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Diagnostic accuracy of Tensiomyography parameters for monitoring peripheral neuromuscular fatigue

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ABSTRACT

The diagnostic accuracy of tensiomyography (TMG) parameters compared to the gold standard in neuromuscular fatigue evaluation using voluntary and electrically induced muscle activation is unclear. This study aimed to investigate the diagnostic accuracy of TMG parameters to detect individual changes after interventions that were designed to induce central or peripheral fatigue. Nineteen males (age: 32.2 ± 9.3 years) performed two interventions, consisting of maintaining 25% of maximal voluntary contraction ($MViC_{25\%}$) and a 30 s all-out cycling test (Wingate), respectively. TMG parameters, maximum voluntary contraction (PtMViC), voluntary activation (VA%) and electrically elicited double twitches (Dtw) were assessed on the knee extensors before (PRE), one minute (POST) and seven minutes after (POST7) the intervention. The diagnostic accuracy (AUC) of TMG parameters were evaluated in comparison to two criteria measures (PtMViC and Dtw). RM ANOVA revealed a significant interaction between the effects of *intervention* and *time* on VA% ($p = 0.001$) and Dtw ($p < 0.001$) but not for PtMViC ($p = 0.420$). AUC showed that TMG parameters had a good ability in detecting muscular fatigue assessed by Dtw but not by PtMViC. The results of the current study suggest that TMG parameters can be used to monitor peripheral neuromuscular fatigue.

1. Introduction

One of the most used methods to quantify neuromuscular fatigue (NMF) is the use of maximal voluntary contraction (Place et al. 2007a). However, this method is highly dependent on the motivation of participants to perform at their best and cannot distinguish between central and peripheral fatigue mechanisms. It is generally accepted that comparing voluntary and evoked force in response to electrically induced muscle activation provides more insight into NMF. In fact, the preferred method for assessing neuromuscular properties consists of various techniques inducing transcutaneous supramaximal stimulation of a motor nerve (Place and Millet 2020). The contribution of central fatiguing mechanisms can be determined by measuring the voluntary activation level with some derivatives of the interpolated twitch technique (Merton 1954). Usually, a high-frequency (from 80 to 100 Hz) supramaximal electrical stimulation of the peripheral nerve is elicited during a maximal voluntary isometric contraction (MViC) and at rest (Millet et al. 2011) to evaluate the level of voluntary drive during an effort (Gandevia 2001).

However, the use of supramaximal nerve stimulation can be perceived as painful or unpleasant by some participants, especially when paired stimuli are elicited (Place and Millet 2020), making this technique difficult to apply in some groups of participants. Recent advances in percutaneous magnetic stimulation offer a reliable and valid alternative to electrical stimulation (Verges et al. 2009); however, it has its own limitations. For example, the shape of the coil defines the position in which we can access the peripheral nerve and this technique is particularly susceptible to fat tissue; thus, its use in overweight persons is limited (Verges et al. 2009). In addition, expensive special equipment like dynamometers, data acquisition systems and electrical stimulation or magnetic coils are used for such measurements. Thus, these measurements have primarily been used in the laboratory setting for fundamental research (Millet et al. 2011) and are not suitable for daily use in the field.

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Tensiomyography (TMG) has been recently proposed as an easy-to-handle, portable and valid tool for neuromuscular assessment. TMG relies on electrical stimulation and a high-precision displacement sensor to record the radial deformation of the muscle belly following percutaneous twitch electrical stimulation (Valencic and Knez 1997; Šimunič 2012). Compared to other methods, representing the gold standard in neuromuscular function evaluation, such as isokinetic dynamometers, force plates, or interpolated twitch technique, neuromuscular assessment with TMG is independent of motivation or volitional effort, which are known as moderators of physical performance (Gandevia 2001). From TMG response, several time- and displacement-based parameters are derived; however, the contraction time (Tc) (Šimunič et al. 2019) and maximal displacement amplitude (Dm) (Šimunič et al. 2011) proved to be the most reliable (Šimunič 2012; Paravlić et al. 2017) and clinically relevant (Pišot et al. 2008; Paravlic et al. 2020). TMG has emerged as a technique that can detect the presence of NMF (see review (Macgregor et al. 2018; Cè et al. 2020) for such studies). Specifically, out of 11 studies, eight reported decreased Dm, two increased Dm, two decreased Tc and three increased Tc, after different fatiguing protocols. Considerable variation of TMG parameters after fatiguing protocols could be partly explained by fatigue modality (Macgregor et al. 2018); however, it warrants further investigations. In recent literature, TMG parameters have already been evaluated for their diagnostic accuracy, presenting moderate accuracy (Lohr et al. 2019). In the aforementioned studies, fatigue was induced by one or several days of intensive training. They compared TMG parameters to a criterion measure based on voluntary contraction like: MViC (Hunter et al. 2012; de Paula Simola et al. 2015, 2016), one-repetition maximum (1RM) (Raeder et al. 2016), countermovement jump (CMJ) (Wiewelhove et al. 2017) or repeated sprint ability (RSA) tests (Wiewelhove et al. 2021). Although some authors claimed their fatiguing intervention induced central fatigue, this issue has not been empirically investigated by applying supramaximal nerve stimulation techniques and TMG. One of the first trials aimed to investigate differences between parameters of muscle contraction estimated from longitudinal and transversal isometric actions measured by dynamometry and TMG was conducted by Koren et al. (2015). The authors found shorter delay time, half-relaxation time and Tc of 23%, 42.7% and 26.2%, respectively, when assessed with TMG than with dynamometry. Furthermore, there was no correlation in abovementioned parameters when estimated with both methods. These results suggest that transversal muscle actions estimated with TMG are more likely to reflect intrinsic contractile properties. Although the latter results favour TMG over torque measurement in assessing intrinsic muscle properties, Koren et al. (2015) elicited mechanical muscle responses by using submaximal electrical stimuli that could bias the results obtained with dynamometry. Therefore, it would be necessary to assess TMG parameters for their diagnostic accuracy in comparison to mechanical responses elicited by supramaximal electrical stimulation of the muscle. In addition, the central origin of NMF is mostly investigated by MViC and voluntary activation level (%) measurements, whereas the latter is often characterized as an unpleasant neuromuscular assessment method for the end-user and therefore cannot be routinely implemented into practice. Thus, we would like to investigate the feasibility of the TMG technique, which is based on the submaximal electrical stimulation technique and has been shown to be a reliable, portable, and easy-to-use tool.

