Tensiomyography Variable Trend of Changes After Acute Muscle Fatigue Induced by Acute Exercise: a Systematic Review and Meta-analysis

Seunghyeok Yeom
Incheon National University
Hyungwoo Lee
Incheon National University
Kyoungkyu Jeon (jeonkay@inu.ac.kr)
Incheon National University

Research Article

Keywords: Tensiomyography (TMG), Muscle fatigue, Acute exercise, Meta-analysis

Posted Date: August 23rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-822118/v1

Version of Record: A version of this preprint was published at Korean Journal of Sport Science on March 31st, 2022. See the published version at https://doi.org/10.24985/kjss.2022.33.1.19.

Abstract

Tensiomyography (TMG) has advantage in measuring fatigue. However, no studies have used a meta-analysis approach to analyze the trend of changes in TMG variables for acute muscle fatigue induced by an acute exercise. This study is the first systematic review and meta-analysis to establish criteria for measuring acute fatigue using TMG by quantifying trend of changes in TMG variables. Searches were conducted in Web of Science and Pubmed from December 6, 2020 to January 7, 2021. 16 studies were included that they used in TMG for measuring acute muscle fatigue that was caused by acute exercises in rectus femoris or biceps femoris. The meta-analysis results indicated that in the biceps femoris, showed a significant ($p < .05$) decrease in all TMG variables of the elite athletes. Also, in the overall effects of maximum displacement and mean velocity until 90% Dm (Vc90) showed significant ($p < .05$) decreasing trend. In the rectus femoris, showed a significant ($p < .05$) decreasing trend was found for maximum displacement (Dm) in the average person, while contraction time (Tc) showed a decreasing trend in elite athletes and overall. In conclusion, acute muscle fatigue was induced decreased Dm, Tc, Vc90 in the TMG measurement after an acute exercise. These results TMG could be used as a muscle fatigue indicator and help develop a more proper protocol for testing the response of body to muscle fatigue.

Introduction

Tensiomyography (TMG) is a mechanomyography method that non-invasively evaluates the mechanical properties of skeletal and neuromuscular muscles. It is used to measure the stiffness of a single muscle and neuromuscular muscle fatigue, especially after an acute exercise [1,2,3]. TMG induces mechanical contraction by stimulating the muscle with a single electric stimulation of 0–100 mA for 1 ms and then measures the response [4]. TMG evaluates the maximum contraction displacement of the muscle (i.e., maximum displacement [Dm]), the time taken to contract from 10–90% of the maximum contraction displacement (i.e., the contraction time [Tc]), the time taken from the start of stimulation to 10% of the maximum contraction displacement (i.e., the delay time [Td]), the time from 50% of the maximum contraction displacement to 50% of the descending curve (i.e., the sustain time [Ts]), and the time taken from 90–50% of the maximum contraction displacement in the descending curve (i.e., the relaxation time [Tr]). Measurement-remeasurement and intra-evaluator reliability indices are assessed as Poor (< 0.5), Moderate (0.5 to < 0.75), Good (0.75 to < 0.9), and Excellent (≥ 0.9) based on the 95% confidence interval (CI) of the intraclass correlation coefficient (ICC). Dm (0.91–0.99) and Tc (0.70–0.98) are the most reliable TMG variables in repeated measurements [5,6]. However, Tc can be affected by the Dm size as Tc represents the time taken to reach 90% of Dm. Therefore, the normalized response speed (Vrn), radial displacement velocity (Vrd), the mean velocity until 10% Dm (Vc10), and the mean velocity until 90% Dm (Vc90) compensate for this when calculating muscle contraction speed [2,4,7].

Running, jumping, and turning movements common in sports occur in the lower body. During running, the knee flexors and extensors compensate for the gastrocnemius activity decrease due to fatigue to maintain the stride pattern [8]. In jumping motions, the hamstrings and quadriceps are elongated to store elastic energy and play an important role in exerting power [9,10]. As the hamstrings and quadriceps play an essential role in lower body movement, they are widely used in post-exercise fatigue measurements. However, fatigue measurement studies using TMG have also been conducted with the biceps femoris (BF) and rectus femoris (RF) [4,11,12], but the criteria for measuring the degree of fatigue are ambiguous as these previous studies reported inconsistent results. Some reported decreased Dm due to increased muscle stiffness after the induction of fatigue [3,13,14,15,16], while others reported increased Dm due to decreased muscle stiffness [12,17]. Additionally, BF and RF have different responses after the same movement owing to differences in each muscle's role during the movement, which manifests as different responses [4,13,18].

Although TMG has a potential advantage in measuring fatigue, but the result interpretation is ambiguous as the reported trend of changes in the literature are inconstant. However, no studies have used a meta-analysis approach to analyze the trend of changes in TMG variables for acute muscle fatigue induced by an acute exercise. This study aimed to establish criteria for measuring fatigue using TMG by quantifying trend of changes in TMG variables.

Methods

Literature Review

We performed a literature search, systematic research identification review, and meta-analysis using specific variables. The literature search focused on studies measuring muscle fatigue with TMG before and after an acute exercise to examine muscle condition changes after an acute exercise. The search engines used were PubMed and Web of Science, starting December 6, 2020, and ending January 7, 2021. The keywords were: (1) "Tensiomyography." The literature inclusion criteria were: studies on TMG measurement before and after an acute exercise, RF or BF measurement studies, and studies on TMG measurement immediately after exercise fatigue. The exclusion criteria included unrelated literature, such as review papers, case studies, and animal studies. One researcher conducted the literature search. In total, 282 papers were initially identified, and 266 were excluded after reading the title and summary; 107 were duplicate studies, 11 were review papers, 32 were case studies, and 116 were unrelated subjects. Finally, 16 papers were included in the meta-analysis (Fig. 1)[2,3,4,11,12,13,14,15,16,17,18,19,20,21,22,23].

Tensiomyography

TMG was used to evaluate muscle fatigue induced by an acute exercise. The included studies evaluated the BF, RF, vastus lateralis (VL), vastus medialis (VM), semitendinosus (ST), and medial gastrocnemius (GM) muscles and the Dm, Tc, Td, Ts, Tr, Vrn, Vrd, Vc10 and Vc90 TMG measurement variables. For the analysis, Vrn was converted into Tc using the formula $\mathrm{Vrn} = \frac{0.8}{\mathrm{Tc}}$ [24]. Vc90 was calculated using $\mathrm{Vc90} = \frac{\mathrm{Dm}*0.9}{\mathrm{Tc}+\mathrm{Td}}$ to determine the muscle contraction velocity [7]. All of the studies measured TMG before and immediately after exercise. The BF measurement was taken with the subject prone position on a wedge foam cushion with a 5–15° flexion in the knee joint. The RF measurement was taken with the subject supine position on a special triangular wedge foam cushion with the knee extension at 140–150° [25]. During the measurements, the electric potential was administered with an intensity of 0–100 mA for 1 ms and gradually increased until maximal Dm. There was at least a 10 s break between measurements [26].

This study analyzed two muscles (BF and RF) and three TMG intervention variables (Dm, Tc, and Vc90). Muscle fatigue was induced by the exercise specified in each study [2], the most measured muscles, and reliable TMG measurement variables were used for our analysis [6].

Acute Exercise

The following an acute exercises were used to induce fatigue: repeated sprint ability (RSA), maximal incremental cycling test (MICT), maximal voluntary isometric contraction (MVIC), weight training, running, swimming, forward-tucked somersaults, and surfing.

Meta-analytic approaches

All statistical data analyses were performed using Comprehensive Meta-Analysis software (version 3.0, Biostat Inc., USA). The individual and overall effect sizes (ES) were calculated using Hedges' g with 95% CI [27]. Variable increases were labeled as positive, and decreases were labeled as negative. For example, a positive Hedges' g value for Tc, Dm, and Vc90 indicated an increase in each variable after the exercise. For reliability, the ES of all values were calculated, and values more than twice the standard deviation were excluded through a moderate process [28]. Random-effects meta-analysis models were used, assuming that no common ES appeared in individual studies [29]. ES was evaluated as Very Small (< 0.2), Small (0.2 to < 0.6), Average (0.6 to < 1.2), Large (1.2 to < 2.0), and Very Large (≥ 2.0) [30]. All meta-analysis results are shown in figure by forest plot.

The Higgins and Green I^2 test was used to identify the level of heterogeneity in the literature, and an I^2 value of 50% or higher was considered heterogeneous [31]. The methods used for the literature bias test were: (1) the original funnel plot was compared with a revised funnel plot after applying the trim-and-fill technique [32], and (2) the Egger's regression test was based on the null hypothesis that symmetry exists in the funnel plot. Thus, a P-value for the intercept (β0) < 0.05 indicated a violation of the symmetry assumption, representing a high publication bias [33].

