Original

Reproducibility of muscle response measurements using tensiomyography in a range of positions

D. Rodríguez-Matoso [a], D. Rodríguez-Ruiz [a], S. Sarmiento [a], D. Vaamonde [b], M.E. Da Silva-Grigoletto [c] and J.M. García-Manso [a]

[a] *Physical Education Department. School of Physical Activity and Sport Sciences. University of Las Palmas de Gran Canaria. Las Palmas de Gran Canaria. Spain.*
[b] *Morphological Sciences Department. School of Medicine. University of Córdoba. Córdoba. Spain.*
[c] *Andalusian Center of Sports Medicine. Córdoba. Spain.*

ABSTRACT

Aim. To verify that tensiomyography (TMG) is a reliable method for the non-invasive assessment of the contractile properties of muscles, independently of sensor position.
Methods. TMG was used to assess radial displacement of the anterior rectus femoris in the dominant leg of 25 individuals (age: 25.7 ± 4.7 years). The measurements were taken in three positions; one position was mid-point while the other two were at a ±2 cm distance from the latter. The following parameters were measured: maximum radial displacement of the muscle belly (Dm), contraction time (Tc), reaction time (Td), contraction sustain time (Ts) and relaxation time (Tr).
Results. Analysis of reproducibility yielded the following Cronbach alpha coefficients: 0.970, 0.920, 0.897, 0.976 and 0.984 for Tc, Dm, Td, Ts and Tr, respectively.
Conclusions. TMG is shown to be a tool with a high degree of reproducibility for assessing the contractile properties of muscles. To ensure maximum reliability on repeated measurements, it is necessary to adhere closely to a measurement protocol in order to avoid altering the muscle response; in this respect, the positioning of the sensor and the complete relaxation of the muscle are two factors of fundamental importance.

© 2009 Revista Andaluza de Medicina del Deporte.

RESUMEN

Medidas de reproducibilidad de la respuesta muscular mediante tensiomiografía en distintas posiciones

Objetivo. Verificar que la tensiomiografía (TMG) es un método fiable para evaluar, de forma no invasiva, las propiedades contráctiles del músculo, independientemente de la posición del sensor.
Métodos. Se empleó la TMG en 25 individuos (edad: 25,7 ± 4,7 años) para evaluar el desplazamiento radial medido en el recto anterior femoral de la pierna dominante. Las mediciones se realizaron en tres posiciones diferentes, una en el punto medio y las otras dos con una separación ±2 cm de este. Los parámetros medidos fueron: desplazamiento máximo radial del vientre muscular (Dm), tiempo de contracción (Tc), tiempo de reacción (Td), tiempo que mantiene la contracción (Ts) y tiempo de relajación (Tr).
Resultados. Tras el análisis de reproducibilidad, los coeficientes alfa de Cronbach obtenidos fueron los siguientes: 0,970, 0,920, 0,897, 0,976 y 0,984 para Tc, Dm, Td, Ts y Tr respectivamente.
Conclusiones. La TMG se muestra como una herramienta con alta reproducibilidad para evaluar las propiedades contráctiles de los músculos. Para garantizar la máxima fiabilidad en medidas repetidas es necesario seguir fielmente un protocolo de medición que no altere la respuesta muscular. La colocación del sensor y la relajación completa del músculo son dos aspectos fundamentales.

© 2009 Revista Andaluza de Medicina del Deporte.

Correspondence:
J.M. García-Manso.
Campus Universitario de Tafira, s/n.
Edificio de Ciencias de la Actividad Física y el Deporte.
35017 Las Palmas de Gran Canaria. Gran Canaria.
E-mail: jgarcia@def.ulpgc.es

Introduction

Tensiomyography (TMG) is a non-invasive method for measuring the contractile properties of skeletal muscles. It requires no effort on the part of the subject being assessed, and provides rapid, accurate information, without disrupting the daily working lives of sportsmen and women. It is used to assess muscle contraction characteristics and the contractile capacity of the superficial muscles[1-7].

