



Reduced radial displacement of the Gastrocnemius Medialis muscle following electrically elicited fatigue

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1 Abstract

2 **Context:** Assessments of skeletal muscle functional capacity often necessitate maximal
3 contractile effort, which exacerbates muscle fatigue or injury. Tensiomyography (TMG) has
4 been investigated as a means to assess muscle contractile function following fatigue;
5 however observations have not been contextualised by concurrent physiological measures.

6 **Objective:** The aim of the present investigation was to measure peripheral fatigue-induced
7 alterations in mechanical and contractile properties of the plantar flexor muscles through
8 non-invasive TMG concurrently with maximal voluntary contraction (MVC) and passive
9 muscle tension (PMT) in order to validate TMG as a gauge of peripheral fatigue. **Design:**
10 Pre- and post-test intervention with control. **Setting:** University laboratory. **Participants:**
11 Twenty-one healthy male volunteers. **Interventions:** Subjects plantar flexors were tested for
12 TMG parameters, along with MVC and PMT, before and after either a 5 minute rest period
13 (control) or a 5 minute electrical stimulation intervention (fatigue). **Main Outcome**
14 **Measures:** Temporal (contraction velocity) and spatial (radial displacement) contractile
15 parameters of the Gastrocnemius Medialis were recorded through TMG. MVC was
16 measured as an indicator of muscle fatigue and PMT was measured to assess muscle
17 stiffness. **Results:** Radial displacement demonstrated a fatigue-associated reduction ($3.3 \pm$
18 1.2 vs. 4.0 ± 1.4 mm vs, $p=0.031$), while contraction velocity remained unaltered.
19 **Additionally, MVC significantly declined by 122.6 ± 104 N ($p<0.001$) following stimulation**
20 **(fatigue). PMT was significantly increased following fatigue (139.8 ± 54.3 vs. 111.3 ± 44.6**
21 **N, $p=0.007$). Conclusion:** TMG successfully detected fatigue, evident from reduced MVC,
22 **by displaying impaired muscle displacement, accompanied by elevated PMT. TMG could**

23 be useful in establishing fatigue status of skeletal muscle without exacerbating the
24 functional decrement of the muscle.

25

26 **Key words:** muscle contractile properties, maximal voluntary contraction, TMG, passive
27 muscle tension, peripheral fatigue

28

29 Introduction

30 Muscle fatigue is characterised by a decrease in the external force or torque generating
31 capacity,¹ and/or by impairment in peak power output.² The manifestation and magnitude
32 of this reduced function depends upon multiple factors including the muscle contraction
33 mode,¹ the nature of the fatigue protocol³ and the source of the fatigue.⁴ Fatigue-related
34 alterations of skeletal muscle can be observed, amongst other factors, by changes in its
35 contractile and mechanical properties.

36 Since fatigue is a condition that affects both athletic performance and clinical mobility, the
37 need for a valid monitor of muscle response is important to enable optimal management of
38 athletes and patients. In situations of muscle fatigue, or indeed musculoskeletal injury, it is
39 impractical to assess muscle function through a measure which makes use of voluntary
40 efforts (i.e. MVC), due to centrally mediated inhibition.⁵ Furthermore, the potential for
41 aggravation of any damage to the musculoskeletal unit cannot be ruled out. Having been
42 developed over the last 15 years, tensiomyography (TMG) is a portable and non-invasive
43 means of measuring muscle response through combined use of sub-maximal (below
44 voluntary maximal activation) electrical stimulus and a digital displacement sensor,⁶⁻⁸ similar

45 to that used in mechanomyography.⁹ TMG records spatial and temporal parameters of the
46 radial displacement of the muscle belly in response to electrical stimuli¹⁰ and is reliable
47 within¹¹ and between days.¹² Furthermore, TMG has also demonstrated good long-term
48 stability following fatigue¹³ and has displayed significant interclass correlation coefficient
49 with decline and recovery of maximal voluntary contraction (MVC) following exercise-
50 induced muscle damage.¹⁴ **In particular muscle displacement (Dm) and contraction time**
51 **(Tc) have shown greatest stability.**¹²