Therefore, the aim of this study was to investigate the diagnostic accuracy of TMG parameters to detect individual changes due to fatigue and recovery after two exercise interventions designed to induce central or peripheral fatigue. Based on recent literature investigating the diagnostic accuracy of TMG parameters in detecting changes after fatiguing interventions, we hypothesised that TMG parameters accurately represent the muscle mechanical changes elicited by single and paired electrical impulses but are less efficient in accurately detecting changes in voluntary contracted muscles.

2. Methods

2.1. Study design

The study followed a cross-over exeprimental design, where each participant performed two different fatiguing exercise interventions: $MViC_{25\%}$ - knee extensors sustained submaximal isometric contraction at 25% of MViC and Wingate − 30 s maximal power cycling test. Each exercise intervention was performed on different visits with at least 48 h between measuring days. At the beginning of each session, subjects underwent a 6-minute warm-up routine consisting of bench stepping (20 cm high) at a frequency of 0.5 Hz, swapping the leading leg at one-minute intervals. TMG, as well as other neuromuscular assessments, were performed at three timepoints: before (PRE), one minute after the intervention (POST) and seven minutes (POST7) after the intervention. The neuromuscular assessment comprised MViC of the knee extensors, superimposed high-frequency double twitch (TWsup), and resting high-frequency double twitch (Dtw). All assessments were performed on the right leg. A detailed overview of the study design, timeline of the experimental procedures, participant position and example data are represented in Fig. 1.

2.2. Participants

In the conceptualisation phase of the study, we conducted a power analysis using the G*Power software (Faul et al. 2007). Based on previous fatigue studies, we expected to find a medium to large effects between the two interventions (0.4) (Cohen 1988). With the a priori power of 0.95 and $\alpha = 0.05$, two-tailed, the software calculated a sample size of 18 participants. According to the calculation, 19 young, healthy males (age: 32.2 ± 9.3 years, height: 177.1 ± 6.4 cm, mass: 82.9 ± 15.6 kg) were recruited in this study. All participants were recreationally trained and engaged in moderate physical activities 3 times per week. Exclusion criteria were acute injuries of the lower extremities, locomotor dysfunctions, cardiovascular or neurological conditions. All participants signed the written informed consent, and the protocol was approved by the National Medical Ethics Committee of Slovenia [n 0120-84/2020/4].

3. Testing procedures

3.1. Participant's position

During the neuromuscular assessment, the participants were seated in an upright position in a chair-like knee extension dynamometer (S2P, Ljubljana, Slovenia) equipped with a load cell. Hip fixed at 100° angle. The knee joint was aligned with the rotational axis of the dynamometer, with the shinpad placed just above the malleolus. The right knee was fixed at a 60° angle (0° = knee fully extended).

3.2. Tensiomyography

The contractile properties of the individual muscles were assessed by the non-invasive TMG method. We measured vastus lateralis (VL) muscle of the right leg only while seated in an upright position in the dynamometry chair as described above. The well-established methodology was used as previously described (Šimunič et al. 2011; Paravlic et al. 2020, 2022). Briefly, following an electrically induced isometric twitch, the radial displacement of the muscle belly was recorded at the skin surface using a sensitive digital displacement sensor (TMG-BMC, Ljubljana, Slovenia). The sensor was set perpendicular to the skin's normal plane above the muscle belly. The rounded (5-cm diameter) self-adhesive cathode and anode (Axelgaard, Aarhus, Denmark) were set 5 cm distally and 5 cm proximally to the measuring point on all muscles assessed. Electrical stimulation was applied through a TMG-100 System electro stimulator (TMG-BMC d.o.o., Ljubljana, Slovenia) with a pulse

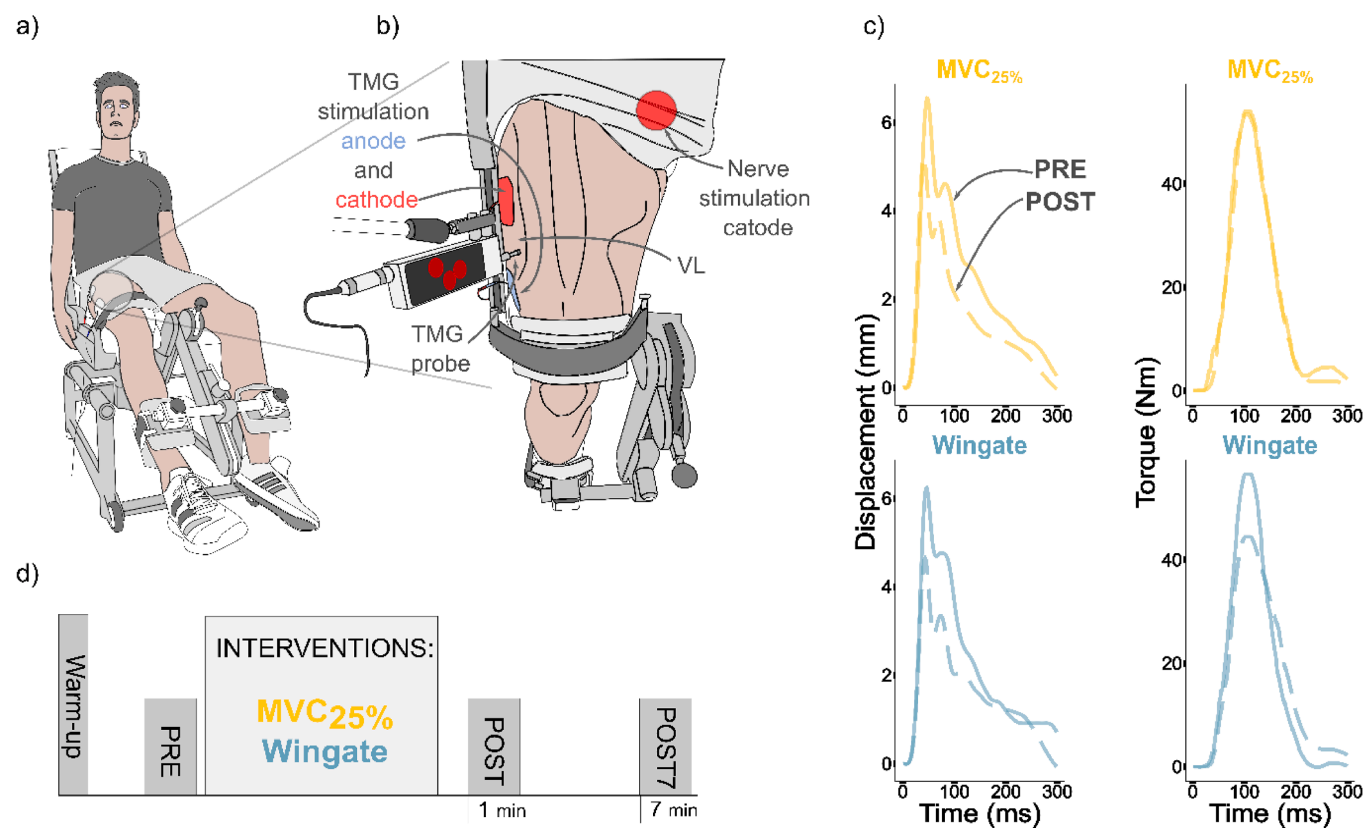

Fig. 1. Graphical representation of the participant's position (a) and detailed view of the right leg (b). Example of pre and post TMG (left pan) and single twitch (right pan) raw data from a representative participant (c). The timeline of the experimental procedures (d).

