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Shoulder Tensiomyography and Isometric Strength in Swimmers Before and After a Fatiguing Protocol

Alex Buoite Stella, PhD*†; Andrea Cargnel, PT*; Alessandra Raffini, MEng, PhD student‡; Laura Mazzari, PT*; Miriam Martini, PT*; Miloš Ajčević, MEng, PhD‡; Agostino Accardo, MEng, PhD‡; Manuela Deodato, PT, PhD*; Luigi Murena, MD*†

*School of Physiotherapy, Department of Medicine, Surgery and Health Sciences, †Department of Medicine, Surgery and Health Sciences, and ‡Department of Engineering and Architecture, University of Trieste, Italy

Context: Shoulder muscles are active during front-crawl swimming to provide propulsion and stabilize the glenohumeral and scapulothoracic joints. Researchers have proposed that fatigue might contribute to altered activation of these muscles and represent a risk factor for injuries. Tensiomyography (TMG) might function as a noninvasive tool to detect changes in contractile measures of the skeletal muscles due to exercise-induced neuromuscular fatigue, though it has not yet been used in the shoulder muscles of swimmers.

Objective: To assess the effects of a fatiguing swimming protocol on shoulder muscle TMG measures and isometric strength in competitive swimmers.

Design: Cross-sectional study.

Setting: Swimming pool facility.

Patients or Other Participants: A total of 14 young front-crawl competitive swimmers (11 males and 3 females; age = 21 ± 3 years [range, 17–26 years], height = 1.78 ± 0.06 m, mass = 73.1 ± 9.2 kg).

Main Outcome Measure(s): Participants completed TMG and isometric strength assessments before and after 30-minute, high-intensity swim training. The TMG assessment was performed on 7 muscles of the shoulder according to front-crawl biomechanics and the applicability of the technique to obtain data, such as time to contraction and muscle-belly radial displacement. Isometric strength was assessed using a digital handheld dynamometer during shoulder flexion, extension, external rotation, and internal rotation.

Results: Fatigue induced a smaller radial displacement, mostly observable in latissimus dorsi (−1.0 mm; 95% CI = −1.7, −0.3 mm; P = .007) and pectoralis major muscles (−1.4 mm; 95% CI = −2.4, −0.4 mm; P = .007). Only shoulder extension showed an isometric strength reduction after the fatiguing protocol (−0.03 N/kg; 95% CI = −0.05, −0.01 N/kg; $F_{1,13} = 4.936$; P = .045; $\eta_p^2 = 0.275$).

Conclusions: This study provides preliminary evidence for the usefulness of TMG to detect fatigue-induced changes in contractile properties of the shoulder muscles in swimmers, in particular the latissimus dorsi and pectoralis major.

Key Words: fatigue, swimming, muscle, neuromuscular, contraction

Key Points

- Tensiomyography is a noninvasive tool to detect skeletal muscle contractile properties and could be used to evaluate the effects of fatigue in swimmers.
- In front-crawl swimmers, tensiomyography indicated increased indexes of fatigue in the latissimus dorsi and pectoralis major muscles.
- The maximal isometric strength of the extensor muscles decreased after a fatiguing swimming protocol.

Competitive swimming is a sport characterized by a large training volume, with an estimated exposure of the shoulder muscles and joint to between 16 000 and 25 000 rotations during a typical training week.[1,2] The activation of several muscles might contribute to fatigue after swim training. Researchers have reported that the shoulder is an area where fatigue and pain could commonly occur in swimmers. Indeed, these athletes often report shoulder pain and may develop shoulder overuse injuries.[1] Researchers have suggested that fatigue might affect the shoulder's strength, proprioception, and range of motion, representing possible risk factors for overuse shoulder injury[2]; indeed, decreased muscle endurance or either hypo- or hyperactivation of shoulder muscles could lead to abnormal movement of the glenohumeral and scapulothoracic joints and, consequently, continuous aggravation of susceptible tissues.[2–5] As such, determining the muscles that might be more influenced by fatigue in swimming might help clinicians recognize athletes at a higher risk of developing shoulder pain and design training and physiotherapy protocols aimed at strengthening and improving endurance in these specific muscles.

