

# Differences in the effects of a startle stimulus on rate of force development between resistance-trained rock climbers and untrained individuals: Evidence for reticulospinal adaptations?

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The aim of the present cross-sectional study was to determine if chronic rock climbing and climbing-specific resistance training (RT) would modify the reticulospinal tract (RST) efficacy. Sixteen healthy, elite level climbers (CL;  $n = 16$ , 5 F;  $29.8 \pm 6.7$  years) with  $12 \pm 7$  years of climbing and climbing-specific RT experience and 15 healthy recreationally active participants (CON;  $n = 15$ , 4 F;  $24.6 \pm 5.9$  years), volunteered for the study. We quantified RST efficacy by comparing the effects of a startle stimulus over reaction time ( $R_{\text{time}}$ ) and measured rate of force development (RFD) and surface electromyography (sEMG) in representative muscles during powerful hand grip contractions. Both groups performed two  $R_{\text{time}}$  tasks while performing rapid, powerful gripping with the right hand (Task 1) or during 3-s-long maximal voluntary right hand grip contractions in response to an imperative visual signal alone (V), or combined with a auditory-non startle stimulus (A) or/and startling auditory stimulus (S). We also tested the reproducibility of these responses on two separate days in CON. Intersession reliability ranged from 0.34 to 0.96 for all variables. The CL versus CON was 37% stronger ( $p = 0.003$ ). The S stimulus decreased  $R_{\text{time}}$  and increased RFD and sEMG in both groups during both tasks (all  $p < 0.001$ ).  $R_{\text{time}}$  was similar between groups in all conditions. However, CL had a greater RFD from 50 to 100 ms compared with CON only after the S stimulus in both tasks ( $p < 0.05$ ,  $d = 0.85\text{--}0.96$ ). The data

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tentatively suggest that chronic rock climbing and climbing-specific RT might improve RST efficacy, by increasing RST input to the  $\alpha$ -motoneurons.

#### KEYWORDS

neural adaptations, reaction time task, startle response, strength training

## 1 | INTRODUCTION

When so designed, resistance training (RT) improves the ability to generate maximal voluntary muscle (MVC) force. Increases in MVC force after the start of RT are thought to occur through a reorganization of the structure, function, and connections at different sites of the nervous system.<sup>1,2</sup> Numerous studies have examined how such “neural adaptations” underlie the increase in MVC force after RT.<sup>3–7</sup> Current evidence suggests that RT increases the neural drive to the muscle<sup>7–11</sup> but the structures of such adaptations remain elusive.<sup>12–15</sup> Although motoneurons receive descending and segmental synaptic inputs during forceful voluntary contractions, changes in the properties of spinal motoneurons, primary motor cortex (M1) and the corticospinal tract have received most attention.<sup>12–15</sup> Recent meta-analytical evidence suggests that RT may indeed increase corticospinal excitability and reduce intracortical inhibition, which altogether would increase the magnitude and efficacy of the motor command, recruiting more of the available muscle fibers and thus increasing MVC force.<sup>5</sup> However, recent studies not included in the meta-analyses have failed to confirm those conclusions, showing no changes in corticospinal excitability<sup>16,17</sup> or intracortical inhibition<sup>17</sup> after RT periods. Therefore, it is possible that RT induces neuroplasticity in descending tracts other than the corticospinal path.<sup>12–15,18</sup>

The reticulospinal tract (RST) is a bilateral descending pathway arising from the pontomedullary reticular formation in the brainstem that projects directly and indirectly to  $\alpha$ -motoneurons of distal and proximal muscles.<sup>19,20</sup> A single axon from the RST projects to different motoneuron pools, facilitating the coactivation of synergistic groups of muscles during gross motor function.<sup>20–22</sup> Although the main role of the RST has been traditionally associated with postural control and locomotion, there is evidence for a role of the RST in upper limb force generation.<sup>20,23,24</sup> Indeed, there is a direct relationship between reticular formation cells firing rate and force generation during pulling movements in non-human primates, reinforcing the role of the RST for tuning muscle force during multi-joint movements in the upper limbs.<sup>24</sup> Studies in non-human primates have for the first time also shown increases in M1 and RST responses to electrical stimulation after RT, suggesting an increased synaptic efficacy of the

reticulospinal inputs to the spinal cord.<sup>25</sup> This makes the RST one of the key locus of RT-associated neuroplasticity underlying MVC force improvements.<sup>18</sup>

Direct measurement of RST synaptic efficacy in humans is not possible with non-invasive methods due to the deep location of the reticular formation, making it difficult to replicate results obtained in non-human primates.<sup>25</sup> A simple and non-invasive indirect method to test RST synaptic efficacy exposes participants to an unexpected, loud auditory stimulus (i.e., startle stimulus) combined with an imperative visual stimulus during a simple reaction time task, the so called “StartReact” paradigm.<sup>18,26–28</sup> When the two stimuli are combined, there is a sharp reduction in reaction time.<sup>28–30</sup> If the predetermined response of the reaction time task involves maximal rapid force generation, the reduction in reaction time is also accompanied by a greater rate of force development (RFD).<sup>31–33</sup> The effects of the startle stimulus over reaction time and RFD are thought to be mediated by the release of the preplanned action from the reticular formation, which would speed the initial response and add to the corticospinal input, increasing the overall neural input to the  $\alpha$ -motoneuron.<sup>28</sup> In agreement with this hypothesis, steeper RFD during a fast knee extension movement in response to a startle stimulus are accompanied by higher  $\alpha$ -motoneuron discharge rates.<sup>31</sup>

The effects of the StartleReact paradigm over reaction time and agonist activation using surface electromyography (sEMG) have been used before as markers of RST efficacy in healthy adults and participants with spinal cord injury.<sup>34</sup> The authors reported that strength of elbow flexors, but not the extensors, was similar in the two groups. Similarity of elbow flexor strength was accompanied by greater startle stimulus effect over reaction time in a task involving the activation of the biceps brachii. These data suggest injury-induced RST neuroplasticity that might have compensated for the decrease in the corticospinal input to the elbow flexors, thus normalizing MVC force.<sup>34</sup> Therefore, because the time-course of RST adaptations in response to RT, if any, is currently unknown, we designed a cross-sectional study to detect possible differences in RST efficacy between RT participants and untrained controls. Although not without controversy, previous cross-sectional studies<sup>35–39</sup> have observed that this kind of design could detect differences between long-term

resistance trained participants and untrained controls in several indices of neural adaptations such as a corticospinal efficiency<sup>39</sup> or antagonist muscle activation.<sup>38</sup>

Therefore, the aim of the present cross-sectional study was to determine if RT would modify RST efficacy. To this aim, and because we used a hand grip as the test task, we recruited elite level rock climbers as a model of RT athletes. Such athletes compared with untrained individuals normally generate higher hand grip strength.<sup>40</sup> In addition to frequent practice of rock climbing, an activity that requires forceful finger flexor isometric contractions to hold bodyweight against gravity, the recruited athletes also self-reported engagement in weekly climbing-specific RT. We quantified RST efficacy by comparing the effects of a startle stimulus over reaction time and RFD during powerful right hand grip contractions between rock climbers and untrained individuals. We also tested those effects on sEMG as a surrogate measure of the neural drive to representative muscles activated during gripping. We hypothesized that in addition to greater hand grip strength, resistance-trained climbers, who would have experienced increases in reticulospinal input efficacy due to chronic climbing and RT, would exhibit greater reductions in reaction times and increases in RFD and sEMG when exposed to a startle stimulus during a reaction time task. Additionally, to examine if the effects of a startle stimulus over reaction time, sEMG and RFD could be used to track longitudinal changes in RST efficacy in future studies, we tested the reproducibility of these responses over two separate sessions in the control sample.