width of 1 ms and an initial amplitude of 20 mA. During a baseline measurement, the amplitude was progressively increased by 20 mA increments until there was no further increase in the amplitude of the TMG response (Dm), which was usually accompanied by the maximal stimuli of 110 mA. All post-measurements were conducted with a single maximal stimulus. Rest periods between two stimuli of 10 s were given between each stimulus to minimise the effects of fatigue and potentiation. More detailed testing procedures were previously described elsewhere (Šimunič et al. 2011; Paravlić et al. 2017). From two maximal twitch responses, several TMG parameters were calculated as follows: delay time (Td) as time from an electrical impulse to 10 % of the Dm; Tc as time from 10 % to 90% of Dm. Additionally, the index representing the velocity of contraction V10 (0.1 · Dm / Tc) and V90 (0.9 · Dm/Tc) (Pereira et al. 2019) were calculated.

3.3. Femoral nerve electrical stimulation

The femoral nerve was stimulated with square-wave impulses of the duration of 1 ms delivered by a high-voltage constant current electrical stimulator (DS7R; Digitimer, Hertfordshire, UK). A 2.5 cm circular self-adhesive electrode (J10R00, Axelgaard, Denmark) served as a cathode and was pressed against the femoral nerve in the iliac triangle. The anode (50 × 90 mm, MyoTrode PLUS, Globus, Italy) was placed under the gluteal fold. The impulses were used to trigger muscle responses which were registered as changes in knee extensors torque. The stimulation intensity to elicit maximum knee extensors isometric twitch was determined in each participant at the beginning of each visit and maintained for the entire visit. Starting from an intensity of 20 mA, the stimulation intensity was progressively increased by 10 mA until no further increase in muscle torque was observed despite a further increase in electrical current. We additionally increased the current to 130% to obtain a supramaximal stimulus (Verges et al. 2009). Stimulation intensities ranged from 90 to 160 mA.

3.4. Double twitch

The change in torque induced by a high-frequency double (10 ms interstimulus interval) supramaximal electrical stimulation of the femoral nerve (Place et al. 2007a; Verges et al. 2009) was used to induce changes in knee extensors torque. The highest torque (Dtw) was used in further analysis.

3.5. Maximal voluntary contraction and superimposed twitch

Participants were instructed to contract their knee extensors and reach maximal torque in 1 s and maintain this level for 4 s (Verges et al. 2009). Visual feedback and loud verbal encouragement were given during the maximal effort. The highest torque value of the voluntary contraction (PtMViC) was further used in the data analysis. During the voluntary torque plateau, a high-frequency double supramaximal twitch (10 ms inter-stimuli interval) was elicited in the femoral nerve causing a further rise in torque (TWsup – comprising the voluntary torque plateau and the additional torque caused by the superimposed stimulation) (Allen et al. 1995). The following formula first introduced by Allen et al. (1995) was used to calculate the level of voluntary muscular activation (VA%):

$$VA\% = \left(1 - \frac{TWsup - PtMViC}{Dtw}\right) * 100\%$$

3.6. Fatiguing exercise intervention

Each participant undertook two different fatiguing exercise interventions:

i) $MViC_{25\%}$: The participants were instructed to contract their knee extensors and press against the lever arm of the dynamometer, exerting torque equal to 25 % of MViC. The target and exerted torque were displayed on a monitor using lines of different colours. The participants were loudly verbally encouraged to maintain the exerted torque until the torque dropped under 20 % MViC for three consecutive seconds. The exercise load was selected based on previous studies, where a similar exercise modality induced central fatigue (Place et al. 2007b).
ii) Wingate: The participants were instructed to perform an all-out 30-second cycling test on the Monark LC6 ergometer (Vansbro, Sweden). The braking load, measured in kiloponds (kp), was individualized according to the manufacturer's instructions. One kilopond (kp) is the force exerted on one kilogram, with 1 kp equal to 9.81 N. Power (P) is defined as the amount of work per time unit, and work on a Monark ergometer is calculated as W = Braking load × Distance, where one revolution on the crank equals six meters in distance and the braking load is in kiloponds or Newtons. The maximal braking resistance exerted by the machine was set at 7.5% of each participant's body mass (expressed in kp). Immediately after the maximal effort test, the participant returned to the knee extension dynamometer. This intervention has been previously proven to affect parameters representing peripheral fatigue (Krüger et al. 2019).

3.7. Statistical analysis

Data were analysed using R (version 4.1) programming language (R Core Team 2020). The normality of distribution was verified using the Shapiro-Wilk test for small samples across all parameters. A 2 × 3 two-way repeated measures ANOVA was conducted using the Afex package (Singmann et al. 2020) to determine the effect of different *fatiguing* paradigms ($MViC_{25\%}$, Wingate) over *time* (PRE, POST, POST7) on all measured variables. The assumption of sphericity was assessed using the Mauchly test. Whenever the assumption of sphericity was violated, the degrees of freedom were corrected using the Greenhouse-Geiser correction. Planned contrasts were computed to assess differences in effects between $MViC_{25\%}$ and Wingate interventions. Post hoc tests were performed as Sidak corrected t-tests with the Emmenas package (Lenth et al. 2020) to determine the differences between single treatments at different time points. Statistical significance was set at the level of $p < 0.05$. The magnitude of changes between timepoints and the effects of different fatiguing interventions were assessed using the effect size (ES). Hedges' g was used as a measure of effect size and interpreted according to Hopkins et al. (2009): 0.2 (small), 0.6 (moderate), 1.2 (large), 2.0 (very large), 4.0 (extremely large).

