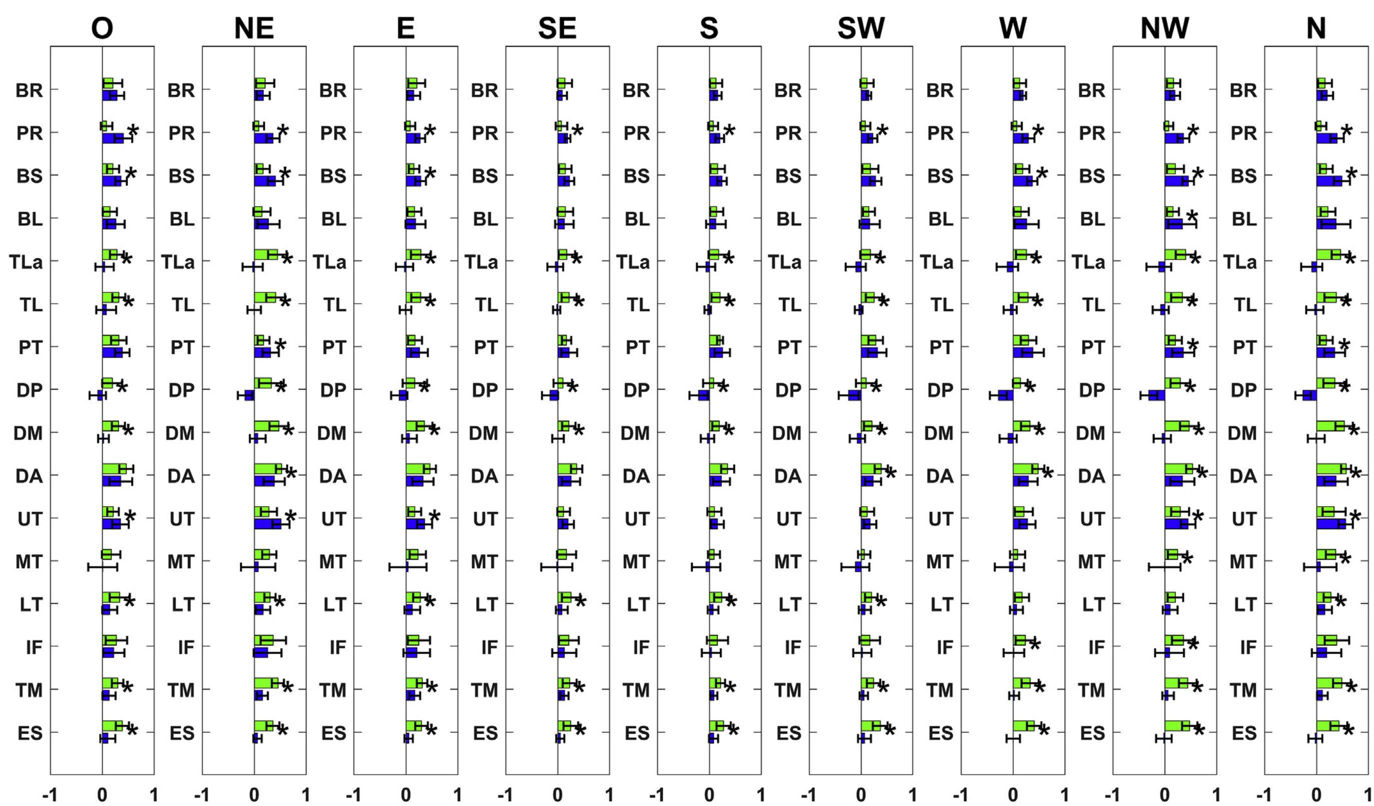

Fig. 11. Frontal Sector: Bar-plot with phasic acceleration (blue) and deceleration (green) directional tuning for all the subjects the frontal sector. Asterisks indicate statistically significant difference ($p < 0.05$).