## 2 | METHODS

### 2.1 | Participants

As a sample of RT-trained individuals, we recruited 16 healthy, elite level (according to IRCRA- scale)<sup>41</sup> rock climbers (CL;  $n = 16$ , 5 F;  $29.8 \pm 6.7$  years; two left handed; max grade climbed during last year  $F = 7b+$  to  $8a$ ;  $M = 7c$  to  $9a$  on the French scale) with  $12 \pm 7$  years of climbing experience. These athletes self-reported through questionnaires to perform, in addition to climbing training ( $3 \pm 1.4$  days/week), climbing-specific RT<sup>42</sup> (finger dead hangs, campusboard, heavy pulls, etc.) a minimum of one (6 climbers) or two (10 climbers) days/week, with an experience of  $7.5 \pm 5.2$  years. Therefore, we consider our participants as chronically RT rock climbers. Healthy recreationally active participants (CON;  $n = 15$ , 4 F;  $25.6 \pm 5.9$  years; one left handed), volunteered for the study. We confirmed through questionnaires and personal interviews that CON had no previous RT, climbing, and judo experience or any other physical activity or sport

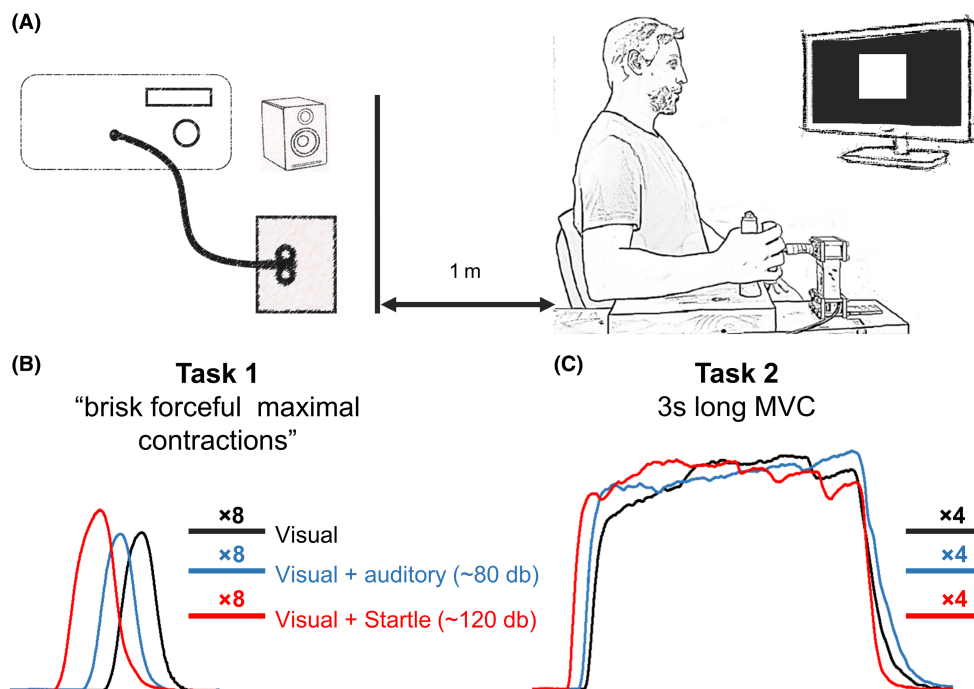
history requiring intense grip exercises. Recreational activities included 2–3 h/week of sports (mostly team sports) or aerobic training. Participants gave written informed consent for the experimental procedures approved by the university's ethic committee. Participants were asked to refrain from consuming alcoholic or caffeinated beverages for 2 h before the experimental sessions and from exercising at least 48 h before each testing session. The experiments were performed in accordance with the latest version of the Declaration of Helsinki.

### 2.2 | Study design

Climbers participants came to the laboratory once, CON participants visited the laboratory twice, performing two identical sessions interspersed with 5–7 days of rest. A familiarization session was not performed to limit the effects of the habituation on the startle stimulus. First, participants performed a warm-up consisting of eight submaximal right-hand grip contractions ( $3 \times 30\%$ ,  $3 \times 60\%$ ,  $2 \times 80\%$  of perceived maximal voluntary force), then they performed two, 3–5-s long MVC hand grips with 2 min of rest between trials. For the MVCs, participants were instructed to squeeze the dynamometer as hard and as fast as possible, and they were continuously encouraged by the investigators. Visual feedback of grip force was displayed online on a computer screen in front of them. After these MVCs, participants performed two different tasks involving isometric maximal contractions in response to a visual imperative signal.

### 2.3 | Experimental set-up

Participants sat in a chair with the right forearm on an armrest, the shoulders adducted, the elbow flexed at  $\sim 90^\circ$ , and the forearm in neutral position. In this position, right hand grip force was measured with a custom made hand dynamometer using a commercial strain gauge (NL63, 200 kg; Digitimer) (Figure 1A) with the distance between handles adjusted to each participant (50% of the distance between the middle finger tip to the metacarpophalangeal flexion crease at the base of the thumb). All the fingers were taped around the handles of the dynamometer to maintain a consistent hand position. The force signal was amplified ( $\times 484$ ) and sampled (2 kHz) for off-line analysis (Power 1401, Cambridge Electronic Design, United Kingdom; sampling frequency 2 kHz). Surface electromyography (EMG) was recorded from the right flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC) using Ag-AgCl surface electrodes (2 cm interelectrode distance). After shaving and wiping the



**FIGURE 1** Experimental set-up (A). During Task 1 (B) participants performed 24 forceful right hand grip contractions as hard and as fast as possible in response to an imperative visual signal (a big white square appearing on a black monitor background situated 1 m in front of the subject). The contraction was followed by relaxation. During Task 2 (C) participants were asked to perform 12, 3-s long, maximal voluntary right hand grip isometric contractions in response to the same visual signal. In one third of the attempts of each task, the visual stimulus appeared alone (Visual), in another third the visual signal was simultaneously accompanied by an auditory-non startle stimulus (80 dB, Visual + Auditory), and in the remaining third of the trials, the visual signal was simultaneously accompanied by a startling auditory stimulus (110–120 dB, Visual + Startle). Figures B and C show force traces of a participant in response to only Visual (black), Visual + Auditory (blue), and Visual + Startle (red) stimulus during each task.

skin with alcohol, FDS EMG electrodes were placed attached to the skin, slightly ulnarly at the middle third of a line drawn from the middle of the wrist to the biceps tendon. EDC EMG were placed in the middle of the forearm, between the ulnar and radial borders. A ground electrode was placed on the lateral epicondyle of the humerus. The EMG signal was amplified ( $\times 1000$ ), band-pass-filtered (10–500 Hz) and sampled (2 kHz, Digitimer) using data acquisition interface and software (Power 1401, Signal v5.12a, Cambridge Electronic Design Ltd.).

