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ORIGINAL ARTICLE

The effect of sensor position shifts on tensiomyographic parameters

Stefanie John ✉ . *Department of Sports Science. Otto-von-Guericke-University Magdeburg. Magdeburg, Germany.*
Nico Leon Stallmach. *Department of Sports Science. Otto-von-Guericke-University Magdeburg. Magdeburg, Germany.*
Kerstin Witte. *Department of Sports Science. Otto-von-Guericke-University Magdeburg. Magdeburg, Germany.*

ABSTRACT

Tensiomyography (TMG) is a non-invasive method to determine contractile parameters of skeletal muscles. Several methodological factors, however, might affect TMG results. The aim of this study was to investigate the effect of specific sensor position shifts on tensiomyographic parameters. 14 healthy males (age: 22.6 ± 1.2 years) participated in the study. TMG measurements were performed for rectus femoris (RF), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL) on five sensor positions. The original sensor position (OP) was the recommended position on the muscle belly while for the shifted positions, the sensor was displaced one centimetre medially, laterally, proximally, and distally. TMG parameters measured were maximum radial displacement (Dm) and contraction time (Tc). To investigate the effect of sensor position shift, repeated-measures ANOVAs were performed. The ANOVAs revealed significant differences across the five sensor positions for RF and GM. Posthoc analysis showed significant reductions in Dm by 10 % (p = .03) and in Tc by 12 % (p = .008) in the laterally shifted sensor position for RF. For GM, Dm was significantly reduced by 20 % (p = .038) in the medially displaced sensor position. The results suggest that incorrect sensor positioning has an impact on TMG parameters, especially when incorrectly positioned in the medial-lateral direction.
Keywords: Performance analysis of sport, Muscle contractile properties, Tensiomyography, Sensor position, Measurement error.

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✉ **Corresponding author.** *Institute of Sports Science, Otto-von-Guericke-University Magdeburg, Zschokkestraße 32, 39104 Magdeburg, Germany.*
E-mail: Stefanie.John@ovgu.de
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INTRODUCTION

Tensiomyography (TMG) is a non-invasive method for determining the contractile properties of superficial skeletal muscles in response to electrical stimuli. The electrical stimulus induced by two electrodes placed on the muscle belly causes a radial displacement of the muscle, which is recorded by a digital displacement sensor. To assess the condition of the muscle, five parameters can be derived from the displacement time curve (Figure 1): Delay time (Td), contraction time (Tc), sustain time (Ts), relaxation time (Tr) and maximal radial displacement (Dm) (Macgregor et al., 2018).

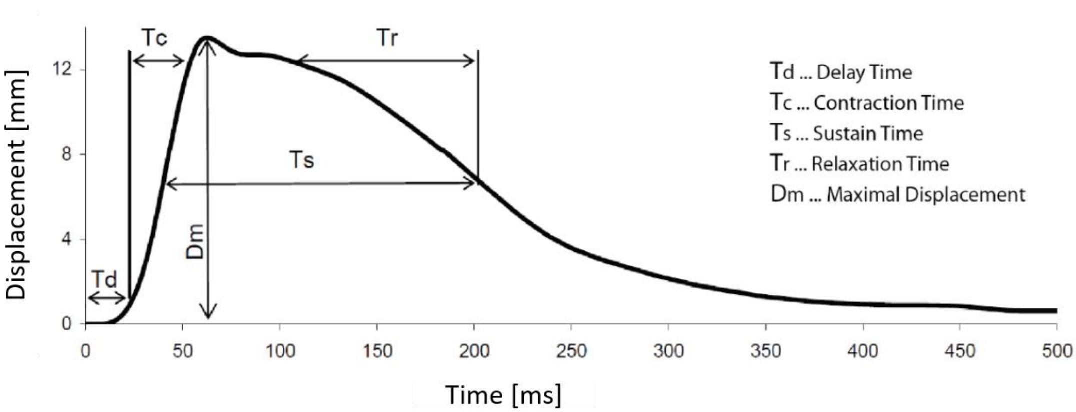


Figure 1. Exemplary displacement-time curve with the derived TMG parameters.

Dm describes the maximum contraction amplitude of the muscle and has been demonstrated to provide information about muscle stiffness and muscle atrophy (Ditroilo et al., 2011; Hunter et al., 2012; Pisot et al., 2008). Tc, which is defined as the time between 10 % and 90 % of the maximum contraction amplitude, has been shown to correlate with fibre composition (Dahmane et al., 2001; Simunič, 2012) and contraction velocity (Loturco et al., 2016).

Due to its non-invasive, rapid and practicable measurement, TMG has been gaining popularity in the field of sports applications, especially for lower extremity muscle diagnostics. These include monitoring training loads and fatigue (García-Manso et al., 2011; Rauno Á. de Paula Simola et al., 2015; Rauno Álvaro de Paula Simola et al., 2015; Rojas-Valverde et al., 2021) as well as determining muscle impairments, muscle asymmetries and recovery after injuries (Alvarez-Diaz et al., 2015; García-García et al., 2017).