To classify a participant as fatigued, we first determined the smallest worthwhile change (SWC), which is concept used in various fields, including medicine, to evaluate the effectiveness of interventions or to identify clinically significant changes in outcomes. In this study, the SWC was defined by calculating 0.5 times the PRE-intervention standard deviation for each torque (PtMViC and Dtw) and TMG parameter (Dm, Tc, Td, V10, V90), following the method proposed by Turner et al. (2015). We then considered individuals fatigued if their changes at POST or POST7 exceeded the difference between their PRE-intervention measurement and the SWC. Two 2 × 2 contingency tables (PRE – POST and PRE – POST7) were used to evaluate further the diagnostic accuracy of TMG measures in comparison to two fatigue criteria measures (PtMViC and Dtw). The table was composed of horizontal lines to indicate the presence or absence of fatigue (according to changes in TMG parameters) and vertical lines to indicate the "true" condition of an individual according to each criterion measure of fatigue. Receiver-operating characteristic (ROC) curves were used to investigate the diagnostic accuracy of the TMG parameters for the assessment of neuromuscular fatigue in comparison to two criterion measures: PtMViC and Dtw, respectively. A ROC curve plots the true positive rate (i.e., sensitivity) against the true negative rate (i.e., specificity) to produce an area under the curve (AUC). An AUC serves to estimate how high the discriminative power of the test is. The AUC can have any value between 0.00 and 1.00, and it is a good indicator of the goodness of a test. A perfect diagnostic test has an AUC of 1.00, whereas a non-discriminating test has an AUC of 0.50 (Šimundić 2009). An AUC > 0.70 have been classified as a good benchmark. Diagnostic accuracy measures calculated from the contingency tables are presented in Table 1.

Pearson correlation coefficients were calculated between between TMG parameters: Dm, Tc, Td, and MViC and Dtw, respectively.

4. Results

Descriptive statistics can be found in Table 2. Participants maintained the isometric contraction for 439.2 ± 165 s in the MViC25% intervention and produced an average absolute power of 583.76 ± 105.72 W and an average relative power of 7.34 ± 0.80 W/kg in the Wingate intervention.

A two-way RM ANOVA revealed that there was an interaction between the effects of *intervention* and *time* on VA% (F (2.0, 35.9) = 8.427, p = 0.001, $\eta_p^2 = 0.319$), Dtw (F (1.7, 30.5) = 17.241, p < 0.001, $\eta_p^2 = 0.489$), Dm (F (1.8, 31.6) = 23.065, p < 0.001, $\eta_p^2 = 0.562$), Tc (F (2.0, 35.7) = 17.511, p < 0.001, $\eta_p^2 = 0.493$) and Td (F (1.7, 31.0) = 14.101, p < 0.001, $\eta_p^2 = 0.439$) respectively. There was no interaction between the effects of *intervention* and *time* on PtMViC (F (1.7, 31.0) = 0.855, p = 0.420, $\eta_p^2 = 0.045$). Simple main effects analysis showed that both *intervention* and *time* did affect PtMViC (p = 0.037 and p = 0.053, respectively). Detailed results of planned contrasts and post hoc tests are depicted in Fig. 2.

The determination of the AUC showed that TMG parameters had a good ability to detect peripheral muscular fatigue assessed by Dtw (Dm = 0.73, Tc = 0.67, Td = 0.77) and a poor ability to detect muscular fatigue assessed by a voluntary contraction - PtMViC (Dm = 0.47, Tc = 0.43, Td = 0.51). The data derived from the contingency table revealed good diagnostic effectiveness for all TMG parameters in detecting peripheral fatigue in an electrically elicited contraction - Dtw (Dm = 0.74, Tc = 0.66, Td = 0.76) and a poor ability of TMG parameters to detect muscular fatigue assessed by voluntary contraction - PtMViC (Dm = 0.42, Tc = 0.50, Td = 0.55). Fig. 3 and Fig. 4 depicts individual differences and fatigue categories for PtMViC and Dtw and respective fatigue categories from TMG parameters. All diagnostic accuracy data derived from the contingency tables are reported in Table 3. There were low and non-significant correlations in changes from baseline between TMG parameters: Dm, Tc, Td, and MViC and Dtw respectively (Fig. 5).

5. Discussion

The aim of this study was to investigate the diagnostic accuracy of selected TMG parameters to detect changes in neuromuscular function

Table 1
Diagnostic accuracy measures.

Diagnostic accuracy measures	*Measure explanation*
DE - Diagnostic effectiveness	The proportion of correctly classified participants among all participants
SN - Sensitivity	The proportion of participants correctly classified as fatigued
SP - Specificity	The proportion of participants correctly classified as non-fatigued
PPV - Positive predictive value	The proportion of participants classified as fatigued by TMG who are in fact fatigued
NPV - Negative predictive value	The proportion of participants classified as non-fatigued by TMG who are in fact non-fatigued
Y - Youden's index	The ratio of anticipated TMG results in fatigued participants to the non-fatigued participants, where 0 represents poor diagnostic accuracy and 1 represents large diagnostic accuracy

Table 2
Descriptive statistics.

	PRE		POST					POST7				
	mean ± SD	SWC	mean ± SD	% Δ	p (2 – 1)	G	p (int)	mean ± SD	% Δ	p (3 – 1)	G	p (int)
Maximum voluntary contraction – PtMViC (Nm)												
$MviC_{25\%}$	234.5 ± 57.0	28.5	216.6 ± 59.4	−7.7	0.022	−0.6	0.685	227.3 ± 44.3	−3.1	0.677	−0.2	0.746
Wingate	218.1 ± 49.8	24.9	207.9 ± 46.6	−4.6	0.285	−0.3		203.7 ± 48.5	−6.6	0.182	−0.4	
Level of voluntary activation – VA% (%)												
$MviC_{25\%}$	84.2 ± 8.3	4.2	76.8 ± 11.8	−8.7	0.020	−0.6	0.005	85.1 ± 8.2	1.1	0.901	0.1	0.979
Wingate	84.1 ± 9.8	4.9	87.2 ± 9.3	3.7	0.260	0.3		84.5 ± 9.5	0.5	0.983	0.0	
Doublet peak torque – Dtw (Nm)												
$MviC_{25\%}$	82.4 ± 16.7	8.4	80.0 ± 16.6	−3.0	0.525	−0.2	0.000	81.8 ± 15.3	−0.8	0.942	−0.1	0.002
Wingate	84.9 ± 19.6	9.8	60.8 ± 13.7	−28.4	0.000	−1.4		70.3 ± 15.0	−17.3	0.000	−1.1	
TMG Displacement – Dm (mm)												
$MviC_{25\%}$	4.6 ± 1.3	0.6	4.1 ± 1.0	−10.2	0.055	−0.5	0.000	4.1 ± 1.4	−10.8	0.015	−0.7	0.001
Wingate	5.2 ± 1.5	0.8	3.2 ± 1.2	−38.5	0.000	−2.0		3.7 ± 1.4	−28.4	0.000	−1.4	
TMG Contraction time – Tc (ms)												
$MviC_{25\%}$	18.8 ± 1.8	0.9	17.4 ± 1.5	−7.4	0.000	−1.1	0.001	18.5 ± 1.9	−1.7	0.482	−0.2	0.241
Wingate	18.9 ± 1.7	0.9	19.1 ± 1.8	1.0	0.795	0.1		18.0 ± 1.8	−4.6	0.005	−0.8	
TMG Delay time – Td (ms)												
$MviC_{25\%}$	21.1 ± 1.8	0.9	20.4 ± 1.5	−3.4	0.015	−0.7	0.000	20.7 ± 1.1	−1.8	0.267	−0.3	0.022
Wingate	21.2 ± 1.3	0.6	22.7 ± 2.5	7.3	0.003	0.8		21.8 ± 1.3	2.8	0.015	0.7	

