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--Manuscript Draft--

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Full Title:	Effects of visual feedback absence on force control during isometric contraction
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Keywords:	force accuracy; force stability; learning effect; visual deprivation; EMG
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Abbreviations

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- 4 CV: coefficient of variation
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- 6 EMG: electromyographic signal
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- 8 F: mean force
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- 10 FB: with visual feedback
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- 12 MF: mean frequency
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- 14 MVC: maximal voluntary contraction
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- 16 noFB: without any form of visual feedback
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- 18 RMS: root mean square
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- 20 SD: standard deviation
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- 22 t-target: time during which force was maintained within the target
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- 24 ΔF : distance of the force signal from the required target
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Introduction

Two main mechanisms are involved in skeletal muscle force output modulation during isometric contraction: spatial recruitment, which determines the number and types of the recruited motor units, and temporal recruitment, which controls their firing rate (Moritani et al. 1987; Sale 1987; Freund 1983). Scheduling, modulation and control of muscle contraction involves also sensorial information. Most of the daily physical activities depend on a continuous monitoring of muscle contraction based on the proprioceptive and exteroceptive sensory feedbacks (Hu et al. 2011; Nowak et al. 2003). The nature and characteristics of these feedbacks contribute significantly to force control. On the proprioceptive side, muscle, aponeurosis and tendon receptors (e.g., neuromuscular spindles and Golgi tendon organs) provide real-time information on the degree of muscle fibers stretching and tension level, together with body segments spatial position (Dimitriou and Edin 2010). On the exteroceptive side, vision and pressure are the most important sensory components for force modulation (Sayenko et al. 2012; Lin and Yang 2011). A continuous information transfer among sensory components, cerebral cortex and effector organs takes place during contraction. This exchange through feedback and feed-forward mechanisms allows continuous readjustments and corrections of contraction according to the purpose of the action (Vaillancourt et al. 2003a; Vaillancourt et al. 2006; Glickstein 2000). The control mechanisms of both static and dynamic muscle contraction have been already studied extensively (Svendson et al. 2011; Janczyk et al. 2009; Harbst et al. 2000; Hu et al. 2011). Isometric force control has been observed to be influenced by many extrinsic and intrinsic variables, including number, size and type of active muscles (Prodoehl and Vaillancourt 2010; Tracy 2007b), force intensity (Baweja et al. 2009), training status (Enoka et al. 1999), fatigue (Esposito et al. 2009), age (Ofori et al. 2010; Kennedy and Christou 2011; Schiffman et al. 2002) and visual feedback characteristics (Newell et al. 2003; Sosnoff et al. 2006; Tracy 2007b). Visual feedback is an essential component when attempting to minimize force fluctuations and to hold force steady (Prodoehl and Vaillancourt 2010). During visuomotor control, indeed, visual feedback is transferred from the visual cortex to the parietal and premotor areas of the cortex and subcortical areas of the basal ganglia and cerebellum (Vaillancourt et al. 2003b; Glickstein 2000; Milner and Goodale 1993; Vaillancourt et al. 2006). Different degrees of somatotopic organization have been shown in each of these regions of the brain and the visual feedback may be processed differently based on the body effector where the feedback-based correction is used (Alkadhi et al. 2002; Flanders 2005; Grodd et al. 2001).

During isometric tasks, force control is usually assisted by visual feedback on a computer display to maintain the force target as accurate as possible. The influence of visual feedback on isometric force control, though, has been already widely investigated. The success in maintaining the required force target, indeed, has been found to be strongly influenced by the modality (Slifkin et al. 2000; Miall et al. 1993), delay (Sosnoff and Newell 2007; Miall et al. 1985) and gain (number of pixels on the screen per unit of force) with which the visual feedback is shown to the subject (Sosnoff and Newell 2005,

2006; Vaillancourt et al. 2006). Slifkin et al. (2000) investigated the influence of different gains of visual feedback during sustained isometric contraction of the index flexor. The gain was found to be directly correlated to force accuracy (i.e., a precision of force signal with respect to the target) and inversely correlated to force stability (i.e., a degree of force signal fluctuation as the ratio of mean force output over the within-participant standard deviation). Sosnoff et al. (2006) found that the relationship between gain and variability in force control can be represented by a “U function”, showing greater force fluctuations with the lower and higher gains, and minor force fluctuations in the central part of the curve. Schiffman et al. (2006) investigated the isometric force control of elbow flexors and knee extensors with visual feedback administration in a continuous line matching or in a discrete bandwidth, that was provided only when the force signal was out of the intensity range required ($\pm 4\%$). With discrete bandwidth, the force feedback resulted in a greater inaccuracy but also in a better stability. The wider force fluctuations in the presence of a continuous visual feedback were explained by continuous sensorial information, which possibly induced the subject to a greater number of adjustments and corrections of the force output (Sherwood 1988). The amplitude of force fluctuation, an index of force stability, is also inversely related to the level of effort and to the number of the recruited motor units (Hamilton et al. 2004), and has been shown to be influenced directly by alterations in synergistic muscle activation (Shinohara et al. 2009). Overall, visual feedback removal during an isometric task either did not influence (Christou et al. 2004; Vaillancourt and Russell 2002) or reduce force variability ~~accuracy~~ making more stable the signal (Welsh et al. 2007; Christou 2005; Tracy et al. 2007; Baweja et al. 2009; Kennedy and Christou 2011; Schiffman et al. 2002; Tracy 2007b). ~~Conversely, Moreover,~~ when visual feedback is removed, the force accuracy was compromised because the force output tended to drift away from the required target (Tracy 2007b; Vaillancourt and Russell 2002).

However, the effects of visual feedback absence from the very beginning of the task have never been studied yet. Visual feedback, indeed, has been either removed during isometric contraction (Schiffman et al. 2002; Tracy 2007b) or provided intermittently throughout the task (Slifkin et al. 2000; Baweja et al. 2009; Madeleine et al. 2002). During an isometric task without visual feedback following the same task performed with the aid of visual feedback, force output can be reasonably supposed to be handled by the central nervous system in a different way because of an altered somatosensory feedback involvement. A previous experience in a particular task, indeed, leads to the storage of appropriate control parameters which are used in programming subsequent tasks (Miall et al. 1995). In many working and sport activities, such as photography, driving, windsurfing, para- and hand-gliding or skiing activities, isometric force control in the absence of a visual feedback might be a crucial issue for task accomplishment.