The reliability of TMG measurements, especially of the parameters Dm and Tc, has been examined in several studies. High to excellent within-day reliability was demonstrated for Dm and Tc (Krizaj et al., 2008; Christine Lohr et al., 2018; Piqueras-Sanchiz et al., 2020). Good to high reliabilities of Tc and Dm were also shown for between-day TMG measurements (Paravlić et al., 2017; Rauno Á. de Paula Simola et al., 2015; Simunič, 2012). Although relative reliability of TMG measurements has been established and confirmed, recent reviews expressed the need for a standardized measurement protocol and higher methodological standards to achieve accurate results (Hanney et al., 2021; C. Lohr et al., 2019; Martín-Rodríguez et al., 2017). For TMG measurements, there are several methodological factors concerning electrode placement and electrical stimulation, which have been shown to affect the TMG output parameters. Tous-Fajardo et al. (2010) reported that reducing the inter-electrode distance from 5 cm to 3 cm resulted in a significantly decreased Dm. Wilson et al. (2018) confirmed the effect of different inter-electrode distances on Dm and additionally showed that altering the interval between stimuli significantly affected Dm and Tc. In the study of Piqueras-Sanchiz et al. (2020), it was reported that the use of larger electrodes and higher stimulus pulse duration resulted in a significantly increased Dm.

Another important methodological factor is the positioning of the sensor. It is recommended to position the sensor on the thickest part of the muscle belly as this is suggested to be the largest area for fibre recruitment (Valencic & Knez, 1997). In many studies, the sensor position is visually identified by the thickest part of the muscle and/or by palpation through voluntary contraction (Rojas-Valverde et al., 2021; Wilson et al., 2018) To improve accurate sensor positioning, some studies refer to specifications from electromyography to accurately locate the muscle belly (Simunič, 2012; Tous-Fajardo et al., 2010). In sports applications, however, time is scarce and TMG users need to locate the muscle belly fast, such as when monitoring acute fatigue. This can lead to the muscle belly not being identified correctly and the sensor not being positioned accurately. However, the effect of this potential measurement error has not yet been examined. To optimize the measurement accuracy of TMG, the exact effects of methodological factors need to be revealed. Therefore, the aim of this study was to investigate and quantify the influence of specific sensor displacements (medial, lateral, proximal and distal shifts) on the most commonly studied and reported tensiomyographic parameters Dm and Tc. We hypothesized that the displacement of the sensor would have an effect on the TMG parameters.

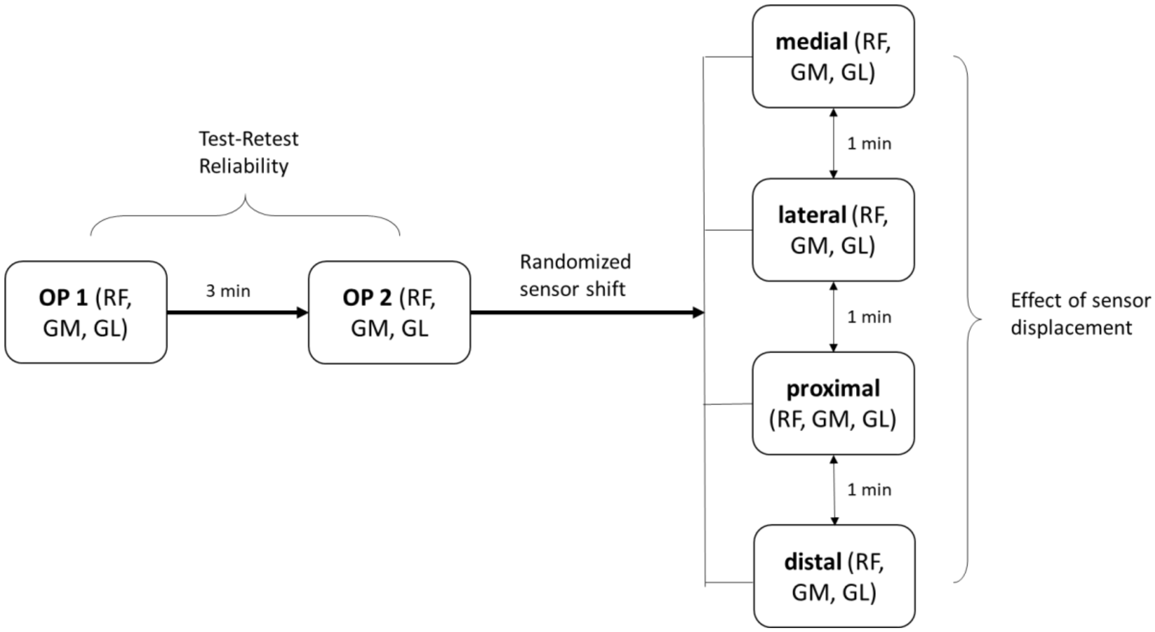
METHODS

Participants

Fourteen healthy male sports students (age: 22.6 ± 1.2 years, height: 182.6 ± 7.4 cm, body mass: 80.1 ± 9.1 kg) were recruited to participate in the study. Exclusion criteria included neuromuscular diseases and lower extremity muscle injuries in the previous six months. All participants were fully informed about the study procedure, its goals and potential risks associated with participation before providing written informed consent. The study was conducted in line with the Declaration of Helsinki for human research.

