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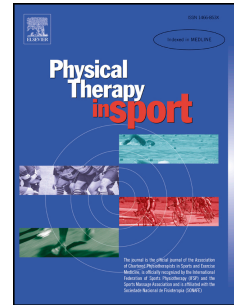
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1 **Influence of Fatigue and Velocity on the Latency and Recruitment Order of**
2 **Scapular Muscles**

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1 **Influence of Fatigue and Velocity on the Latency and Recruitment Order of**
2 **Scapular Muscles**

3 **Abstract**

4 **Objectives:** To determine the influence of velocity and fatigue on scapular muscle
5 activation latency and recruitment order during a voluntary arm raise task, in healthy
6 individuals.

7 **Design:** Cross-sectional study.

8 **Setting:** University laboratory.

9 **Participants:** Twenty three male adults per group (high-velocity and low-velocity).

10 **Main outcome measures:** Onset latency of scapular muscles [Anterior deltoid (AD),
11 lower trapezius (LT), middle trapezius (MT), upper trapezius (UT), and serratus
12 anterior(SA)] was assessed by surface electromyography. The participants were
13 assigned to one of two groups: low-velocity or high-velocity. Both groups performed a
14 voluntary arm raise task in the scapular plane under two conditions: no-fatigue and
15 fatigue.

16 **Results:** The UT showed early activation ($p < 0.01$) in the fatigue condition when
17 performing the arm raise task at a high velocity. At a low velocity and with no muscular
18 fatigue, the recruitment order was MT, LT, SA, AD, and UT. However, the recruitment
19 order changed in the high-velocity with muscular fatigue condition, since the
20 recruitment order was UT, AD, SA, LT, and MT.

21 **Conclusions:** The simultaneous presence of fatigue and high-velocity in an arm raise
22 task is associated with a decrease in the UT activation latency and a modification of the
23 recruitment order of scapular muscles.

24

25 **Keywords:** Timing; Neuromuscular control; Speed; Recruitment pattern.

26

27 **Highlights:**

28 • Upper trapezius shows an early activation latency with the simultaneous presence of
29 fatigue and high velocity

30 • Muscle recruitment order is modified during an arm raise task at different velocities.

31 • Muscle fatigue or an increase in velocity alone do not substantially modify activation
32 latency

33 1. Introduction

34

35 The balance between the trapezius and serratus anterior (SA) muscles maintains
36 the dynamic stability of the scapula during arm movement (Ludewig et al., 2004; Kibler
37 et al., 2007; Larsen et al., 2013; Hwang et al., 2017; Kara et al 2017). These functions
38 depend on muscle strength and appropriate motor control, i.e., appropriate onset latency
39 (timing) and muscle recruitment order (Cools et al., 2003; Phadke & Ludewig, 2013;
40 Struyf et al., 2014). In the scapular muscles, the onset latency has been typically
41 quantified as the time between the electromyographic (EMG) activation of a specific
42 muscle and the activation of the anterior deltoid which is the primary motor muscle
43 (Phadke & Ludewig, 2013). Thus, the latency of the muscles surrounding the scapula,
44 and their recruitment order during the execution of a motor task, can be calculated.

45 To our knowledge, there are few reports on the influence of velocity of
46 movement on scapular muscle activation latency and recruitment order. It has been
47 observed that the scapulohumeral rhythm has a ratio of 2:1 during movements at low-
48 velocity (Sugamoto et al., 2002; Prinold et al., 2013), while during movements at high-
49 velocity, the scapular contribution is higher (Sugamoto et al., 2002). On the other hand,
50 Roy et al. (2008) showed that the activation latency of the scapular muscles, under a
51 condition of no-fatigue, is modified at different arm raise velocities (Roy et al., 2008).
52 Thus, there is inconsistency in the reported influence of velocity on scapular muscle
53 motor control strategies.

54 Instability (Myers et al., 2004), the “subacromial impingement” syndrome
55 (Cools et al., 2003; Phadke & Ludewig, 2013), the level of contraction (Myers et al.,
56 2003), and pain (Santos et al., 2010) are all factors that affect the activation latency of

57 the glenohumeral and scapular muscles. It is possible that scapular motor control is most
58 demanding with high-velocity movements (Sugamoto et al., 2002; Thomas et al., 2003)
59 and with the simultaneous presence of other physiological factors, e.g., fatigue and pain
60 (Santos et al., 2010). In this context, a late scapular muscle response (i.e., latency
61 increase) has been observed after a sudden arm fall (unpredictable) from a 90°
62 abduction in fatigued scapular muscles (Cools et al., 2002). In a recent study, we
63 investigated the effect of predictable and unpredictable motor tasks on scapular muscle
64 activation latency (Mendez-Rebolledo et al., 2016). Our results indicated that scapular
65 muscles presented a specific recruitment order during a predictable task: SA was
66 activated prior to the anterior deltoid (AD), and the upper trapezius (UT) was activated
67 after the AD. While in an unpredictable motor task, all muscles were activated after the
68 destabilization, without a specific recruitment order; instead, there was simultaneous
69 activation. These results contribute to the understanding of motor control strategies in
70 predictable tasks; however, the mechanisms involved have not yet been reported in
71 detail. In line with this, it is necessary to increase knowledge about the simultaneous
72 effects of muscular fatigue and velocity increases during the arm raise task, in terms of
73 scapular muscle activation latency and recruitment order.