SWC – Smallest Worthwhile Change; ***G*** – Hedge's G; ***p (2–1)*** – p value between POST and PRE measurement; ***p (3–1)*** – p value between POST7 and PRE measurement; ***p (int)*** – p value between interventions; ***% Δ*** – relative change from baseline.

after two exercise interventions aimed at inducing central and peripheral fatigue in knee extensors. Results showed that both fatiguing interventions ($MViC_{25\%}$ and Wingate) had a similar effect on the PtMViC. However, as hypothesised, the interventions induced different fatiguing mechanisms. Indeed, Dtw parameter decreased and VA% stayed unaltered after the Wingate test, suggesting that the Wingate test primarily affected the peripheral fatiguing mechanism. On the contrary, the Dtw stayed unaltered, whereas VA% decreased after the $MViC_{25\%}$ intervention suggesting that $MViC_{25\%}$ intervention mainly affected central fatiguing mechanisms. An interesting finding was that TMG parameters were selectively altered after fatiguing interventions. Dm decreased after both $MViC_{25\%}$ (-10.2%) and Wingate (-38.5), whereas Tc shortened only after $MViC_{25\%}$ (-7.4%) intervention. In addition, the TMG parameters showed good diagnostic efficacy in detecting peripheral fatigue during an electrically triggered contraction - Dtw (Dm = 0.74, Tc = 0.66, Td = 0.76), whereas in contrast, they showed poor ability to detect NMF evaluated by voluntary contraction - PtMViC (Dm = 0.42, Tc = 0.50, Td = 0.55). Lower Dm, an indirect measure of increased passive muscle stiffness and tone was reported previously after acute eccentric exercise triggering neuromuscular fatigue (Hunter et al. 2012) and after chronic plyometric exercise exposure (Zubac and Šimunic 2017). Decreased Dm reflects swelling response and/or increased intracellular water and increased passive muscle stiffness being regularly reported after neuromuscular fatigue. The shortening of the Tc parameter found after the $MViC_{25\%}$ intervention is difficult to explain, especially considering the Wingate intervention did not significantly affected this parameter. We should point out, that the investigation of the underlying fatiguing mechanisms are out of the scope of this article and we need more studies to exactly understand the relation between various forms of fatigue and TMG parameters.

To the best of our knowledge, this is the first study where TMG parameters were used to assess exercise-induced fatigue after two fatiguing protocols aimed to induce central or peripheral fatigue, respectively. The major finding of this study was that the TMG parameters demonstrated acceptable diagnostic accuracy (DE > 0.70) in detecting significant muscular changes immediately after both fatiguing protocols (POST) when compared to Dtw. Similar results were identified by Raeder et al. (2016), who compared pre-post exercise changes of Dm parameter to 1RM. The results of our and Raeder's (2016) study largely exceed the results reported in other studies, where TMG parameters were not sensitive enough to detect significant muscular performance changes compared to RSA (Wiewelhove et al. 2015) and CMJ (Wiewelhove et al. 2017, 2021). Similarly, TMG parameters in the present study were not sensitive enough to detect changes in maximal voluntary contraction PtMViC (DE = 0.47 Dm), which is similar to the results reported in the aforementioned studies (Wiewelhove et al. 2015, 2017, 2021).

There are some crucial differences between the present and previously published studies investigating the diagnostic accuracy of TMG parameters to detect fatigue-induced changes in muscle performance. For example, all previously published studies investigating the diagnostic accuracy of TMG parameters compared TMG parameters to functional criterion measures, which were based on voluntary tasks like MViC, RSA and CMJ. Although MViC, RSA or CMJ are easy to assess, they are not optimal for assessing the effects of exerciser-induced muscular fatigue since those are severely affected by participants' motivation (Millet et al. 2011). Thus, one cannot simply define the origin of fatigue (central or peripheral) by assessing MViC, RSA or CMJ alone. Thus, externally elicited electrical or magnetic stimulation contractions are recommended as more valuable methods to differentiate between peripheral and central NMF (Place and Millet 2020).

Although Dm and Dtw showed similar patterns, which can be confirmed by a similar decline of both parameters after fatiguing interventions and by a satisfactory level of diagnostic accuracy, the correlation between the aforementioned parameters was low (r ranging from 0.2 to 0.4 – see Fig. 5). Moreover, Dtw demonstrated a better diagnostic accuracy with PtMViC (0.59) compared to Dm (0.47). Although both electrically evoked twitches and TMG parameters were previously proposed as reliable tools for investigating changes in muscle contractile mechanisms (Paravlić et al. 2017), the two measurements are intrinsically different. First, TMG parameters are extrapolated from the maximal radial displacement of an individual muscle head, whereas Dtw represents the force produced by all muscle heads from the evaluated muscle group (e.g., the whole quadriceps muscle). Both TMG parameters and Dtw were used to evaluate the muscle contractile characteristics since both can detect changes in excitation–contraction coupling mechanisms. However, it is known that exercise can affect viscoelastic characteristics, liquid contents, and muscle–tendon complex stiffness. Furthermore, in the case of quadriceps muscle assessment, Dtw also captures the force translations over the knee joint, which results in a more extended time-related parameter such as delay time, Tc and Tr than when those are estimated from the TMG response (Koren et al. 2015). Latter suggests that TMG likely reflects more intrinsic contractile properties of the muscle than Dtw.

