BRIEF REVIEW

RELIABILITY AND MEASUREMENT ERROR OF TENSIOMYOGRAPHY TO ASSESS MECHANICAL MUSCLE FUNCTION: A SYSTEMATIC REVIEW

SAÚL MARTÍN-RODRÍGUEZ,[1] IRINEU LOTURCO,[2] ANGUS M. HUNTER,[3] DAVID RODRÍGUEZ-RUIZ,[4] AND DIEGO MUNGUIA-IZQUIERDO[5]

[1]Official College of Graduates in Physical Education of the Canary Islands (COLEF), Las Palmas de Gran Canaria, Gran Canaria, Spain; [2]NAR—Nucleus of High Performance in Sport, São Paulo, Brazil; [3]Health and Exercise Sciences Research Group, University of Stirling, Stirling, United Kingdom; [4]Department of Physical Education, University of Las Palmas de Gran Canaria, Gran Canaria, Spain; and [5]Department of Sports and Computer Science, Section of Physical Education and Sports, Universidad Pablo de Olavide, Seville, Spain

ABSTRACT

Martín-Rodríguez, S, Loturco, I, Hunter, AM, Rodríguez-Ruiz, D, and Munguia-Izquierdo, D. Reliability and measurement error of tensiomyography to assess mechanical muscle function: A systematic review. *J Strength Cond Res* 31(12): 3524–3536, 2017—Interest in studying mechanical skeletal muscle function through tensiomyography (TMG) has increased in recent years. This systematic review aimed to (a) report the reliability and measurement error of all TMG parameters (i.e., maximum radial displacement of the muscle belly [Dm], contraction time [Tc], delay time [Td], half-relaxation time [½ Tr], and sustained contraction time [Ts]) and (b) to provide critical reflection on how to perform accurate and appropriate measurements for informing clinicians, exercise professionals, and researchers. A comprehensive literature search was performed of the Pubmed, Scopus, Science Direct, and Cochrane databases up to July 2017. Eight studies were included in this systematic review. Meta-analysis could not be performed because of the low quality of the evidence of some studies evaluated. Overall, the review of the 9 studies involving 158 participants revealed high relative reliability (intraclass correlation coefficient [ICC]) for Dm (0.91–0.99); moderate-to-high ICC for Ts (0.80–0.96), Tc (0.70–0.98), and ½ Tr (0.77–0.93); and low-to-high ICC for Td (0.60–0.98), independently of the evaluated muscles. In addition, absolute reliability (coefficient of variation [CV]) was low for all TMG parameters except for ½ Tr (CV = >20%), whereas measurement error indexes were high for this parameter. In conclusion, this study indicates that 3 of the TMG parameters (Dm, Td, and Tc) are highly reliable, whereas ½ Tr demonstrate insufficient reliability, and thus should not be used in future studies.

KEY WORDS muscle contractile properties, relative reliability, absolute reliability

INTRODUCTION

Mechanical muscle properties have been widely assessed and examined using several methodological approaches in the literature. The importance of understanding how muscles can adapt to physiological stress or unloading (e.g., training or tapering periods) is a broad field of study (41). In this context, different technologies have been developed to study muscle function and its behavior, such as surface electromyography (sEMG) (60), muscle torque production (70), shear wave ultrasound elastography (35), and mechanomyographic (MMG) methods (30), such as phonomyography (47) soundmyography (68), and vibromyography (26). Promising results have been obtained with the abovementioned approaches, but nevertheless, they present some technical disadvantages, such as low noise signal (high variability), complex setup, laborious postsignal processing, and data filtering (46,67). Furthermore, these respective methods are heavy and quite expensive, which makes it difficult to use in the professional clinical and performance environments. More recently, a portable validated MMG method called tensiomyography (TMG) (69) has been widely used with very promising results to assess in vivo passive muscle contractile properties. Tensiomyography uses a high-precision (4 μm) digital transducer placed perpendicularly to the muscle surface, capable of assessing different parameters extracted from its waveform after a submaximal-to-maximal percutaneous neuromuscular stimulation (1). Each waveform integrates and calculates the following parameters: maximum radial displacement of the muscle belly (Dm), contraction time (Tc), delay time (Td), half-relaxation time

---

Address correspondence to Saúl Martín-Rodríguez, saulmrguez@gmail.com.

31(12)/3524–3536

Journal of Strength and Conditioning Research

(½ Tr), and sustained contraction time (Ts) (Figure 1). Dm represents the maximal radial displacement of the muscle belly expressed in millimeters; Td indicates the time taken for the muscle to reach 10% of total observed displacement after stimulation; Tc is the time elapsed 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 and is calculated by measuring the time elapsed between the moment when initial deformation reaches 50% of its maximum value, and the moment when deformation readings return (during relaxation) to 50% of Dm. Finally, ½ Tr is the time from 90 to 50% of Dm on the descending curve. The fact that TMG analyses muscle function in a noninvasive and selective way is especially appreciated by strength and conditioning coaches, physiotherapists, and sport scientists, who preferentially seek accurate and practical assessment methods which do not disturb their professional routines (1,40).

Compared with other MMG techniques (30), because of the high precision of its transducer (63), TMG does not present problems with the large measurement variability usually caused by the slight muscle pretension ($0.2\ \text{N}\cdot\text{cm}^{-2}$). This pretension increases the main drawback of the MMG methods–a low signal-to-noise ratio to that exertion (64). Regarding noise, 1 important aspect of every MMG method lies in the type of sensor selected for data acquisition; i.e., contact-displacement sensor (CDS) or laser-displacement sensor (LDS) (54,65), accelerometers (3), or acoustic sensors (45). The last 2 above-mentioned methods (i.e., accelerometers and acoustic sensors) have been shown to be unreliable (3,66), whereas a recent investigation has shown that both CDS and LDS seem to be highly reliable for both Dm and Tc (54). These authors indicated that the CDS (similar to TMG's sensor) seems to be more sensitive to Dm, possibly because of its ability to measure underlying muscle movement that would not normally be translated to the skin's surface, whereas the laser sensor displayed an increased sensitivity to temporal parameters (i.e., Tc and ½ Tr). The latter issue is of importance in both performance and clinical fields because some of the TMG parameters (Dm, Tc, and ½ Tr) have been related to changes in muscle passive stiffness and atrophic processes (Dm) (18,49), fatigue (Dm and Tc) (11,13,20–23,29,36,37,53), efficiency of Ca^{2+} reuptake (Tr) (31), and fiber type (Tc and Tr) (9,10,31,57,71). More recently, some investigations have used TMG-derived parameters from Dm, Tc, and Td, called rate of deformation development, until 10% Dm (10% Dm/Δ time) and 90% Dm (90% Dm/Δ time), respectively, showing that decrements in these parameters correlated significantly with decreases in maximal voluntary contraction (11). Evidence about TMG has grown in the past 10 years (+70 peer-review articles), presenting different utilities in exercise testing, training, and health environments, which has been recently highlighted by Martín-Rodríguez et al. (40), who stressed the potential use of this tool for screening, diagnosis, and monitoring the response to surgical treatment in sports injuries together with monitoring peripheral fatigue of any superficial muscle. In the same line, a recent investigation (62) has shown that