74 These two factors (velocity and fatigue) are frequent physiological conditions
75 that occur during daily activities, work, and sporting tasks (Thomas et al., 2003; Santos
76 et al., 2010; Joshi et al., 2011). A better understanding of how motor control is required
77 during predictable movements at high-velocity, and during conditions of fatigue, would
78 allow for better planning and selection of the most appropriate outcomes and the most
79 suitable exercises for rehabilitation plans (Santos et al., 2010; Joshi et al., 2011). Thus,
80 the objective of the current study was to determine the influence of velocity and fatigue

81 on scapular muscle activation latency and recruitment order during a voluntary
82 (predictable) arm raise task, in healthy individuals. We hypothesized that the presence
83 of fatigue in the scapular muscles, during an arm raise task at high-velocity, would
84 modify scapular muscle activation latency and recruitment order.

85

86 **2. Methods**

87

88 *2.1. Study design*

89 This cross-sectional study was conducted in the XXX. The results reported here
90 correspond to the second stage of a larger investigation. The first stage was recently
91 published (Mendez-Rebolledo et al., 2016). The dependent variable in the current study
92 was onset latency of the scapular muscles: lower trapezius (LT), middle trapezius (MT),
93 UT, and SA. Independent variables included velocity (low and high) and the absence or
94 presence of fatigue. The method was designed considering the Helsinki Consensus
95 (1975) on biomedical research in humans. The Bioethics Committee of the XXX
96 approved all procedures (Folio 2015106GM) and an informed consent form was read
97 and signed by each participant before participating in the study.

98

99 *2.2. Participants*

100 The participants presented the following baseline characteristics: age, 21.4 ± 1.6
101 years; height, 1.72 ± 0.05 m; weight, 72.4 ± 6.4 kg; body mass index (BMI), 24.4 ± 2.9
102 kg/m^2 ; and physical/sporting activity, 3 ± 1.2 times per week. The study involved a non-
103 probability sample of students from the Facultad de Ciencias de la Salud de la
104 Universidad de Talca recruited via advertising. A sample of 23 voluntary participants

105 per group (high and low velocity) was calculated based on a 95% confidence interval, a
106 power of 0.8, and an expected 15% loss. A mean of 159.6 ms and a standard deviation
107 of 56.4 ms for UT onset latency was obtained in a previous study (Cools et al., 2002),
108 and was considered for the sample size calculation. Exclusion criteria were: (1) BMI
109 greater than 29.9 kg/m^2 , as the extra subcutaneous tissue can compromise the quality of
110 the EMG signal (Phadke & Ludewig, 2013); (2) incomplete range of motion of the
111 shoulder; (3) a current or past history of shoulder pain; (4) participation in overhead
112 sports; and (5) history of trauma, dislocation, rotator cuff tear, spinal deformities,
113 radicular symptoms, and/or neurological diseases.

114

115 2.3. Instrumentation

116 An accelerometer (Delsys Inc., Boston, MA, USA) was used on the anterior
117 deltoid's surface of each volunteer to determine the beginning and end of the elevation
118 movement. This procedure was modified from previous reports where different
119 movement tasks were measured (Körver et al., 2014). The surface EMG (sEMG) signal
120 was acquired with a Delsys Trigno™ Wireless EMG System (Delsys Inc., Boston, MA,
121 USA) and recorded with the EMGworks Acquisition 4.2.0 (Delsys Inc., Boston, MA,
122 USA) software. The sEMG was sampled at 2000 Hz and stored on a computer using a
123 16-bit analog-digital converter. The electrodes were made of silver (99.9%) and had an
124 inter-electrode distance of 10 mm. A bandpass filter was used (fourth-order, zero-delay
125 butterworth filter with frequencies between 20-450 Hz) and the signal was digitally
126 amplified with a gain of 300, common mode rejection ratio > 80 dB, signal-to-noise
127 ratio < 0.75 mV RMS.

128

129 *2.4. Procedures and data collection*

130 Anthropometric assessments of the participants (weight and height), and warm-
131 up exercises of the scapular and rotator cuff muscles, were performed at the beginning
132 of each session (day 1 and 2). Prior to electrode placement, the hair was shaved and the
133 skin was cleaned with dermoabrasive paper and 70% isopropyl alcohol solution, to
134 reduce the impedance (typically $\leq 10 \text{ k}\Omega$). The EMG signals were recorded from the
135 dominant arm; the electrodes were located on the UT, MT, LT, SA, and AD muscles.
136 The electrodes were placed parallel to the presumed direction of the muscle fibers,
137 according to SENIAM recommendations (Hermens et al., 2000). For the SA, electrodes
138 were placed according to a previous study (Lehman et al., 2008). The position of each
139 electrode on the skin was marked with a hypoallergenic pencil to ensure the location of
140 the electrodes. Finally, an accelerometer was placed in the lateral region of the arm.
141 Proper electrode placement was further verified by observing the EMG signal on a
142 computer monitor during maximal voluntary isometric contraction of the arm, according
143 to the SENIAM recommendations.