Finally, the critical appraisal tool (CAT) scale was used to estimate the methodology quality [34]. The CAT consists of 13 questions with five items on the study validity and reliability, four items only on the study validity, and four items only on the reliability (Table 1).

Table 1
The CAT explanation of 13 questions

Question	Contents
Question 1	If human subjects were used, did the authors give a detailed description of the sample of subjects used to perform the (index) test?
Question 2	Did the authors clarify the qualification, or competence of the rater(s) who performed the (index) test?
Question 3	Was the reference standard explained?
Question 4	If interrater reliability was tested, were raters blinded to the findings of other raters?
Question 5	If intrarater reliability was tested, were raters blinded to their own prior findings of the test under evaluation?
Question 6	Was the order of examination varied?
Question 7	If human subjects were used, was the time period between the reference standard and the index test short enough to be reasonably sure that the target condition did not change between the two tests?
Question 8	Was the stability (or theoretical stability) of the variable being measured taken into account when determining the suitability of the time interval between repeated measures?
Question 9	Was the reference standard independent of the index test?
Question 10	Was the execution of the (index) test described in sufficient detail to permit replication of the test?
Question 11	Was the execution of the reference standard described in sufficient detail to permit its replication?
Question 12	Were withdrawals from the study explained?
Question 13	Were the statistical methods appropriate for the purpose of the study?

The answers to the questions are either yes, no, or not applicable, with 1 point for yes and 0 points for no. As CAT does not provide an overall quality score, the evaluation method by was modified so that the methodological quality could be evaluated [35]. A score of 8 points or higher indicated a low risk of bias and excellent methodological quality, 7 points indicated a moderate risk of bias and average methodological quality, and 6 or fewer points indicated a high risk of bias and low methodological quality. Three researchers conducted independent assessments for quality assessment and derived the final score after a discussion.

Results

Subjects and Study Characteristics

16 papers met the meta-analysis inclusion criteria and analyzed TMG for muscle fatigue after an acute exercise in 393 healthy participants. 8 papers studied elite athletes, 7 studied amateurs and active individuals, and 1 studied both amateur and elite athletes. Regarding the study design, 9 were single-group pre-posttest studies, 6 were crossover studies, and 1 was a randomized controlled trial (Table 2).

Table 2
Information of the study

Study (Year of Publication)	Study Design	Participants	Age (Year ± SD)	Gender	Training Level	Exercise Protocol	Measure Muscle	TMG Variables
Barcala-Furelos (2020)	single group pre-posttest	20	24.0 ± 4.9	16Male 4Female	active	swimming / 100 m with fins to the victim, and towing the victim 100 m back (victim: height, 160–190 cm; weight, 60–90 kg)	RF	Dm, Tc
Beato (2019)	randomized controlled trial	32	21 ± 3	Male	amateur	train / 15 min workout programs	VL, VM, RF	Dm, Tc, Td, Vc10, Vc90
Berzosa (2020)	Crossover	10	27 ± 1.5	Male	active	squat / each exercise session consisted of 4 sets of 7 repetitions interspersed by 2 min between-set rest intervals.	RF, BF	Dm, Tc
Calderón-Pellegrino (2020)	single group pre-posttest	32	23 ± 5	Male	elite	RSA / seven repeated sprints of 30 m, with 20 s of active recovery between	RF, BF	Dm, Tc, Td
García-García (2020)	single group pre-posttest	48	20.2 ± 2.3	Male	elite	maximal incremental cycling test / increased 20 W·min^{-1}, frequency of 80–90 rev·min^{-1}, reached an average of 393.8 ± 41.6 W (5.8 ± 0.4 Wpeak·kg^{-1}) test duration was 1228 ± 120 s	VL, RF, BF	Dm, Tc, Td, Ts, Vrd
García-Unanue (2020)	single group pre-posttest	33	23.4 ± 4.4	Male	elite / amateur	RSA / seven repeated sprints of 30 m, with 20 s of active recovery between	RF, BF	Dm, Tc, Td, Ts, Tr
López-Fernández (2017)	Crossover	16	22.2 ± 3.4	Male	amateur	soccer simulation protocol / 3 bouts of the SSP, Each bout last 16 min with 3 min of rest between bouts.	RF, BF	Dm, Tc, Td, Ts, Tr

Study (Year of Publication)	Study Design	Participants	Age (Year ± SD)	Gender	Training Level	Exercise Protocol	Measure Muscle	TMG Variables
Martín-San Agustín (2020)	single group pre-posttest	35	22 ± 2	16Male 19Female	active	MVIC / measure 3 MVIC, and 60 s fatiguing isometric contraction at 70% MVC	VL, VM, RF	Dm, Tc, Vc10, Vc90
Pereira (2020)	Crossover	14	21.8 ± 2.6	Male	elite	train / 40–50 min workout programs	RF, BF	Vc90
Rodríguez-Matoso (2015)	single group pre-posttest	11	28.2 ± 2.9	Male	elite	surfing / wave size 1–1½ m wave length 6–9 s wave direction right distance paddling 40–50 m, heat length 20 min	VL, VM, RF, BF, ST	Dm, Ts, Tr, Vrn
Rojas-Barrionuevo (2017)	Crossover	14	20.7 ± 3.1	Male	elite	forward tucked somersaults / 12 sets of 6 repetitions of forward tucked somersaults, a rest period of 2 min between sets, 5 s between repetitions was implemented	VL, VM, RF, BF, GM	Vrn
Rojas-Valverde (2020)	Crossover	20	20.4 ± 3.2	Male	active	running / 30 min running	RF, BF	Dm, Tc
Sánchez-Sánchez (2018)	single group pre-posttest	20	25.5 ± 6.1	Male	elite	RSA / seven repeated sprints of 30 m, with 20 s of active recovery between	RF, BF	Dm, Tc, Td, Ts
Sánchez-Sánchez (2019)	single group pre-posttest	62	14.6 ± 2.0	Male Female	elite	RSA / seven repeated sprints of 30 m, with 20 s of active recovery between	RF, BF	Dm, Tc, Td
Santana (2018)	single group pre-posttest	11	20.8 ± 3.2	Male	elite	forward tucked somersaults / 12 sets of 6 repetitions of forward tucked somersaults, A rest period of 2 min between sets, 5 s between repetitions was implemented	VL, VM, RF, BF, GM	Dm, Tc, Td, Vrn

Study (Year of Publication)	Study Design	Participants	Age (Year ± SD)	Gender	Training Level	Exercise Protocol	Measure Muscle	TMG Variables
Ubago Guisado (2017)	Crossover	15	23.4 ± 3.4	Female	amateur	modified RSA / consisted of six sprints of 40 m (20 + 20 m) with 20 s of passive recovery	RF, BF	Dm, Tc, Td, Tr

Caption *RSA repeated sprint ability, MVIC maximal voluntary isometric contraction BF biceps femoris, RF rectus femoris, VL vastus lateralis, VM vastus medialis, ST semitendinosus, GM medial gastrocnemius Dm maximum displacement, Tc contraction time, Td delay time, Ts sustain time, Tr relaxation time, Vrd radial displacement velocity, Vrn normalized response speed, Vc10 mean velocity until 10% Dm, Vc90 mean velocity until 90% Dm*

Tensiomyography

All 16 studies analyzed RF, 13 studies measured BF, 6 measured VL, 5 measured VM, 1 measured ST, and 2 measured GM. Regarding TMG variables, 14 studies measured Dm, 13 measured Tc, 9 measured Td, 3 measured Vc90, 1 measured Vc10, 5 measured Ts, 4 measured Tr, 3 measured Vrn, and 1 measured Vrd. Papers that presented Dm, Tc, and Td together used the Vc90 calculation formula to convert them into Vc90 (Table 2).

Exercise Protocols

Of the 16 studies, 4 used RSA, 1 used MICT, 1 used MVIC, 3 used weight training, 3 used running, 1 used swimming, 2 used forward-tucked somersaults, and 1 used surfing to induce acute muscle fatigue (Table 2).

Methodological Bias Assessment

The mean CAT score and SD was 9.5 ± 1.5 (range 6–11), 14 papers had a low risk of bias and good methodological quality, 1 had a moderate risk of bias and average methodological quality, and 1 had a high risk of bias and low methodological quality (Table 3).

