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Two-dimensional spatial error distribution of key tensiomyographic parameters

Boštjan Šimunič

Science and Research Centre Koper, Koper, Slovenia

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ABSTRACT

Tensiomyography detects the contraction time (Tc) and amplitude (Dm) of muscle belly thickening during maximal isometric twitch contraction. The assessment of both parameters is highly reliable; however, it seems that their calculation depends on the measurement point. The aim of the study was to determine spatial relative error distribution of Tc and/or Dm within a two-dimensional array of 27 (3×9) measurement points in comparison to the reference point (RP) in 12 male participants (22.5 ± 3.1 years). The RPs were determined as follows: in the biceps brachii (BB) at 50% of the humerus length; in the erector spinae (ES) at the height of the iliac crest; in the vastus lateralis (VL), vastus medalis (VM), and rectus femoris (RF) at 30%, 20%, and 50% of femur length above the patella, respectively. The surface area under the 3% relative error in Dm (BB: 4.0; VL: 3.8; VM; 8.2; RF: 6.2; ES: 2.4 cm^2) was lower than in Tc (BB: 6.9; VL: 3.8; VM; 4.6; RF: 9.5; ES: 3.7 cm^2), yielding merged values (BB: 3.9; VL: 3.7; VM: 4.8; RF: 5.1; ES: 2.4 cm^2). Dm show twice as steep relative error rate when moving away from the RP in comparison to Tc, which seems to be less sensitive to spatial sensor positioning.

1. Introduction

Tensiomyography (TMG) allows for simple, non-invasive (Valenčič, 1990), and reliable (Ditroilo et al., 2013; Križaj et al., 2008; Šimunič, 2012; Tous-Fajardo et al., 2010) assessment of muscle belly enlargement in the transversal plane during an isometric twitch contraction by means of a digital, high-precision displacement sensor to assess the muscle mechanical contractile responses. It is a mechanomyographic technique, such as are also phonomyography (Maton et al., 1990), soundmyography (Orizio and Veicsteinas, 1992), acoustic myography (Barry et al., 1985), and vibromyography (Zhang et al., 1992). The main distinction between TMG and other mechanomyographic techniques is in the slight pre-tension that the displacement sensor exerts on the muscle belly before the contraction (Valenčič, 1990). This pretension ($0.2\ N/cm^2$) overcomes the main drawback of other mechanomyographic techniques – a low signal-to-noise ratio. Therefore, TMG does not require any post-processing and yields high short-term (Križaj et al., 2008; Tous-Fajardo et al., 2010) and long-term (Ditroilo et al., 2013; Šimunič, 2012) repeatability of estimated contractile parameters at least in non-obese adults.

TMG-derived contractile parameters (Contraction time – Tc; Delay time – Td, and Half-relaxation time – Tr) can be used to estimate the percentage of type I myosin heavy chains, at least in the vastus lateralis (VL) muscle (Šimunič et al., 2011), and possibly also in other muscles. In relation to dynamometry, TMG response is more sensitive, as the time-based parameters are shorter when calculated from TMG response (−23.4% for Td; −42.7% for Tc; −26.2% for Tr) and are not correlated to dynamometry-based estimations (Koren et al., 2015). Thus, TMG response gives better insights to muscle contractility, as it is less affected by the surrounding tissues (Evetovich et al., 1997; Koren et al., 2015). The maximum amplitude of TMG response (Maximal displacement – Dm) was validated against muscle atrophy, where it was found that Dm increases after 35 days of bed rest (Pišot et al., 2008) in correlation to muscle thickness decrease. However, recent findings confirm that Dm is more sensitive to muscle atrophy than bioimaging techniques (Šimunič et al., 2019). It increases within 1 to 6 days (depending on a muscle) after the start of physical inactivity, when muscle thickness is still unchanged; meanwhile the rate of increase is 1.5 to 4.2-times higher than the thickness decreases during 35-day bed rest, which sets TMG as an important evaluation technique also in clinical settings. At least six TMG-derived contractile parameters are regularly reported; whereas Tc and Dm (or the ratio between them) are the most commonly reported parameters and are for now considered as key TMG-derived contractile parameters.

