J Musculoskelet Neuronal Interact 2022; 22(4):465-473

Journal of Musculoskeletal and Neuronal Interactions JMNI

Original Article

Effects of NMES-elicited versus voluntary low-level conditioning contractions on explosive knee extensions

Federica Gonnelli[1,2], **Enrico Rejc**[3,4], **Mirco Floreani**[1,2], **Stefano Lazzer**[1,2]

[1]Department of Medicine, University of Udine, Udine, Italy;
[2]School of Sport Sciences, University of Udine, Udine, Italy;
[3]Kentucky Spinal Cord Injury Research Center, University of Louisville, Louisville, Kentucky, USA;
[4]Department of Neurosurgery, University of Louisville, Louisville, Kentucky, USA

Abstract

Objectives: Electrically-induced or voluntary conditioning-contractions (CC) can be used to affect contractile properties of a subsequent explosive contraction (EC). Here, we aimed at comparing the effect of neuromuscular-electrical-stimulation (NMES) vs voluntary CC performed prior to explosive contractions of the knee extensors. **Methods**: A 10 sec NMES CC (100Hz, 1000μs, 10% MVC), or a voluntary contraction (VOL CC) mimicking the NMES CC, preceded an isometric EC of the knee extensors. Explosive contraction was performed with the goal to reach the target (70% MVC) as quickly as possible. **Results**: All the parameters related with the explosive contractions' muscle-output were similar between protocols (difference ranging from 0.23%, Mean Torque; to 5.8%, Time to Target), except for the Time to Peak Torque, which was lower when preceded by NMES (11.1%, p=0.019). Interestingly, the RTD 0–50 ms_EC was 37.3% higher after the NMES compared with the VOL CC protocol. **Conclusion**: Explosive contraction was potentiated by an NMES CC as compared with a voluntary CC. This may be due to a reduction in descending drive following VOL CC, which has been shown to occur even with low-level voluntary efforts. These findings could be used to improve rehabilitation or training protocols that include conditioning contractions.

Keywords: Afferent pathways, Electrical Stimulation, Explosive contraction, Rate of Torque development

Introduction

The neuromuscular system can be conditioned by its activation history. For example, active warm-up or high intensity conditioning contractions can improve short-term performance by influencing neural properties such as the transmission rate of nerve impulses, muscular properties such as force-velocity relationship or muscle stiffness, and by enhancing bioenergetics mechanisms[1,2].

Also, post-activation potentiation resulting in acute enhancement of contractile properties (i.e. peak torque and rate of torque development) can be promoted by brief, high-intensity conditioning muscle contractions (CC)[2]. As well, the type of muscle contraction (isometric or dynamic) does not seem to influence potentiation characteristics[2]. Potentiation can be achieved by maximal and submaximal voluntary contractions as well as electrically-evoked muscle contractions[3,4]. When potentiation is achieved voluntarily, the conditioning contraction muscle output usually ranges between 100% and 75% Maximal Voluntary Contraction (MVC), with a duration ranging between 5 and 10 seconds[5-7]. Mechanisms that are involved in potentiation effects are linked to calcium release. In fact, after a conditioning contraction, sensitivity to Ca^{+2} is increased because of the phosphorylation of myosin regulatory light chains by the myosin light chain kinase[8,9].

However, neuromuscular system activations preceding a given effort may also result in fatigue and impaired muscle mechanical output. This phenomenon can occur even during submaximal muscle contractions, during which both central and peripheral fatigue can impair muscle output[10]. For example, during a sustained low level muscle contraction

---

The authors have no conflict of interest.

Corresponding author: Dr Federica Gonnelli, Department of Medicine, University of Udine, P.le M. Kolbe 4, 33100 Udine, Italy
E-mail: gonnelli.federica@spes.uniud.it

