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ORIGINAL ARTICLE

The type of visual biofeedback influences maximal handgrip strength and activation strategies

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Abstract

Purpose This study investigated the effects of force and electromyographic (EMG) feedbacks on forearm muscle activations and handgrip maximal isometric voluntary contraction (MIVC).

Methods Sixteen males performed a set of MIVC in four different feedback conditions: (1) NO-FB: no feedback is given to the participant; (2) FORCE-FB: participants received a visual feedback of the produced force; (3) AGO-FB: participants received a visual feedback of the EMG activity of two agonist grip muscles; (4) ANTAGO-FB: participants received a visual feedback of the EMG activity of two hand extensors muscles. Each feedback was displayed by monitoring the signal of either force or electrical activity of the corresponding muscles.

Results Compared to NO-FB, FORCE-FB was associated with a higher MIVC force (+11%, $P<0.05$), a higher EMG activity of agonist and antagonist muscles (+8.7% and +9.2%, respectively, $P<0.05$) and a better MIVC/EMG ratio with the agonist muscles ($P<0.05$). AGO-FB was associated with a higher EMG activity of agonist muscles ($P<0.05$) and ANTAGO-FB was associated with a higher EMG activity of antagonist muscles ($P<0.05$). MIVC force was higher in the agonist feedback condition than in the antagonist feedback condition (+5.9%, $P<0.05$).

Conclusion Our results showed that the MIVC force can be influenced by different visuals feedback, such as force or EMG feedbacks. Moreover, these results suggested that the type of feedback employed could modify the EMG-to-force relationships. Finally, EMG biofeedback could represent an interesting tool to optimize motor strategies. But in the purpose of performing the highest strength independently of the strategy, the force feedback should be recommended.

Keywords Force · Electromyography · Maximal voluntary contraction · Motor control

Abbreviations

AGO FB	Agonist muscles feedback condition
ANOVA	Analysis of variance
ANTAGO FB	Antagonist muscles feedback condition
EDS	Extensor digitori superficialis
EDU	Extensor digitori ulnaris
EMG	Electromyography
FDS	Flexor digitorum superficialis
FORCE FB	Force feedback condition
MIVC	Maximal isometric voluntary contractions
NO FB	No feedback condition
PL	Palmaris Longus
RMS	Root mean square
SD	Standard deviation

Introduction

The maximal force is often used in the literature as a global marker of plasticity of the motor system, following an acute or a chronic intervention. However, the force production capacity depends upon a very wide range of factors, among which the use of proprioceptive and exteroceptive sensory feedbacks plays a major role (Nowak et al. 2003; Hu et al. 2011). Visual feedback has been proposed as a strong tool to improve many variables of the force production capacity, such as the rate of force development (Campenella et al. 2000) or force variability (Christou 2005), although its effect seems limited over time when the effort is repeated (Kanemura et al. 1999). This visual feedback is often

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embodied by the monitoring of the mechanical signal provided by a constraint gauge that enables continuous recording of the force at the considered joint. This signal is then displayed on a screen in front of the participant. Such visual feedback has been extensively used in the literature for submaximal isometric tasks, to provide participants a way to control their motor output (Baweja et al. 2009; Athreya et al. 2012). Therefore, the capacity to sustain a sub-maximal isometric task at an accurate level of force has been shown to depend upon various factors related to the visual feedback provided, such as the modality of displaying (Miall et al. 1993; Slifkin et al. 2000; Madeleine et al. 2002), the time delay of the displayed feedback (Sosnoff and Newell 2007) or the spatial and temporal resolution of the signal (Sosnoff and Newell 2006; Vaillancourt et al. 2006). Limonta and colleagues assessed the accuracy to target, without force feedback, sub-maximal forces from 20 to 60% of the maximal force in knee extension (Limonta et al. 2015). They found that force accuracy decreased significantly without visual feedback, the force exerted being over- or underestimated according to the level of force targeted. However, this does not account for the potential difference in maximal force per se. Indeed, the importance of such feedback on maximal force capacity is still rare in the literature. For example, monitoring the force signal has been shown to increase the peak of isometric maximal voluntary force of the plantar flexors by more than 15% in recreationally active participants (Toumi et al. 2016).

The main hypothesis to explain such an increase in maximal force capacity with a visual force feedback is twofold: (1) it provides a supplemental sensory feedback for the regulation of the motor output by the central nervous system and (2) it increases awareness of one's own capacity and therefore increase the motivational aspects of such performance. The second point is emphasized when an additional visual target to reach and overcome is provided to the participant (Toumi et al. 2016). But regarding the second point, there exists another type of feedback that can importantly affect the force production capacity, relying on physiological markers of performance: the electromyographic, or EMG biofeedback. This method involves displaying the myoelectrical activity of targeted muscles recorded through surface electrodes on a screen as a feedback of one's performance. The signal can be displayed as raw or modeled to a more playful visual representation. The EMG represents the summation of motor units' activities detected under the electrodes (Suzuki et al. 2002) whose signal properties reflect the voluntary neural drive (Gandevia 2001). In fact, the magnitude of the EMG signal considered for biofeedback represents a marker of the neural system activity as a whole (Place et al. 2007), not allowing alone to dissociate its different components, such as voluntary neural drive, spinal excitability or neuromuscular junction properties. The EMG biofeedback has been used in rehabilitation, allowing for example to dissociate the activations of several muscles of a same group, e.g. the quadriceps muscles (Draper 1990; Levitt et al. 1995). For more fundamental purposes, EMG feedback was also used to provide single motor unit recording with better accuracy, highlighting the capacity of each individual to use this type of feedback to active his/her muscle (Farina et al. 2004, 2005). Place and colleagues in 2007 showed that participants could sustain an isometric effort of the knee extensor longer with a constant EMG-biofeedback activity than with a constant force biofeedback.