Table 3
Quility and risk of bias assessment of the included validity studies, utilized with the critical appraisal tool (CAT)

Author (Year of Publication)	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**	**Q13**	**Total**	**Risk of bias**
Barcala-Furelos (2020)	Y	Y	Y	N/A	N/A	N	Y	N	N	Y	Y	Y	Y	8/11	Low
Beato (2019)	Y	N	Y	N/A	N/A	Y	N	Y	Y	Y	Y	Y	Y	9/11	Low
Berzosa (2020)	Y	N	Y	N/A	N/A	N	Y	N	N	Y	Y	Y	Y	7/11	Moderate
Calderon-Pellegrino (2020)	Y	Y	Y	N/A	N/A	Y	N	Y	Y	Y	Y	Y	Y	10/11	Low
Garcia-Garcia (2020)	Y	N	Y	N/A	N/A	Y	N	Y	Y	Y	Y	Y	Y	9/11	Low
Garcia-Unanue (2020)	Y	Y	Y	N/A	N/A	Y	N	Y	Y	Y	Y	Y	Y	10/11	Low
Lopez-Fernandez (2017)	Y	Y	Y	N/A	N/A	Y	Y	Y	Y	Y	Y	Y	Y	11/11	Low
Martin-San Agustin (2020)	Y	Y	Y	N/A	N/A	Y	Y	Y	Y	Y	Y	Y	Y	11/11	Low
Pereira (2020)	Y	Y	Y	N/A	N/A	Y	Y	Y	Y	Y	Y	Y	Y	11/11	Low
Rodriguez-Matoso (2015)	Y	N	N	N/A	N/A	Y	N	Y	Y	N	N	Y	Y	6/11	High
Rojas-Barrionuevo (2017)	Y	Y	Y	N/A	N/A	Y	Y	N	Y	Y	Y	Y	Y	10/11	Low
Rojas-Valverde (2020)	Y	N	Y	N/A	N/A	Y	Y	Y	Y	Y	Y	Y	Y	10/11	Low
Sanchez-Sanchez (2018)	Y	Y	Y	N/A	N/A	Y	N	Y	Y	Y	Y	Y	Y	10/11	Low
Sanchez-Sanchez (2019)	Y	Y	Y	N/A	N/A	Y	Y	Y	Y	Y	Y	Y	Y	11/11	Low
Santana (2018)	Y	N	Y	N/A	N/A	Y	Y	Y	Y	Y	Y	Y	Y	10/11	Low
Ubago (2017)	Y	Y	Y	N/A	N/A	Y	N	N	Y	Y	Y	Y	Y	9/11	Low

Caption *Q question, Y yes, N no, N/A not applicable*

Meta-analysis Results

Heterogeneity Evaluation and publication bias

The overall heterogeneity was I^2 = 35.77% ± 30.30(SD). It was either moderate or high. Some studies had significant Q-value, in the RF Dm that showed elite athletes I^2: 55.47% and overall I^2 = 52.67%. The BF Vc90 showed elite athletes I^2 = 60.71% and overall I^2 = 55.15%. The RF Vc90 showed an average person I^2 = 85.01%, elite athletes I^2 = 80.11%, and overall I^2 = 82.28%. However, there I^2 were insignificantly heterogeneous. And all analysis were not publication bias

Comparison Between Elite Athletes and Average Persons

The random effects meta-analysis model analyzed the differences in the TMG variables that measured BF and RF muscle fatigue after an acute exercise.

The ES of BF Dm was insignificant for the average person (Hedges's g = 0.007, 95% CI = -0.189 to 0.202, p = 0.946, I^2 = 0.00%), whereas the elite athletes showed a small but significant decrease (Hedges's g = -0.386, 95% CI = -0.566 to -0.207, p = 0.000, I^2 = 9.50%). The overall effect also showed a small but significant decrease (Hedges's g = -0.207, 95% CI = -0.339 to -0.075, p = 0.002, I^2 = 24.51%). And the ES of RF Dm showed a small but significant decrease for the average person (Hedges's g = -0.298, 95% CI = -0.518 to -0.078, p = 0.008, I^2 = 34.94%), whereas the change was insignificant in elite athletes (Hedges's g = 0.132, 95% CI = -0.101 to 0.366, p = 0.266, I^2 = 55.47%). The overall effect was statistically insignificant (Hedges's g = -0.095, 95% CI = -0.256 to 0.065, p = 0.242, I^2 = 52.67%) (Fig. 2).

The ES of BF Tc change was insignificant in the average person (Hedges's g = 0.014, 95% CI = -0.180 to 0.209, p = 0.885, I^2 = 0.00%), but showed a very small but significant decrease in elite athletes (Hedges's g = -0.164, 95% CI = -0.316 to -0.013, p = 0.033, I^2 = 0.00%). However, the overall effect was statistically insignificant (Hedges's g = -0.097, 95% CI = -0.216 to 0.022, p = 0.111, I^2 = 0.00%). And the ES of RF Tc change was insignificant in the average person (Hedges's g = -0.144, 95% CI = -0.304 to 0.016, p = 0.078, I^2 = 0.00%), yet showed a very small but significant decrease in elite athlete (Hedges's g = -0.172, 95% CI = -0.336 to -0.007, p = 0.041, I^2 = 8.51%). The overall effect also showed a very small but significant decrease (Hedges's g = -0.157, 95% CI = -0.272 to -0.043, p = 0.007, I^2 = 0.00%) (Fig. 3).

The ES of BF Vc90 change was insignificant in the average person (Hedges's g = -0.159, 95% CI = -0.498 to 0.181, p = 0.359, I^2 = 15.20%), but showed a small but significant decrease in elite athletes (Hedges's g = -0.387, 95% CI = -0.663 to -0.111, p = 0.006, I^2 = 60.71%). The overall effect also showed a small but significant decrease (Hedges's g = -0.296, 95% CI = -0.510 to -0.082, p = 0.007, I^2 = 55.15%). And the ES of RF Vc90 change was insignificant for the average person (Hedges's g = 0.335, 95% CI = -0.295 to 0.965, p = 0.298, I^2 = 85.01%), elite athletes (Hedges's g = 0.115, 95% CI = -0.253 to 0.484, p = 0.540, I^2 = 80.11%), and in the overall effect (Hedges's g = 0.171, 95% CI = -0.147 to 0.489, p = 0.292, I^2 = 82.28%) (Fig. 4).

Thus, in BF a substantial decreasing trend in all variables was observed in the elite athletes, with a substantial decreasing trend in the overall effects of Dm and Vc90. Whereas, in RF a substantial decreasing trend was found for Tc in the elite athletes, while Dm was substantial decreasing trend in the average person.

Discussion

This study is the first to conduct a systematic literature review and meta-analysis on TMG variable trend of changes when measuring acute muscle fatigue induced by an acute exercise using a large sample number obtained from the literature. The CAT evaluation showed that the bias risk and the methodological level were excellent. Further, the meta-analysis results confirmed a specific trend of changes when measuring acute muscle fatigue induced by an acute exercise with TMG, and the trend of changes were different for BF and RF.

The literature analysis demonstrated a substantial decrease in the overall effect in BF Dm and Vc90 and RF Tc. The ES of BF Dm was Hedges's g = -0.207, the ES of BF Vc90 was Hedges's g = -0.296, and the ES of RF Tc was Hedges's g = -0.157. Elite athletes showed a substantial decrease in all BF variables and RF Tc after an acute exercise. The ES was Hedges's g = -0.386

for BF Dm, Hedges's g = -0.164 for BF Tc, Hedges's g = -0.387 for BF Vc90, and Hedges's g = -0.172 for RF Tc. Conversely, in the average person only the RF Dm showed a substantial decrease, and the ES of RF Dm was Hedges's g = -0.298.

Regarding the overall ES, there was a substantial decrease in the BF Vc90, which is consistent with the results of a study that reported a decrease in Vc90 after an acute exercise [2,22]. This result is owing to the pH inside the muscle fibers, which decreases due to acute muscle fatigue, reducing the transmission rate of the action potential and affecting the contraction force and contraction rate. A decrease in the number of adenosine triphosphates may cause a decrease in the contractile force by reducing actin-myosin cross-bridge. Additionally, the ratio of fast-twitch muscle fibers (Type II) in the quadriceps and hamstrings is higher than slow-twitch muscle fibers (Type I). Type II muscle fibers have fewer mitochondria and less oxidative metabolism for energy production than Type I, resulting in low fatigue resistance, potentially leading to a contraction rate decrease by becoming fatigued first during exercise [36,37,38,39,40]. Furthermore, there was a substantial decreasing trend of changes in Dm, which is consistent with previous results reporting that muscle fatigue after an exercise increases tension and stiffness [3,13,15,16,21].

That study reported that muscle fatigue causes a decrease in pH from accumulating H^+ and Pi in the muscle fiber, thereby increasing Ca^{2+}, which reduces the sensitivity of troponin to Ca^{2+} and inhibits reabsorption in the sarcoplasmic reticulum. Ultimately, stiffness increases as a result of a reduced actin-myosin bond separation rate [38,40]. This phenomenon can be thought of as a way to store more energy generated during exercise by increasing muscle stiffness instead of decreasing muscle activity when muscle fatigue increases [41].