## 2.4 | Task 1

During Task 1, participants performed 24 brisk short, powerful right hand grip contractions in response to an imperative visual signal: a big white square appearing on a black background on the monitor situated 1 m in front of the subject. Participants were instructed to squeeze the force dynamometer “as hard and fast as possible” and then relaxing the hand without maintaining the maximal force (Figure 1B). In eight of the 24 contractions, the imperative visual signal was simultaneously accompanied by

an auditory-non startle stimulus (A) emitted by a speaker positioned 1 m behind the subject, and consisting of a 500 Hz tone burst lasting 100 ms, with an intensity of 70–80 dB. In other eight of the 24 contractions, the imperative visual signal was simultaneously accompanied by a startling auditory stimulus (S) with an intensity of 110–120 dB obtained by discharging a Magstim 200 stimulator (100% maximal stimulator output; Magstim Company) over a metallic platform positioned at a distance of 1 m behind the subject on the floor (Figure 1), as has been done in previous studies.<sup>26,32,43</sup> The remaining eight contractions were performed in response to the imperative visual signal alone (V). The order of trials was randomized and administered with ~45 s of inter-trial rest. Before the start of each trial, participants were reminded to avoid any pre-tension and countermovement, and received a preparatory signal from the computer screen 3–5 s before the imperative signal to maintain focus on the task. Before the start of the task, participants were familiarized with the brisk powerful contractions in response to the visual signal (~five attempts). Participants were also familiarized with the startle stimulus with three consecutive startling cues without performing contractions.

## 2.5 | Task 2

During Task 2, participants were asked to perform 12, 3-s long, maximal voluntary right hand grip isometric contractions in response to a V ( $n = 4$ ), A ( $n = 4$ ) or S ( $n = 4$ ) stimulus (Figure 1C). The order of trials was randomized and administered with ~90s inter-trial rest. Before each trial, participants were reminded to avoid pre-tension and counter-movement, and received the same preparatory signal as in Task 1 from the computer screen to facilitate focusing on the task.

## 2.6 | Data analysis

Reaction time ( $R_{\text{time}}$ ), RFD and the root mean square of the EMG activity from FDS (rmsFDS) and EDC (rmsEDC) were the main variables of interest.  $R_{\text{time}}$  was calculated as the time between the visual stimulus (either accompanied or not by A or S stimulus) and the EMG onset of the FDS. The EMG onset was determined semi-automatically at the point where the rectified FDS EMG signal exceed three times the SD of the mean value of the 200 ms before the visual stimulus.<sup>44</sup> The FDS EMG onset was then used to measure the rmsFDS and rmsEDC for the intervals 0–50 and 50–100 ms for both tasks. For RFD, the start of force onset (0 ms) was semi-automatically determined at the point where force signal exceed three times the SD of the mean value of the 200 ms before the visual stimulus<sup>33</sup>; however, an investigator visually inspected the attempts and readjusted the onset if the automatically detected onset was not appropriate. We did not use arbitrary thresholds of baseline force stability because participants were asked to produce a low level of force so that the handle would be grasped gently. Specifically, baseline force before contraction onset was around  $1.19 \pm 0.68\%$  of MVC. Statistical analyses revealed no condition or group main effects or an interaction effect. RFD was determined as the first derivative of force signal for the intervals 0–50 ms and 50–100 for both tasks. The two time intervals chose (0–50 and 50–100) were based on previous studies showing a startle effect on the RFD on those intervals.<sup>31</sup> Additionally peak force (PF) from 0–500 ms ( $PF_{0-500}$ ) and from 0 to maximum peak force ( $PF_{\text{max}}$ ) were also determined only for Task 2. Out of all trials, the five and three with the highest RFD value in the first 100 ms were selected and averaged for full analysis for Task 1 and 2, respectively.

## 2.7 | Statistics

Data normality was tested using the Shapiro–Wilk's test and homogeneity of variances was tested by the Levene's

test of equality. Intersession reliability of measurements obtained in sessions 1 and 2 for CON participants was assessed by the coefficient of variation ( $CV = SD/\text{Mean} \times 100$ ) and intraclass correlation coefficients (ICC [1, 2] two-way mixed effect model) with 95% confidence intervals. The ICC was interpreted with values below 0.5, 0.5–0.75, 0.75–0.90, and >0.90 indicating, respectively, low, moderate, good, and excellent reliability.<sup>45</sup> For normally distributed data measured at two different but equally longer time periods (0–50 ms and 50–100 ms) a three-way repeated measures analysis of variance (RM-ANOVA) was performed with condition (V, A, and S), time (0–50 and 50–100), and group (CL and CON) as factors. For average values measured at different time lengths (0–500 and 0– $F_{\text{max}}$ ) or at discrete time points ( $R_{\text{time}}$ ), a two-way RM-ANOVA was performed with condition (V, A, and S) and group (CL and CON) as factors. If sphericity was violated (Mauchly's test), degrees of freedom were corrected by Greenhouse–Geisser estimates of sphericity. When significant interactions or main effects were found, Bonferroni correction was applied to account for multiple comparisons in the posthoc analyses. When data was not normally distributed, a log transformation was applied. If normality was not confirmed to log transformed data, we used a non-parametric ANOVA-type test.<sup>46</sup> When significant main effects or interactions were found with the non-parametric ANOVA-type test, a Wilcoxon signed rank test or a Mann–Whitney  $U$ -test with Bonferroni adjustment was used for paired or between group comparisons, respectively. An independent samples  $T$ -test was used to compare the baseline maximal voluntary hand grip force between groups. Effects sizes are presented as partial eta-squared values ( $\eta_p^2$ ; small: 0.01; medium: 0.06; large: 0.14) for the factors of the RM-ANOVAs and as Cohen's  $d$  ( $\pm 95\%$  CI) for the paired comparisons. The level of significance was set at  $p < 0.05$  except for when Wilcoxon signed-rank tests were used for three comparisons, where the significance level was corrected for multiple comparisons and set at  $p < 0.017$ . Data are reported as means  $\pm$  standard deviation (SD) in the text and figures. SPSS 28.0 software (SPSS) and nparLD R software package were used for statistical analysis.

## 3 | RESULTS

The baseline maximal voluntary isometric hand grip force and the rmsFDS during 500 ms around the peak force were greater in the CL group ( $453 \pm 112$  N;  $0.53 \pm 0.17$  mV) than in CON ( $331 \pm 94$  N;  $p = 0.003$ ;  $d = 1.18 \pm 0.76$ ;  $0.39 \pm 0.16$  mV,  $p = 0.025$ ,  $d = 0.85 \pm 0.74$ ). There were no differences in rmsEDC (CL:  $0.51 \pm 0.14$  mV; CON:  $0.57 \pm 0.28$  mV;  $p = 0.85$ ;  $d = 0.27 \pm 0.71$ ).

### 3.1 | Reliability

Intersession reliability ranged from 0.34 to 0.96 for all variables. For both tasks,  $R_{\text{time}}$  (0.47 to 0.79) and rmsFDS at 0–50 (0.41–0.84) and 50–100 ms (0.39–0.63) had the lower ICC values. However, RFD (0.57–0.96) and PF (0.93–0.95) had greater ICC values (See [Table S1](#) for detailed CV and ICC values for each variable and condition [V, A, or S]).