52 TMG has successfully detected fatigue-associated changes following ultra-endurance
53 triathlon,¹⁵ and resistance exercise.¹⁶ However, these studies report inconsistent results in
54 the fatigue-induced alteration of the TMG parameters, perhaps due to the vast differences
55 in the fatigue protocols administered and the different muscles measured. Furthermore,
56 previous studies have failed to relate the TMG alterations to any valid functional measure,
57 such as maximal voluntary contraction (MVC) or passive muscle tension (PMT), which leaves
58 the physiological interpretation of the TMG data open to question. Therefore, in order to
59 effectively provide meaningful validation of TMG measurement to local fatigue it is
60 important to overcome this limitation. In practical terms, sub-maximal TMG could offer an
61 attractive measure for sport and medical practitioners in their assessment of muscle
62 response and status following fatigue based activity without necessitating voluntary
63 contractile effort.

64 Accordingly, the aim of the present investigation was to evaluate peripheral fatigue-induced
65 alterations in mechanical and contractile properties of the Gastrocnemius muscle, as
66 measured by TMG. MVC and PMT were measured before and after intervention, to quantify
67 the extent of muscle fatigue, and allow us to better interpret changes in TMG response; to

68 our knowledge this has not been previously reported. **It was hypothesised that a reduction**
69 **in size and velocity of muscle displacement would indicate muscle fatigue in line with**
70 **impairments in muscle function (decreased MVC) and elevated muscle stiffness (increased**
71 **PMT). The findings of this study could help to establish TMG as a non-invasive alternative**
72 **to quantify muscle fatigue.**

73

74 **Methods**

75 *Participants*

76 Twenty-one healthy males with a mean (\pm SD) age, height, and mass of 21.3 ± 3.4 years,
77 182.0 ± 6.1 cm, and 79.5 ± 10.0 kg, volunteered and gave their written informed consent to
78 participate in this study. **All participants were recreationally active and free from injury.**
79 **Females were excluded from the study in order to maintain cohort homogeneity.** The
80 study was performed in accordance with the principles outlined in the *Declaration of*
81 *Helsinki* and was approved by the local research ethics committee.

82 *Design*

83 Mechanical and contractile properties of the right Gastrocnemius Medialis (GM) were
84 monitored using TMG (BMC Ltd, Ljubljana). **GM is one of the propulsive muscles,**
85 **fundamental to different types of human locomotion and is located superficially, making it**
86 **clearly measurable by TMG.** Participants were also tested for PMT and MVC of the right
87 plantar flexors. Testing was carried out on two occasions, one week apart, as illustrated in
88 figure 1. Measurements were taken at a number of time points before and after either the
89 control or fatigue intervention, according to the following order: TMG and PMT

90 (measurement 1, M1), warm-up, TMG and PMT + MVC (M2), either control or fatigue
91 intervention in random order, TMG and PMT + MVC (M3). Both TMG and PMT
92 measurements were recorded three minutes after the warm-up, and after the control or
93 fatigue intervention, to limit the effects of post activation potentiation in the GM muscle.¹⁸
94 Participants reported to the laboratory on the morning of each experimental trial in a fasted
95 and rested state. Twenty-four hour dietary intake records were completed on the day
96 preceding each trial, and participants were instructed to replicate their dietary intake before
97 each visit.

98 *Warm-up*

99 Participants warmed up by cycling at a low intensity (75 Watts) on an electromagnetically
100 braked cycle ergometer (Lode Ergometer, Netherlands) for 5 minutes at a cadence between
101 80 and 90 rpm.

102

103 *TMG protocol*

104 **TMG measurements were performed exactly as described by Ditroilo et al (2013).¹³ Briefly,**
105 **participants lay in a prone position on a padded bench. A foam pad, placed slightly**
106 **proximal to the ankle joint, supported a knee flexion angle of around 5°. The digital**
107 **displacement transducer (TMG–BMC Ltd, Ljubljana) was then positioned perpendicular to**
108 **the muscle belly of the right GM with an initial pressure of 1.5×10^{-2} N/mm², controlled by**
109 **consistently retracting the spring-loaded transducer probe to 50% of its length.** This
110 measuring position was selected by first manually palpating the GM to locate the thickest
111 part of the muscle and then later, if needed, the position was slightly adjusted to obtain the