RF only showed a substantial decreasing trend for Tc, likely explained by the fact that the acute exercise used in each study did not cause substantial muscle fatigue. Several studies included in the analysis reported that the exercise was not enough to induce fatigue in RF [20,23], and reported an improvement in the movement response time due to the post-exercise post-activation potentiation (PAP), which can induce a Tc reduction. Additionally, although not substantial, the RF Vc90 slightly increased, which was affected by the inclusion of some studies that reported such results [22].

There was a difference in the fatigue measurement results between the average person and elite athletes. The average person only showed a substantial decrease in the RF Dm, whereas elite athletes showed a substantial decrease in the all BF variables and RF Tc. This difference is thought to be because the acute exercise used in the literature had many movements requiring explosive muscle strength where hamstring activity is very important, such as running and jumping [42]. The degree of fatigue could have also been affected by the difference in the level of muscular activation during exercise, as there are differences between an average person and an elite athlete in their performance ability and training level, as demonstrated by previous studies [43,44,45]. Previous studies detailed that a higher training level shows a faster and stronger expression of muscular strength and greater activity [46,47,48]. Therefore, the athletes likely generated a greater force in the hamstrings during the exercise compared to the average person, perhaps resulting in a higher fatigue level after exercise [46,47,49]. The quadriceps assist with knee stability during exercise, and during explosive movements, it creates motion in coordination with the hip extensor muscle [50,51,52]. In the acute exercise used in these studies, RF performs this role and is thought to explain the decrease in Tc and Dm in elite athletes and average persons.

This analysis had some limitations. The number of papers was small because research using TMG is relatively new. Further, the muscle fatigue response induced by acute exercise was reported differently in each study [3,53]. Therefore, to identify trend of changes, more studies measuring acute muscle fatigue induced by acute exercise are required. Furthermore, the exercises used in the studies are multiple joint exercise, which could have been inappropriate for inducing localized fatigue [54,55]. Thus, it is necessary to use an exercise that induces fatigue exactly at the measurement site [52,56,57], and additional research should verify whether the exercise, the amount, and the intensity are sufficient. Further, a study that reported the PAP response due to multiple joint exercise was also included in our analysis. However, PAP wasn't clear how it works so continual research on exercise and PAP response is also necessary [58,59]. Lastly, there was only one researcher who collected papers, and only English publications were considered for this study, potentially causing unintentional sampling bias.

Conclusions

Our study results indicate that acute muscle fatigue was induced if Dm, Tc, and Vc90 decreased in TMG measurement after an acute exercise. These results could be used as a muscle fatigue indicator when attempting to induce fatigue through exercise, which could help develop a more suitable protocol for testing the body's response to muscle fatigue. Athletes could also check their fatigue level after exercise by checking for decreases in Dm, Tc, and Vc90 in the BF after a complex lower body movement, which could help optimize exercise programs.

Declarations

Conflict of interest

The authors report no conflict of interest.

Acknowledgements

None.

References

1. Rusu, L. D. *et al.* Tensiomyography method used for neuromuscular assessment of muscle training. *Journal of neuroengineering and rehabilitation* **10**, 1-8 (2013).
2. Pereira, L. A. *et al.* Is Tensiomyography-Derived Velocity of Contraction a Sensitive Marker to Detect Acute Performance Changes in Elite Team-Sport Athletes? *International Journal of Sports Physiology and Performance* **15**, 31-37 (2020).
3. García-García, O. *et al.* A maximal incremental test in cyclists causes greater peripheral fatigue in biceps femoris. *Research quarterly for exercise and sport* **91**, 460-468 (2020).
4. García-Unanue, J. *et al.* Muscular and physical response to an agility and repeated sprint tests according to the level of competition in futsal players. *Frontiers in Psychology* **11**, 3671 (2020).
5. Križaj, D., Šimunič, B. & Žagar, T. Short-term repeatability of parameters extracted from radial displacement of muscle belly. *Journal of Electromyography and Kinesiology* **18**, 645-651 (2008).
6. Martín-Rodríguez, S., Loturco, I., Hunter, A. M., Rodríguez-Ruiz, D. & Munguia-Izquierdo, D. Reliability and measurement error of tensiomyography to assess mechanical muscle function: A systematic review. *The Journal of Strength & Conditioning Research* **31**, 3524-3536 (2017).
7. de Paula Simola, R. Á. *et al.* Assessment of neuromuscular function after different strength training protocols using tensiomyography. *The Journal of Strength & Conditioning Research* **29**, 1339-1348 (2015).
8. Rabita, G., Couturier, A., Dorel, S., Hausswirth, C. & Le Meur, Y. Changes in spring-mass behavior and muscle activity during an exhaustive run at VO2max. *Journal of biomechanics* **46**, 2011-2017 (2013).
9. Peng, H.-T., Kernozek, T. W. & Song, C.-Y. Quadricep and hamstring activation during drop jumps with changes in drop height. *Physical Therapy in Sport* **12**, 127-132 (2011).
10. Padulo, J. *et al.* EMG amplitude of the biceps femoris during jumping compared to landing movements. *Springerplus* **2**, 1-7 (2013).
11. Santana, M. V., Rojas, N. A., Montosa, I. & Bedoya, J. L. Application of tensiomyography to assess the muscle response in the lower limbs of acrobatic gymnasts. *European Journal of Human Movement*, 96-110 (2018).
12. López-Fernández, J. *et al.* Neuromuscular responses and physiological patterns during a soccer simulation protocol. Artificial turf versus natural grass. *J Sports Med Phys Fitness* **22**, 07768-07764 (2017).
13. Sánchez-Sánchez, J. *et al.* Repeated sprint ability and muscular responses according to the age category in elite youth soccer players. *Frontiers in physiology* **10**, 175 (2019).

14. Martín-San Agustín, R. *et al.* Tensiomyographical responsiveness to peripheral fatigue in quadriceps femoris. *PeerJ* **8**, e8674 (2020).
15. Calderón-Pellegrino, G. *et al.* Influence of artificial turf temperature on physical performance and muscle contractile properties in football players after a repeated-sprint ability test. *Scientific Reports* **10**, 1-8 (2020).
16. Berzosa, C. *et al.* Effect of Three Half-Squat Protocols on the Tensiomyographic Twitch Response and Tissue Damage of the Rectus Femoris and the Biceps Femoris. *Journal of Human Kinetics* **75**, 15-27 (2020).
17. Rojas-Barrionuevo, N. A., Vernetta-Santana, M., Alvariñas-Villaverde, M. & López-Bedoya, J. Acute effect of acrobatic jumps on different elastic platforms in the muscle response evaluated through tensiomyography. (2017).
18. Sánchez-Sánchez, J. *et al.* Effect of a Repeated Sprint Ability test on the muscle contractile properties in elite futsal players. *Scientific Reports* **8**, 1-8 (2018).
19. Ubago Guisado, E. *et al.* Muscle contractile properties on different sport surfaces using tensiomyography. (2017).
20. Rojas-Valverde, D., Ugalde-Ramírez, J. A., Sánchez-Ureña, B. & Gutiérrez-Vargas, R. Influence of Altitude and Environmental Temperature on Muscle Functional and Mechanical Activation After 30'Time Trial Run. *MHSalud* **17**, 19-33 (2020).
21. Rodríguez-Matoso, D. *et al.* Mechanical response of knee muscles in high level bodyboarders during performance. *Revista Brasileira de Medicina do Esporte* **21**, 144-147 (2015).
22. Beato, M., Madruga-Parera, M., Piqueras-Sanchiz, F., Moreno-Pérez, V. & Romero-Rodriguez, D. Acute Effect of Eccentric Overload Exercises on Change of Direction Performance and Lower-Limb Muscle Contractile Function. *Journal of strength and conditioning research* (2019).
23. Barcala-Furelos, R. *et al.* Is Low-Frequency Electrical Stimulation a Tool for Recovery after a Water Rescue? A Cross-Over Study with Lifeguards. *International Journal of Environmental Research and Public Health* **17**, 5854 (2020).
24. Park, S. Theory and usage of tensiomyography and the analysis method for the patient with low back pain. *Journal of Exercise Rehabilitation* **16**, 325 (2020).
25. García-García, O., Cuba-Dorado, A., Fernández-Redondo, D. & López-Chicharro, J. Neuromuscular parameters predict the performance in an incremental cycling test. *International journal of sports medicine* **39**, 909-915 (2018).
26. Hunter, A. M. *et al.* Assessment of eccentric exercise-induced muscle damage of the elbow flexors by tensiomyography. *Journal of Electromyography and Kinesiology* **22**, 334-341 (2012).
27. Hedges, L. V. & Olkin, I. *Statistical methods for meta-analysis*. (Academic press, 2014).
28. Bodner, T. E. Standardized effect sizes for moderated conditional fixed effects with continuous moderator variables. *Frontiers in psychology* **8**, 562 (2017).
29. Borenstein, M., Hedges, L. V., Higgins, J. P. & Rothstein, H. R. A basic introduction to fixed-effect and random-effects models for meta-analysis. *Research synthesis methods* **1**, 97-111 (2010).
30. Hopkins, W., Marshall, S., Batterham, A. & Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Medicine+ Science in Sports+ Exercise* **41**, 3 (2009).
31. Higgins, J. P. & Thompson, S. G. Quantifying heterogeneity in a meta-analysis. *Statistics in medicine* **21**, 1539-1558 (2002).
32. Duval, S. & Tweedie, R. Trim and fill: a simple funnel-plot–based method of testing and adjusting for publication bias in meta-analysis. *Biometrics* **56**, 455-463 (2000).
33. Egger, M., Smith, G. D., Schneider, M. & Minder, C. Bias in meta-analysis detected by a simple, graphical test. *Bmj* **315**, 629-634 (1997).
34. Brink, Y. & Louw, Q. A. Clinical instruments: reliability and validity critical appraisal. *Journal of evaluation in clinical practice* **18**, 1126-1132 (2012).
35. Carlsson, H. & Rasmussen-Barr, E. Clinical screening tests for assessing movement control in non-specific low-back pain. A systematic review of intra-and inter-observer reliability studies. *Manual therapy* **18**, 103-110 (2013).
36. Meznaric, M. & Cvetko, E. Size and proportions of slow-twitch and fast-twitch muscle fibers in human costal diaphragm. *BioMed research international* **2016** (2016).