144 The participants were assigned through simple random sampling (random
145 number generator) to one of two groups: low-velocity or high-velocity. Both groups
146 performed a voluntary arm raise task in the scapular plane under two conditions: no-
147 fatigue and fatigue (Fig. 1). A custom-made device based on previous studies (Ludewig
148 & Cook, 2000; Moraes et al., 2008) was used to standardize the upper limb position to
149 ensure that the movement was made in the scapular plane. This device consisted in a
150 rectangular glass positioned in front of the arm, 30° anterior to the frontal plane
151 (scapular plane). The low-velocity group executed the task with a velocity of four
152 seconds per cycle of arm elevation, in a range of motion of 180° , and the high-velocity

153 group executed the task with a velocity of two seconds per cycle (Sugamoto et al.,
154 2002). In the no-fatigue condition, the participants were instructed to reproduce the
155 movement velocity following the established rhythm of a metronome; they practiced the
156 movement at least two times prior to the measurements. This task was executed
157 voluntarily, without interruptions, and in the presence of visual (opened eyes),
158 somatosensory (gravity effect on the upper limb) and auditory information
159 (metronome), in order to ensure the task was "predictable" (Kanekar & Aruin, 2015).
160 Participants rested for 5 min before completing the fatigue condition.



161

162 **Fig. 1.** Voluntary arm raise task: voluntary arm elevation of 180° with the glenohumeral joint at 30° of
163 horizontal adduction.

164

165 Each participant was given instructions about the fatigue protocol for shoulder
166 muscles. This protocol consisted of execution of a cycle of bilateral arm elevation
167 (180°) in the scapular plane (describe above) at a rate of 1 cycle per second, as many
168 times as possible. The movement was performed with a dumbbell according to body
169 weight; 1.4 kg for those participants weighing less than 68.1 kg, and 2.3 kg for those
170 participants weighing greater than 68.1 kg. The use of this criterion allowed us to
171 observe alterations in scapular movement in participants performing an arm raise task
172 against a resistance based on their body weight (McClure et al., 2009). Enoka (2012)
173 indicated that the fatigue experienced by an individual depends on both perceptions of
174 fatigue and the level of fatigability. For these reasons, each participant was provided
175 with instructions regarding the modified Borg's Rate of Perceived Exertion Scale
176 (Zanca et al., 2016), and time of task failure, during the fatigue protocol (bilateral arm
177 elevation) described previously. Every 20 cycles of arm elevation, participants were
178 asked about their level of shoulder fatigue on a scale from 0 to 10. The fatigue protocol
179 was discontinued when the participant reached a score equal to or greater than 8, and
180 were not able to maintain the bilateral arm elevation. Once fatigued, participants again
181 performed the voluntary arm raise task. Finally, the EMG signals of the scapular
182 muscles (UT, MT, LT, and SA) and the AD were recorded, and the average of three
183 trials performed by each group, and under condition (no-fatigue or fatigue), was
184 calculated. A signal-to-noise ratio of less than 20% was confirmed in all the signals.
185 Additionally, the arm elevation and fall times were calculated through accelerometry.
186 No significant differences between elevation and fall times were observed in each group
187 (fatigue; no-fatigue) and condition (low-velocity; high-velocity).

188

189 2.5. *Data processing*

190 All raw EMGs signals were analyzed with EMGworks Analysis 4.2.0 (Delsys
191 Inc., Boston, MA, USA). The signals were full-wave rectified and filtered with a low-
192 pass filter (fourth-order, zero delay, butterworth filter) with a cutoff frequency of 50 Hz
193 (Phadke & Ludewig, 2013). The onset latency variable for each scapular muscle was
194 calculated as the difference in latency relative to that of AD activation (Phadke &
195 Ludewig, 2013; Mendez-Rebolledo et al., 2016). Onset was defined as the point where
196 the EMG activity passed the threshold of at least three standard deviations above the
197 average of the signal at rest, and maintained this level of activation for at least 25 ms
198 (Myers et al., 2003; Phadke & Ludewig, 2013). The standard deviation was calculated
199 in relation to a period of 200 ms of rest signal. One researcher visually confirmed all
200 muscle onset latencies.

201

202 2.6. *Statistical analysis*

203 The mean of the three trials for each group and condition (no-fatigue or fatigue)
204 was used for the statistical analysis. To determine differences in the BMI between low-
205 velocity and high-velocity groups, a *t*-test for independent groups was used. An alpha
206 level <0.05 was considered in all the statistical tests. SPSS statistical software (SPSS
207 20.0, SPSS Inc., IL, USA) was used.