Among several tasks, the handgrip force is one of the gold standards to evaluate functional capacity of one individual. As many tasks, grip force is greatly affected by structural factors, such as the configuration of the joint during the completion of the contraction (Ambike et al. 2014). But more importantly, given the necessity to coordinate the different digits and the numerous muscles in the forearm, the sensitivity of such type of performance to small environmental variations is very high. For example, grip force is modulated when participants perform the task with eyes opened or closed (Ambike et al. 2014). Therefore, the management of handgrip performance is greatly dependent upon the use of visual feedback (Limonta et al. 2015). Regarding EMG components, many small muscles are involved in the performance of handgrip. Besides the fact that antagonists co-activation phenomenon exists at many joints of the lower and upper limbs, extension muscles of the forearm can be especially predictable of the flexion force (Hoozemans and Van Dieën 2005). From a practical point of view, the focus on handgrip performance and its associated effects of EMG biofeedback make particular sense since hand function is one of the main body parts studied for the development of prostheses that can be controlled through EMG processing interfaces (Dosen et al. 2015).

To summarize, although the use of a visual feedback to target an isometric sub-maximal performance is common in the literature, the influence of such a feedback on maximal performance itself remains unclear. More precisely, to date, the influence of the type of feedback on maximal force capacity of the upper limb, i.e. force or EMG biofeedback, is still unknown. Consequently, the aim of the present study was to evaluate the handgrip force capacity of healthy individuals in presence of different visual feedbacks, including EMG biofeedback of agonist and antagonist muscles. It can be hypothesized that the presence of a visual feedback would lead to higher performances, due to the addition of different sensory feedbacks. The EMG biofeedback should also have additional effects on force production capacity, since it helps the participant to directly visualize its motor outputs and find the optimal strategy to increase the force. Regarding antagonist biofeedback, two hypotheses can be raised: (1) considering co-activation would remain the same between the conditions, increasing antagonist activity would result in an even more important increase of agonist force, or (2) antagonist feedback would modulate co-activation phenomenon and lead to similar or decreased agonist force.

Methods

Participants

Sixteen young healthy males gave written informed consent to participate in the present experiment (age: 23.1 ± 3.1 years old; height: 179.4 ± 6.4 cm; body mass: 74.8 ± 9.1 kg). None of them reported neurological or physical disorders. Participants were physically active, reporting an average of 5.2 ± 3.7 h of sport per week in various activities from collective sports to cycling and running. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield 1971), obtaining a mean score of + 73.1 ± 13% (− 100: absolute left-handed; 0: perfectly ambidextrous; + 100: absolute right-handed). The study was performed in accordance with the last version of the Declaration of Helsinki and approved by the Regional Ethics Committee.

Experimental design

The experiment was carried out in a single session, performed between 2.00 and 4.00 PM. All tests were performed on the dominant limb, i.e. the right forearm. Participants sat in a comfortable chair in front of a table to have the upper arm aligned with the trunk (shoulder abduction and elevation angles at 0°) and elbow flexed at 90°. Right forearm was resting on the table to keep relaxed shoulder muscles and elbow muscles, by adjusting the chair's height if necessary. Participants were holding the grip force transducer (ADInstruments, Sydney, Australia) in the right hand placed in neutral position, i.e. forearm lying on the table by the ulnar side and hand resting on the hypothenar eminence. They were asked to place the hand around the transducer so that the four upper digits were in contact with it, surrounded by the thumb. Given that handgrip force is dependent upon grip width (Chaffin et al. 2006), particular care was taken to ensure that participants kept the same digit and hand disposition among the different conditions. A wide screen was placed in front of the participant (distance 1.5 m). An operator was placed on the side and could switch the type of image displayed on the screen by manipulating the software on a second screen that the participant was not able to see (Fig. 1).