112 highest mechanical response with the least amount of co-activation when externally
113 stimulated; co-activation was typically identified by a second peak in the TMG response
114 curve. Once the appropriate position was obtained, it was marked with a permanent marker
115 pen to ensure exact uniformity when the sensor was repositioned for subsequent
116 measurements. The centre point of each of the 2 stimulating electrodes (5cm²) (Axelgaard,
117 USA) was located approximately half way from the position of the sensor (~5cm) to the start
118 of the respective GM proximal distal tendons. After each measurement these electrodes
119 were left in place and unplugged to avoid any possible changes in muscle response via
120 alterations in surface electrodes distance.¹⁰ A single 1ms wide stimulation pulse was
121 delivered, which applied initial current amplitude of 20mA. **This amplitude was**
122 **progressively increased by 10mA increments until maximal response was obtained, i.e. no**
123 **further displacement of the muscle belly could be produced as identified by a plateau in**
124 **the twitch response curves.** In order to minimize the effects of fatigue and potentiation,
125 rest periods of 10 seconds were allowed between each stimulation pulse. Typical maximal
126 responses were observed at amplitude between 40 and 70mA and only the output data for
127 that particular stimulation intensity were used for analysis. Figure 2 shows a typical TMG
128 displacement/ time curve before and after the administration of the fatigue protocol.
129 Output parameters were extracted and analysed from each maximal twitch response:¹⁰
130 *Displacement* (Dm), the extent of maximal radial deformation (mm) of the muscle belly
131 during contraction; *Contraction velocity* (Vc), the rate (mm·s⁻¹) of contraction between 10%
132 and 90% of maximal displacement. **Raw data were extracted from the TMG software and**
133 **Vc was calculated according to the formula: [Vc = Dm80/Tc] where Tc = contraction time**
134 **between 10% and 90% of peak radial displacement of the muscle belly; Dm80 = the radial**
135 **displacement occurring during the time period of Tc.**¹⁹ Muscle contraction time (Tc) has

136 been widely reported in previous studies,^{10,15-16} as the temporal change from 10%-90% of
137 muscle Dm, providing a value relative to the spatial characteristics of each muscle. However,
138 when assessing intramuscular alterations, i.e. pre- and post- fatigue, the significance of
139 calculating Tc in this manner should be questioned. **Indeed, in the absence of signal**
140 **latency, it is possible that a decrease in Dm could associate with a decrease in Tc, when**
141 **calculated as described above. Apparent decreases in Tc, suggesting a faster twitch**
142 **response, could be reported simply as a result of reduced overall muscle contraction (Dm).**
143 It was therefore proposed that assessment of Vc could provide greater insight, when
144 monitoring the fatigue status of a muscle.

145 **Maximal voluntary contraction (MVC) protocol**

146 **Plantar flexor isometric MVC was performed in an isokinetic dynamometer (Kin-Com,**
147 **Chattanooga Group Inc., USA). The participant had their right foot fastened securely into**
148 **the plantar flexion attachment and was also held in place using two securely fastened**
149 **shoulder straps and a lap belt. A 90° ankle angle to the tibia was ensured for each subject**
150 **(figure 3). Following two sub-maximal warm-up sets, participants each performed a 5-s**
151 **MVC of the right plantar flexors. Three trials of the MVC were completed with 60s**
152 **recovery between attempts. Participants were verbally motivated to ensure the greatest**
153 **possible effort for the duration of all attempts.**

154

155 *Passive muscle tension (PMT) protocol*

156 **Measurements of PMT of the right plantar flexors were made on the same isokinetic**
157 **dynamometer, with a set-up identical to the MVC protocol (figure 3). Participants were**

158 **instructed to completely relax once in position, and the mean passive force of the ankle**
159 **flexed at 90° was recorded during a period of 15s, as a measure of passive muscle tension**
160 **in the plantar flexors in a static position.**²⁰ A single measure was taken to determine PMT,
161 as subsequent stretching of the ankle joint would cause an accumulative stretch effect. **An**
162 **intra-session reliability, as measured by the intraclass correlation coefficient, ≥ 0.80 has**
163 **been previously reported for this type of measurement.**²¹