Tensiomyography (TMG) is a noninvasive technique that has been suggested to measure several mechanical contractile properties of skeletal muscle.[6,7] Researchers have reported that TMG can detect the effects of exercise-induced fatigue on the different muscles of the lower limbs and, in particular, decreased maximal radial displacement (D_m).[8–13] In the upper limb, TMG has been reported to be highly sensitive in detecting fatigue-induced changes in biceps brachii after high-volume and high-load resistance exercises.[14] Although isometric strength assessment and TMG-derived measures might reflect different aspects of fatigue-induced alterations in muscle contraction, the muscles presenting altered TMG measures (eg, decreased D_m) after a fatiguing protocol may be the same muscles that are primarily active during specific shoulder movements and present fatigue-induced reduction in isometric strength. Indeed, Hunter et al reported that exercise-induced muscle damage of the elbow flexors induced a reduction of maximal voluntary isometric contraction, rate of torque development, and TMG D_m.[15] As such, TMG could provide additional information about muscle contractile properties in swimming and might be associated with isometric strength before and after fatigue in specific shoulder movements.

The purpose of our study was to assess the effects of fatigue on shoulder muscles by concomitantly measuring isometric strength and TMG measures in healthy shoulders of young competitive swimmers before and after performing high-intensity swim training.

METHODS

Participants

Volunteers were recruited from local swim clubs to participate in this cross-sectional study between January and April 2023. Of the 16 swimmers who volunteered, 14 swimmers (11 males and 3 females; age = 21 ± 3 years [range, 17–26 years], height = 1.78 ± 0.06 m, mass = 73.1 ± 9.2 kg) who completed all assessments were included. Participant characteristics and training habits are reported in Table 1. Inclusion criteria were age between 16 and 35 years, participation in swimming for at least 3 years, a training volume of ≥4.5 h/wk, and use of the front crawl as the main swimming style. Participants were excluded if they had a history of acute or chronic muscular or joint disease of the tested shoulder or upper limb. All participants and their legal guardians provided written informed consent or assent, as appropriate, and the study was approved by the University of Trieste Ethics Committee (122/2022).

Study Protocol

All volunteers attended a first visit to the university laboratory, where we collected their characteristics, including information about training habits, and confirmed that they met the inclusion criteria. They familiarized themselves with the procedures of each assessment (ie, shoulder TMG and isometric strength evaluation). Training was repeated until participants were confident with the assessment techniques. They received a copy of the fatiguing protocol designed by the research team and an expert swimming trainer (A.C.), and they were recommended to try it in the following days. They were invited to the experimental session between 7 and 14 days after the first visit. The experimental session was conducted in a local swimming pool (depth = 25 m; water temperature range, 26°C–29°C). Measurements were collected in the morning at least 2 hours after participants woke. Participants were instructed to avoid strenuous training in the 48 hours before the study and to refrain from smoking and consuming alcohol the morning of the study. After arriving at the swim facility, they were asked to don their swimwear. The TMG and strength assessments were performed. Next, they performed the fatiguing protocol, consisting of 30 minutes of front-crawl swimming at different incremental intensities (Figure 1; see Supplemental Appendix, available online at https://dx.doi.org/10.4085/1062-6050-0265.23.S1); the overall exercise intensity was monitored with a waterproof heart rate monitor, with a heart rate of >70% the maximum for >90% of the training time and >80% for >30% of the training time. Participants were also asked to rate perceived exertion (rating of perceived exertion from 1 [*least exertion*] to 10 [*greatest exertion*]) during the different phases of the fatiguing protocol with respect to the training protocol, as reported in Supplemental Appendix and Figure 1. The TMG and isometric strength assessments were then repeated using the same measurement protocol within 20 minutes after completion of the fatiguing protocol. To reduce the influence of arm dominance, we randomly tested participants on their dominant or nondominant shoulder and according to the absence of any shoulder pain symptoms. The *dominant arm* was defined as the arm usually used for throwing an object.

Table 1. Participant and Training Characteristics of the Included Sample (N = 14)

Characteristic	Mean ± SD
Age, y	21 ± 3
Height, m	1.78 ± 0.06
Mass, kg	73.1 ± 9.2
Body mass index, kg/m^2	23.0 ± 1.6
Time training in swimming, y	13 ± 4
Training frequency, sessions/wk	6 ± 1
Training volume, h/wk	13 ± 2
	n (%)
Sex	
Female	3 (21)
Male	11 (79)
Competition level	
Regional	6 (43)
National or international	8 (56)

