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REVIEW

Clinical utility of tensiomyography for muscle function analysis in athletes

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Abstract: An exhaustive review has been made to filter the studies that have analyzed muscle function though tensiomyography (TMG) with elite or well-trained athletes. The results of this review indicate that the several protocols used in athletes to find the displacement-time curve with greater maximum radial muscle displacement showed a good-excellent reliability. TMG has been used to characterize athletes' muscles contractile properties from specific sports disciplines, although there are very few sports that have been deeply analyzed. TMG seems to be useful to determine changes in muscles contractile properties after stimuli of competition, training or recovery. These changes have been strongly related with the fatigue produced after an effort. In addition, TMG parameters could be used to control training effects during a specific period or throughout the season being also a very useful tool to individualize athletes training loads. In this sense, it also seems to provide sports performance information in cyclic sports by relating some TMG parameters with performance indicators. On the other hand, the TMG-BCM algorithm has been used as a lateral and functional symmetry measure and as a monitoring tool for injury prevention and recovery. However, it seems to be no clear criterion that determines asymmetry degree, nor established contractile properties values as a reference to prevent or recover sports injuries. Despite the utility shown in these fields, there are still very few sports analyzed and it is really necessary to continue advancing in the knowledge of the contractile properties behavior, such as the effects of athletes' training, competitions and injuries and even in the parameters interpretation obtained with the TMG.

Keywords: TMG, contractile properties, elite athletes, neuromuscular parameters, muscle assessment, muscle response

Introduction

Tensiomyography (TMG) has been used since the 1990s to evaluate the contractile properties of superficial muscles. It is a non-invasive method and does not require physical effort from the athlete. From our knowledge, the works of Burger et al[1] and Valencic and Knez[2] are the ones which show for the first time the possibility of obtaining a displacement-time curve of the superficial skeletal muscle through a displacement sensor with a certain pretension on the muscle belly. Later, this type of sensor would be validated as a micromachined accelerometer for muscle belly radial displacement measurement.[3] Currently, this type of displacement sensor (contact sensor) has been compared with a laser sensor (without contact with the muscular belly): both sensors obtained good to excellent test–retest reliability, as well as similar displacement and time measurements.[4] Though, the sensors showed

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some differences between them, although according to these authors, these differences could be clinically irrelevant.

The TMG measures the radial deformation of the muscular belly produced by a single electrical stimulus of the muscle fiber, whose duration can be 0.2, 0.5 or the traditionally used of a 1 ms. The intensity of the electrical stimulus can be modulated between 1 and 110 mA. As a result of this electrical stimulus, a displacement-time curve is recorded where the following parameters are integrated. Maximum radial muscle displacement (Dm) as the peak space transverse deformation in the muscle in mm. Contraction time (Tc) as the time in ms from 10% to 90% of Dm on the ascending curve. Delay time (Td) as the time in ms from onset to 10% of Dm on the ascending curve. Sustain time (Ts) as the time in ms between 50% of Dm on both the ascending and descending sides of the curve. Half-time relaxation (Tr) as the time taken from 90% to 50% of Dm on descending curve. In addition, several measures have been established derived from the relationship between the Dm and the Tc that could be called radial displacement velocity, normalized response velocity or velocity of deformation (V_r, Vc, V_{rn},$V_{90,}$ V_{10} or Vd), ie, as the rate ($mm \cdot s^{-1}$) between the peak radial displacement occurring during the time period of Tc (Dm80) and Tc [Dm80/Tc]. Still, more research is needed to establish the most appropriate way to standardize this derived measure.[5]

To date, several reviews have been published about the use, utility, validity and reliability of this tool. However, it seems that part of these variables may be modulated by the evaluated population. In this line, the construct validity and reliability of TMG has been established, however not for specialist populations (ie, elite athletes),[5] so it seems appropriate to review the usefulness of the data provided by TMG for the development of well-trained and elite athletes. Therefore, the objective of this work is to determine the usefulness of the TMG to analyze muscle function in athletes.