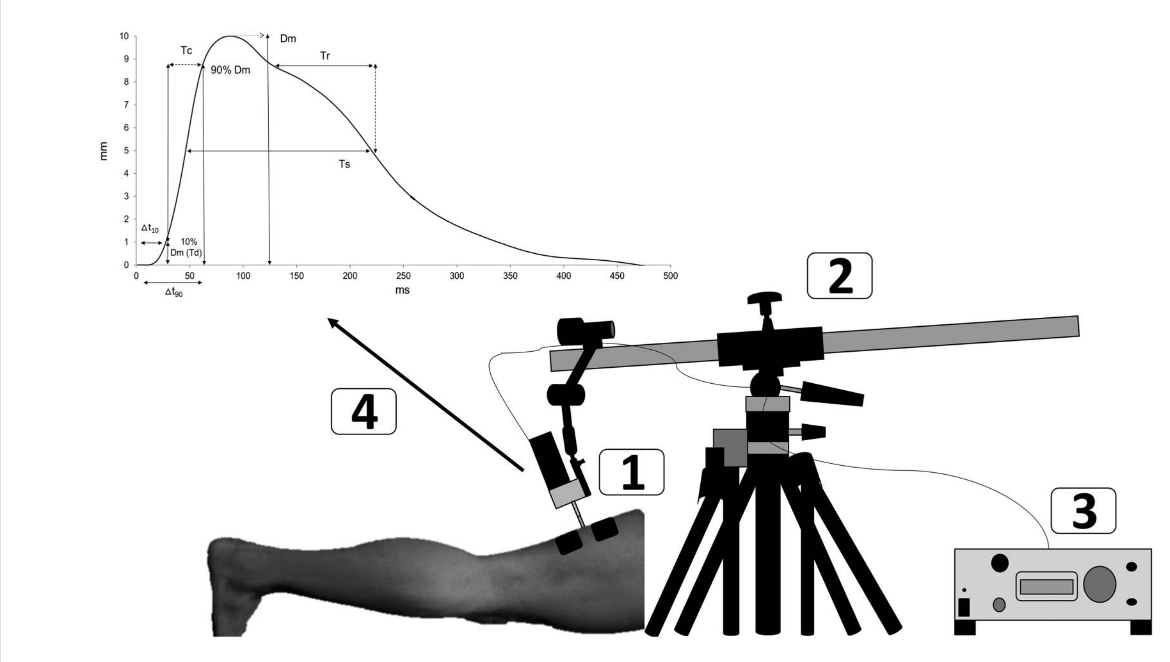

Figure 1. Illustration of the tensiomyography (TMG) equipment and the classic wave of twitch response with all its parameters. 1 = Mechanical sensor and electrodes. 2 = Tripod with manipulating hand. 3 = Data acquisition subunit. 4 = Typical wave extracted from TMG response.

the ongoing monitoring of muscle contractile properties of muscles in athletes may aid in the prediction of fatigued-induced muscle injury because these authors demonstrated that MMG is more sensitive in detecting accumulated muscle fatigue than the "gold standard" measures of maximum voluntary contraction and median power frequency of sEMG. Although the above is promising, little attention has been paid to the study of the reliability and measurement error of MMG methods, but TMG is receiving more attention in this issue in the literature. In this sense, factors such as the method of sensor location, interelectrode distances, and joint angles may all impact TMG's parameters variability. Thus, studies analyzing the reliability, reproducibility, and measurement error of this kind of techniques should include and specify detailed information about all the above-mentioned factors.

Despite the extensive number of publications involving TMG, to date, there is no available consensus about reliability and reproducibility of this technique in the literature. Whereas relative (intraclass correlation coefficient [ICC]) and absolute (coefficient of variation [CV]) reliability is the degree to which an assessment instrument produces consistent outcomes, reproducibility refers to the variation in measurements made on a subject under changing conditions (4). Providing an estimate of the reliability and reproducibility of TMG will help sport scientists to understand how large (or small) the error is when using the TMG system. Thus, the aim of this systematic review was to examine whether TMG is a reliable and reproducible method, able to appropriately assess muscle mechanical properties to recommend or not its use both in practical and clinical settings.

Methods

Experimental Approach to the Problem

Preferred reporting items for systematic reviews and meta-analyses guidelines for systematic reviews were followed (42). A systematic literature search was performed in the following computerized databases: Pubmed, Scopus, and Science Direct through July 2017 without any time restrictions. The Cochrane database was consulted if there were any reviews about TMG. The search was performed using the medical subject heading terms and text words (or synonyms) for ("reliability" OR "reproducibility" OR "measurements error" AND "tensiomyography") and derivatives of these terms. Reference lists were screened to identify additional relevant studies. The authors also consulted experts in the field to include any additional studies published or accepted after July 2017. Reliability and reproducibility studies were considered for this review. The search for articles, removal of duplicates, and checking was performed by 2 authors: S. Martín-Rodríguez and D. Rodríguez-Ruiz.

Study Selection and Inclusion Criteria

The selection of studies was performed in accordance with the following inclusion criteria: (a) studies must be written in English and; (b) must be strictly focused on investigating issues related to reliability and reproducibility of TMG. Furthermore, only peer-reviewed articles published in scientific journals between January 1990 (i.e., first article about TMG) and July 2017 were considered. Reviews, conference abstracts, monographs, dissertations, and theses were not included. Nonreliability or reproducibility studies, those written in languages other than English, and those published in nonindexed journals were not included. A flow chart of study selection is listed in Figure 2.

Data Extraction

First, the following data were extracted from the studies: (a) author(s)/year/location; (b) design/sample/age; (c) type (product or process) and measure of TMG; (d) statistics and reliability scores; (e) main results; and (f) conclusions. Two reviewers (S.M.-R. and D.R.-R.) independently extracted data. In case of disagreement between the 2 reviewers, there was discussion to reach consensus. If necessary, a third reviewer (D.M.-I.) made the decision. In case of missing data, the authors were contacted. Second, the methodological quality of the studies and the quality of the reliability and measurement error properties of the TMG were evaluated. Finally, a best evidence synthesis was performed.

Quality Assessment of the Studies

The methodological quality of the studies was assessed using the Consensus-based Standards for the Selection of Health Measurement Instruments (COSMIN) checklist with the 4-point rating scale, which is recommended for use in systematic reviews about clinimetric properties (www.cosmin.nl) (59). The COSMIN checklist was developed and validated by an international consortium of 43 experts with different backgrounds, especially for the evaluation of health measurement instruments (43). Test-retest reliability and measurement error are evaluated separately in the COSMIN checklist, including items regarding design requirements and statistical methods. Design requirements for determining measurement error are similar to those for reliability. The COSMIN items are individually scored on a 4-point rating scale (i.e., "poor," "fair," "good," or "excellent") (60). Quality assessment scores are listed in Table 1.

For each study, we evaluated the quality of the reliability and measurement error based on COSMIN standards (43). The overall rating for a clinimetric property is "good" (+), "indeterminate" (?), or "negative" (−) (58). Reliability was rated good when ICC was $\geq$0.7 or the Pearson correlation coefficient was $>$0.8. Measurement error was rated good when the minimal important change (MIC) was greater than the smallest detectable change (SDC) or when the MIC was outside the limits of agreement (58). The MIC represents the size that is perceived as significant by a patient or health care professional (14). Intraclass correlation coefficient ranges from low ($<$0.70), good (0.70–0.79), high (0.80–0.89), and excellent ($\geq$0.90) (2,38). Two reviewers (S.M.-R. and

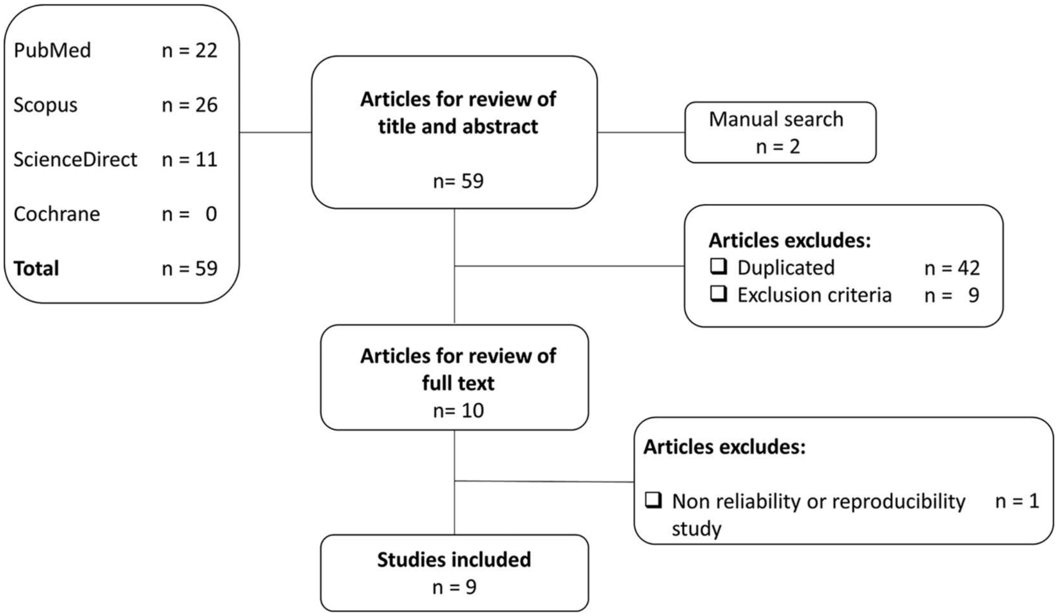

Figure 2. Flow chart of study identification procedure.