E-mail address: bostjan.simunic@zrs-kp.si

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From 1997 to 2019 there were 109 TMG publications published in impact journals available in the PubMed database. It is also important to note that just in 2018 there were 20 publications available, signalling an exponential rise in the use of TMG in science. There was also a first review available from 2018 (Macgregor et al., 2018), emphasizing that care must be taken to ensure the precise positioning of sensors and electrodes in order to avoid detecting the co-activation of deeper or neighbouring muscles. In the vast majority of TMG publications authors determined a measurement point for the positioning of the displacement sensor based on several criteria: (i) the thickest part of the muscle belly, which is established visually and through palpation during a voluntary contraction (De Paula Simola et al., 2015; Garcia-Garcia et al., 2013; García-Manso et al., 2011; Gutiérrez-Vargas et al., 2018; Macgregor et al., 2016; Raeder et al., 2016; Rey et al., 2016; Wiewelhove et al., 2015); or (ii) as a point of maximal muscle belly contraction, detected during prior measurements of electrically evoked muscle contractions (Harmsen et al., 2019; Koren et al., 2015; Paravlič et al., 2017; Šimunic et al., 2018; Zubac and Šimunič, 2017); or (iii) as a certain percent of anatomical length (Loturco et al., 2018; Schroeder et al., 2017; Šimunič et al., 2011, 2017, 2019); or (iv) based on anatomical guides for electromyographers (Alentorn-Geli et al., 2015a, 2015b; Pišot et al., 2008; Šimunič, 2012; Tous-Fajardo et al., 2010); or (v) the method used was not specified (Gil et al., 2015; Križaj et al., 2008; Rusu et al., 2013). However, due to muscle anatomical differences found in athletes (Valenčič and Djordjevič, 2001) some authors already used multiple criteria for measurement point determination to compensate the anatomical individuality of athletes, e.g. criteria (i) and (ii) (García-García et al., 2015); or criteria (i), (ii) and (iv) (García-García et al., 2017). Obviously, measurement points depend greatly on the method being used, and there is no study reporting on the spatial variation of TMG results depending on the measurement point selected.

The study's aim was therefore to determine the spatial distribution of the relative error in Tc and Dm between 27 (3×9) homogenously distributed assessment points in comparison to the reference point (Fig. 1A), determined by a percentage of anatomical length. Furthermore, after the interpolation of relative error we calculated the area under 3%, 5%, and 10% of the relative errors for each of two parameters *per se*, as well as for the combination of both.

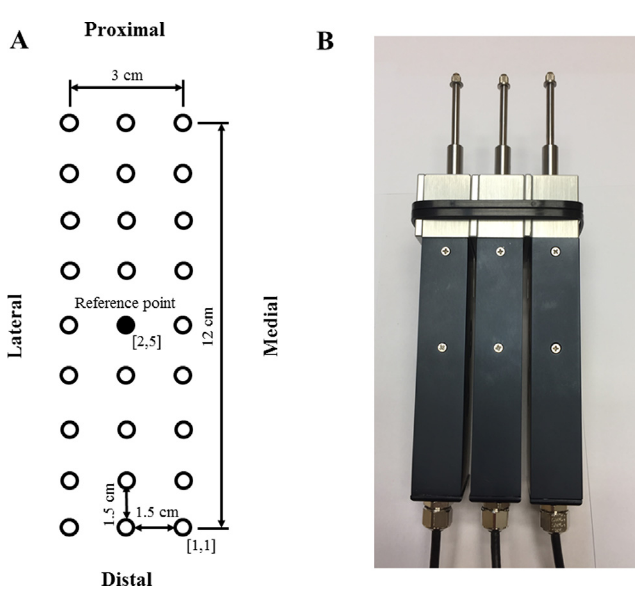

Fig. 1. Three standard tensiomyography sensors were paralleled for the purpose of the study (B); the twenty-seven (3×9) measurement points in each muscle (A). The lateral and longitudinal distance between neighbouring measurement points was 1.5 cm.