Edited by: G. Lyritis
Accepted 7 July 2022

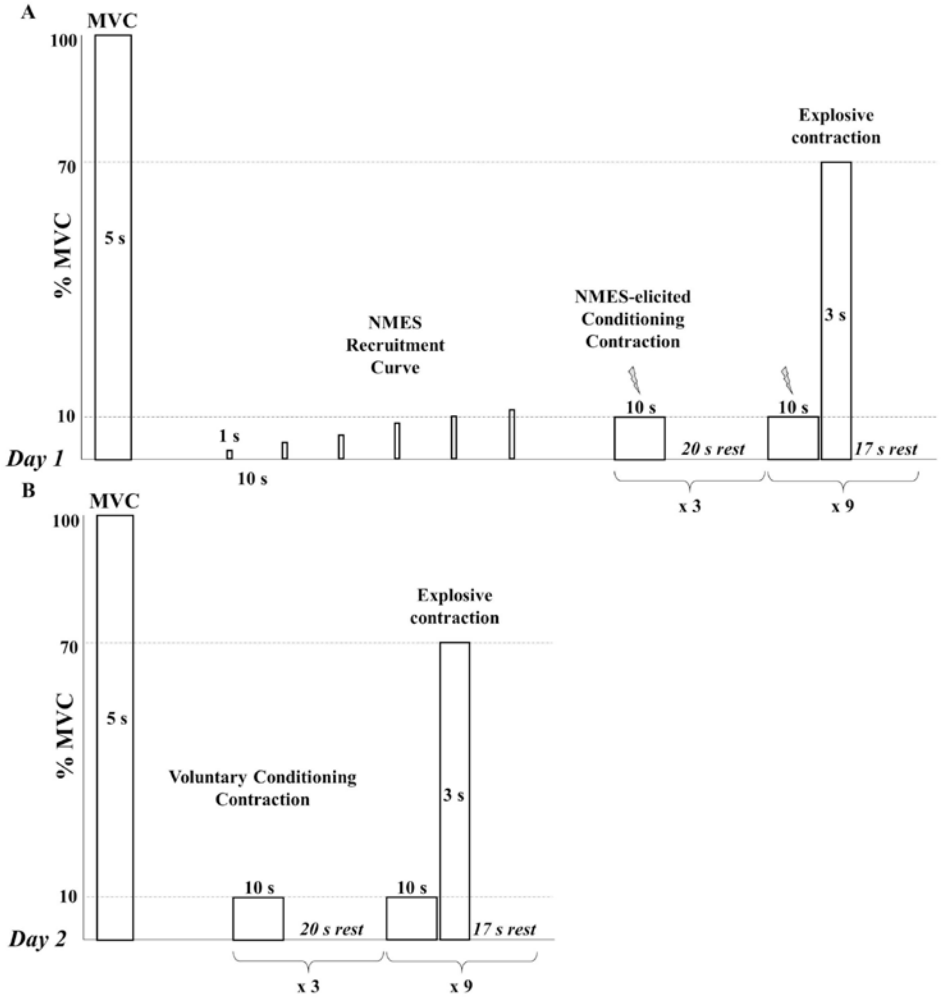

Figure 1. Schematic representation of the experimental protocol (A-B). Maximal Voluntary Contraction (MVC), Neuromuscular Electrical stimulation (NMES) recruitment curve and the NMES Conditioning Contractions protocol were performed on Day 1 (A). MVC and the Voluntary Conditioning Contractions protocol were performed on Day 2 (B).

at 5-30% MVC, when active muscle fibers are fatigued, the subject needs to increase their voluntary effort and engage more motor units and/or increase their firing rate[10]. Thus, neuromuscular fatigue initially determines a change in motor units recruitment without a clear decrement in task performance[10]. On the other hand, when a voluntary maximal effort (i.e. MVC) is maintained or repeatedly generated, the motor unit discharge frequency declines rapidly (~30sec)[11]. Therefore, a possible contributor for central fatigue is a decreased descending drive from cortical structure[12,13].

As mentioned previously, electrical stimulation is an alternative approach to voluntary contractions for achieving post-activation potentiation effects. Neuromuscular electrical stimulation (NMES) might have an even higher effect on potentiation as compared to a voluntary low-level muscle contraction. In fact, during NMES-elicited muscle contraction, type II muscle fibers contribute to a greater extent than type I muscle fibers to force generation[14]. Larger Motor Units (MUs) are primarily recruited via efferent pathways during the electrical stimulus and have high force generation capacity as compared to a voluntary contraction at the same low level muscle output[15,16]. Therefore, NMES has been implemented to generate conditioning contractions at lower muscle force output. For example, findings from Requena et al.[17] show that isometric peak twitch torque of knee extensors are potentiated (+117% compared to rest) after a 7 sec electrically evoked contraction at 25% MVC as compared to a voluntary contraction at the same muscle torque. A possible upside of using NMES for conditioning contractions preceding voluntary explosive efforts is that supraspinal voluntary neural drive to the muscle is not involved, and this may have a positive impact on how supraspinal fatigue would affect the subsequent explosive efforts[18]. Another property of NMES applied with long pulse width, high frequency, low amplitude and long duration (long-low NMES) is that it may also lead to spinal circuitry and motor neuron activation via afferent pathways, contributing to a more physiological recruitment order of motor units[19,20].

In this study, we aimed at assessing the effects of voluntary or long-low NMES-elicited conditioning contractions on the subsequent voluntary, isometric explosive muscle contractions performed to simulate an exercise session. We hypothesized that long-low NMES-elicited conditioning contractions would promote better contractile properties of the voluntary explosive efforts as compared to voluntary conditioning contractions.

Materials and Methods

Subjects

A total of 20 subjects (15 males and 5 females) recruited at the School of Sport Sciences (University of Udine, Italy) participated in this study. Mean age was 26±7 (years), stature was 1.79±0.08 (m) and body mass was 75.3±13.8 (kg), with BMI equal to 23.5±3.0 ($kg \cdot m^{-2}$). Subjects were healthy, moderately active and had no history of orthopedic and neurological injuries. The experimental protocol was conducted in accordance with the declaration of Helsinki, and was approved by the Institutional Review Boards of University of Udine (Italy) (9/IRB DAME_17). Before the study began, the purpose and objectives of the study were carefully explained to each subject and written informed consent was obtained.