D.R.-R.) independently extracted the data and assessed the methodological quality. In case of disagreement between the 2 reviewers, there was discussion to reach consensus. Any remaining disagreements between them were solved by a third reviewer (D.M.-I.).

Data Synthesis

We reported the overall level of evidence for TMG by combining the results of the methodological quality ranking for the studies with the statistical findings for reliability and measurement error. We followed the recommendations of the Cochrane Back Review Group for this synthesis (19,65). The level of evidence was rated as follows: (a) strong (consistent findings in multiple studies of good methodological quality or in 1 study of excellent methodological quality); (b) moderate (consistent findings in multiple studies of fair methodological quality or in 1 study of good methodological quality); (c) limited (1 study of fair methodological quality); (d) conflicting (conflicting findings); and (e) unknown (only studies of poor methodological quality).

Results

The study populations ranged from 10 to 23 subjects per study (all male subjects, excepting 1 study), with ages ranging from 21.3 ± 3.4 to 30.7 ± 7.4 years. Nine eligible studies were identified. Evidence for reliability and measurement error of Dm, Tc, Td, ½ Tr, and Ts parameters of muscles evaluated were reported in the 8 studies (Table 1). In all studies, items 2, 7, 8, and 10 were scored fair, whereas items 1 and 3 were scored good and poor, respectively. Item 4 was scored poor in 3 studies (16,51,53). Item 5 was scored fair or poor in all studies, excepting 1 which was scored excellent (63). Item 6 was scored fair in almost studies excepting 2 which was scored excellent (12,17). Item 9 was scored fair or good in 7 studies (8,16,33,51,53,63), whereas 2 were scored excellent (12,17). Item 11a was scored fair in 5 studies (12,48,51,53,56). Item 11b was scored poor in 5 studies (8,16,48,51,53). Items 12, 13, and 14 were scored as not applicable. Methodological quality (COSMIN score) of all studies was scored poor. However, quality ranking of clinimetric property logic was scored as indeterminate (as MIC was not reported in any study). Test-retest reliability was assessed in most studies through ICC and CV. Measurement error methods used by authors were bias, *SEM*, normalized-standard error of the mean (N-*SEM*), random error (RE), minimum detectable change (MDC), and %MDC (percentage of MDC).

All studies (Table 2) except 1 (53), showed high-to-excellent ICC values for Dm (0.82–0.99); good-to-excellent ICC values for Tc (0.70–0.99), Ts (0.80–0.96), and Tr (0.77–0.93); and low-to-excellent ICC values for Td (0.60–0.98). Only 1 study (17) found low ICC values (0.60) for Td. All studies evaluated muscles from the thigh excepting 2 that assessed the gastrocnemius medialis (GM) (17) and gastrocnemius lateralis (GL) (12), and another 1 which assessed the biceps brachii (BB) (33). The rectus femoris (RF) was evaluated in 4 studies (8,12,48,53), showing good-to-high ICC values in all parameters evaluated (0.83–0.99); however,

TABLE 1. Quality assessment of the included studies.

Box B and C. Reliability and measurement error	Piqueras-Sanchiz et al. (48)	de Paula Simola et al. (12)	Ditroilo et al. (13)	Rey et al. (51)	Simunic (56)	Carrasco et al. (8)	Ditroilo et al. (16)	Rodríguez-Matoso et al. (53)	Tous-Fajardo et al. (63)	Krizaj et al. (33)
Design requirements: Reliability and measurement error										
1. Was the percentage of missing items given?	Good	Good	Good	Good	Good	Good	Good	Good	Good	Good
2. Was there a description of how missing items were handled?	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair
3. Was the sample size included in the analysis adequate?	Poor	Poor	Poor	Poor	Poor	Poor	Poor	Poor	Poor	Poor
4. Were at least 2 measurements available?	Excellent	Excellent	Excellent	Poor	Excellent	Excellent	Poor	Poor	Excellent	Excellent
5. Were the administrations independent?	Fair	Fair	Fair	Fair	Poor	Fair	Fair	Fair	Excellent	Fair
6. Was the time interval stated?	Fair	Excellent	Excellent	Fair	Fair	Fair	Fair	Fair	Fair	Fair
7. Were patients stable in the interim period on the construct to be measured?	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair
8. Was the time interval appropriate?	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair
9. Were the test conditions similar for both measurements?	Good	Excellent	Excellent	Fair	Excellent	Fair	Fair	Fair	Fair	Fair
10. Were there any important flaws in the design or methods of the study?	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair	Fair
Statistical methods. Reliability										
11a. For continuous scores: Was an intraclass correlation coefficient calculated?	Fair	Fair	Excellent	Fair	Fair	Fair	Excellent	Poor	Excellent	Excellent
12. For dichotomous/nominal/ordinal scores: Was kappa calculated?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
13. For ordinal scores: Was a weighted kappa calculated?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14. For ordinal scores: Was the weighting scheme described?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Statistical methods. Measurement error										
11b. Was the *SE* of measurement, smallest detectable change, or limits of agreement calculated?	Poor	Excellent	Excellent	Poor	Excellent	Poor	Poor	Poor	Excellent	Excellent

TABLE 2. Methodological rank of studies and quality of evidence.*

Study	Population	Equipment	Stimulation amplitude, IED, and measurement area	Muscles evaluated	Rest time interval between measurements	Test-retest reliability	Measurement error
Piqueras-Sanchiz et al. (48)	$n = 23$ men Age 27.3 ± 4.1	TMG-S1 (GK 40; Panoptik d.o.o., Ljubljana, Slovenia)	Initial stimuli of 30 mA with increments of 10 mA until there was no further increase in Dm or maximal stimulator output (100 mA)	Biceps femoris, rectus femoris, semitendinosus, vastus lateralis, and medialis	10 s	High BF Tc (ICC = 0.98–0.99; CV = 24.10–30.2%) RF Tc (ICC = 0.98–0.99; CV = 11.98–12.10%) ST Tc (ICC = 0.98; CV = 20–63–23.68) VL Tc (ICC = 0.96–0.99; CV = 14.61–17.44%) VM Tc (ICC = 0.97–0.99; CV = 10.79–17.20%)	*SEM*, SDC, MIC, or LoA not reported
de Paula Simola et al. (12)	$n = 21$ men	TMG S-2 (BMC Ltd.)	Initial stimuli of 40 mA with increments of 20 mA until there was no further increase in Dm or maximal stimulator output (110 mA)	Biceps femoris, rectus femoris, gastrocnemius lateralis	10 s	Good	
	Age 26.5 + 6.7		IED IED ± 5 cm Measurement area: Muscle belly			RF Dm (ICC = 0.92; CV = 9.30%) Td (ICC = 0.87; CV = 3.80%) Tc (ICC = 0.94; CV = 4.90%) Tr (ICC = 0.86; CV = 32.80%) Ts (ICC = 0.85; CV = 21.30%) BF Dm (ICC = 0.95; CV = 10.40%) Td (ICC = 0.92; CV = 2.40%) Tc (ICC = 0.91; CV = 8.70%) Tr (ICC = 0.70; CV = 20.6%) Ts (ICC = 0.88; CV = 4.9%) GL Dm (ICC = 0.94; CV = 13.70%) Td (ICC = 0.90; CV = 4.20%) Tc (ICC = 0.93; CV = 8.50%) Tr (ICC = 0.93; CV = 12.6%) Ts (ICC = 0.87; CV = 8.5%)	RF Dm (bias = 0.10 ± 1.40; *SEM* = 1.00) Td (bias = 0.50 ± 1.70; *SEM* = 1.20) Tc (bias = −0.50 ± 2.60; *SEM* = 1.90) Tr (bias = 15.9 ± 38.00; *SEM* = 26.90) Ts (bias = 15.70 ± 41.10; *SEM* = 29.00) BF Dm (bias = 0.10 ± 1.40; *SEM* = 1.00) Td (bias = −0.10 ± 1.10; *SEM* = 0.80) Tc (bias = −3.20 ± 7.90; *SEM* = 5.60) Tr (bias = −3.40 ± 31.20; *SEM* = 22.10) Ts (bias = 1.40 ± 18.80; *SEM* = 13.30) GL Dm (bias = −0.2 ± 1.30; *SEM* = 0.90) Td (bias = −0.80 ± 1.80; *SEM* = 1.30) Tc (bias = −3.40 ± 9.60; *SEM* = 6.80) Tr (bias = −1.90 ± 11.50; *SEM* = 8.10) Ts (bias = 12.50 ± 30.50; *SEM* = 21.60)