On this basis, the first aim of the study was to evaluate the effect of visual feedback absence on force output control. Secondly, the possibility to improve performance due to repeated contractions in the absence of visual feedback was also

1 assessed. Given that the complexity of the force variability decreases when less visual information is provided (Slifkin et al.
2 2000), hypothesis can be made that when visual feedback is not provided, force control relies on the ability to maintain
3 force accuracy and stability by exteroceptive and proprioceptive information and by the memory of a previous identical
4 task. To this purpose, participants performed sustained isometric tasks at different contraction intensities, with and in the
5 complete absence of visual feedback.
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10 11 12 **Methods**

13 14 15 *Participants*

16 **Twelve** healthy, physically active males, (age 23 ± 1 years; stature 1.74 ± 0.07 m; body mass 71 ± 6 kg; mean \pm standard
17 deviation, SD) volunteered to participate in this study. They did not report any neuromuscular disease and had normal or
18 corrected to normal vision. All participants were involved in recreational activities 2-3 times per week, but none of them
19 was involved in a specific strength training program. After full explanation of the experimental design and procedures, each
20 participant gave written informed consent before engaging in the study. The participants were naive to the purpose of the
21 experiment. The study was approved by the local Ethics Committee, in accordance with the principles of the 1964
22 Declaration of Helsinki.
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31 32 33 *Experimental design*

34 All tests were carried out in a climate-controlled laboratory (constant temperature of 20 ± 1 °C and relative humidity of 50
35 ± 5 %). Participants were asked to report to the laboratory on two different days, without any form of strenuous physical
36 exercise in the previous 3 days and with the last meal at least three hours before tests. They were also asked to abstain from
37 caffeine or any other similar beverages the day of the test. A schematic draft of the experimental design is provided in
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INSERT FIGURE 1 ABOUT HERE

66 The first visit served for familiarization purpose. Participants were instructed with the experimental procedures and were
67 allowed to try the ergometer involved in the study.

68 During the second visit, the maximal voluntary contraction (MVC) of the knee extensor muscles of the dominant leg was
69 determined isometrically at a knee joint angle of 90 degrees. MVC was defined as the highest value of three trials, each
70 lasting 3 s. Among trials, 5 min of recovery were allowed. Thereafter, after 20 min of rest, participants performed isometric
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1 tasks of the knee extensors at 20%, 40% and 60% MVC for a duration of 20 s, in a random order. For each intensity, a
2 trial performed with the aid of a visual feedback (FB) of force output was followed by 3 trials without any form of visual
3 feedback (noFB). Among trials, 2 min of recovery were allowed.
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7 *Experimental procedures*

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9 During tests, participants seated on a knee-extensor ergometer with the knee joint at 90 degrees. The load cell on the
10 ergometer was connected to a carbon shin pad positioned on the dominant leg of the subject by an inextensible steel wire.
11 The position of the subject on the ergometer and the placement of the shin pad on the leg was carefully standardized. To
12 isolate the knee extensor muscles contribution to the force output, limiting accessory muscles involvement, subjects were
13 also secured to the ergometer with Velcro straps at the chest.
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16 During contraction, force feedback was provided by a computer monitor at a resolution of 1280 x 800 pixels, placed 1 m in
17 front of the subject. The visual feedback of the target force was indicated by two horizontal lines corresponding to $\pm 3\%$ of
18 the requested force. The force output was represented by a red vertical bar of increasing amplitude, which turned green
19 when the force output was within the target. The relative force intensity corresponding to the target was manipulated so that
20 the target window was always centered on the monitor and with the same size.
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23 **The participants were asked to reach the target within 3-4 seconds and to sustain the required force as constant as possible**
24 **for 20 seconds. During the task with real-time visual feedback, participants were suggested to perceive carefully the**
25 **proprioceptive sensations of the muscle tension level and exteroceptive information (the shin pad pressure on the surface of**
26 **the tibia), to be used during the tasks without visual feedback. In addition, the force tracing of the previous trial was shown**
27 **retrospectively on a computer monitor during the 2 minutes of recovery among noFB trials.**
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42 *Measurements*

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44 During muscle contraction, force output and electromyographic (EMG) signal from the *vastus lateralis* muscle were
45 recorded. The force output of the knee extensor muscles was recorded using a previously calibrated load-cell (mod. SM-
46 2000N, Interface, Scottsdale, UK). The force signal was filtered (bandwidth 2–64 Hz) and stored on a personal computer
47 after A/D conversion (mod. UM150, Biopac System, Goleta, USA) with a sampling frequency of 2048 Hz. The EMG probe
48 was positioned on the belly of the muscle, with the electrodes (4 silver bars with 1 mm diameter and 1 cm length, 1 cm
49 interelectrode distance) perpendicular to the fibers major axis. The skin area under the EMG electrodes was shaved, gently
50 abraded with fine sand paper and carefully cleaned with ethyl alcohol and conductive gel, to achieve an inter-electrode
51 impedance below 2000 Ω . EMG was amplified (gain of 1000; mod. ASE16, LiSin, Turin, Italy; input impedance: 60 M Ω ;
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1 common-mode rejection ratio: >90 dB), filtered (bandwidth 10–500 Hz) and stored on a personal computer after A/D
2 conversion (mod. UM150, Biopac System, Goleta, USA) at a sampling rate of 2048 Hz.
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5 *Data analysis and statistics*

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7 Analysis of the data focused only on 15 s of contraction, as the first 3 seconds and the last 2 seconds of each trial were
8
9 discarded to avoid the interference of transient phenomena. Each trial was then divided in 0.25 s time frames.

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11 Force: the mean force (F) with standard deviation (SD), coefficient of variation (CV = SD/mean), as an index of muscle
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13 contraction stability, and ΔF (the distance of force signal from the required target), as an index of muscle contraction
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15 accuracy, were calculated off-line from the force signal. Moreover, the time during which force was maintained within the
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17 target (t-target) was also calculated.

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19 EMG: from the time and frequency domain analysis of the signal, the root mean square (RMS) and the mean frequency
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21 (MF) of the power spectral distribution were calculated.

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23 Statistical analysis was performed using a statistical software package (SigmaPlot for Windows, v 12, Systat Software Inc.,
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25 USA). To check the normal distribution of the sampling, a Kolgomorov-Smirnov test was applied. A sample size of 12
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27 participants was selected to ensure a statistical power higher than 0.70. A 3-way (condition, intensity and time) ANOVA
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29 for repeated measures was applied. To detect the location of significant differences, a Holm-Sidak post-hoc test was utilized
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31 when appropriate. The level of significance was set at $\alpha < 0.05$. Unless otherwise stated, values are expressed as means \pm
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33 standard error (SE).
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39 **Results**

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42 The average MVC across participants was 679.14 ± 38.22 N , so that the 20%, 40% and 60% MVC force requirements
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44 were 136.22 ± 7.84 N, 271.46 ± 14.7 N and 407.68 ± 1.84 N, respectively. Figure 2 shows the force-time trajectories
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46 sampled under different conditions (FB and noFB-1) in a representative participant.
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INSERT FIGURE 2 ABOUT HERE

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As expected, during FB condition participants were able to increase their force output until they reached the required target,
thereafter keeping it as constant as possible. In noFB, different force signal behaviors were observed among subjects,
according to force intensity.