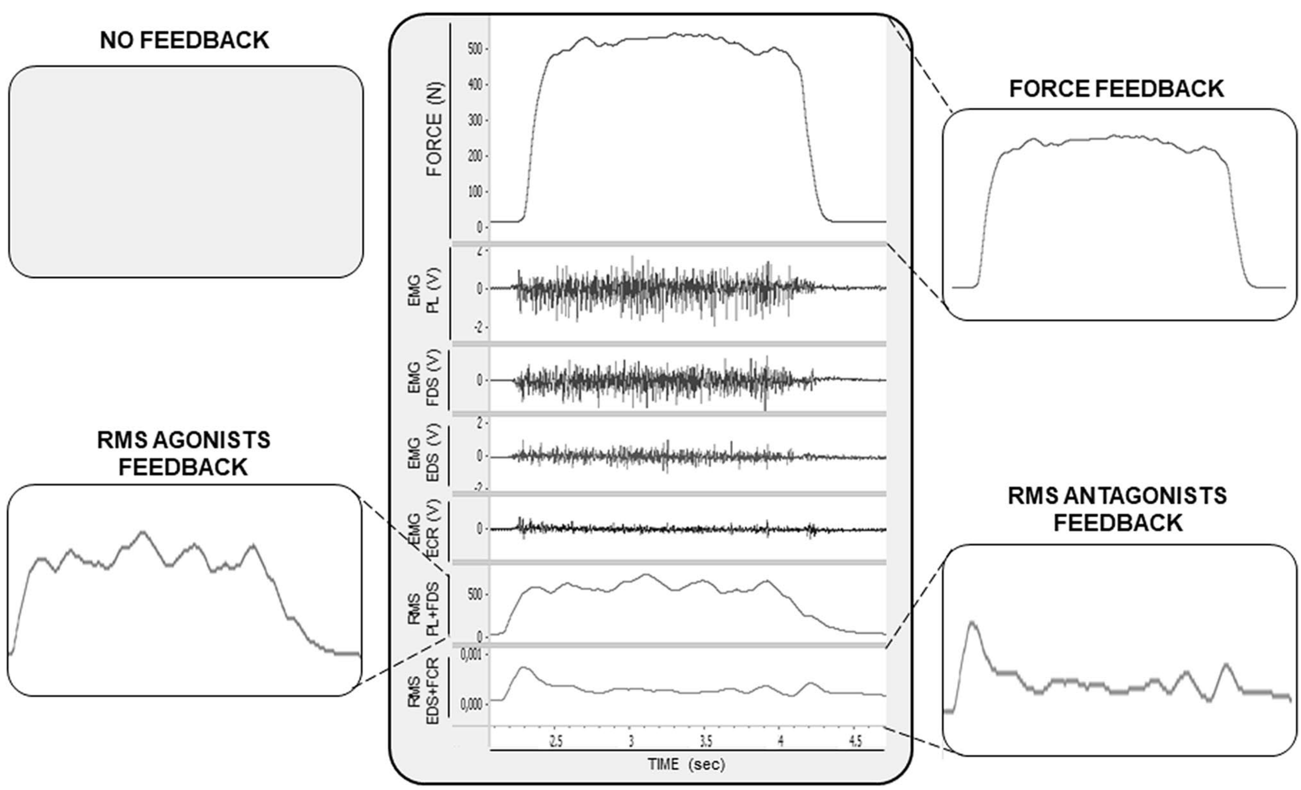


Fig. 1 Study protocol: visualization of the different feedbacks. In the central image is displayed the view of the experimenter, and in the side boxes are displayed the four different feedback conditions

After positioning the electromyography electrodes, participants received the instructions. They were asked to perform a set of handgrip maximal isometric voluntary contractions (MIVC) in various feedback conditions, by focusing on the signal displayed on the screen in front of them. For each trial, participants were asked to clench the fist as hard as possible without flexing the wrist, not taking the elbow off the table nor elevating the shoulder. Four feedback conditions were randomly performed (Fig. 1). These conditions correspond to the type of signal displayed on the screen in front of the participants:

- No feedback (NO FB): a grey screen was displayed.
- Force feedback (FORCE FB): the mechanical signal (in Newton) given by the force transducer was displayed on the screen.
- Agonist EMG feedback (AGO FB): the signal displayed represents the total electromyographic activity of two grip muscles: the palmaris longus (PL) and the flexor digitorum superficialis (FDS).
- Antagonist EMG feedback (ANTAGO FB): the signal displayed represents the total electromyographic activity of two digit and hand extensor muscles: the extensor digitori superficialis (EDS) and the extensor digitori ulnaris (EDU).

Particular care was taken to show these different signals in full screen with the same color and line thickness. For EMG biofeedback (AGO FB and ANTAGO FB), the summation of the root mean square (RMS) of both muscles was calculated over a 0.1 s moving window and displayed on a single channel in the acquisition software (LabChart 8, ADInstruments, Sydney, Australia). For each of the conditions, participants were informed of what type of feedback was displayed on the screen. Two trials were performed per condition. If the variation in force performance exceeds 5%, additional trials were performed. Each MIVC trial duration was approximatively 2–3 s. A minimal amount of 30 s of rest was applied between each trial. The force and other recorded signals were always displayed on the experimenter's monitor. To standardize the measurements, no verbal encouragement was given for each of the trials.

Force recordings

Grip force was recorded by means of a MLT004/ST Grip Force Transducer (ADInstruments, Sydney, Australia). The mechanical signals were digitized on-line (sampling frequency 2 kHz) and simultaneously recorded with electromyography of the targeted muscles. Signals were stored for analysis in Labchart software (LabChart 8, ADInstruments, Sydney, Australia).