Experimental procedures

All participants visited the laboratory twice, and each visit was separated by at least 48 h. Subjects were asked to refrain from any strenuous activity 24 h before each testing day. Each experimental session lasted between 1 and 1.5 h (Figure 1).

During the first experimental session, anthropometric measurements preceded the assessment of MVC of knee extensors. After a 10-minute break, research subjects underwent the NMES recruitment curve to assess the relationship between NMES amplitude and torque output of knee extensors. After additional 10 minutes of rest, the experimental protocol consisting of NMES-elicited conditioning contractions interleaved by voluntary explosive knee extensions (NMES-CC protocol) was performed. During the second experimental session the voluntary conditioning contractions protocol (VOL CC protocol) was performed. First, the MVC of knee extensors was re-tested to assess the neuromuscular status and compared it with the first experimental session. After 10 minutes of rest, the experimental protocol including voluntary conditioning contractions interleaved by voluntary explosive knee extensions was performed. The VOL CC protocol was always performed on the second experimental session in order to optimize the matching of the torque output generated by the NMES-elicited conditioning contractions.

Anthropometric measurements

Body mass (BM) was measured to the nearest 0.1 kg with a manual weighing scale (Seca 709, Hamburg, Germany) with the subject dressed only in light underwear and no shoes. Stature was measured to the nearest 0.5 cm on a standardized wall-mounted height board. Body mass index (BMI) was calculated as BM (kg) · $stature^{-2}$ (m).

Maximal voluntary contraction of knee extensors

Participants performed MVCs of the right knee extensors while sitting on the isometric dynamometer previously described by Rejc and colleagues[21]. Hips and knees were flexed at 90° and a crossover shoulder strap and a strap around the ankle (5 cm proximal to the malleoli) were set in order to minimize movements of the trunk and leg.

During the initial warm up each participant was instructed to generate between 20 and 30 4-second contractions, at a self-selected and increasing intensity. After a 3-minute rest period, participants were asked to perform a maximal isometric knee extension of approximately 6 seconds. Three MVC attempts were performed, separated by a 5-minutes rest in between attempts, and the contraction that resulted in the highest peak force was considered for further analysis. All data were collected as a force output and then transformed in torque data during off-line analysis. To calculate the torque value in each subject, force values were multiplied by the force lever arm which was the distance between the center of the knee join and the 5 cm proximal to the superior malleoli of the ankle where the center of the force cell (AM C3, Laumas Elettronica, Italy; Sensitivity: 2.2mv/V ± 10%) was placed. Torque data were recorded by custom LabVIEW software (National Instrument Inc., Austin, TX) and sampled at 1 kHz. LabChart 8 (ADInstruments) was used to low-pass filter at 10 Hz all torque data and for the subsequent analysis.

To evaluate muscle activation, electromyography (EMG) activity was recorded from the vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF). First, the skin was shaved, rubbed with abrasive paste, and cleaned with a paper towel. Then, pre-gelled surface EMG electrodes (type N-00-S/25, Ambu A/S, Denmark) were placed, with an interelectrode distance of 20mm, at the midpoint between the anterior superior iliac spine and the superior portion of the patella for the RF muscle, at the two-third of the distance between the anterior superior iliac spine and the lateral portion of the patella for the VL muscle and at the midpoint between the ischial tuberosity and the lateral epicondyle of the tibia for the BF muscle[22]. A four-channel electromyography system was used (EMG100C, BIOPAC Systems, Inc., USA; Low Pass Filter: 500 Hz; High Pass Filter: 10 Hz; Noise Voltage (10–500 Hz): 0.2 lV (rms); Zin: 2 M ohm; CMRR: 110 dB). Data was sampled at 2kHz using a data acquisition system (MP100, BIOPAC Systems, Inc., USA) and processed using MatLab2016. EMG activity of each muscle was assessed by calculating the Root-mean-square (RMS) applying a 0.5 sec overlapping moving window and then expressed as a percentage of the maximal EMG activity during the MVC (RMS %MVC).

NMES recruitment curve

After at least 10 minutes from the end of MVC testing, the relationship between NMES amplitude and peak torque exerted (i.e. recruitment curve)[23] was assessed. Stimulation pads (size: 5×10 cm; Axelgaard Manufacturing Co., Ltd., Fallbrook, CA) were positioned above the quadriceps muscle belly with the distal portion placed at 50% and 10% of the distance between the anterior superior iliac spine and the superior margin of the patella, for proximal and distal pads respectively[24]. Then, a monophasic pulsed electrical stimulator (Digitimer DS7A, Hertfordshire, UK; Maximal Voltage 400V) was used to deliver a 1 second monophasic positive rectangular waveform with 1000µs pulse width at constant frequency and voltage of 100 Hz and 400 V, respectively. Stimulation trains were delivered to the muscle every 10 seconds. NMES was applied starting with a stimulation amplitude of 5 mA, and increasing it by 5 mA for every subsequent stimulation until a minimum torque equal to 10% of Peak Torque was elicited and either the participant requested to stop the stimulation because of discomfort or the recruitment curve reached a plateau.