Testing procedure

The participants attended one testing session in which all measurements were performed by the same rater. The rater had six months of testing experience with the performance of several TMG measurements before the main test. Participants were asked to refrain from fatiguing exercise for 24 hours before TMG measurements. On the day of testing, anthropometric data and sports history were recorded. As all TMG measurements were performed exclusively on the dominant leg, the dominant leg was determined to be the leg that participants would use to kick a ball (van Melick et al., 2017). Due to the relevance for many sports, three muscles of the lower extremities were chosen for TMG analysis: rectus femoris (RF), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL). The testing procedure can be seen in Figure 2. Before investigating the effect of modified sensor positions on tensiomyographic parameters, test-retest reliability was determined for the original sensor position (OP) of each muscle. The order of the measured muscles was randomized. For the effect of sensor displacement, both the sensor and the electrodes were displaced one centimetre from the original position. A displacement of one centimetre was chosen because this was within the suspected range of incorrect sensor positioning. Measurements were performed with medial, lateral, proximal and distal displacements from the original position. The measurements at the four different displacement positions were randomized with one minute of rest in between.



Note. OP - original sensor position; RF - rectus femoris; GM - gastrocnemius medialis; GL - gastrocnemius lateralis.

Figure 2. Schematic illustration of the study procedure.

TMG set-up / TMG measurement

TMG measurements were performed using a TMG-S2 electrical stimulator (TMG-BMC d.o.o., Ljubljana, Slovenia), a G30 displacement sensor (TMG-BMC d.o.o., Ljubljana, Slovenia) and two self-adhesive electrodes (5x5 cm, AXELGAARD manufacturing CO. LTD., USA). For the original sensor position, an anatomical guide for electromyography was used to locate the muscle belly (Perotto & Delagi, 2011). In RF, the muscle belly is located midway between the anterior superior iliac spine and the superior border of the patella. In GM and GL, the muscle belly can be found one handbreadth below the popliteal crease on the medial/lateral mass of the calf (Perotto & Delagi, 2011). The exact measuring point for each muscle (thickest part of the muscle belly) was additionally carefully determined through visual assessment and accurate palpation during voluntary contraction. For RF measurements, the participants were instructed to lay in a supine position with their arms resting at their sides. One triangular foam pad, which was provided by the manufacturer, was placed under the dominant leg leading to knee flexion of approximately 135°. For GM and GL measurements, participants were in a prone position. A pad under the ankle joints of the dominant leg ensured that flexion of approximately 175° was generated in the knee joint.

Once the exact sensor position was determined, two electrodes were applied distally and proximally with a distance of 2.5 cm from the marked position leading to an inter-electrode distance (edge-to-edge) of 5 cm (Figure 3a) according to previous investigations (García-García et al., 2017; Piqueras-Sanchiz et al., 2020). Both, the position of the sensor and electrodes were marked using a dermatological pen. The digital sensor was positioned perpendicular to the measurement point of the muscle belly. The tip of the sensor was compressed into the muscle belly by 50 % of its length.

The electrical stimulation consisted of monophasic stimuli with a duration of one millisecond. For the first measurement of each muscle (OP1), electrical stimulation was applied starting at an amplitude of 20 mA. The current amplitude was gradually increased by 10 mA with 10 s between consecutive stimuli until the maximum Dm was achieved or the maximum output of the stimulator (100 mA) was reached. The maximum applied current was noted for each participant. After the retest measurement in the original position of the sensor (OP2), the sensor tip and the electrodes were displaced by one centimetre in medial, lateral, proximal and lateral directions compared to the original position (Figure 3b). For the measurement points OP2 and the sensor displacement positions (medial, lateral, proximal, distal), only one measurement of each muscle was performed with the maximum current value of OP1, which had previously induced the highest contraction amplitude.

The two main parameters of all six measurements considered for further analyses were Dm and Tc, which were extracted from the displacement-time curve generated by the TMG software.

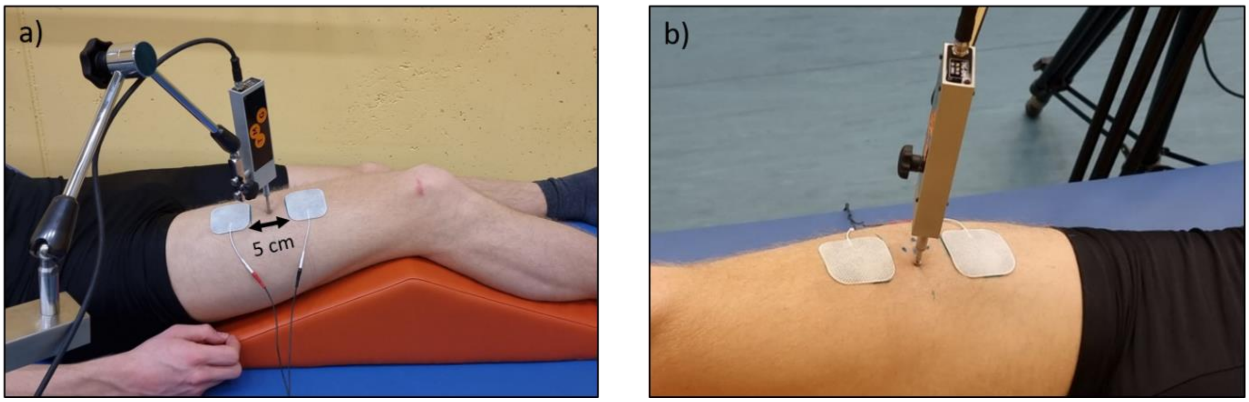


Figure 3. a) TMG measurement set-up for RF with an inter-electrode distance of 5 cm. b) Medial shift displacement of the sensor position.