### 3.2 | Task 1

During Task 1,  $R_{\text{time}}$  was shorter during S ( $94 \pm 15$  ms) than during V ( $220 \pm 44$  ms;  $Z = -4.9$ ;  $p < 0.001$ ) and A ( $172 \pm 39$  ms;  $Z = -4.9$ ;  $p < 0.001$ ) trials, and during A than V ( $Z = -4.6$ ,  $p < 0.001$ ) trials, without group differences ([Figure 2](#), see [Table 1](#) for statistics results).

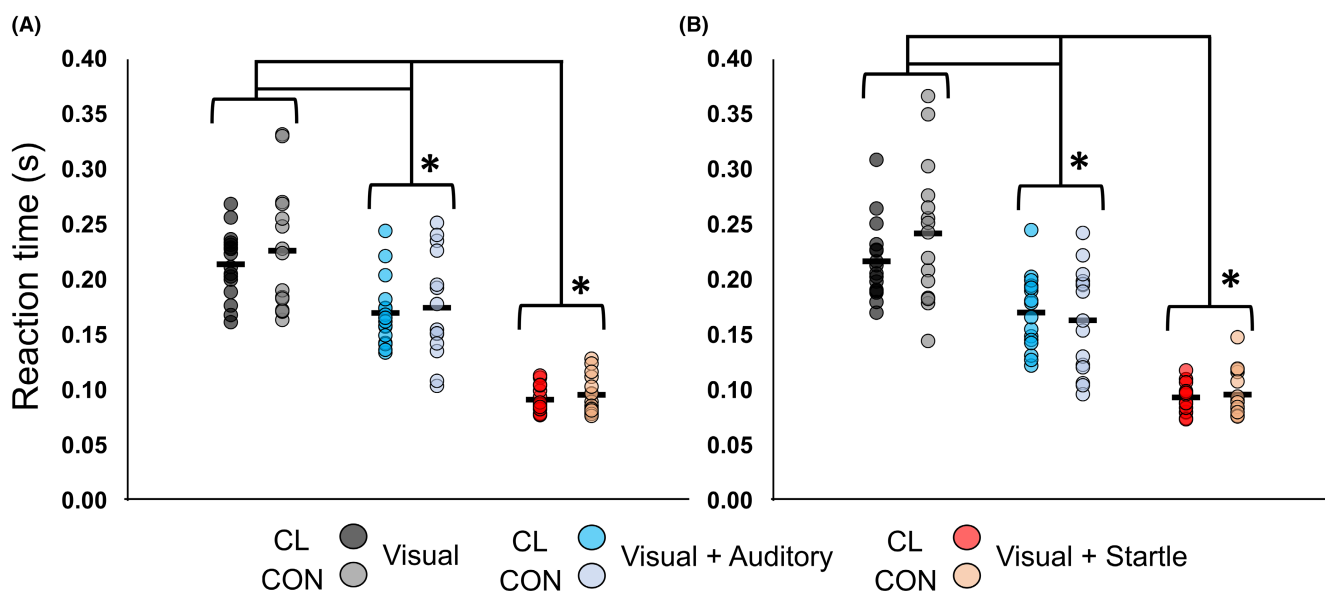
S increased RFD compared with V (19%,  $p < 0.001$ ,  $d = 0.34 \pm 0.50$ ) and A trials (17%,  $p < 0.001$ ,  $d = 0.31 \pm 0.50$ ). Over pooled data, there were no differences between groups. However, the condition  $\times$  time  $\times$  group interaction (see [Table 2](#)), shows that while there were no differences in RFD between groups during V (+17%,  $p = 0.092$ ;  $d = 0.63 \pm 0.72$ ) and A (+12%,  $p = 0.23$ ;  $d = 0.44 \pm 0.71$ ) trials, RFD during S was greater in CL than in CON at 50–100 ms (+25%,  $p = 0.012$ ,  $d = 0.96 \pm 0.74$ , [Figure 3](#)). The improved mechanical performance during S trials was accompanied by greater FDS and EDC activation during S compared with V (rmsFDS: 20%,  $p < 0.001$ ;  $d = 0.43 \pm 0.50$  and rmsEDC: 20%,  $p < 0.001$ ,  $d = 0.42 \pm 0.50$ , [Figure 4](#)) and A trials (rmsFDS: 15%,  $p < 0.001$ ,  $d = 0.33 \pm 0.50$ ; and rmsEDC: 15%,  $p < 0.001$ ,  $d = 0.31 \pm 0.50$ ). However, no

significant between group differences or significant interactions including the group factor were found for the FDS or EDC rmsEMG.

### 3.3 | Task 2

During Task 2,  $R_{\text{time}}$  was shorter during S ( $95 \pm 17$  ms) than during V ( $229 \pm 52$  ms;  $Z = -4.9$ ;  $p < 0.001$ ) and A trials ( $167 \pm 40$  ms;  $Z = -4.9$ ;  $p < 0.001$ ), and lower during A than V trials ( $Z = -4.7$ ,  $p < 0.001$ ), without group differences (see [Table 1](#) for statistics results).

As was the case in Task 1, RFD during the first 100 ms (condition effect, see [Table 2](#) for statistics results) shows that S increased RFD compared with V (27%,  $p < 0.001$ ,  $d = 0.43 \pm 0.50$ ) and A trials (22%,  $p < 0.001$ ,  $d = 0.36 \pm 0.50$ ). Over pooled data, there were no differences between groups. However, as during Task 1, the condition  $\times$  time  $\times$  group interaction (see [Table 2](#)) shows a greater force production in CL than CON during the S condition at the 50–100 ms interval (+24%,  $p = 0.025$ ;  $d = 0.85 \pm 0.74$ , [Figure 3](#)) but not during V (+10%,  $p = 0.40$ ;  $d = 0.31 \pm 0.71$ ) or A (+15%,  $p = 0.21$ ;  $d = 0.46 \pm 0.71$ ) conditions. It also shows no S effect in RFD at the 50–100 ms interval in the CON group (S vs. V: 10%  $p = 0.15$ ,  $d = 0.28 \pm 0.72$ ). Together with the improved mechanical performance, S also increased rmsFDS and rmsEDC compared with V (FDS: 28%,  $p < 0.001$ ,  $d = 0.52 \pm 0.51$ ; EDC: 28%,  $p < 0.001$ ,  $d = 0.55 \pm 0.51$ , [Figure 4](#)) and A (FDS: 21%,  $p < 0.001$ ,  $d = 0.41 \pm 0.50$ ; EDC: 20%,  $p < 0.001$ ,  $d = 0.41 \pm 0.50$ ) trials. rmsFDS was greater in CL than in CON (35%,  $p = 0.032$ ;  $d = 0.62 \pm 0.72$ ), without differences



**FIGURE 2** Task 1 (A) and Task 2 (B) individual (dots) and mean (black horizontal line) reaction time values of Climbers (CL) and Controls (CON) during Visual, Visual + Auditory and Visual + Startle trials. \*Significantly different to Visual ( $p < 0.001$ ).

**TABLE 1** Mean values ( $\pm$ SD) and statistics results for two-way repeated measures parametric analysis of variance (ANOVA) and non-parametric ANOVA-type test.