NMES-conditioning contraction protocol

On the first testing day participants performed voluntary explosive contractions preceded by long-low NMES-elicited conditioning contractions.

This experimental protocol was performed 10 minutes after the NMES recruitment curve. NMES CC protocol consisted of twelve 10-sec NMES-elicited contractions, with 20 sec in between each NMES CC. NMES frequency and pulse width were maintained at 100 Hz and 1000 us, respectively. Amplitude was selected in order to initially elicit a torque output equal to 10% MVC based on the recruitment curve described above. Based on preliminary observations, the first 3 NMES CCs were delivered with the goal of priming the neuromuscular system and activating the spinal circuitry via afferent pathways. NMES CC and voluntary explosive knee extensions were interleaved from the fourth to twelfth NMES CC. In particular, participants were instructed to perform the voluntary explosive knee extension immediately after the end of NMES CC, aiming at reaching the target of 70% MVC as fast as possible, and maintaining it for 3 sec. Real-time visual feedback of torque output was provided.

Voluntary-conditioning contraction protocol

During the second experimental session, participants initially performed MVC of knee extensors in order to compare their neuromuscular status with the first experimental day. After 10 minutes of rest, participants performed the VOL CC protocol, which mirrored the NMES CC described above; the only difference was that conditioning contractions were performed voluntarily (and not by NMES). Participants were asked to perform a voluntary conditioning contraction matching the mean muscle output of the NMES-elicited conditioning contractions performed in the previous session. To achieve this goal, the Mean Torque of the NMES-elicited conditioning contractions was calculated, and the subjects were instructed to reach and maintain the targeted muscle output for ten seconds. In particular, twelve 10-sec voluntary conditioning contractions were performed with 20 sec in between each contraction. Voluntary conditioning contractions and voluntary explosive knee extensions were interleaved from the fourth to twelfth conditioning contraction.

Muscle Mechanical output and EMG activity

During the NMES-CC and VOL CC protocols, knee extensors torque output and EMG activity from the vastus lateralis, rectus femoris and biceps femoris were recorded and used for further analysis. In particular, onset and offset of each contraction were defined considering a torque threshold equal to the baseline (calculated between 650 and 150 ms prior to the delivery of NMES) + 3 standard deviations. Peak Torque was calculated by applying a 0.5 sec moving window for explosive voluntary contractions (Peak Torque$_{\_EC}$). Mean Torque was calculated for both NMES-elicited conditioning contractions (Mean Torque$_{\_CC}$) and for voluntary explosive muscle contractions (Mean Torque$_{\_EC}$) by the Mean Torque value from the beginning to end of each contraction. Torque-time integral (TTI) was calculated to estimate muscle work of the conditioning contractions (TTI$_{\_CC}$) and of the explosive voluntary contractions (TTI$_{\_EC}$). Rate of torque development of the explosive voluntary contraction was computed over the time windows 0–50 ms (RTD 0–50 ms$_{\_EC}$) and 0–100 ms (RTD 0–100 ms$_{\_EC}$). EMG values were used to assess possible marker of afferent pathways activation (RMS VL_marker; RMS RF_marker; RMS BF_marker) during the NMES CC protocol. In particular, only for the first 3 NMES-elicited conditioning contractions performed without a following explosive contraction, the RMS marker analysis was carried out by selecting a 4 second time window 0.5 sec after the end of the NMES-elicited conditioning contraction. Then, the RMS marker values were compared to RMS baseline values. Also, EMG values were used to assess muscle electrical activation during the explosive voluntary contractions (RMS VL$_{\_EC}$; RMS RF$_{\_EC}$; RMS BF$_{\_EC}$).

Statistical analysis

All results are expressed as mean and standard deviation (SD). Normal distribution of the data was tested using the Kolmogorov–Smirnov test. Sphericity (homogeneity of covariance) was verified by the Mauchly's test. When the assumption of sphericity was not met, the significance of the F-ratios was adjusted according to the Greenhouse–Geisser procedure. The comparison between the NMES CC and VOL CC protocols parameters of Peak Torque (Peak Torque$_{\_EC}$), Mean Torque (Mean Torque$_{\_CC}$; Mean Torque$_{\_EC}$), Torque