Electromyographic activity

EMG activity was recorded from four muscles of the right forearm, two representative of agonists muscles for grip force contraction (PL, FDS) and two considered as representative of the antagonists (EDS, EDU) (Smets et al. 2009). Before electrode placement, the skin was first shaved and dry-cleaned with alcohol to keep low impedance (<5 kΩ). EMG signals were obtained using two silver chloride surface electrodes (8 mm diameter) placed with an inter-electrode center-to-center distance of 2 cm. Electrodes were placed according to the guideline of Perotto (Perotto 2011). Regarding grip agonists, electrodes were positioned over the muscle belly at 1/3 of the distance from the medial epicondyle and the radial styloid processor for PL muscle, and at 2/3 for FDS. Regarding antagonist muscles, electrodes were placed on the dorsal face of the forearm at 1/3 of the distance between the lateral epicondyle and the radial styloid process for the EDS and at 1/3 of the distance between lateral epicondyle and the ulnar distal head for the EDU. EMG signals were amplified with a bandwidth frequency ranging from 0.3 Hz to 2 kHz (gain: 1000) and digitized on-line (sampling frequency: 2 kHz) with Labchart software (LabChart 8, ADInstruments, Sydney, Australia).

Data analysis

For each feedback condition, the maximal value of force among all trials was taken for analysis. The force value (in Newton) taken into account was the mean of 500 ms when the force plateaued at its maximal value. The RMS values of PL, FDS, EDS and EDU muscles' EMG signals were determined with an integration time of 500 ms over the same plateau as the one taken for grip force MIVCs. We also analyzed the differences in the sum of RMS which were displayed during AGO FB and ANTAGO FB conditions, i.e. PL + FDS and EDS + EDU, respectively.

To account for the link between EMG RMS and the force produced, the ratio between RMS of each muscle and the MIVC force obtained in each condition has been calculated.

Statistical analysis

All data are presented as the mean ± standard deviation (SD). The normality and the homogeneity of the data were verified by the Shapiro–Wilk test and the Levene test, respectively. For each dependent variable (RMS, force), a one-way repeated measures analysis of variance (ANOVA) was performed with the factor "feedback" (No FB, FORCE FB, AGO FB, ANTAGO FB). When a main effect was found, a Tukey HSD post hoc test was performed. Statistical analysis was performed using STATISTICA (8.0 version, Statsoft, Tulsa, Okhlaoma, USA). The level of significance was set at $P<0.05$.

Results

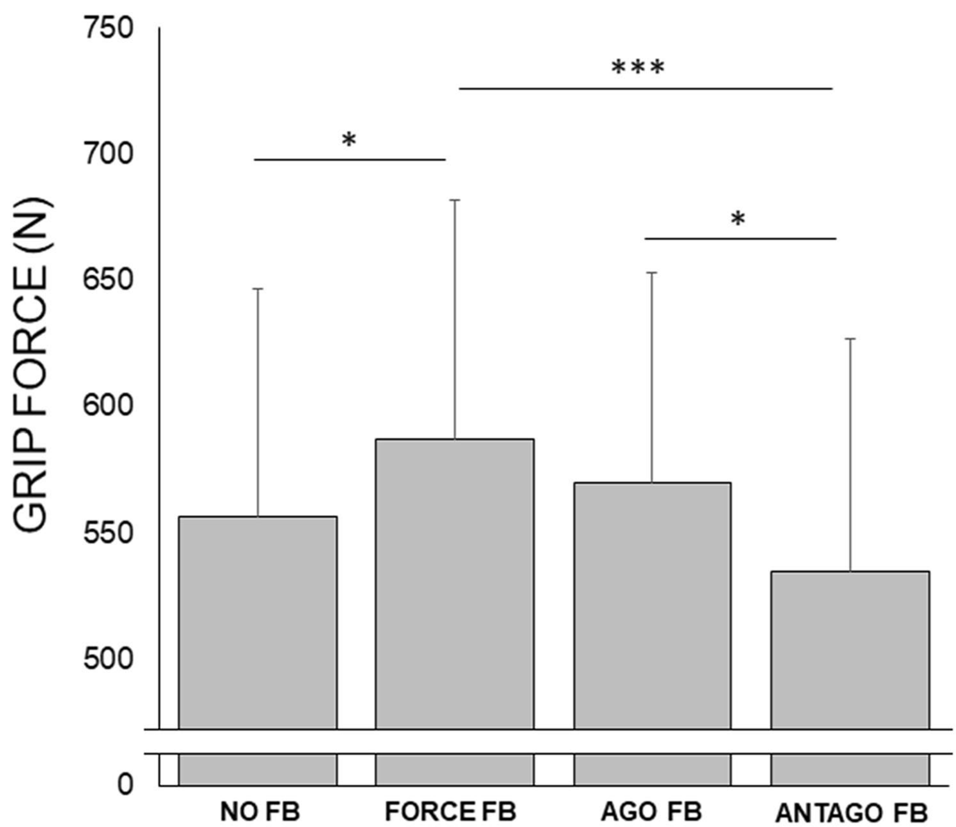
A significant effect of the factor "feedback" was found on forces ($F_{3,45}=4.745$; $P=0.006$). The grip force obtained during FORCE FB was significantly higher than NO FB, by 11.23 ± 4.14% ($P=0.036$) and then ANTAGO FB, by 7.5 ± 2.6% ($P<0.001$). The maximal force recorded during AGO FB was significantly higher than that recorded during ANTAGO FB, by 5.9 ± 2.0% ($P=0.019$). No other significant difference has been found in maximal grip forces (Fig. 2).