164 *Fatigue protocol*

165 **The fatigue intervention used in the current investigation differs from previous studies in**
166 **this area**^{15,16} **in a number of key ways. Firstly, fatigue was induced locally with a low**
167 **frequency stimulation that will necessitate a prolonged recovery, compared to higher**
168 **frequency fatigue.**¹⁷ **Secondly, as motor unit discharge rarely exceeds 30Hz during**
169 **voluntary contraction,**¹⁷ **low frequency stimulus can be considered a more functionally**
170 **relevant intervention. Finally, as TMG is a passive and peripheral measurement it will**
171 **minimise confounding variables such as the variability of central control factors.** Whilst
172 remaining secured in the same position as for PMT the participants received the fatigue
173 intervention, which consisted of a 5 minute electrical stimulation of the right GM, to evoke
174 fatigue. The stimulation protocol involved a train of 15 electrical pulses (1 every 100ms)
175 with a 1 second gap before the start of each subsequent train. The protocol lasted 5 minutes
176 and participants were asked to endure the maximum current they could, to ensure fatigue
177 (~110 mA). The control intervention consisted of the same positioning but receiving no
178 stimulation for a period of 5 minutes to account for the effect of time. Also in the same
179 position, with the ankle placed at 90°, isometric MVC of the plantar flexors was measured,
180 before and after both intervention and control, to assess whether fatigue occurred. Each

181 participant performed three 5 second MVCs, with 60 seconds recovery between attempts.
182 Participants were provided with consistent verbal motivation to ensure maximal effort
183 throughout.

184 *Statistical Analysis*

185 All data are presented as mean \pm SD. **After testing for assumption of normality of the**
186 **dependent variables and log-transforming where necessary (i.e. when not normally**
187 **distributed)**, a 3 (measurements: before warm-up, M1; after warm-up, M2; after
188 intervention, M3) x 2 (condition: control and fatigue intervention) ANOVA with repeated
189 measures on both factors was used to detect differences in PMT and TMG parameters as a
190 result of the fatigue/ control protocol. Where a significant F value was found a Tukey post
191 hoc test was used to identify where any significant difference occurred. Paired *t-test* was
192 conducted to compare the pre- / post-fatigue MVC difference between the control and
193 fatigue intervention. Effect size (ES) was also calculated using eta-squared (η^2) and
194 interpreted as small (0.01), moderate (0.06) or large (0.14).²² The percentage differences
195 between control and fatigue intervention were also calculated and interpreted based on the
196 minimum detectable change as reported in a previous reliability study.¹³ An alpha level of p
197 < 0.05 was considered statistically significant. Statistical analysis was performed using
198 Statistica version 10 (Statsoft LTD, Bedford, UK).

199

200 **Results**

201 *TMG parameters*

202 **Dm demonstrated a fatigue-associated alteration. A significant main effect for 'condition'**
203 **($F=7.2$, $p=0.002$, $\eta^2 = 0.27$) was documented for Dm, along with a post-hoc difference at**
204 **M3 demonstrating that the fatigue condition was significantly lower than control**
205 **condition (3.3 ± 1.2 vs 4.0 ± 1.4 mm, $p=0.031$; figure 4), with a percentage difference of**
206 **17.7%. No significant difference was found for any of the factors or their interaction for**
207 **Vc, which exhibited 121.8 ± 43.2 vs 124.7 ± 45.5 mm·s⁻¹ at M1, 121.3 ± 45.7 vs 124.9 ± 44.7**
208 **mm·s⁻¹ at M2, 131.3 ± 44.6 vs 139.8 ± 50.6 mm·s⁻¹ at M3.**

209 *MVC and PMT*

210 **Plantar flexor isometric MVC exhibited a significant interaction 'condition x measurement'**
211 **($F=12.4$, $p=0.001$, $\eta^2 = 0.91$) with post-hoc analysis showing a significant decline following**
212 **the fatigue intervention (-122.6 ± 104 N; $p<0.001$) but not following control (-25.7 ± 71.3**
213 **N, $p=0.115$). The PMT exhibited a significant interaction 'condition x measurement' ($F=5.9$,**
214 **$p=0.005$, $\eta^2 = 0.23$). The post-hoc analysis revealed at M3 that fatigue caused significantly**
215 **more tension than control (139.8 ± 54.3 vs. 111.3 ± 44.6 N, $p=0.007$; figure 5), with a**
216 **percentage difference of 20.4%.**