Instrumentation

TMG. The TMG is a mechanomyographic method that has been used in several studies and functions as a promising tool to assess in vivo skeletal muscle mechanical contractile properties; unlike other methods, such as myotonometry or shear-wave elastography, it is based on D_m after electrical stimulation, presenting an "active" response of the muscle.[7,16,17] A sensitive digital displacement sensor (TMG-BMC, Ltd) placed on the skin surface at the measuring site of the muscle of interest was used to record muscle-belly oscillations induced by a single 1-millisecond maximal monophasic electrical impulse. The stimulation amplitude was gradually increased from the minimum intensity to induce a recordable oscillation until the measured D_m during the twitch contraction (in millimeters) did not increase further, with electrical pulses ranging between 85 and 110 mA at a constant 30 V. To provide sufficient resting, we chose a 10- to 15-second interstimulation interval. The analyzed measures were recorded from 2 maximal responses, averaged, and included in the final analysis. The standardized TMG-derived measures included

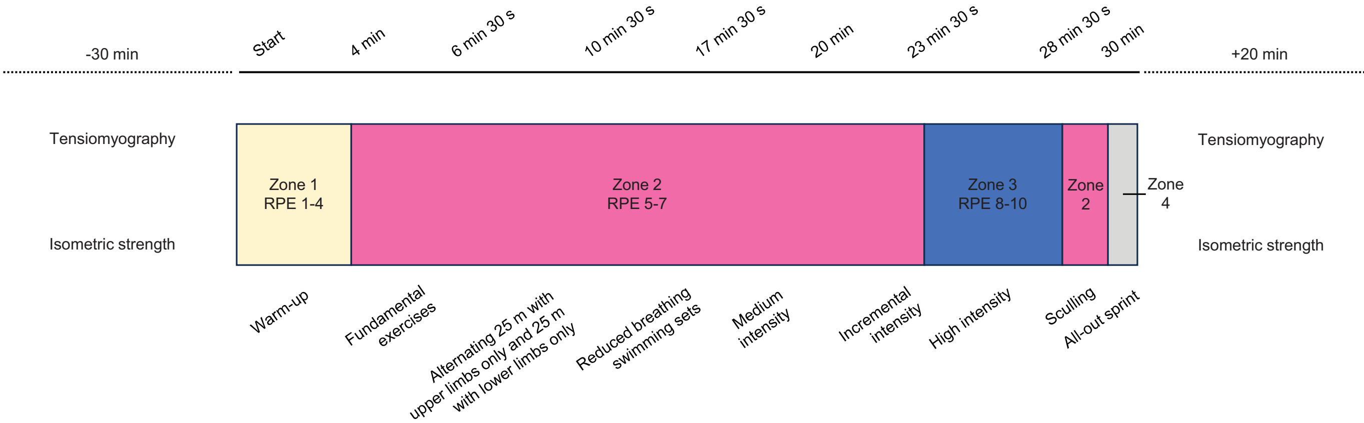

Figure 1. Representation of the swim-training protocol to induce fatigue. The outcomes assessment was performed before and after the 30-minute training protocol. Intensity zones from 1 to 4 and their corresponding rating of perceived exertion (RPE) are provided.

the D_m (in millimeters), the time from electrical pulse to 10% of D_m (delay time [T_d]; in milliseconds), the time to contraction between 10% and 90% of D_m (contraction time [T_c]; in milliseconds), the time when the response was >50% of D_m (sustain time [T_s]; in milliseconds), and the time between 90% and 50% of D_m during the muscle relaxation phase (half-relaxation time [T_r]; in milliseconds). All measures were extracted using TMG software (version 3.6.16) and used for offline analysis.[17] A smaller D_m has been suggested as an index of increased muscle stiffness, whereas a larger D_m implies lower muscle stiffness. *Delay time* represents a measure of muscle responsiveness. *Contraction time* represents the speed of twitch-force generation and has been reported to reflect muscle fiber type or tendon stiffness. *Sustain time* and T_r are the least studied measures, with T_s possibly being important for assessing muscle fiber fatigue status, although these last 2 measures require further investigation.[18] In particular, Martín-Rodríguez et al reported high reliability for T_c, T_d, and D_m and poor reliability for T_r.[18] Substantial evidence is available for the reliability of TMG in assessing exercise-induced muscle fatigue, although more studies are required to determine its accuracy and validity.[9] The following muscles were investigated according to their role in front-crawl swimming biomechanics and their validation with TMG according to the manufacturer's guidelines: anterior deltoid, medial deltoid, latissimus dorsi (mLD), pectoralis major (mPM), upper trapezius (mUT), middle trapezius, and lower trapezius (mLT).[19] The participants were tested while sitting (anterior deltoid, medial deltoid, and mUT) and lying supine (mPM) and prone (mLD, middle trapezius, and mLT). The electrodes and sensor were placed by the same researcher (A.B.S.) with expertise in the use of TMG on the muscle area, and positions were marked with waterproof drawing ink to ensure the constant location of the electrodes on the skin over the repetitions.