37. Li, B. *et al.* Profiling and functional analysis of circular RNAs in porcine fast and slow muscles. *Frontiers in Cell and Developmental Biology* **8**, 322 (2020).
38. Fitts, R. H. The cross-bridge cycle and skeletal muscle fatigue. *Journal of applied physiology* **104**, 551-558 (2008).
39. Evangelidis, P. E. *et al.* The functional significance of hamstrings composition: is it really a “fast” muscle group? *Scandinavian journal of medicine & science in sports* **27**, 1181-1189 (2017).
40. Boyas, S. & Guével, A. Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of physical and rehabilitation medicine* **54**, 88-108 (2011).
41. Dumke, C. L., Pfaffenroth, C. M., McBride, J. M. & McCauley, G. O. Relationship between muscle strength, power and stiffness and running economy in trained male runners. *International journal of sports physiology and performance* **5**, 249-261 (2010).
42. Morin, J.-B. *et al.* Sprint acceleration mechanics: the major role of hamstrings in horizontal force production. *Frontiers in physiology* **6**, 404 (2015).
43. Zhang, J. H. *et al.* How do training experience and geographical origin of a runner affect running biomechanics? *Gait & Posture* **84**, 209-214 (2021).
44. Maniar, N., Schache, A., Heiderscheit, B. & Opar, D. in *Prevention and Rehabilitation of Hamstring Injuries* 65-81 (Springer, 2020).
45. Hébert-Losier, K., Mourot, L. & Holmberg, H.-C. Elite and amateur orienteers’ running biomechanics on three surfaces at three speeds. *Medicine & Science in Sports & Exercise* **47**, 381-389 (2015).
46. Schoenfeld, B. J., Contreras, B., Willardson, J. M., Fontana, F. & Tiryaki-Sonmez, G. Muscle activation during low-versus high-load resistance training in well-trained men. *European journal of applied physiology* **114**, 2491-2497 (2014).
47. Janusevicius, D. *et al.* Effects of high velocity elastic band versus heavy resistance training on hamstring strength, activation, and sprint running performance. *Journal of sports science & medicine* **16**, 239 (2017).
48. Higashihara, A., Nagano, Y., Ono, T. & Fukubayashi, T. Differences in hamstring activation characteristics between the acceleration and maximum-speed phases of sprinting. *Journal of sports sciences* **36**, 1313-1318 (2018).
49. Chumanov, E. S., Heiderscheit, B. C. & Thelen, D. G. Hamstring musculotendon dynamics during stance and swing phases of high speed running. *Medicine and science in sports and exercise* **43**, 525 (2011).
50. Shaw, T., Williams, M. T. & Chipchase, L. S. Do early quadriceps exercises affect the outcome of ACL reconstruction? A randomised controlled trial. *Australian Journal of Physiotherapy* **51**, 9-17 (2005).
51. Lewek, M., Rudolph, K., Axe, M. & Snyder-Mackler, L. The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. *Clinical biomechanics* **17**, 56-63 (2002).
52. Kakehata, G., Goto, Y., Iso, S. & Kanosue, K. Timing of Rectus Femoris and Biceps Femoris Muscle Activities in Both Legs at Maximal Running Speed. *Medicine and Science in Sports and Exercise* **53**, 643-652 (2021).
53. Piqueras-Sanchiz, F. *et al.* Effects of moderate vs. high iso-inertial loads on power, velocity, work and hamstring contractile function after flywheel resistance exercise. *PLoS One* **14**, e0211700 (2019).
54. Moore, R. D., Romine, M. W., O'connor, P. J. & Tomporowski, P. D. The influence of exercise-induced fatigue on cognitive function. *Journal of sports sciences* **30**, 841-850 (2012).
55. Marino, F. E., Gard, M. & Drinkwater, E. J. The limits to exercise performance and the future of fatigue research. *British journal of sports medicine* **45**, 65-67 (2011).
56. MacKenzie, S. J., Lavers, R. J. & Wallace, B. B. A biomechanical comparison of the vertical jump, power clean, and jump squat. *Journal of sports sciences* **32**, 1576-1585 (2014).
57. Higashihara, A., Ono, T., Kubota, J., Okuwaki, T. & Fukubayashi, T. Functional differences in the activity of the hamstring muscles with increasing running speed. *Journal of sports sciences* **28**, 1085-1092 (2010).
58. Batista, M. A. *et al.* Intermittent exercise as a conditioning activity to induce postactivation potentiation. *The Journal of Strength & Conditioning Research* **21**, 837-840 (2007).

59. Esformes, J. I., Cameron, N. & Bampouras, T. M. Postactivation potentiation following different modes of exercise. *The Journal of Strength & Conditioning Research* **24**, 1911-1916 (2010).

