



## Functional and morphological changes in shoulder girdle muscles after repeated climbing exercise

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1 **Functional and Morphological Changes in Shoulder Girdle Muscles After Repeated Climbing**  
2 **Exercise**

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4  
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## ABSTRACT

26 This study aimed to investigate the acute effect of repeated climbing actions on functional and  
27 morphological measures of the shoulder girdle. Fifteen male indoor climbers participated in this study.  
28 All the climbers declared route level 6a+, as the best climbing grade (French climbing grade scale).  
29 Functional (range of motion - ROM and muscle strength), and morphological measurements  
30 (muscle/tendon stiffness and thickness) after a repeated climbing exercise protocol were analyzed. The  
31 ROM and muscle strength showed significant decreases from baseline to Immediate-Post (IA) as well  
32 as significant increases from IA to 1h-Post for all movements ( $p \leq .001$  for all). Muscle stiffness showed  
33 significant increases from baseline to IA after as well as significant decreases from IA to 1h-Post for all  
34 muscles ( $p \leq .001$  for all). However, thickness showed significant increases from baseline to IA for  
35 supraspinatus tendon and muscle thickness and occupation ratio ( $p \leq .001$  for all), while a significant  
36 decrease was observed in acromiohumeral distance ( $p \leq .001$ ). Significant decreases from IA to 1h-Post  
37 were found for muscles/tendons and occupation ratio ( $p \leq .001$  for all), while a significant increase for  
38 AHD ( $p \leq .001$ ). Our data demonstrated acute alterations in tendon thickness due to acute signs of  
39 implement symptom in climbers.

40 **Key Words:** muscle stiffness, thickness, overhead, fatigue, climbing

## INTRODUCTION

41

42 Indoor climbing is gaining popularity as a form of physical activity and recreation. Currently,  
43 indoor and outdoor climbing have developed on a competitive level culminating by the debut of indoor  
44 climbing at the 2020 Olympic Games in Tokyo (Lutter et al., 2017). Climbers are characterized by high  
45 physical performance in endurance, flexibility and strength (Grant et al., 1996;Mermier et al.,  
46 2000;Grant et al., 2001). Previous studies have shown that climbers exhibit greater strength of the grip  
47 and fingers, flexibility of the upper extremity and endurance of the shoulder girdle compared with non-  
48 climbing controls (Grant et al., 1996). Range of motion (ROM) of the shoulder is a key element in  
49 climbing, especially during overhead and horizontal movements, e.g., single and double arm pull ups as  
50 well as hangings during climbing (Deyhle et al., 2015;MacLean and Dickerson, 2019).

51 Repetitive upper extremity activity have been shown to alter morphological properties of  
52 tendons and muscles, including changes in thickness (McCreesh et al., 2017;Klich et al., 2020;Mifune  
53 et al., 2020;Porter et al., 2020;Pozzi et al., 2021) as well as shoulder ROM and strength (Yu and Lee,  
54 2013;Oliver et al., 2020). Previous experimental studies have shown that a repeated exercise bout of an  
55 rotator cuff muscles exercise led to an acute alteration of increased supraspinatus tendon thickness  
56 (McCreesh et al., 2017;Klich et al., 2020). Similarly, a short exercise bout in overhead athletes (Klich  
57 et al., 2020;Porter et al., 2020), and longer term repetitive work activity (Pozzi et al., 2021) have led to  
58 an increase in supraspinatus tendon thickness. An increase in muscle stiffness has also been  
59 demonstrated after repetitive upper extremity activity of the pectoralis major, deltoid, infraspinatus and  
60 upper trapezius (Dashottar et al., 2014;Klich et al., 2020). And repeated exercise bout specifically of the  
61 rotator cuff caused increases in the infraspinatus stiffness and supraspinatus tendon thickness (Klich et  
62 al., 2020), and reduction in shoulder ROM (Dashottar et al., 2014).

63 Schöffl et al. (2011) reported shoulder impingement syndrome as the most frequently disorders  
64 of the shoulder in climbers. The understanding of both muscle stiffness with tendon morphology changes  
65 might be a novel approach to provide the advancement in our understanding of mechanisms of the  
66 development of shoulder pain related to tendinopathy. Therefore, the aim of this study was to investigate  
67 the acute effect of repeated climbing actions on functional and morphological measures of the shoulder  
68 girdle. Specifically, we hypothesized that after repeated climbing exercise protocol: (1) the rotator cuff  
69 tendons would be thicker with a concurrent reduction of the subacromial space, and the supraspinatus  
70 tendon will occupy a greater proportion of the subacromial space; (2) there would be an increase in  
71 rotator cuff muscle stiffness.

