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Original Article

Analysis of Muscle Recruitment Patterns During Shoulder Rehabilitation Exercises With and Without Elastic Resistance

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Abstract

Objectives: This investigation examined the muscle's activation patterns of shoulder girdle principal muscles during a set of rehabilitation exercises. **Methods**: Thirty healthy participants (21 males, 9 females) performed a randomized set (12 repetitions at 2 s/repetition) of 7 exercises under natural and elastic loading conditions. The activation of 8 muscles was measured by surface electromyography (sEMG) and quantified as percentage of their maximal activation (%MVC). A linear encoder allowed to recognise the concentric and eccentric phases. **Results**: The execution time of 2 s was provided for most of exercises and conditions; however, females showed a higher variability especially in the elastic load condition. Considering a 20 %MVC as a sEMG threshold for low muscular activation, the ranking order of each muscle was determined for each exercise and loading conditions. By performing regression analysis with respect to the sEMG levels and ranking order, a neuromuscular cost can be evaluated and consequently the ability to perform the same work but with different efficiency. **Conclusions**: Linear and non-linear regression curves can be calculated and suggested as reference models. Hence the data presented here can be used as guideline for a more individualised rehabilitation programs or for specific tasks in the resistance strength training.

Keywords: Efficiency, EMG, Pattern Strategy, Rehabilitation Exercises, Shoulder Muscles

Introduction

In the field of the shoulder rehabilitation and of the shoulder anatomical functions[1,2], a consistent number of studies has focused on rehabilitation protocols or physiological muscle recruitment mechanisms. The electromyography (EMG) is widely used to assess the muscle activation levels and patterns. Both the muscle torque and the activation of the rotator cuff and axioscapular muscles were analysed[3-5] with increased load during dynamic shoulder flexion, extension, rotation and isometric adduction.

In a comprehensive review[6] the shoulder girdle muscle activation was investigated during common internal rotation (IR) exercises to develop evidence-based rehabilitation and injury prevention programs. However, the results did not reveal a clear optimal activation pattern with respect to the strengthening of key shoulder girdle muscles. These authors investigated the activity of 16 shoulder girdle muscles during shoulder IR exercises and they pointed out that IR at 0° abduction generates low-to-moderate muscle activation, while at 90° abduction, the subscapularis muscle (SBS) activity during IR exercises was higher for trials with low-to moderate activation of pectoralis major, latissimus dorsi, teres major, supporting this exercise for selective SBS activation.

For the external rotation exercises (ER), the angle of humeral abduction that maximizes the infraspinatus to posterior deltoid activation ratio (INFRA/PD) was investigated[7]. These authors pointed out that abduction significantly reduced overall infraspinatus activity but increased posterior deltoid activity, and average and peak INFRA/PD decreased as abduction angle increased. Thus, they suggested that ER should be performed at 0° abduction

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to maximize infraspinatus isolation. Slight abduction, such as placing a towel under the humerus, as recommended by some clinicians, may improve patient comfort, but did not increase infraspinatus isolation under those experimental conditions.

Beside the muscular activation in single exercises like IR and ER without adding external loads, other investigations considered the same type of exercises performed with elastic loading[8,9].

The effect of elastic loading, and exercise posture (supine and seated position according to the classical situation in a hospital bed) was investigated in healthy subjects which performed four upper body strengthening exercises: diagonal pull, shoulder flexion, flyer and reverse flyer (3 repetitions of each exercise at low and high intensity with 1 min of rest between sets and 1.5 min rest between exercises using elastic bands with different resistant levels)[9]. Surface electromyography was recorded from 12 muscles of the shoulder and upper arm: infraspinatus, serratus anterior, trapezius descendens, transversalis and ascendens, deltoids anterior, medius and posterior, latissimus dorsi, pectoralis major, biceps and triceps brachii. For all exercises performed at high intensity, most of these muscles presented moderate (>40%) to high (>60%) levels of normalised EMG activity. No significant differences were found between the supine and seated positions for any exercise. Therefore, high levels of shoulder and arm muscle activity can be achieved while lying or sitting in a hospital bed using appropriate exercises with elastic bands, and this data could be used by physiotherapists to guide for selecting suitable and effective strengthening exercises during in-hospital rehabilitation to counteract bed-rest related muscle atrophy in the upper body.

Another study[10] showed the increase of EMG activity as load increases for the first 90° range of motion (ROM) and EMG activity decreases for the last 30° ROM, while faster speed was associated to higher EMG during the first 60° of motion and lower EMG in the last 60°.

Despite the studies have shown how shoulder muscles are activated (relatively to its maximum - quantitative aspect, as well as within shoulder muscles - qualitative aspect), there are some open questions: Is there an order of shoulder girdle muscles activation level across different shoulder exercises? If not, which principles guide such order of activation? Thus, the aim of the present study was to verify and evaluate the muscle's activation for classical shoulder rehabilitation exercises performed according to the anatomical plane of movement. We will compare the muscle activity among exercises under different load conditions and test whether male and female participants have similar muscle activation strategies across exercises. Furthermore, we will propose a neuromuscular efficiency index in terms of cumulative percentage of involved muscles under the same loading conditions.

Material and Methods

Participants

Thirty healthy individuals (21 males, 23.2 ± 2.2 yr. old, 179.2 ± 8.2 cm tall, 74.8 ± 11.9 kg mass, and 9 females, 23.0±2.7 years-old, 170.0 ± 3.7 cm tall, 60.7 ± 5.9 kg mass) volunteered to participate in the study. For participants' selection, the following criteria were set: no pregnancy, no progressive diseases or shoulder pain within a period of 12 months before the experiment, no traumatic injury in the shoulder region.

EMG Measurements

Surface EMG was recorded from 8 muscles acting on the shoulder girdle complex: pectoralis major (PM), anterior deltoid (AD), median deltoid (MD), biceps brachii (BB), upper trapezius (UT), posterior deltoid (PD), infraspinatus (ISP), teres major (TM) locations were consistent with established guidelines[11-15]. For ISP, we were aware that the proper way to detect its signal is by fine-wire electrodes[6] which was not available in our study; thus, for reason of uniformity and according to other recommendations[16], we chose this simplification. The reference electrode was placed on a bony landmark away from the experimental shoulder. For signal acquisition, a FreeEMG100 System (BTS-Milan) was used. Signals were preamplified with band wide 10-500 Hz, electrodes were wireless Ambu Blue Sensor Ag/AgCl, 28mm^2 acquiring surface. Before the electrodes were placed, the skin was shaved and cleaned with scrubbing gel (Meditec, Parma, Italy) to lower skin impedance (5 kΩ). Further details are input impedance >10 GΩ, CMMR>110 dB @ 50-60Hz, sensitivity 1µV. Raw EMG signals were recorded at 1 kHz sampling rate and digitized with 16bit resolution by software BTS SMART capture.

Raw EMG signals were smoothed (root mean square, RMS, with T=100 ms) and the time integral was calculated (IEMG). To compare participants and conditions, RMS EMG values was normalized by the maximum voluntary activation (MVC) for each muscle. Therefore, values were expressed as %RMS-MVC or %IEMG-MVC. For MVC, the following isometric exercises were chosen: the empty cam, the flex 125 and the palm press for AD, MD and PM respectively[17], a specific exercise for PD[18,19], the humerus adduction at 90° for TM, the humerus extra rotation at 0° for ISP[18] and the elbow flexion at 90° for BB. For all exercises, the participants performed 2 single repetitions (6 seconds) with a rest of 2 minutes between the repetitions from a sitting position. Maximal RMS and IEMG values were calculated when the signal reached a plateau for at least 1.5 s. To avoid compensatory movements and to better control the degrees of freedom during the MVC trials, opposite shoulder and legs were fastened by belts.