Shoulder Strength. Isometric shoulder strength assessments were performed using a digital handheld dynamometer (model K-Pull; Kinvent) with participants in the supine position on a treatment bed. Shoulder flexion and extension were performed with the shoulder abducted to 140° in the scapular plane (30° anterior to the frontal plane), the elbow extended, and the forearm pronated. To assess external rotation and internal rotation, we positioned the arm in 90° of shoulder abduction with the forearm vertical and the elbow flexed to 90°. All starting positions were confirmed using a goniometer, and the dynamometer was aligned to be perpendicular to the forearm. These positions were chosen according to previous literature, suggesting that they are similar to the shoulder position during the relevant phases of the crawl swim stroke.[20] Swimmers were instructed to keep the trunk from moving during testing without any external stabilization; such a protocol and shoulder positions have been reported to have excellent intrarater reliability.[20] An experienced sport physiotherapist (M.M.) performed the strength measurements and instructed the participants on the assessment protocol. Before the measurements, all participants were allowed to perform a short warm-up and familiarize themselves with the positions and movements at submaximal effort. The different movements were assessed in a randomized order, and 2 repetitions of each strength test were performed with a rest period of 5 seconds between each repetition and 30 seconds between each test. Swimmers were asked to gradually build up to a maximal force, maintain this effort, then relax when instructed after a total of 5 seconds. Oral encouragement was provided to participants during testing to produce a maximal effort (make test), according to previous literature.[20] The maximal value (in newtons) was chosen and normalized by body mass.

Statistical Analysis

Outcomes are reported as mean, SD, count, and proportion (%), as appropriate. Two-tailed testing was performed. Normality testing using the Shapiro-Wilk test was performed for all datasets. Given that TMG T_r and T_s were not normally distributed in all the assessed muscles, we applied a log transformation for these variables. A repeated-measures analysis of variance was performed. Given the different muscles assessed with TMG, a 2-way repeated-measures analysis of variance was performed to examine the effect of time (before and after the protocol) and muscle (the 7 assessed muscles). A Greenhouse-Geisser correction was applied in case of lack of sphericity, and a Sidak correction was applied for post hoc analyses. The effect size was determined using partial η^2 (η_p^2). When we observed a main group effect, we computed simple main effects to compare each muscle independently. Finally, Pearson product moment correlation coefficients were computed between the changes in isometric strength and TMG measures before and after the fatiguing