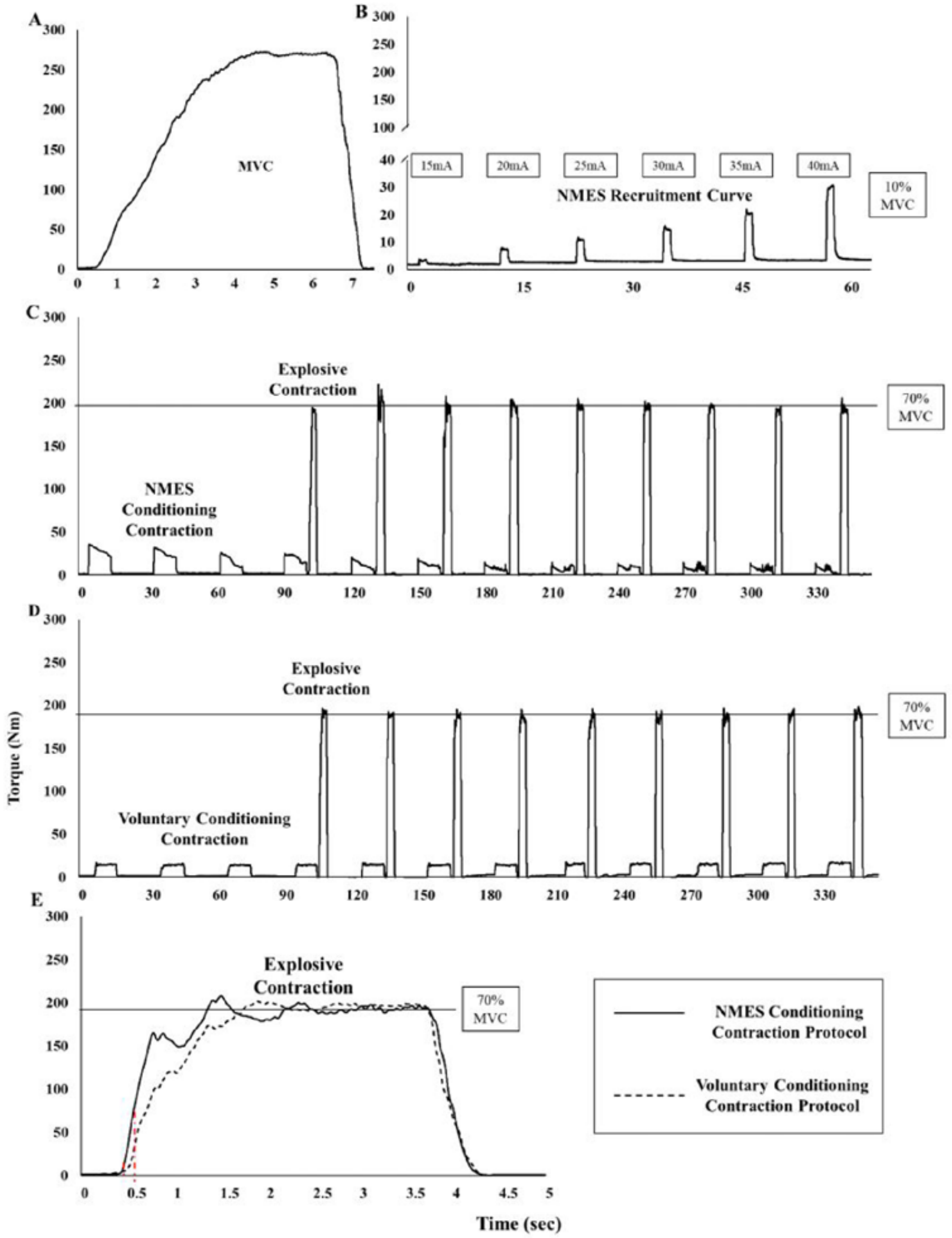

Figure 2. Muscle mechanical output for one representative subject. Maximal Voluntary Contraction (MVC) (A) was first performed to identify the 10% MVC to be elicited during the Neuromuscular Electrical stimulation (NMES) recruitment phase (B) and during the NMES-Conditioning Contractions protocol. Explosive Voluntary contractions of knee extensors were performed at 70% MVC during the NMES-elicited Conditioning Contractions protocol and the Voluntary one (D). Muscle contractile properties of knee extensors were evaluated during explosive contractions in the first phase after contraction on-set (E).

Time Integral (TTI$_{\_CC}$; TTI$_{\_EC}$), Rate of torque development over the time windows 0–50 ms (RTD 0–50 ms$_{\_EC}$) and 0–100 ms (RTD 0–100 ms$_{\_EC}$), RMS VL_marker, RMS RF_marker, RMS BF_marker, RMS VL$_{\_EC}$, RMS RF$_{\_EC}$, RMS BF$_{\_EC}$ were performed by applying a paired T-test using GraphPad Prism 7.0 with significance set at p≤0.05.

Results

Subjects generated similar MVC of knee extensors in the two experimental sessions, (227±69 and 226±70 Nm; p=0.395) indicating a similar neuromuscular status. As exemplified in Figure 2C and D, the participants were able

Table 1. Muscle mechanical output and contractile properties of the knee extensors and *vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF)* electromyographic amplitude during voluntary explosive isometric contractions (EC) and conditioning contractions (CC) generated during the electrical stimulation (NMES) CC protocol or the voluntary (VOL) CC protocol.