Figures

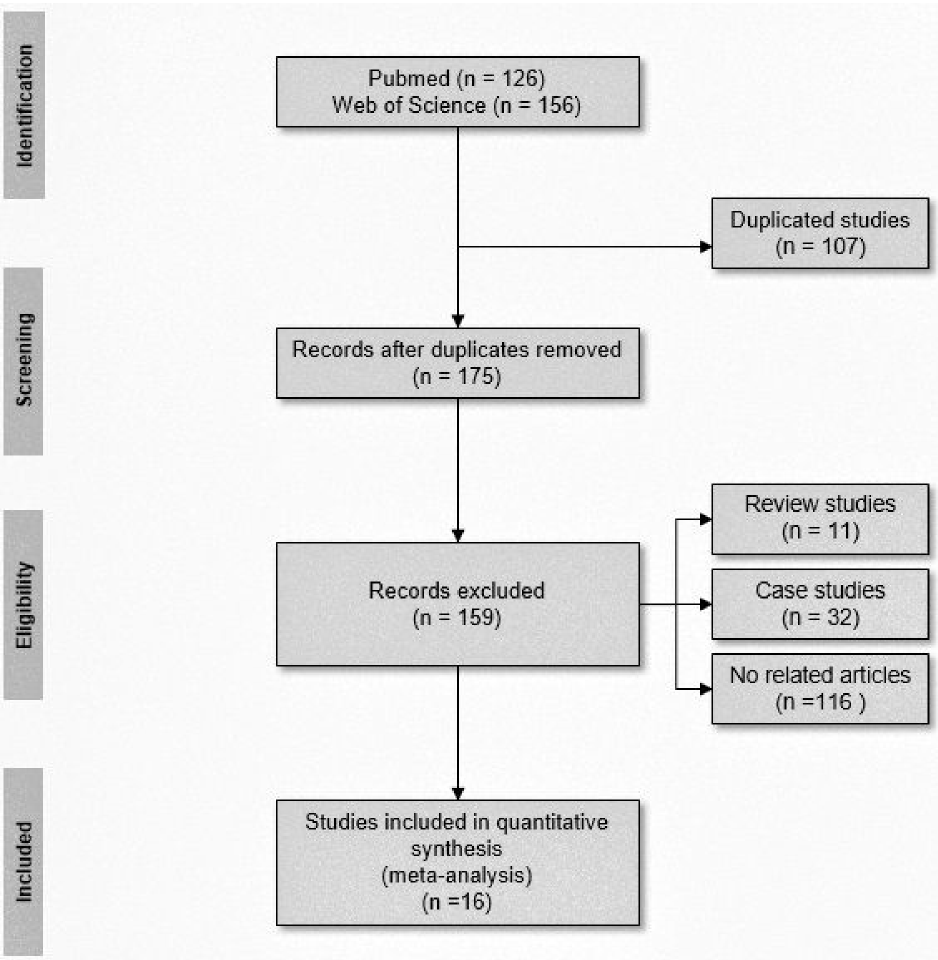

Figure 1

Search procedure and results according to PRISMA flow chart

Study Name	Participants	Outcome	Hedges's g	LL	UL	*P*-value
Results of Biceps femoris maximum radial displacement meta analysis						
Berzosa 2020L	Average	BF Dm	0.028	- 0.811	0.868	0.947
Berzosa 2020R	Average	BF Dm	- 0.517	- 1.371	0.338	0.236
Berzosa 2020-1L	Average	BF Dm	- 0.208	- 1.050	0.634	0.628
Berzosa 2020-1R	Average	BF Dm	- 0.517	- 1.371	0.338	0.236
Berzosa 2020-2L	Average	BF Dm	- 0.149	- 0.990	0.692	0.729
Berzosa 2020-2R	Average	BF Dm	- 0.751	- 1.622	0.120	0.091
Garcia Unanue 2020-1	Average	BF Dm	- 0.372	- 1.124	0.379	0.331
Lopez 2017L	Average	BF Dm	0.046	- 0.629	0.722	0.893
Lopez 2017R	Average	BF Dm	0.195	- 0.482	0.872	0.572
Lopez 2017-1L	Average	BF Dm	0.456	- 0.228	1.141	0.191
Lopez 2017-1R	Average	BF Dm	0.021	- 0.654	0.697	0.950
Rojas 2020	Average	BF Dm	0.188	- 0.421	0.797	0.546
Rojas 2020-1	Average	BF Dm	0.312	- 0.299	0.923	0.317
Ubago 2017	Average	BF Dm	0.404	- 0.300	1.107	0.261
		Average overall	**0.007**	**- 0.189**	**0.202**	**0.946**
Calderon 2020	Elite	BF Dm	- 0.835	- 1.340	- 0.329	0.001
Calderon 2020-1	Elite	BF Dm	- 0.490	- 0.982	0.001	0.050
Garcia 2020	Elite	BF Dm	- 0.811	- 1.224	- 0.398	0.000
Garcia Unanue 2020	Elite	BF Dm	- 0.103	- 0.711	0.505	0.740
Rodriguez 2015L	Elite	BF Dm	0.000	- 0.804	0.804	1.000
Rodriguez 2015R	Elite	BF Dm	- 0.279	- 1.088	0.529	0.498
Sanchez 2018D	Elite	BF Dm	0.000	- 0.607	0.607	1.000
Sanchez 2018ND	Elite	BF Dm	- 0.148	- 0.756	0.461	0.634
Sanchez 2019	Elite	BF Dm	- 0.187	- 0.782	0.408	0.538
Sanchez 2019-1	Elite	BF Dm	- 0.262	- 0.872	0.348	0.400
Sanchez 2019-2	Elite	BF Dm	- 0.231	- 0.826	0.365	0.447
Santana 2018	Elite	BF Dm	- 0.535	- 1.354	0.285	0.201
		Elite overall	**- 0.386**	**- 0.566**	**- 0.207**	**0.000**
Random effects model		**Overall**	**- 0.207**	**- 0.339**	**- 0.075**	**0.002**
Results of Rectus femoris maximum radial displacement meta analysis						
Barcala 2020	Average	RF Dm	- 0.350	- 0.962	0.262	0.262
Barcala 2020-1	Average	RF Dm	- 0.218	- 0.827	0.392	0.484
Beato 2019	Average	RF Dm	- 0.793	- 1.630	0.045	0.063
Beato 2019-1	Average	RF Dm	- 0.358	- 1.204	0.489	0.408
Beato 2019-2	Average	RF Dm	- 0.730	- 1.599	0.139	0.100
Berzosa 2020L	Average	RF Dm	- 0.263	- 1.106	0.581	0.541
Berzosa 2020R	Average	RF Dm	- 0.279	- 1.122	0.565	0.518
Berzosa 2020-1L	Average	RF Dm	- 0.278	- 1.122	0.566	0.519
Berzosa 2020-1R	Average	RF Dm	- 0.753	- 1.624	0.119	0.090
Berzosa 2020-2L	Average	RF Dm	- 0.867	- 1.749	0.014	0.054
Berzosa 2020-2R	Average	RF Dm	- 0.672	- 1.537	0.193	0.128
Garcia Unanue 2020-1	Average	RF Dm	0.270	- 0.478	1.018	0.479
Lopez 2017L	Average	RF Dm	- 0.234	- 0.912	0.444	0.499
Lopez 2017R	Average	RF Dm	0.081	- 0.595	0.757	0.814
Lopez 2017-1L	Average	RF Dm	0.153	- 0.524	0.829	0.658
Lopez 2017-1R	Average	RF Dm	0.069	- 0.607	0.745	0.842
Martin 2020-1	Average	RF Dm	- 1.287	- 1.974	- 0.601	0.000
Ubago 2017	Average	RF Dm	0.600	- 0.113	1.313	0.099
		Average overall	**- 0.298**	**- 0.518**	**- 0.078**	**0.008**
Calderon 2020	Elite	RF Dm	- 0.303	- 0.789	0.184	0.223
Calderon 2020-1	Elite	RF Dm	0.306	- 0.181	0.793	0.218
Garcia 2020	Elite	RF Dm	- 0.380	- 0.781	0.020	0.063
Garcia Unanue 2020	Elite	RF Dm	0.416	- 0.198	1.030	0.184
Rodriguez 2015L	Elite	RF Dm	0.385	- 0.427	1.197	0.353
Rodriguez 2015R	Elite	RF Dm	0.050	- 0.754	0.854	0.903
Rojas 2020	Elite	RF Dm	0.488	- 0.129	1.105	0.121
Rojas 2020-1	Elite	RF Dm	0.711	0.084	1.338	0.026
Rojas 2020-2	Elite	RF Dm	0.756	0.126	1.385	0.019
Sanchez 2018D	Elite	RF Dm	0.688	0.062	1.314	0.031
Sanchez 2018ND	Elite	RF Dm	0.106	- 0.501	0.714	0.731
Sanchez 2019	Elite	RF Dm	- 0.282	- 0.879	0.314	0.354
Sanchez 2019-1	Elite	RF Dm	- 0.733	- 1.361	- 0.104	0.022
Sanchez 2019-2	Elite	RF Dm	0.041	- 0.553	0.634	0.893
Santana 2018	Elite	RF Dm	0.028	- 0.776	0.832	0.945
		Elite overall	**0.132**	**- 0.101**	**0.366**	**0.266**
Random effects model		**Overall**	**- 0.095**	**- 0.256**	**0.065**	**0.242**

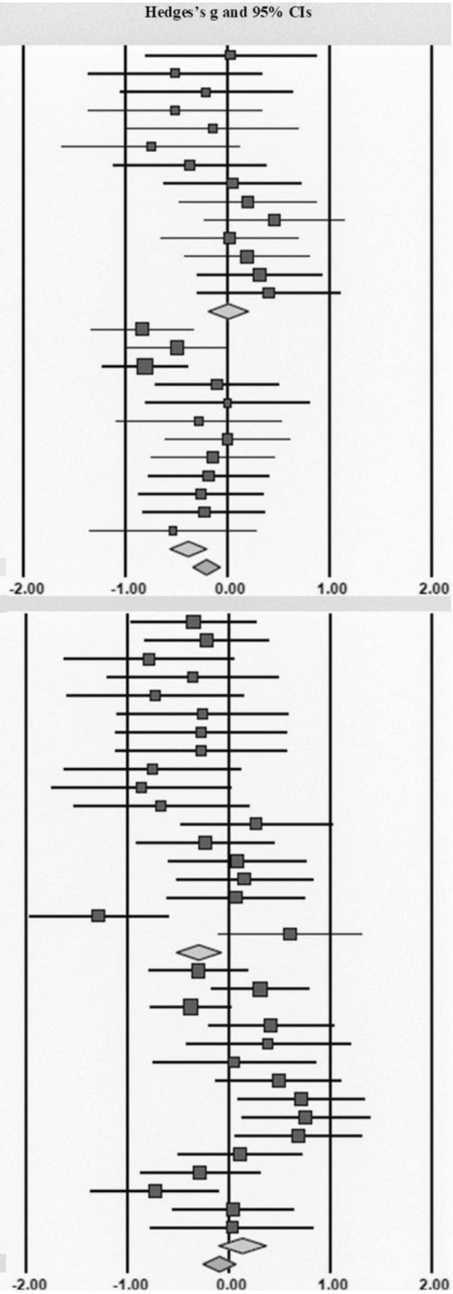

Figure 2

Results of the biceps femoris and the rectus femoris maximum radial displacement meta-analysis Caption L left, R right, D dominant, ND non-dominant, LL lower-limit, UL upper-limit, BF Dm biceps femoris maximum radial displacement, RF Dm rectus femoris maximum radial displacement, CLs confident intervals Each size of individual effects was proportional to their weight; Diamonds indicate overall effect size