Variable	Group	V	A	S	Condition	Group	Interaction
<b>Task 1</b>							
$R_{\text{time}}$ (ms) <sup>a</sup>	CL	214 $\pm$ 30	170 $\pm$ 31	92 $\pm$ 12	$F_{1,77,\infty} = 223.69$ , $p < 0.001$	$F_{1,\infty} = 0.16$ , $p = 0.68$	$F_{1,77,\infty} = 0.16$ , $p = 0.96$
	CON	227 $\pm$ 56	175 $\pm$ 47	96 $\pm$ 17			
<b>Task 2</b>							
$R_{\text{time}}$ (ms) <sup>a</sup>	CL	217 $\pm$ 35	171 $\pm$ 33	94 $\pm$ 13	$F_{1,97,\infty} = 212.42$ , $p < 0.001$	$F_{1,\infty} = 0.03$ , $p = 0.85$	$F_{1,97,\infty} = 0.73$ , $p = 0.48$
	CON	242 $\pm$ 64	163 $\pm$ 47	96 $\pm$ 21			
PF <sub>0-500</sub> (N)	CL	322 $\pm$ 91	329 $\pm$ 95	341 $\pm$ 86	$F_{2,58} = 25.3$ , $p < 0.001$ ; $\eta_p^2 = 0.47$	$F_{1,29} = 6.8$ , $p = 0.014$ ; $\eta_p^2 = 0.19$	$F_{2,58} = 0.2$ , $p = 0.84$ ; $\eta_p^2 = 0.01$
	CON	246 $\pm$ 74	250 $\pm$ 75	264 $\pm$ 70			
PF <sub>Fmax</sub> (N)	CL	364 $\pm$ 100	370 $\pm$ 104	370 $\pm$ 104	$F_{2,58} = 7.7$ , $p = 0.001$ ; $\eta_p^2 = 0.21$	$F_{1,29} = 9.7$ , $p = 0.004$ ; $\eta_p^2 = 0.25$	$F_{2,58} = 0.01$ , $p = 0.99$ ; $\eta_p^2 = 0.01$
	CON	263 $\pm$ 78	269 $\pm$ 79	270 $\pm$ 74			

Abbreviations: A, Visual + Auditory stimulus; CL, Climbers; CON, Controls; PF<sub>0-500</sub>, Peak force during the first 500 ms; PF<sub>Fmax</sub>, Peak force;  $R_{\text{time}}$ , Reaction time; S, Visual + Startle stimulus; V, Visual stimulus alone.

<sup>a</sup> Non-parametric data analyzed with a non-parametric ANOVA-type test.

between groups for rmsEDC. Overall rmsFDS from 0 to 100 ms (condition  $\times$  group effect, see Table 2) showed a greater rmsFDS in CL than CON during S (43%;  $p = 0.009$ ,  $d = 0.86 \pm 0.74$ ) and A (40%;  $p = 0.021$ ;  $d = 0.68 \pm 0.73$ ) trials but not V trials (19%;  $p = 0.25$ ;  $d = 0.34 \pm 0.71$ ). It also shows a greater rmsFDS during S compared with V only for CL (38%;  $p < 0.001$ ;  $d = 0.72 \pm 0.72$ ) but not CON group (16%;  $p = 0.10$ ;  $d = 0.31 \pm 0.72$ ). For rmsEDC there were no significant interactions.

Force production over longer intervals was still influenced by the S stimulus with PF<sub>0-500</sub> being greater during S than during V (6%,  $p < 0.001$ ;  $d = 0.21 \pm 0.50$ ) or A trials (4%,  $p < 0.001$ ;  $d = 0.14 \pm 0.50$ ) and during A than V trials (2%,  $p = 0.048$ ;  $d = 0.07 \pm 0.50$ ). During the first 500 ms, force production was a 30% greater in CL than CON ( $p = 0.14$ ,  $d = 0.95 \pm 0.74$ ) but there was no condition  $\times$  group interaction. For the peak force of the MVCs there was also a condition effect showing greater PF<sub>max</sub> during S and A trials compared with V trials (S vs. V = 2.5%,  $p = 0.003$ ,  $d = 0.08 \pm 0.50$  and A vs. V = 2%,  $p = 0.007$ ,  $d = 0.06 \pm 0.50$ ). PF<sub>max</sub> was a 38% greater in CL than CON ( $p = 0.004$ ,  $d = 1.14 \pm 0.76$ ) but there was no condition  $\times$  group interaction.

## 4 | DISCUSSION

In this cross-sectional study, we determined if chronic practice of repeated high-intensity finger flexor isometric muscle contractions during rock climbing and climbing-specific RT, might modify RST efficacy. We quantified RST efficacy by comparing the effects of a startle stimulus over  $R_{\text{time}}$ , RFD, and sEMG during powerful gripping with

the right hand between resistance-trained climbers and untrained individuals. Our results show that S trials reduced  $R_{\text{times}}$ , and enhanced RFD and rmsEMG amplitude compared with V or A trials in both groups. However, in partial agreement with our initial hypothesis, the increase in the RFD from 50 to 100 ms was greater in CL than CON participants only during the S trials. These findings suggest that resistance-trained climbers had a greater RST input to the  $\alpha$ -motoneurons during S trials, which may be mediated by adaptations in RST efficacy triggered by chronic rock climbing and climbing-specific RT.

When a loud auditory stimulus is combined with an imperative visual signal during a  $R_{\text{time}}$  task, the pre-planned action is performed at a very short latency. This sharp reduction in the  $R_{\text{time}}$  was described for the first time in 1995<sup>26</sup> and several studies have confirmed the effect in different tasks involving upper and lower limb muscles.<sup>27,28,31,47</sup> In accordance with previous studies, our results show a reduction of  $\sim 126$  (Task 1) and  $\sim 134$  ms (Task 2) during S trials compared with V trials. Furthermore, the S trials had a  $R_{\text{time}}$  78 (Task 1) and 72 ms (Task 2) shorter than the A trials, suggesting that inter-sensory facilitation resulting from the summation of a visual and an auditory signal was not responsible for all the  $R_{\text{time}}$  reduction during S trials. Instead, this large reduction in  $R_{\text{time}}$  is compatible with the hypothesis of the S stimulus triggering the motor programme stored at the reticular formation, bypassing the cortical circuitry, and leading to an earlier recruitment of  $\alpha$ -motoneurons.<sup>28,48</sup>