	NMES CC	VOL CC	p value
Mean Torque_$_{EC}$ (Nm)	129.6 ± 39.4	129.9 ± 39.0	0.920
Mean Torque_$_{CC}$ (Nm)	10.1 ± 4.8	10.0 ± 4.4	0.553
Peak Torque_$_{EC}$ (Nm)	166.5 ± 50.5	166.9 ± 50.6	0.870
TTI_$_{EC}$ (Nm·s)	4687 ± 1488	4709 ± 1451	0.673
TTI_$_{CC}$ (Nm·s)	1227 ± 580	1205 ± 535	0.197
Time to Peak_$_{EC}$ (sec)	1.76 ± 0.38	1.98 ± 0.41	0.019*
Time to Target_$_{EC}$ (sec)	0.98 ± 0.38	1.04 ± 0.48	0.632
RTD 0-50ms_$_{EC}$ (Nm·s^{-1})	216 ± 194	135 ± 160	0.027*
RTD 0-100ms_$_{EC}$ (Nm·s^{-1})	325 ± 243	241 ± 236	0.082
RMS VL_$_{EC}$ (%MVC)	66 ± 23	65 ± 29	0.833
RMS RF_$_{EC}$ (%MVC)	63 ± 23	61 ± 17	0.534
RMS BF_$_{EC}$ (%MVC)	24 ± 29	19 ± 14	0.460

*TTI: Torque Time Integral; RTD: Rate of Torque Development calculated in the 0-50ms and 0-100ms time windows; RMS: Root Mean Square. EC: Explosive Contraction; CC: Conditioning Contraction; Values are mean ± standard deviation. N = 20 research subjects. * Significant difference by Paired t test.*

to achieve the torque target in all explosive contractions performed during both NMES CC and VOL CC protocols. Also, the torque output generated during the conditioning contractions tended to decrease throughout the NMES CC protocol, whereas no decrement was observed in the conditioning contractions generated voluntarily.

During the NMES and VOL CC protocols, Mean Torque_$_{CC}$ and TTI_$_{CC}$ of the conditioning contractions were not different, indicating that participants were able to perform similar muscle mechanical output (p>0.05) during the two testing days (Table 1). Also, explosive contractions performed during the two protocols generated similar Mean Torque_$_{EC}$, Peak Torque_$_{EC}$ and TTI_$_{EC}$ (p>0.05).

Also, during voluntary explosive contractions, the Time to Peak_$_{EC}$ was significantly lower during the NMES CC protocol than the VOL CC one, with a percentage difference of 11% (p=0.019). However, the Time to Target was similar between protocols (p>0.05) with a difference of 6%.

Interestingly, the RTD 0–50 ms_$_{EC}$ which is the rate of torque increment calculated in the earliest phase of contraction, was significantly higher (+38%) for the NMES CC protocol than the VOL CC one (p=0.027) (Table 1; Figure 2). On the other hand, the RTD 0–100 ms_$_{EC}$ calculated by also considering the later contraction phase, did not reach statistical significance (p=0.082) with a difference of 26% between the NMES and VOL protocol.

Interestingly, during the NMES and VOL CC, muscle activation was not different indicating that participants had similar % EMG amplitude during the two testing days (Table 1). We also evaluated a possible EMG marker of afferent pathways activation mechanisms that compares baseline and post-NMES time windows (see *Muscle Mechanical output and EMG activity* in the Methods). This approach showed negligible differences between baseline and post-NMES time windows for the RMS VL_marker (2±2%MVC, p=0.357), RMS RF_marker (4±6 %MVC, p=0.719) and RMS BF_marker (2±3 %MVC, p=0.417).

Discussion

In the present study we compared the effects of applying electrically induced or voluntarily generated conditioning contractions on the explosive characteristics of isometric voluntary contractions of knee extensors at 70% MVC. When comparing the different nature of conditioning contractions on a following isometric explosive contraction of knee extensors, the early explosive characteristics of the contraction were impaired by a voluntary activation as compared to an electrically induced one that performed the same muscle mechanical work.

NMES elicited vs Voluntary Conditioning Contractions Protocol

During the VOL CC protocol, performed on the second experimental day, muscle mechanical output from both explosive contractions and conditioning contractions was matched with the results from the previous testing day (NMES protocol). Potentiation was evaluated by mean of RTD in the early (50ms) and late phase (100ms) of the explosive contraction. RTD is considered to give valuable information on the neuromuscular system, particularly in the early phase[25], because it is influenced by neural mechanisms and motor unit's activation[26].

It is possible that the enhanced RTD 0–50 $\text{ms}_{\text{—EC}}$ evaluated after a conditioning contraction performed electrically was the result of a potentiated status that enabled to overcome those spinal and supra-spinal pathways involved in central fatigue mechanisms. On the other hand, these mechanisms are well involved during a sustained voluntary contraction even at relatively low-level force[5,27]. It has been described previously that, after a tetanic electrically evoked conditioning contraction of *tibialis anterior*, RTD of a ballistic contraction is increased as compared to a conditioning stimulus performed voluntary[5].