Literature search

Between the months of May and October of 2018, the search of relevant literature for this study was carried out. We searched the Scopus, Web of Science and Sport Discus databases using the following terms: (tensiomyograph* or TMG or tensiomiography) and (performance or sport or competiti*). This search produced more than 1,000 articles that were analyzed to select only articles related to the usefulness of Tensiomiography in well-trained athletes of different sports. Articles written in Spanish, English and Portuguese were taken into account. Figure 1 shows the search process and articles selection.

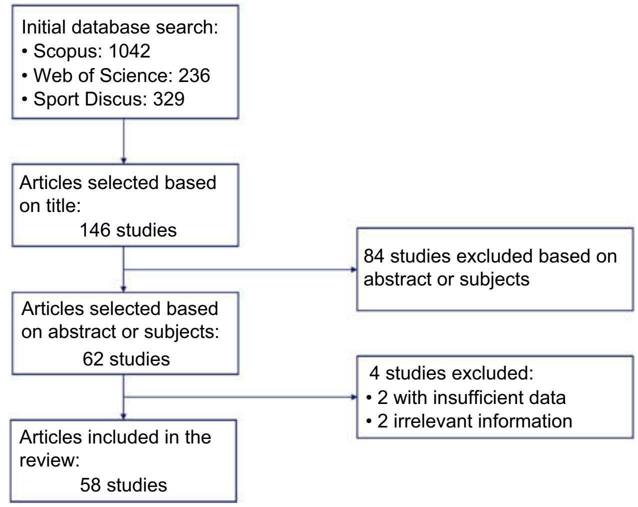

Figure 1 Flowchart of the literature search and the selection process.

Measurement protocols and reliability in athletes

It is not the aim of this review to discuss the validity of the TMG since TMG would still require much more research dedicated to this topic before it could be considered a valid and reliable assessment tool.[6] Yet, it does seem necessary to analyze the TMG measurement protocols that have been used to evaluate the athletes' muscular function and the reliability they have shown.

More and more authors[7–9] explicitly state the condition that the evaluator should be an expert, which requires that he has made a good number of measurements and its intra-evaluator reliability is very high.

There is consensus that the protocol used aims to find the displacement-time curve that has the highest Dm in the muscle. However, few studies specify which of the displacement-time curves are selected to extract the data from the TMG parameters. Wiewelhove et al[10] and Simola et al[11] specify that "average of two maximal twitches was used for futher analyzes" or Giovanelli et al[12] suggest recording two maximum responses for the subsequent analysis. Nevertheless, García-García et al[13] propose "only the curve with the highest maximum radial displacement was included in the analysis for each muscle assessed". We suggest that the protocol with TMG must specify exactly which displacement-time curves are taken into consideration for the subsequent analysis.

The most commonly protocols used with athletes are detailed in Table 1

The incremental protocol until reaching the "plateau", has also been defined as until no future displacement of the muscle belly could be produced[9] or until the maximum displacement of the muscle belly was reached.[20–22]

The incremental protocol until reaching the maximum stimulus, in our opinion, is the only one that allows determining the maximal radial displacement of the muscle belly. In this sense, it is suggested that elite athletes usually reach the maximum Dm between 90 and 110 mA, while other non-athletic or recreational populations reach it at clearly lower intensities, so using other protocols with a limited number of stimuli does not seem the right solution with elite or well-trained athletes to obtain the maximum Dm.[5,13]

The relative and absolute reliability of the TMG parameters has been generally analyzed with non-healthy athletes, obtaining good results.[28] The results that reported the reliability of TMG parameters with athlete population also indicate a high reliability, generally measured through the intraclass correlation and to a lesser extent, through the coefficient of variation. The muscles usually evaluated were those of the lower limb (ie, biceps femoris, rectus femoris, vastus medialis (VM), etc.), although some studies have also evaluated the upper limb (ie, trapezius, deltoideus, etc.).