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Figure 3 shows the mean F and SD during the three tasks at 20%, 40% and 60% MVC under different experimental conditions. Significant differences were detected only between FB and noFB-1 condition during the first part of the contraction at 20% and 40% MVC, and in the last part of contraction at 60% MVC ($P<0.05$).

INSERT FIGURE 3 ABOUT HERE

CV values show a slightly downward trend from the beginning to the end of the contraction at all force intensities. ~~No significant difference was found between FB and noFB-1 and among the three noFB trials.~~

The CV of force did not change between FB and noFB-1, suggesting that participants were able to maintain the force constant, even in the absence of a visual feedback. However, the CV was significantly lower at 60% MVC compared to 20% and 40% MVC ($P<0.05$) in both FB and noFB-1 conditions. No significant changes were observed in the CV among noFB trials at any investigated contraction intensity.

INSERT FIGURE 4 ABOUT HERE

As seen in Figure 5 (left panels, FB vs noFB-1), ΔF increased as a function of force intensity in both conditions, achieving statistical significance between 20% MVC and 60% MVC ($P<0.05$). ~~In particular, in the absence of visual feedback In noFB-1 participants expressed a higher level of force output with respect to the target at 20% and 40% MVC, and a lower level of force output at 60% MVC (see also Figure 2). A significant decrease with time in ΔF was also observed in both conditions (FB and noFB-1) at all contraction intensities, with the only exception of noFB-1 at 60% MVC ($P<0.05$). Lastly, ΔF in noFB-1 was higher ($P<0.05$) with respect to FB at all contraction intensities. A significant difference among the three contraction intensities ($P<0.05$) was detected only when considering the part of contraction where ΔF stabilized (last 10 s of contraction in Figure 5).~~

When comparing the three trials in the absence of a visual feedback (Figure 5, right panels, noFB-1, noFB-2, and noFB-3), a decrease in ΔF ($P<0.05$) between the first and the third trial at 20% MVC was observed (Figure 5). No significant differences were detected at the other intensities, despite a tendency to a reduction from noFB-1 to noFB-3.

INSERT FIGURE 5 ABOUT HERE

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~~The CV of force did not change between FB and noFB-1, suggesting that participants were able to maintain the force constant, even in the absence of a visual feedback. However, the CV was significantly lower at 60% MVC compared to 20% and 40% MVC ($P<0.05$) in both FB and noFB-1 conditions. No significant changes were observed in the CV among noFB trials at any investigated contraction intensity.~~

The EMG-RMS and EMG-MF during FB and noFB-1 contractions at all contraction intensities are reported in Figure 6. The comparison between the two experimental conditions showed a statistical difference only for EMG-RMS at 40% and 60% MVC ($P<0.05$). A significant EMG-MF reduction with time ($P<0.05$) was observed in both conditions at all contraction intensities.

INSERT FIGURE 6 ABOUT HERE

Figure 7 shows the EMG-RMS and EMG-MF during the three noFB trials at 20%, 40% and 60% MVC. No significant differences were detected among trials at 20% and 40% MVC. A significant difference, instead, was observed in EMG-RMS during the second part of contraction at 60% MVC. EMG-MF declined significantly from the first to the last second of contraction in all conditions and at all contraction intensities.

INSERT FIGURE 7 ABOUT HERE

In Table 1 the t-target in all experimental conditions is given. As expected, a drop in t-target without visual feedback was observed ($P<0.05$). t-target values had a tendency to decrease with the increase in contraction intensity. Between the three no-feedback trials a significant increase from noFB-1 to noFB-3 was detected at 20% MVC.

INSERT TABLE 1 ABOUT HERE

Discussion

The ability of the neuromuscular system to control force accuracy and stability in the complete absence of a visual feedback has not been assessed yet. The main results of the present study were that force accuracy at low and moderate contraction intensity decreased significantly without visual feedback. Conversely, force stability was not altered in the absence of visual feedback, meaning that visual information can be obviated by other feedbacks for force stability control. Lastly,

1 when trials without visual feedback were repeated, force accuracy increased significantly at low contraction intensity, thus
2 unveiling a potential capability to improve the performance in this kind of motor tasks.
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5 *Effect of visual feedback (noFB-1 vs FB)*