S directions ($p < 0.01$); TU in the O direction ($p < 0.01$); PT in the W directions ($p < 0.01$); TL in the NE, E and N directions ($p < 0.01$); BL in the SE and S directions ($p < 0.01$); PR in the O and E directions ($p < 0.01$), LT in the NW direction; DA in the NE, NW, and N direction ($p <$

0.05); PT in the NE, SW, NW and N directions ($p < 0.05$); TL in the O and NW ($p < 0.05$); TLa in the NE, NW and N direction ($p < 0.05$); BL in the O, NE, E, SW and N directions ($p < 0.05$); BS in the W and NW directions ($p < 0.05$) and PR in the SE direction ($p < 0.05$).

In all other cases, statistically significant difference was not found ($p > 0.05$).

3.5.2. Up sector

Fig. 12 shows the directional tuning related to the acceleration and deceleration phases in the up sector. Fig. 13 represents the mean activations of each muscle in both acceleration and deceleration phases as histograms. The analysis of this dataset outlined that BR, PR, BS, BL, TLa, TL, PT, DP, DM, UT and MT presented a predominant activity in the acceleration phase of the movement. Instead, TL, LT, IF, TM and ES showed predominant activity in the deceleration phase. The DA did not present a specific predominant activity. This muscle was more active in the acceleration phase while moving in the NE and N directions, while it presented a higher activity in the deceleration phase in all other directions.

In detail, we found that the previous findings were found with the following levels of significativity: TM in all directions ($p < 0.001$); IF in all but SE and S directions ($p < 0.001$); LT in the O NE, W NW and N directions ($p < 0.001$); MT in O, E, SE, S, SW and W directions ($p < 0.001$); UT in all directions except for N ($p < 0.001$); DM in all directions ($p < 0.001$); DP in all directions but N ($p < 0.001$); BL all directions but SE and SW ($p < 0.001$); BS in S and SW directions ($p < 0.001$); PR in W direction and in BR, O, E, SE, S and SW directions ($p < 0.001$); ES in the O, SW and W directions ($p < 0.01$); IF in the SE and S directions ($p < 0.01$); LT muscle in E and SW directions ($p < 0.01$); MT muscle in NE and NW directions ($p < 0.01$); UT in the N direction ($p < 0.01$); DP in the N direction ($p < 0.01$); PT in all directions but E and S ($p < 0.01$); TLa in SE and S ($p < 0.01$); BL in SE and SW directions ($p < 0.01$); BS in SE direction ($p < 0.01$); PR in O, SE, S, SW and NW directions ($p < 0.01$) and BR in the W, NW and N directions ($p < 0.01$); ES in the NW directions ($p < 0.05$); DA in the SW direction ($p < 0.05$); LT in the S directions ($p < 0.05$); MT in the N direction ($p < 0.05$); PT in the E and S directions ($p < 0.05$); TLa in the SW direction ($p < 0.05$); BS in W and NW directions ($p < 0.05$); PR in the N direction ($p < 0.05$) and BR in the NE direction ($p < 0.05$).

In all remaining cases, no statistically significant difference was found. We note that in DA and TL, EMG activities for acceleration and deceleration in almost all directions were not statistically different.

4. Discussion

4.1. EMG characterization: summary of the results

In this study, we provided a comprehensive characterization of EMG activations in paradigmatic point-to-point upper limb movements, frequently found in rehabilitation, motor control and, recently, also in works targeting industrial applications. We investigated in detail the relationships between the phasic and tonic EMG, and an in-depth analysis was provided on the phasic contribution to quantify the EMG activity employed in the acceleration and deceleration of the limb. Our results showed that, depending on the considered muscle, neither tonic nor phasic activations are in general negligible, and their entity may vary across muscles and directions; secondly, we showed that each muscle may contribute in a remarkably different way to the acceleration or deceleration phase. In the next sections, we discuss our results in detail.