The use of different protocols does not seem to affect the TMG assessment reliability. Although it seems that the incremental protocol until the maximum stimulus has slightly higher values than the other two protocols (Table 1). As can be seen in Table 1, the incremental protocol up to the maximum stimulus has shown high reliability in Tc and Dm in professional cyclists, in elite kayakers men and women and in professional footballers. In the same way, the incremental protocol until reaching the "plateau" has shown a high reliability for Dm and Tc in team sports players and in combat sports athletes. A high reliability is also obtained with the single or some stimulus to concrete intensities in soccer players.

Athletes´ stimulus response

TMG has been used to measure the muscle response to different stimuli. Several works have focused their study

Table 1 TMG protocols used in scientific literature

Protocol	Description	Study (year)	ICC	Sample
Incremental until reaching maximum stimulus	It starts with an intensity of 20–30 mA and increases progressively in 10 mA or in 5 mA until reaching the maximal stimulator output (110 mA).	García-García et al[7]	0.98[b]–0.97[a]	Professional soccer players
		García-García et al[9]	0.97[b]–0.99[a]	
		García-García[15]	-	Professional cyclists
		García-García et al[16]	-	
		García-García et al[17]	0.92[b]–0.97[a]	
		García-García et al[13]	0.97–0.99	
		García-García et al[18]	0.94–0.96	Elite kayakers
Incremental until reaching "plateau"	It starts with an intensity of 20 mA- 30 mA and increases progressively, generally in 10 mA until the Dm suffers a descent or a flattening of the curve called "plateau"	Alvarez-Diaz et al[19]	-	Soccer players
		Loturco et al[20]	-	Professional soccer players
		Gil et al[21]	-	
		Loturco et al[22]	-	Elite athletes[c]
		Giovanelli et al[12]	-	Mountain marathon runners
		de Paula Simola et al[11]	-	Cyclists strength athletes
		Wiewelhove et al[10]	0.92–0.95[a] 0.91–0.94[b]	Elite Juniors tennis players
A single or some stimulis at specific intensities	A single concrete intensity stimulus is applied and a only displacement-time curve is obtained	Rey et al[23]	-	Soccer players
		Rey et al[24]	-	
		Rey et al[8]	0.86[b]–0.95[a]	
		García-Manso et al[25]	-	Ultraendurance triathletes
		Rodríguez-Ruiz et al[26]	-	Elite volleyball players
		Rodríguez-Ruiz et al[27]	-	

Notes: [a]Dm; [b]Tc; [c]jumper, runners, throwers.
Abbreviation: ICC: Intraclass correlation coefficient. Confidence Interval 95%.

on the competition stimuli effect. After running a marathon or a mountain race the parameters related to time (Vc, Tc, Ts, Tr, Td) decrease while the radial muscle belly displacement (Dm) increases. This means a reduction of muscular stiffness and an increase of neuromuscular fatigue.[12,25,29,30] Very similar results are obtained with surfers after a bodyboard competition.[30] These findings suggest that mountain runners could improve their performance through strength training[12] as well as ironman athletes (Table 2).[25]

On the other hand, recovery stimuli effects on muscle properties have been evaluated (Table 2). A cold water immersion protocol (4x4 min at 4 ºC) in lower limbs of semi-professional players entails a decrease in Dm and an increase in response and contraction speed.[31] Though, no differences in contractile properties between elite soccer players who have worn or not a kinesiotape bandage for 3 days.[32]

Regarding the sports practice stimuli, a tumbling session produces a reduction in Tc and in Td of gymnasts' biceps femoris (BF), without affecting the same way to the rectus femoris (RF).[33,34] Also in relation with gymnasts, an increase in Vr, Ts and a decrease in Dm (increase in stiffness) and Tr was determined in the BF of young gymnasts after performing a muscle stretching session through static-stretching and contract-relax. These changes were more marked with the contract-relax method (Table 2).[35]