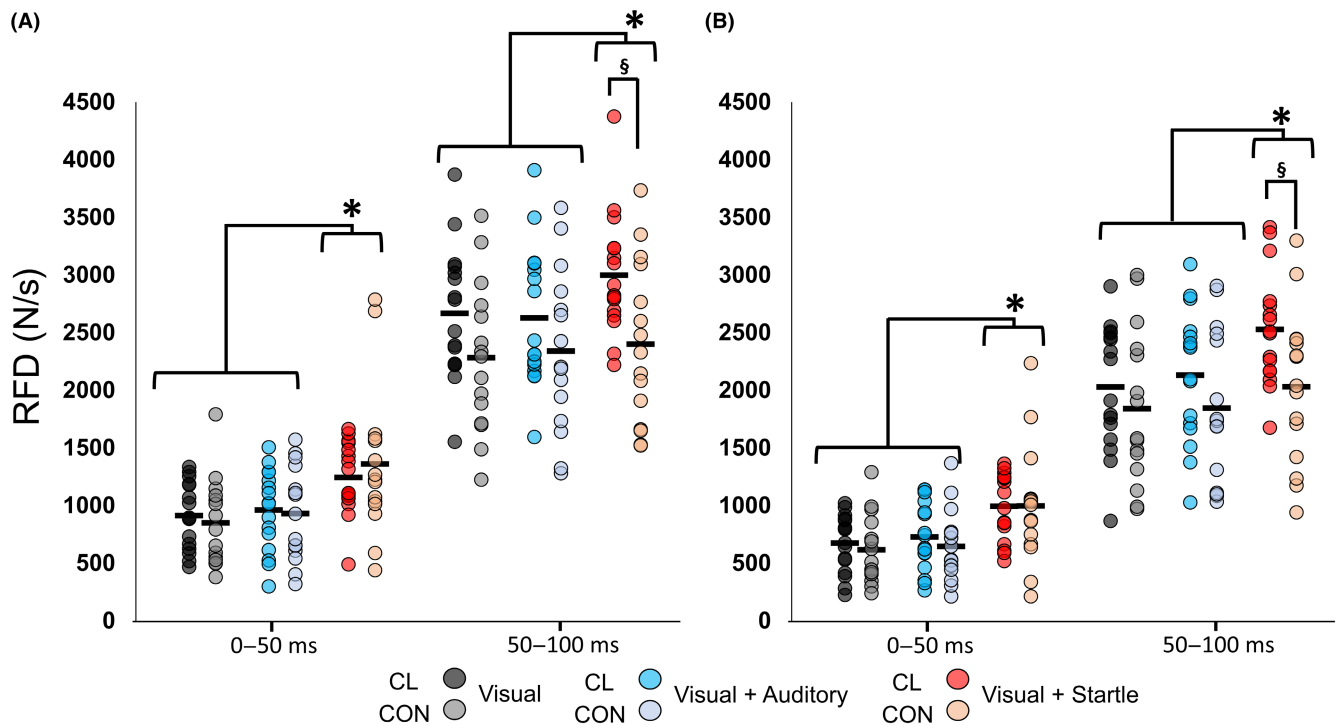
In addition to the effect on  $R_{\text{time}}$ , when the predetermined response of the  $R_{\text{time}}$  task involves maximal static or dynamic muscle force contractions, RFD is steeper.<sup>31-33</sup> Our results showed an overall increase in RFD during the

TABLE 2 Mean values ( $\pm$ SD) and statistics results for three-way repeated measures analysis of variance.