TMG measures geometrical changes (radial enlargement) taking place in the muscle belly during isometric contraction, in response to an electrical stimulus. The assessment is made using a pressure sensor connected to a high-precision digital displacement transducer placed perpendicular to the muscle belly. The muscle is stimulated with single twitch stimulus (pulse of 1 ms duration) using two self-adhesive electrodes (2-5 cm apart) placed symmetrically to the sensor, in such a way as not to affect the tendons.

As Valenčič[8] reports, TMG assessment offers information, in the time domain, regarding the following parameters: maximal radial deformation or displacement of the muscle belly (Dm), contraction time (Tc), reaction time (Td), sustain time (Ts) and relaxation time (Tr). These parameters are used to assess the stiffness of the muscle and its balance vis-a-vis other muscle structures, muscle chains (flexion-extension) and extremities (right and left).

The value of Dm provides information on the radial deformation of the muscle belly caused by stimulation, expressed in millimetres. It indicates and assesses muscular stiffness, which differs from subject to subject and by muscle group as a function of morphofunctional characteristics and of the work that these structures have been required to perform. Low scores, compared to the average scores of a typical population, are indicative of a high degree of muscle tone and excessive stiffness in muscle structures. High scores, by contrast, indicate a lack of muscle tone[3,5,9]. The Td parameter indicates the time taken for the muscle to reach 10% of total observed displacement following stimulation. This will depend on the predominant fibre type, muscle fatigue status, and potentiation and activation levels[10]. Tc represents the time elapsing from the end of Td (10% of Dm) until 90% of maximum deformation is reached. The value of Ts represents the theoretical time over which the contraction is sustained; it is calculated by measuring the time elapsing between the moment when initial deformation reaches 50% of its maximum value, and the moment when deformation readings return, during relaxation, to 50% of maximum deformation. Tr provides information about fatigue levels: increased scores compared to normal scores for the subject, indicate potential fatigue status.

Although the reproducibility of the method has already been investigated by other researchers[9,11,12], it is important to emphasise that methodological aspects are crucial for assuring precise and reliable measurements. This involves faithfully following a set protocol for each assessment.

Simunic[11] suggests that is a variability of less than 5%, regardless of muscle tonus and sensor positioning. Krijaz et al[9] reported a high level of reproducibility in the biceps brachii, with an error of 0.5- 2% and an intra-class correlation coefficient ranging between 0.86 and 0.98 for the five parameters they analysed. Earlier research by the present authors found that an error in sensor placement could affect the results in terms of muscle deformation measurement (Dm), although not influencing results for the other variables (Tc, Td, Ts and Tr)[12].

In order to obtain robust and reliable data using pre-post measurements, it is necessary to minimise potential errors (differences detected between two measurements) that may derive from the measurement process (assessment protocol) due to an incorrect application of the measuring technique. Failure to adhere to a rigorous protocol may undermine the value of the method. One potential methodological issue could be the point at which the sensor is located. Simunic et al[6] explored this possibility, although in their study the error caused by incorrect selection of the measurement point remained below 5%.

Starting from the assumption that no completely reliable assessment tool exists, the aim of the present study was to evaluate the reproducibility of the readings provided by TMG, analysing the consistency of measurements obtained from three assessments carried out on the same muscle group, in order to confirm the hypothesis that the result of an assessment does not vary significantly after repeated measurements of the same muscles in the same subjects, and thus that TMG is a potentially useful tool for studying muscles of sportsmen and women. The contractile properties of skeletal muscles were therefore analysed using TMG, placing the sensor in three different – albeit neighbouring – muscle locations.

Methods

Sample

Twenty five subjects (age: 25.7 ± 4.7; height: 179.75 ± 4.12 cm; body weight: 79.30 ± 2.35 kg); moderately active; all majoring in Sports Sciences. All participants were fully informed of the potential risks associated with the study, and signed written consent forms previously approved by the Research Ethics Committee of the Universidad de Las Palmas de Gran Canaria (ULPGC) (Canary Islands, Spain) in line with the criteria of the Helsinki Declaration for research involving human beings.