(continued on next page)

Ditroilo et al. (13)	*n* = 21 men Age 21.3 ± 3.4	TMG (BMC Ltd.)	40–70 mA IED ± 5 cm Measurement area: Muscle belly	Gastrocnemius medialis	10 s	Good Dm (ICC = 0.91; CV = 11%) Td (ICC = 0.60; CV = 8.1%) Tc (ICC = 0.70; CV = 7.60%) Tr (ICC = 0.77; CV = 30.1%) Ts (ICC = 0.80; CV = 6.50%)	Dm (*SEM* ± 0.24; MDC = 0.66; %MDC = 18.11) Td (*SEM* ± 1.32; MDC = 3.67; %MDC = 16.90) Tc (*SEM* ± 1.13; MDC = 3.13; %MDC = 12.94) Tr (*SEM* ± 14.93; MDC = 41.38; %MDC = 59.13) Ts (*SEM* ± 6.86; MDC = 19.01; %MDC = 11.47)
Rey et al. (51)	*n* = 15 men Age 26.6 ± 4.4	Trans-Tek (GK 40; Panoptik d.o.o.)	50, 75, and 100 mA IED ± 5 cm Measurement area: Muscle belly	Biceps femoris	10 s	Good Dm (ICC = 0.95) Td (ICC = 0.82) Tc (ICC = 0.86) Tr (ICC = 0.78) Ts (ICC = 0.94)	*SEM*, SDC, MIC, or LoA not reported
Simunic (56)	*n* = 10 men Age 24.6 ± 3.0	TMG (BMC Ltd.)	Not specified IED ± 5 cm Measurement area: Muscle belly	Vastus medialis, vastus lateralis, and biceps femoris	Not reported	Good VM Dm (ICC = 0.98; CV = 4.70%) Td (ICC = 0.94; CV = 2.80%) Tc (ICC = 0.98; CV = 2.20%) Tr (ICC = 0.88; CV = 6.40%) Ts (ICC = 0.94; CV = 4.90%) VL Dm (ICC = 0.99; CV = 4.70%) Td (ICC = 0.89; CV = 1.80%) Tc (ICC = 0.98; CV = 1.50%) Tr (ICC = 0.89; CV = 7.60%) Ts (ICC = 0.96; CV = 4.40%) BF BF Dm (ICC = 0.99; CV = 4.20%); Td (ICC = 0.98; CV = 2.60%) Tc (ICC = 0.98; CV = 4.90%) Tr (ICC = 0.89; CV = 9.30%) Ts (ICC = 0.95; CV = 3.30%)	VM Dm (bias = 0.23; RE ± 0.30; *SEM* ± 0.17) Td (bias = 0.19; RE ± 0.62; *SEM* ± 0.42) Tc (bias = 0.07; RE ± 0.56; *SEM* ± 0.4) Tr (bias = 1.51; RE ± 0.30; *SEM* ± 0.17) Ts (bias = 6.29; RE ± 8.64; *SEM* ± 5.46) VL Dm (bias = −0.23; RE ± 0.38; *SEM* ± 0.25) Td (bias = 0.12; RE ± 0.44; *SEM* ± 0.30) Tc (bias = 0.32; RE ± 0.41; *SEM* ± 0.25) Tr (bias = 3.59; RE ± 4.63; *SEM* ± 3.18) Ts (bias = 3.22; RE ± 7.09; *SEM* ± 4.99) BF Dm (bias = 0.13; RE ± 0.23; *SEM* ± 0.43) Td (bias = 0.07; RE ± 0.61; *SEM* ± 0.40) Tc (bias = 1.03; RE ± 1.50; *SEM* ± 1.06) Tr (bias = 4.81; RE ± 6.19; *SEM* ± 4.12) Ts (bias = 1.48; RE ± 6.57; *SEM* ± 5.01)

Carrasco et al. (8)	*n* = 12 men	Trans-Tek (GK 40; Panoptik d.o.o.)	Initial stimuli of 30 mA with increments of 10 mA until there was no further increase in Dm or maximal stimulator output (110 mA)	Rectus femoris	15 s	Good	*SEM*, SDC, MIC, or LoA not reported
	Age 24.2 ± 0.6		IED ± 5 cm Measurement area: Muscle belly			Dm (ICC = 0.92) Td (ICC = 0.89) Tc (ICC = 0.83) Tr (ICC = 0.88) Ts (ICC = 0.90)	
Ditroilo et al. (16)	*n* = 16 (12 men, 2 women)	Spring-loaded displacement sensor (digital-optical comparator;	Initial stimuli not described with increments of 10 mA until there was no further increase in Dm or maximal stimulator output. Authors reported maximal response between 40 and 70 mA.	Biceps femoris	10 s	Moderate to good	*SEM*, SDC, MIC, or LoA not reported
	Age 23.4 ± 4.9	RLS Ltd., Slovenia)	IED ± 5 cm Measurement area: Muscle belly			At 0° knee joint angle Dm (ICC = 0.82; CV = 19.8%) Tc (ICC = 0.82; CV = 16.5%) At 45° knee joint angle Dm (ICC = 0.57; CV = 19.7) Tc (ICC = 0.62; CV = 20.5) Poor At 90° knee joint angle (ICC = −0.57; CV = 43.1%) Tc (ICC = −0.40; CV; 33.3%)	
Rodríguez-Matoso et al. (53)	*n* = 25 men Age 25.7 ± 4.7	TMG (BMC Ltd.)	50, 75, and 100 mA IED ± 5 cm Measurement area: Muscle belly	Rectus femoris	Not reported	Good Dm (Cα = 0.92) Td (Cα = 0.90) Tc (Cα = 0.97) Tr (Cα = 0.99) Ts (Cα = 0.98)	*SEM*, SDC, MIC, or LoA not reported
Tous-Fajardo et al. (63)	*n* = 18 men	TMG-S1 (EMF-Furlan and Co. d.o.o., Ljubljana,	Initial stimuli of 50 mA with increments of 10 mA until there was no further increase in Dm or maximal stimulator output (110 mA)	Vastus medialis	10 s	Good	
	Age 22.9 ± 3.8	Slovenia)	IED ± 3 and ±5 cm			Dm (ICC = 0.97; CV = 4.70%)	Dm (bias = −0.3; RE ± 0.9; *SEM* ± 0.3)
			Measurement area: Muscle belly			Td (ICC = 0.86; CV = 2.70%)	Td (bias = 0.6; RE ± 2.7; *SEM* ± 0.9)
						Tc (ICC = 0.92; CV = 3.40%)	Tc (bias = 0.3; RE ± 2.5; *SEM* ± 0.9)
						Tr (ICC = 0.77; CV = 14.20%)	Tr (bias = −0.7; RE ± 52.2; *SEM* ±18.3)
						Ts (ICC = 0.96; CV = 2.40%)	Ts (bias = −0.7; RE ± 20.3; *SEM* ±7.2)
Krizaj et al. (33)	*n* = 13 men Age 30.7 ± 7.4	G40; RLS, Inc.	40–70 mA IED ± 5 cm Measurement area: Muscle belly	Biceps brachii	10 s	Good Dm (ICC = 0.98) Td (ICC = 0.94) Tc (ICC = 0.97) Tr (ICC = 0.89) Ts (ICC = 0.86)	Dm (N-*SEM* = 1.23) Td (N-*SEM* = 0.43) Tc (N-*SEM* = 0.48) Tr (N-*SEM* = 1.92) Ts (N-*SEM* = 1.30)