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8 In the present study, ΔF under noFB-1 condition was significantly higher than in FB at all contraction intensities, indicating
9 that force accuracy was altered by the absence of visual feedback. Therefore, feedbacks from other afferents did not provide
10 sufficient information on force signal intensity to reach accurately the target. **Moreover, the force tracing behavior of the**
11 **representative participant of the present study shows a tendency to overshoot the target at the lower intensities in noFB-1.**
12 **This behavior is also in agreement with the higher average force output at the very beginning of contraction in noFB-1 at**
13 **20% and 40% MVC, but not at 60% MVC.**
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20 When comparing our findings with those during visual feedback removal present in the literature (Vaillancourt and Russell
21 2002; Baweja et al. 2009; Prodoehl and Vaillancourt 2010; Tracy 2007b), somehow similar data can be found showing a
22 force drift from the force target when visual feedback was taken away, especially at high force levels. This phenomenon
23 became more evident as force level increased (Baweja et al. 2009). Vaillancourt and Russell (2002) and Tracy et al. (2007)
24 reported that the direction of force drift depends on the level of force intensity. In particular, when visual feedback was
25 removed, force output tended to overshoot the target at low force levels, and to undershoot the target at high force levels
26 (Tracy et al. 2007; Vaillancourt and Russell 2002). This is consistent with the standard range effect (positive error at low
27 movement amplitude and negative error at high amplitude) shown in many psychophysical tasks (Laming and Martin
28 1997). **Interestingly, also under dynamic condition the exerted force overshoot the requested force at low effort intensities**
29 **without real-time visual feedback, while consistent undershooting occurred when force intensity increased (Jackson et al.**
30 **2006). Hypothesis was made that if perceptual estimation of effort grows faster than the produced effort, the perceptually**
31 **controlled production of force may grow slower than the desired effort. Collectively, all these data show that real-time**
32 **visual feedback is crucial to achieve maximum force accuracy.**
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46 Conversely, the CV of the force signal (an index of force stability) was not different between FB and noFB-1, suggesting
47 that the absence of visual feedback did not increase the level of force fluctuations. Although visual feedback could be
48 intuitively considered necessary to successfully produce a constant level of force, and providing it more frequently should
49 contribute to a less variable performance, the present results seem to suggest that the ability to maintain force stability can
50 be obviated by other exteroceptive and proprioceptive information. Other studies comparing conditions with and without
51 visual feedback showed that visual feedback removal either did not influence force stability (Vaillancourt and Russell 2002;
52 Christou 2005) or even improved it (Baweja et al. 2009; Tracy 2007a, b). Recently, Athreya and colleagues (2012)
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1 investigated the effects of the complete absence of visual feedback on force output during an isometric contraction of the
2 index finger flexor at a self-selected force intensity, without an imposed force target. Also in this case, the absence of visual
3 feedback reduced force signal fluctuations. One possible explanation for the discrepancy among studies (no effect or
4 increase in force stability with the absence of visual feedback) may be retrieved in the type or number of muscles analyzed.
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6 The studies showing no effect of visual feedback removal on force stability were conducted during small muscle mass
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8 (finger flexor) contractions, whereas the studies retrieving an increase in force stability were performed with larger muscle
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10 masses of the upper (elbow flexors) or lower limbs (knee extensors, foot plantarflexors or dorsiflexors).
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13 When force stability improved, explanation was given that force fluctuations appeared to be wider with visual feedback
14 because of a greater number of force adjustments and corrections induced by visual information (Tracy 2007b). Overall, our
15 results reveal a lower complexity (signal noise in its time domain structure) of the force variability without vision, which is
16 consistent with earlier studies showing that the complexity of the force variability decreases when less visual information is
17 provided (Slifkin et al. 2000).
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20 While at 20% and 40% MVC no differences occurred between the two conditions in electrical muscle activation, EMG-
21 RMS at 60% MVC was significantly lower in the absence of visual feedback, suggesting the presence of a possible
22 difference in motor unit activation pattern between the two conditions at this level of force. In particular, the possible lower
23 level of motor unit recruitment at 60% MVC may be due to the higher ΔF (under the target) in no-FB condition, indicating
24 a greater distance from the force target because of the lower levels of force output (about 78.4 N). This was not the case at
25 20% and 40% MVC, where higher EMG-RMS values would be expected due to the greater levels of force output (about
26 29.4 N and 49 N at 20% and 40% MVC, respectively). However, differences in force output between 20% and 40% MVC
27 were probably too low to be detected by surface EMG. A recent study of Baweja et al. (2009), involving the first dorsal
28 interosseus muscle of index finger, showed that EMG amplitude was greater in the presence of visual feedback with respect
29 to a condition in which feedback was removed. The authors hypothesized that the greater neural drive to the muscle in the
30 presence of visual feedback was due to the higher antagonist activity for visuomotor corrections. In force control, indeed,
31 many combinations of muscle activation patterns around a joint exist that can be utilized to maintain a given force output
32 (Latash et al. 2001), and fluctuations in force have been shown to be influenced by changes in synergistic muscle activation
33 (Shinohara et al. 2006; Shinohara et al. 2009). Other studies indicated that higher control centers in humans are activated
34 differently in the presence or absence of visual feedback (Lee and Keller 2008; Prodoehl et al. 2008). Sogaard et al. (2003)
35 studied fatiguing isometric contractions of *biceps brachii* muscle at 30% MVC with visual or proprioceptive feedback,
36 demonstrating different motor unit activation strategies in the two experimental modalities. Another study reported lower
37 EMG-RMS values with proprioceptive feedback during continuous contractions of the elbow flexor muscles at 10% and
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30% MVC compared to the same contractions performed with visual feedback (Madeleine et al. 2002; Sjogaard et al. 2000). According to these findings, our EMG-RMS data may suggest a different activation of higher centers between the two experimental conditions and, consequently, a different muscle activation by the motor cortex. It should be taken into account, though, that our protocol involved a type of contraction where multiple muscles contribute to force output and that EMG signal was recorded only from the *vastus lateralis* muscle.

Effect of repeated contractions without visual feedback (noFB-2 and noFB-3 vs noFB-1)

According to the second aim, the presence of an improvement due to repeated contractions in the absence of real-time visual feedback was assessed. Indeed, a tendency for force accuracy enhancement (ΔF reduction) and t-target increase between the first and the last no-FB contraction occurred, even though a statistical significance was reached only at 20% MVC.

In the absence of real-time visual feedback, participants had to reproduce and maintain the required target during noFB-1 with the remaining sources of sensory information (proprioceptive and tactile feedbacks). During noFB-2 and noFB-3, though, also the ~~retroactive~~ retrospective visual feedback of force output (shown to the participants on the computer monitor during recovery) concurred to better adjust the force output and increase force accuracy. Hence, despite the retrospective visualization of the force signal cannot be compared to a real-time visual feedback, it was effective to better tune the force output with the target during the subsequent noFB trial. This phenomenon cannot be simply attributed to a gradual familiarization with the type of exercise. Indeed, the progressively longer time interval between the initial trial with real time visual feedback and the other trials should eventually worsen the required performance. Collectively, this may suggest that the subjects of the present study were able to utilize appropriately the proprioceptive and exteroceptive information when integrated with the memory of the visual feedback during recovery.

Previous studies on the effects of task repetition on target achievement with and without visual feedback were conducted only under dynamic condition (Franklin et al. 2007; Scheidt et al. 2005). The absence of one sensory modality/feedback was found to be compensated by some form of internal visuo-motor memory supporting motor control. Even though studies on this subject have not been conducted yet under isometric contraction, it is conceivable that there would be a similar integrative process to take up the withdrawal of some exteroceptive and proprioceptive information with other sources of feedback. The notion of an internal visuo-motor memory may help to interpret also our findings. Therefore, both sensory information alternative to visual feedback and the memory of the visual feedback concurred to the process of isometric force control in the absence of real-time visual feedback.

1 The increase in force accuracy and t-target achieved statistical significance only at 20% MVC, possibly because peripheral
2 fatigue may have occurred at higher contraction intensities throughout contraction, thus interfering with the sensory and
3 visuo-motor memory integration process. Indeed, in spite of a similar decline of EMG-MF throughout contraction, EMG-
4 RMS at 60% MVC was significantly higher in noFB-2 and noFB-3 in the second half of contraction. Taking into account
5 that EMG-MF parameter is mainly influenced by sarcolemmal conduction velocity (Rainoldi et al. 1999), it may be argued
6 that changes in central command due to neuromuscular fatigue throughout contraction were similar among noFB conditions
7 in terms of decrease in average motor unit conduction velocity. However, a possible tendency toward a
8 synchronization/grouping effect, reflected in the higher EMG-RMS values, to maintain the same level of force output may
9 have taken place at 60% MVC (Krogh-Lund and Jorgensen 1993).
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20 **Conclusions**

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22
23 The results of this study suggest that, even in the complete absence of real-time visual feedback from the beginning of the
24 task, the force control during isometric contraction was not completely lost. The use of proprioceptive and exteroceptive
25 information can determine a motor memory that allows to compensate, at least in part, the absence of visual feedback.
26 Moreover, a capacity to improve the precision and accuracy of the trial in the absence of real-time visual feedback occurred
27 already in a single session. A useful development of this study should investigate whether differences in control ability
28 under isometric contraction exist in athletes used to different types of training programs. A training modality to improve
29 this capacity may also be investigated in further studies. Indeed, the ability to modulate and adapt the characteristics of
30 muscle contraction through different feedback modalities could be extremely suitable in sports where the control of
31 technical movements is a crucial factor for an effective performance.
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51 **Conflict of interest**

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53 No conflicts of interests to declare.
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Table 1. Time within the target (t-target, s).