208 The Shapiro-Wilk test, Levene's test, and Mauchly's test of sphericity were
209 applied to calculate the distribution, homogeneity of variance, and sphericity,
210 respectively. To determine the interaction between velocity and fatigue, a two-way
211 repeated measure analysis of variance (ANOVA) with within and between factors:
212 velocity (two levels) and fatigue (two levels) was performed. When the repeated

213 measure ANOVA showed interaction between factors, Bonferroni corrected t - tests
214 were used to compare the onset latencies between factors. To determine differences
215 between scapular muscles onset latencies in each condition, i.e. differences in the
216 recruitment order, a one-way repeated measures ANOVA with factor muscle (four
217 levels) was performed. Bonferroni corrected t -tests were used to compare the scapular
218 muscles response.

219 Partial eta-squared (η_p^2) for ANOVA was used to examine the effect size. A η_p^2 less
220 than 0.06 was classified as “small”, 0.07-0.14 as “moderate”, and greater than 0.14 as
221 “large”. In addition, Cohen d for paired samples was used as an indicator of the effect
222 size. A Cohen d less than 0.2 was classified as “trivial”, 0.2-0.5 as “small”, 0.5-0.8 as
223 “moderate”, and greater than 0.8 as “large”.

224

225 **3. Results**

226

227 Two participants (one from each group) were not included in the analysis
228 because these presented EMG signals with excessive noise and artifacts. Therefore, the
229 following results consider 22 participants for each group (low-velocity and high-
230 velocity). There were not significant differences in BMI between groups ($p > 0.05$). The
231 time of task failure was 192 ± 79 sec for the low-velocity group and 158 ± 86 sec for the
232 high-velocity group. All data presented a normal distribution, sphericity, and
233 homogeneity of variance.

234

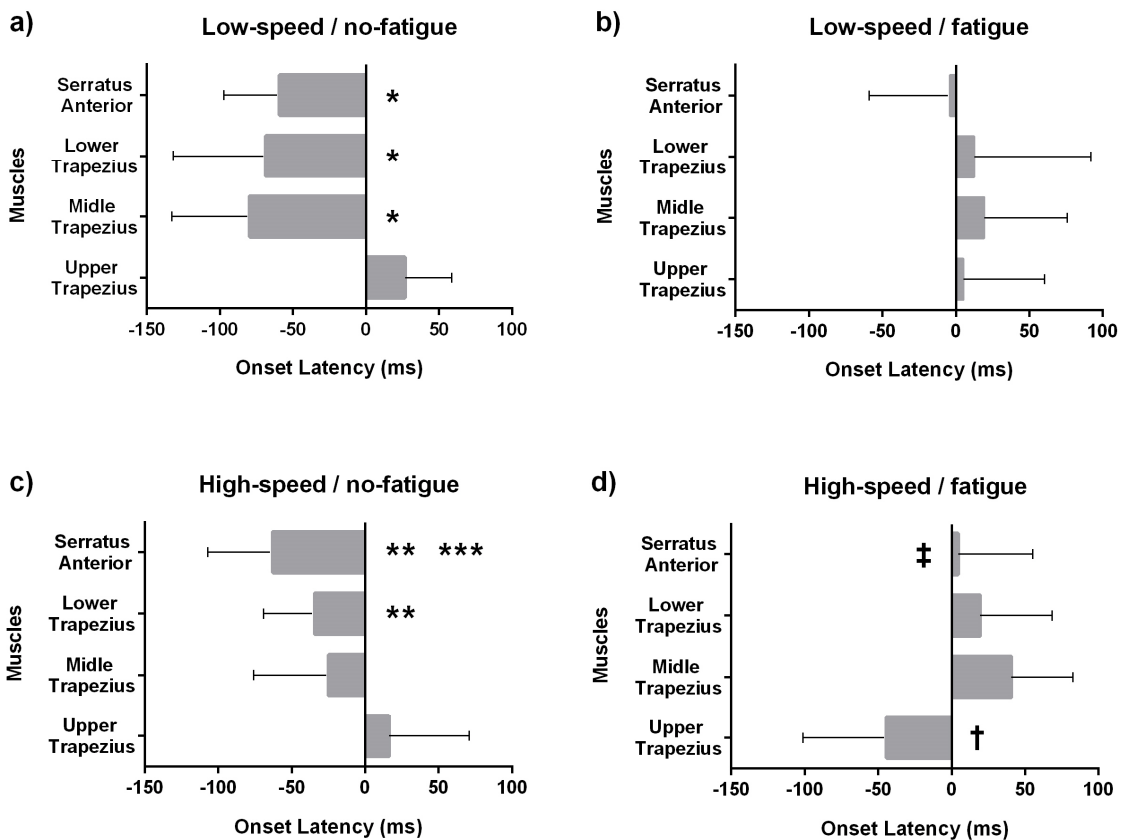
235 *3.1. Influence of velocity and fatigue in scapular muscles onset latencies.*