2. Materials and methods

2.1. Participants

Twelve healthy men (Table 1) with no history of neuromuscular or cardiovascular disorders participated in our study. The study was approved by the Institutional Ethics Committee of Faculty of Electrical Engineering at the University of Ljubljana. All participants were fully informed about the study's procedures and the possible health risks from participating in the study. Informed, written consent was obtained from all participants before the study. All procedures were in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its amendments.

2.2. Experimental design

All participants arrived at the laboratory in the morning and stayed for measurements for approximately two hours. The first 10 min were used to familiarise participants with maximal electrical pulses in each muscle of interest. Then we assessed tensiomyographic responses in five skeletal muscles (in this order): biceps brachii (BB), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), and erector spinae (ES).

In each muscle three experienced TMG operators (all with more than 10 years of experiences in TMG assessments) reached a consensus on a measurement point that was later selected in agreement as a reference point for further comparisons. The reference points were determined as follows: in the BB at 50% of the humerus length; in the VL at 30% of the femur length above the patella on the lateral side; in the VM at 20% of the femur length above the patella on the medial side; in the RF at 50% of the femur length above the patella; in the ES (longissimus part) at the height of the iliac crest. In all muscles the reference point was determined at the mid-muscle width.

All muscles were assessed on a dominant site (right site in all participants). Measurements were taken on the BB when seated at rest, at an elbow angle set at 90°, where 0° represents the straight, extended joint, with the shoulder in a natural position and the hand in a pronated position. Measurements on the VL, VM, and RF were taken supine, at a knee angle set at 30° knee flexion and on the ES prone. Hard foam pads were used for arm and leg support, and straps were used to assure isometric conditions.

2.3. Tensiomyography

Three TMG sensors were joined for parallel assessments in 3 measurement points (Fig. 1B). For the purpose of the study, standard TMG hardware and acquisition software (TMG BMC Ltd., Slovenia) were upgraded with a custom-made controller and graphic user interface to allow for simultaneous 1 kHz assessment and display of 3 linear displacements sensors. There was no

Table 1
Anthropometric data of participants.

	Average ± SD
N	12 (all males)
Age/years	22.5 ± 3.1
Body height/m	1.82 ± 4.5
Body mass/kg	78.7 ± 8.7
Body mass index/kg/m^2	23.8 ± 2.9

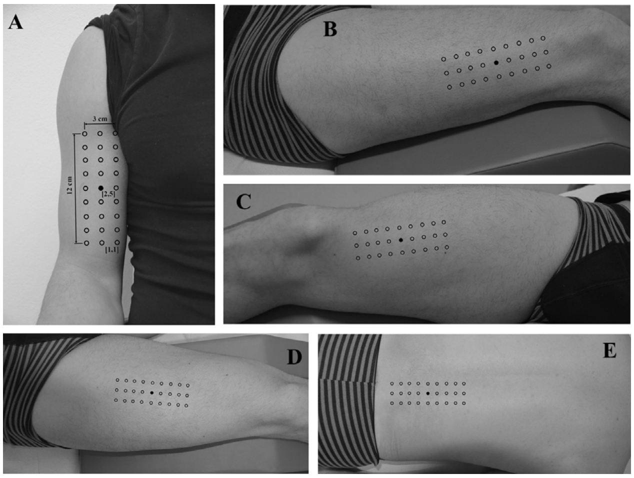

Fig. 2. Reference measurement points (closed circle) and other measurement points (open circles) in biceps brachii (A), vastus lateralis (B), vastus medialis (C), rectus femoris (D), and erector spinae (E).

additional post-processing of the responses before the contractile parameter estimation. A coordinate system of measurement points was marked for the labelling of all 27 measurement points (Figs. 1A and 2A-E; three in the lateral and nine in longitudinal direction of the muscle belly), where [1,1] represents the most distal-medial measurement point and [2,5] represents the reference measurement point.