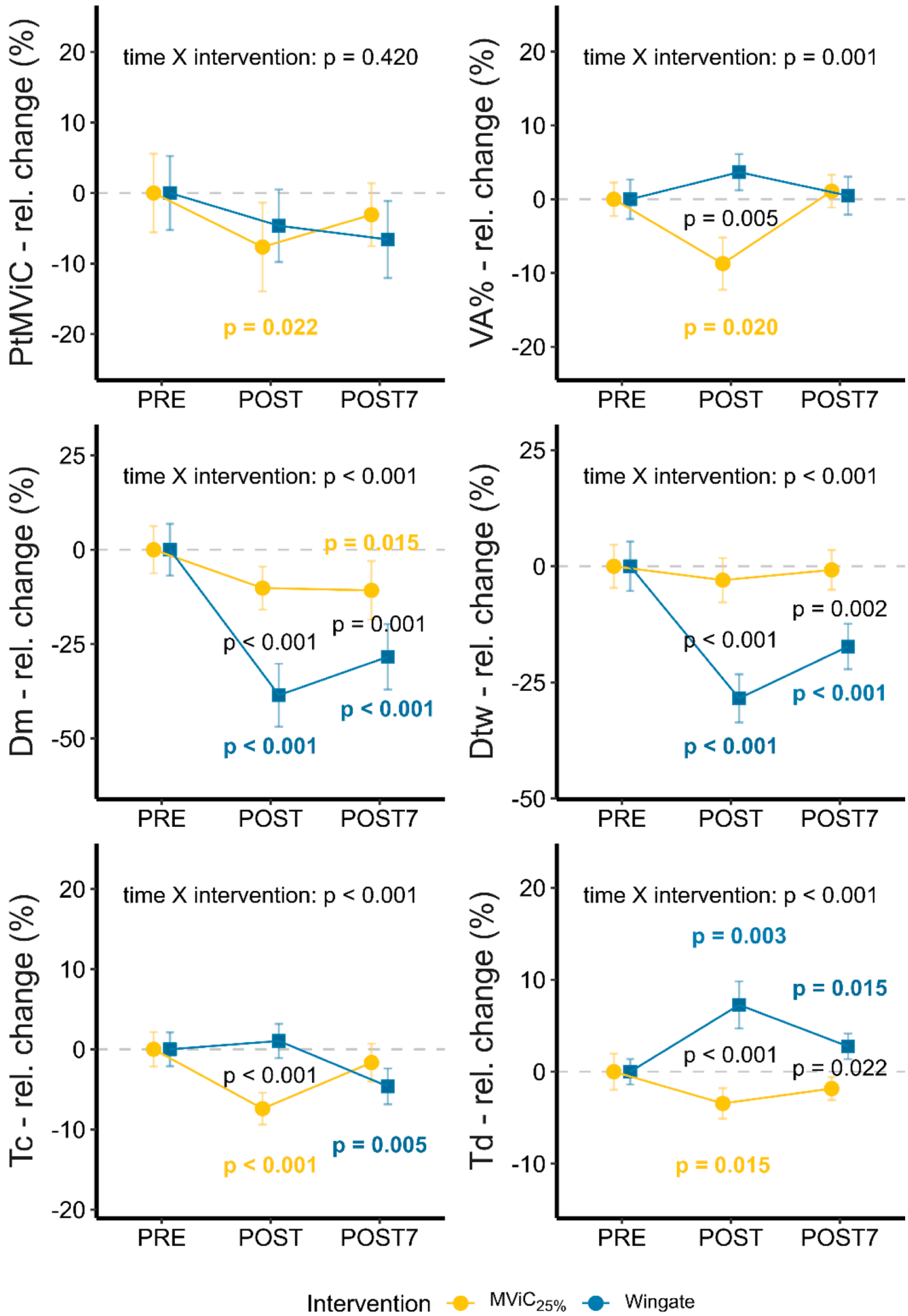

Fig. 2. Relative changes from baseline (mean and standard error) for force (PtMViC, VA%, Dtw) and TMG parameters (Dm, Tc, Td). Yellow circles represent MViC25% intervention; blue squares represent Wingate intervention. Yellow and blue text represent statistically significant differences from the baseline for $MViC_{25\%}$ and Wingate intervention, respectively. Black text represents statistically significant differences in contrasts between $MViC_{25\%}$ and Wingate interventions.

Second, Dtw represents the summation of torques produced in all electrically stimulated muscles in the joint. Depending on the motor task, muscles have different roles within a joint, which could result in distinct expressions of fatigue within the same muscle group (Martín-San Agustín et al. 2020). For example, a recent study (Martín-San Agustín et al. 2020) reported unchanged Tc in the rectus femoris, whereas vastus lateralis Tc and vastus medialis Tc were significantly reduced following an intervention aimed to induce peripheral fatigue (i.e., 70% of MViC). Therefore, we can speculate that quadriceps femoris heads were affected differently by the exercise interventions performed in this study. It seems that exercise-induced changes in Dtw may misrepresent the changes in torque displayed by distinct quadriceps heads. Although it was not measured in this study, we can assume that diagnostic accuracy differs according to motor task and evaluated muscle within a joint.

In line with previous findings (Martín-San Agustín et al. 2020), the current study suggests that TMG parameters such as Dm and Tc can be used to monitor NMF. Compared to functional testing and traditionally induced electrical twitches, we would like to point out several advantages of using the TMG technique for NMF assessment. First, supramaximal percutaneous nerve stimulation used to assess Dtw might be painful and unpleasant for some individuals (Place and Millet 2020).