Study Name	participants	Outcome	Hedges's g	LL	UL	*P*-value
Results of Biceps femoris contraction time meta analysis						
Berzosa 2020L	Average	BF Tc	0.292	- 0.552	1.136	0.498
Berzosa 2020R	Average	BF Tc	0.043	- 0.797	0.883	0.920
Berzosa 2020-1L	Average	BF Tc	0.175	- 0.666	1.016	0.684
Berzosa 2020-1R	Average	BF Tc	0.372	- 0.475	1.220	0.389
Berzosa 2020-2L	Average	BF Tc	0.542	- 0.314	1.398	0.215
Berzosa 2020-2R	Average	BF Tc	0.315	- 0.530	1.160	0.465
Garcia Unanue 2020-1	Average	BF Tc	- 0.170	- 0.916	0.576	0.654
Lopez 2017L	Average	BF Tc	0.318	- 0.362	0.998	0.360
Lopez 2017R	Average	BF Tc	- 0.053	- 0.729	0.623	0.878
Lopez 2017-1R	Average	BF Tc	0.088	- 0.587	0.764	0.798
Rojas 2020	Average	BF Tc	- 0.691	- 1.432	0.051	0.068
Rojas 2020-1	Average	BF Tc	- 0.465	- 1.194	0.265	0.212
Rojas 2020-2	Average	BF Tc	- 0.170	- 0.891	0.550	0.643
Ubago 2017	Average	BF Tc	0.025	- 0.672	0.721	0.944
Ubago 2017-1	Average	BF Tc	- 0.045	- 0.741	0.652	0.900
		Average overall	**0.014**	**- 0.180**	**0.209**	**0.885**
Calderon 2020	Elite	BF Tc	- 0.416	- 0.905	0.074	0.096
Calderon 2020-1	Elite	BF Tc	- 0.013	- 0.497	0.471	0.958
Garcia 2020	Elite	BF Tc	- 0.483	- 0.886	- 0.081	0.019
Garcia Unanue 2020	Elite	BF Tc	0.060	- 0.547	0.668	0.846
Rodriguez 2015L	Elite	BF Tc	- 0.250	- 1.058	0.557	0.544
Rodriguez 2015R	Elite	BF Tc	- 0.388	- 1.200	0.424	0.349
Rojas Barrionuevo 2017	Elite	BF Tc	- 0.200	- 0.810	0.409	0.519
Rojas Barrionuevo 2017-1	Elite	BF Tc	- 0.072	- 0.680	0.536	0.817
Rojas Barrionuevo 2017-2	Elite	BF Tc	0.136	- 0.472	0.744	0.661
Sanchez 2018D	Elite	BF Tc	0.245	- 0.365	0.855	0.431
Sanchez 2018ND	Elite	BF Tc	- 0.077	- 0.685	0.531	0.803
Sanchez 2019	Elite	BF Tc	- 0.190	- 0.784	0.405	0.532
Sanchez 2019-1	Elite	BF Tc	- 0.135	- 0.743	0.473	0.664
Sanchez 2019-2	Elite	BF Tc	- 0.209	- 0.804	0.386	0.491
Santana 2018	Elite	BF Tc	- 0.134	- 0.939	0.671	0.744
		Elite overall	**- 0.164**	**- 0.316**	**- 0.013**	**0.033**
Random effects model		**Overall**	**- 0.097**	**- 0.216**	**0.022**	**0.111**
Results of Rectus femoris contraction time meta analysis						
Barcala 2020	Average	RF Tc	0.346	- 0.266	0.958	0.268
Barcala 2020-1	Average	RF Tc	0.304	- 0.307	0.915	0.329
Beato 2019	Average	RF Tc	- 0.127	- 0.932	0.677	0.756
Beato 2019-1	Average	RF Tc	- 0.118	- 0.958	0.722	0.783
Beato 2019-2	Average	RF Tc	0.055	- 0.785	0.895	0.898
Berzosa 2020L	Average	RF Tc	- 0.573	- 1.431	0.285	0.191
Berzosa 2020R	Average	RF Tc	- 0.333	- 1.178	0.513	0.441
Berzosa 2020-1L	Average	RF Tc	- 0.186	- 1.028	0.655	0.664
Berzosa 2020-1R	Average	RF Tc	- 0.382	- 1.229	0.466	0.378
Berzosa 2020-2R	Average	RF Tc	- 0.623	- 1.485	0.238	0.156
Garcia Unanue 2020-1	Average	RF Tc	- 0.440	- 1.194	0.314	0.253
Lopez 2017L	Average	RF Tc	- 0.049	- 0.725	0.626	0.886
Lopez 2017R	Average	RF Tc	- 0.153	- 0.830	0.523	0.657
Lopez 2017-1L	Average	RF Tc	- 0.109	- 0.785	0.567	0.753
Lopez 2017-1R	Average	RF Tc	- 0.214	- 0.891	0.464	0.536
Martin 2020	Average	RF Tc	- 0.011	- 0.686	0.665	0.975
Martin 2020-1	Average	RF Tc	0.216	- 0.408	0.841	0.498
Rojas 2020-1	Average	RF Tc	- 0.739	- 1.367	- 0.110	0.021
Rojas 2020-2	Average	RF Tc	- 0.481	- 1.097	0.136	0.127
Ubago 2017	Average	RF Tc	0.158	- 0.539	0.856	0.657
		Average overall	**- 0.144**	**- 0.304**	**0.016**	**0.078**
Calderon 2020	Elite	RF Tc	- 0.257	- 0.743	0.230	0.301
Calderon 2020-1	Elite	RF Tc	0.269	- 0.217	0.755	0.279
Garcia 2020	Elite	RF Tc	- 0.365	- 0.766	0.035	0.074
Garcia Unanue 2020	Elite	RF Tc	- 0.552	- 1.171	0.068	0.081
Rodriguez 2015L	Elite	RF Tc	- 0.143	- 0.948	0.662	0.728
Rodriguez 2015R	Elite	RF Tc	- 0.728	- 1.561	0.104	0.086
Rojas Barrionuevo 2017	Elite	RF Tc	- 0.190	- 0.911	0.531	0.605
Rojas Barrionuevo 2017-1	Elite	RF Tc	- 0.363	- 1.088	0.362	0.327
Rojas Barrionuevo 2017-2	Elite	RF Tc	- 0.034	- 0.753	0.686	0.927
Sanchez 2018D	Elite	RF Tc	- 0.511	- 1.129	0.107	0.105
Sanchez 2018ND	Elite	RF Tc	- 0.411	- 1.025	0.203	0.190
Sanchez 2019	Elite	RF Tc	0.463	- 0.139	1.064	0.132
Sanchez 2019-1	Elite	RF Tc	0.026	- 0.581	0.634	0.932
Sanchez 2019-2	Elite	RF Tc	0.148	- 0.446	0.742	0.625
Santana 2018	Elite	RF Tc	- 0.226	- 1.033	0.580	0.582
		Elite overall	**- 0.172**	**- 0.336**	**- 0.007**	**0.041**
Random effects model		**Overall**	**- 0.157**	**- 0.272**	**- 0.043**	**0.007**

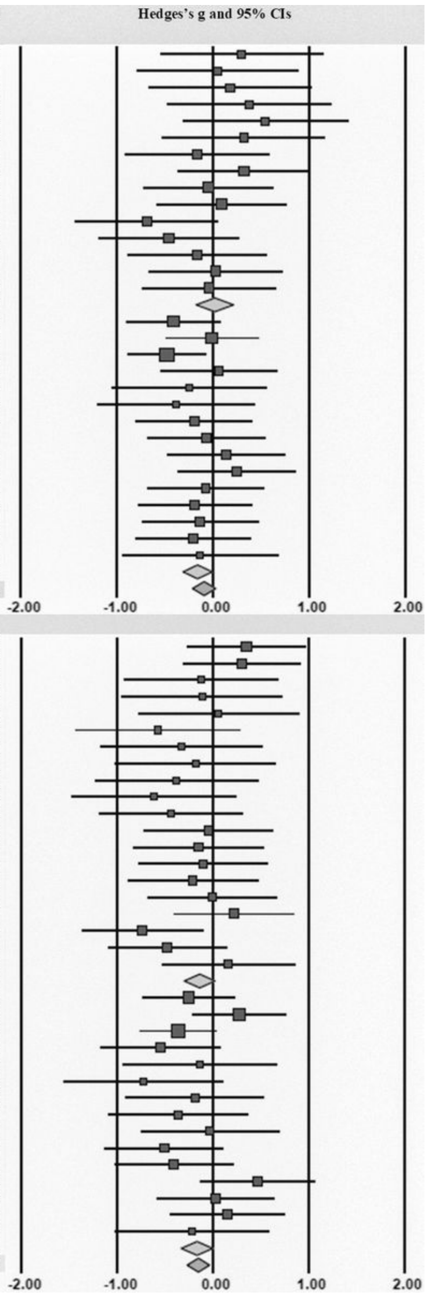

Figure 3

Results of the biceps femoris and the rectus femoris contraction time meta-analysis Caption L left, R right, D dominant, ND non-dominant, LL lower-limit, UL upper-limit, BF Tc biceps femoris contraction time, RF Tc rectus femoris contraction time, CLs confident intervals Each size of individual effects was proportional to their weight, Diamonds indicate overall effect size