During the pilot study, performed only in BB, independence was checked between three parallel sensors with and without simultaneous assessment.

The TMG assessment has been described previously in more details (Šimunič, 2012; Šimunič et al., 2011; Šimunic et al., 2018). However, important to say is that we used single 1-ms maximal monophasic electrical impulse (30 Volts with amplitude ranging from 60 to 100 mA) was used to elicit a twitch that caused the muscle belly to oscillate and thicken. These oscillations were recorded using three sensitive digital displacement sensors (TMG-BMC, Ljubljana, Slovenia) that were placed on the surface of the skin over the net determined as described before (Fig. 1A). The maximal stimulation amplitude was determined for a referenced measurement point and kept the same for all measurement points. Initially, the stimulation amplitude was set just above the threshold and then gradually (every 10 s) increased until the Dm of the reference measurement point increase no further. For every measurement point two maximal twitch responses were saved, Tc and Dm calculated, and the average was used for further analysis. Tc was defined as the time for the amplitude to increase from 10% to 90% of Dm.

2.4. Statistical analysis

The Matlab (R2018b; Mathworks, USA) and SPSS (Version 24.0; IBM, USA) software suites were used for all calculations. A visual inspection and the Shapiro-Wilk test indicated that all data were normally distributed. Independence between the three sensors was analysed in BB by using a repeated measures General Linear Model, where we compared the average values for all measurement points that were measured with a single sensor or with an array of three sensors. Statistical significance was accepted at $p \leq 0.05$. For the main analysis a cubic spline interpolation was applied before the estimation of relative error (in %) was calculated as the relative difference between each measurement point in comparison to a reference measurement point for both TMG parameters (Tc and Dm). Due to 27 measurement points a cubic spline technique was found to be very robust with decreasing error in modelling interpolation of more than six points (Xu et al., 2010). Furthermore, the area around the reference point (in cm^2) was calculated for three relative errors, ≤3%, ≤5%, and ≤10%, separately for Tc and Dm, as well as for both.

3. Results

During the pilot study, which was conducted only in BB, independence was met between three parallel sensors with and without simultaneous assessment. The repeated measures General Linear Model confirmed that there was no main effect for simultaneous assessment (P = .799). Therefore, a distance of 1.5 cm between sensors allowed for independent measurement in an array of three measurement points simultaneously. Furthermore, Table 2 presents descriptive Tc and Dm values for all five muscles measured at the reference measurement point.

Figs. 3 and 4 presents the Tc and Dm, respectively, relative error for each muscle and each measurement point in comparison to reference measurement points. It is obvious that relative error is higher in Dm than in Tc, also yielding a smaller area under the 10% of relative error (Table 3). Furthermore, we could also notice that the largest relative error was in the narrow ES muscle, both for Tc and Dm as well as for the combination of both. Therefore, disregarding ES, the average area under the 3%, 5%, and 10% in Tc of four muscles was $6.2 \pm 2.6\ cm^2$, $10.5 \pm 3.8\ cm^2$, and $22.9 \pm 4.5\ cm^2$, respectively. Similarly, disregarding ES, the average area under the 3%, 5%, and 10% in Dm of four muscles was $5.6 \pm 2.1\ cm^2$, $7.5 \pm 2.0\ cm^2$, and $12.4 \pm 2.8\ cm^2$, respectively. Keeping in mind both parameters, and disregarding ES, the average area under the 3%, 5%, and 10% of four muscles was $4.4 \pm 0.7\ cm^2$, $6.3 \pm 0.8\ cm^2$, and $10.7 \pm 0.8\ cm^2$, respectively.