236 The repeated measures ANOVA revealed a significant velocity x fatigue
 237 interaction with a moderate effect size ($F_1 = 4.25$; $P = 0.045$; $\eta p^2 = 0.09$) only for UT
 238 onset latency. The post-hoc analysis showed that the UT exhibited a significantly earlier
 239 onset latency in the fatigue condition to high-velocity than in all other conditions (Table
 240 1). The above significant differences presented a large effect size. The other scapular
 241 muscles onset latencies did not show a significant velocity x fatigue interaction: MT (F_3
 242 $= 2.18$; $P = 0.147$; $\eta p^2 = 0.05$), LT ($F_3 = 0.45$; $P = 0.503$; $\eta p^2 = 0.01$), and SA ($F_3 =$
 243 0.49 ; $P = 0.486$; $\eta p^2 = 0.01$).

244

245 3.2. Influence of velocity and fatigue in scapular muscle recruitment order.

246 In the no-fatigue condition of slow-velocity group, the first muscle activated was



247 MT, followed by the LT, SA, AD and UT (Fig. 2a). The repeated measures ANOVA
 248 showed a main effect for muscle with a large effect size ($F_4 = 19.15$; $P < 0.0001$; $\eta p^2 =$
 249 0.81). The post-hoc analysis showed that the MT, LT and SA were activated
 250 significantly earlier than the AD and UT (Table 2). In addition, the AD was activated
 251 significantly earlier than UT. The above significant differences presented a large effect
 252 size. In the fatigue condition of this same group, the first muscle activated was the SA,
 253 followed by the AD, UT, LT and MT (Fig. 2b). However, the repeated measures
 254 ANOVA did not revealed a main effect for muscle ($F_4 = 0.91$; $P = 0.458$; $\eta p^2 = 0.04$).

255 **Fig. 2.** Scapular muscles onset latencies and recruitmet order in each velocity and condition; a) low-
 256 velocity/no-fatigue; b) low-velocity/fatigue; c) high-velocity/no-fatigue; d) high-velocity fatigue. Time
 257 zero represents the onset latency of anterior deltoid during the voluntary arm raise task and the error bars
 258 indicate standard deviation.

259 * MT, LT and SA were activated significantly earlier than the AD and UT. $P < 0.0001$

260 ** SA and LT muscles were activated significantly earlier than the AD and UT. $P < 0.01$

261 *** SA was activated significantly earlier than the MT. $P < 0.05$

262 † UT was activated significantly earlier that the AD, SA, LT and MT. $P < 0.01$

263 ‡ AD and SA were activated significantly earlier than the MT. $P < 0.05$

264

265 In the no-fatigue condition of high-velocity group, the first muscle activated was
 266 SA, followed by the LT, MT, AD and UT (Fig. 2c). The repeated measures ANOVA
 267 showed a main effect for muscle with a large effect size ($F_4 = 14.93$; $P < 0.0001$; $\eta p^2 =$
 268 0.41). Post-hoc analysis showed that the SA and LT muscles were activated
 269 significantly earlier than the AD and UT; and the SA was activated significantly earlier
 270 than the MT (Table 2). Conversely, in the fatigue condition of this same group, the first
 271 muscle activated was the UT followed by the AD, SA, LT and MT (Fig. 2d). The
 272 repeated measures ANOVA showed a main effect for muscles with a large effect size

273 ($F_4 = 13.25$; $P < 0.0001$; $\eta p^2 = 0.38$). The post-hoc analysis revealed that the UT was
274 activated significantly earlier than the AD, SA, LT and MT; and the AD and SA were
275 activated significantly earlier than the MT (Table 2).

276

277 **4. Discussion**

278

279 Our results indicate that the velocity of movement and muscular fatigue modify
280 activation latency and scapular muscle recruitment order during a voluntary arm raise
281 task. Specifically, (1) activation latency of the UT muscle showed early activation in the
282 condition of fatigue and high velocity movement, in comparison to the other conditions
283 (no-fatigue and low velocity). In addition, (2) the order of recruitment was significantly
284 different during the arm raise task at different velocities; at low velocity and with no
285 muscle fatigue, the order of recruitment was MT, LT, SA, AD, and UT; at high velocity
286 and with no muscle fatigue, the order of recruitment was SA, LT, MT, AD, and UT,
287 exhibiting a pattern of recruitment similar to the initial condition; and finally, at high
288 velocity and with muscle fatigue, the recruitment order was UT, AD, SA, LT, and MT,
289 which is a considerable variation compared to the two previous conditions.