Regarding the associated EMG activities (RMS), a main effect of the factor "feedback" has been found for PL ($F_{3,45}=4.5312$; $P=0.007$), FDS ($F_{3,45}=3.665$; $P=0.019$), EDU ($F_{3,45}=3.411$; $P=0.025$), and EDS ($F_{3,45}=3.339$; $P=0.027$). However, post hoc analysis indicated different behavior among muscles (Fig. 3). In PL, RMS was greater in FORCE FB than in NO FB ($P<0.001$), AGO FB ($P=0.041$) and ANTAGO FB ($P=0.013$). In FDS, RMS was the lowest in NO FB, statistically lower than FORCE FB ($P=0.004$), AGO FB ($P=0.011$) and ANTAGO FB ($P=0.031$). In EDS, RMS was greater in FORCE FB than in NO FB ($P=0.043$). RMS was greater in ANTAGO FB than in AGO FB ($P=0.039$) and NO FB ($P=0.006$). EDU RMS was greater in ANTAGO FB than in NO FB ($P=0.003$) and AGO FB ($P=0.044$).

The sum of the EMG activity of the two agonist muscles (PL + FDS) and the two antagonist muscles (EDS + EDU) is presented in Fig. 4. These values were those displayed on the monitor for EMG biofeedback conditions. The results revealed that FORCE FB increased EMG activity of agonist ($P<0.001$) and antagonist muscles ($P=0.026$) compared to NO FB. Still compared to NO FB, AGO FB increased EMG activity of agonist muscles ($P=0.036$) and ANTAGO FB increased EMG activation of antagonist muscles ($P<0.001$).

The relationship between RMS and force, evaluated through the MIVC/RMS ratio, displayed different behavior among muscles (Fig. 5). The ratio between force and EMG activity of agonist muscles was higher in FORCE FB than in NO FB ($P<0.05$). Also, compared to AGO FB, the ratio between force and EMG activity of antagonist muscles was higher in ANTAGO FB ($P<0.05$).

Fig. 2 Grip force in the four feedback (FB) conditions. No FB: participants in front of the neutral gray screen; Force FB: force signal displayed; AGO FB: summed RMS of palmaris longus and flexor digitorum superficialis EMG activities; ANTAGO FB: summed RMS of extensor digitori superficialis and extensor digitori ulnaris. *,***Difference between conditions at $P<0.05$ and $P<0.001$, respectively



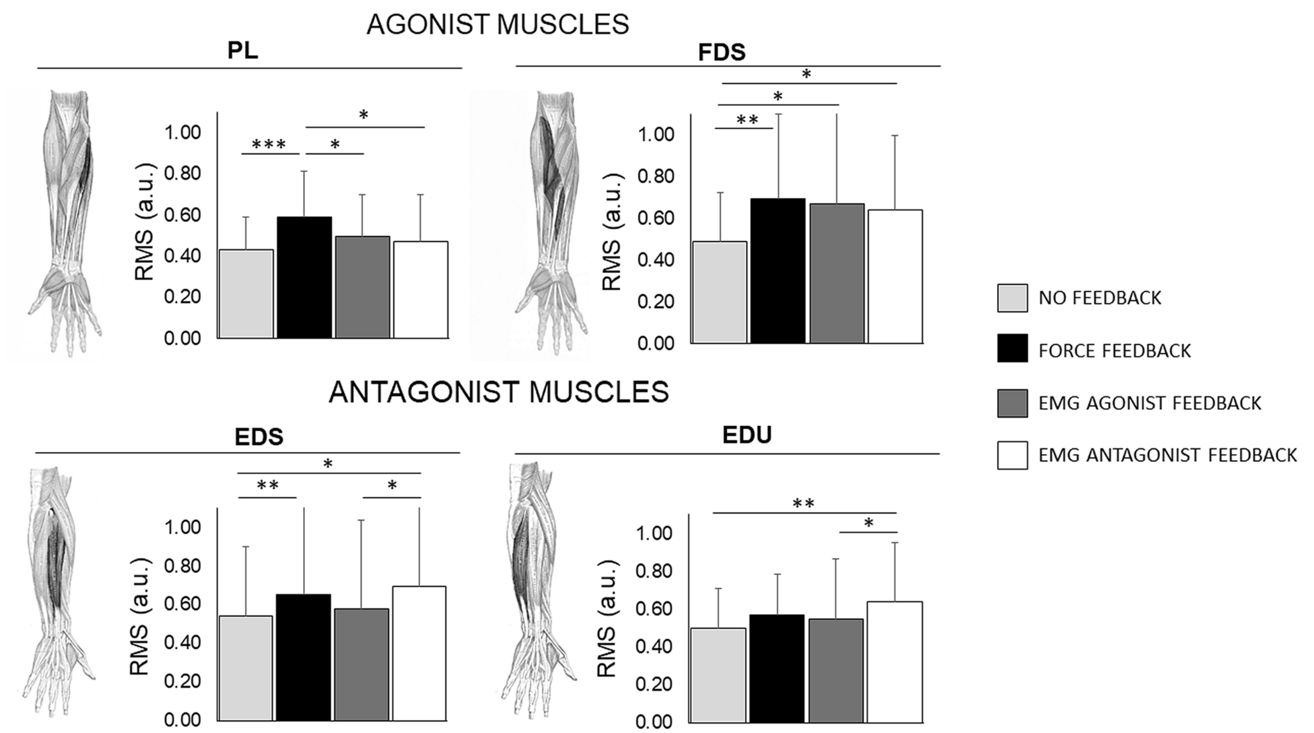


Fig. 3 EMG activities during the four feedback conditions. *a.u.* arbitrary units, *RMS* root mean square, *PL* palmaris longus, *FDS* flexor digitorum superficialis, *EDS* extensor digitori superficialis, *EDU* extensor digitori ulnaris. *Difference between conditions at $P < 0.05$