	20% MVC	40% MVC	60% MVC
FB	14.03 ± 0.61	13.88 ± 0.56	13.55 ± 0.53
noFB-1	3.08 ± 1.21 *	3.93 ± 0.90 *	3.23 ± 1.21 *
noFB-2	5.20 ± 1.73	4.58 ± 1.73	2.00 ± 0.90
noFB-3	8.18 ± 1.74 [#]	5.28 ± 1.36	2.95 ± 1.41

**P*<0.05 vs FB; [#]*P*<0.05 vs noFB-1.

Legends

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Figure 1: Schematic draft of the experimental design. The group of contractions that were randomized are indicated by curly brackets.

Figure 2: Force signal tracings at 20%, 40% and 60% MVC, as a function of contraction time, in FB and noFB-1 condition in a representative participant. Horizontal dashed lines represent the force target for any %MVC.

Figure 3: Force (F) average values at 20%, 40% and 60% MVC as a function of contraction time in FB and noFB condition (mean \pm standard deviation, SD). * $P < 0.05$ vs noFB-1.

Figure 4: Coefficient of variation CV average values (mean \pm SE) as a function of contraction time in FB and noFB condition at 20%, 40% and 60% MVC.

Figure 5: ΔF average values as a function of contraction time in FB and noFB condition at 20%, 40% and 60% MVC (mean \pm SE). * $P < 0.05$ FB vs noFB-1; # $P < 0.05$ noFB-1 vs noFB-3.

Figure 6: EMG-RMS and EMG-MF average values (mean \pm SE) as a function of contraction time in FB and noFB-1 condition at 20%, 40% and 60% MVC. * $P < 0.05$ vs noFB-1.

Figure 7: EMG-RMS and EMG-MF average values (mean \pm SE) as a function of contraction time in the three noFB trials (noFB-1, noFB-2, noFB-3) at 20%, 40% and 60% MVC. * $P < 0.05$ noFB-1 vs noFB-3.