Statistical analyses

Statistical analyses were performed with SPSS Statistics 26 (IBM, Armonk, NY USA). Descriptive statistics were determined for all anthropometric and TMG variables and reported as mean (M) ± standard deviation (SD). To examine the test-retest reliability of Tc and Dm at the original sensor position, the intra-class correlation coefficient (ICC) estimates and their 95 % confidence intervals (CI) were calculated based on a single-rating, absolute agreement and a two-way mixed-effects model (Koo & Li, 2016). According to Koo and Li, ICCs greater than 0.90 were interpreted as excellent reliability, ICC values between 0.75 and 0.90 as good reliability and ICCs between 0.50 and 0.75 as moderate reliability. ICC values less than 0.50 were interpreted as poor reliability. To determine the effect of sensor position shifts on Dm and Tc, within-subject repeated-measures ANOVAs were performed. Pairwise posthoc comparisons with Bonferroni correction for multiple comparisons followed when appropriate. The significance level was set a $p < .05$.

RESULTS

The results of the test-retest reliability analysis of the original sensor position are presented in Table 1. For Tc and Dm, ICC values of 0.90 or higher were achieved for RF, GM, and GL indicating excellent test-retest reliability.

In Table 2, the results of the repeated-measures ANOVAs investigating the effect of the sensor displacement are presented. The analysis revealed significant differences across the five different sensor measurement positions for RF for Dm ($F(4,48) = 3.44$, $p = .015$) and for Tc ($F(4,5) = 15.52$, $p < .00$) as well as for GM for

Dm (F(2.37,30.83) = 6.61, *p* = .003) and for Tc (F(2.31,27.76) = 4.38, *p* = .02). No effect of sensor position was found for GL for both tensiomyographic parameters (*p* > .05).

Table 1. Test-retest reliability analysis of Dm and Tc for the original sensor position (OP) for rectus femoris (RF), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL).

M.	Var.	OP 1	OP2	ICC	95 % CI
RF	Dm [mm]	9.8 ± 2.6	9.7 ± 2.9	0.97	0.89-0.99
RF	Tc [ms]	32.4 ± 8.4	33.0 ± 8.7	0.99	0.97-1.0
GM	Dm [mm]	4.8 ± 1.7	4.9 ± 1.9	0.94	0.81–0.98
GM	Tc [ms]	28.1 ± 8.5	27.2 ± 5.9	0.93	0.77-0.98
GL	Dm [mm]	6.1 ± 2.4	5.4 ± 2.2	0.95	0.60-0.99
GL	Tc [ms]	47.8 ± 20.5	42.8 ± 20.5	0.90	0.69-0.97

Note. M. - Muscle; Var. - Variable; Dm – Maximal radial displacement; Tc – Contraction time; ICC – Intra-class correlation coefficient, CI – Confidence interval.

Table 2. The effect of different sensor measurement positions on Dm and Tc for rectus femoris (RF), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL).

M.	Var.	OP	Medial	Lateral	Proximal	Distal	*p*-value ANOVA
RF	Dm [mm]	9.7 ± 2.9	9.3 ± 2.5	8.8 ± 2.7	10.1 ± 2.7	9.4 ± 2.8	**.015***
RF	Tc [ms]	33.0 ± 8.7	36.2 ± 9.4	28.9 ± 7.2	32.8 ± 7.7	33.2 ± 8.7	**.000***
GM	Dm [mm]	4.9 ± 1.9	4.0 ± 1.4	4.9 ± 1.7	4.8 ± 1.7	4.7 ± 1.6	**.003***
GM	Tc [ms]	27.2 ± 5.9	25.4 ± 5.1	28.2 ± 6.8	25.9 ± 5.7	28.1 ± 7.4	**.02***
GL	Dm [mm]	5.4 ± 2.2	5.9 ± 2.3	5.0 ± 1.9	5.3 ± 2.1	5.4 ± 2.5	.08
GL	Tc [ms]	42.8 ± 20.5	41.8 ± 17.7	36.5 ± 18.2	44.1 ± 20.8	40.4 ± 19.5	.40

*Note. M. - Muscle; Var. – Variable; Dm – Maximal displacement; Tc – Contraction time; OP - Original sensor position**; *Significant differences** across sensor measurement positions (p < .05).*

Due to significant results of the ANOVAs, pairwise comparisons were performed between the original sensor position and the four displaced positions (medial, lateral, proximal, distal). The mean differences between the original sensor position and the displacement positions are shown in Table 3. For RF, significant differences were detected between the original sensor position and the laterally displaced sensor position for both tensiomyographic parameters. In the laterally displaced position of the sensor, Dm was reduced by 0.9 mm compared to the original position (*p* = .03), which corresponds to a relative deviation of approximately 10 %. Tc was reduced by 4 ms (*p* = .008) representing a relative deviation of 12 % compared to the original sensor position. For GM, a significant difference was found between the original sensor position and the medial displacement for Dm (*p* = .038). For the medially shifted sensor position, an amplitude reduction of almost 1 cm was identified, which corresponds to a relative deviation of approximately 20 %.