Concerning to resistance stimuli (Table 2), a 6-day running-based HIIT-microcycle with a total of 11 sessions provokes an increase in the Tc of RF and the BF on male and female team sport athletes without any differences in the Dm.[36] However, there are no changes in junior tennis players after a 4-day HIIT microcycle, despite having significantly ($p<0.001$) reduced performance.[10] The effect of strength training stimuli during a short period of time has also been evaluated with TMG.[37] The results suggest that TMG can detect fatigue caused by high-resistance strength training in combat sports and intermittent game sports, since muscle contractile properties (ie, Dm, Vc) are reduced in the same way as performance indicators (ie, 1RM, CMJ, etc.). In this sense, it has also been reported that the changes in Dm, Tc and Vc after a 6-day intensified strength training microcycle distinguishes between athletes trained in strength or endurance, and ensure regular monitoring of athletes´ fatigue and recovery status.

The sports practice surface has also been used as external stimuli to evaluate its influence on the contractile properties measured through TMG. Specifically, the RF and BF have been evaluated performing tests over different sports surfaces.[38,39] In female amateur rugby players the Tc and Dm values in RF after performing a repeated-sprint ability shuttle test on sand and natural grass were higher in sand than in natural grass, while in BF no significant differences were found between both surfaces (Table 2).[38] However, no significant differences were found in amateur soccer players neuromuscular responses between artificial turf and natural grass after completing three bouts of soccer simulation protocol on each surface.[39] On the other hand, the changes in muscle mechanics in vastus lateralis (VL), RF, VM, BF and gastrocnemius medialis (GM) after a training protocol in three different elastic platforms (gymnastics floor, tumbling track and trampolining) showed that the trampolining fatigue levels and recovery time were higher in VM and BF than in gymnastics floor and tumbling .[40]

In summary, the TMG seems to be useful to determine muscle contractile properties changes after competition, training and recovery stimulus. These changes can be related to muscle fatigue which would help to decide the athlete's next training load orientation. In addition, TMG can also be useful to check the surface muscle fatigue influence in which the sports activity is carried out, observing that softer surfaces affect fatigue and recovery time in a greater extent after exertion, while it seems that sports practice on artificial turf does not cause greater fatigue than natural grass.

Training period and/or competition effect

TMG has also been used to measure muscle contractile properties changes during training periods. The purpose of these measurements has been to determine the effect of certain training loads and competitions during a mesocycle or the season.

If a mesocycle is taken as reference (training period where an objective of acute training effect has been reached), the soccer players have been the athletes who have received the most attention (Table 2). A 6-week isometric-concentric strength training mesocycle produces a decrease in Tc and an increase in Dm in the RF of young soccer players, whereas if it is only a concentric strength training mesocycle produces the opposite effect.[46] Professional soccer players also seem to have changes of muscles contractile properties with trainings and competitions. For example, they decrease their Vc in the BF and RF muscles together with a decrease in their sprint speed, both linear and with change of direction, after performing an 8-week endurance and strength-power training period,

Table 2 Characteristics of the studies that assessed specific muscle performance effects