*TMG = tensiomyography; SDC = smallest detectable change; MIC = minimal important change; LoA = limits of agreement; BF = biceps femoris; GL = gastrocnemius lateralis; ICC = intraclass correlation coefficient; CV = coefficient of variation; RF = rectus femoris; ST = semitendinosus; VL = vastus lateralis; VM = vastus medialis; MDC = minimum detectable change; RE = random error.

there was inconsistency in 1 of the studies because of the use of Cronbach's alpha (Cα) instead of ICC (53). Three of the 4 studies that evaluated RF did not report data about measurement error (8,48,53). Gastrocnemius medialis and GL were evaluated by 2 studies (12,17) showing low-to-excellent (0.60–0.91) and high-to-excellent (0.87–0.94) ICC values, respectively. Both gastrocnemii showed low measurement error for Dm, Tc, and Td, whereas high for Ts and ½ Tr (Table 2). Last, in terms of absolute reliability, ½ Tr was shown as the parameter with the highest variability (CV = >20%) and measurement error indexes (12,17,33,56,63), whereas all the other parameters showed low variability (Table 2).

The electrical stimuli used in all studies were different, as can be observed in Table 2. Four studies used an initial stimulus of 30–50 mA with progressive increments of 10–20 mA, until there was no further increase in Dm or the maximum electrical output provided by the equipment was reached (i.e., 100–110 mA) (8,12,48,63). The remaining studies used varied stimuli (from 40 to 100 mA), depending on the muscle evaluated. One investigation (56) did not report the amplitude of stimuli used. The articles listed in Table 2 used the same measurement equipment (TMG; BMC Ltd., Ljubljana, Slovenia), only differing in the current amplitude (i.e., 100 or 110 mA) which enabled us to perform direct comparisons between them. The difference in current amplitude does not affect the TMG's outputs and was due to a European restriction (Council Directive 93/42/EEC) in terms of maximal current permitted for clinical use (information clarified by TMG-BMC company). All studies adopted interval times ranging from 10 to 15 seconds between the successive assessments, excepting 2 studies which did not detail these data (53,56). All studies located the sensor tip position (i.e., most prominent area of muscle belly) using the same (or similar) anatomical guide for the electromyographer (15). One study (63) evaluated the muscle response with 2 different inter-electrode distance (IED) (i.e., ±3 and ±5 cm). Last, only 1 study (16) analyzed the effect of joint angle alteration on the TMG outputs showing that at 0°, knee joint angle presented high relative and absolute reliability (ICC = 0.82; CV = 19.8%), whereas 45 and 90° presented insufficient reliability scores.

DISCUSSION

This review clearly exposes the scarcity of studies with high methodological quality investigating muscle mechanical properties using TMG. There is evident interest in the use of this technique to assess muscle function but with an important lack of attention to establishing a standardized measurement protocol to increase reliability and reduce measurement error. Evidence found in 9 studies supported that almost all TMG parameters (except for ½ Tr) possess both high-to-excellent absolute and relative reliability and low measurement error. Accordingly, ½ Tr was identified as a parameter with insufficient absolute reliability and highest measurement error in several of the examined studies; therefore, we do not recommend the use of this parameter for future studies or clinical practices, at least until these technical issues are addressed and resolved.

Relative reliability scores of 3 specific TMG parameters (Dm, Td, and Tc) were evaluated in 7 distinct muscles (i.e., RF, vastus lateralis, vastus medialis [VM], biceps femoris [BF], BB, GM, and GL) showing high-to-excellent (0.80–0.99) reliability and low measurement error. Despite the foregoing, 1 study (17) analyzed the GM muscle, reporting an excellent score of ICC for Dm (0.91) and low-to-good scores of ICC for Td and Tc (0.60 and 0.70, respectively). More recently, other authors (12) assessed a very similar muscle (GL), finding excellent ICC values in Td (0.90) and Tc (0.93). Both studies used the same sample sizes (21 males) and rest interval times (10 seconds); however, they differed in the study design, as the study of Ditroilo et al. (17) was a long-term study (4 weeks) and the study of de Paula Simola et al. (12) was composed of 2 single measurements, performed over a 1-week period. From their results, Ditroilo et al. (17) concluded that the overall level of absolute reliability was good, whereas the relative reliability level was poor to excellent; but, they also indicated that ½ Tr yielded overall insufficient reliability. In this line, because of the low reliability of ½ Tr, Tous-Fajardo et al. (64) suggested not to use this parameter for future TMG studies. This recommendation is in line with previous studies, which have already indicated that ½ Tr is a TMG parameter with low-to-high reliability scores but with high measurement error (12,17,56). The issue about the insufficient reliability of ½ Tr could be due to the technology used by TMG (i.e., CDS) because a recent investigation (54) has showed that LDS displayed an increased sensitivity to temporal MMG parameters compared with the CDS. Despite the above, these authors found that although the relative reliability was good to high (ICC = 0.89 in LDS vs. 0.77 in CDS), both type of sensors had similar poor absolute reliability (CV = ~28%) values (calculated from the study because the authors did not report CV). These authors also indicated that the CDS sensor seemed to be more sensitive to muscle belly displacement (i.e., Dm), possibly because of its ability to measure underlying muscle movement that would not normally be translated to the skin's surface. Moreover, the authors revealed that ½ Tr demonstrated high variability, and thus, weak uniformity between sensors because the wide limits of agreement identified (−19.0 and 25.2 ms) are considered unreliable from a clinical perspective. These authors suggested that the high variability observed between measures of ½ Tr is believed to be due to its greater sensitivity to muscle fatigue after consecutive electrical stimulations and the longer recovery time required for it to return to an unfatigued value according to the findings of Orizio et al. (44). In terms of recovery time between measures, Seidl et al. (54) used a 60-second interval between trials, which is 4–5 times greater than that the interval used in TMG, to minimize the effect of muscle fatigue because of repetitive stimulation. Although a 60-second interval between trials may seem large for an experimental setup, Orizio et al. (44) has already demonstrated that–after electrically induced local muscle fatigue through sustained or repetitive electrical stimulations–all MMG parameters demonstrated significant ($p \leq 0.05$) differences to their initial unfatigued state. In this regard, although Tc and Dm values returned to baseline values within 1 minute, ½ Tr remained significantly different to its prefatigued value for the entirety of the recovery period (6 minutes). The rest time interval used in all studies evaluated ranged from 10 to 15 seconds, 10 seconds being the most common. In accordance with several authors working on TMG (8,17,63), a 10-second rest time interval is needed to minimize the effects of post-tetanic potentiation (28). Although all the authors publishing about TMG have used the same (or similar) rest time interval, none of them have analyzed if these interval times are the optimal or not to avoid fatigue derived from consecutive electrical stimulations. As previously appointed by Orizio et al. (44), a 60-second interval between trials is enough for the key parameters (Dm and Tc) to return to baseline values; but otherwise, it takes lot of time to recover the initial values of ½ Tr because after 6 minutes of recovery, this parameter was still significantly ($p \leq 0.05$) different from the reference value. These authors argued that repetitive twitch stimulation alters sarcoplasmic reticulum Ca^{2+} reuptake capacity that in turn determines the persisting alteration in ½ Tr. The results of Orizio et al. (44) are in line with other authors who in the 1990s found that ½ Tr maintained still significantly different from the reference value after 30 minutes of recovery from intermittent fatiguing stimulation in frog semitendinosus muscle (61). We believe that studies analyzing the optimal rest interval time between TMG measures are needed, owing to the lack of studies on this matter in human skeletal muscle. In fact, we note that there is an important need to understand why ½ Tr presents high variability because its physiological meaning is important for muscle studies (54). In theory, the best explanation about the variability of ½ Tr is suggested to be its "greater sensitivity to musculoskeletal fatigue following consecutive electrical stimulations and the longer recovery time required for it to return to an unfatigued value" (44,54,61). Currently, the use of ½ Tr is no longer recommended because of its insufficient reliability reflected in the studies analyzed and because of the longer recovery time required for it to return to baseline values, which clearly makes it difficult for the experimental setup of future studies.