72

## MATERIAL AND METHODS

### Study design

74 An observational, case series study assessing functional and morphological changes after  
75 repeated climbing exercise measurements was conducted. The functional measurements were rate of  
76 perceived exertion (RPE), shoulder ROM and maximal strength. The morphological measurements were

77 myotonometry and ultrasonography at baseline, immediately after (Immediate-Post) and 1-hour post  
78 exercise protocol (1h-Post). The time elapsed from the end of the repeated climbing exercise protocol  
79 to the beginning of the measurements was 30 seconds or less, and all measurements were made within  
80 5 minutes. Measurements were made in the same order starting with (1) RPE, (2) myotonometry  
81 including muscle stiffness of the shoulder girdle, specifically of the pectoralis major, deltoid anterior,  
82 deltoid posterior, and infraspinatus, (3) ultrasonography of the tendons and muscles of the supraspinatus  
83 and infraspinatus, and subacromial space via acromiohumeral distance (AHD); (4) ROM, (5) isometric  
84 maximal strength of shoulder flexion, abduction, and internal rotation. All measurements were taken on  
85 the dominant shoulder.

86 Participants read and signed an informed consent form approved by the Senate Research Ethics  
87 Committee (project identification code: 26/2016 approval date: 13.10.2016). The study was conducted  
88 according to the Declaration of Helsinki.

### 89 **Participants**

90 A group of healthy male recreational indoor climbers ( $n=15$ , age  $28.8\pm 7.4$  years, body height  
91  $178\pm 9.3$  cm, body weight  $74.5\pm 6.7$  kg, BMI  $23.7\pm 1.5$  kg·m<sup>-2</sup>) voluntarily participated in this study. All  
92 participants were right-handed with training experience in indoor climbing of  $6\pm 2$  years and training  
93 duration of  $10\pm 1$  hours per week. The difficulty level of the route was strictly adapted to the climber's  
94 skills and performance, based on the French climbing grade scale (Draper et al., 2011).

95 The recruitment process consisted of two parts: (1) An interview including questions about  
96 experience, training frequency (per week), rate of advancement (route grade) as well as history of pain  
97 and injuries in the upper extremity. (2) A screening evaluation using ultrasound assessment of the rotator  
98 cuff tendons/muscles performed by a experienced physical therapist, and further evaluated by an  
99 experienced orthopedic surgeon (specialized in shoulder) to avoid acute and chronic rotator cuff tears,  
100 or other tendon/muscle damage. The images were blind evaluated to increase the quality of the  
101 recruitment process. During the recruitment process, the participants reported their best climbing grade  
102 achieved in the past 2 years during a free climbing route. All the climbers declared route level 6a+, as  
103 the best climbing grade. The inclusion criteria were: 1) training experience in indoor climbing  $\leq 5$  years,  
104 training duration  $\geq 8$  hours per week, and climbing best level at 6a. This climbing route has an overhang  
105 with small, smooth and more oval handholds placed at greeter distance involving multi-planar  
106 movements. Exclusion criteria consisted of no intensive strength training 2 weeks prior to the study,  
107 previous upper extremity trauma, previous upper extremity surgery, and previous pain in the shoulder  
108 in the past 6 months.

109 The G\*Power software (version 3.1.9.2; Kiel University, Kiel, Germany) (Faul et al., 2007) was  
110 used to estimate the required sample size. We calculated the power ( $1-\beta$ ) for repeated measure ANOVA  
111 within factors, by defining the sample size as 13 (for all ultrasound measurements), set a minimum  
112 expected effect size (Cohen's  $f$ ) of 0.5, an  $\alpha$  level of 0.05, and a power of 0.95 and correlation for repeated

113 measures of 0.6. Also, power of shoulder stiffness, ROM and strength was calculated by defining the  
114 sample size as 13,  $\alpha$  as 0.05, and effect size as 0.45; 0.35 and 0.38 respectively.

## 115 **Procedure**

116 The measurements were obtained three times; baseline, Immediate-Post, and 1h-Post. The  
117 participants were asked to refrain from climbing and to avoid strenuous physical activity 2 days before  
118 participating in the study.

119 After baseline measurements, the participants took part in a 15-minutes warm-up exercise  
120 program based on global exercises (including mobility and stability) of the shoulder girdle, trunk and  
121 forearm joints, and muscles. The warm-up ended with a single climb on the wall at the grade level of  
122 6a+, to familiarize the participant with the specific climbing route. Following a 5-minutes rest, each  
123 subject performed a repeated climbing exercise protocol on a climbing wall. The wall was 15 meters  
124 high, including an overhang of about 7° from the right angle (83°). Grips had different sizes, shapes and  
125 were placed at different distances to occur the shoulder movement both vertically and horizontally. The  
126 exercise procedure consisted of five times climbs (grade level 6a+) for a total time of 5-minutes per  
127 climb, followed by a 5-minute rest. Immediately after the exercise protocol and 1-hour post, measures  
128 were taken (**Figure 1**).

## 129 **Measurements**

### 130 **Rate of perceived exertion (RPE)**

131 The participants were asked to determine the level of fatigue with the 6 to 20 RPE scale (Borg,  
132 1998). During the evaluation, participants had to indicate the RPE scale according to their upper  
133 extremity and shoulder.

### 134 **Functional measurements**

#### 135 **Range of motion (ROM)**

136 A wired twin-axis electrogoniometer (Noraxon USA Inc., Arizona, USA) was used to record  
137 shoulder movement during flexion, abduction and internal rotation. This device consists of a central  
138 strain gauged flexible shim that runs the length of the device with two end plates attached to the shim.