Kinematics Measurements

To find the duration and the range of motion of each motion phases, e.g. flexion-extension or abduction-adduction, a linear encoder measuring linear velocity (PT5AV-100-

Table 1. Description of the 14 tested exercises (na: natural loading, el: elastic band loading, E(*i*): nomenclature for exercises rankings reported in Table 3, Figure 1 and Figure 2) .

Exercise	No load	Elastic load	Test Description
E1	ABD-SCA_90_na	ABD-SCA_90_el	90° abduction of the humerus in the scapular plane, associated to 30° flexion in the transversal plane. Fixed small elbow flexion
E2	ABD-FRO_90_na	ABD-FRO_90_el	90° abduction of the humerus in the frontal plane (as commonly performed), associated to 30° flexion in the transversal plane. Fixed with a very small elbow flexion
E3	ELEV_na	ELEV_el	Pure elevation of the shoulder (shrugs) with fully extended elbows along the trunk's side.
E4	FLEX-EXT_30_na	FLEX-EXT_30_el	Shoulder flexion 45° in the sagittal plane (30° humerus abduction) followed by maximal extension of humerus, fixed elbow flexion and forearm supination. Resistance is applied at extension
E5	FLEX-EXT_na	FLEX-EXT_el	Shoulder flexion 45° in the sagittal plane (0° humerus abduction) followed by maximal extension of humerus, fixed elbow flexion and forearm supination. Resistance is applied at flexion
E6	IR-ER_90_sit_na		Internal and external rotation of humerus, with 90° humerus abduction and 90° elbow flexion from sitting position
E7	IR-ER_90_sup_na		Internal and external rotation of humerus, with 90° humerus abduction and 90° elbow flexion, from supine lying
E8		IR_90_el	Internal rotation of humerus, with 90° humerus's and 90° elbow flexion, from supine lying and starting with the forearm perpendicular to the frontal plane
E9		ER_90_el	External rotation of humerus, with 90° humerus's and 90° elbow flexion, from supine lying and starting with the forearm perpendicular to the frontal plane

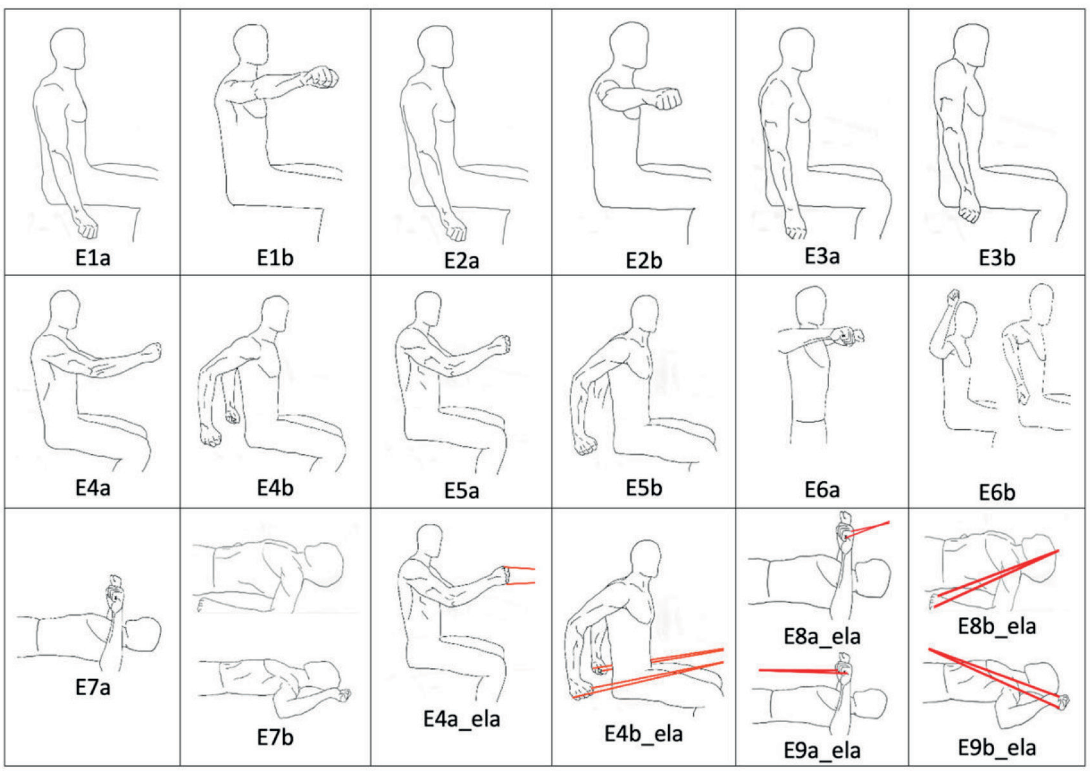

Figure 1. Schematic representation of the tested exercise with initial (E*n*a) and final position (E*n*b). Example of exercise with elastic resistance are showed for exercises E4, E8 and E9 (with red elastic band).

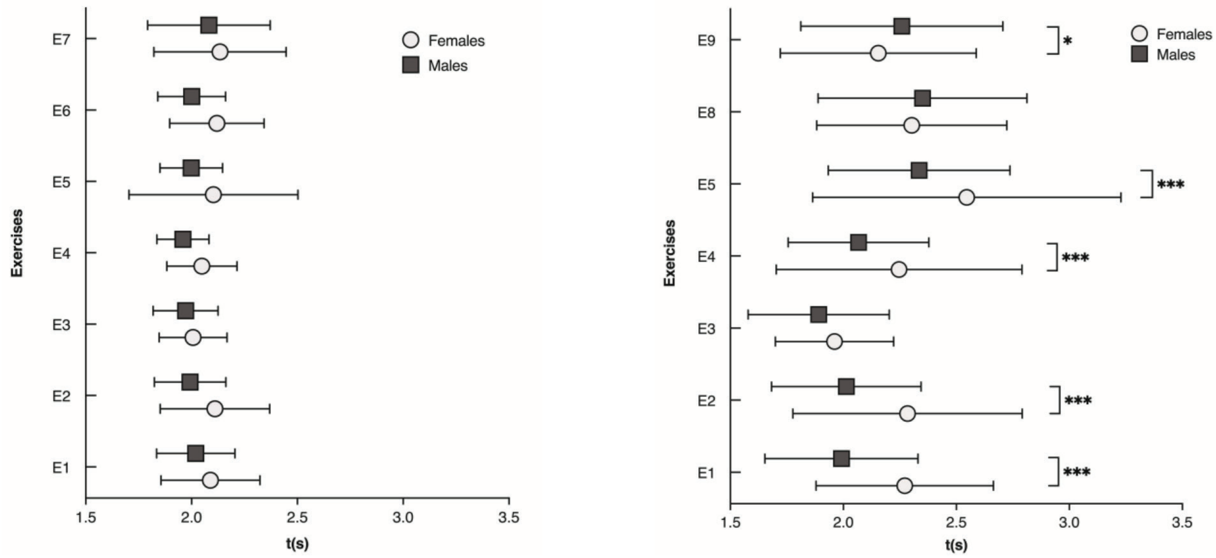

Figure 2. Mean and standard deviations of the total execution time for each exercise and gender (*=p<0.05, ***=p<0.001). Left panel: natural load, right panel: elastic resistance.