Figure 1

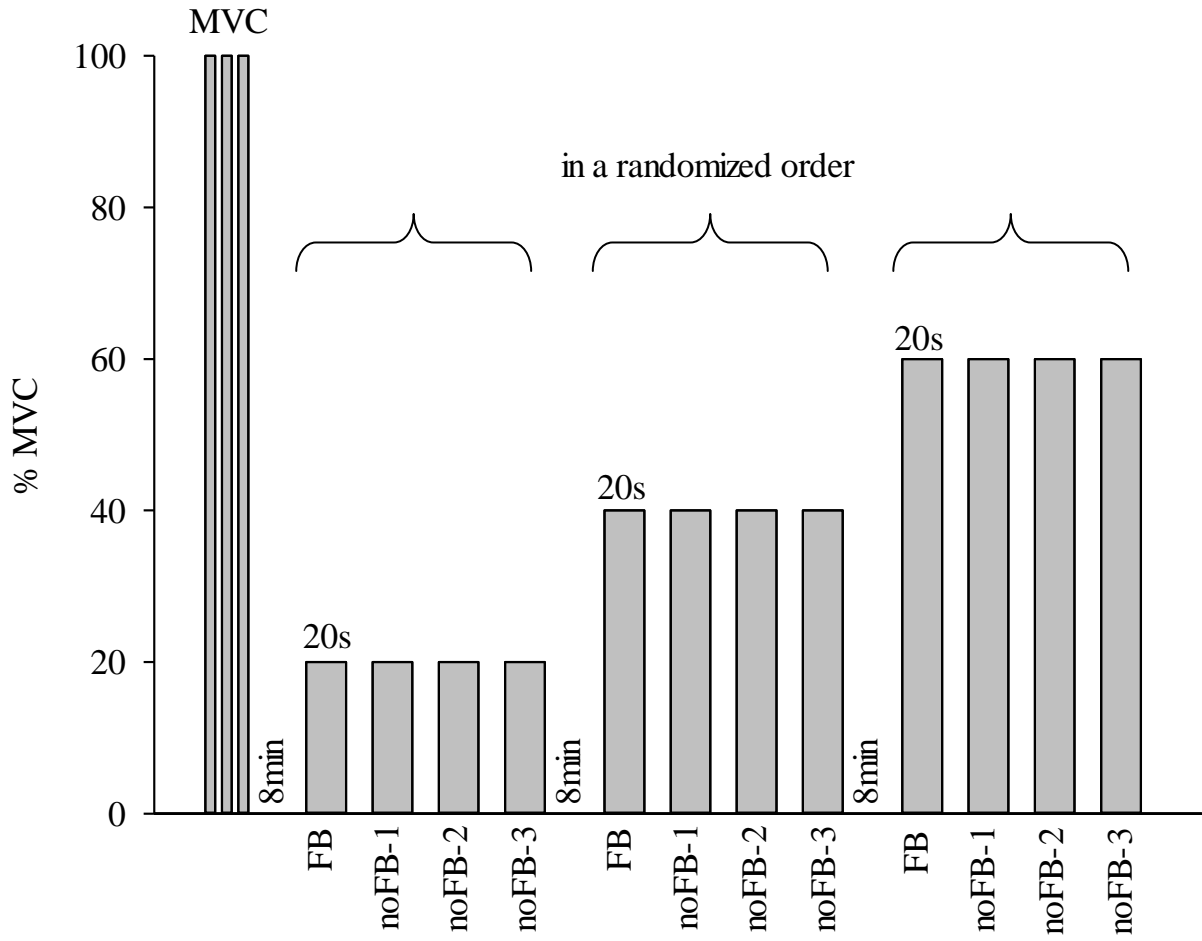


Figure 2

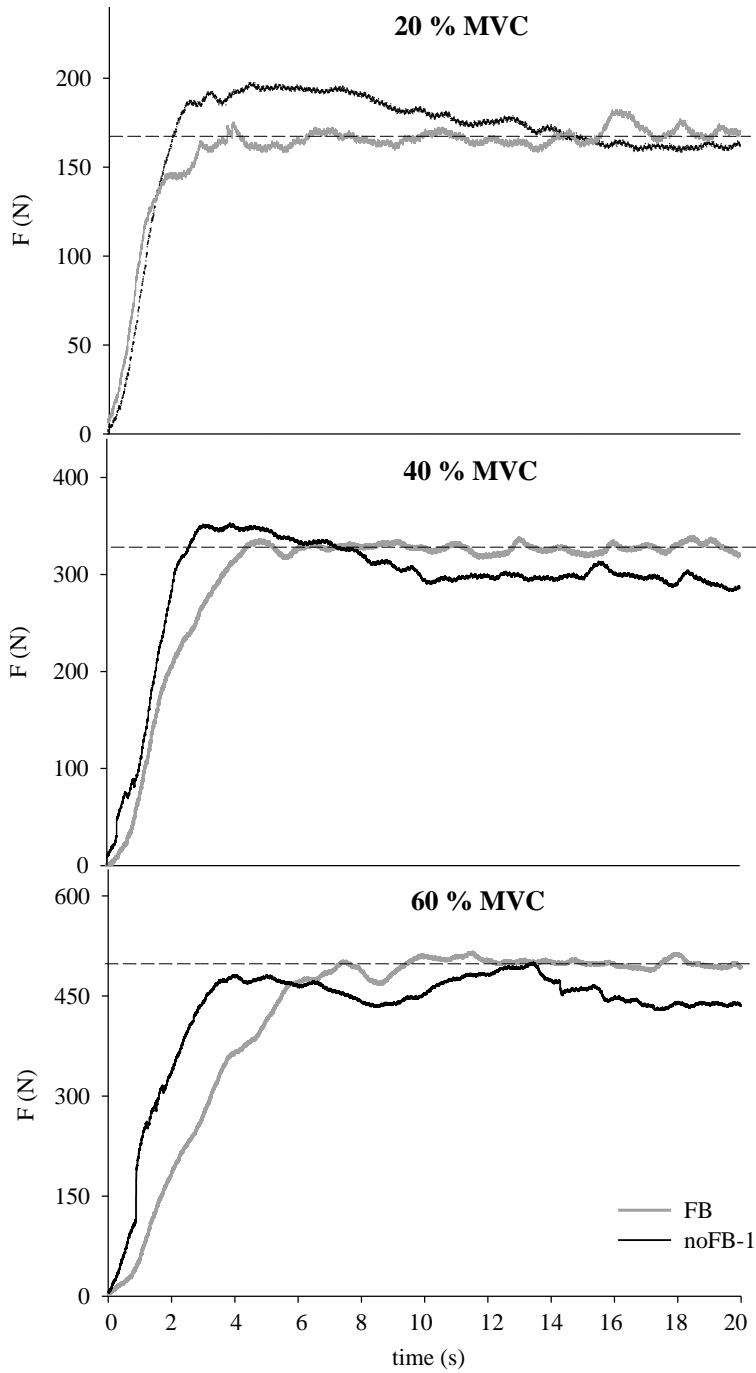


Figure 3

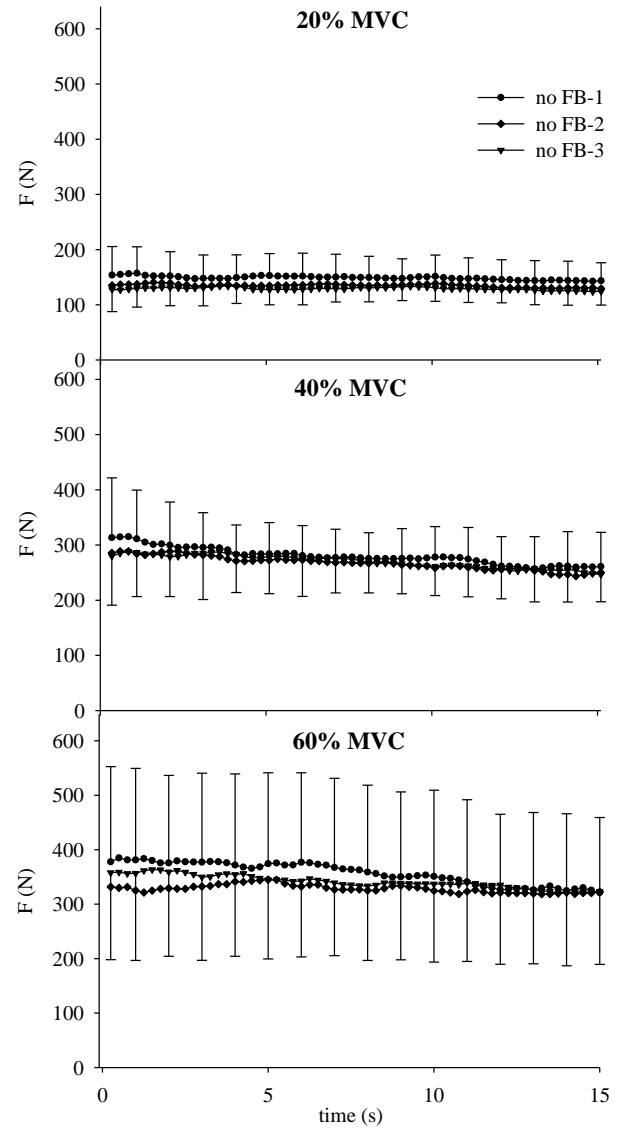
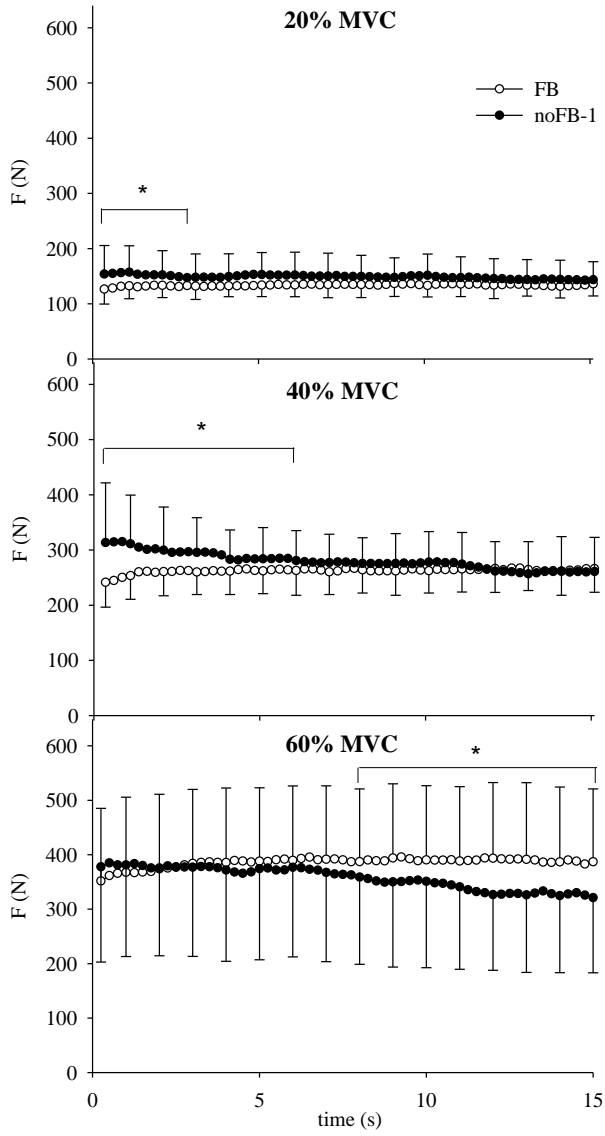