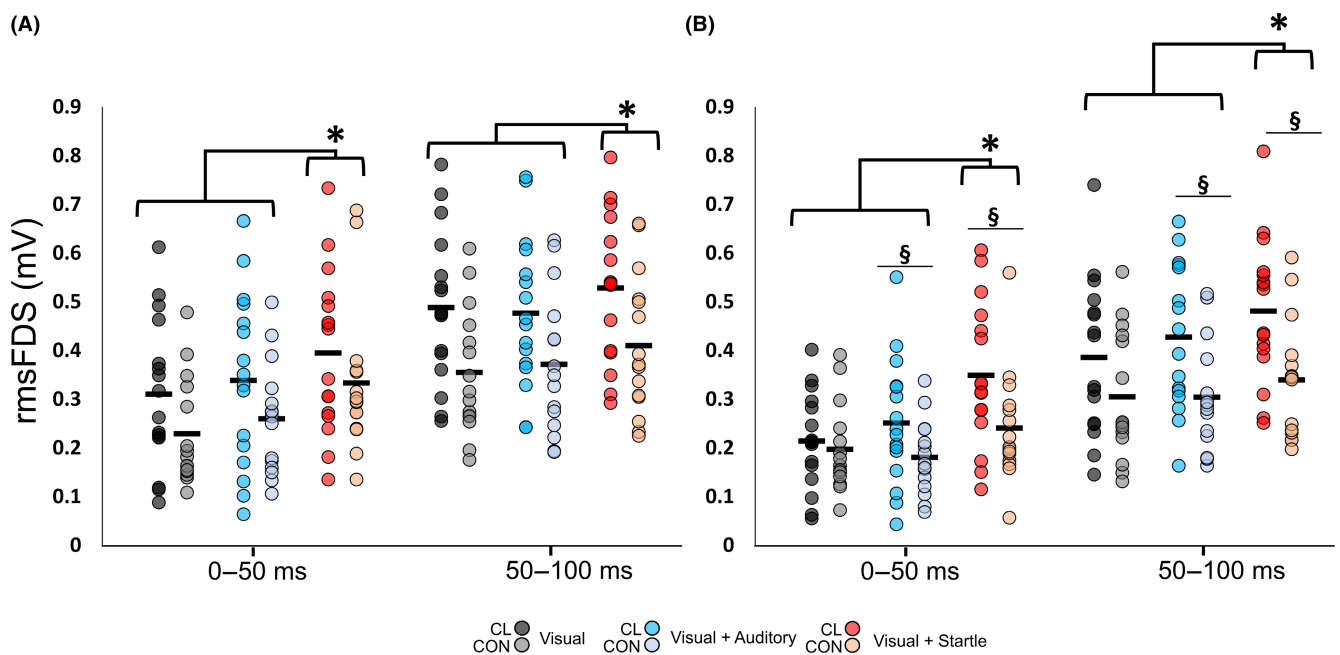
Variable	Time (ms)	Group	V	A	S	Condition	Time	Group	Condition $\times$ time	Condition $\times$ group	Time $\times$ Group	Condition $\times$ time $\times$ group
Task 1												
RFD	0-50	CL	914 $\pm$ 290	962 $\pm$ 352	1244 $\pm$ 313	$F_{1,6,46,3} = 52.9,$ $p < 0.001;$ $\eta_p^2 = 0.65$	$F_{1,29} = 360.55,$ $p < 0.001;$ $\eta_p^2 = 0.93$	$F_{1,29} = 1.5,$ $p = 0.22;$ $\eta_p^2 = 0.05$	$F_{1,4,39,9} = 7.6,$ $p = 0.004;$ $\eta_p^2 = 0.21$	$F_{1,6,46,3} = 0.8,$ $p = 0.44;$ $\eta_p^2 = 0.03$	$F_{1,29} = 7.3, p = 0.01;$ $\eta_p^2 = 0.20$	$F_{1,4,39,9} = 11.4,$ $p < 0.001;$ $\eta_p^2 = 0.28$
		CON	850 $\pm$ 380	931 $\pm$ 406	1362 $\pm$ 651							
rmsFDS	0-50	CL	2668 $\pm$ 576	2628 $\pm$ 607	2999 $\pm$ 527							
		CON	2283 $\pm$ 654	2341 $\pm$ 707	2401 $\pm$ 706							
rmsEDC	0-50	CL	0.310 $\pm$ 0.153	0.338 $\pm$ 0.179	0.395 $\pm$ 0.166	$F_{1,6,46,5} = 29.0,$ $p < 0.001;$ $\eta_p^2 = 0.50$	$F_{1,29} = 57.9,$ $p < 0.001;$ $\eta_p^2 = 0.67$	$F_{1,29} = 3.1,$ $p = 0.09;$ $\eta_p^2 = 0.10$	$F_{1,6,46,4} = 7.6,$ $p = 0.003;$ $\eta_p^2 = 0.21$	$F_{1,6,46,5} = 1.0,$ $p = 0.36;$ $\eta_p^2 = 0.03$	$F_{1,29} = 0.6, p = 0.43;$ $\eta_p^2 = 0.02$	$F_{1,6,46,4} = 0.7, p = 0.93;$ $\eta_p^2 = 0.01$
		CON	0.229 $\pm$ 0.110	0.260 $\pm$ 0.115	0.333 $\pm$ 0.153							
rmsEDC	50-100	CL	0.488 $\pm$ 0.158	0.477 $\pm$ 0.156	0.528 $\pm$ 0.151							
		CON	0.355 $\pm$ 0.130	0.371 $\pm$ 0.145	0.410 $\pm$ 0.144							
rmsEDC	0-50	CL	0.362 $\pm$ 0.229	0.399 $\pm$ 0.268	0.471 $\pm$ 0.280	$F_{2,58} = 29.3,$ $p < 0.001;$ $\eta_p^2 = 0.50$	$F_{1,29} = 58.3,$ $p < 0.001;$ $\eta_p^2 = 0.67$	$F_{1,29} = 0.2,$ $p = 0.90;$ $\eta_p^2 = 0.01$	$F_{2,58} = 10.5,$ $p < 0.001;$ $\eta_p^2 = 0.27$	$F_{2,58} = 0.01,$ $p = 0.99;$ $\eta_p^2 = 0.01$	$F_{1,29} = 0.9, p = 0.34;$ $\eta_p^2 = 0.03$	$F_{2,58} = 0.5, p < 0.63;$ $\eta_p^2 = 0.02$
		CON	0.344 $\pm$ 0.120	0.393 $\pm$ 0.167	0.483 $\pm$ 0.212							
rmsEDC	50-100	CL	0.549 $\pm$ 0.185	0.552 $\pm$ 0.154	0.596 $\pm$ 0.147							
		CON	0.542 $\pm$ 0.182	0.535 $\pm$ 0.206	0.608 $\pm$ 0.233							
Task 2												
RFD	0-50	CL	675 $\pm$ 251	728 $\pm$ 296	995 $\pm$ 293	$F_{2,58} = 44.8,$ $p < 0.001;$ $\eta_p^2 = 0.61$	$F_{1,29} = 318.5,$ $p < 0.001;$ $\eta_p^2 = 0.92$	$F_{1,29} = 1.5,$ $p = 0.22;$ $\eta_p^2 = 0.05$	$F_{1,4,39,7} = 0.3,$ $p = 0.91;$ $\eta_p^2 = 0.01$	$F_{2,58} = 1.2,$ $p = 0.30;$ $\eta_p^2 = 0.04$	$F_{1,29} = 3.7, p = 0.06;$ $\eta_p^2 = 0.11$	$F_{1,4,39,7} = 4.2, p = 0.03;$ $\eta_p^2 = 0.13$
		CON	617 $\pm$ 300	646 $\pm$ 315	998 $\pm$ 513							
rmsFDS	0-50	CL	2029 $\pm$ 548	2132 $\pm$ 576	2530 $\pm$ 492							
		CON	1841 $\pm$ 674	1846 $\pm$ 662	2031 $\pm$ 671							
rmsFDS	0-50	CL	0.214 $\pm$ 0.099	0.251 $\pm$ 0.130	0.349 $\pm$ 0.148	$F_{2,58} = 25.9,$ $p < 0.001;$ $\eta_p^2 = 0.47$	$F_{1,29} = 95.2,$ $p < 0.001;$ $\eta_p^2 = 0.77$	$F_{1,29} = 5.1,$ $p = 0.03;$ $\eta_p^2 = 0.15$	$F_{2,58} = 2.0,$ $p = 0.14;$ $\eta_p^2 = 0.06$	$F_{2,58} = 5.7,$ $p = 0.005;$ $\eta_p^2 = 0.17$	$F_{1,29} = 3.2, p = 0.08;$ $\eta_p^2 = 0.10$	$F_{2,58} = 0.4, p = 0.69;$ $\eta_p^2 = 0.01$
		CON	0.197 $\pm$ 0.090	0.181 $\pm$ 0.075	0.241 $\pm$ 0.114							
rmsEDC	0-50	CL	0.386 $\pm$ 0.161	0.427 $\pm$ 0.150	0.480 $\pm$ 0.148							
		CON	0.305 $\pm$ 0.132	0.304 $\pm$ 0.112	0.339 $\pm$ 0.122							
rmsEDC	50-100	CL	0.268 $\pm$ 0.162	0.324 $\pm$ 0.171	0.408 $\pm$ 0.223	$F_{1,7,48,6} = 23.9,$ $p < 0.001;$ $\eta_p^2 = 0.45$	$F_{1,29} = 126.3,$ $p < 0.001;$ $\eta_p^2 = 0.81$	$F_{1,29} = 0.1,$ $p = 0.99;$ $\eta_p^2 = 0.01$	$F_{2,58} = 7.1,$ $p = 0.002;$ $\eta_p^2 = 0.20$	$F_{1,7,48,6} = 2.7,$ $p = 0.09;$ $\eta_p^2 = 0.09$	$F_{1,29} = 3.0, p = 0.09;$ $\eta_p^2 = 0.09$	$F_{2,58} = 0.3, p = 0.74;$ $\eta_p^2 = 0.01$
		C	0.297 $\pm$ 0.129	0.299 $\pm$ 0.155	0.409 $\pm$ 0.171							
rmsEDC	50-100	CL	0.458 $\pm$ 0.161	0.517 $\pm$ 0.184	0.557 $\pm$ 0.169							
		C	0.468 $\pm$ 0.200	0.447 $\pm$ 0.172	0.543 $\pm$ 0.220							

Abbreviations: A, Visual + Auditory stimulus; CL, Climbers; CON, Controls; EDC, extensor digitorum communis; FDS, Flexor digitorum superficialis; RFD, Rate of force development; rms, root mean square; S, Visual + Startle stimulus; V, Visual stimulus alone.





**FIGURE 3** Task 1 (A) and Task 2 (B) individual (dots) and mean (black horizontal line) RFD values at 0–50 (left) and 50–100 ms (right) intervals of Climbers (CL) and Controls (CON) during Visual, Visual + Auditory and Visual + Startle trials. \*Significantly different to Visual and Visual + Auditory trials ( $p < 0.001$ ). §Significantly different to CON ( $p < 0.05$ ).