S47-FR-500-M6, Chatsworth-CA) was attached to the hand. By raw signal integration, we calculated the hand's linear displacement. During the exercises under elastic loading, it corresponds to the concentric and eccentric muscle activation modes. In addition, a video camera (50 Hz) was used to record each repetition for later control of the correct posture of elbow joint and of the predetermined execution plane.

Exercises

Fourteen exercises were performed, 10 in a seated position and 4 in supine lying position (Table 1, Figure 1). The loading conditions were achieved by the arm's weight, or by an elastic band (Domyos Training Band with 15 kg at maximal elongation). For each participant, the band elongation, i.e. the loading intensity, was chosen to enable a maximum of 12 repetitions. To control the execution time, a metronome was set at 60 B/min, and each movement phase (e.g. flexion and extension) should be performed in 1 s, achieving a total time of 2.0 s. The first and last repetition were not taken into the analysis. After performing the entire testing exercises subjects were required to complete the MVC test as described above.

Statistical analysis

Data are presented as means and standard deviations (SD) and, if appropriate, accompanied by the standard error of the mean (SE). To find significant differences between selected samples, three-way (exercise-load-sex) analysis of variance (ANOVA) has been performed using a statistical software (STATISTICA v. 10, StatSoft Inc.). For significant differences detected by ANOVA, follow-up Newman–Keuls post hoc comparisons were performed. The statistical level of significance was set at an exploratory α level of <0.05 for all analyses.

Results

Temporal reproducibility

Figure 2 show the mean values of the total time of execution for each exercise and in relation to the influence factors, loading conditions and sex. Under the natural loading conditions, for males, there are no significant differences among exercises and the overall value of time is consistent with the preselected value (2.06±0.32 s and 2.0 s, respectively); while females show a tendency to an higher variability even if, generally, the values do not exceed 2.12 s; in one case, the difference is significant (ELEV_na 2.01±0.16 s vs IR-ER_90_sup_na 2.13±0.31 s, p=0.04). The more pronounced standard deviation for the females in almost all the exercises.

For the elastic loading, males confirmed a timing structure close to the preselected value of 2.0 s for the exercises FLEX-EXT_30_el (2.07±0.31 s), ELEV-el (1.89±0.31 s), ABD-SCA_90_el (1.99±0.34 s) and ABD-FRO_90_el (2.01±0.33 s), while for the females this was found only for the exercises ELEV_el (1.96±0.26 s) and ER_90_el (2.15±0.43 s). Comparing males and females, females showed longer total time than males for the exercises ABD-SCA_90_el, ABD-FRO_90_el, FLEX-EXT_el, FLEX-EXT_30_el (p<0.001) and

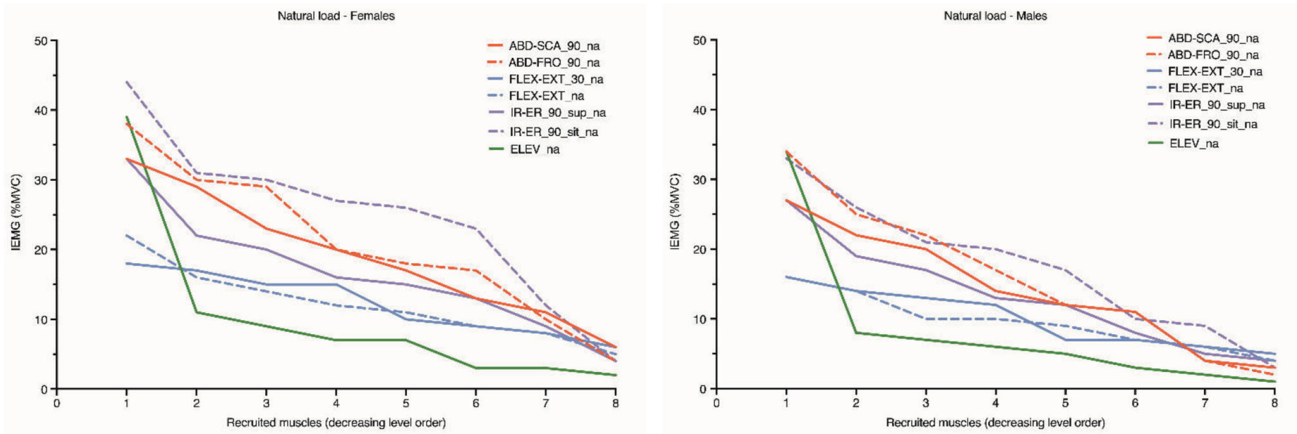

Figure 3. Ranking distribution of muscle's activation under **natural loading conditions** as means of IEMG values (%of MVC) for all tested exercises performed by females (left panels) and by males (right panels). Exercises are labelled according to Table 1. The muscle ranking (1 to 8) is listed for each exercise and gender in Table 2 (lower panels), respectively.

shorter for ER_90_el (p<0.05).

Although the total time could be compared as a single parameter, the timing structure was divided in concentric and eccentric phases, which should be 1.0 s long. While the trials under natural loading conditions both groups have not showed significant overall differences in each phase (females: conc 1.00±0.04 s, ecc 1.08±0.06 s; males conc 0.98±0.03s, ecc 1.03±0.04 s), it was not the case for the elastic loading. Females showed longer duration for both phases (conc 1.09±0.08 s vs 1.00±0.10 s and ecc. 1.16±0.11 s vs 1.13±0.10 s, respectively).

The muscular activation ranking in exercises with natural load

Figure 3 and Table 2 (upper panels) summarize the main results of the muscular activation strategies for each exercise and groups, females and males, under natural loading condition. The mean IEMG values for the total activation of each muscle were plotted as percentage of theirs MVC (i.e. %MVC). For each graph, the ranking order of muscles recruitment for the corresponding exercise is presented in table 2. The 20% MVC was set as a threshold for low muscular activation[3,9].

Scapular plane abduction (ABD-SCA_90_na)

Both groups showed the same muscle recruitment ranking with MD, AD and UT between 27% and 21% for males and 33% and 23% for females who also presented 20% activation for the ISP muscle. Significant differences between males and females were found for MD (27% vs 33%, p<0.001) and AD (22% vs 29%, p<0.001). Standard deviations are significantly more pronounced for females.

For both groups, the main activation was achieved in the concentric phase for the muscles MD, AD, UT, ISP (38% to 20% for males and 49% to 28% with BB at 22% for females respectively).

Frontal plane abduction (ABD-FRO_90_na)

For this exercise, the recruitment ranking is different with MD 34%, UT 25% and AD 22% for males and MD 38%, AD 30%, UT 29% and PD 20% for females. No significant differences between groups are present in the standard deviations. Between males and females, significant differences of activation levels were found for MD (34% vs 38%, p<0.01), AD (22% vs 30%, p<0.001) and PD (17% vs 20%, p<0.05). During the concentric phase, the main activation was achieved for the muscles MD, UT, AD and PD for males (49% to 24%) as well for females (55% to 40%) with ISP and BB at 25%.