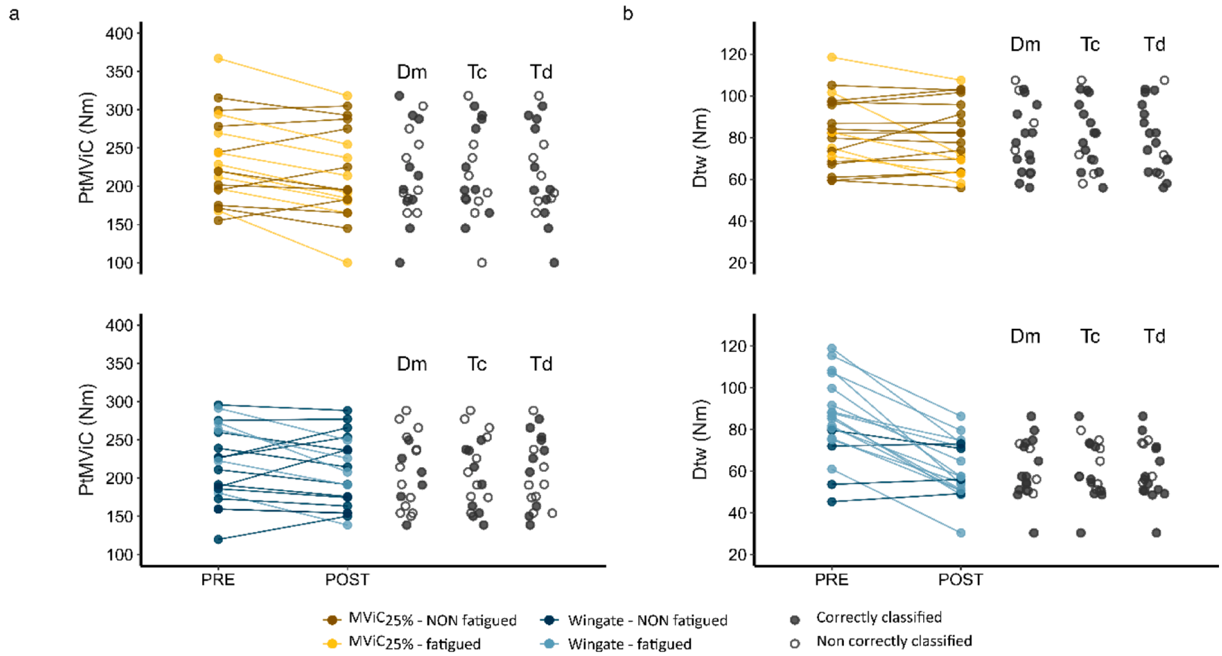

Fig. 3. Connected lines represent individual PRE- to POST-intervention data for PtMViC (A) and Dtw (B). Yellow and brown lines denote participants categorized as fatigued or non-fatigued, respectively, for $MViC_{25\%}$ intervention. While, light and dark blue lines represent participants categorized as fatigued and non-fatigued, respectively, for the Wingate intervention. Individual dots on the right of each subplot show TMG parameters (Dm, Tc, Td) for participants that were accurately classified as fatigued (filled circles) or misclassified (empty circles) in comparison to PtMViC and Dtw values. Note that participant classification was based on SWC metrics.

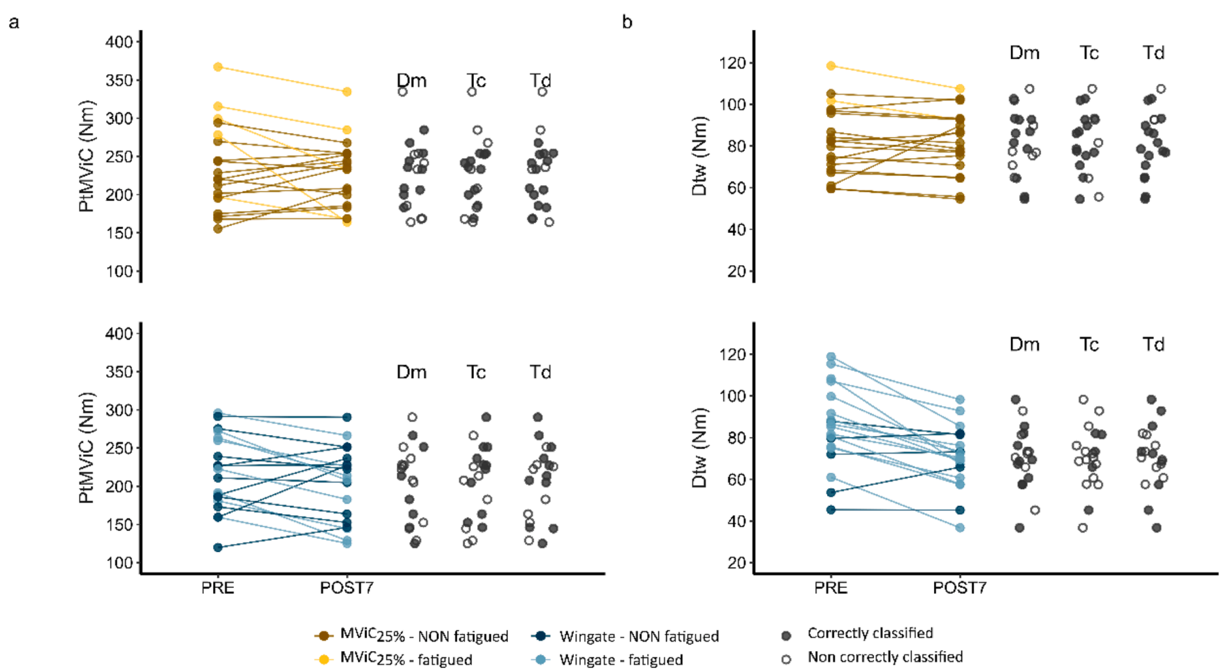

Fig. 4. Connected lines represent individual PRE to POST7 data for PtMViC (A) and Dtw (B). Yellow and brown lines denote participants categorized as fatigued or non-fatigued, respectively, for $MViC_{25\%}$ intervention. While, light and dark blue lines represent participants categorized as fatigued and non-fatigued, respectively, for the Wingate intervention. Individual dots on the right of each subplot show TMG parameters (Dm, Tc, Td) for participants that were accurately classified as fatigued (filled circles) or misclassified (empty circles) in comparison to PtMViC and Dtw values. Note that participant classification was based on SWC metrics.

This can be avoided by using a magnetic stimulation device or large electrodes placed proximally to characterise neural and contractile properties of the knee extensor muscles (Place and Millet 2020). Although TMG uses percutaneous electrical stimulation of a similar intensity compared to nerve stimulation (110 mA vs 90–160 mA respectively), the uses of larger electrodes placed on the muscle belly provide a less unpleasant experience. After a short familiarisation, the initial discomfort is dimmed. Second, Dtw cannot be measured from nerve stimulation of every muscle, even when the nerve is superficial enough. For example, stimulation of the musculocutaneous nerve to evoke a motor response of the elbow flexors induce co-contraction of the elbow extensors invalidating the mechanical response (Millet et al. 2011).

Table 3
Diagnostic accuracy data derived from contingency tables.