Figure 4

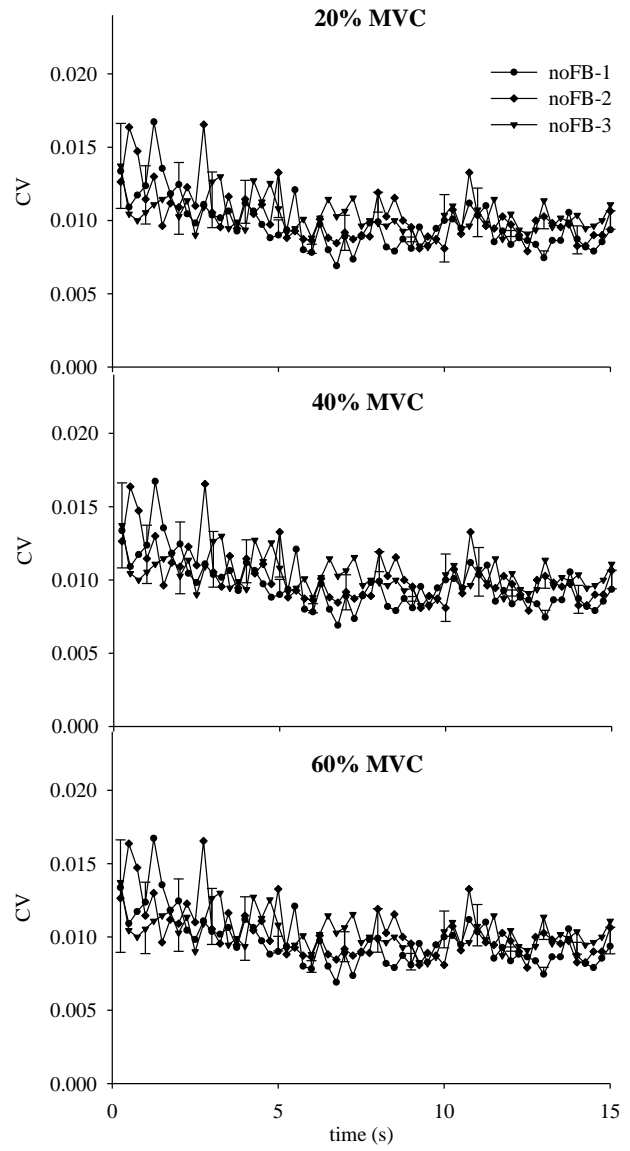
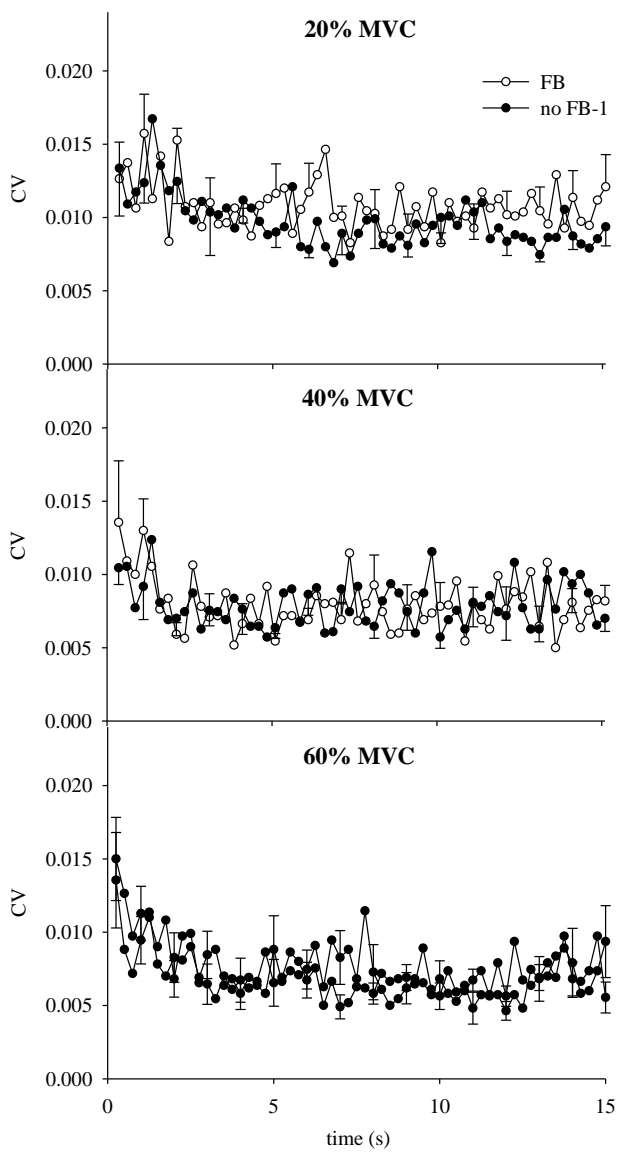