More than 35 years ago, Shrout and Fleiss (55) described that there are 6 types of ICC. All types are virtually identical and the main difference lies in their denominator (32). Therefore, the choice of the denominator drastically affects the magnitude of the resulting correlation. All studies reviewed, except 1 (53), used ICC to assess reliability; however, only 1 (63) specified what type of ICC was used for analysis purposes. Shrout and Fleiss (55) reviewed each 1 of the ICC types, showing that what is relevant to calculate ICC is to make the right choice of the appropriate statistical model. The above-mentioned is in line with the results described by Lahey et al. (34), who have already shown that using the same data, the magnitude of correlations is different depending on the type of ICC considered. As such, to strengthen the conclusions drawn from ICC analysis, it is crucial to correctly select the ICC calculation mode. With this caution in mind, sport scientists can produce comparable TMG data, thus reducing the effects of using different treatments and experimental designs. In closing, the same should be applied to the way the measurement error is calculated to also produce comparable data.

However, the electrical amplitude in all studies varied from 30 to 50 mA, increasing from 10 to 20 mA, until there was no further increase in Dm or maximal stimulator output (110 mA). The stimuli amplitude depends on the individual's muscle responses and many other factors (i.e., muscle composition or fiber orientation). Therefore, it is essential to individualize the stimuli amplitude for each subject, to achieve the peak muscle displacement. Although it would be desirable to optimize the measurement times and standardize the protocols, this is not possible because the muscular response of each subject is different attending to their morphological characteristics (i.e., type of predominant fiber type, subcutaneous fat thickness, pennation angle, motor nerve branching, or fiber orientation) (25,63). That is, each person will respond differently to the same stimulus so that a single stimulus should not be used when taking TMG measurements. Despite the above, some authors have used a unique amplitude of 100–110 mA in the vastus lateralis (VL) and BF muscles (52,53). However, as has been previously argued, the use of a unique stimulus is a mistake because high stimulus could led to muscle coactivation which will artificially increase muscle displacement (17). Apart from the above, a recent investigation (7) used increasing current intensities ranging between 10 and 65 mA to measure several muscles from the upper and lower limb. The previous has been recently criticized (39) as low intensities (i.e., 10–65 mA interval) may not have achieved the optimal response of major muscles (e.g., RF or BF) and because they did not analyze the reliability and measurement error of their measurements (being affordable as it was a case study). The above highlights the importance of performing a specific and detailed measurement of each muscle. Thus, based on the current evidence, we do recommend starting with an amplitude of 40 mA with increases of 10–20 mA until there is no further increase in Dm or maximal stimulator output (100–110 mA, depending on the stimulator device) to find the optimal muscle stimuli (i.e., peak curve), which will be different for each subject and for each muscle. Finally, another crucial point associated with the intensity of the electrical current is the optimal IED configurations able to recruit as many motor neurons as possible. In this regard, only 1 study (63) investigated the effects of 2 different IED configurations (±3 and ±5 cm) on muscle responses, showing that with smaller IEDs (i.e., ±3 cm) the Dm was lower, whereas all the other parameters showed a trend toward significance. These findings are in line with previous studies which have previously demonstrated possible alterations in muscle responses with changes in different IED configurations, for both muscle belly (5) and motor nerve (50) stimulation. For previous reasons, Tous-Fajardo et al. (2010) raised that it would be logical to think that decreasing IED from ±5 to ±3 cm would have resulted in lower and more superficial spatial recruitment of muscle fibers. However, Tous-Fajardo et al. (63) did not measure motor unit activation (MUa) in both IED configurations; so, the lack of this crucial information added to the lack of studies about the influence of different IED configurations on muscle response (using TMG) and MUa, making it difficult to understand why Dm was lower in the configuration of ±3 cm than in the ±5 cm. In terms of IED configurations, we suggest that, because TMG works with an electrostimulator, the primary motor points (6) should be used instead of the current measurement method (i.e., maximal muscle belly detection) because motor points activation results in higher MUa (24,25). Nonetheless, this suggestion lacks evidence to support; thus, we encourage researchers to search for (possible) patterns in MUa and muscle responses, when muscle parameters are assessed with TMG. In this regard, future studies are needed to assess the influence of sensor location, IED configurations (large and small), rest interval times between trials on time-derived parameters (especially on ½ Tr), and different joint angle configurations on muscle mechanical response assessed by TMG.

We recognize that this review is limited by several factors, highlighting the scarcity of data regarding the reliability and measurement error of TMG. In addition, all studies ($n = 158$) were conducted with small samples of men (excepting 1 which included 2 women) in a selected age range (from 21.3 ± 3.4 to 30.7 ± 7.4) and most of them used the same muscles in their experimental designs. Furthermore, taking into consideration, the lack of consensus regarding the use of ICC measures as reliability indices (27), it is important to further test the TMG consistency in well-designed and high-quality studies using different statistical approaches (e.g., CV, *SEM*, SDC, and bias).

PRACTICAL APPLICATIONS

Based on current research studies and recommendations, we could conclude that TMG is a consistent method to assess muscle contractile properties, specifically through 3 high reliable parameters (Dm, Td, and Tc). Remarkably, as a noninvasive, passive and rapid technique, TMG can be straightforwardly used to analyze the state of muscular contractility in top-level sports, where time is scarce and of great importance. Using the information provided by systematic TMG measurements, coaches and technical staff may regulate the exercise content throughout the different training phases, frequently adjusting the training loads (volume and intensity) in accordance with the equivalent muscle mechanical responses. From an applied perspective, it would be important not only to improve athletic performance, but also to reduce the associated injury risk. Considering that ½ Tr demonstrated unacceptable reliability, we strongly suggest that it should not be considered for accurate measurements of skeletal muscle function in practice or in future studies.