Procedure

Radial displacement was measured on the anterior rectus femoris in the dominant leg of each participant. The subjects lay on a stretcher, with elasticated strapping over their legs to hold their lower body in place. A tensiomyograph (digital displacement transducer TMG-BMC) was used, placing the sensor perpendicular to the tangential plane on the largest area above the muscle belly (fig. 1) in three distinct muscle positions. The first reading (O) was taken at the point recommended by the manufacturer (subjectively determined by the researcher, and identified both visually and by palpation), seeking out the area with the greatest amount of muscle belly, with the sensor at the midpoint in the line between the self-adhesive bipolar electrodes. Electrodes were symmetrically placed 5 cm distal and 5 cm proximal to the perpendicularly-positioned sensor tip. The measuring point was anatomically determined on the basis of the anatomical guide for electromyographers[13]. The other two measurement points, randomly assigned, were -2 and +2 cm away from the first measuring point.

The stimulation pulse was 1 ms, while amplitude was varied (50, 75 and 100 mAp) and selected so as to obtain a maximal response. The sensor was positioned in a way that applied an approximate pressure of 1.5 x 10^{-2} N/mm^2 over an area of 113 m^2, as suggested by Dahmane et al[3]. In order to achieve this pressure, the sensor was calibrated beforehand by marking a pressure point on the sensor that had to be reached prior to each stimulus.
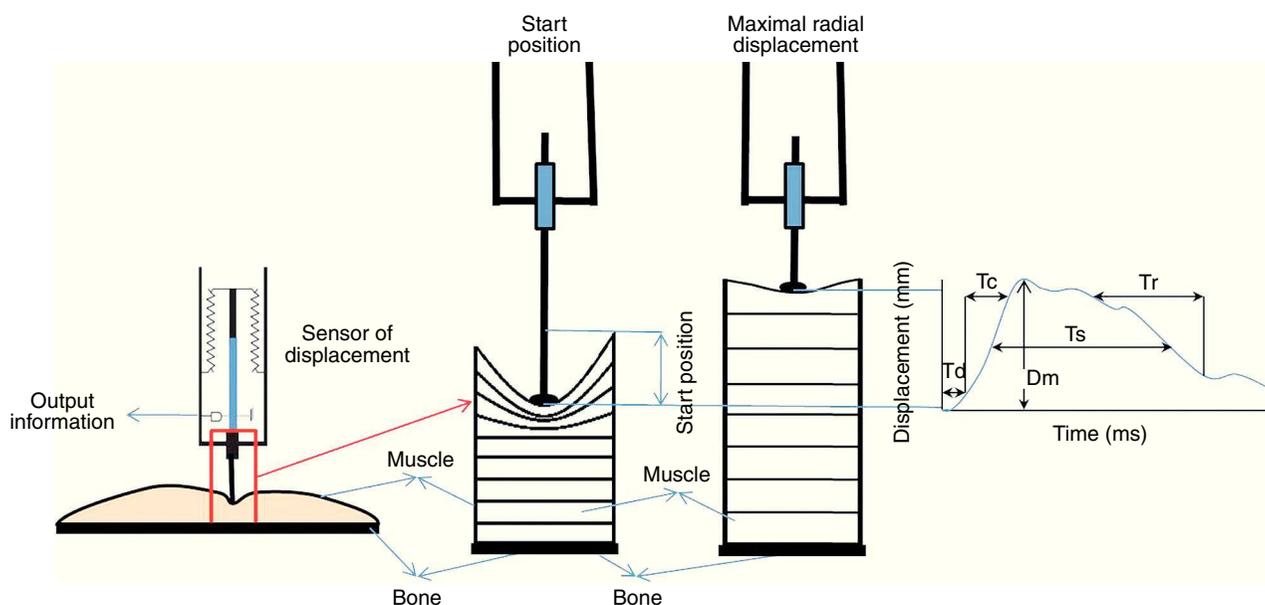
Fig. 1. Positioning of the displacement sensor on the muscle, and data collection process triggered by the electrical stimulus.
Dm: maximum radial displacement of the muscle belly; Tc: contraction time; Td: reaction time; Ts:contraction sustain time; Tr: relaxation time.