Shoulder elevation (ELEV_na)

The principal activation refers to the UT muscle (males 34% vs females 39%, p<0.001) where most other muscles show an activation level near 10%. Mean values of standard deviation are similar for both groups (±5%). During the concentric phase, UT presented a significant higher activation for both groups (males 53%, females 59%), while TM reach the nearest high level (11% and 14% respectively).

Shoulder flexion and extension (FLEX-EXT_na)

For both groups, the four most activated muscles are similar with different recruitment ranking: PD, TM, UT and MD for males (from 16% to 10%) and TM, PD, MD and UT for females (from 22% to 12%). Comparing the groups, males show a significant lower activation level for TM (14% vs 22%, p<0.001). During the extension movement, i.e. the concentric phase, the TM and PD activations were higher for both groups

Table 2. Normalized means, standard deviations (SD) of total muscle activation IEMG (%MVC) according to load intensity, gender and exercise. For **each exercise**, muscles are ordinated vertically according to their ranking value *. Upper panels: natural load; lower panels: elastic load. *AD, anterior deltoid; BB, biceps brachii; ISP, infraspinatus; MD, median deltoid; PD, posterior deltoid; PM, pectoralis major; TM, teres major; UT, upper trapezius.

Load	Sex	Muscle Ranking	ABD-SCA_90_na		ABD-FRO_90_na		ELEV_na		FLEX-EXT_30_na		FLEX-EXT_na		IR-ER_90_sit_na		IR-ER_90_sup_na	
			Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)
NATURAL	FEMALES	M1	MD	33.1 ± 14.4	MD	37.7 ± 9.1	UT	39.1 ±12.4	UT	17.5 ± 13.1	TM	22.1 ± 9.4	MD	43.8 ± 10.6	MD	33.3 ± 10.9
		M2	AD	29.3 ± 8.3	AD	29.7 ± 7.7	TM	11.4 ± 8.1	MD	17.4 ± 4.7	PD	16.3 ± 6.7	UT	30.6 ± 24.1	PD	21.5 ± 7.1
		M3	UT	23.3 ± 10.3	UT	28.7 ± 9.8	ISP	8.6 ± 5.9	TM	15.2 ± 5.9	MD	13.7 ± 5.3	AD	30.3 ± 12.2	AD	20.1 ± 8.6
		M4	ISP	19.8 ± 7.7	PD	20.3 ± 10.6	PM	6.9 ± 3.6	PD	15.0 ± 4.4	UT	11.9 ± 10.6	ISP	27.1 ± 10.7	ISP	16.1 ± 6.8
		M5	BB	16.7 ± 8.6	BB	18.0 ± 8.3	PD	6.6 ± 7.0	AD	10.4 ± 3.9	ISP	11.2 ± 5.7	BB	26.0 ± 16.7	BB	14.7 ± 7.0
		M6	PD	13.1 ± 11.8	ISP	17.4 ± 6.4	AD	3.1 ± 2.1	ISP	9.0 ± 7.2	BB	8.8 ± 3.8	PD	23.1 ± 8.2	UT	12.6 ± 7.5
		M7	TM	10.9 ± 6.3	TM	9.9 ± 4.2	MD	2.5 ± 1.4	BB	8.2 ± 3.1	AD	8.0 ± 3.6	TM	11.9 ± 6.3	TM	9.0 ± 5.1
		M8	PM	6,26 ± 2,5	PM	2.6 ± 1.3	BB	1.6 ± 0.8	PM	6.0 ± 2.4	PM	4.8 ± 1.9	PM	4.1 ± 1.2	PM	3.8 ± 1.7
	MALES	M1	MD	26.6 ± 8.6	MD	33.9 ± 8.9	UT	33.6 ± 13.8	PD	16.3 ± 7.1	PD	15.5 ± 7.1	MD	33.4 ± 13.9	MD	26.8 ± 14.8
		M2	AD	22.1 ± 6.3	UT	25.1 ± 8.3	TM	7.7 ± 6.7	MD	13.6 ± 6.5	TM	14.0 ± 6.0	UT	25.8 ± 18.5	PD	18.5 ± 11.6
		M3	UT	20.4 ± 8.2	AD	21.6 ± 8.2	PD	7.1 ± 4.6	UT	12.6 ± 5.9	UT	10.3 ± 5.8	ISP	21.1 ± 6.6	ISP	17.1 ± 7.6
		M4	ISP	14.1 ± 5.4	PD	17.2 ± 7.5	ISP	6.4 ± 4.7	TM	12.3 ± 5.4	MD	10.1 ± 5.7	PD	19.9 ± 10.3	AD	12.9 ± 5.3
		M5	BB	11.7 ± 6.8	ISP	12.0 ± 5.2	PM	4.7 ± 5.6	ISP	7.4 ± 3.0	ISP	8.6 ± 3.8	AD	16.8 ± 8.4	UT	12.0 ± 10.1
		M6	PD	10.5 ± 6.6	BB	11.3 ± 7.6	MD	2.5 ± 1.8	AD	7.3 ± 3.0	BB	6.7 ± 5.1	BB	10.2 ± 4.2	BB	8.1 ± 3.5
		M7	TM	3.9 ± 2.1	TM	3.8 ± 1.8	AD	1.8 ± 1.4	BB	6.1 ± 4.2	AD	6.5 ± 2.3	TM	8.6 ± 10.7	TM	4.9 ± 2.8
		M8	PM	3.4 ± 3.2	PM	2.5 ± 1.5	BB	1.1 ± 0.7	PM	5.2 ± 2.9	PM	4.2 ± 2.6	PM	2.9 ± 1.8	PM	3.8 ± 2.5
Load	Sex	Muscle Ranking	ABD-SCA_90_el		ABD-FRO_90_el		ELEV_el		FLEX-EXT_30_el		FLEX-EXT_el		IR_90_el		ER_90_el	
			Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)
ELASTIC	FEMALES	M1	UT	49.5 ± 15.8	MD	53.0 ± 13.9	UT	48.1 ± 25.0	TM	48.9 ± 30.3	AD	41.2 ± 12.0	TM	32.8 ± 13.8	ISP	42.5 ± 29.6
		M2	MD	48.8 ± 11.7	UT	51.3 ± 15.2	TM	16.4 ± 8.5	PD	35.5 ± 12.1	BB	38.6 ± 22.0	ISP	28.1 ± 20.2	MD	29.8 ± 10.3
		M3	AD	48.1 ± 12.8	AD	44.8 ± 14.3	PM	11.1 ± 5.3	MD	31.9 ± 13.1	PM	35.7 ± 11.2	PD	13.6 ± 6.7	UT	26.9 ± 17.0
		M4	ISP	44.7 ± 19.2	BB	38.8 ± 17.8	PD	10.9 ± 8.3	ISP	22.4 ± 12.5	MD	25. ± 6.77	MD	11.9 ± 10.3	PD	26.5 ± 11.2
		M5	BB	40.1 ± 24.8	ISP	37.9 ± 17.4	ISP	10.7 ± 6.0	UT	21.3 ± 12.5	ISP	18.7 ± 8.4	PM	11.6 ± 7.7	BB	21.8 ± 7.0
		M6	PD	26.4 ± 12.4	PD	30.9 ± 13.3	MD	4.1 ± 2.6	BB	16.1 ± 11.7	TM	18. ± 15.7	BB	5.4 ± 4.0	TM	21.3 ± 7.1
		M7	TM	17.9 ± 8.7	TM	15.6 ± 8.1	AD	3.4 ± 2.6	AD	16.1 ± 6.6	UT	15.2 ± 8.6	UT	4.8 ± 4.9	AD	18.1 ± 6.4
		M8	PM	9.8 ± 5.1	PM	5.5 ± 1.4	BB	2.7 ± 1.6	PM	9.6 ± 3.5	PD	8.0 ± 3.2	AD	2.9 ± 0.8	PM	7.7 ± 4.0
	MALES	M1	MD	51.6 ± 13.6	MD	58.5 ± 13.1	UT	39.8 ± 14.2	PD	33.5 ± 8.8	AD	38.2 ± 12.3	TM	19.7 ± 11.2	ISP	33.3 ± 10.1