139 For all ROM measurements, the participants were seated with on a chair, with arms placed at  
140 the side of the body in neutral position and thumb pointing forward. For internal rotation measurements,  
141 the arms were positioned in flexion of the elbow of 90°. To assess ROM during flexion an investigator  
142 placed the sensor over the lateral board of the scapula and the anterior part of the arm, with the center  
143 of the sensor positioned over the acromion. For abduction, the sensor was placed with over the spine of  
144 the scapula and the arm, with the center of the sensor positioned over the acromion (Ribeiro et al., 2016).  
145 The ROM in the transverse plane was measured using two sensors, where one was positioned for flexion,  
146 while the second was placed over the lateral side of the arm radial part of the forearm. The ROM was  
147 measured and collected at 1500 Hz by TeleMyo 2400T G2 and PC interface (MyoResearch XP Master

148 Edition 1.08.09, Noraxon). All sensors were attached using double-sided tape and supported by an  
149 elastic band to avoid extra movements of sensors. Before repeated measurement the electrogoniometer  
150 was calibrated and set to 0°. Each measurement was made twice and maximum values were extracted.  
151 The relative reliability ranged from good to excellent for all analyzed movements (ICC<sub>2,1</sub> from 0.87 to  
152 0.92) (Landis and Kock, 1977). The absolute reliability showed that SEMs were 2.3° to 4.5°, while  
153 MDC90% ranged from 6.3° to 12.4°.

#### 154 **Maximal strength**

155 A handheld dynamometer (HHD) (Hoggan Scientific, Lafayette, IN) was used to measure  
156 strength peak force during maximal voluntary isometric contraction (Harrington et al., 2011). Shoulder  
157 strength testing was performed in a seated position with their feet flat on the floor, with knees and hips  
158 at approximately 90°. For flexion and abduction the arm was placed in 90° of elevation, while for  
159 external rotation the arm was positioned by the side with a towel roll under the axilla, and the elbow  
160 flexed to 90°. The HHD was stabilized with an external device and aligned with the posterior forearm  
161 just proximal to the ulnar styloid process for flexion and abduction strength. For internal rotation  
162 strength, the HHD was placed on the anterior forearm just proximal to the wrist (Michener et al., 2021).  
163 The order of strength testing was randomized to minimize potential effect of fatigue. During the  
164 measurements, participants were informed to “push as hard as you can” for 5 seconds. Thirty seconds  
165 and 1 min rest were given between each trial and testing position, respectively (Harrington et al., 2011).  
166 Each measurement was taken twice and the maximum values were averaged prior to statistical analysis.  
167 The relative reliability was good to excellent for all analyzed strength (ICC<sub>2,1</sub> from 0.82 to 0.90). The  
168 absolute reliability showed SEMs were 5.5 N to 13.0 N, while MDC90% were 15.0 N to 34.0 N.

#### 169 **Morphological measurements**

##### 170 **Muscle stiffness**

171 A hand-held myotonometer device (MyotonPro, Myoton Ltd, Estonia) was used to measure  
172 the stiffness of the pectoralis major, deltoideus anterior and posterior, and infraspinatus muscle. Muscle  
173 stiffness is defined as the property that characterizes resistance to the contraction or to a stretching  
174 external force that deforms the initial shape of the tissue. Stiffness (N/m) was computed as  
175  $S = a_{\max} m_{\text{probe}} / \Delta l$ , where  $a$  is the acceleration of the damped oscillation;  $m_{\text{probe}}$  is the mass of the  
176 measurement mechanism and  $\Delta l$  is the probe displacement (Kawczynski et al., 2018). The examiner  
177 located the probe perpendicular to the tested area and then the probe generated three impulses exerted  
178 on the tested muscles (Kelly et al., 2018). The probe was placed perpendicular to the tested area and  
179 generated three impulses exerted on the testing area. The subject was seated with their back on a chair,  
180 arms on the table with the forearms pronated. Measures of stiffness were performed over the shoulder  
181 on four locations: (1) infraspinatus – two fingers width below the center spine of scapula (Kelly et al.,  
182 2018), (2) anterior deltoid, (3) posterior deltoid, and (4) pectoralis major – muscle belly halfway between

183 clavicle and humeral bone (Klich et al., 2020). The relative reliability was good to excellent for stiffness  
184 of all analyzed muscles ( $ICC_{2,1}$  from 0.86 to 0.94). The absolute reliability showed that SEMs ranged  
185 from 10 N/m to 17 N/m, while MDC90% ranged from 28 N/m to 48 N/m.