217

218 **Discussion**

219 This study was designed to evaluate the validity of TMG, as a sub-maximal assessment
220 method, to detect local muscular fatigue, against functional physiological measures. Fatigue
221 of the GM was achieved, as evidenced by the significant decline in peak force (MVC), which
222 was absent following the control condition. This alteration in functional capacity of the
223 muscle was associated with a significant decline in TMG Dm, similar to previous studies

224 following dynamic fatigue.^{16,23} In addition, plantar flexor PMT increased following the
225 fatigue intervention suggesting that the GM skeletal muscle-tendon unit became stiffer.
226 Despite these alterations, muscle twitch Vc appeared to remain unaffected by fatigue.

227 When considering the physiological effects of fatigue there are a number of important
228 variables to examine. We have previously demonstrated that during fatigued voluntary
229 contractions muscle fibre conduction velocity declines due to a reduction in extracellular
230 pH.²⁴ It is likely that this occurs due to a pH driven alteration of the Na⁺ and K⁺ gradient
231 across the sarcolemma²⁵ and impairs action potential propagation. Therefore, during TMG
232 measurement the electrical stimulus applied to the surface of the fatigued muscle should
233 result in a slowing down of the action potentials propagated to reduce Ca²⁺ release and
234 subsequent excitation-contraction (E-C) coupling. Low-frequency fatigue, as characterized
235 by a disproportionate reduction in force at lower stimulation frequencies, has been
236 associated with E-C uncoupling.²⁶ It has been suggested that E-C uncoupling is attributable
237 to, amongst other factors, impaired Ca²⁺ transport via Ryanodine receptor channels in the
238 triadic compartment.²⁷ Furthermore, other contributing factors will be from increased Pi
239 which can push the cross-bridge into a low force generating status²⁸ and may also cause
240 actin and myosin to detach.²⁹ These altered characteristics of muscle function will inevitably
241 impair its force generation capacity, as shown by the significant decline in MVC.

242 **It has been reported previously that a stiffer muscle, as we have evidenced here by the**
243 **rise in PMT (figure 5), will be associated with a reduced TMG Dm measurement.⁸ In**
244 **contrast to the current findings, Garcia-Manso et al¹⁵ showed an *increase* in Biceps**
245 **Femoris TMG Dm associated with fatigue following an ironman triathlon. The precise**
246 **reasons for this disparity are unclear; however Morin, Tomazin, Edouard, & Millet³⁰**

247 showed a small decline in whole leg stiffness during a running task, following a 24-hour
248 marathon. These authors postulated that central fatigue would have been apparent which
249 would have been linked to altered peripheral feedback from muscle afferents triggered
250 from cytokines. This, we suggest, may be why an increase in TMG Dm was observed
251 following an ironman triathlon when a decline has been reported with other types of
252 fatigue from far shorter contractile/ exercise durations. Other studies have also
253 demonstrated alterations in Dm alongside muscle architectural changes. Firstly, Pisot et al,⁸
254 showed that following 35 days of bed rest, TMG Dm increased alongside the reduction in
255 muscle thickness which the authors suggested would have contributed to reduced muscle
256 stiffness. Secondly, we previously demonstrated³¹ that altering the length of the muscle will
257 determine the magnitude of TMG parameters, such that longer muscle length, as achieved
258 through altered joint angle, results in reduced Dm. Thirdly, although not relating the decline
259 in TMG Dm to muscle stiffness changes, other studies^{16,23} have also demonstrated a decline
260 in TMG Dm following fatigue, suggesting that this is an important parameter when assessing
261 the muscle status in this regard.