4. Discussion

We observed a similar shape in the TMG responses for all measurement points, with the highest Dm in a reference measurement point. Despite the similar shape of responses, the Tc and Dm depended on the sensor position. Therefore, we have provided the surface area under the 3%, 5%, and 10% of relative error around the expert-established reference measurement point in five skeletal muscles for the two most regularly reported TMG parameters (Tc and Dm). Our results confirm that there are preferred regions on the muscle surface that provide a low measurement error in

Table 2
Descriptive tensiomyographic data for contraction time (Tc) and maximal displacement (Dm) of all five muscles for the reference measurement point [2,5]. Average relative Tc and Dm errors are presented for neighbouring points to the reference point [1–3, 4–6].

Muscle	Tc at [2,5]/ms	Relative Tc error at [1–3,4–6]/%	Dm at [2,5]/mm	Relative Dm error at [1–3, 4–6]/%
Biceps brachii	30.2 ± 5.8	7.9	16.4 ± 3.1	20.9
Vastus lateralis	24.4 ± 4.6	8.4	5.0 ± 1.9	15.4
Vastus medialis	27.2 ± 3.3	6.3	8.1 ± 2.3	9.6
Rectus femoris	28.8 ± 9.7	5.7	7.8 ± 4.5	12.2
Erector spinae	22.5 ± 3.1	13.1	4.1 ± 2.0	22.6

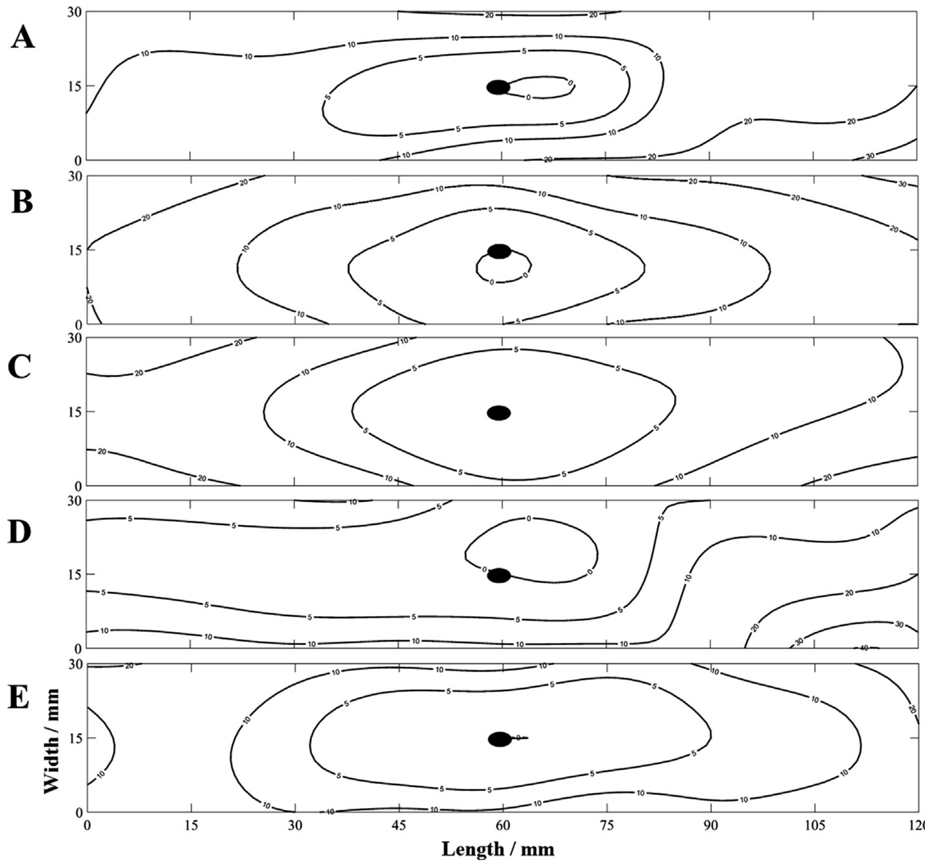

Fig. 3. The spatial model of relative error of contraction time (Tc) in biceps brachii (A), vastus lateralis (B), vastus medialis (C), rectus femoris (D), and erector spinae (E) in comparison to a reference measurement point (closed circle).

comparison to the reference point. The preferred region was narrower in the ES muscle due to its smaller anatomical dimensions.