REFERENCES

1. Alentorn-Geli, E, Alvarez-Diaz, P, Ramon, S, Marin, M, Steinbacher, G, Rius, M, Seijas, R, Ares, O, and Cugat, R. Assessment of gastrocnemius tensiomyographic neuromuscular characteristics as risk factors for anterior cruciate ligament injury in male soccer players. *Knee Surg Sports Traumatol Arthrosc* 23: 2502–2507, 2015.
2. Atkinson, G and Nevill, AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med* 26: 217–238, 1998.
3. Barry, DT, Geiringer, SR, and Ball, RD. Acoustic myography: A noninvasive monitor of motor unit fatigue. *Muscle Nerve* 8: 189–194, 1985.
4. Bartlett, JW and Frost, C. Reliability, repeatability and reproducibility: Analysis of measurement errors in continuous variables. *Ultrasound Obstet Gynecol* 31: 466–475, 2008.
5. Bergman, BC, Martin, DT, and Wilkinson, JG. Knee extensor torque and perceived discomfort during symmetrical biphasic electromyostimulation. *J Strength Cond Res* 15: 1–5, 2001.
6. Botter, A, Oprandi, G, Lanfranco, F, Allasia, S, Maffiuletti, NA, and Minetto, MA. Atlas of the muscle motor points for the lower limb: Implications for electrical stimulation procedures and electrode positioning. *Eur J Appl Physiol* 111: 2461–2471, 2011.
7. Calvo, S, Quintero, I, and Herrero, P. Effects of dry needling (DNHS technique) on the contractile properties of spastic muscles in a patient with stroke: A case report. *Int J Rehabil Res* 39: 372–376, 2016.
8. Carrasco, L, Sanudo, B, de Hoyo, M, Pradas, F, and Da Silva, ME. Effectiveness of low-frequency vibration recovery method on blood lactate removal, muscle contractile properties and on time to exhaustion during cycling at VO(2)max power output. *Eur J Appl Physiol* 111: 2271–2279, 2011.
9. Dahmane, R, Djordjevic, S, Simunic, B, and Valencic, V. Spatial fiber type distribution in normal human muscle histochemical and tensiomyographical evaluation. *J Biomech* 38: 2451–2459, 2005.
10. Dahmane, R, Valen i, V, Knez, N, and 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* 39: 51–55, 2001.
11. de Paula Simola, RA, Harms, N, Raeder, C, Kellmann, M, Meyer, T, Pfeiffer, M, and Ferrauti, A. Assessment of neuromuscular function after different strength training protocols using tensiomyography. *J Strength Cond Res* 29: 1339–1348, 2015.
12. de Paula Simola, RÁ, Harms, N, Raeder, C, Kellmann, M, Meyer, T, Pfeiffer, M, and Ferrauti, A. Tensiomyography reliability and prediction of changes in muscle force following heavy eccentric strength exercise using muscle mechanical properties. *Sports Technol* 8: 1–9, 2016.
13. de Paula Simola, RÁ, Raeder, C, Wiewelhove, T, Kellmann, M, Meyer, T, Pfeiffer, M, and Ferrauti, A. Muscle mechanical properties of strength and endurance athletes and changes after one week of intensive training. *J Electromyogr Kinesiol* 30: 73–80, 2016.
14. de Vet, HC, Terwee, CB, Knol, DL, and Bouter, LM. When to use agreement versus reliability measures. *J Clin Epidemiol* 59: 1033–1039, 2006.

15. Delagi, EF and Perotto, A. *Anatomic Guide for the Electromyographer—The Limbs*. Springfield, IL: Charles C. Thomas Publisher, 1975.
16. Ditroilo, M, Hunter, AM, Haslam, S, and De Vito, G. The effectiveness of two novel techniques in establishing the mechanical and contractile responses of biceps femoris. *Physiol Meas* 32: 1315–1326, 2011.
17. Ditroilo, M, Smith, IJ, Fairweather, MM, and Hunter, AM. Long-term stability of tensiomyography measured under different muscle conditions. *J Electromyogr Kinesiol* 23: 558–563, 2013.
18. Evetovich, TK, Housh, TJ, Stout, JR, Johnson, GO, Smith, DB, and Ebersole, KT. Mechanomyographic responses to concentric isokinetic muscle contractions. *Eur J Appl Physiol Occup Physiol* 75: 166–169, 1997.
19. Furlan, AD, Pennick, V, Bombardier, C, and van Tulder, M; Editorial Board CBRG. 2009 updated method guidelines for systematic reviews in the Cochrane Back Review Group. *Spine (Phila Pa 1976)* 34: 1929–1941, 2009.
20. Garcia-Manso, JM, Rodriguez-Matoso, D, Rodriguez-Ruiz, D, Sarmiento, S, de Saa, Y, and Calderon, J. Effect of cold-water immersion on skeletal muscle contractile properties in soccer players. *Am J Phys Med Rehabil* 90: 356–363, 2011.
21. Garcia-Manso, JM, Rodriguez-Matoso, D, Sarmiento, S, de Saa, Y, Vaamonde, D, Rodriguez-Ruiz, D, and Da Silva-Grigoletto, ME. Effect of high-load and high-volume resistance exercise on the tensiomyographic twitch response of biceps brachii. *J Electromyogr Kinesiol* 22: 612–619, 2012.
22. Garcia-Manso, JM, Rodriguez-Ruiz, D, Rodriguez-Matoso, D, de Saa, Y, Sarmiento, S, and Quiroga, M. Assessment of muscle fatigue after an ultra-endurance triathlon using tensiomyography (TMG). *J Sports Sci* 29: 619–625, 2011.
23. Giovanelli, N, Taboga, P, Rejc, E, Simunic, B, Antonutto, G, and Lazzer, S. Effects of an uphill marathon on running mechanics and lower-limb muscle fatigue. *Int J Sports Physiol Perform* 11: 522–529, 2016.
24. Gobbo, M, Maffiuletti, NA, Orizio, C, and Minetto, MA. Muscle motor point identification is essential for optimizing neuromuscular electrical stimulation use. *J Neuroeng Rehabil* 11: 17, 2014.
25. Gorelick, ML and Brown, JMM. Mechanomyographic assessment of contractile properties within seven segments of the human deltoid muscle. *Eur J Appl Physiol* 100: 35–44, 2007.
26. Herzog, W, Zhang, YT, Vaz, MA, Guimaraes, AC, and Janssen, C. Assessment of muscular fatigue using vibromyography. *Muscle Nerve* 17: 1156–1161, 1994.
27. Hopkins, WG. Measures of reliability in sports medicine and science. *Sports Med* 30: 1–15, 2000.
28. Hughes, JR. Post-tetanic potentiation. *Physiol Rev* 38: 91–113, 1958.
29. Hunter, AM, Galloway, SD, Smith, IJ, Tallent, J, Ditroilo, M, Fairweather, MM, and Howatson, G. Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography. *J Electromyogr Kinesiol* 22: 334–341, 2012.
30. Islam, MA, Sundaraj, K, Ahmad, RB, and Ahamed, NU. Mechanomyogram for muscle function assessment: A review. *PLoS One* 8: e58902, 2013.
31. Klug, GA, Leberer, E, Leisner, E, Simoneau, JA, and Pette, D. Relationship between parvalbumin content and the speed of relaxation in chronically stimulated rabbit fast-twitch muscle. *Pflugers Arch* 411: 126–131, 1988.
32. Krebs, DE. Declare your ICC type. *Phys Ther* 66: 1431, 1986.
33. Krizaj, D, Simunic, B, and Zagar, T. Short-term repeatability of parameters extracted from radial displacement of muscle belly. *J Electromyogr Kinesiol* 18: 645–651, 2008.
34. Lahey, MA, Downey, RG, and Saal, FE. Intraclass correlations: There's more there than meets the eye. *Psychol Bull* 93: 586–595, 1983.
35. Lima, K, Costa Junior, JFS, Pereira, WCA, and Oliveira, LF. Assessment of the mechanical properties of the muscle-tendon unit by supersonic shear wave imaging elastography: A review. *Ultrasonography*, 2017. Epub ahead of print.
36. Loturco, I, Gil, S, Laurino, CF, Roschel, H, Kobal, R, Cal Abad, CC, and Nakamura, FY. Differences in muscle mechanical properties between elite power and endurance athletes: A comparative study. *J Strength Cond Res* 29: 1723–1728, 2015.
37. Loturco, I, Pereira, LA, Kobal, R, Kitamura, K, Ramirez-Campillo, R, Zanetti, V, Abad, CC, and Nakamura, FY. Muscle contraction velocity: A suitable approach to analyze the functional adaptations in elite soccer players. *J Sports Sci Med* 15: 483–491, 2016.
38. McGraw, KO and Wong, S. Forming inferences about some intraclass correlation coefficients. *Psychol Meth* 1: 30–46, 1996.
39. Martin-Rodriguez, S and Guimaraes-Ribeiro, D. Methodological issues to consider when taking tensiomyographic measurements. *Int J Rehabil Res* 39: 377–378, 2016.
40. Martín-Rodríguez, S, Alentorn-Geli, E, Tous-Fajardo, J, Samuelsson, K, Marin, M, Alvarez-Diaz, P, and Cugat, R. Is tensiomyography a useful assessment tool in sports medicine? *Knee Surg Sports Traumatol Arthrosc*, 2017. Epub ahead of print.
41. Millet, GY, Martin, V, Martin, A, and Verges, S. Electrical stimulation for testing neuromuscular function: From sport to pathology. *Eur J Appl Physiol* 111: 2489–2500, 2011.
42. Moher, D, Liberati, A, Tetzlaff, J, Altman, DG, and Group, P. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Ann Intern Med* 151: 264–269, 2009.
43. Mokkink, LB, Terwee, CB, Patrick, DL, Alonso, J, Stratford, PW, Knol, DL, Bouter, LM, and de Vet, HC. The COSMIN study reached international consensus on taxonomy, terminology, and definitions of measurement properties for health-related patient-reported outcomes. *J Clin Epidemiol* 63: 737–745, 2010.
44. Orizio, C, Diemont, B, Esposito, F, Alfonsi, E, Parrinello, G, Moglia, A, and Veicsteinas, A. Surface mechanomyogram reflects the changes in the mechanical properties of muscle at fatigue. *Eur J Appl Physiol Occup Physiol* 80: 276–284, 1999.
45. Orizio, C, Liberati, D, Locatelli, C, De Grandis, D, and Veicsteinas, A. Surface mechanomyogram reflects muscle fibres twitches summation. *J Biomech* 29: 475–481, 1996.
46. Orizio, C. Comments on the letter "accelerometer and mechanomyogram". *J Biomech* 35: 385, 2002.
47. Petitjean, M, Maton, B, and Cnockaert, JC. Evaluation of human dynamic contraction by phonomyography. *J Appl Physiol (1985)* 73: 2567–2573, 1992.
48. Piqueras-Sanchiz, P, Martin-Rodriguez, S, Gonzalez-Hernandez, JM, and Garcia Garcia, O. In-season analysis of the muscle response speed of knee extensors and flexors in elite futsal players. *Adv Skeletal Muscle Funct Assess* 1: 17–22, 2017.
49. Pisot, R, Narici, MV, Simunic, B, De Boer, M, Seynnes, O, Jurdana, M, Biolo, G, and Mekjavic, IB. Whole muscle contractile parameters and thickness loss during 35-day bed rest. *Eur J Appl Physiol* 104: 409–414, 2008.
50. Plastaras, CT, Marciniak, CM, Sipple, DP, D'Amore, KG, Garvan, C, and Zaman, SM. Effect of interelectrode distance on sural nerve action potential parameters. *Am J Phys Med Rehabil* 87: 183–188, 2008.
51. Rey, E, Lago-Penas, C, and Lago-Ballesteros, J. Tensiomyography of selected lower-limb muscles in professional soccer players. *J Electromyogr Kinesiol* 22: 866–872, 2012.
52. Rodríguez-Matoso, D, Mantecón, A, Barbosa-Almeida, E, Valverde, T, García-Manso, JM, and Rodríguez-Ruiz, D. Mechanical response of knee muscles in high level bodyboarders during performance. *Rev Bras Med Esporte* 21: 144–147, 2015.
53. Rodríguez-Matoso, D, Rodríguez-Ruiz, D, Sarmiento, S, Vaamonde, D, Da Silva-Grigoletto, ME, and García-Manso, JM. Reproducibility of muscle response measurements using tensiomyography in a range of positions. *Rev Andal Med Deporte* 3: 81–86, 2010.