It is important to consider that fatigue is also induced by an electrical stimulus, but mainly involving peripheral structures. Therefore, it is plausible that an electrically evoked conditioning contraction was able to initiate a Ca^{2+} release in the sarcoplasmic space and induce potentiation over the following voluntary explosive contraction overcoming the development of peripheral fatigue[4,5]. However, when considering the later phase of RTD (0-100ms time window), no significant difference was found (p=0.082) between the NMES CC and VOL CC protocols. This result might reflect the preserved mechanical properties of the muscles, that are not influenced by an increased neural drive[28]. At the same time, similar values of Time to $\text{Peak}_{\text{—EC}}$ can be considered as an indicator of preserved muscle contractile properties[25]. On the other hand, it is important to highlight that, in the present study, Time to $\text{Target}_{\text{—EC}}$ was significantly lower during the NMES CC protocol compared with the VOL CC one (-6%). This might be explained by differences in RTD in the very early phase of contraction and by a tendency for this parameter to remain higher during the NMES CC protocol also in the later phase of contraction (RTD 0–100 $\text{ms}_{\text{—EC}}$).

As mentioned above, another aspect that needs to be considered is central fatigue. In fact, it is possible not only that a conditioning contraction performed electrically can enhance a following explosive contraction, but also that a voluntary conditioning contraction can limit potentiation due to increased central fatigue at spinal and supraspinal level. Even though central fatigue is developed more slowly at submaximal force level, as in this case, it is possible that afferent fibers (small diameters type III and IV afferents) are engaged in sustained contraction thus limiting cortical output and therefore voluntary activation[10,29].

Even if in the present study participants were always able to reach the required muscle output (70% MVC), it is plausible that in the VOL CC protocol, contraction explosiveness could have been affected by an ongoing development of central fatigue to the muscle caused by repeated activation of the cortico-spinal pathways both during sustained low level muscle contractions and explosive contractions. Similar results were highlighted by D'Amico et al.[18] investigating a hand muscle, as they showed that voluntary activation and motoneuron excitability were affected by a voluntary fatiguing task rather than an electrically evoked one.

Moreover, it is important to highlight that, even though a long-low NMES paradigm was applied, the enhanced explosiveness was not promoted by activation of afferent pathways. In fact, we did not detect any marker of spinal circuitry involvement as evaluated by the RMS values after the end of the NMES elicited conditioning contraction. A possible explanation for this outcome is the relevant interindividual variability in our participants with respect to the response to the specific type of long-low NMES paradigm. This might be explained by peripheral factors (i.e. intrinsic muscle properties) such as Ca^{2+} release, and sensitivity and/or phosphorylation of myosin light chain[30,31].

Limitations

The present study presents some limitations. First, it is important to considered that inferences on muscle fatigue occurrence were made without evaluating the phenomenon. For future studies, voluntary activation might be evaluated by the interpolated-twitch technique and cortical activation be using the transcranial magnetic stimulation. Second, it is not possible to precisely identify the source of the enhanced explosiveness during the NMES CC protocol because no evidence of afferent activation pattern was found. Also, the non-randomized order of the two experimental protocols (i.e. Day 1 and Day 2), which was required to properly match the muscle torque output, might be taken into consideration as a limit of this study. To overcome this last limitation, in future studies, a control group could be added to the experimental design.

Conclusion

In conclusion, we demonstrated that the explosiveness of an isometric contraction of knee extensors was potentiated by an electrical evoked conditioning contraction performed at submaximal force level, as compared to a voluntary conditioning contraction.

The present findings can be important for those training paradigms during which athletes are asked to generate high level of muscle force as quickly as possible. Furthermore, an exercise strategy that enhances muscle explosive performance while also promoting higher volume of muscle work could be useful to design new strategies for training in the elderly population. In fact, the ability to rapidly generate higher level of muscle force is also essential in frail populations to reduce risk of falls and improve mobility.

Acknowledgements

We thank all research participants for their valuable contribution to this study.

References

1. Bishop D. Warm up I. Sports medicine 2003;33(6):439-454.
2. Baudry S, Duchateau J. Postactivation potentiation in human muscle is not related to the type of maximal conditioning contraction. Muscle Nerve 2004; 30(3):328-36.