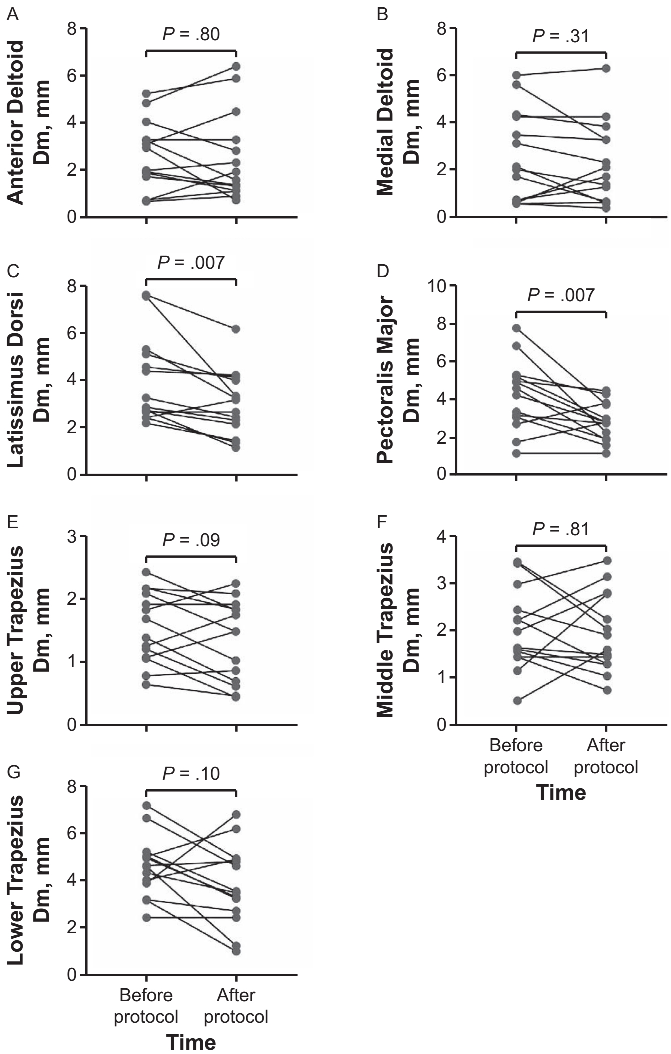

Figure 2. Radial displacement of the selected shoulder muscles before and after a fatiguing swimming protocol (N = 14). We observed a time × muscle interaction ($F_{6,78}$ = 2.504, P = .03, η_p^2 = 0.161).

protocol. We set the α level at .05. All statistical analyses were performed using SPSS (version 23; IBM Corp).

RESULTS

Tensiomyography

An interaction effect of time and the tested muscle was found for D_m ($F_{6,78} = 2.504$, $P = .03$, $\eta_p^2 = 0.161$). In particular, after the fatiguing protocol, reduced D_m was found in the mLD (−1.0 mm; 95% CI = −1.7, −0.3 mm; $P = .007$) and mPM (−1.4 mm; 95% CI = −2.4, −0.4 mm; $P = .007$). However, no differences were found for the other TMG-derived measures (Figure 2; Table 2).

Shoulder Strength

Shoulder strength was affected by the fatiguing protocol, as a time effect was found during the extension task ($F_{1,13} = 4.936$, $P = .045$, $\eta_p^2 = 0.275$). In particular, maximal isometric strength during extension was reduced by 0.03 N/kg (95% CI = 0.01, 0.05 N/kg; Figure 3). No effects were reported during flexion, external rotation, or internal rotation (Table 3).

Table 2. Muscle Tensiomyography Measures Before and After the Fatiguing Swimming Protocol (Mean ± SD)

Measure	Before Protocol	After Protocol	*P* Value
Anterior deltoid			
Time of contraction, ms	16.4 ± 4.4	15.1 ± 2.2	.23
Time of delay, ms	17.8 ± 1.7	17.9 ± 1.5	.82
Time of relaxation, ms	34.3 ± 66.6	18.9 ± 16.7	.81
Maximal radial displacement, mm	2.6 ± 1.5	2.5 ± 1.8	.80
Time of sustain, ms	140.4 ± 255.1	171.6 ± 304.2	.92
Medial deltoid			
Time of contraction, ms	14.8 ± 3.2	14.5 ± 2.5	.69
Time of delay, ms	17.8 ± 1.9	17.4 ± 1.7	.21
Time of relaxation, ms	65.9 ± 150.1	15.3 ± 18.3	.19
Maximal radial displacement, mm	2.6 ± 1.9	2.3 ± 1.7	.32
Time of sustain, ms	140.3 ± 259.3	58.0 ± 111.7	.28
Latissimus dorsi			
Time of contraction, ms	42.1 ± 4.4	38.4 ± 6.0	.04[a]
Time of delay, ms	23.6 ± 3.5	22.8 ± 3.9	.60
Time of relaxation, ms	39.9 ± 15.6	31.3 ± 10.0	.01[a]
Maximal radial displacement, mm	4.0 ± 1.8	3.0 ± 1.4	.007[a]
Time of sustain, ms	105.2 ± 27.3	93.7 ± 15.4	.08
Pectoralis major			
Time of contraction, ms	24.9 ± 4.9	25.1 ± 5.6	.85
Time of delay, ms	25.2 ± 4.1	24.6 ± 5.7	.54
Time of relaxation, ms	35.4 ± 41.5	44.3 ± 56.8	.72
Maximal radial displacement, mm	4.2 ± 1.8	2.8 ± 1.0	.007[a]
Time of sustain, ms	67.6 ± 49.0	117.3 ± 195.2	.46
Upper trapezius			
Time of contraction, ms	20.5 ± 6.6	18.7 ± 3.0	.40
Time of delay, ms	19.6 ± 2.8	19.9 ± 3.7	.67
Time of relaxation, ms	69.3 ± 63.6	103.4 ± 199.6	.90
Maximal radial displacement, mm	1.5 ± 0.5	1.3 ± 0.6	.09
Time of sustain, ms	116.4 ± 74.4	162.4 ± 238.2	.79
Middle trapezius			
Time of contraction, ms	18.1 ± 3.5	18.2 ± 3.1	.85
Time of delay, ms	20.1 ± 2.7	20.1 ± 1.8	.96
Time of relaxation, ms	60.3 ± 44.7	77.1 ± 74.5	.98
Maximal radial displacement, mm	2.0 ± 0.8	1.9 ± 0.8	.81
Time of sustain, ms	111.2 ± 66.3	110.6 ± 84.7	.69
Lower trapezius			
Time of contraction, ms	41.2 ± 23.5	30.8 ± 12.7	.20
Time of delay, ms	22.8 ± 2.9	21.9 ± 1.5	.25
Time of relaxation, ms	101.6 ± 117.7	134.1 ± 228.7	.59
Maximal radial displacement, mm	4.6 ± 1.3	3.8 ± 1.7	.10
Time of sustain, ms	291.2 ± 192.9	318.4 ± 244.5	.83