A graphical representation of the effect of the sensor position shift on Dm and Tc can be seen in Figure 3. The mean differences of the sensor displacement positions compared to the original position are presented. Positive values for the displacement positions correspond to a decrease in Dm or Tc compared to the original position. Negative values correspond to an increase in the tensiomyographic parameters.

Table 3. Mean Differences (Mean Diff.) between original sensor position (OP) and shifted positions for Dm and Tc and relative deviations (Rel. Dev.) for rectus femoris (RF), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL).

	Dm		Tc	
	Mean Diff. [mm]	**Rel. Dev.**	**Mean Diff. [ms]**	**Rel. Dev.**
RF				
OP – medial	0.49	5 %	-3.16	10 %
OP – lateral	0.93*	10 %	4.10*	12 %
OP – proximal	-0.33	3 %	0.21	<1 %
OP – distal	0.33	3 %	-0.23	<1 %
GM				
OP – medial	0.96*	20 %	1.86	7 %
OP – lateral	0.06	1 %	-0.97	4 %
OP – proximal	0.16	3 %	1.37	5 %
OP – distal	0.21	4 %	-0.88	3 %
GL				
OP – medial	-0.53	10 %	0.94	2 %
OP – lateral	0.35	6 %	6.28	15 %
OP – proximal	0.06	1 %	-1.30	3 %
OP – distal	-0.06	1 %	2.37	6 %

*Note. Dm – Maximal displacement; Tc – Contraction time; ****Significant differences*** *between the original position and shifted position ($p < .05$).*

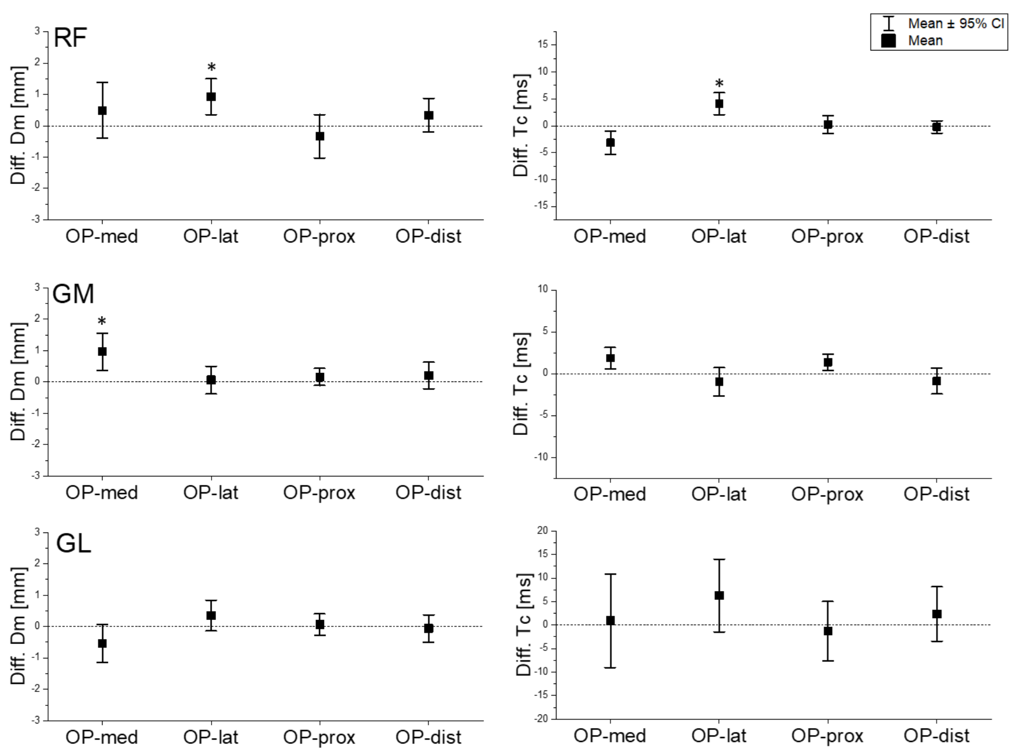


Figure 3. Mean differences and CIs of Tc (left side) and Dm (right side) of the sensor displacement positions compared to the original sensor position (OP) for rectus femoris (RF), gastrocnemius medialis (GM) and gastrocnemius lateralis (GL). Significant differences are indicated by an asterisk *.