Study (year)	Sample (n)	Mean Age ± SD (years)	Muscle Performance/ Effect/Exercise assessed	Muscles	Results	Conclusions
de Hoyo et al[32]	18 elite soccer players	18.20±2.45	Power output, Countermovement Jump and 10-m-Sprint Test with RF Kinesio taping	VL and VM of the dominant limb	↑performance test ↑ Tr in VM and VL with Kinesio ↓ Ts in VL	Kinesio taping does not produce a short-term improvement in muscle performance
de Paula Simona et al[11]	25 male (14 experienced strength athletes +11 well-trained male cyclists)	Strength: 24.1±2.0 Cyclists: 25.5±4.8	6-day intensive training (11 sessions of strength + endurance)	VL of the dominant lower limb	↓ in Dm, V_{10}, and V_{90} in strength athletes ↓ only in Dm in cyclists ↑ correlation (r =0.878) between Tc and muscle fiber type	Dm, V_{10}, and V_{90} are able to detect fatigue after intensive strenght training while only Dm seems to be sensitive after intensive endurance training
Díez-Vega et al[41]	16 professional female volleyball players	20.32±1.68	4 months of training and physical conditioning	VM, FR, VL, BF and ST	↑in Vrn in all muscles except VM in both limbs were Vrn was maintained Only Vrn*	Mechanical adaptations in VL are related to the requirements of volleyball
Díez-Vega et al[52]	16 professional female volleyball players	20.32±1.68	4 months of training and physical conditioning	VM, FR, VL and BF	Changes in both in Dm and Tc in all muslces	TMG is enough sensitive to detect changes in volleybal
García-García[15]	10 profesional road cycling	27.5±5.5	VO2max cycling test	VM, VL, RF and BF	Positive correlations between: VO2max and Dm of RF and BF Wmax and Dm of BF	Dm of BF and RF is related to the performance of a bicycle test

(*Continued*)

Table 2 (Continued).

Study (year)	Sample (n)	Mean Age ± SD (years)	Muscle Performance/ Effect/Exercise assessed	Muscles	Results	Conclusions
García-García at al[16]	10 professionals road cyclists	27.5±5.5	Cycling Season (preparatory period and Competitive period)	VM, VL, RF an BF	↑in Tc between preparatory and competitive period in VM, VL and left RF ↓ in TC of BF ↓ in Dm in competitive period in all muscle excep left VM Differences between Tc values in all muscles for both periods*	Differences between the knee extensors (↑Tc) and the knee flexor (↓Tc) TMG can help to control the training load, provide training effect information, asymmetries or muscle imbalances.
García-García at al[7]	37 subjects (21 professional soccer player +16 CG)	Soccer players: 27.2±3.3 Non-soccer players: 22.2±1.9	10-week soccer training	VM, VL, RF and BF	↓ in Tc of VM, VL and RF ↓ in Dm of VM and RF ↑ in Dm of BF ↓ in Td and Tr of VL and RF ↑ in Td of BF	Tc, Td and Dm apperar to be more sensitive to soccer players neuromuscular changes
García-García[13]	50 elite cyclists	19.7±2.4	Maximal incremental cycling test	VM, VL, RF and BF	Wmax related: ↑ in Tc of RF and Dm of VM and VL ↓in Vrn of BF	TMG parameters can partially explain the performance in a specific cycling test
García-Manso et al[31]	12 professionals soccer players	25.89±5.86	Cold-water immersions	VL of the dominant leg	↓in Dm* ↓in Vd and Vc ↑ in Ts and Tr when exposure to cold water is prolonged.	↑ muscle stiffness ↓in response velocity and contraction velocity
García-Manso et al[25]	19 male triathletes	37.9±7.1	Ultraendurance triathlon	RF and BF	↑ in Tc, Dm and Tr of BF* ↓ in Td of RF*	Large loss in contractile capacity reflected in changes in the neuromuscular response

(*Continued*)

Table 2 (Continued).