Study Name	Participants	Outcome	Hedges's g	LL	UL	*P*-value
Results of Biceps femoris mean velocity untill 90% Dm meta analysis						
Garcia Unanue 2020-1	Average	BF Vc90	- 0.519	- 1.276	0.239	0.180
Lopez 2017L	Average	BF Vc90	- 0.573	- 1.263	0.117	0.103
Lopez 2017-1L	Average	BF Vc90	- 0.124	- 0.800	0.552	0.719
Lopez 2017-1R	Average	BF Vc90	0.000	- 0.675	0.675	1.000
Ubago 2017	Average	BF Vc90	0.378	- 0.325	1.081	0.292
		Averageoverall	**- 0.159**	**- 0.498**	**0.181**	**0.359**
Calderon 2020-1	Elite	BF Vc90	- 1.492	- 2.041	- 0.943	0.000
Garcia 2020	Elite	BF Vc90	- 1.021	- 1.443	- 0.598	0.000
Garcia Unanue 2020	Elite	BF Vc90	- 0.215	- 0.825	0.394	0.489
Pereira 2020	Elite	BF Vc90	- 0.291	- 1.014	0.432	0.431
Pereira 2020-1	Elite	BF Vc90	- 0.281	- 1.004	0.442	0.446
Pereira 2020-2	Elite	BF Vc90	- 0.494	- 1.225	0.237	0.185
Pereira 2020-3	Elite	BF Vc90	0.328	- 0.396	1.053	0.374
Sanchez 2018D	Elite	BF Vc90	- 0.169	- 0.778	0.440	0.586
Sanchez 2018ND	Elite	BF Vc90	- 0.251	- 0.861	0.359	0.420
Sanchez 2019	Elite	BF Vc90	- 0.055	- 0.649	0.539	0.856
Sanchez 2019-1	Elite	BF Vc90	- 0.327	- 0.939	0.285	0.295
Sanchez 2019-2	Elite	BF Vc90	- 0.182	- 0.777	0.413	0.549
Santana 2018	Elite	BF Vc90	- 0.191	- 0.997	0.615	0.641
		Elite overall	**- 0.387**	**- 0.663**	**- 0.111**	**0.006**
Random effects model		**Overall**	**- 0.296**	**- 0.510**	**- 0.082**	**0.007**
Results of Rectus femoris mean velocity untill 90% Dm meta analysis						
Beato 2019	Average	RF Vc90	- 0.625	- 1.450	0.200	0.137
Beato 2019-1	Average	RF Vc90	- 0.215	- 1.057	0.628	0.617
Beato 2019-2	Average	RF Vc90	- 0.682	- 1.548	0.183	0.122
Garcia Unanue 2020-1	Average	RF Vc90	1.131	0.325	1.936	0.006
Lopez 2017L	Average	RF Vc90	- 0.273	- 0.951	0.406	0.431
Lopez 2017R	Average	RF Vc90	1.442	0.680	2.205	0.000
Lopez 2017-1L	Average	RF Vc90	1.861	1.046	2.676	0.000
Lopez 2017-1R	Average	RF Vc90	0.830	0.124	1.535	0.021
Martin 2020	Average	RF Vc90	- 1.095	- 1.821	- 0.368	0.003
Ubago 2017	Average	RF Vc90	0.960	0.222	1.697	0.011
		Averageoverall	**0.335**	**- 0.295**	**0.965**	**0.298**
Calderon 2020	Elite	RF Vc90	- 0.336	- 0.823	0.152	0.177
Calderon 2020-1	Elite	RF Vc90	0.312	- 0.175	0.799	0.209
Garcia 2020	Elite	RF Vc90	- 0.465	- 0.868	- 0.063	0.023
Garcia Unanue 2020	Elite	RF Vc90	1.167	0.508	1.826	0.001
Pereira 2020	Elite	RF Vc90	- 0.118	- 0.838	0.601	0.747
Pereira 2020-1	Elite	RF Vc90	- 0.321	- 1.045	0.403	0.385
Pereira 2020-2	Elite	RF Vc90	- 0.239	- 0.961	0.483	0.517
Pereira 2020-3	Elite	RF Vc90	0.162	- 0.559	0.882	0.660
Sanchez 2018D	Elite	RF Vc90	2.051	1.296	2.807	0.000
Sanchez 2018ND	Elite	RF Vc90	0.480	- 0.136	1.097	0.127
Sanchez 2019	Elite	RF Vc90	- 0.851	- 1.472	- 0.231	0.007
Sanchez 2019-1	Elite	RF Vc90	- 0.607	- 1.229	0.014	0.056
Sanchez 2019-2	Elite	RF Vc90	0.119	- 0.475	0.713	0.696
Santana 2018	Elite	RF Vc90	0.549	- 0.271	1.369	0.189
		Elite overall	**0.115**	**- 0.253**	**0.484**	**0.540**
Random effects model		**Overall**	**0.171**	**- 0.147**	**0.489**	**0.292**

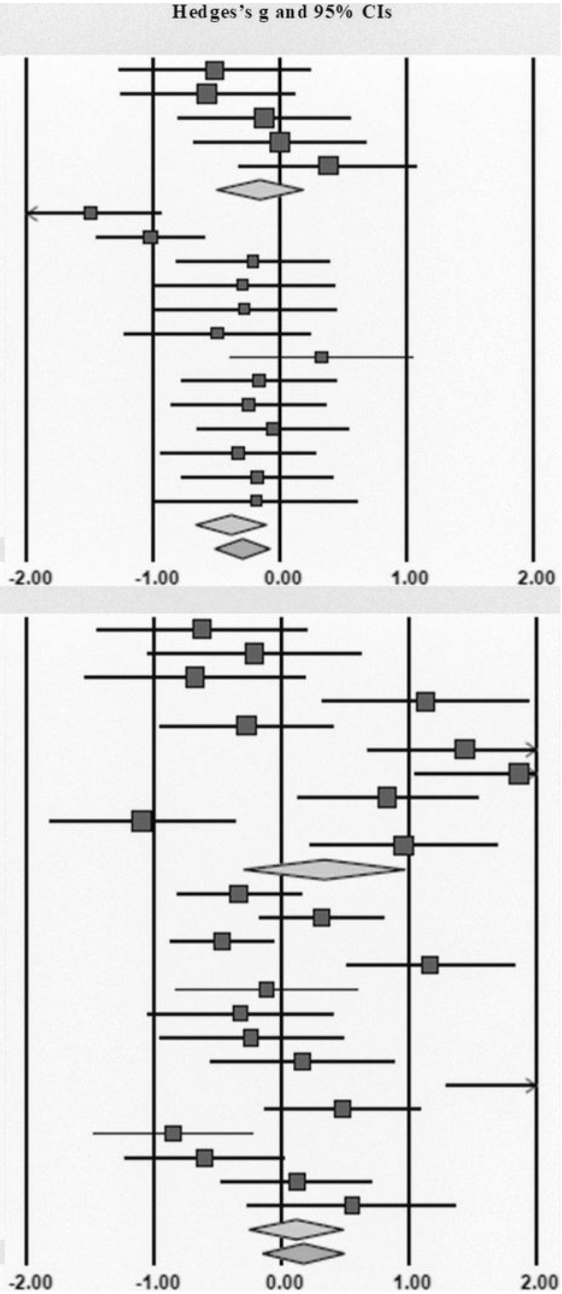

Figure 4

Results of the biceps femoris and the rectus femoris mean velocity until 90 % Dm meta-analysis Caption L left, R right, D dominant, ND non-dominant, LL lower-limit, UL upper-limit, BF Vc90 biceps femoris mean velocity until 90% Dm, RF Vc90 rectus femoris mean velocity until 90% Dm, CLs confident intervals Each size of individual effects was proportional to their weight, Diamonds indicate overall effect size

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- PRISMAchecklistTMGmetaFinal.docx