Figure 5

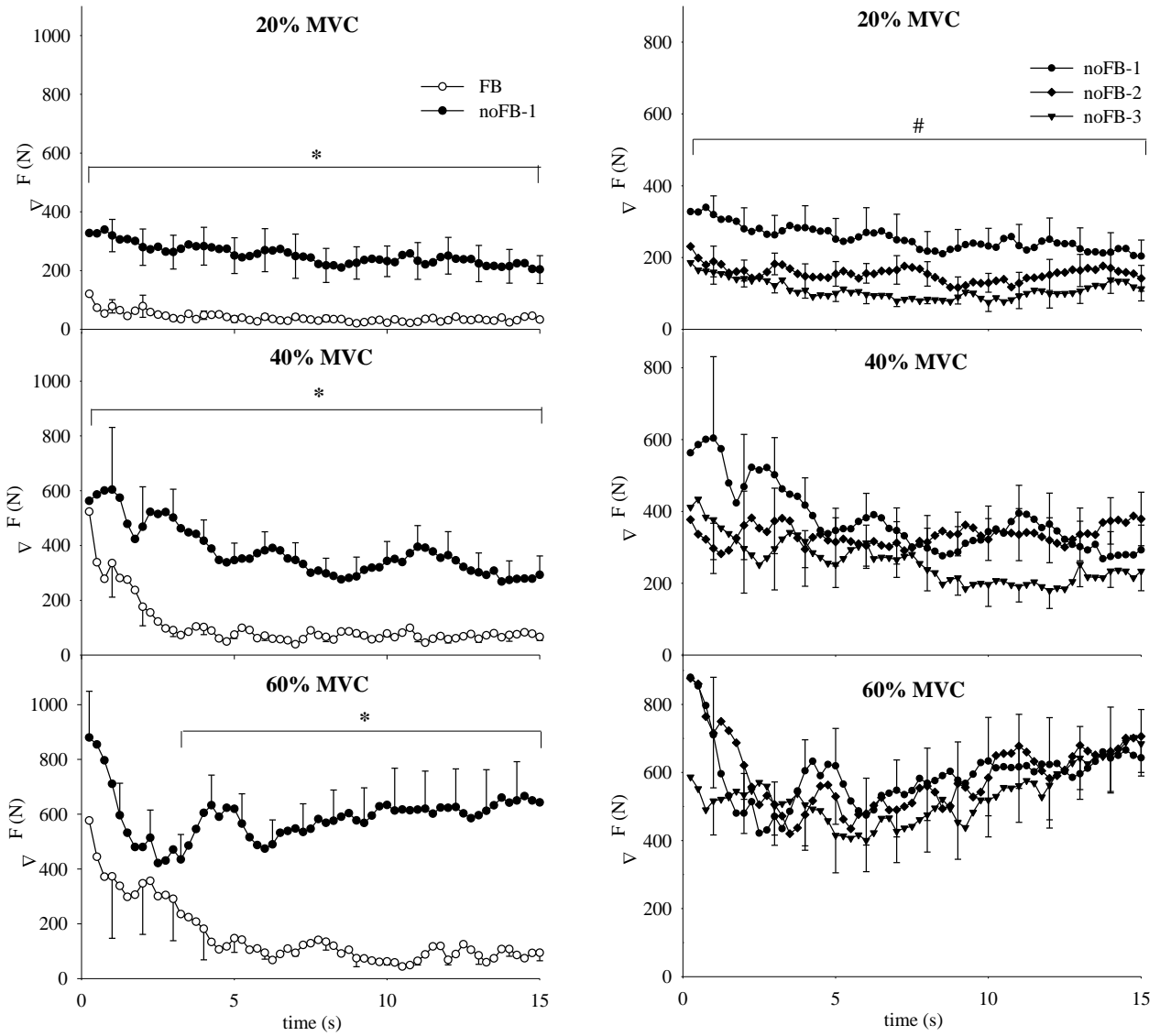


Figure 6

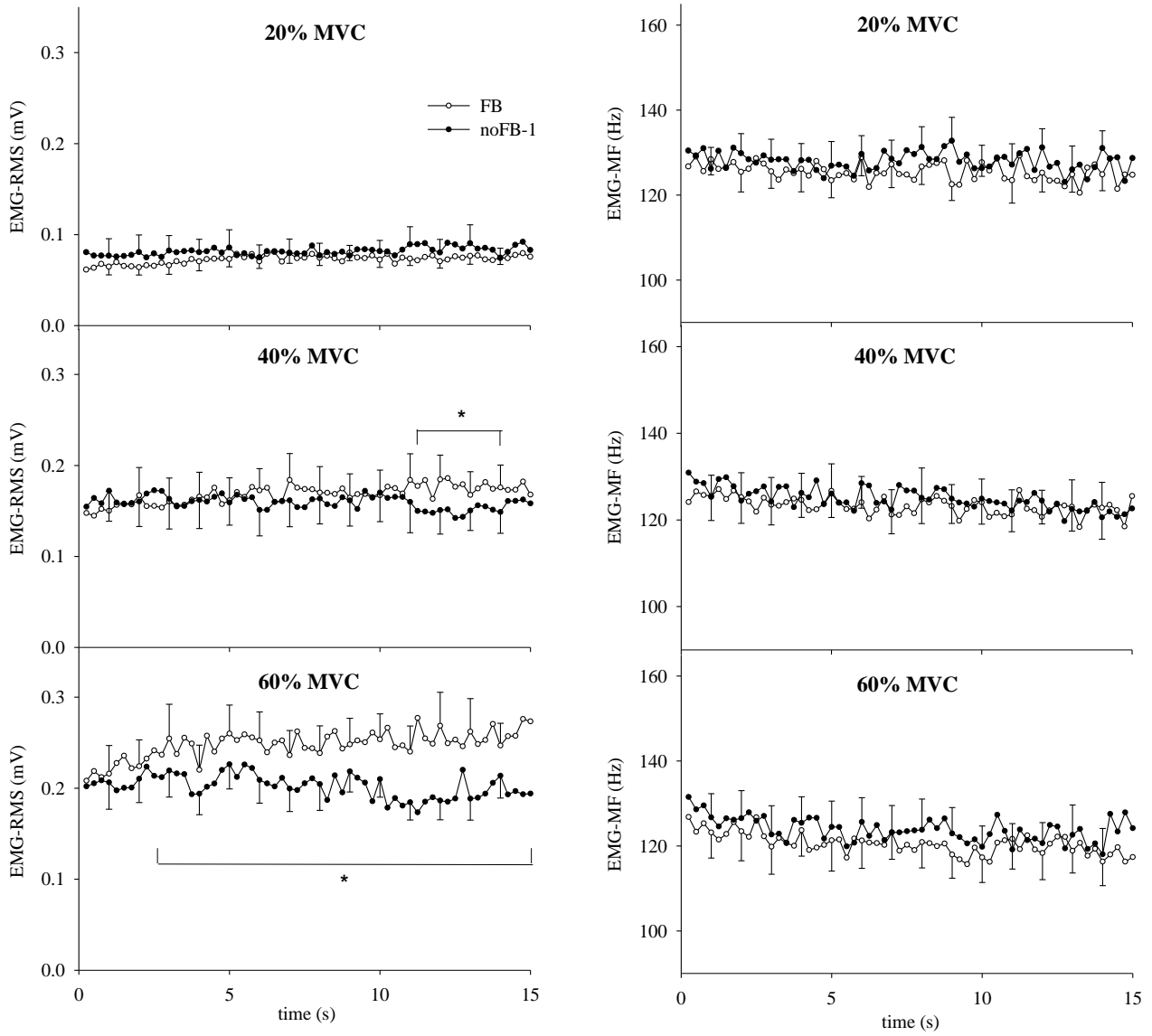


Figure 7