Study (year)	Sample (n)	Mean Age ± SD (years)	Muscle Performance/ Effect/Exercise assessed	Muscles	Results	Conclusions
García-Manso et al[42]	16 subjects accustomed to strength training	21.1±2.6	Arm-curl with bar: HV and HL	BB	1° set ↑ Vc and ↓in Tr, Ts and Dm of HL and HL ↑ Siffness in HV ↓Stiffness in HL 3 first sets	HL firsts to show fatigue
García-Manso et al[35]	10 young female gymnasts	13.2±1.8	Stretching protocols: contract-relax and static-stretching.	BF of the dominant leg	↑ in velocity of deformation, Stiffness and Ts ↓ in Tr ↓V_{3mm} after stretching	Both protocols similar responses in evaluated parameters
Gil et al[21]	20 elite soccer players	23.3±4.8	Countermovement jump, drop jump and sprint test	RF and BF	↓ in Dm of BF and RF in higher contact time ↓ in Dm of BF in higher strength index No correlations between TMG and height of jumps and sprints velocity	Moderate association between TMG and factors linked to a stretch-hortening cycle related task performance
Giovanelli et al[12]	25 male runners	42.8±9.9	Uphill marathon	VL	↓ in Tc, Ts, Tr and Td ↑ in Dm	↓muscle stiffness ↑muslce sensibility to the electrical stimulus
Gutierrez-Vargas et al[29]	18 marathon runners	35.6±6.9	Marathon race	RF and VM	↑ in Dm and Tc of RF* Smaller effects in VM Linear correlation between the Δ% of Tc in RF and CPK	↓ in lower-limb stiffness and high rates of neuromuscular fatigue accompanied by several products of muscle damage

(*Continued*)

Table 2 (Continued).

Study (year)	Sample (n)	Mean Age ± SD (years)	Muscle Performance/ Effect/Exercise assessed	Muscles	Results	Conclusions
López-Fernández et al[39]	16 amateur soccer players	22.17±3.43	Soccer simulation protocol in two surfaces	RF and BF	↓ in Tr of RF on natural grass ↓ in Ts of RF and Ts and Tr of BF on artificial turf ↑ in Tc of BF on artificial turf No significant differences between both surfaces	Artificial turf does not cause greater muscular fatigue than natural grass in soccer players
Loturco et al[20]	22 male elite soccer players	23.8±4.2	8-week training period	RF and BF from dominant leg	↓in BF and comparing pre- and post-tests ↑ in Tc and Td and ↓in Dm and Vc of RF	Vc is capable of detecting functional changes in the muscle mechanical properties
Loturco et al[22]	41 elite track and field athletes (22 power athletes, 19 endurance)	Power: 27.2±3.6 Endurance: 27.1±6.9	Squat jump, countermovement jump and drop jump	RF and BF	↓ in Tc, Dm and TD in power athletes ↑ in performance in jumps in power athletes	Significant correlations between TMG values and vertical jumping ability in elite athletes
Murray et al[43]	12 elite squash players	14.2±1.4	Foam Roller	Anterior thigh of the treated leg	No effect on Tc, Dm or Td	No effect on muscle contractility marckers
Raeder et al[37]	23 (14 male and 9 female) strength-trained athletes of combat and intermittent game sports	Men: 24.1±2.0 Women: 25.4±1.9	6-days intensified strength training	VM	↓ Dm and V90 after training period* Td and Tc remained unaffected	Male athletes fatigued greater Dm and V90 remained reduced following three days
Rey et al[23]	62 Spanish male professional soccer players	26.9±4.9	Quadriceps flexibility and passive straight leg raise	RF and BF dominant leg	↑in Dm of RF in higher quadriceps flexibility No correlations between TMG and hamstrings flexibility	Relationships between TMG parameters and flexibility in soccer players are not clear

(Continued)

Table 2 (Continued).