[a] Indicates simple main effect ($P < .05$).

Correlation Analysis

A correlation was found between the change in isometric strength during extension and mLD T_c ($r = -0.544$, $P = .044$), mLD D_m ($r = 0.549$, $P = .042$), and mUT T_c ($r = 0.645$, $P = .01$) and between isometric strength during flexion and mUT T_c ($r = 0.683$, $P = .007$).

DISCUSSION

Our study provides preliminary evidence that TMG could help detect skeletal muscle contractile changes after a fatiguing protocol in swimmers and provides an evaluation map of the most affected muscles. In particular, reduced D_m was reported in the overall assessed muscles, and the mLD and mPM were most affected.

Although a reduction in T_c has been previously observed after a lower limb fatiguing protocol, the physiological mechanism underlying such alteration in the time needed to reach D_m remains unclear.[21] However, one might speculate that such reduced time could be associated with reduced D_m, as reported in this study.[17] Indeed, researchers have suggested that lower D_m, which is an indirect measure of muscle stiffness to

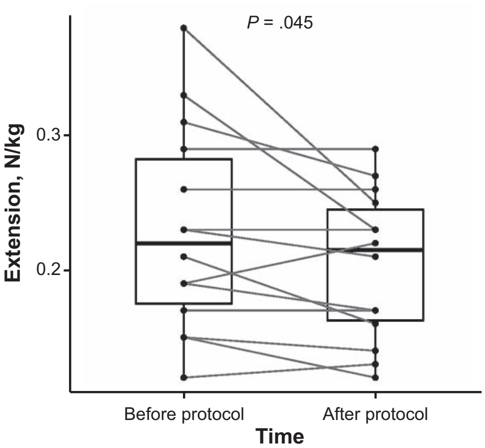

Figure 3. Isometric strength during shoulder extension before and after a fatiguing swimming protocol (N = 14). We observed a time effect ($F_{1,13}$ = 4.936, P = .045, η_p^2 = 0.275).

Table 3. Shoulder Isometric Strength Before and After the Fatiguing Swimming Protocol (N = 14; Mean ± SD)

Isometric Strength	Before Protocol, N/kg	After Protocol, N/kg	*P* Value
Flexion	0.22 ± 0.08	0.21 ± 0.08	.34
Extension	0.23 ± 0.08	0.20 ± 0.05	.045[a]
External rotation	0.28 ± 0.07	0.26 ± 0.06	.08
Internal rotation	0.32 ± 0.06	0.30 ± 0.07	.44

[a] Indicates difference ($P < .05$).

electrical stimulation, could be observed after fatiguing tasks, and this might be due to the swelling response and increased intracellular water content after exercise-induced muscle fatigue, resulting in increased muscle stiffness.[7,15,17,21,22] More specifically, local fatigue has been reported to reduce D_m in skeletal muscles due to impaired propagation of the electrical stimulus along the sarcolemma, resulting from pH-driven alterations of the sodium and potassium gradient across the muscle membrane that influence excitation-contraction coupling.[23] Finally, D_m of the muscle might be further impaired by an accumulation of inorganic phosphate within muscle cells that results in reduced Ca^{2+} and subsequent excitation-contraction coupling or by direct accumulation of inorganic phosphate within muscle cells.[13,17] In general, our findings seem to agree with those of some previous researchers suggesting that D_m could be reduced after exercise-induced muscle fatigue, whereas T_c presents conflicting results and requires additional research.[8,9]