DISCUSSION

This study investigated the effect of sensor position shifts compared to the original sensor position on the tensiomyographic parameters Dm and Tc. Before sensor displacements, test-retest reliability of Tc and Dm of the original sensor position was confirmed for all three muscles RF, GM and GL with ICC values of 0.90 and higher. These findings are consistent with previous studies determining test-retest reliability within-day of Tc and Dm (Rauno Á. de Paula Simola et al., 2015; Piqueras-Sanchiz et al., 2020; Wilson et al., 2018).

Displacing the sensor one centimetre medially, laterally, proximally, and distally from the original position resulted in significant differences between the measurement points for RF and GM. Posthoc analysis revealed a significant reduction of Dm and Tc in the laterally shifted position of the sensor for RF. Dm was also significantly reduced in the medially displaced sensor position for GM compared to the original sensor position. No differences were observed for GL.

To the authors' knowledge, this is the first study to examine the effect of specifically altered sensor positions on tensiomyograpic parameters. One previous study evaluated the reproducibility of TMG parameters by shifting the sensor tip +/-2 cm from the original measurement position on the RF (Rodríguez-Matoso et al., 2010). No significant differences between the three measurement positions of the sensor were observed. The authors, however, did not specify in which directions the sensor position shifts occurred making it difficult to interpret these results.

In this current study, contraction amplitude Dm was reduced at most of the displaced sensor positions of all three muscles. This was most evident for the medial and lateral sensor displacements with mean differences of up to nearly 1 cm in contraction amplitude. Relative deviations ranged between 1 % and 20 % compared to the original sensor position. On the contrary, for proximal and distal sensor displacements, mean differences in contraction amplitude were observed of up to 0.3 cm with relative deviations between 1 % and 4 %.

RF, GL and GM are relatively large and long muscles and it can be assumed that when the sensor position was shifted longitudinally, the sensor tip still remained on the thickest part of the muscle belly. This may explain why relatively small, non-significant differences were found for proximal and distal sensor displacements of Dm for all three muscles. By shifting the sensor transversally, however, the sensor tip may have not been located on the thickest part of the muscle belly anymore. Santos et al. support this assumption, as they reported a muscle thickness of RF in young men of approximately two centimetres (Santos et al., 2018). Due to the displacement of one centimetre in the medial and lateral direction from the midpoint of the muscle bellies, the sensor position may have been at the edges of the thickest part of the muscles which may explain the reduced contraction amplitudes measured by the sensor. These results suggest that the measurement error for Dm is higher in the medial-lateral direction than in the proximal-distal direction when the sensor is incorrectly positioned.

Concerning the parameter Tc, the mean differences between the shifted sensor positions and the original sensor position ranged between 0.21 and 6.28 ms. The only significant effect of sensor position shift on Tc was seen for RF. In the laterally displaced position of the sensor, Tc was reduced by 4 ms compared to the original sensor position indicating a faster contraction time at the displaced position. Relative deviations of Tc were in general also higher for medial-lateral sensor displacements (2 %-15 %) than for proximal-distal sensor displacements (up to 6 %), just as observed for Dm. This confirms previous findings of studies that stated that changes in Dm necessarily induce changes in Tc (Macgregor et al., 2016; Rauno Á. de Paula Simola et al., 2015).

However, the effect of sensor position shift on Tc is not easy to interpret as the values were inconsistently increased or decreased at the displaced positions compared to the original sensor position. Previous studies investigating the impact of different methodological parameters on TMG parameters also reported that the parameter Dm was most affected (Ditroilo et al., 2011; Piqueras-Sanchiz et al., 2020; Tous-Fajardo et al., 2010; Wilson et al., 2018) by methodological changes whereas the impact on Tc was smaller and not as clear (Piqueras-Sanchiz et al., 2020).

Although the effect of sensor shift on tensiomyographic parameters was not as great as anticipated, the change in sensor position resulted in a modified muscle response for RF, GM and GL leading to different values of Tc and especially Dm. For sports practical applications, TMG users need to be aware of the changes in the magnitude of TMG parameters that can derive from even small sensor displacements (Rodríguez-Matoso et al., 2010). This is especially relevant for evaluating the muscle condition of athletes during repeated measurements to monitor training loads, fatigue or changes in the rehabilitation process. As seen in our study relative deviations of up to 20 % can result from shifting the sensor one centimetre off the muscle belly. Since we measured relatively large and long muscles, the error of incorrect sensor positioning could be even higher for smaller muscles. We suggest that in addition to accurately positioning the sensor based on anatomical landmarks and palpating the muscle bellies during voluntary contraction, photographs should be taken of the measurement set-up for reference during subsequent TMG measurements.

Some limitations need to be addressed for this study. One major limitation is the small number of participants included in the study. Studies with larger samples and the inclusion of women must confirm the results presented. One further limitation is that only three muscles were measured. Investigations on the effect of sensor position shifts on tensiomyographic parameters need to be extended to all muscles relevant to sports to determine which muscles are most affected by incorrect sensor positioning, especially smaller muscles.