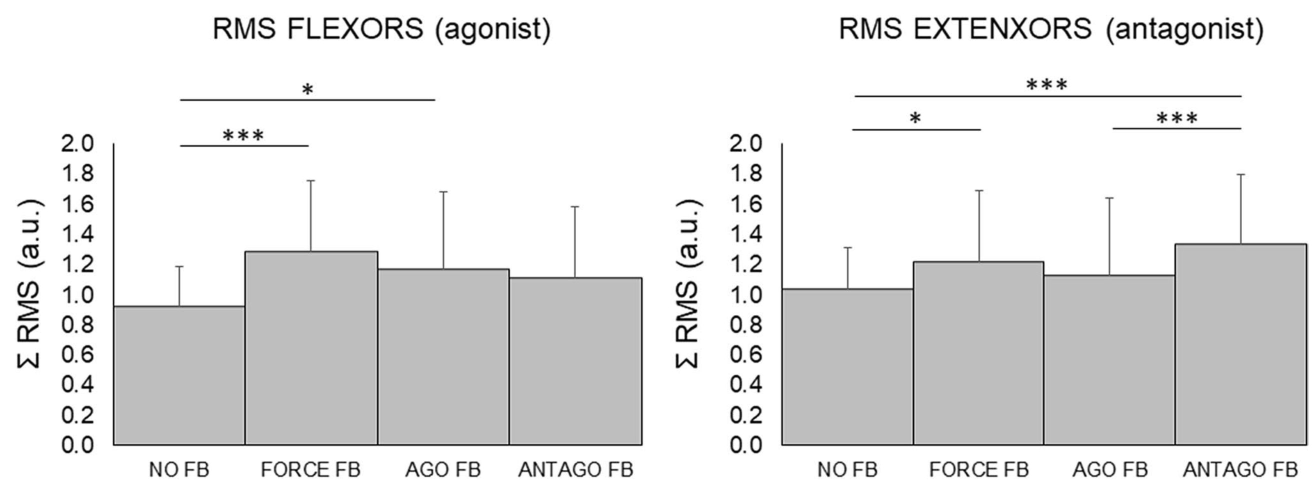


Fig. 4 Sum of the RMS values of the two agonist (PL and FDS) and the two antagonist (EDS and EDU) muscles (signal values displayed for EMG feedback conditions). *RMS* root mean square, *PL* palmaris longus, *FDS* flexor digitorum superficialis, *EDS* extensor digitori superficialis, *EDU* extensor digitori ulnaris. *,***Difference between conditions at $P < 0.05$ and $P < 0.001$, respectively

Discussion

The purpose of the present study was to assess the effect of different feedbacks, from force to EMG signals, on the handgrip force capacity. The main results revealed that feedback of force increased the MIVC force in handgrip as well as the myoelectrical activity of agonist (PL and FDS) and antagonist (EDS) muscles, as compared with NO FB condition. On the other hand, contrary to our hypothesis, the biofeedback coming from the agonist and antagonist muscles did not improve the MIVC force in handgrip compared to the NO FB condition. However, MIVC force was higher in the agonist feedback condition than in the

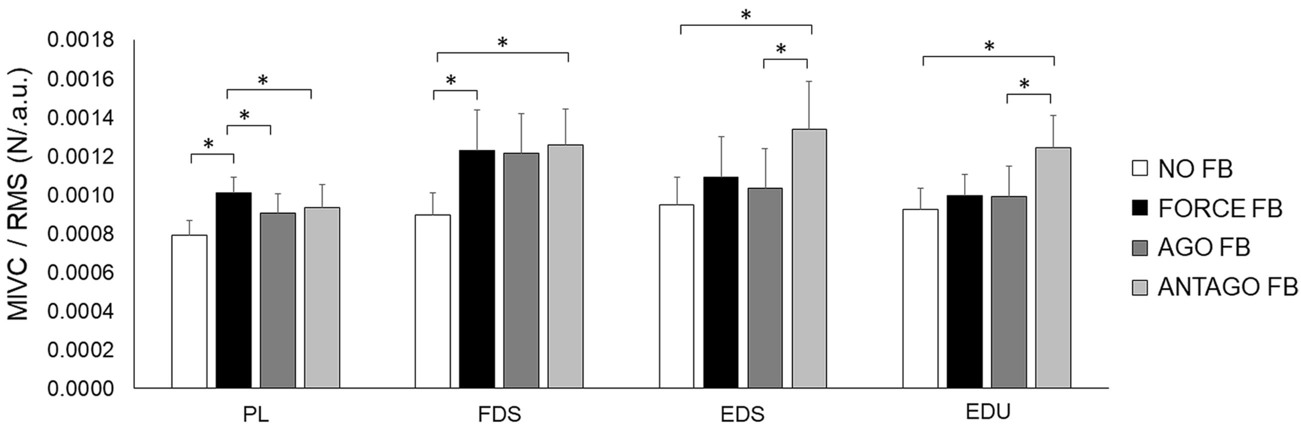


Fig. 5 Relationships between force and EMG. MIVC/RMS force ratios for each muscle and condition. *PL* palmaris longus, *FDS* flexor digitorum superficialis, *EDS* extensor digitori superficialis, *EDU* extensor digitori ulnaris. *Difference between conditions at $P < 0.05$