262 In the present study we observed decreases in TMG Dm without significant alterations in Vc.
263 Given previously described reductions in action potential propagation and muscle fibre
264 conduction velocity, associated with fatigue,²⁴ it may have been expected that TMG Vc
265 would be observed to decline post-fatigue, in concurrence with Dm. It is plausible that the
266 lack of significant alteration in Vc is due to the high degree of inter-individual variability
267 associated with the measurement. **Indeed, changes between measurements (M1, M2, M3)**
268 **ranged from about -25% to +25% between participants.** The comparably low amplitude of
269 the electrical stimulation used to elicit the peak TMG response, may perhaps render these

270 data difficult to compare to existing conduction velocity findings. As such, it may be
271 inappropriate to consider alterations in the speed/ time component of the TMG response,
272 when assessing muscle fatigue, with the focus instead being placed on spatial alterations
273 (Dm), which we have shown here to be indicative of increased muscle stiffness.

274 As with any type of physiological measurement there will be a degree of variability. We have
275 previously accounted for this variability with TMG measured under different muscle
276 conditions¹³ and shown Dm to be well within acceptable limits. Analogous to this is
277 establishing minimal detectable change so practitioners and researchers can be confident
278 that the given magnitude of observed change following any intervention is real and
279 physiologically significant. We have demonstrated in this study that the fatigue-altered Dm
280 parameter (17.7%) clearly exceeds the minimal detectable change thresholds of 15.1%.¹³
281 Furthermore, the effect size for the data presented in this study, as described by Cohen,²² is
282 “large” suggesting that this particular TMG measure is sufficiently sensitive to adequately
283 detect local muscular fatigue. **Nonetheless, a number of limitations must be considered.**
284 **Current findings can only be applied to a healthy, young male population. It remains to be**
285 **seen whether TMG measurements are sufficiently sensitive to detect fatigue associated**
286 **changes in alternative cohorts. Additionally, GM was selected for investigation as its**
287 **anatomical position facilitates measurement using TMG. Muscles which are not located**
288 **superficially, but may still be of interest, are not measureable using the methods**
289 **described herein.**

290 Conclusion

291 This is the first study to demonstrate that TMG was effective in detecting local muscular
292 fatigue in the GM. We propose that this response was directly related to increased stiffness

293 of the muscle from impaired contractile capacity. It should be emphasised that, when
294 assessing local muscular fatigue, Dm of the muscle is a valid measure, **however it remains**
295 **to be seen whether TMG has the sensitivity to detect any changes in Vc in a different**
296 **context.** The current findings have important implications for researchers and practitioners
297 seeking to establish fatigue status of skeletal muscle, with implications for prevention of
298 **over-training injuries** in sports-related activities. Given the **non-invasive and sub-maximal**
299 nature of this type of measurement, TMG can be used to determine local muscular fatigue
300 in patients who may be unable to exert the maximal effort required for voluntary muscle
301 function assessments. **Additionally, TMG measurements are exempt from the bias of**
302 **volitional effort and motivation, facilitating the incorporation of the procedure into**
303 **existing programmes.**³² Furthermore, TMG could be utilised regularly, as a monitoring
304 **tool, without fear of detriment to muscle function.**