4.2. Phasic vs tonic activations

Previous studies available in the literature show that phasic and tonic EMG are associated to motion and postural control, respectively (Flanders et al., 1996). In this work, we found that, with the employed linear-ramp model, the tonic activity is higher than the phasic in most of the muscles. Such a result highlights that, in normal/physiological conditions, gravitational EMG has a higher magnitude than

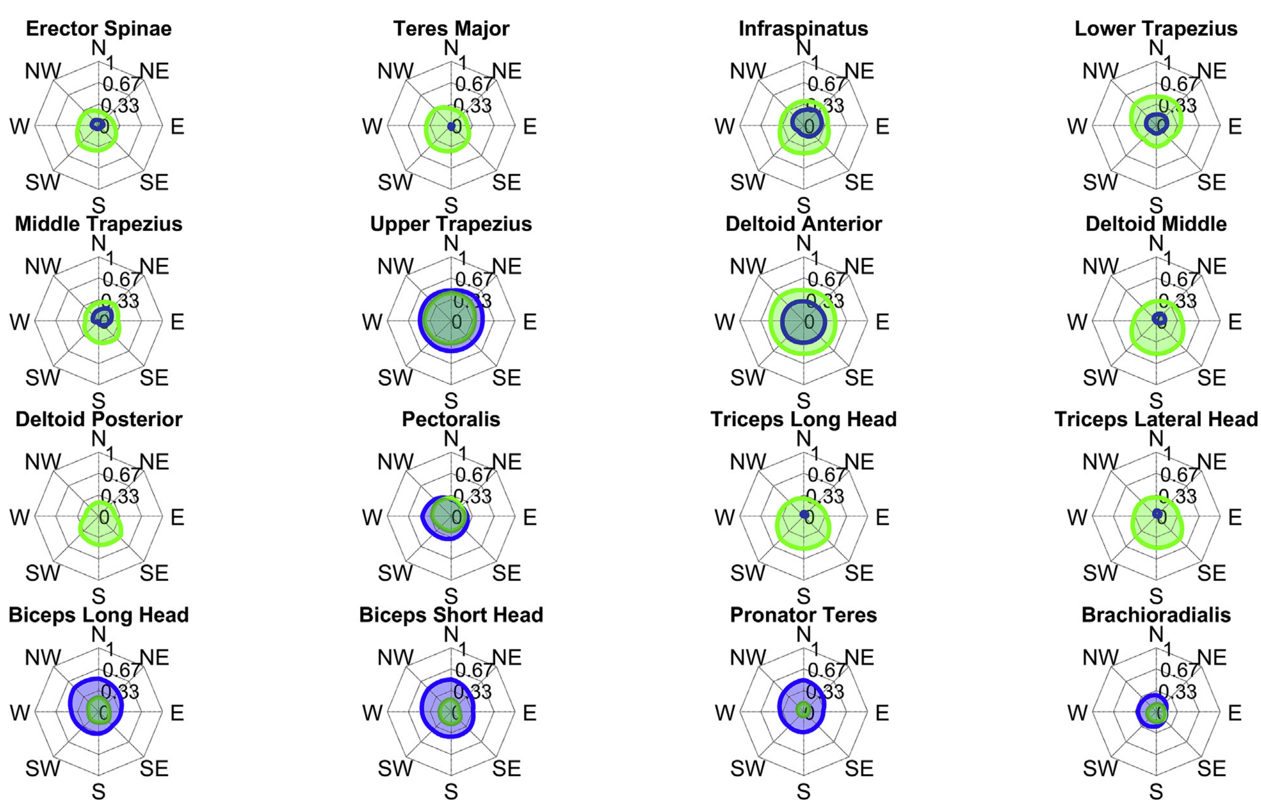

Fig. 12. Up Sector: Radar-plot with acceleration (blue) and deceleration (green) directional tuning (mean of all subjects).