Study (year)	Sample (n)	Mean Age ± SD (years)	Muscle Performance/ Effect/Exercise assessed	Muscles	Results	Conclusions
Rojas-Barrionuevo et al[33]	12 high-performance male gymnasts	20.6±2.6	Tumbling session	GM, VL, RF, VM, BF	↓Td and Tc values in all muscle groups Max Dm in VM and RF at 15′ ↓ VL, VM and GM values during the first 30 mins	TMG allows estimating the states of activation-enhancing of the musculature responsible of jumping in tumblers
Rojas-Barrionuevo et al[40]	14 high-performance male gymnasts	20.7±3.1	Training protocol in three surfaces (trampoline, tumbling and gymnastics floor)	VL, VM, BF, RF, GM	↑ fatigue levels and recovery time in VM and BF in trampoline	The muscle response varies in a different way according to the gymnastic surface used
Rojas-Valverde et al[44]	10 male professional soccer players	27.78±2.87	4 official matches	RF	↓ in Tc and ↑ in Dm during championship	As the season progresses TMG is sensitive to changes in response to physical training
Rodriguez-Matoso et al[30]	11 highly experienced male body boarders	28.17±2.89	High-level bodyboard competition	RF, VL, VM, BF and ST	↓ in Ts of RF, VL, VM and ST in both legs ↓ in Tr of VM ↑ in Dm of all muscles analysed ↑in Vrn of right RF and left ST*	Performance causes fatigue in the knee extensor and flexor muscles.
Peterson & Quiggle[45]	5 female Division I National Collegiate Athletics Association basketball players	20±1.0	20-week training	RF, BF and AL	No significantly differents in Tc and Dm in weekly values Correlation between Tc and external measures of IMA™*	TMG may be better suited for detecting internal load alterations from relative external load
Rusu et al[46]	30 junior soccer players	16±0.4	6-week training	RF	↓ in Tc of EG ↑in Tc of CG ↑ in Dm of EG ↓ in Dm of CG	↑ in muscle tone in EG ↓Tc correlated to an↑ in Dm

(*Continued*)

Table 2 (Continued).

Study (year)	Sample (n)	Mean Age ± SD (years)	Muscle Performance/ Effect/Exercise assessed	Muscles	Results	Conclusions
Ubago et al[38]	15 female amateur rugby players	23.4±4.42	Repeated-Sprint ability shuttle test	RF and BF	↑ in Tc and Dm of RF in sand with regard natural grass	Repetitive-sprint-actions on sand regarding the natural grass produces higher levels of muscle fatigue on RF but not on BF
Valenzuela et al[47]	14 Olympic women's Rugby Sevens team	27±5	Wingate test	VM, RF and VL	↓in Dm, Vd and Td of VL in higher PPO	TMG parameters of VL were strongly related to the power production capacity
Wiewelhove et al[36]	22 (11 males and 11 females) well-trained team sport athletes	23.0±2.7	6-day running-based HIIT	RF and BF	↓in Tc in both muscles* Dm was unaltered	Tc of the RF and BF may be a potential marker for monitoring fatigue and recovery
Wiewelhove et al[10]	14 male junior tennis players	14.9±1.2	4-day HIIT	RF of the dominant limb	No changes during the study in Dm, Tc, Ts and Td	TMG parameters were not sensitive enough to detect changes in elite youth athletes
Zubac et al[50]	10 male elite kickboxing athletes	22.1±4.1	2-weeks tapering period by gradual body-mass loss	VL, VM AND BF of dominant leg	↓ in Tc of BF and VL ↓ in Dm of BF There is a moderate association between TC and Creatine kinase activity	TMG could be used in the tapering period to check the muscle fatigue level

Note: *p-value<0.05.

Abbreviations: BB, biceps brachii; VL, vastus lateralis; VM, vastus medialis; RF, rectus femoris; ST, semitendinosus; BF, biceps femoris; AL, adductor longus; GM, gastrocnemius medialis; TA, tibialis anterior; HV, high volume; HL, high load; Dm, maximal displacement; Tc, contraction time; Td, delay time; Ts, sustained time; Tr, half-relaxation time; Vrn, normalized response speed; Vd, velocity of muscle deformation at the onset of contraction (10% Dm); Vc, velocity of the mean contraction observed between 10% Dm and 90% Dm ($Dm/dt); V_{3mm},speed of response at 3 mm deformation; V_{10} and V_{90}, rate of deformation development until 10% Dm (10%Dm/Δtime) and 90% Dm (90%Dm/Δtime; CPK, creatine phosphokinase; EG, experimental group; CG, control group.

between two consecutive official tournaments,[20] suggesting to these authors that Vc can be used to monitor negative specific-soccer training effects related to potential impairments in maximum speed. In this line, professional soccer players in-season changes have been evaluated in two separated moments by 10-weeks of speed and strength training and their corresponding matches.[7] The results show a severe decrease in Tc, Dm and Td of the knee extensors and an increase in the Dm and Td of the knee flexors.