305 Acknowledgements

306 

307

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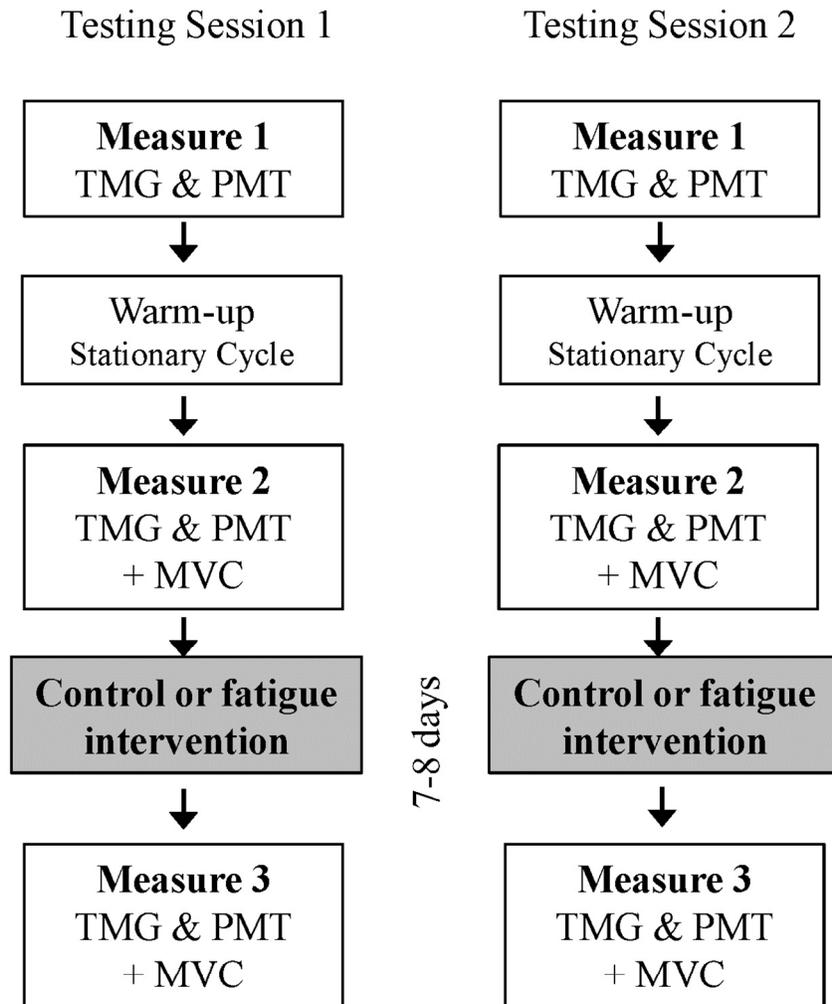


Figure 1. Schematic representation of the research design. TMG = Tensiomyography; PMT = passive muscle tension.

120x150mm (300 x 300 DPI)

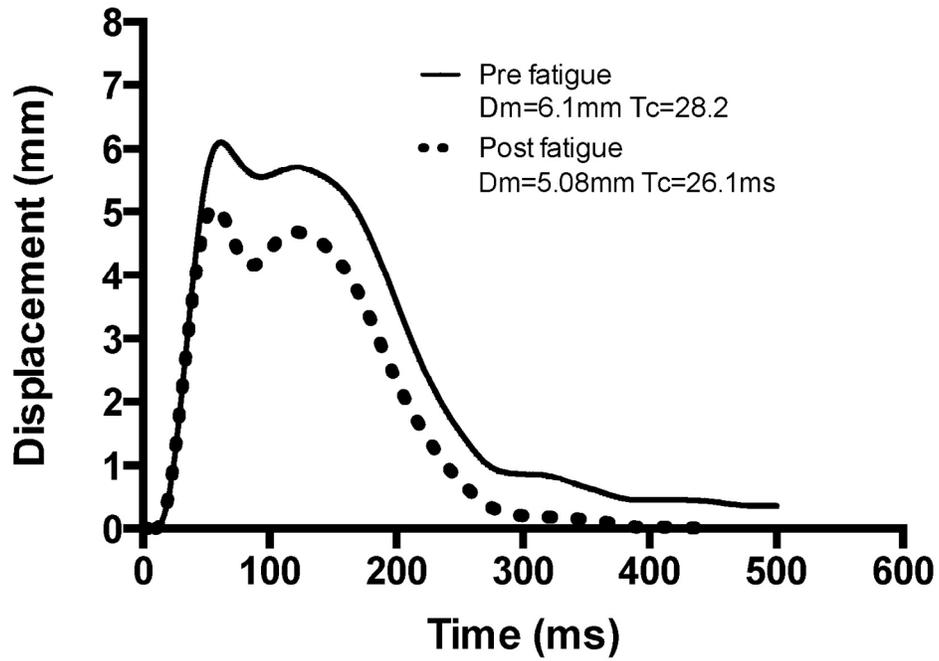


Figure 2. Typical displacement/ time curve of the tensiomyographic signal before and after the administration of the fatigue protocol. Dm = muscle displacement; Tc = contraction time.
150x110mm (300 x 300 DPI)



Figure 3. Isokinetic dynamometer setup for PMT and MVC assessment. Ankle flexed at 90° relative to the tibia.