### 186 **Tendon and muscle thickness, acromiohumeral distance (AHD) and occupation ratio**

187 Ultrasonography was performed using an ultrasound scanner (HS-2200, Honda, Toyohashi,  
188 Japan) with a 7.5 (6.0 to 11.0) MHz and 40 mm linear array transducer (HLS-584 M, Honda, Toyohashi,  
189 Japan) in greyscale B-mode. The settings of the ultrasound system were standardized for all participants  
190 and kept identical for all measures. A single examiner (a certificated physical therapist with a practice  
191 in musculoskeletal ultrasonography) obtained ultrasound images of (1) supraspinatus tendon thickness  
192 in short axis (SST- $S_{Thick}$ ), (2) supraspinatus tendon in the long axis (SST- $L_{Thick}$ ), (3) supraspinatus  
193 muscle thickness ( $SSM_{Thick}$ ), (4) infraspinatus muscle thickness ( $INFM_{Thick}$ ) and (5) acromiohumeral  
194 distance (AHD). The positioning of the participant and measurement procedures for SST- $S_{Thick}$ , SST-  
195  $L_{Thick}$ , and AHD (**Figure 2a-f**) were performed according to Michener et al. (2015) and , while  
196 Schneebeli et al. (2014) for  $SSM_{Thick}$  (**Figure 2g, h**) and Koppenhaver et al. (2009) for  $INFM_{Thick}$  (**Figure**  
197 **2i, j**). Each measurement was made twice and averaged for data analysis. The ultrasound images were  
198 coded to blind the evaluator and ranked in a random order to decrease the potential learning effect.  
199 Additionally, after data collection, the occupation ratio was calculated to specify alterations in the  
200 shoulder. The occupation ratio was defined as supraspinatus cross-sectional tendon thickness a % of  
201 AHD (Michener et al., 2015). The relative reliability was good to excellent for all analyzed tendon and  
202 muscle thickness and AHD ( $ICC_{2,1}$  from 0.88 to 0.95). The absolute reliability showed that SEMs ranged  
203 from 0.2 mm to 0.4 mm, while MDC90% ranged from 0.3 mm to 0.5 mm.

### 204 **Statistical analysis**

205 The SPSS 18 statistical software (SPSS Inc., Chicago, Illinois, USA) was used for data analysis.  
206 Mean values  $\pm$  standard deviation (SD) as well as mean differences with confidence interval (CI 95%)  
207 have been reported. Normality of the data distribution was applied through the Shapiro–Wilk tests,  
208 while homogeneity of variance was analyzed by Levene’s test. The analyzed data was normally  
209 distributed for all parameters, while the variances for all parameters were equal. A one-way analysis of  
210 variance with repeated measure (RM-ANOVA) with *time* (baseline, Immediate-Post, 1h-Post) was used  
211 as a within-subject factor for differences in RPE, ROM, maximal strength, ultrasonography and  
212 myotonometry measurements. If an interaction between variables was found, the Bonferroni adjustment  
213 for multiple comparisons was used for post hoc tests ( $p=0.001$ ). The effect size was estimated using  
214 partial eta square ( $\eta^2$ ), classified as small ( $.2 < \eta^2 < .49$ ), medium ( $.5 < \eta^2 < .79$ ) or large ( $\eta^2 \leq .8$ ) (Richardson,  
215 2011). For all statistical tests,  $p$ -value  $< 0.05$  was considered significant.

## 216 **RESULTS**

### 217 **Functional measurements**

218 **Table 1** reports the mean±SD of the RPE, ROM and muscle strength at baseline, Immediate-  
219 Post and 1h-Post repeated climbing exercise protocol. The one-way RM-ANOVA revealed a statistically  
220 significant effect of *Time* in RPE ( $F_{2,28}=403.7$ ,  $p\leq.001$ ,  $\eta^2=.97$ ). The post-hoc analysis showed  
221 significant increase from baseline to IA after, while a significant decrease from IA to 1-h-Post ( $p\leq.001$   
222 for all). See Table 1.

223 The one-way RM-ANOVA revealed a statistically significant effect of *Time* in ROM  
224 ( $F_{2,88}=317.5$ ,  $p\leq.001$ ,  $\eta^2=.88$ ). Post-hoc analysis showed significant decreases from baseline to  
225 Immediate-Post after for flexion, abduction and internal rotation as well as significant increases from  
226 Immediate-Post to 1h-Post for flexion, abduction and internal rotation ( $p\leq.001$  for all).

227 Similarly, the one-way RM-ANOVA showed a statistically significant effect of *Time* in  
228 maximal strength ( $F_{2,88}=1070.5$ ,  $p\leq.001$ ,  $\eta^2=.96$ ). The post-hoc analysis showed significant decreases  
229 from baseline to Immediate-Post after for flexion, abduction and internal rotation as well as significant  
230 increases from Immediate-Post to 1h-Post for flexion, abduction and internal rotation ( $p\leq.001$  for all).  
231 See Table 1.

### 232 **Morphological measurements**

233 **Table 2** shows the mean±SD of muscle stiffness of pectoralis major, deltoideus anterior and  
234 posterior, and infraspinatus as well as shoulder tendon and muscle thickness, AHD and occupation ratio  
235 at baseline, IA and 1-h-Post repeated climbing exercise protocol. The one-way RM-ANOVA revealed  
236 statistically significant effect of *Time* in muscle stiffness ( $F_{2,118}=306.8$ ,  $p\leq.001$ ,  $\eta^2=.84$ ). The post-hoc  
237 analysis showed significant increases from baseline to IA after for pectoralis major, deltoideus anterior  
238 and posterior, and infraspinatus muscle as well as significant decreases from Immediate-Post to 1h-Post  
239 for pectoralis major, deltoideus anterior and posterior, and infraspinatus muscle ( $p\leq.001$  for all).