3. Krarup C. Enhancement and diminution of mechanical tension evoked by staircase and by tetanus in rat muscle. J Physiol 1981;311:355-72.
4. Vandervoort A, Quinlan J, McComas A. Twitch potentiation after voluntary contraction. Experimental Neurology 1983;81(1):141-152.
5. Smith CB, Allen MD, Rice CL. Voluntary rate of torque development is impaired after a voluntary versus tetanic conditioning contraction. Muscle Nerve 2014; 49(2):218-24.
6. Sale D. Postactivation potentiation: role in performance. British Journal of Sports Medicine 2004;38(4):386-387.
7. Sweeney HL, Stull JT. Alteration of cross-bridge kinetics by myosin light chain phosphorylation in rabbit skeletal muscle: implications for regulation of actin-myosin interaction. Proceedings of the National Academy of Sciences 1990;87(1):414-418.
8. Grange RW, Vandenboom R, Houston ME. Physiological significance of myosin phosphorylation in skeletal muscle. Canadian Journal of Applied Physiology 1993;18(3):229-242.
9. Sweeney H, Bowman BF, Stull JT. Myosin light chain phosphorylation in vertebrate striated muscle: regulation and function. American Journal of Physiology-Cell Physiology 1993;264(5):C1085-C1095.
10. Taylor JL, Gandevia SC. A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. Journal of Applied Physiology 2008;104(2):542-550.
11. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. Physiological Reviews 2001.
12. Smith JL, Martin PG, Gandevia SC, Taylor JL. Sustained contraction at very low forces produces prominent supraspinal fatigue in human elbow flexor muscles. Journal of Applied Physiology 2007;103(2):560-568.
13. Søgaard K, Gandevia SC, Todd G, Petersen NT, Taylor JL. The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. The Journal of Physiology 2006;573(2):511-523.
14. Maffiuletti NA. Physiological and methodological considerations for the use of neuromuscular electrical stimulation. European Journal of Applied Physiology 2010;110(2):223-234.
15. Feiereisen P, Duchateau J, Hainaut K. Motor unit recruitment order during voluntary and electrically induced contractions in the tibialis anterior. Experimental Brain Research 1997;114(1):117-123.
16. Knaflitz M, Merletti R, De Luca CJ. Inference of motor unit recruitment order in voluntary and electrically elicited contractions. Journal of Applied Physiology 1990;68(4):1657-1667.
17. Requena B, Gapeyeva H, García I, Ereline J, Pääsuke M. Twitch potentiation after voluntary versus electrically induced isometric contractions in human knee extensor muscles. European Journal of Applied Physiology 2008;104(3):463-472.
18. D'Amico JM, Rouffet DM, Gandevia SC, Taylor JL. Unlike voluntary contractions, stimulated contractions of a hand muscle do not reduce voluntary activation or motoneuronal excitability. Journal of Applied Physiology 2020;128(5):1412-1422.
19. Collins D, Burke D, Gandevia S. Large involuntary forces consistent with plateau-like behavior of human motoneurons. Journal of Neuroscience 2001;21(11):4059-4065.
20. Dean JC, Yates LM, Collins DF. Turning on the central contribution to contractions evoked by neuromuscular electrical stimulation. Journal of Applied Physiology 2007;103(1):170-176.
21. Rejc E, Lazzer S, Antonutto G, Isola M, Di Prampero PE. Bilateral deficit and EMG activity during explosive lower limb contractions against different overloads. European Journal of Applied Physiology 2010;108(1):157.
22. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol 2000;10(5):361-74.
23. Gonnelli F, Rejc E, Giovanelli N, Floreani M, Porcelli S, Harkema S, Willhite A, Stills S, Richardson T, Lazzer S. Effects of NMES pulse width and intensity on muscle mechanical output and oxygen extraction in able-bodied and paraplegic individuals. Eur J Appl Physiol 2021;121(6):1653-1664.
24. Arpin D, Ugiliweneza B, Forrest GF, Harkema SJ, Rejc E. Optimizing neuromuscular electrical stimulation pulse width and amplitude to promote central activation in individuals with severe spinal cord injury. Frontiers in Physiology 2019;10:1310.
25. D'Emanuele S, Maffiuletti NA, Tarperi C, Rainoldi A, Schena F, Boccia G. Rate of Force Development as an Indicator of Neuromuscular Fatigue: A Scoping Review. Frontiers in Human Neuroscience 2021:387.
26. Del Vecchio A, Negro F, Holobar A, Casolo A, Folland JP, Felici F, Farina D. You are as fast as your motor neurons: speed of recruitment and maximal discharge of motor neurons determine the maximal rate of force development in humans. The Journal of physiology 2019;597(9):2445-2456.
27. Sacco P, Thickbroom GW, Thompson ML, Mastaglia FL. Changes in corticomotor excitation and inhibition during prolonged submaximal muscle contractions. Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine 1997;20(9):1158-1166.
28. Folland J, Buckthorpe M, Hannah R. Human capacity for explosive force production: neural and contractile determinants. Scandinavian Journal of Medicine & Science in Sports 2014;24(6):894-906.
29. Gandevia S, Allen GM, Butler JE, Taylor JL. Supraspinal factors in human muscle fatigue: evidence for suboptimal output from the motor cortex. The Journal of Physiology 1996;490(2):529-536.
30. Frigon A, Thompson CK, Johnson MD, Manuel M, Hornby TG, Heckman C. Extra forces evoked during electrical

stimulation of the muscle or its nerve are generated and modulated by a length-dependent intrinsic property of muscle in humans and cats. Journal of Neuroscience 2011;31(15):5579-5588.

31. Neyroud D, Gonzalez M, Mueller S, Agostino D, Grosprêtre S, Maffiuletti NA, Kayser B, Place N. Neuromuscular adaptations to wide-pulse high-frequency neuromuscular electrical stimulation training. European Journal of Applied Physiology 2019;119(5):1105-1116.