antagonist condition, which revealed an influence of the type of biofeedback on maximal force capacity. Finally, the results showed that the relationship between force and EMG was not linear but influenced by external factors, such as the type of feedback provided.

First, the results of the present study revealed that a visual force feedback improves the maximal isometric handgrip force capacity. Indeed, the developed force was higher in the FORCE FB condition than in the NO FB condition (Fig. 2). In general, the importance of a feedback to control the force output has often been put in evidence (Lauber et al. 2016). However, if this has been widely studied regarding force precision and gradation, for performances as targeting an accurate sub-maximal force, less is known about the maximal force capacity. Regarding this latter, the 11% increase observed in our study is close to the 8% increase previously observed during a similar grip strength exercise (Berger 1967). Based on previous literature, this effect seems to be muscle specific, with an increase in MIVC force of 3% for elbow flexor (Pierson and Rasch 1964), 9% for knee extensor (Luc et al. 2016), 16% for the ankle plantar flexors (Toumi et al. 2016) and with no effect found for dorsi-flexors (Toumi et al. 2016). It was hypothesized that a visual feedback increases awareness of one's own capacity and, therefore, increases the motivational aspects of such performance (Berger 1967; Toumi et al. 2016). Moreover, a visual feedback can provide a supplemental sensory feedback for the regulation of the motor output by the central nervous system (Taylor 2009). These mechanisms seem to be confirmed by the EMG results of our study which displayed a higher EMG activity of the agonist and antagonist muscles in the FORCE FB condition than in the NO FB condition (Fig. 3). Similarly, a greater EMG in presence of force visual feedback has also been observed in upper limb (Baweja et al. 2009). Thus, providing visual feedback would increase motivation on the one hand and provide additional sensory feedback on the other, resulting in increased recruitment of motor units from the central nervous system as measured by the EMG activity. The increase of EMG activity can thus, explain the improvement of the MIVC force in handgrip, the agonist muscles being effectors of the force production and the co-activation of the antagonist muscles may contribute to the flexion force (Hoozemans and Van Dieën 2005). However, in the present study, the increase in antagonist activity should be more an indirect effect of the increase in agonist motor command to maintain a secure level of co-activation in the joint. When the antagonist EMG was even more increased, i.e. in the ANTAGO FB, the force output was shown to be less affected by the presence of a feedback. Finally, as shown in Fig. 5, the ratio between the EMG activity of the agonist muscles and the level of force was higher in FORCE FB condition than in NO FB condition. This result revealed a better efficiency in the relationship between EMG activity and the force produced. Thus, this better efficiency can also be a reason of the increase in the production of force in the FORCE FB condition.

Second, our study revealed an effect of EMG feedback on the EMG activation of the flexor and extensor muscles of the forearm. The results showed that in AGO FB condition, the EMG activity of the flexor muscles (FDS + PL) increases compared to NO FB condition (Fig. 4). In addition, in the ANTAGO FB condition, the EMG activity of the extensor muscles (EDS + EDU) increases, without effect on the flexor muscles (Fig. 4). This highlighted that EMG biofeedback does not lead to a global arousal of muscle activity but rather depends on the muscle targeted. Similar results have been observed by Ekblom and Eriksson (2012) with maximal voluntary knee extension exercises. Indeed, the authors observed that EMG feedback from the vastus medialis increases the EMG activity of this muscle itself but does not enhance the activation of the vastus lateralis. However, unlike our study, the EMG feedback from the vastus medialis was accompanied by an increase in the activation of the antagonist muscles (hamstrings) and in the production of force (Ekblom and Eriksson 2012). During an EMG-biofeedback sustained isometric contraction, it was shown that the activation pattern of the different synergists may vary if not all muscles are included in the biofeedback (Place et al. 2006). Therefore, our results showed that the increase in the EMG signal with an EMG biofeedback is likely due to a voluntary increase in the excitation of the motor neurons of the targeted muscles, rather than to a global arousal of all factors included in handgrip force. However, while the increase in central activation seems directed toward specific muscles (PL and FDS), the lack of increased force in the AGO FB condition as compared to NO FB appears surprising. As a counterpoint, Ekblom and Eriksson (2012) had shown an increase in the knee extensor maximal strength from an EMG biofeedback of the vastus medialis only, but not of other quadriceps muscles. Moreover, it should be noticed that previous literature showing an effect of AGO-FB is performed on lower limbs, for which muscles are fewer in numbers, of greater volume and with simpler actions (often monoarticular with one degree of freedom). As a consequence, it is possible that in legs EMG would cover a higher proportion of specific agonist muscle mass than in forearm muscle, in which there are many small muscles that act at both hand and elbow in multiple actions (grip, pronation/supination, wrist/digit/elbow flexion). This makes rather complex the action of forearm muscles, and shows here that increasing the activity of selected forearm muscles would not necessarily lead to an increased force in the specific handgrip action. Therefore, the choice of which muscle to use for EMG biofeedback is of major importance in performance. The importance in the choice of muscles is also confirmed by the comparison between AGO FB and ANTAGO FB conditions. Indeed, although the EMG activation of the flexors was similar between the two conditions, the activation of the extensors was higher in ANTAGO FB condition than in AGO FB condition (Fig. 4). This latter result was accompanied by a lower level of force in ANTAGO FB condition than in AGO FB condition (Fig. 1). Consequently, it appears that an EMG biofeedback can modify the motor strategies of the participants, thus influencing the EMG activation of the targeted muscles and the developed strength levels. More particularly, using antagonist biofeedback can lead to an upward modulation of co-activation level.