240 Finally, the one-way RM-ANOVA revealed statistically significant effect of *Time* in  
241 ultrasonographic evaluation ( $F_{2,148}=27.2$ ,  $p\leq.001$ ,  $\eta^2=.27$ ). The post-hoc analysis showed significant  
242 increases from baseline to IA after for SST-S<sub>Thick</sub>, SSM<sub>Thick</sub>, INFM<sub>Thick</sub> and occupation ratio ( $p\leq.001$  for  
243 all) and SST-L<sub>Thick</sub> ( $p<.01$ ), while a significant decrease was observed in AHD ( $p\leq.001$ ). Significant  
244 decreases from Immediate-Post to 1h-Post were found for SST-S<sub>Thick</sub>, SST-L<sub>Thick</sub>, SSM<sub>Thick</sub>, INFM<sub>Thick</sub>  
245 and occupation ratio ( $p\leq.001$  for all), while a significant increase for AHD ( $p\leq.001$ ), See Table 2.

### 246 **DISCUSSION**

247 The current study revealed the presence of alterations in shoulder function and morphological  
248 properties after repeated climbing exercise in recreational indoor climbers. Changes in shoulder function  
249 were characterized by decreases in ROM and maximal strength during flexion, abduction and internal  
250 rotation, with a simultaneous increase in RPE immediately after the exercise protocol. Moreover, after  
251 1-hour rest we observed an increase in ROM and maximal strength as well as a decrease of RPE. The  
252 morphological properties, expressed as rotator cuff tendon and muscle thickness, showed greater

253 supraspinatus tendon ( $SST-S_{Thick}$ ,  $SST-L_{Thick}$ ) and muscle thickness ( $SSM_{Thick}$ ), infraspinatus muscle  
254 thickness ( $INFM_{Thick}$ ), and occupation ratio, with a simultaneous decrease in AHD immediately after  
255 exercise protocol. In parallel, we observed a decrease in tendon and muscle thickness, and occupation  
256 ratio as well as an increase in AHD after 1-hour rest. The results of our study were in agreement with  
257 the hypotheses suggesting acute alterations in tendon and muscle thickness in the shoulder girdle after  
258 a climbing exercise protocol in indoor climbers.

259 This study evaluated shoulder function, expressed by ROM and maximal strength after a  
260 repeated climbing exercise protocol in indoor climbers. Beside the expected increase in RPE, the  
261 analysis of our results showed a decrease in flexion and abduction by 15%, while internal rotation  
262 decreased by 29% from baseline to Immediate-Post climbing. For maximal strength, flexion and internal  
263 rotation decreased 34 and 42%, respectively. Previous studies have investigated ROM (Seminati et al.,  
264 2015; Schwesig et al., 2016; Matthews et al., 2017; Moreno-Pérez et al., 2019) and maximal strength  
265 (Mullaney and McHugh, 2006; Andrade et al., 2016; Schwesig et al., 2016; Matthews et al.,  
266 2017; Moreno-Pérez et al., 2019) after specific exercise protocols in overhead athletes. Our results for  
267 ROM and maximal strength are in line with previous studies showing a decrease in ROM for flexion  
268 (10 to 15%), abduction (11 to 15%) and internal rotation (18 to 26%) as well as decrease strength in  
269 internal rotation (24 to 34%) after repetitive overhead movement protocols (Mullaney and McHugh,  
270 2006; Seminati et al., 2015; Schwesig et al., 2016; Klich et al., 2021). The current protocol enabled to  
271 explore the acute morphological changes due to fatigue even if task failure was not achieved in line with  
272 previous studies (Duchateau and Enoka, 2008).

273 In this study we investigated morphological alterations in rotator cuff tendons/ muscles  
274 thickness and stiffness of the shoulder girdle Immediate-Post and 1h-Post an indoor climbing protocol.  
275 Previous studies have assessed rotator cuff tendon thickness and stiffness of shoulder muscles (Klich et  
276 al., 2020; Mifune et al., 2020; Porter et al., 2020) in overhead athletes. However, only Klich et al. (2020)  
277 and Mifune et al. (2020) investigated both thickness and stiffness analyzed rotator cuff muscle thickness  
278 (supraspinatus and infraspinatus), trapezius and shoulder muscles stiffness (pectoralis major, deltoid  
279 anterior and posterior, rhomboids and serratus anterior). The analysis of our results showed an increase  
280 in stiffness for all shoulder muscles; the highest increase was observed in the deltoideus posterior (73%),  
281 and the lowest in the infraspinatus (43%). Our results showed an increase in the supraspinatus tendon  
282 and muscle thickness (19 to 25%) and the infraspinatus muscle (10%), with simultaneous decrease in  
283 AHD (22%) from baseline to Immediate-Post. The present differences in thickness can be explained by  
284 differences in exertion and fatigability of these muscles (Enoka and Duchateau 2008). Finally, the  
285 supraspinatus tendon occupied a greater proportion of the subacromial space, expressed by an increase  
286 in occupation ratio by 36%. In our previous study (Klich et al., 2020), we reported lower stiffness and  
287 thickness, with greater AHD compared with current results. Moreover, after 1 hour we observed  
288 decrease in stiffness and thickness, with decrease of AHD. Porter et al. (2021) reported a greater

289 thickness in the supraspinatus tendon immediately after exercise swimming protocol. They reported  
290 thickness after 6 and 24 hours post showing a decrease compared with immediately after.