Table 2. *(Cont. from previous page).*

Load	Sex	Muscle Ranking	ABD-SCA_90_el		ABD-FRO_90_el		ELEV_el		FLEX-EXT_30_el		FLEX-EXT_el		IR_90_el		ER_90_el	
			Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)	Muscle	Mean ± SD (%)
ELASTIC	MALES	M2	UT	51.2 ± 17.1	UT	50.8 ± 17.2	PD	18.9 ± 12.1	TM	28.9 ± 10.9	BB	31.4 ± 13.0	ISP	14.8 ± 9.0	MD	30.9 ± 15.7
		M3	AD	42.8 ± 10.4	AD	43.0 ± 10.3	TM	13.3 ± 8.0	MD	25.5 ± 10.2	PM	29.4 ± 12.3	PD	11.5 ± 6.2	PD	21.1 ± 11.2
		M4	ISP	38.7 ± 17.1	ISP	35.6 ± 12.9	ISP	8.6 ± 6.3	UT	17.4 ± 8.3	MD	23.5 ± 12.1	MD	11.2 ± 6.5	UT	20.8 ± 11.9
		M5	BB	29.7 ± 13.7	PD	32.9 ± 11.6	PM	8.4 ± 8.0	ISP	14.6 ± 6.4	UT	18.4 ± 12.0	PM	9.7 ± 7.8	AD	17.9 ± 9.2
		M6	PD	27.3 ± 8.6	BB	29.7 ± 15.7	MD	5.5 ± 9.0	AD	9.8 ± 4.6	ISP	17.9 ± 7.8	UT	4.9 ± 4.1	BB	16.8 ± 10.9
		M7	TM	9.0 ± 4.4	TM	8.4 ± 3.7	AD	2.4 ± 1.6	BB	7.8 ± 3.2	PD	6.4 ± 3.3	BB	3.4 ± 2.1	TM	13.9 ± 8.8
		M8	PM	7.1 ± 7.3	PM	4.5 ± 2.6	BB	2.0 ± 1.1	PM	6.6 ± 3.7	TM	6.3 ± 3.4	AD	2.5 ± 1.3	PM	5.3 ± 3.8

**AD, anterior deltoid; BB, biceps brachii; ISP, infraspinatus; MD, median deltoid; PD, posterior deltoid; PM, pectoralis major; TM, teres major; UT, upper trapezius.*

(males 22% and 24%; females 30% and 24% respectively). MD showed 12% for males and 16% for females.

Shoulder flexion and extension at 30° abduction (FLEX-EXT_30_na)

According to the previous exercise, the activation order occurs for the same muscles but with slightly different order: PD, MD, UT and TM for males (from 16% to 12%) and UT, MD, TM and PD for females (from 18% to 15%). During the extension movement, the highest activation in both the groups was found for PD (17% for males and 22% for females), for TM (19% and 21% respectively) and for MD (17% and 22% respectively).

Internal and external rotation in sitting position (IR_ER_90_sit_na)

For both groups, the MD shows the highest activation (males 33% vs females 44%, $p<0.001$) followed by UT (26% vs 31%, $p<0.05$ respectively). At the third ranking position, there is a difference, ISP for males with 21%, but AD for females with 30%. Furthermore, significant differences were also found for BB (10% for males and 26% for females, $p<0.001$) and for PD (20% vs 23%, $p<0.05$ respectively). In both groups, high standard deviations (±19% and ±24% respectively) occurs for UT, and for BB in females (±17%). During both movements, external and internal rotation, MD presents the highest activation for males and females (32% ER and 41% IR; 35% ER and 47% IR respectively), while the second values is shown by the ISP with 30% ER for males and 38% ER for females ($p<0.001$). Following the ranking positions, males show UT with 27% in ER and 25% in IR, PD with 21% in IR and AD with 18% in ER. On the contrary, females show a different pattern namely ISP with 38% in ER, TM with 34% in ER, AD with 30% in both ER and IR, TM with 28% in IR, BB with 28% in IR and 24% in ER, and PD with 24% in ER and 23% in IR respectively.

Internal and external rotation in supine position (IR_ER_90_sup_na)

Due to the different influence of gravity in the supine posture, the muscle activation ranking order shows some dissimilarity to the previous execution. For males, the relevant activation pattern was MD with 27%, PD with 19% and ISP with 17%, while for females MD with 33%, PD with 22% and AD with 20%. At the fourth position, males show AD with 13% and females ISP with 16%.

The muscular activation ranking in exercises with elastic load

Similarly to the previous session, the principal muscular activation strategies patterns during the exercise performed with the elastic bands are plotted in Figure 4 and listed in Table 2 (lower panels). The activation levels increased with respect to the exercises under natural loading, however differences between groups were evident.

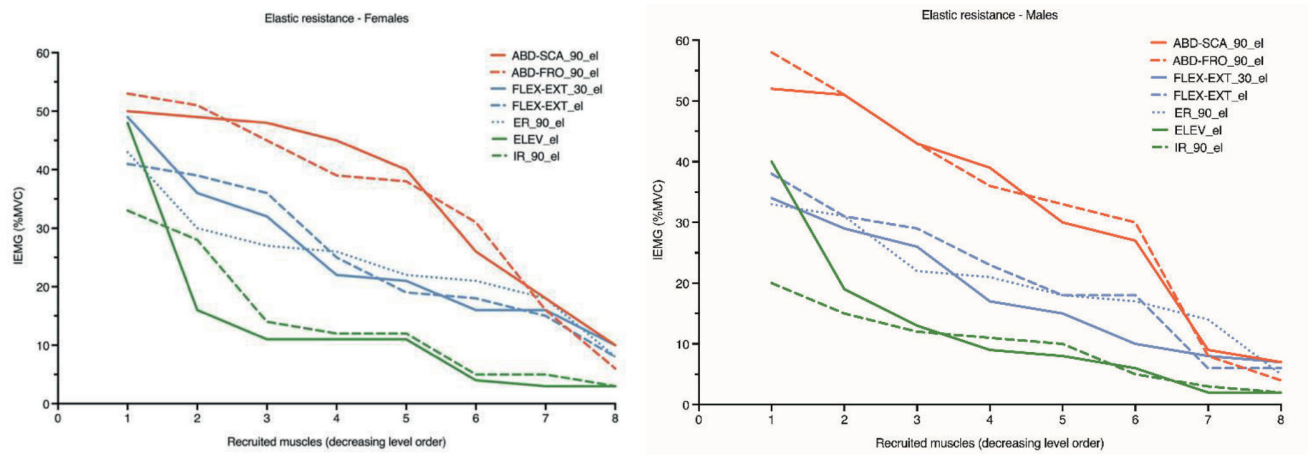

Figure 4. Ranking distribution of muscle's activation under **elastic loading conditions** as means of IEMG values (%of MVC) for all tested exercises performed by females (left panels) and by males (right panels). Exercises are labelled according to Table 1. The muscle ranking (1 to 8) is listed for each exercise and gender in Table 2 (upper panels), respectively.