The skeletal muscles acting on the shoulder joint during swimming that presented the largest changes postexercise were the mLD, mPM, and mLT, but only the values of the first 2 were statistically different. The mLD is primarily activated during the middle and late pull-through phases, whereas the mPM is mainly active during the early and middle pull-through phases.[24] Electromyographic assessment of muscle fatigue during the 100-m front crawl showed decreased mean power frequency of these muscles.[25] The mLT plays an important role in scapula movement and positioning and dynamic scapula stability, and it might be important during swimming and impaired after a 3-minute maximal effort in swimmers.[26,27] If the fatiguing exercise protocol in this study affected all tested muscles and, in particular, the mLD and mPM, given their important role in front crawl, the protocol's effect on the mUT and mLT compared with other muscles, if confirmed in other studies with larger samples, could inform about its contribution in swimming.

Shoulder strength was assessed during isometric tasks aimed at testing the effects of fatigue on flexion, extension, and external and internal rotation, providing values in line with those reported in previous literature.[20] Shoulder extension contributes to pulling the body over the upper extremity through the water in the front-crawl stroke.[20] By contrast, shoulder flexors might have a minor role in the front crawl, as no differences in flexion have been found between swimmers and healthy young adults.[20] In previous swimming research, Matthews et al reported that maximal strength during internal and external rotation was not affected by fatigue.[2] In our study, only extension was reduced after the fatiguing swimming protocol. Subscapularis muscles and the mLD are found to be more active during shoulder extension than flexion, whereas the supraspinatus, infraspinatus, deltoid, trapezius, and serratus anterior muscles are more highly activated during flexion than during extension.[28] In addition, the pectoralis muscles are part of the shoulder-stabilizing structures and are active in shoulder extension.[29] Regarding the trapezius, the mLT is mainly activated during flexion, although it might be active during extension.[30] Interestingly, the larger fatigue-induced TMG-related changes were found in muscles that might have a major role in shoulder extension, which showed an isometric strength reduction. Indeed, the correlation analysis suggested an association between the decrease in extension strength and decreased mLD D_m (ie, index of fatigue). Curiously, a longer time to contraction of the mLD and shorter time to contraction of the mUT were correlated with decreased extension strength, and a shorter time to contraction of the mUT was correlated with decreased flexion strength, confirming the above-mentioned conflicting results about this measure and fatigue.

Taken together, our results are in line with those reported in the previous literature suggesting that TMG might help detect some hallmarks of muscle fatigue, and reduced D_m might reflect increased stiffness due to exercise-induced alterations of muscle contractile properties.[15,22] Although such findings have been suggested in other studies, to the best of our knowledge, we are the first to report TMG alterations in shoulder muscles after a fatiguing swimming protocol.[15,22] In addition, isometric strength was assessed during different shoulder movements, suggesting some potential associations between the muscles that presented with the most impaired TMG measures and reduced isometric strength. Despite such promising results, our study included a relatively small sample size, and other individual factors might have affected the outcomes; therefore, further studies are needed to confirm the proposed findings. Given the role of the tested muscles to stabilize and prevent pain and injuries, future research should be performed to evaluate the role of fatigue in the development of such conditions and to assess if "shoulder pain" could influence the reported outcomes in competitive swimmers.

Exercise-induced muscle fatigue in swimming could be detected using TMG measures in the shoulder muscles and, in particular, as reduced D_m. The mLD and mPM were found to be the most affected muscles, although an effect of fatigue was reported overall for the tested muscles. According to the isometric strength assessment, only shoulder extension was reduced after the fatiguing exercise protocol. Our findings encourage the use of TMG as a noninvasive assessment tool to detect peripheral fatigue and also fatigue in shoulder muscles and could help athletic trainers and physiotherapists design training and rehabilitation protocols based on the most affected muscles and suggest specific exercises that might focus on the most affected muscles (eg, mPM and mLD), combining swimming and strength training.[31]

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Data Availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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SUPPLEMENTAL MATERIAL

Supplemental Appendix. Swim Training Fatiguing Protocol.

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Address correspondence to Alex Buoite Stella, PhD, School of Physiotherapy, Department of Medicine, Surgery and Health Sciences, University of Trieste, via Pascoli, n 31 – 34141, Trieste, Italy. Address email to abuoitestella@units.it.