We found a lower relative error in Tc than in Dm; however, in both parameters the precision of measurement could be controlled by accurate sensor positioning in the area of $4.4 \pm 0.7\ cm^2$, $6.3 \pm 0.8\ cm^2$, and $10.7 \pm 0.8\ cm^2$ for controlling 3%, 5%, and 10% of relative error in BB, VL, VM, and RF muscles, respectively. Only in ES was the area significantly smaller, namely $2.4\ cm^2$, $3.9\ cm^2$, and $7.6\ cm^2$, for controlling 3%, 5%, and 10% of relative error, respectively.

An extensive reliability analysis had already been performed for three out of five studied skeletal muscles in this study (Križaj et al., 2008; Šimunič, 2012; Tous-Fajardo et al., 2010). Reliability studies have reported the basic reliability statistics needed to calculate the smallest detectable change for those three muscles: in BB the smallest relative detectable change was 7.8% for Dm and 6.5% for Tc (Križaj et al., 2008); in VM the smallest relative detectable change was 11.7% for Dm and 11.8% for Tc (Tous-Fajardo et al., 2010); in VL the smallest relative detectable change was 7.8% for Dm and 3.9% for Tc (Šimunič, 2012). It seems that highest difference needed to be statistically confirmed above the standard error of measurement is needed in the VM muscle. This might be due to increased measurement error, as the VM has two anatomical heads (longus and obliques) (Vieira, 2011), where a recent study presented different TMG contractile properties between both anatomical heads (Šimunič et al., 2019). Although our study did not distinguish between those two heads, we could confirm that the VM reference point [2,5] was on the VM obliques part, whereas points [1, 6–9], [2, 6–9], and [3, 5–9] were in the VM longus part.

The ES muscle was found to have highest relative error and by 29–53% the lowest area under the 3%, 5%, and 10% of relative error. The TMG measurement was performed in the longissimus column of the ES and the reference point was in the mid-lumbar curve. In this region the ES muscle is anatomically very narrow, yielding a high relative error in the [1, 1–9] and [3, 1–9] measurement points. Obviously, the ES measurement points in those arrays were on the edge of the muscle belly yielding 30–45% lower Dm when comparing to the reference point (Fig. 4E). Therefore, it is important to find the thickest part of the muscle in the lateral direction for a measurement point. This is difficult in participants with high body fat in that region; nonetheless, voluntary contractions with visual observation and palpation might help.

In Dm we found a relative error rate that was twice as steep when moving away from the reference point. For example, when moving 1.5 cm in each direction [1–3, 4–6] from the reference point, the average relative error for Tc and Dm was already 8.3% and 16.1%, respectively. This is important especially for narrow muscle heads, where not only the correct measurement point must be used, but also the perpendicular direction of the sensor to the tangential plane needs to be assured for proper Dm assessment; however, the later issue needs to be investigated. It seems that Tc is less sensitive to this error; however, this must be considered when calculating the velocity of radial displacement, which is calculated using the quotient of the Dm and Tc values (Rodríguez-Ruiz et al., 2014).

It is important to justify a triple-sensor development and use in our study. Although there is no study available to justify inter-twitch period (or number of twitches applied) in assessing multiple muscle twitch responses, an inter-twitch period of 10 s