54. Seidl, L, Tosovic, D, and Brown, JM. Test-retest reliability and reproducibility of laser- versus contact-displacement sensors in mechanomyography: Implications for musculoskeletal research. *J Appl Biomech* 33: 130–136, 2017.
55. Shrout, PE and Fleiss, JL. Intraclass correlations: Uses in assessing rater reliability. *Psychol Bull* 86: 420–428, 1979.
56. Simunic, B. Between-day reliability of a method for non-invasive estimation of muscle composition. *J Electromyogr Kinesiol* 22: 527–530, 2012.
57. Simunic, B, Degens, H, Rittweger, J, Narici, M, Mekjavic, IB, and Pisot, R. Noninvasive estimation of myosin heavy chain composition in human skeletal muscle. *Med Sci Sports Exerc* 43: 1619–1625, 2011.
58. Terwee, CB, Bot, SD, de Boer, MR, van der Windt, DA, Knol, DL, Dekker, J, Boutler, L, and de Vet, HC. Quality criteria were proposed for measurement properties of health status questionnaires. *J Clin Epidemiol* 60: 34–42, 2007.
59. Terwee, CB, Mokkink, LB, Knol, DL, Ostelo, RW, Bouter, LM, and de Vet, HC. Rating the methodological quality in systematic reviews of studies on measurement properties: A scoring system for the COSMIN checklist. *Qual Life Res* 21: 651–657, 2012.
60. Tesch, PA, Dudley, GA, Duvoisin, MR, Hather, BM, and Harris, RT. Force and EMG signal patterns during repeated bouts of concentric or eccentric muscle actions. *Acta Physiol Scand* 138: 263–271, 1990.
61. Thompson, LV, Balog, EM, Riley, DA, and Fitts, RH. Muscle fatigue in frog semitendinosus: Alterations in contractile function. *Am J Physiol* 262: C1500–C1506, 1992.
62. Tosovic, D, Than, C, and Brown, JM. The effects of accumulated muscle fatigue on the mechanomyographic waveform: Implications for injury prediction. *Eur J Appl Physiol* 116: 1485–1494, 2016.
63. Tous-Fajardo, J, Moras, G, Rodriguez-Jimenez, S, Usach, R, Doutres, DM, and Maffiuletti, NA. Inter-rater reliability of muscle contractile property measurements using non-invasive tensiomyography. *J Electromyogr Kinesiol* 20: 761–766, 2010.
64. Valencic, V and Knez, N. Measuring of skeletal muscles' dynamic properties. *Artif Organs* 21: 240–242, 1997.
65. van Tulder, M, Furlan, A, Bombardier, C, and Bouter, L; Editorial Board of the Cochrane Collaboration Back Review G. Updated method guidelines for systematic reviews in the Cochrane collaboration back review group. *Spine (Phila Pa 1976)* 28: 1290–1299, 2003.
66. Watakabe, M, Mita, K, Akataki, K, and Itoh, Y. Mechanical behaviour of condenser microphone in mechanomyography. *Med Biol Eng Comput* 39: 195–201, 2001.
67. Wong, YM. Accelerometer and mechanomyogram. *J Biomech* 34: 557, 2001.
68. Yoshitake, Y and Moritani, T. The muscle sound properties of different muscle fiber types during voluntary and electrically induced contractions. *J Electromyogr Kinesiol* 9: 209–217, 1999.
69. Žagar, T and Križaj, D. Validation of an accelerometer for determination of muscle belly radial displacement. *Med Biol Eng Comput* 43: 78–84, 2005.
70. Zijdewind, I, Toering, ST, Bessem, B, Van Der Laan, O, and Diercks, RL. Effects of imagery motor training on torque production of ankle plantar flexor muscles. *Muscle Nerve* 28: 168–173, 2003.
71. Zubac, D and Simunic, B. Skeletal muscle contraction time and tone decrease after 8 weeks of plyometric training. *J Strength Cond Res* 31: 1610–1619, 2017.