342x192mm (300 x 300 DPI)

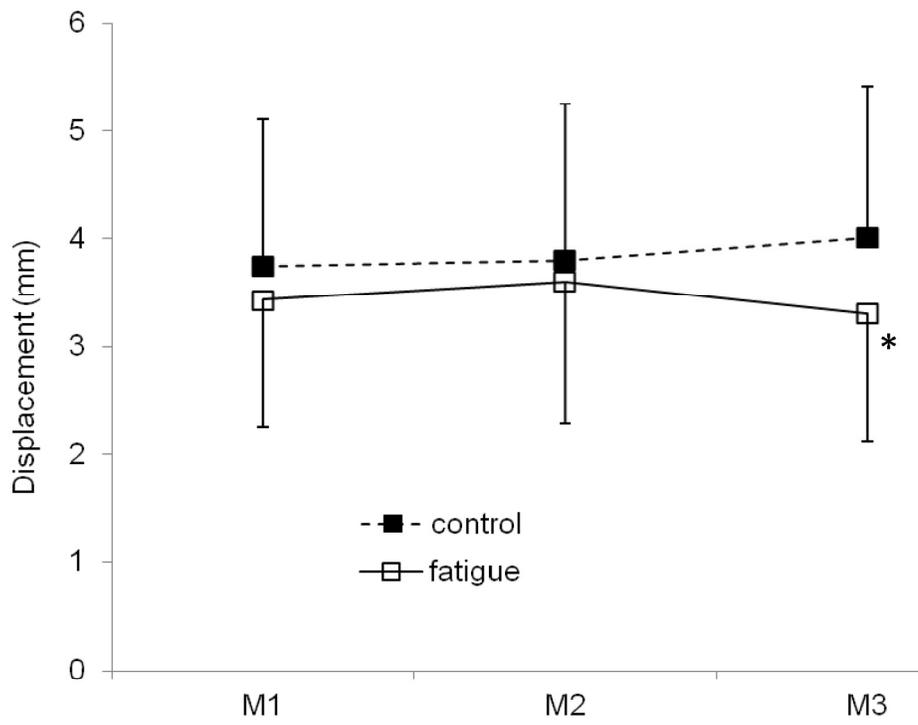


Figure 4. Average values (+ SD) of passive muscle tension as assessed on the isokinetic dynamometer at the three measurement points. * = significant different from 'control' at M3, $p < 0.01$.
442x383mm (96 x 96 DPI)

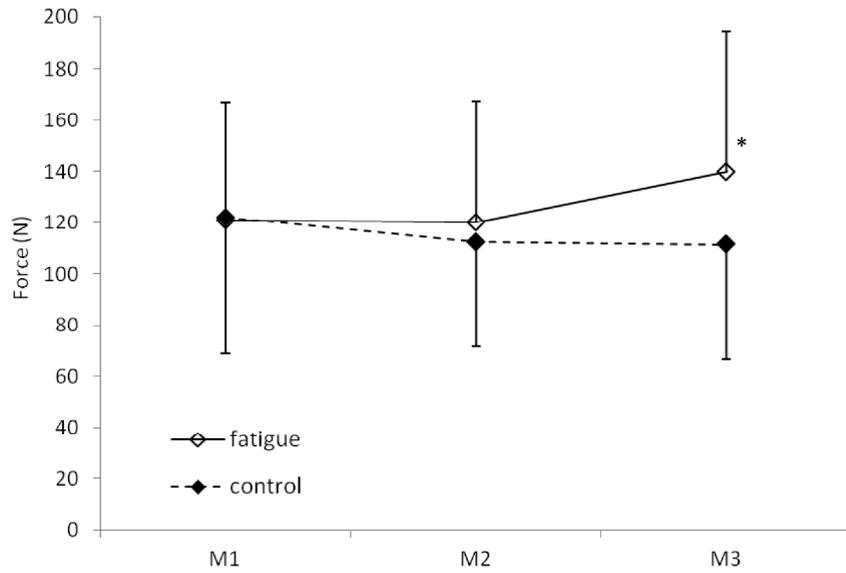


Figure 5. Average values (+ SD) of muscle displacement as assessed by tensiomyography at the three measurement points. * = significant different from 'control' at M3, $p < 0.05$.
254x190mm (300 x 300 DPI)