CONCLUSION

This is the first study to demonstrate that sensor position shifts of one centimetre affected the tensiomyographic parameters Dm and Tc for the muscles RF and GM. Dm and Tc were most affected when the sensor was shifted medially or laterally to the original sensor position. These results suggest that incorrect sensor positioning in the medial-lateral direction has a greater impact on tensiomyographic parameters than in the proximal-distal direction, at least for the muscles investigated. Concerning the practical application of TMG measurement, there is a possibility that even small sensor displacements induce changes in TMG parameters that can be misinterpreted, especially for repeated measurements of athletes. Accurate sensor positioning is a fundamental aspect of TMG measurement protocol and needs to be standardized as much as possible, possibly even using photographs.

AUTHOR CONTRIBUTIONS

The idea for this study and the study design were proposed by KW and SJ. SJ analysed the data and drafted the manuscript. NLS performed measurements and contributed to the data analysis and writing of the manuscript. KW critically reviewed the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

REFERENCES

Alvarez-Diaz, P., Alentorn-Geli, E., Ramon, S., Marin, M., Steinbacher, G., Rius, M., Seijas, R., Ballester, J., & Cugat, R. (2015). Effects of anterior cruciate ligament reconstruction on neuromuscular tensiomyographic characteristics of the lower extremity in competitive male soccer players. Knee Surgery, Sports Traumatology, Arthroscopy : Official Journal of the ESSKA, 23(11), 3407–3413. https://doi.org/10.1007/s00167-014-3165-4

Dahmane, R., Valen i, V., Knez, N., & Er en, I. (2001). Evaluation of the ability to make non-invasive estimation of muscle contractile properties on the basis of the muscle belly response. Medical & Biological Engineering & Computing, 39(1), 51–55. https://doi.org/10.1007/bf02345266

Ditroilo, M., Hunter, A. M., Haslam, S., & Vito, G. de (2011). The effectiveness of two novel techniques in establishing the mechanical and contractile responses of biceps femoris. Physiological Measurement, 32(8), 1315–1326. https://doi.org/10.1088/0967-3334/32/8/020

García-García, O., Serrano-Gómez, V., Hernández-Mendo, A., & Morales-Sánchez, V. (2017). Baseline Mechanical and Neuromuscular Profile of Knee Extensor and Flexor Muscles in Professional Soccer Players at the Start of the Pre-Season. Journal of Human Kinetics, 58, 23–34. https://doi.org/10.1515/hukin-2017-0066

García-Manso, J. M., Rodríguez-Ruiz, D., Rodríguez-Matoso, D., Saa, Y. de, Sarmiento, S., & Quiroga, M. (2011). Assessment of muscle fatigue after an ultra-endurance triathlon using tensiomyography (TMG). Journal of Sports Sciences, 29(6), 619–625. https://doi.org/10.1080/02640414.2010.548822

Hanney, W. J., Kolber, M. J., Salamh, P. A., Moise, S., Hampton, D., & Wilson, A. T. (2021). The Reliability of Tensiomyography for Assessment of Muscle Function in the Healthy Population. Strength & Conditioning Journal, Publish Ahead of Print. https://doi.org/10.1519/ssc.0000000000000699

Hunter, A. M., Galloway, S. D. R., Smith, I. J., Tallent, J., Ditroilo, M., Fairweather, M. M., & Howatson, G. (2012). Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography. Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 22(3), 334–341. https://doi.org/10.1016/j.jelekin.2012.01.009

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. Journal of Chiropractic Medicine, 15(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012

Krizaj, D., Simunic, B., & Zagar, T. (2008). Short-term repeatability of parameters extracted from radial displacement of muscle belly. Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 18(4), 645–651. https://doi.org/10.1016/j.jelekin.2007.01.008

Lohr, C [C.], Schmidt, T [T.], Medina-Porqueres, I., Braumann, K.-M [K-M], Reer, R [R.], & Porthun, J. (2019). Diagnostic accuracy, validity, and reliability of Tensiomyography to assess muscle function and exercise-induced fatigue in healthy participants. A systematic review with meta-analysis. Journal of

Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 47, 65–87. https://doi.org/10.1016/j.jelekin.2019.05.005

Lohr, C [Christine], Braumann, K.-M [Klaus-Michael], Reer, R [Ruediger], Schroeder, J., & Schmidt, T [Tobias] (2018). Reliability of tensiomyography and myotonometry in detecting mechanical and contractile characteristics of the lumbar erector spinae in healthy volunteers. European Journal of Applied Physiology, 118(7), 1349–1359. https://doi.org/10.1007/s00421-018-3867-2

Loturco, I., Pereira, L. A., Kobal, R., Kitamura, K., Ramírez-Campillo, R., Zanetti, V., Abad, C. C. C., & Nakamura, F. Y. (2016). Muscle Contraction Velocity: A Suitable Approach to Analyze the Functional Adaptations in Elite Soccer Players. Journal of Sports Science & Medicine, 15(3), 483–491.