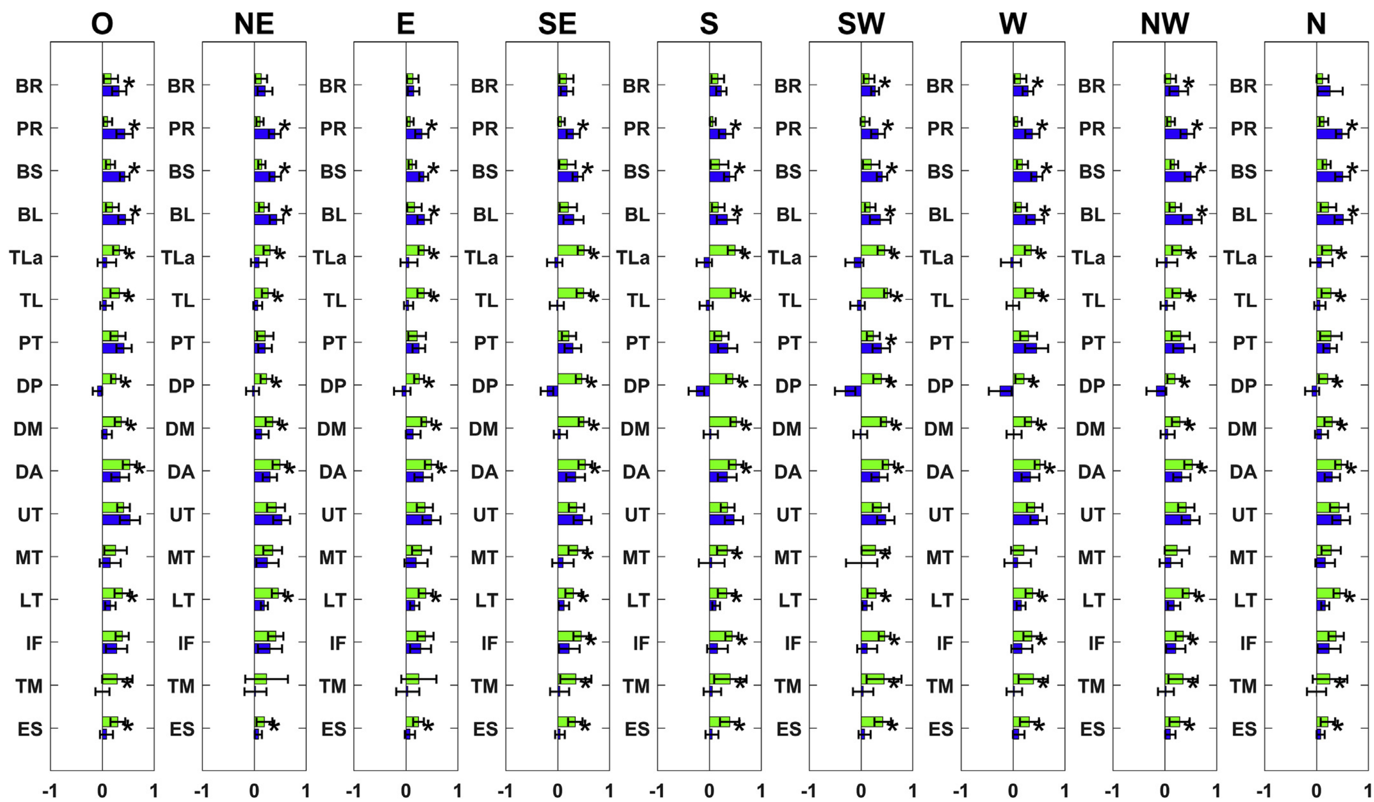

Fig. 13. Up sector: bar-plot with phasic acceleration (blue) and deceleration (green) directional tuning for all the subjects. Asterisks indicate statistically significant difference ($p < 0.05$).