Statistical analysis

Data distribution was initially checked using the Kolmogorov-Smirnov test. Internal consistency was tested using Cronbach's alpha coefficient with values ranging between 0 (no internal consistency) and 1 (high internal consistency). The reproducibility of the test was determined by calculating the intra-class correlation (ANOVA for repeated measurements, with a Bonferroni multiple comparisons test with an alpha level significance value of 0.05) and the variation coefficient (individual and joint). The ANOVA for repeated measurements and Cronbach's alpha coefficient were determined on the basis of the subdivision of the total variation in three components (variation between subjects; variation between tests and variation arising from the relationships between subjects and tests). Individual and joint variation coefficients were determined on the basis of mean values and standard deviation for the three measurements undertaken. A coefficient of variation (CV) percentage below 5% was considered optimal, 5-10% acceptable and above 10% unacceptable. All statistics were calculated using the SPSS statistical package, version 17.0 (SPSS Inc., Chicago, IL, USA).

Results

Table 1 shows descriptive statistics (mean, standard deviation, maximum value and minimum value) for each of the variables analysed (Tc, Dm, Td, Ts and Tr) in the assessment of muscle performance in the anterior rectus.

Table 2 shows internal consistency of the TMG using Cronbach's alpha coefficient for the five muscle parameters assessed (Tc, Dm, Td, Ts and Tr). It is noticeable that the index was greater than 0.95 for three of the variables analysed (Tc, Ts and Tr); for the other two (Dm and Td) it was greater than or close to 0.90, thus indicating a high degree of internal consistency.

Table 3 shows reproducibility results obtained by repeated measurements (ANOVA), together with the results of the Bonferroni multiple-

Table 1
Descriptive values for variables contraction time, muscle belly, reaction time, contraction sustain time and relaxation time

Variables	Mean	Standard deviation	Minimum	Maximum
Tc1 (- 2 cm)	31.42 ms	5.59 ms	21.08 ms	46.10 ms
Tc2 (0)	32.20 ms	6.16 ms	21.65 ms	51.20 ms
Tc3 (+2 cm)	31.81 ms	5.56 ms	21.86 ms	44.80 ms
Dm1 (- 2 cm)	8.66 mm	1.99 mm	3.10 mm	13.20 mm
Dm2 (0)	8.59 mm	1.70 mm	5.60 mm	11.80 mm
Dm3 (+ 2 cm)	8.07 mm	1.33 mm	5.50 mm	10.30 mm
Td1 (- 2 cm)	23.77 ms	2.24 ms	19.42 ms	29.20 ms
Td2 (0)	23.47 ms	2.18 ms	19.79 ms	29.30 ms
Td3 (+ 2 cm)	23.71 ms	2.15 ms	20.14 ms	28.50 ms
Ts1 (- 2 cm)	130.43 ms	65.45 ms	38.80 ms	291.30 ms
Ts2 (0)	129.97 ms	68.01 ms	47.30 ms	294.90 ms
Ts3 (+ 2 cm)	118.84 ms	59.33 ms	39.60 ms	274.50 ms
Tr1 (- 2 cm)	77.36 ms	51.79 ms	12.30 ms	192.90 ms
Tr2 (0)	71.58 ms	47.96 ms	14.10 ms	181.70 ms
Tr3 (+ 2 cm)	70.47 ms	49.27 ms	10.70 ms	180.68 ms

(N = 25). Dm: maximum radial displacement of the muscle belly; Tc: contraction time; Td: reaction time; Tr: relaxation time; Ts:contraction sustain time.

Table 2
Cronbach's alpha reliability coefficients

Muscle parameters	Cronbach's alpha
Tc	0.970
Dm	0.920
Td	0.897
Ts	0.976
Tr	0.984

Tensiomyography (TMG) internal consistency as determined by Cronbach's alpha coefficient for the five muscle parameters assessed (contraction time, muscle belly, reaction time, contraction sustain time and relaxation time). (N = 25).
Dm: maximum radial displacement of the muscle belly; Tc: contraction time; Td: reaction time; Tr: relaxation time; Ts:contraction sustain time.

means comparison test, based on assessment of the mechanical muscle characteristics using parameters provided by the TMG.