**FIGURE 4** Task 1 (A) and Task 2 (B) individual (dots) and mean (black horizontal line) rmsFDS values at 0–50 (left) and 50–100 ms (right) intervals of Climbers (CL) and Controls (CON) during Visual, Visual + Auditory and Visual + Startle trials. Significantly different to Visual and Visual + Auditory trials ( $p < 0.001$ ). §Significantly different to CON ( $p < 0.05$ ).

first 100 ms (Task 1: 19%; Task 2: 27%), with a greater effect during 0–50 ms than 50–100 ms interval (Task 1: 47% vs. 9%; Task 2: 54% vs. 17%), similar to results reported in a recent study with an isometric  $R_{\text{time}}$  task performed

with the knee extensors (0–50 ms: 33%–49%; 50–100 ms: 9%–13%).<sup>31</sup> Additionally, together with the improved mechanical performance, we showed that S stimulus also increased sEMG amplitude of the FDS and EDC during

the first 100 ms. sEMG has several limitations that precludes its use as an index of neural drive toward the muscle.<sup>49</sup> These findings are compatible with those of a recent study using high density sEMG showing greater  $\alpha$ -motoneurons discharge rates during S trials,<sup>31</sup> which may have contributed to increased sEMG found in the present study. Together, these results suggest that the RST input increasing  $\alpha$ -motoneuron output during S trials may reach its maximum over the first 50 ms of a forceful isometric contraction, decreasing thereafter. However, during Task 2, where participants were asked to maintain force for 3 s, the results show that the S stimulus also increased force production over the first 500 ms (6% vs. V, 4% vs. A) and maximum force production (2.5% vs. V, 2% vs. A). Despite the lower magnitude, these results are similar to the 7% increase in maximum force production in the same task reported previously.<sup>33</sup> Therefore, although RST input after a S stimulus may reach its maximum during early contraction phases, it may be still present during longer intervals, influencing force production.

As expected, MVC force at baseline was significantly higher (37%) in CL than CON participants. The analysis of subsequent tasks shows that CL did not have a greater RFD than CON participants during the first 100 ms, neither during brisk forceful contraction (Task 1) nor during a sustained MVC (Task 2). The lack of difference in RFD between groups could be related to the lower specificity of the power grip compared to specific finger flexor exercises resembling the edges typically found in rock climbing. However, CL produced more force than CON (30%) already 500 ms into the contraction (Task 2). Therefore, rock climbing and climbing-specific RT, involving heavy pulls and finger flexor exercises, leads to increased power grip strength, which agrees with recent studies showing differences even between recreational climbers and non-climbers.<sup>40</sup>

Notwithstanding, the novel element of the present study was the comparison of the effects of a S stimulus between a population of resistance-trained climbers and untrained participants. Chronic RT induces adaptations in the efficacy of the RST in non-human primates, increasing the response to electrical stimulation of the medial longitudinal fasciculus, which contains RST fibers.<sup>25</sup> Those adaptations may be one of the mechanisms responsible of MVC force increases with training.<sup>18</sup> Such direct methods cannot be used in humans, however, given the role of the RST in the effects of the S stimulus during a  $R_{\text{time}}$  task,<sup>50</sup> this paradigm can be used in humans to indirectly detect RST neuroplasticity.<sup>18,34,51</sup> For example, an acute session of a paired stimulation technique combining loud sound stimulus and muscle electrical stimulation, enhanced the reduction in  $R_{\text{time}}$  in response to a S stimulus, suggesting a certain type of

plasticity in the RST.<sup>51</sup> However, our results show no differences in  $R_{\text{time}}$  between CL and CON participants, but a steeper RFD in CL than CON participants from 50 to 100 ms only during S trials. We hypothesize that, as in non-human primates, chronic RT may increase RST synapse efficacy to the  $\alpha$ -motoneuron.<sup>18,25</sup> We assume that input from cochlear nuclei is maximal or near maximal early after the S stimulus, leading to maximal output of the RST, as suggests the greater effects of the S stimulus over RFD or  $\alpha$ -motoneuron discharge rate during the first 50 ms.<sup>31</sup> Therefore, any increase in RST synaptic efficacy would have a lower influence over RST output, because the maximal sensory input already recruits RST near its maximum discharge rate, limiting the scope for detecting differences in  $R_{\text{time}}$  or RFD from 0 to 50 ms. However, if the output of the RST decreases thereafter, the greater efficacy of the RST present in trained individuals would allow them to maintain a submaximal but greater RST output to the  $\alpha$ -motoneurons, explaining the steeper RFD from 50 to 100 ms in resistance-trained climbers. Alternatively, the inherent greater variability of force production during the first 50 ms could also have made difficult to detect differences between groups at those stages of the contraction.<sup>52</sup> While we did not measure it, increased synaptic efficacy could arise from increased strength of communication between RST and motoneurons and/or from an increase in the probability and amount of neurotransmitter released from pre-synaptic RST neurons and the number of postsynaptic motoneuron receptors activated.<sup>25</sup> Indeed, increase in synaptic efficacy has been described following a number of interventions including but not limited to sensory manipulations (i.e., whole body vibration in rodents and electrical nerve stimulation).<sup>53,54</sup>

Due to the indirect nature of measurements and because there are no other cross-sectional or longitudinal studies focused on RT-induced adaptations in the RST, the present results should be interpreted with caution. Cross-sectional studies do not exclude the possibility of selection bias so that innate differences between participants instead of chronic training would account for the RST findings. Therefore longitudinal studies are needed to provide further evidence about the effects of RT in the RST using the present or alternative paradigms.<sup>18</sup> In this regard, our results show that  $R_{\text{time}}$  values had a moderate reliability between sessions, while RFD had a moderate to excellent reliability.<sup>45</sup> It is possible that a familiarization session might have increased the reliability of measurements. However, a lack of familiarization sessions likely did not affect the conclusions because neither group did receive familiarization. The reproducibility values, together with the main results of the present study, inform future longitudinal RT studies aiming to track changes in

RST using the current paradigm, which should focus not only on  $R_{\text{time}}$ , but mainly on RFD. Lastly, although recent data in primates seem to confirm the hypothesis of putative role of the RST in the effects of a S stimulus over  $R_{\text{time}}$ , we cannot ignore the possibility that differences between the two groups in structures other than the RST underlie our findings.

Experienced rock climbers produced a steeper rate of force development than untrained participants when a startle stimulus was combined with an imperative visual signal during a  $R_{\text{time}}$  task, a difference not present in  $R_{\text{time}}$ . Collectively, the data tentatively suggest that chronic rock climbing and climbing-specific RT might improve RST efficacy and increase RST input to the  $\alpha$ -motoneurons.

## 5 | PERSPECTIVES

The neural adaptations contributing to the greatest capacity to produce force after chronic resistance training are still an area of debate.<sup>12–15</sup> During last years, several reviews have highlighted the possibility of inconsistencies being partially related to an excessive focus on measuring adaptations on the corticospinal tract while overlooking other sites of the nervous system susceptible of contributing to force generation.<sup>12–15</sup> While there is robust data to suggest that the RST could be a key locus of RT-associated neuroplasticity underlying MVC force improvement, this data is limited to primates.<sup>25</sup> Here we use an indirect, but simple, non-invasive, and reproducible method, never used before in the field of neural adaptations induced by RT, to obtain information about RST function in healthy humans. Additionally, with a cross-sectional design we shown that resistance-trained rock climbers produced steeper rate of force development than untrained participants when a startle stimulus was combined with an imperative visual signal, which tentatively suggest an increased RST input to  $\alpha$ -motoneurons. This finding may aid future research focused on elucidating the neural adaptations to RT in order to optimize exercise prescription in different populations.

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### CONFLICT OF INTEREST STATEMENT

None of the authors declare conflict of interest.

### DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.


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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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