movement-related EMG; phasic EMG consists instead in a "bell-shaped" burst (occasionally biphasic) to accelerate/decelerate the limb. Moreover, for many muscles, the phasic contribution to point-to-point multi-directional reaching movements is quasi-negligible, while the same cannot be said especially for shoulder flexors such as deltoid anterior and upper trapezius. It is indeed of interest of many scenarios to distinguish phasic and tonic components, as they reflect different neural pathways underlying specific physiological functions (Ivanenko and Gurfinkel, 2018), as reported in a review (Shadmehr, 2017) that describes different circuitry for movement or hold activities performed with muscles. In this study, the authors associate the rostral region of the primary motor cortex (M1) with the movement commands while the caudal region and some spinal nerves intervene in both posture control and movement (Shadmehr, 2017). Other studies have identified a deterioration in the tonic contraction capabilities of elderly people (Cogliati et al., 2019), suggesting that this behavior is to be attributed to changes in the peripheral properties of motor units. Following this, we removed some older subjects from our analysis, even though on our set-up their results were comparable to those of younger subjects. In-depth decomposition of the EMG would help deepening the understanding regarding motor control in various contexts. This would be especially relevant for some pathological conditions such as dystonia or stroke that may present high tonic postural EMG (Pisano et al., 2000), making it difficult to detect movement-related activity; or even in low-functioning patients to clearly separate movement-related components when their magnitude is low (Dimitrijevic et al., 1977). Other rehabilitation-related applications benefitting from the proposed approach could extend to functional electrical stimulation (Jonsdottir et al., 2017), (Thorsen et al., 2013), for example to trigger assistance when needed. In such conditions, waving EMG tonic components may help in detecting the amount of EMG which is really due to the patient's motor capability and provide more accurate and reliable instrumental assessments. Thus, when a user is interacting with a robot providing weight support – as in rehabilitation (Scano et al., 2015), (Otten et al., 2015) or industrial scenarios (Zhang and Huang, 2018), phasic and tonic EMG components can be separated in order to correctly interpret the effect of weight-support. In fact, it is known that in rehabilitation, robot devices are used to allow motion in portions of the workspace where movement is not usually allowed by the residual motor capability of the patient. However, weight-support features should only intervene on tonic EMG, possibly stimulating the emergence of phasic EMG. Instead, non-idealities or assistance can induce alterations that can influence motor learning. These differences are worth being quantified separately, to assess muscle activations related to motion or postural control, that are implemented differently also at "hardware level" in spinal and brain circuitry (Sabatini, 2002). These would be a step forward in the understanding of the effects of assistive devices in medical environment. As previously suggested, frameworks such as muscle synergies (d'Avella et al., 2006), (Bizzi et al., 1991) commonly employed for patients' assessment, may take advantage in separating phasic and tonic components as it was investigated in recent comprehensive studies on the upper-limb (Scano et al., 2019).

Similar considerations may also be applied to industrial exoskeletons that are used in recent applications and research to assist workers to reduce the risk of injuries and the burden associated to weight lifting (Alemi et al., 2019), (Abdoli-e and Stevenson, 2008). While these devices are mainly tested in static or quasi-static conditions such as overhead tasks (Kim et al., 2018), recent studies have guessed the relevance of motion, needed to pick up and position objects or to interact with the environment, and started to assess devices even in dynamic scenarios (Pacifico et al., 2020). Interestingly, many conclusions could be drawn when tonic and phasic synergies are separated, hypothesizing that the design of a device would only act on postural components without interfering with normal motion.

Further interesting applications of this type of analysis could expand to the control of robotic prosthesis through EMG. This type of control mechanism requires a deep and thorough analysis and classification of the signal (Bellingegni et al., 2017). A more detailed decomposition of the EMG could further aid the analysis in this field. Furthermore, considering the different of activations of muscles, it could be easier to design more comfortable prosthesis that respond more easily to commands.

We believe our assessment on healthy people can be a useful pilot dataset to promote the quantification of the phasic and tonic components of the EMG.

4.3. Phasic Acceleration vs Deceleration

In this study, we also considered the separation of tonic and phasic components and proceeded to a characterization of EMG activity of the acceleration and deceleration phases. The separation between phasic components sheds further light on the physiological role played by each muscle in accelerating, decelerating or stabilizing the limb during motion. We proved how integrating activations "on the whole" movement (from the beginning to the end point) may not allow to detect specific physiological function absolved by each muscle, reducing the power of the interpretation of the results.