As table 3 shows, the mean values for Td, Tc, Ts and Tr in the three measurements displayed considerable uniformity; the mean value for

Table 3
Reproducibility values by repeated measurements ANOVA, and Bonferroni's post-hoc test

Comparison of means	Significance	95% confidence intervals	
		Lower limit	Upper limit
Td1 – Td2	1.000	–1.2119	1.8223
Td1 – Td3	1.000	–1.4539	1.5803
Td2 – Td3	1.000	–1.7591	1.2751
Tc1 – Tc2	1.000	–4.7853	3.2277
Tc1 – Tc3	1.000	–4.3937	3.6193
Tc2 – Tc3	1.000	–3.6149	4.3981
Ts1 – Ts2	1.000	–44.1688	45.0808
Ts1 – Ts3	1.000	–33.0444	56.2052
Ts2 – Ts3	1.000	–33.5004	55.7492
Tr1 – Tr2	1.000	–28.6778	40.2354
Td1 – Td3	1.000	–27.5666	41.3466
Tr2 – Tr3	1.000	–33.3454	35.5678
Dm1 – Dm2	1.000	–1.1092	1.2412
Dm1 – Dm3	0.671	–0.5868	1.7636
Dm2 – Dm3	0.839	–0.6528	1.6976

N = 25. Dm: maximum radial displacement of the muscle belly; Tc: contraction time; Td: reaction time; Tr: relaxation time; Ts: contraction sustain time.

Table 4
Correlation Coefficient (Pearson) between the three measurements for the five parameters assessed (reaction time, contraction time, contraction sustain time, relaxation time and muscle belly)

Parameter	Td1	Td2	Td3
Td1	–	0.872*	0.702*
Td2	0.872*	–	0.656*
Parameter	**Tc1**	**Tc2**	**Tc3**
Tc1	–	0.932*	0.915*
Tc2	0.932*	–	0.906*
Parameter	**Ts1**	**Ts2**	**Ts3**
Ts1	–	0.907*	0.972*
Ts2	0.907*	–	0.930*
Parameter	**Tr1**	**Tr2**	**Tr3**
Tr1	–	0.950*	0.948*
Tr2	0.950*	–	0.971*
Parameter	**Dm1**	**Dm2**	**Dm3**
Dm1	–	0.838*	0.762*
Dm2	0.838*	–	0.885*

* Statistically significant correlation (p < 0.01).
N = 25. Dm: maximum radial displacement of the muscle belly; Tc: contraction time; Td: reaction time; Tr: relaxation time; Ts: contraction sustain time.

Dm displayed minor differences between measurements as indicated by the comparison of means test (p = 1 for the comparison the T1 vs. T2; p = 0.839 for T2 vs. T3 series; and p = 0.671 for T1 vs. T3). The average value for Dm declined slightly as the number of stimuli increased and as the sensor moved away from the first measurement point.

Strong correlations were noted in all three measurements ($r > 0.9$) for Tc, Tr and Ts (table 4). Correlations for Td and Dm were slightly lower ($r > 0.9$), especially with respect to the third measurement.

The box plot in figure 2 shows distribution of the data obtained from the three measurements (+2, 0, -2) for the five variables assessed by TMG (A: Td; B: Tc; C: Ts; D: Tr; E: Dm).

Discussion

The findings show that, at least for measurements made on the rectus femoris, TMG offers a high degree of reproducibility; this makes it an excellent tool for assessing muscle structure status and the capacity of the muscle to respond to an external stimulus (single electrical stimulus).

However, the data shown confirm that failure to implement the methodological procedures scrupulously during measurement can cause minor changes to the final results. The most difficult factor to control in repeated measurements is the exact position of the sensor above the muscle. Modifying the position causes changes in muscle response, evident in the magnitude of the displacement recorded by the sensor. To the best of the authors' knowledge, this is the first study of reproducibility using three distinct positions for the five most common parameters and with a sample that provides the requisite statistical power.