290

291 *4.1. Onset latency of scapular muscles*

292 This is the first report regarding the simultaneous influence of velocity and
293 fatigue on scapular muscle latency and recruitment order during an arm raise task. The
294 UT was the only muscle that exhibited a decrease in activation latency with the presence
295 of fatigue and high velocity arm raise movements, modifying the latency from 26.8 to -
296 44.4 ms. This result differs from previous reports. Roy et al. (2008) found that muscle

297 activation latency of the shoulder complex did not vary with increased velocity in an
298 arm raise task, among a sample of healthy participants. This motor task was performed
299 in the presence of no muscular fatigue, and involved arm raises with 90° range of
300 movement in the scapular plane. Only one report analyzed the influence of scapular
301 muscle fatigue; this study found an increase in activation latency in the fatigued
302 scapular muscles during sudden arm fall from a 90° position of abduction, under
303 conditions of visual, auditory, and somatosensory deprivation (Cools et al., 2002). In the
304 present investigation, the task was characterized as predictable and voluntary, since the
305 participants had visual (opened eyes) and somatosensory (effect of gravity on the upper
306 limb) information, before and during the arm raise task (Kanekar & Aruin, 2015). In
307 addition, auditory cues (metronome) helped to regulate the velocity of arm elevation
308 during the different conditions. This allows for anticipated activation of the scapular
309 muscles in order to maintain joint stability. In this context, the differences observed in
310 the present study, as compared to the previous reports, can be attributed to the nature of
311 the motor task employed in each study (Mendez-Rebolledo et al., 2016), and the
312 simultaneous presence of fatigue and high velocity in the execution of the movements.

313 Based on the previous research, it is likely that fatigue is the determining
314 condition for this modification in muscular latency during movement execution at high
315 velocity. One possible explanation for this decrease in UT latency is the type of fiber in
316 each compartment of the trapezius muscle. The LT has a high proportion of type I fibers
317 (resistant to fatigue) while the UT has a high proportion of type II fibers (non-resistant
318 to fatigue) (Lindman et al., 1990; Lindman et al., 1991; Larsson et al., 2001). Due to
319 these histochemical characteristics, the fibers of the UT fatigue faster, generating
320 overactivation and an increase in firing rate, in order to maintain scapular function

321 (Falla et al., 2009; Ge et al., 2012). On the contrary, the fibers of the LT and MT are
322 more resistant to fatigue and maintain their activation with no major variations. This is
323 based on the results by Westgaard and De Luca (2001) who showed that the inferior
324 fibers of the trapezius muscle have a larger proportion of low threshold motor units
325 which are usually associated with muscle fibers with higher aerobic capacity and
326 therefore are able to activate for longer periods compared to high threshold motor units.
327 Therefore, the observed changes in muscle recruitment might be explained by the
328 different peripheral properties of the scapular muscles. However, it is also likely that
329 central adjustments influenced the recruitment order as it has been shown that the
330 central nervous system may change the recruitment strategy to satisfy the demands of
331 the task (Strang & Berg, 2007; Mendez-Rebolledo et al., 2016). In this context, the large
332 standard deviation (variability) of the muscle onset latencies of the groups may mask
333 potential differences. This could be potentially explained by different neural strategies
334 used by the participants during the arm elevation, despite that the demands of the task
335 remained consistent for each individual condition

336 On the other hand, the results of the present study indicate that the activation
337 latencies of the MT, LT, and SA muscles are not modified when the arm raise task is
338 performed at varying velocities. These results are consistent with previous reports where
339 MT, LT, and SA are activated prior to the AD muscle (shown as negative values for
340 onset latencies), both in healthy non-athletes who performed a movement at low-
341 velocity (Roy et al., 2008; Mendez-Rebolledo et al., 2016), and in healthy tennis players
342 who executed a serve at high-velocity (Kibler et al., 2007). It is probable that the high
343 demand of a high-velocity arm movement is addressed by a greater contribution of the
344 scapular kinematics (Sugamoto et al., 2002; Prinold et al., 2013) and EMG amplitude

345 (Gaudet et al., 2017), without variations in the activation latency of MT, LT, and SA.
346 These muscles are considered the main scapular stabilizers which allow dynamic
347 control of the scapula during arm movements (Kibler et al., 2007; Boettcher et al.,
348 2010), and therefore, are the main active muscles required in diverse environmental
349 conditions.

350

351 *4.2. Scapular muscle recruitment order and sport*

352 The results of our investigation reveal a specific recruitment pattern of the
353 scapular muscles, in the absence of fatigue, and during high and low velocity
354 conditions: the stabilizing scapular muscles, i.e., MT, LT, and SA (Kibler et al., 2007;
355 Boettcher et al., 2010; Phadke & Ludewig, 2013), are likely to be activated prior to the
356 AD muscle, and the scapular mobilizing muscle, i.e., UT (Kibler et al., 2007; Boettcher
357 et al., 2010; Phadke & Ludewig, 2013), is activated after the AD. This order of
358 recruitment has been observed in a tennis serve (Kibler et al., 2007) and a baseball pitch
359 (Hirashima et al., 2002), where the movements of the arm are performed at high-
360 velocity.