The patterns of phasic muscle activations presented in this study are coherent with precedent findings in literature (Tokuda et al., 2016), (Sabatini, 2002). The activity of deltoid anterior (DA) during the acceleration phase is not surprising; on the contrary, we also found increased activity of the DA in the deceleration phase most likely as a response to the increased activity of the antagonist muscle (posterior deltoid) used to decelerate the limb (Tokuda et al., 2016). This response is most likely a strong co-contraction that is needed for the deceleration phase to stop and stabilize the limb (Kornecki et al., 2001). The upper trapezius (UT) presented great activity in the initial phase of the movement but did not cease its contribution in the deceleration phase, acting as a phasic and anti-gravity muscle. This was previously reported in a reach to grasp study where the EMG was obtained by decomposing the movement in phases using the acceleration, highlighting the anti-gravity role of the upper trapezius (Tokuda et al., 2016). While many applications consider DA as the main shoulder elevator, we found that UT play this role in a major extent in the accelerating phase (Sabatini, 2002). Focusing on the elbow articulation, we instead found high activity of the biceps short and long head in the accelerating phase, counterbalanced with a strong triceps activation in the decelerating phase, probably to extend the forearm and stop the acceleration of the limb.

We believe these data may play a relevant role when interpreting motor performance from reaching movements performed by patients with disability. In example, a recent study classified post-stroke patients according to their residual EMG/muscle synergy activity (Scano et al., 2017). Such classifications may be reviewed with the use of the proposed benchmarking data that may help in shedding light into the mechanisms of disability and motor recovery providing a reference to which patients' performance can be compared.

This distinction may play a crucial role in understanding whether the support of a device is for example assisting the acceleration phase against gravity, and what repercussion it has on the deceleration phase. This effect was previously detected when investigating proprioception and physiological exploitation of shoulder torque in free movements and robot-assisted ones (Caimmi et al., 2012). In this study, authors show that the net torque in the decelerating phase is reduced due to exploitation of inertia acquired in the accelerating phase, and due to co-contraction. In our study we showed how deltoid anterior is strongly active in the deceleration phase to stabilize the limb, while deltoid posterior acted reducing the net torque at shoulder level as found in the mentioned study (Caimmi et al., 2012).

Since assisting exoskeleton devices are usually designed to provide extra torque at shoulder level (counter-clockwise direction to elevate the limb) (Sylla et al., 2014), (Huysamen et al., 2018), they particularly empower deltoid anterior and upper trapezius (reducing their effort), but possibly they might also affect the deltoid posterior that is required to exert extra torque to stop the accelerated limb. Both muscles strongly co-contract to stop and stabilize the limb in the deceleration phase. We believe this methodology might help in providing further details regarding the human-robot interaction investigating it in more detail, for example by affecting the computation of co-contraction indexes (Kornecki et al., 2001) depending on the phase of the movement. In such devices, also the return phase could be analyzed in this framework to understand whether undesired effects are found at muscle level when moving against the elevating torque provided by the devices.

4.4. Limitations

Despite providing novel reference EMG data for paradigmatic upper-limb gestures, this study has some limitations. First, the number of enrolled subjects is reasonable but not high. We did not investigate in detail whether factors such as gender or age might affect the results. On the contrary, we removed 4 of the enrolled subjects in order to uniform our cohort ("young adults"). Moreover, while reporting results from 10 repetitions of each movement for each subject, we did not quantify in detail inter-subject and inter-session variability, which in recent studies were considered as relevant to be investigated as possibly affecting the results (Pale et al., 2020). Lastly, we adopted commonly used models for quantifying tonic activity (d'Avella et al., 2006), (Scano et al., 2019) while more refined ones could be employed; our choice is justified with the aim of using a protocol that could quite easily adapt to real scenarios and by previous applications of this approach in relevant studies in the field (d'Avella et al., 2006).

5. Conclusions

In this paper, we analyzed tonic and phasic EMG activations, as well as how EMG is divided into the phasic and tonic components in point-to-point movements.

The main finding of this study was that the tonic EMG components is in general higher than the phasic one; however, even at normal speed, phasic components for some muscles are clearly detectable and only slightly inferior to tonic. We also found that the phasic components in the acceleration and deceleration phases are in general different and their detailed quantification can lead to a more accurate interpretation of the EMG data.

CRediT authorship contribution statement

Robert Mihai Mira: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Lorenzo Molinari Tosatti:** Resources, Project administration, Funding acquisition. **Marco Sacco:** Resources, Project administration, Funding acquisition. **Alessandro Scano:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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