The variable representing radial displacement of the muscle (Dm) displayed appreciable, although not statistically significant, differences between the three points under investigation, separated from the midpoint by 2 cm. The reading from the third measurement was slightly lower (8.07 ± 1.33 mm) than the other two; for example, muscle stiffness increased with the number of stimulations. To a certain extent, this finding runs counter to those of Valenčič et al[5], who reported that the responses recorded by the displacement sensor were not affected by the complex biomechanical properties of joints or of the brace itself.

One possible explanation for this finding could be the time used in the present protocol to carry out each measurement (electrical stimulus). Since stimulation time was not controlled, the time elapsing between stimuli may have been insufficient to allow the muscle to return to a completely relaxed state. The authors believe that repeated electrical stimuli cause a neuromuscular potentiation (post-activation potentiation) that may increase the contractile capacity of skeletal muscle tissue[14,15] and, as a result, affect the level of muscle deformation if they are repeated frequently without allowing sufficient recovery time. It should be stressed that the main muscle potentiation mechanism is the phosphorylation of regulatory myosin light chains (rMLC)[16,17]. The rate of the initial phosphorylation process (kinase proteins) and subsequent dephosphorylation (phosphatases) occuring at each muscle activation is relatively slow, which means that returning to rest levels may take several minutes after the end of the contraction[17].

The likelihood of the muscle not being completely relaxed at the time of each stimulus was increased by the use of three stimuli for each measuring point (low intensity: 50 mAp; medium intensity: 75 mAp; high intensity: 100 mAp), meaning that the subject would have activated the same muscle structure nine times before reaching the maximum stimulus (100 mAp) in the third position (+2 cm). The increase in potentiation time rises when the muscle is stimulated repeatedly[17].

It is also worth highlighting certain trends observed in the values of Ts and Tr when the sensor position was changed and the number of stimulations was increased. The box plot for these two parameters (fig. 2C and 2D), shows a slight tendency for this value to fall in some subjects.