Scapular plane abduction (ABD-SCA_90_el)

Likely to the exercise under natural loading, the muscle recruitment ranking was the same for both groups and almost equivalent to that pattern. The substantial sequence is MD, UT (52% and 51% for males; vs 49% and 50% for females), AD (43% vs 48% respectively), ISP (39% vs 45% respectively), BB (30% vs 40% respectively) and PD (27% vs 26% respectively). The maximal value of standard deviation was ±17% for ISP in males and ±25% for BB in females. Significant differences between groups are present for MD ($p<.0.05$), AD, ISP, BB, TM and PM ($p<0.001$).

Considering the specific phases of the execution, for both groups the higher activation was achieved in the concentric phase and with identical sequence UT, MD, AD, ISP, BB and PD (73%, 71%, 59%, 55%, 40% and 38% in males and 68%, 66%, 65%, 63%, 53% and 36% in females, respectively). Significant differences between groups are presented for AD, ISP, BB, DP, MD and TM ($p<0.001$).

Frontal plane abduction (ABD-FRO_90_el)

For this exercise, there is a substantial identity of the activation pattern with the highest values for MD (58% males vs 53% females) and UT (51% in both groups) followed by AD, ISP, BB and PD (43%, 36%, 30% and 33% males vs 45%, 38%, 39% and 31% females). Only the MD ($p<0.001$) and BB ($p<0.001$) muscles reveal a significant difference between groups.

During the concentric phase, the sequence patterns are mostly coherent between groups and with respect to the total amount of activation i.e. MD, UT, AD, ISP, BB, PD. The values are also similar (81%, 73%, 61%, 51%, 40% and 46% males vs 72%, 72%, 62%, 54%, 52% and 42% females, respectively).

Shoulder elevation (ELEV_el)

The peculiarity of this exercise accounts for a predominant activation of UT (40% males vs 48% females) associated to a moderate PD (19% males) and TM (16% females) activations. During the concentric phase, UT showed a significant difference between groups (61% males vs 73% females $p<0.001$) while the second activation level was PD in males (25%) and UT (23% eccentric phase) and TM (21%) in females. In the eccentric phase, UT activation was different for females and males ($p<0.01$). High values of standard deviation were found for UT (±22% males and 41% females).

Shoulder flexion and extension (FLEX-EXT_el)

In this exercise, the resistance is applied during the flexion movement, i.e. anterior muscles are expected to be more activated. In both groups, the activation pattern shows the same sequence AD, BB, PM, MD and ISP but with significant differences (38%, 31%, 29%, 23% and 18% males vs 41%, 39%, 36%, 25% and 19%, with $p<0.001$ for AD, BB, PM respectively). TM showed higher activation in females (18% vs 6%, $p<0.001$). During the concentric phase, AD, BB, PM, MD and ISP reached their maximum (54% to 25% in males and 58% to 26% in females) while BB and AD also showed noteworthy activation during the eccentric phase (22% males; 25%, 24% females).

Shoulder flexion and extension at 30° abduction (FLEX-EXT_30_el)

In this exercise, the resistance is applied throughout the extension movement, i.e. the posterior muscles of shoulder grid are expected to show higher activation. The most activated muscles are PD, TM, MD and UT (34%, 29%, 26% and 17% males; 36%, 49%, 32%, 21% and 22% for ISP

Table 3. Normalized means, standard deviations (SD) of total muscle activation IEMG (%MVC) according to load intensity, gender and exercise. For **each muscle**, exercises are ordinated vertically according to their ranking value *. Upper panels: natural load; lower panels: elastic load. * The identification of the exercises for each label Ei is given in Table 1 (e.g. E1= ABD_SCA_90).