Macgregor, L. J., Ditroilo, M., Smith, I. J., Fairweather, M. M., & Hunter, A. M. (2016). Reduced Radial Displacement of the Gastrocnemius Medialis Muscle After Electrically Elicited Fatigue. Journal of Sport Rehabilitation, 25(3), 241–247. https://doi.org/10.1123/jsr.2014-0325

Macgregor, L. J., Hunter, A. M., Orizio, C., Fairweather, M. M., & Ditroilo, M. (2018). Assessment of Skeletal Muscle Contractile Properties by Radial Displacement: The Case for Tensiomyography. Sports Medicine (Auckland, N.Z.), 48(7), 1607–1620. https://doi.org/10.1007/s40279-018-0912-6

Martín-Rodríguez, S., Loturco, I., Hunter, A. M., Rodríguez-Ruiz, D., & Munguia-Izquierdo, D. (2017). Reliability and Measurement Error of Tensiomyography to Assess Mechanical Muscle Function: A Systematic Review. Journal of Strength and Conditioning Research, 31(12), 3524–3536. https://doi.org/10.1519/jsc.0000000000002250

Paravlić, A., Zubac, D., & Šimunič, B. (2017). Reliability of the twitch evoked skeletal muscle electromechanical efficiency: A ratio between tensiomyogram and M-wave amplitudes. Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 37, 108–116. https://doi.org/10.1016/j.jelekin.2017.10.002

Paula Simola, R. Á. de [Rauno Á.], Harms, N., Raeder, C., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2015). Assessment of neuromuscular function after different strength training protocols using tensiomyography. Journal of Strength and Conditioning Research, 29(5), 1339–1348. https://doi.org/10.1519/jsc.0000000000000768

Paula Simola, R. Á. de [Rauno Álvaro], Harms, N., Raeder, C., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2015). Tensiomyography reliability and prediction of changes in muscle force following heavy eccentric strength exercise using muscle mechanical properties. Sports Technology, 8(1-2), 58–66. https://doi.org/10.1080/19346182.2015.1117475

Perotto, A., & Delagi, E. F. (2011). Anatomical guide for the electromyographer: The limbs and trunk (5th ed.). Charles C. Thomas.

Piqueras-Sanchiz, F., Martín-Rodríguez, S., Pareja-Blanco, F., Baraja-Vegas, L., Blázquez-Fernández, J., Bautista, I. J., & García-García, Ó. (2020). Mechanomyographic Measures of Muscle Contractile Properties are Influenced by Electrode Size and Stimulation Pulse Duration. Scientific Reports, 10(1), 8192. https://doi.org/10.1038/s41598-020-65111-z

Pisot, R., Narici, M. V., Simunic, B., Boer, M. de, Seynnes, O., Jurdana, M., Biolo, G., & Mekjavić, I. B. (2008). Whole muscle contractile parameters and thickness loss during 35-day bed rest. European Journal of Applied Physiology, 104(2), 409–414. https://doi.org/10.1007/s00421-008-0698-6

Rodríguez-Matoso, D., Rodríguez-Ruiz, D., Sarmiento, S., Vaamonde, D., Da Silva-Grigoletto, M. E., & García-Manso, J. M. (2010). Reproducibility of muscle response measurements using tensiomyography in a range of positions. Revista Andaluza De Medicina Del Deporte, 3, 81–85. https://www.redalyc.org/pdf/3233/323327663001.pdf

Rojas-Valverde, D., Sánchez-Ureña, B., Gómez-Carmona, C. D., Ugalde-Ramírez, A., Trejos-Montoya, A., Pino-Ortega, J., & Gutiérrez-Vargas, R. (2021). Detection of neuromechanical acute fatigue-related responses during a duathlon simulation: Is tensiomyography sensitive enough? Proceedings of the

Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology, 235(1), 53–61. https://doi.org/10.1177/1754337120959736

Santos, R., Valamatos, M. J., Mil-Homens, P., & Armada-da-Silva, P. A. S. (2018). Muscle thickness and echo-intensity changes of the quadriceps femoris muscle during a strength training program. Radiography (London, England : 1995), 24(4), e75-e84. https://doi.org/10.1016/j.radi.2018.03.010

Simunič, B. (2012). Between-day reliability of a method for non-invasive estimation of muscle composition. Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 22(4), 527–530. https://doi.org/10.1016/j.jelekin.2012.04.003

Tous-Fajardo, J., Moras, G., Rodríguez-Jiménez, S., Usach, R., Doutres, D. M., & Maffiuletti, N. A. (2010). Inter-rater reliability of muscle contractile property measurements using non-invasive tensiomyography. Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 20(4), 761–766. https://doi.org/10.1016/j.jelekin.2010.02.008

Valencic, V., & Knez, N. (1997). Measuring of skeletal muscles' dynamic properties. Artificial Organs, 21(3), 240–242. https://doi.org/10.1111/j.1525-1594.1997.tb04658.x

van Melick, N., Meddeler, B. M., Hoogeboom, T. J., Nijhuis-van der Sanden, M. W. G., & van Cingel, R. E. H. (2017). How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults. PloS One, 12(12), e0189876. https://doi.org/10.1371/journal.pone.0189876

Wilson, H. V., Johnson, M. I., & Francis, P. (2018). Repeated stimulation, inter-stimulus interval and inter-electrode distance alters muscle contractile properties as measured by Tensiomyography. PloS One, 13(2), e0191965. https://doi.org/10.1371/journal.pone.0191965