Attention is also drawn to the possible morphological changes taking place in the analysed muscle when the sensor position was changed. Uniform shortening of muscle fibres does not exist in natural biological contexts. It has been suggested that the complexity of muscle architecture and the heterogeneous mechanical properties of muscle and tendon tissue may lead to non-uniform shortening[18-24]. Factors such as the non-uniform length of the sarcomere, myofibre or fascicle can alter the mechanical properties of the whole muscle[25,26].
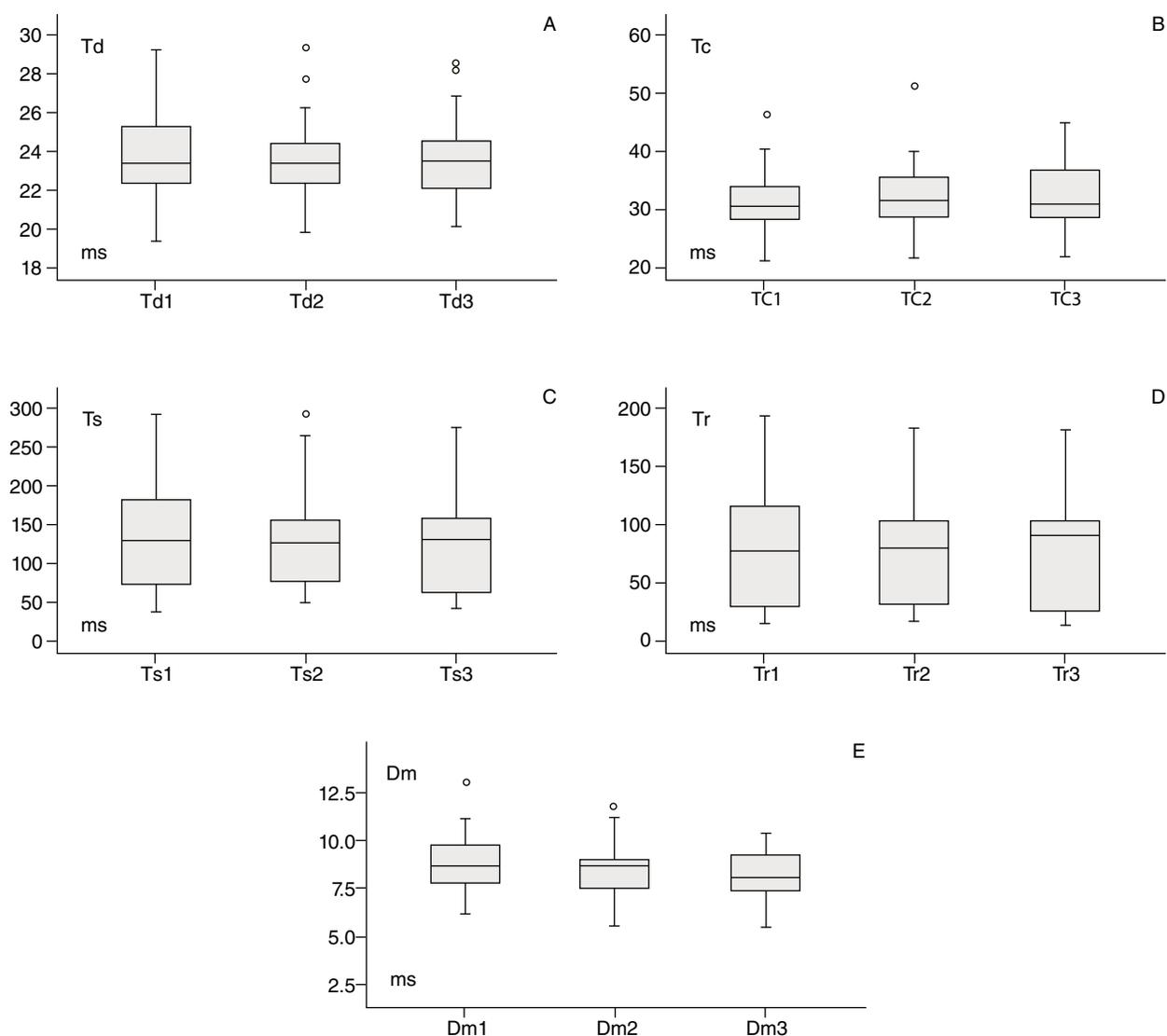
Fig. 2. Distribution of the data obtained from the three measurements (+2, 0, -2) for the five variables assessed by TMG (A: Td; B: Tc; C: Ts; D: Tr; E: Dm). (N = 25). Dm: maximum radial displacement of the muscle belly; Tc: contraction time; Td: reaction time; Tr: relaxation time; Ts: contraction sustain time.

In conclusion, TMG has been shown to be a tool with a high degree of reproducibility for the assessment of muscle contractile properties in the anterior rectus. However, to ensure maximum reliability over repeated measurements it is necessary to adhere closely to a measurement protocol that does not alter muscle response. Sensor placement and complete muscle relaxation are two fundamental aspects of the measurement protocol and must be given due attention.