291 An acute increase in tendon thickness and decrease in AHD might last up to 6 hours and reduce  
292 to baseline after 24 hours (McCreesh et al., 2017). Changes observed in this current and previous studies  
293 (McCreesh et al., 2017; Klich et al., 2020; Porter et al., 2020) of acute fatigue due to different intrinsic  
294 mechanisms. Furthermore, it should be noted that acute alterations in supraspinatus tendon thickness  
295 may be associated with mechanical compression of the tendon in the subacromial space (Michener et  
296 al., 2015; McCreesh et al., 2017) or posteriorly-superiorly between the glenoid and humeral head (Do  
297 and Lim, 2017).

298 Repetitive mechanical overload has been described as the main factor causing muscle-tendon  
299 morphology and altering motor functions (Bissas et al., 2020; Pozzi et al., 2021). An increased thickness  
300 of the supraspinatus tendon might be the first symptom of repetitive loading related to shoulder pain  
301 (Pozzi et al., 2021), and may lead to occupy a greater portion of the subacromial space (Michener et al.,  
302 2015). Repetitive overhead movements in indoor climbers, e.g. bilateral muscle sub-maximal  
303 contractions followed by a short resting time may alter the rotator cuff causing acute impingement  
304 (Schöffl et al., 2011).

305 Previous studies have investigated different models of tendon and muscle degeneration  
306 including the assessment of damage, distribution of fiber recruitment, intra-muscular inflammation or  
307 edema (Proske and Morgan, 2001; Nakama et al., 2005; Fung et al., 2010; McCreesh et al., 2017). Acute  
308 changes in soft tissue's histological alterations might also lead to increased stiffness. Fung et al. (2010)  
309 showed that fatigue might cause increased stiffness and decreased hysteresis at low- and mid-level,  
310 mostly due to changes in fibers recruitment in damaged and undamaged fibers. Increase in stiffness of  
311 the pectoralis major might be related with repetitive elevation during climbing causing tightness of this  
312 muscle (Page, 2011). Furthermore, a higher stiffness of the deltoid posterior and infraspinatus could be  
313 a result of climbing movement pattern caused by positioning of holds on the wall to horizontal  
314 movements (Reinold et al., 2004). The present study revealed concomitant changes in function and  
315 morphological properties of the shoulder girdle in response to repeated climbing.

316 The current study has strength and limitations. A strength relies in the combined field  
317 assessment of functional and morphological changes. We opted for an experimental protocol composed  
318 of repetitive climbing exercise resulting in fatigue-related changes analyzed in a before-after settings in  
319 line with previous study (Côté et al., 2008). Concerning limitations, we only recruited men in our study,  
320 however future experiments should include women to evaluate sex differences in functional and  
321 morphological changes. Second, a control group would facilitate the interpretation of the observed  
322 changes. Third, we reported an acute effect of repeated exercise mimicking bouldering in healthy and  
323 recreational climbers. Future studies could investigate alterations in shoulder function and  
324 morphological properties in relation to speed, lead and bouldering.

325

## CONCLUSIONS

326           The present study showed for the first time changes in shoulder function and morphological  
327 properties after repeated exercise protocol in recreational indoor climbers. Significant increase in  
328 supraspinatus thickness, with simultaneous reduction in AHD resulted in greater occupation ratio. Our  
329 study demonstrated acute alterations in tendon thickness due to acute signs of implement symptom in  
330 climbers. This work provides an important finding about evaluation morphological properties using both  
331 ultrasonography and myotonometry in conjunction with functional measurements.

### 332 **Declaration of Interest Statement**

333 The authors declare no conflict of interest and no funding. Written informed consent was obtained from  
334 the participants.