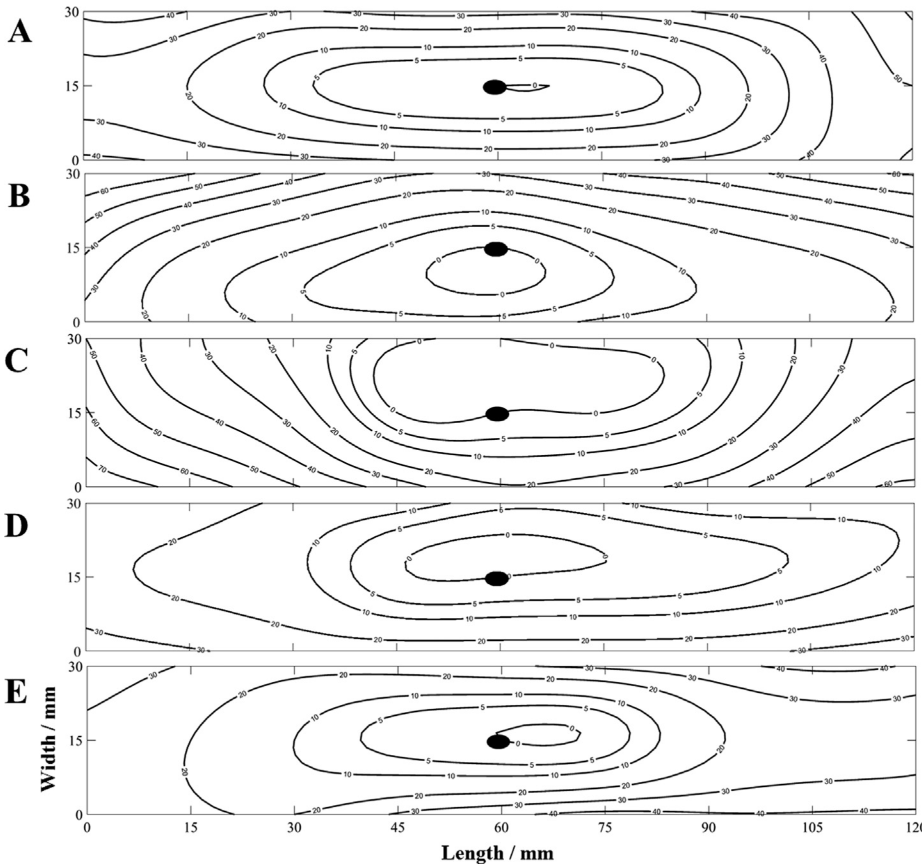

Fig. 4. The spatial model of relative error of maximal amplitude (Dm) in biceps brachii (A), vastus lateralis (B), vastus medialis (C), rectus femoris (D), and erector spinae (E) in comparison to a reference measurement point (closed circle).

Table 3
A surface area (in cm^2) for 3%, 5%, and 10% of the relative error from a reference measurement point. The relative error is presented for contraction time and maximal displacement, separately, and as an overlap of both parameters.

	Contraction time			Maximal displacement			Contraction time and maximal displacement		
Relative error	3%	5%	10%	3%	5%	10%	3%	5%	10%
Biceps brachii	6.9	10.4	23.1	4.0	5.6	9.5	3.9	5.6	9.5
Vastus lateralis	3.8	7.1	16.6	3.8	6.0	11.4	3.7	5.6	10.9
Vastus medialis	4.6	8.8	25.2	8.2	9.4	12.3	4.8	7.0	11.2
Rectus femoris	9.5	15.8	26.7	6.2	9.0	16.2	5.1	6.9	11.3
Erector spinae	3.7	5.9	15.2	2.4	3.9	7.6	2.4	3.9	7.6

is regularly used to avoid muscle potentiation or fatigue. Similarly, we have adopted the same inter-twitch period and by three parallel TMG sensor diminish the twitches needed by 2-times. However, this issue needs to be properly addressed in the future.

It is also important to emphasize that the investigated participants were healthy and young men and not top athletes. However, the proposed criterion we used (see Introduction; criterion (iii)) for the determination of the reference point might not apply in other populations and individuals. The highest Dm must then be tracked with the combination of criteria (see Introduction; criteria (iii) and (ii)).

In conclusion, the signals detected from different muscle locations appears similar in shape, with lower Dm when moving away from the reference measurement point. Despite the shape similarity, the Dm and Tc values were influenced by the sensor position. Therefore, a measurement point with the highest Dm is most likely the correctly selected measurement point in all five muscles and participants.

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Declaration of Competing Interest

There are no conflicts of interest.

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