Load	Sex	PM		AD		MD		PD		UT		ISP		TM		BB	
		Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)
NATURAL	FEMALES	E3	6.9 ± 3.6	E6	30.8 ± 12.2	E6	43.8 ± 10.6	E6	23.2 ± 8.2	E3	39.1 ± 12.4	E6	27.1 ± 10.7	E5	22.1 ± 9.4	E6	26.0 ± 16.7
		E1	6.3 ± 2.5	E2	29.7 ± 7.7	E2	37.7 ± 9.1	E7	21.6 ± 7.1	E6	30.6 ± 24.1	E1	19.8 ± 7.7	E4	15.2 ± 5.9	E2	18.0 ± 8.3
		E4	6.0 ± 2.4	E1	29.4 ± 8.3	E7	33.3 ± 10.9	E2	20.3 ± 10.6	E2	28.7 ± 9.8	E2	17.4 ± 6.4	E6	11.9 ± 6.3	E1	16.7 ± 8.6
		E5	4.8 ± 1.9	E7	20.1 ± 8.6	E1	33.1 ± 14.4	E5	16.4 ± 6.7	E1	23.4 ± 10.3	E7	16.2 ± 6.8	E3	11.4 ± 8.1	E7	14.7 ± 7.0
		E6	4.1 ± 1.2	E4	10.4 ± 3.9	E4	17.4 ± 4.7	E4	15.0 ± 4.4	E4	17.5 ± 13.1	E5	11.2 ± 5.7	E1	10.9 ± 6.3	E5	8.8 ± 3.8
		E7	3.8 ± 1.7	E5	8.0 ± 3.6	E5	13.7 ± 5.3	E1	13.2 ± 11.8	E7	12.6 ± 7.5	E4	9.0 ± 7.2	E2	9.9 ± 4.2	E4	8.2 ± 3.1
		E2	3.6 ± 1.3	E3	3.1 ± 2.1	E3	2.6 ± 1.4	E3	6.7 ± 7.0	E5	11.9 ± 10.6	E3	8.6 ± 5.9	E7	9.0 ± 5.1	E3	1.6 ± 0.8
	MALES	E4	5.2 ± 2.9	E1	22.1 ± 6.3	E2	33.9 ± 8.9	E6	19.9 ± 10.3	E3	33.6 ± 13.8	E6	21.1 ± 6.6	E5	14.0 ± 6.0	E1	11.7 ± 6.8
		E3	4.7 ± 5.6	E2	21.6 ± 8.2	E6	33.4 ± 13.9	E7	18.5 ± 11.6	E6	25.8 ± 18.5	E7	17.1 ± 7.6	E4	12.3 ± 5.4	E2	11.3 ± 7.6
		E5	4.2 ± 2.6	E6	16.8 ± 8.4	E7	26.8 ± 14.8	E2	17.2 ± 7.5	E2	25.1 ± 8.3	E1	14.1 ± 5.4	E6	8.6 ± 10.7	E6	10.2 ± 4.2
		E7	3.9 ± 2.5	E7	12.9 ± 5.3	E1	26.6 ± 8.6	E4	16.4 ± 7.1	E1	20.5 ± 8.2	E2	12.0 ± 5.2	E3	7.8 ± 6.7	E7	8.1 ± 3.5
		E1	3.4 ± 3.2	E4	7.3 ± 3.0	E4	13.7 ± 6.5	E5	15.5 ± 7.1	E4	12.5 ± 5.9	E5	8.6 ± 3.8	E7	4.9 ± 2.8	E5	6.7 ± 5.1
		E6	2.9 ± 1.8	E5	6.5 ± 2.3	E5	10.1 ± 5.7	E1	10.6 ± 6.6	E7	12.1 ± 10.1	E4	7.4 ± 3.0	E1	3.9 ± 2.1	E4	6.1 ± 4.2
		E2	2.5 ± 1.5	E3	1.8 ± 1.4	E3	2.5 ± 1.8	E3	7.1 ± 4.6	E5	10.3 ± 5.8	E3	6.4 ± 4.7	E2	3.8 ± 1.8	E3	1.1 ± 0.7
Load	Sex	PM		AD		MD		PD		UT		ISP		TM		BB	
		Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)	Exer. Rank	Mean ± SD (%)
ELASTIC	FEMALES	E5	35.7 ± 11.2	E1	48.1 ± 12.8	E2	53.0 ± 13.9	E4	35.5 ± 12.1	E2	51.3 ± 15.2	E1	44.7 ± 19.2	E4	48.8 ± 30.3	E1	40.1 ± 24.8
		E8	11.6 ± 7.7	E2	44.9 ± 14.3	E1	48.8 ± 11.7	E2	30.9 ± 13.3	E1	49.5 ± 15.8	E9	42.5 ± 29.6	E8	32.8 ± 13.8	E2	38.8 ± 17.8
		E3	11.1 ± 5.2	E5	41.2 ± 12.0	E4	31.9 ± 13.1	E9	26.5 ± 11.2	E3	48.1 ± 25.0	E2	37.9 ± 17.4	E9	21.2 ± 7.1	E5	38.6 ± 22.0
		E1	9.8 ± 5.0	E9	18.1 ± 6.4	E9	29.8 ± 10.3	E1	26.4 ± 12.4	E9	26.9 ± 17.0	E8	28.1 ± 20.2	E5	18.3 ± 15.7	E9	21.8 ± 7.0
		E4	9.6 ± 3.4	E4	16.1 ± 6.6	E5	25.3 ± 6.7	E8	13.6 ± 6.7	E4	21.4 ± 12.5	E4	22.4 ± 12.5	E1	17.9 ± 8.7	E4	16.1 ± 11.7
		E9	7.7 ± 3.9	E3	3.4 ± 2.6	E8	11.9 ± 10.3	E3	10.9 ± 8.3	E5	15.3 ± 8.6	E5	18.7 ± 8.4	E3	16.4 ± 8.5	E8	5.3 ± 4.0
		E2	5.5 ± 1.4	E8	2.9 ± 0.8	E3	4.1 ± 2.6	E5	8.0 ± 3.3	E8	4.8 ± 4.9	E3	10.7 ± 6.0	E2	15.6 ± 8.1	E3	2.7 ± 1.6
	MALES	E5	29.5 ± 12.3	E2	43.0 ± 10.3	E2	58.5 ± 13.1	E4	33.5 ± 8.8	E1	51.2 ± 17.1	E1	38.7 ± 17.1	E4	28.9 ± 10.9	E5	31.4 ± 13.0
		E8	9.6 ± 7.8	E1	42.8 ± 10.4	E1	51.6 ± 13.6	E2	32.9 ± 11.6	E2	50.8 ± 17.2	E2	35.6 ± 12.9	E8	19.7 ± 11.2	E2	29.7 ± 15.7
		E3	8.4 ± 8.0	E5	38.2 ± 12.3	E9	30.9 ± 15.7	E1	27.3 ± 8.6	E3	39.8 ± 14.2	E9	33.3 ± 10.1	E9	13.9 ± 8.8	E1	29.7 ± 13.7
		E1	7.1 ± 7.3	E9	17.9 ± 9.2	E4	25.5 ± 10.2	E9	21.5 ± 11.2	E9	20.8± 11.9	E5	17.9 ± 7.8	E3	13.3 ± 8.0	E9	16.8 ± 10.9
		E4	6.6 ± 3.7	E4	9.8 ± 4.6	E5	23.5 ± 12.1	E3	18.9 ± 12.1	E5	18.4 ± 12.0	E8	14.8 ± 9.0	E1	9.0 ± 4.4	E4	7.8 ± 3.2
		E9	5.3 ± 3.8	E3	2.5 ± 1.6	E8	11.2 ± 6.5	E8	11.5 ± 6.2	E4	17.4 ± 8.3	E4	14.6 ± 6.4	E2	8.4 ± 3.7	E8	3.4 ± 2.1
		E2	4.5 ± 2.6	E8	2.5 ± 1.3	E3	5.5 ± 9.0	E5	6.4 ± 3.3	E8	4.9 ± 4.1	E3	8.6 ± 6.3	E5	6.3 ± 3.4	E3	2.0 ± 1.1

** The identification of the exercises for each label Ei is given in Table 1 (e.g. E1= ABD_SCA_90).*

females). Excluding PD and UT, all other muscles showed significant differences between groups (p<0.001). TM, in females, showed a high standard deviation (±30%). During the concentric phase, the activation pattern for the first three muscles is almost the same in both groups, PD, TM and MD (41%, 48% and 34% males vs 51%, 67% and 43% females, p<0.001), conversely it follows UT (21%) and PD eccentric (19%) in males, but TM eccentric (31%), ISP (27%) and UT (±24%) in females.

Internal rotation in supine position (IR_90_el)

This exercise is executed from the supine posture and under elastic loading; therefore, it involves the muscles for the pure humerus internal rotation. In both groups, the pattern was TM, ISP and at lower intensity PD (20%, 15% and 12% males vs 33%, 28% and 14% females). Significant differences also exist between groups for TM and ISP (p<0.001), however ISP in females showed a consistent standard deviation (20%). During the concentric phase, the main pattern is confirmed for TM and ISP (25% and 20% males vs 40% and 37 females, p<0.05) followed by dissimilar muscles intervention PD (15%) in males and TM, ISP eccentric (26%, 19% respectively) and PD (18%) in females, with a significant standard deviation for ISP (±29% females) and for TM (±16% males).

External rotation in supine position (ER_90_el)

In this exercise, the load is applied during the pure external rotation of the humerus, therefore, muscles for pure external rotation are expected to be most activated, that is ISP, MD, PD and TS (33%, 31%, 22% and 21% males vs 43%, 30%, 26% and 27% females, with p<0.001 for ISP but with a standard deviation ±30%). The main activation of these muscles was achieved during the concentric phase, i.e., ISP, MD, PD and TS (46%, 36%, 29% and 26% males vs 61%, 36%, 37% and 35% females). It follows a dissimilar pattern MD eccentric, AD, BB, TM, and ISP eccentric in the males (26%, 20%, 20%, 20% and 19%); TM, BB, MD and ISP eccentric, AD in females (30%, 27%, 24%, 24% and 20%). Significant differences between groups occur for TM, PD and ISP (p<0.001), UT (p<0.01) and PM (p<0.05).

Ranking of exercises for each muscle

Similarly, for the muscular activation strategies classification in each exercise, we also conducted a ranking analysis for the exercises in relation to each muscle. Table 3 shows these ranking distributions. Under natural load (Table 3 upper panels) and the 20% MVC threshold, males showed five muscles with higher or equal values, MD (exercises ranking E2, E6, E7 and E1), UT (ranking E3, E6, E2 and E1), AD (ranking E1, E2), PD and ISP (both with only exercise E6).