335

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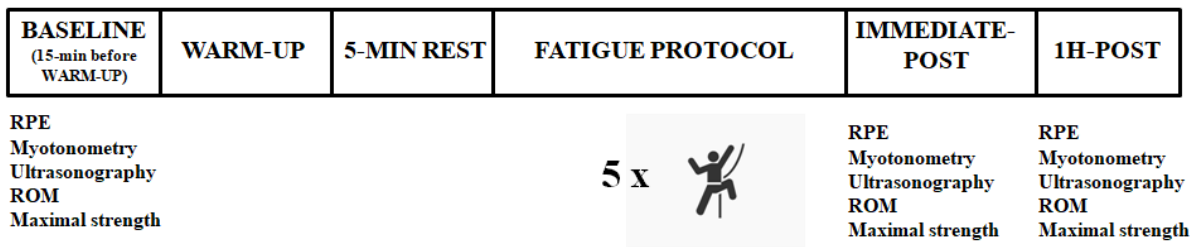
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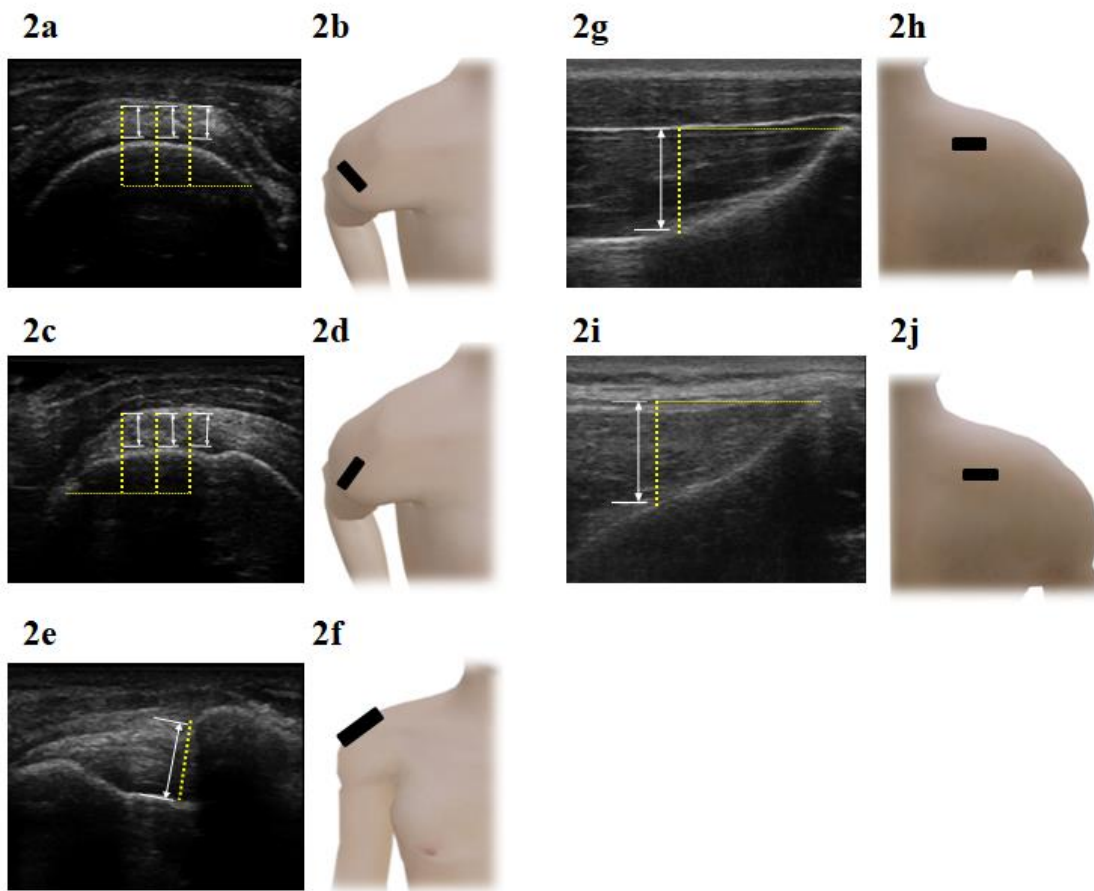
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467 Figure 1. Experimental procedure including rate of perceived exertion (RPE), myotonometry,  
468 ultrasonography, range of motion (ROM) and maximal strength evaluation at baseline, Immediately-  
469 Post and 1 hour Post exercise (1H-Post) after repeated climbing exercise protocol.

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471

472 Figure 2. Ultrasound assessment and measurement of the rotator cuff: a) ultrasound measurement of the  
473 supraspinatus tendon thickness in short axis (SST-S<sub>Thick</sub>); b) ultrasound transducer position (SST-S<sub>Thick</sub>),  
474 c) ultrasound measurement of the supraspinatus tendon thickness in long axis (SST-L<sub>Thick</sub>); d) ultrasound  
475 transducer position (SST-L<sub>Thick</sub>), e) ultrasound measurement of the acromiohumeral distance (AHD); f)  
476 ultrasound transducer position (AHD); f) ultrasound measurement of the supraspinatus muscle thickness  
477 (SSM<sub>Thick</sub>); g) ultrasound transducer position (SSM<sub>Thick</sub>), h) ultrasound measurement of the infraspinatus  
478 muscle (INFM<sub>Thick</sub>); i) ultrasound transducer position (INFM<sub>Thick</sub>).

479 Table 1. Shoulder range of motion (ROM) [°], shoulder maximum isometric strength [N], and rate of perceived exertion (RPE) at baseline-. Immediate-Post-  
480 and 1 hour-Post (1h-Post) repeated climbing exercise protocol. Mean ± SD values