361 In contrast, this muscle pattern varies with the simultaneous presence of fatigue
362 and high velocity arm movement: the scapular mobilizing muscle is activated prior to
363 the AD muscle, and the scapular stabilizing muscles are activated later. These results
364 show that muscle fatigue or an increase in velocity alone do not substantially modify
365 muscle activation latencies (Roy et al., 2008; Gaudet et al., 2017), but the simultaneous
366 presence of muscle fatigue and high velocity movement contributes to the decrease in
367 the activation latency of the UT, and the modification of muscle recruitment order.
368 Where there is greater demand for velocity in a motor task, there is greater rotation of

369 the scapula (Sugamoto et al., 2002; Prinold et al., 2013; Gaudet et al., 2017). This
370 greater demand in the kinematics is reflected by the scapular muscles through a greater
371 EMG amplitude of the stabilizing muscles (SA) (Gaudet et al., 2017) and, according to
372 the results of this study, a relatively stable recruitment order: SA, LT, MT, AD, and UT.
373 However, in the presence of muscular fatigue, the UT modifies its motor control
374 strategy by decreasing its activation latency and considerably modifying the scapular
375 recruitment pattern: UT, AD, SA, LT, and MT. According to our results, the decrease in
376 UT muscle latency significantly influenced the muscular recruitment order, primarily
377 because of the presence of fatigue during the high velocity arm movement. These fast
378 movements are commonly observed in sport activities involving the upper limb, e.g.,
379 baseball, basketball, athletics (throwing), and volleyball (Hirashima et al., 2002; Kibler
380 et al., 2007). In this context, it is likely that in the fatigued (high-velocity) condition, the
381 UT was part of an anticipatory postural adjustment as the onset was prior to AD, which
382 contrasted with the non-fatigued condition. Previous research has shown an over-
383 activation of the UT in subjects with shoulder dysfunction (Ludewig & Cook, 2000;
384 Larsen et al., 2013; Kara et al., 2017); therefore, it could be tempting to suggest that an
385 earlier onset of UT activation during a fatiguing task could increase the risk of injury.
386 However, the upper limb sports mentioned above may require an earlier activation of
387 the UT during a fatigued condition to satisfy the demands of the movement. Therefore,
388 this recruitment pattern would be necessary to enable the performance of the task. These
389 observations (whether the earlier activation of the UT can be considered an adaptive or
390 a mal-adaptive response), need to be confirmed in future studies comparing both healthy
391 and injured populations.

392

393 4.3. Limitations

394 Despite the interesting findings reported in this study we must acknowledge
395 some limitations. The muscle activation latency was based on a threshold of three
396 standard deviations from the resting EMG. Di Fabio (1987) supports the use of this
397 method due to its reliability and maximum comparability between studies. In addition,
398 Hodges & Bui (1996) indicate that this criterion is widely used during dynamic
399 contractions because it reduces the negative influence of artifacts and signal-to-noise
400 ratio. In spite of this, it is necessary to use caution when making comparisons between
401 studies, bearing in mind the method of obtaining muscle activation latency. In addition,
402 the operational definition of arm movement velocity was in accordance with the study
403 of Sugamoto et al. (2002). The low-velocity group executed the task with a velocity of
404 four seconds per cycle of elevation, in a range of motion of 180°, and the high-velocity
405 group executed the task with a velocity of two seconds per cycle. Other reports have
406 indicated that the arm velocity reached during sports involving the upper limb may be
407 higher (Prinold et al., 2013), possibly because of the rotational components of the
408 movements used (e.g., rotation of the shoulder during a pitch). Another limitation of the
409 current study is the lack of investigation of the deeper muscles, however, these muscles
410 are difficult to assess with intramuscular EMG during highly dynamic tasks.

411

412 5. Conclusions

413

414 The simultaneous presence of muscle fatigue and high-velocity arm raise
415 movement is associated with a decrease in the UT activation latency and a modification
416 to the scapular muscle recruitment order. An increase in the arm raise velocity generates

417 a greater demand on the scapular kinematics, which is dealt with by the scapular
418 muscles through a relatively stable order of recruitment: SA, LT, MT, AD, and UT.
419 However, in the presence of muscle fatigue, the UT modifies its motor control strategy
420 by decreasing its activation latency, thereby considerably modifying the order of
421 scapular recruitment: UT, AD, SA, LT, and MT. This study contributes to the
422 understanding of several factors that can influence motor control strategy, especially UT
423 activation latency, during the practice of overhead sports.

424

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426

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539 **Tables**

540 Table 1. Scapular muscles onset latencies and multiple pairwise comparisons between velocities (low and high) and conditions (no-fatigue and fatigue) for upper
 541 trapezius.