For females seven muscles reached this threshold, MD (ranking E6, E2, E7 and E1), UT (ranking E3, E6; E2 and E1), AD (ranking E6, E2, E1 and E7), PD (ranking E6, E7 and E2), ISP (ranking E6 and E1) TM and BB (both with only one exercise E5 and E6 respectively). Exercises E6 (IR-ER_90_sit_na), E2 (ABD-FRO_90_na) and E3 (ELEV_na) are the more efficient for the muscular activation under natural loading conditions.

Considering the elastic loading condition (Table 3 lower panels) for all muscles, there is at least one exercise where the 20% MVC-IEMG threshold is observed. For AD, MD, UT, BB and PM, a high intensity was found for the same exercises E1 (ABD-SCA_90_el), E2 (ABD-FRO_90_el) and E5 (FLEX-EXT_el) respectively. For the other muscles, there is a substantial identity of the exercises, but females showed a greater activation for ISP, PD, TM and UT for exercises E7 (ER_90_el) and E6 (IR_90_el).

Discussion

In this study, the surface EMG was used to evaluate the activation strategies of the shoulder girdle principal muscles (AD, MD, PD, PM, UT, ISP, TM and BB) during seven typical rehabilitation exercises performed under natural loading, i.e. by simply moving the arm, and by applying an external elastic band to the hand. Our primary finding was the stability of the time structure, i.e. the reproducibility of the execution cadence. Considering the exercises performed under natural load, there is a general good reproducibility of the prescribed execution time of 2.0 s (Figure 2). However, females show a higher variability with significant standard deviations for FLEX_EXT_na, IR-ER_90_sup_na, ABD-FRO_90_na and ABD-SCA_90_na, while males show similar discrepancies only for IR-ER_90_sup_na. This suggests that females have a less continuous rhythm, and that the exercise IR-ER_90_sup_na is the most difficult to execute constantly.

Under the elastic band condition, the time structure reveals a pronounced variability. Females presented higher execution time for all exercises except for ELEV_el and ER_90_el (Figure 2 right panel), while males showed consistent values for most of the exercises except FLEX-EXT_el, IR_90_el and ER_90_el, therefore these exercises require a more marked neuromuscular control, which is reflected in the longer duration and variability. This could be explained by the capacity of holding the concentric and eccentric phases time, which is clearly noticeable for the males (0.99±0.20 s conc and 1.07±0.24 s ecc for the males; 1.05±0.23 s conc and 1.12±1.07s ecc for the females, respectively).

One of our main findings is how different is the order of muscles activations across exercises, i.e. in what extend (% of MVC activation) does each muscle contribute to the performed exercise? If two persons performing the same exercise show different intensity levels for the same muscles, it means that the “neuromuscular cost” should also be different between subjects. By performing a linear regression analysis for such association (Figure 2, Figure 3), the lower the slope, the better the muscle activation is. This could be defined as an index of neuromuscular activation economy or neuromuscular efficiency. Therefore, as exemplified in Figure 5 (left panel), for exercise 2, the total activation intensity (IEMG) required to complete the same workout will be lower

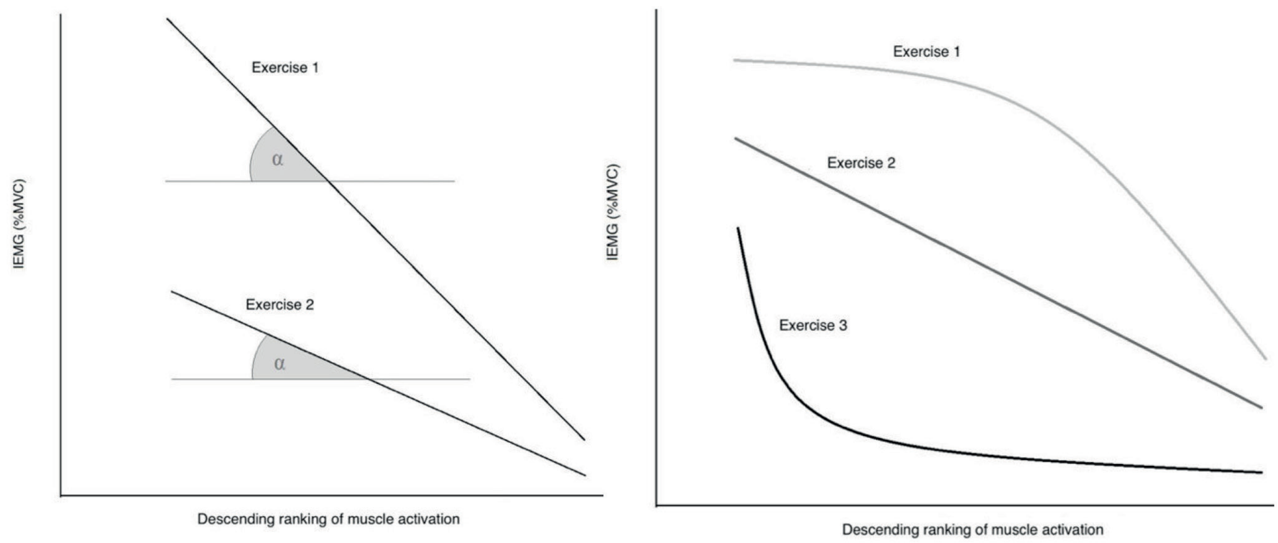

Figure 5. Models of neuromuscular efficiency. Left panel: linear relationship between the level of muscular activation and the ranking of involved muscles. As lower the slope (α angle) as higher the efficiency. Right panel: linear and nonlinear relationships (s. discussion for more explanations).

than for exercise 1. Hence, in exercise 2 the neuromuscular efficiency is higher.

For nonlinear relationships, we have found two main types of regression curves (Figure 5 right panel) which describe two main patterns of intermuscular coordination we called *multiple selectivity* and *single selectivity or muscle isolation*. In the first case, it means that few muscles contribute significantly and with the same intensity to complete the task while the others have extremely low activation level. In the second case, only one muscle is the main actor and no others or only very few of them contribute at all. In this case, according to the different coefficients of the corresponding fitting curves (exponential, polynomial), it will be a pronounced shaping of the curves, i.e. more or less muscles interested to complete the required task.

Conclusions

Our study showed that low to prominent levels of muscle activity can be achieved for the shoulder girdle musculature using classical rehabilitation exercises by modulating the external loading and the posture conditions, and the ranking order of the muscle's recruitment is fixed for each considered exercise. Nevertheless, there are significant differences in this ranking order with respect to both the factors the groups (males vs females) and the loads (natural vs elastic). Based on the current data a model of neuromuscular efficiency is proposed by comparing the cumulative required amount of muscular activation with respect to the ranking order of the corresponding muscles. Linear and non-linear regression curves can be calculated and suggested as reference models. Hence the data presented here can be used as guideline for a more individualised programming during the rehabilitation or for specific tasks in the resistance strength training.

Ethics approval

The study was conducted in accordance with the declaration of Helsinki and was approved by the Institutional Review Boards of the University of Udine (Italy) (038/IRB DAME_2021).

Consent to participate

All participants were informed about the purpose and contents of the study and provided written informed consent.

Authors´ Contributions

AT, RP and RC conceived the study concept and design. AT and RP conducted data acquisition and performed data analysis. SP provided video clips of some exercises usually performed in rehabilitation. LM aided in manuscript development and editing. All authors read and approved the final version of the manuscript.

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