References

1. Valenčič V, Knez N. Measuring of the skeletal muscles dynamic properties. Artific Org. 1997;21:240-2.
2. Dahmane R, et al. Tensiomyography, a non-invasive method reflecting the percentage of slow muscle fiber in human skeletal muscles. Life Sciences. 2000; Gozd Martuljek, Slovenia, Abstract 29.
3. Dahmane R, Valenčič V, Knez N, Er en I. Evaluation of the ability to make non-invasive estimation of muscle contractile properties on the basis of the muscle belly response. Med Biol Eng Comput. 2001;39(1):51-5.
4. Valenčič V, Djordjevic S, Knez N, Dahmane R, Cohr M, Jurcic-Zlobec B et al. Contractile properties of skeletal muscles detection by tensiomyographic measurement method. 2000 Pre-Olympic Congress, Brisbane, Australia, Abstract 507.
5. Valenčič V, Knez N, Simunic B. Tensiomyography: detection of skeletal muscle response by means of radial muscle belly displacement. Biomedical Engineering. 2001;1:1-10.
6. Simunic B. Model of longitudinal contraction and transverse deformations in skeletal muscles. Doctoral Thesis. Faculty of Electrical Engineering. Ljuljana University. 2003.
7. Dahmane R, Djordjevič S, Smerdu V. Adaptive potential of human biceps femoris muscle demonstrated by histochemical, immunohistochemical and mechanomyographical methods. Med Biol Eng Comput. 2006;44(11): 999-1006.
8. Valenčič V. Direct mesurement of the skeletal muscle tonus. Advances in external control of human extremities. Nauka, Belgrado; 1990.
9. Krizaj D, Simunic B, Zagar T. Short-term repeatability of parameters extracted from radial displacement of muscle belly. J Electromyog Kinesiol. 2008;18:645-51.
10. Dahmane R, Djordjevič S, Simunic B, Valenčič V. Spatial fiber type distribution in normal human muscle Histochemical and tensiomyographical evaluation. J Biomech. 2005;38(12):2451-9.
11. Simunic B, Valencia V. Proceedings of X Electrochemical and Computer Science Conference. IEEE Region 8, Slovenian Section IEEE; 2001 Sept 24-26; Portoroz, Eslovenia. 2001. Vol. B. p. 363-6.
12. Rodríguez-Matoso D, Quiroga M, Da Silva-Grigoletto M, Bautista P, Sarmiento, S, García-Manso JM. Evaluación de la reproducibilidad del TGM-BCM. II Congreso Internacional de Ciencias del Deporte. 2009 del 27 al 29 de mayo. El deporte a la luz de los sistemas complejos; Universidad Católica de Murcia. 2009.

13. Perott AO, Delagi EF, Iazzetti J, Morrison D. Anatomical Guide for the electromyographer: The limbs and trunk. Springfield, IL: Charles C. Thomas, Publisher Ltd.; 2005.
14. Persechini A, Stull JT, Cooke R. The effect of myosin phosphorylation on the contractile properties of skinned rabbit skeletal muscle fibers. J Biol Chem. 1985;260(13):7951-4.
15. Green HJ, Jones SR. Does post-tetanic potentiation ompensate for low frequency fatigue? Clin Physiol. 1989;9:499-514.
16. Manning DR, Stull JT. Myosin light chain phosphorilation-dephosphorilation in mammalian skeletal muscle. Am J Physiol. 1982;242:C234-41.
17. Sweeney HL, Stull JT. Alteration of cross-bridge kinetics by myosin light chain phosphorylation in rabbit skeletal muscle: Implications for regulation of actin-myosin interaction. Proc Natl Acad Sci. 1990:87:414-8.
18. Ettema GJ, Huijing PA. Properties of the tendinous structures and series elastic component of EDL muscle-tendon complex of the rat. J Biomech. 1989;22:1209-15.
19. Lieber RL, Leonard ME, Brown CG, Trestik CL. Frog semitendinosis tendon loadstrain and stress-strain properties during passive loading. Am J Physiol. 1991;261:C86-92.
20. Monti RJ, Roy RR, Hodgson JA, Edgerton VR. Transmission of forces within mammalian skeletal muscles. J Biomech. 1999;32:371-80.
21. Zuurbier CJ, Everard AJ, van der Wees P, Huijing PA. Length-force characteristics of the aponeurosis in the passive and active muscle condition and in the isolated condition. J Biomech. 1994;27:445-53.
22. Van Bavel H, Drost MR, Wielders JD, Huyghe JM, Huson A, Janssen JD. Strain distribution on rat medial gastrocnemius (MG) during passive stretch. J Biomech. 1996;29:1069-74.
23. Huijing PA. Muscle as a collagen fiber reinforced composite: a review of force transmission in muscle and whole limb. J Biomech. 1999;32:329-45.
24. Pappas GP, Asakawa DS, Delp SL, Zajac FE, Drace JE. Non uniform shortening in the biceps brachii during elbow flexion. J Appl Physiol. 2002;92:2381-9.
25. Morgan DL. From sarcomeres to whole muscles. J Exp Biol. 1985;115:69-78.
26. Huijing PA. Parameter interdependence and success of skeletal muscle modelling. Hum Mov Sci. 1995;14:443-86.