Interestingly, the present results also raised the fact that the relationship between force and EMG was not always linear, especially if the condition of force production varies. In other words, a higher EMG is not always related to a higher force in same proportion. In similar conditions, the shape of the force-to-EMG relationship was for a long time considered as linear (Moritani and DeVries 1978; Bigland-Ritchie 1981) or sometimes curvilinear (Komi et al. 1972). This could have resulted in misinterpretation of EMG signal in the past, using its amplitude to infer the level of force produced. However, while the nature of this relationship was shown to be influenced by structural and physiological factors, such as muscle's typology (Woods and Bigland Ritchie 1983), the present results also showed that it can widely be influenced by external factors, such as the type of feedback provided. Here, despite similar position and physical condition between conditions, it was shown that the variation of force and EMG activity according to the type of feedback did not follow a linear regression. If so, the ratios MIVC/RMS (Fig. 5) would have been equal among the four conditions for each muscle, which was not the case.

Practical implications

From a methodological point of view, the peak of isometric force relative to MIVC is one of the most common markers of acute or chronic neuromuscular plasticity. The factors affecting such performance are numerous and commonly controlled through standardization procedures, mostly by fixing the posture of the individual and controlling joint angle. However, the importance of environmental factors for the performance in terms of maximal force is also acknowledged (Gandevia 2001). For example, to increase one's motivation to perform his/her maximal performance, it was shown that verbal encouragement can increase the maximal motor response of the elbow flexors (Johansson et al. 1983; McNair et al. 1996). The present study highlights the importance of also controlling the type of feedback displayed to participants, particularly if the monitor displaying the force and/or EMG signal is in their field of view.

As a more practical approach, the present study shows that displaying a feedback in real time during performance can be a powerful tool to modulate and improve the motor function, even if this feedback is a simple line on a screen. Interestingly, it should be emphasized that participants do not need any specific background in neurophysiology to use biofeedback. The use of EMG signals processing has been widely proposed as an interesting tool to control neural prostheses, particularly to restore the hand function (Dosen et al. 2015). Particularly, the lack of sensory feedback during myoelectrical prosthetic manipulation is often highlighted as one of the main limitations. To that matter, the display of visual feedback of EMG signal itself has been shown to provide a better motor controls of the prosthetics hand (Dosen et al. 2015).

EMG biofeedback can also be used for the development of exergame training (Garcia-Hernandez et al. 2018). Exergame are video games developed for health, with the use of technology usually devoted to medical care or research. Handgrip performance and results of the present protocol can easily be transferred to such games, or even to more complex games using virtual reality. Indeed, in most of virtual reality set-up, the participant usually maintains a handle in both hands to play.

Handgrip strength is also indicative of overall physical health and mobility in the elderly (Wearing et al. 2018). A reduction in strength below a certain threshold severely increases the risk of mobility limitations and is predictive for adverse outcomes, such as dependence in daily activities and mortality. An EMG biofeedback training program could be useful in the elderly to decrease the risks of sarcopenia.

Conclusion

Providing a feedback from force signals increased the MIVC force of the forearm and also influenced the motor strategies, by increasing the EMG activation of the agonist and antagonist muscles as well as by modifying the force / EMG ratio. Moreover, an EMG biofeedback from the agonist and antagonist muscles increased the EMG activation of the muscles targeted by such feedback. In future research, it would be interesting to measure the chronic effect of these different types of feedback, both on performance and on the different neuromotor strategies adopted. Finally, these results support previous conclusions (Luc et al. 2016) which indicated that the use of a force feedback provides a more accurate assessment of MIVC force and muscle voluntary activation.

Author contributions SG designed the study, conducted experimentations and analysed the data. SG and PMM wrote the manuscript. PG, AG and GR revised the manuscript. All authors read and approved the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest. The authors declare that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Ethical approval This study was conducted in accordance with the recommendations of the 1964 Declaration of Helsinki and its later amendments. The research plan was examined and approved by the local ethical committee.

Consent to participate Prior to testing, all participants gave a voluntary written informed consent which indicated the purpose, the benefits and the risks of the investigation and the possibility stopping their participation at any time.

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