	Baseline	Immediate- Post	1h-Post	Baseline to Immediate-Post Mean Difference (95% CI)	<i>P</i> value*	Immediate- Post to 1h-Post Mean Difference (95%CI)	<i>P</i> value**
<b>Shoulder Range of Motion [°]</b>							
Flexion	174.4±2.7	147.6±6.6	157.7±6.5	27 (22,32)	<i>p</i> ≤.001	-10 (-11, 9)	<i>p</i> ≤.001
Abduction	169.1± 1.5	142.8±5.5	156.9±4.3	26 (23, 30)	<i>p</i> ≤.001	-14 (-17, -11)	<i>p</i> ≤.001
Internal rotation	60.9± 1.1	43.3±1.9	53.5± 2.4	18 (15, 20)	<i>p</i> ≤.001	-11 (-14, -8)	<i>p</i> ≤.001
<b>Shoulder Maximum Isometric Strength [N]</b>							
Flexion	416.8±34.3	273.6±33.3	332.4±38.2	143 (125, 162)	<i>p</i> ≤.001	-58 (-70, -36)	<i>p</i> ≤.001
Abduction	383.4±20.6	240.3±24.5	299.1±22.6	143 (128, 150)	<i>p</i> ≤.001	-59 (-78, -32)	<i>p</i> ≤.001
Internal rotation	425.6±21.6	246.1±28.4	310.9±23.5	180 (158, 201)	<i>p</i> ≤.001	-65 (-90, -45)	<i>p</i> ≤.001
<b>Rate of Perceived Exertion</b>							
RPE	6±.0	14±1.7	9 ±.8	-8 (-9, -7)	<i>p</i> ≤.001	5 (4, 6)	<i>p</i> ≤.001

481 Significant differences \*- within-group differences between baseline and IA, and \*\*- within-group differences between 1h-Post  
482 and IA (*p*≤0.05).

483 Table 2. Shoulder girdle stiffness (N/m) and rotator cuff tendon and muscle thickness [mm], acromiohumeral distance (AHD) [mm] and  
484 occupational ratio measured at baseline-, Immediate-Post- and 1 hour-Post (1h-Post) repeated climbing exercise protocol. Mean  $\pm$  SD values

	Baseline	Immediate- Post	1h-Post	Baseline to Immediate-Post  Mean Difference (95% CI)	<i>P</i> value*	Immediate-Post to 1h-Post  Mean Difference (95%CI)	<i>P</i> value**
<b>Stiffness [N/m]</b>							
Pectoralis major muscle	203.1 $\pm$ 27.3	541.3 $\pm$ 68.5	271.5 $\pm$ 35.8	-338 (-375, -306)	<i>p</i> $\leq$ .001	269 (238, 308)	<i>p</i> $\leq$ .001
Deltoid anterior muscle	258.4 $\pm$ 72.9	597.6 $\pm$ 60.3	397.6 $\pm$ 60.3	-339 (-362, -316)	<i>p</i> $\leq$ .001	200 (156, 241)	<i>p</i> $\leq$ .001
Deltoid posterior muscle	201.9 $\pm$ 43.4	759.9 $\pm$ 28.	298.2 $\pm$ 28.2	-558 (-570, -543)	<i>p</i> $\leq$ .001	462 (454, 483)	<i>p</i> $\leq$ .001
Infraspinatus muscle	370.1 $\pm$ 154.5	643.3 $\pm$ 126.9	422.8 $\pm$ 146.6	-273 (-301, -250)	<i>p</i> $\leq$ .001	220 (135, 330)	<i>p</i> $\leq$ .001
<b>Thickness [mm]</b>							
Supraspinatus Tendon							
Cross-sectional	4.7 $\pm$ 2.5	6.3 $\pm$ 0.8	5.5 $\pm$ 0.3	-1.6 (-2.1, -1.3)	<i>p</i> $\leq$ .001	0.8 (0.6; 1.2)	<i>p</i> $\leq$ .001
Longitudinal	4.4 $\pm$ 0.5	5.7 $\pm$ 0.7	4.8 $\pm$ 0.2	-1.3 (-1.9, -0.8)	<i>P</i> =.007	0.9 (0.3, 1.3)	<i>p</i> $\leq$ .001
Supraspinatus Muscle	11.2 $\pm$ 0.3	13.9 $\pm$ 0.8	12.3 $\pm$ 0.2	-2.7 (-3.2, -2.2)	<i>p</i> $\leq$ .001	1.6 (1.4, 2.1)	<i>p</i> $\leq$ .001
Infraspinatus Muscle	18.1 $\pm$ 0.3	20.0 $\pm$ 0.3	18.4 $\pm$ 0.4	-1.9 (-2.3, -1.4)	<i>p</i> $\leq$ .001	1.6 (0.7, 1.8)	<i>p</i> $\leq$ .001
AHD [mm]	9.6 $\pm$ 0.5	7.5 $\pm$ 0.3	8.5 $\pm$ 0.2	2.1 (1.6, 2.4)	<i>p</i> $\leq$ .001	-1.0 (-1.5, -0.6)	<i>p</i> $\leq$ .001
Occupational ratio [%]	46.9 $\pm$ 3.3	73.3 $\pm$ 2.9	57.5 $\pm$ 3.2	-26 (-30, -23)	<i>p</i> $\leq$ .001	15 (11, 18)	<i>p</i> $\leq$ .001

485 Occupation ratio: Supraspinatus Cross-sectional tendon thickness as a % of AHD.

486 Significant differences \*- within-group differences between baseline and IA, and \*\*- within-group differences between 1h-Post  
487 and IA (*p* $\leq$ 0.05).

488