	AUC		DE		SN		SP		PPV		NPV		Y	
	POST	POST7	POST	POST7	POST	POST7	POST	POST7	POST	POST7	POST	POST7	POST	POST7
Dtw (Nm)														
Dm (mm)	0.73	0.59	0.74	0.58	0.56	0.50	0.90	0.69	0.83	0.69	0.69	0.50	0.46	0.19
Tc (ms)	0.67	0.43	0.66	0.50	0.94	0.86	0.40	0.00	0.59	0.54	0.89	0.00	0.34	−0.14
Td (ms)	0.77	0.63	0.76	0.66	0.94	0.82	0.60	0.44	0.68	0.67	0.92	0.64	0.54	0.26
CV10 (m/s)	0.68	0.61	0.68	0.58	0.50	0.41	0.85	0.81	0.75	0.75	0.65	0.50	0.35	0.22
CV90 (m/s)	0.70	0.58	0.71	0.55	0.56	0.41	0.85	0.75	0.77	0.69	0.68	0.48	0.41	0.16
PtMViC (Nm)														
Dtw (Nm)	0.59	0.59	0.58	0.60	0.64	0.64	0.54	0.54	0.72	0.72	0.38	0.43	0.18	0.18
Dm (mm)	0.47	0.47	0.42	0.45	0.29	0.40	0.64	0.54	0.58	0.62	0.35	0.32	−0.07	−0.06
Tc (ms)	0.43	0.44	0.50	0.58	0.71	0.88	0.14	0.00	0.59	0.63	0.22	0.00	−0.15	−0.12
Td (ms)	0.51	0.57	0.55	0.63	0.67	0.76	0.36	0.38	0.64	0.70	0.38	0.45	0.02	0.14
CV10 (m/s)	0.41	0.45	0.37	0.39	0.25	0.28	0.57	0.62	0.50	0.58	0.31	0.31	−0.18	−0.10
CV90 (m/s)	0.43	0.53	0.39	0.47	0.29	0.36	0.57	0.69	0.54	0.69	0.32	0.36	−0.14	0.05

AUC – area under the curve in Receiver Operating characteristic curve analysis; ***DE*** – Diagnostic effectiveness; ***SN*** – Sensitivity; ***SP*** – Specificity; ***PPV*** – Positive predictive value; ***NPV*** – Negative predictive value; ***Y*** - Youden's index.

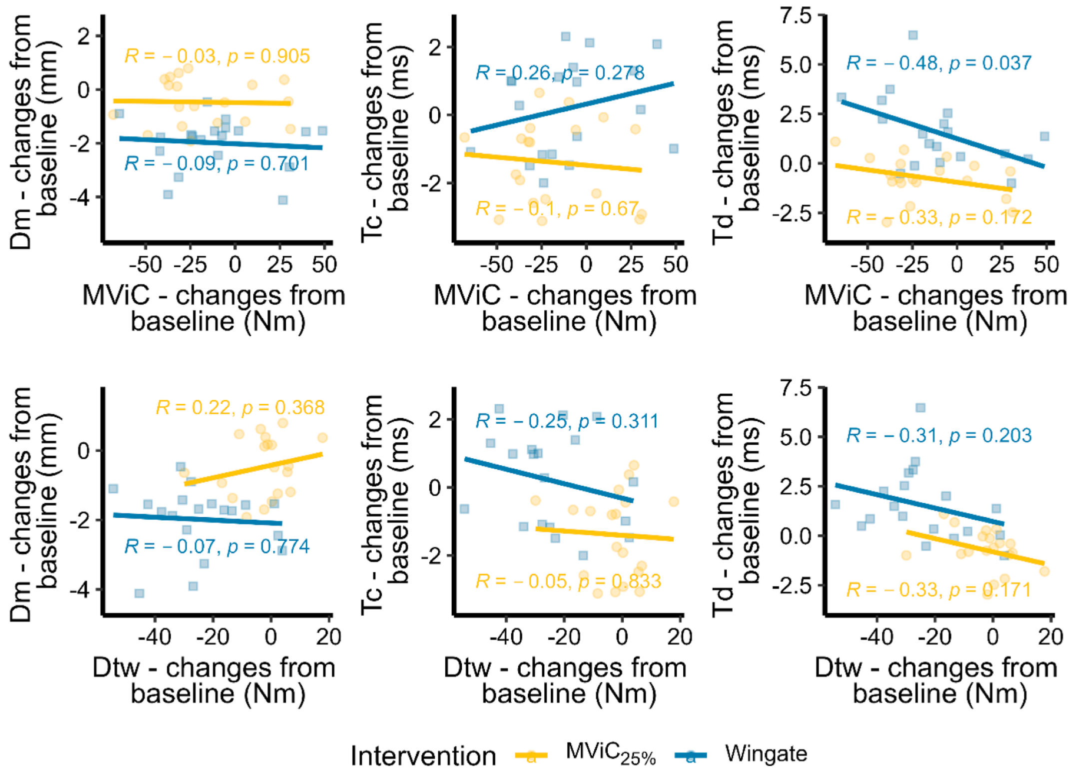

Fig. 5. Correlations between changes in TMG parameters (Dm, Tc and Td) and changes in torque parameters (MViC and Dtw) from PRE to POST. Yellow circles and blue squares represent MViC25% and Wingate intervention, respectively.

However, some studies demonstrated that electrical stimulation using large electrodes (15 × 9 cm) placed on the muscle belly are more pleasant and can be used to reliably detect muscle twitches (Rodriguez-Falces and Place 2013; Place and Millet 2020). Third, Dtw can only be measured in isometric conditions; thus, special dynamometers equipped with load cells should be used for each joint. By contrast, TMG can be assessed in isolation, without using additional equipment.

Some limitations of the study design must be considered. First, even though the sample size was prospectively calculated to allow adequate statistical power for repeated measures ANOVA, the sample size was relatively small for the diagnostic accuracy analysis, lowering the confidence in ROC analysis and contingency table results. Second, the study was performed on recreationally trained participants, which makes it difficult to translate the results of the current study to other participants of interest like children, well-trained athletes or older individuals. Third, M−wave measurements, which could offer valuable insights into sarcolemmal excitability and might be substantially impacted during fatigue, were not included due to technical constraints (strong artifacts arising from muscle belly stimulation) encountered during TMG measurements. Additionally, the submaximal nature of TMG stimulation renders comparisons with supramaximal twitch stimuli less reliable. Fourth, it is worth mentioning that the classification of participants as fatigued might not be directly applicable to a different population or generalized, given that the threshold used to calculate SWC is arbitrarily chosen and alternative metrics could yield different results. Nevertheless, this potential limitation does not undermine the overall validity of the findings within the present study.

Based on the results of this study, we can speculate that TMG could be a useful tool for assessing within-training fatigue in training optimisation and injury prevention of muscles of interest. For example, TMG can be easily assessed on the vastus lateralis muscles between runs in repeated sprinting training.

6. Conclusion

The results of the present study show that TMG parameters are selectively altered after two different fatiguing interventions. Dm decreased after both the MViC25% and Wingate protocols, whereas Tc shortened only after the MViC25% intervention. Moreover, TMG parameters showed good diagnostic efficacy in detecting peripheral fatigue during electrically triggered contraction – Dtw, whereas, in contrast, they showed poor ability to detect NMF assessed by voluntary contraction – PtMViC. Therefore, caution should be used when interpreting TMG results after exercise-induced fatigue, as TMG parameters are more accurate when detecting changes in muscle contractile mechanisms. Thus it is advisable to use TMG in combination with other methods to reliably detect peripheral and central contributions of fatigue.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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