Scapular Muscles	No-fatigue/low-velocity	No-fatigue/high-velocity	Fatigue/low-velocity	Fatigue/high-velocity
Upper trapezius onset latency (ms)	26.8 ± 31.8	16.5 ± 54.4	5.2 ± 55.3	-44.4 ± 56.8
Middle trapezius onset latency (ms)	-79.6 ± 53.1	-24.9 ± 50.8	19.4 ± 56.3	40.8 ± 41.7
Lower trapezius onset latency (ms)	-68.7 ± 63.2	-34.4 ± 34.7	12.6 ± 79.3	19.4 ± 49.2
Serratus anterior onset latency (ms)	-59.1 ± 38.4	-63.0 ± 44.0	-3.8 ± 55.1	4.7 ± 50.7
Upper trapezius	Mean difference	95% CI of difference	P value	Cohen's d
No-fatigue/low-velocity (vs) fatigue/low-velocity	21.6	-9.76 to 53.0	0.233	0.47
No-fatigue/low-velocity (vs) no-fatigue/high-velocity	10.3	-24.6 to 45.1	0.999	0.23
No-fatigue/low-velocity (vs) fatigue/high-velocity	71.2	7.7 to 134.7	0.008	1.54
No-fatigue/high-velocity (vs) fatigue/high-velocity	61	29.6 to 92.3	< 0.0001	1.09
Fatigue/low-velocity (vs) no-fatigue/high-velocity	11.3	- 74.8 to 52.2	0.350	0.20
Fatigue/low-velocity (vs) fatigue/high-velocity	49.6	14.8 to 84.5	0.003	0.88

542 95% CI, 95% confidence interval.

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549 **Table 2.** Multiple pairwise comparisons between scapular muscles in each velocity (low and high) and condition (no-fatigue and fatigue).

Onset latency (ms)	No-fatigue				Fatigue				
	Low-velocity	Mean Dif	95% CI of Dif	<i>P</i> value	Cohen's <i>d</i>	Mean Dif	95% CI of Dif	<i>P</i> value	Cohen's <i>d</i>
Anterior deltoid – upper trapezius		-26.8	-48.1 to -5.5	0.007	1.19	-5.2	-42.1 to 31.7	1.000	0.13
Anterior deltoid – middle trapezius		79.6	44.1 to 115.1	< 0.0001	2.11	-19.4	-57.0 to 18.2	1.000	0.48
Anterior deltoid – lower trapezius		68.7	26.4 to 110.9	< 0.0001	1.53	-12.6	-65.6 to 40.4	1.000	0.22
Anterior deltoid – serratus anterior		59.1	33.4 to 84.8	< 0.0001	2.17	3.9	-33.0 to 40.7	1.000	0.09
Upper trapezius – middle trapezius		106.4	63.6 to 149.1	< 0.0001	2.43	-14.2	-47.2 to 18.8	1.000	0.25
Upper trapezius – lower trapezius		95.5	44.8 to 146.2	< 0.0001	1.90	-7.4	-65.3 to 50.5	1.000	0.10
Upper trapezius – serratus anterior		85.9	52.8 to 119.1	< 0.0001	2.43	9.0	-33.3 to 51.4	1.000	0.16
Middle trapezius – lower trapezius		-10.9	-47.4 to 25.6	1.000	0.17	6.8	-46.3 to 59.9	1.000	0.09
Middle trapezius – serratus anterior		-20.4	-55.6 to 14.8	0.830	0.39	23.2	-14.4 to 60.9	0.666	0.41
Lower trapezius – serratus anterior		-9.5	-56.9 to 37.8	1.000	0.18	16.4	-23.2 to 56.0	1.000	0.24
High-velocity	Mean Dif	95% CI of Dif	<i>P</i> value	<i>d</i>	Mean Dif	95% CI of Dif	<i>P</i> value	<i>d</i>	
Anterior deltoid – upper trapezius	-16.5	-52.9 to 19.9	1.000	0.42	44.4	6.4 to 82.4	0.014	1.10	
Anterior deltoid – middle trapezius	24.9	-9.0 to 58.8	0.318	0.69	-40.8	-68.7 to -12.9	0.002	1.38	
Anterior deltoid – lower trapezius	34.4	11.2 to 57.6	0.001	1.40	-19.4	-52.2 to 13.5	0.785	0.55	
Anterior deltoid – serratus anterior	63.0	33.6 to 92.4	< 0.0001	2.02	-4.7	-38.6 to 29.2	1.000	0.13	
Upper trapezius – middle trapezius	41.4	-0.7 to 83.6	0.057	0.78	-85.2	-122.8 to -47.6	< 0.0001	1.70	
Upper trapezius – lower trapezius	50.9	12.1 to 89.7	0.005	1.11	-63.8	-113.2 to -14.5	0.006	1.20	
Upper trapezius – serratus anterior	79.6	31.1 to 128.1	< 0.0001	1.60	-49.1	-88.9 to -9.4	0.009	0.91	
Middle trapezius – lower trapezius	9.5	-20.6 to 39.5	1.000	0.21	21.4	-22.1 to 64.8	1.000	0.46	
Middle trapezius – serratus anterior	38.1	3.0 to 73.3	0.027	0.80	36.1	5.3 to 66.8	0.014	0.77	
Lower trapezius – serratus anterior	28.7	1.0 to 56.3	0.066	0.72	14.7	-29.3 to 58.7	1.000	0.29	

550 Dif, difference; 95% CI, 95% confidence interval; *d*, effect size Cohen's *d*.