Another sport that has received special attention has been volleyball. The Vrn of VL of professional volleyball players has shown a substantial improvement after 4 months of training and physical conditioning.[41] In addition, it seems that the training adaptations achieved in these female volleyball players are different on every muscle assessed.[48]

On the other hand, if the effect of a training season on muscle contractile properties is taken as reference (Table 2), Tc and Dm parameters seem to be useful for monitoring the effect that physical training has on professional soccer players throughout the season.[44] It has also been pointed out that the Tc parameter correlates moderately and positively with the external load measured with accelerometry performed by basketball players throughout the season.[45] While Tc and Dm do not vary significantly from week to week, they do seem to have throughout the season some explanatory power when they are related to external load changes. These authors suggest that when there is more than 13% change in the relative external load between weeks, the relative internal load, measured through the TMG, also changes to a large extent. In addition, Tc of the knee extensors seems to increase notably throughout the competition season, while Tc of the knee flexors decreases, and on the contrary, Dm does not vary maintaining the muscles and tendons stiffness stable.[16]

In summary, these findings suggest that the TMG parameters can be useful to control and individualize the athletes training load from different sports disciplines, either during a specific period or through the entire season. However, there are still few sports explored and it is necessary to continue advancing in the knowledge of the muscle contractile properties changes due to the effect of the training periods and/or the competition season.

Relationship of contractile properties with sports performance

TMG has been used to establish relationships between neuromuscular parameters and sport performance indicators. Table 2 shows the most relevant findings obtained in this field. One of the first studies that searched TMG parameter relationships with two of the most important cycling performance indicators, such as maximum power (W_{max}) and maximum consumption of oxygen (VO_2max) found a positive correlation between VO_2max and Dm of RF and BF (r=0.637 and r=0.680, p<0.05) and between Wmax and Dm of BF (r=0.652, p<0.05), suggesting that the Dm of these muscles has great importance in professional cyclist performance.[15] Also, it has been analyzed the relationships between the cyclists' power developed in an incremental test until exhaustion and TMG parameters observing correlations between W_{max} and higher values of Tc in RF and Dm in VM and VL, and lower values of Vrn in BF. The results of this work indicate that the neuromuscular parameters can predict, at least partially, the performance in an aerobic test until exhaustion in road cyclists.[13] TMG parameters have also been related to jumping performance (Table 2). A study carry out with high-level power and endurance athletes indicate that power athletes' highest performance in jumping tests is related to lower values of Tc, Dm and Td in RF and BF.[22]

TMG parameter were also associated with power-related motor tasks, such as jumping and sprinting abilities in elite soccer players, finding negative correlations between Dm of the BF and RF and contact time (r =−0.50 and r =−0.51, p<0.05, respectively) and positive correlations between Dm of the BF and reactive strength index (r =0.50, p<0.05); but there were no significant relationships between TMG parameters with jumps height and sprints speed.[21] However, it seems that TMG parameters measured in the BF and RF are not good performance predictors measured by jumping motor tasks in professional soccer players.[21]

On the other hand, soccer player's flexibility and their RF and BF mechanical properties have been related. A positive correlation between the Dm in RF and the quadriceps flexibility (r =0.516, p<0.001) has been shown; yet, there were no significant relationships between the flexibility and Tc in this same muscle, nor with the Dm and Tc of the BF.[23]

Likewise, the relationship between contractile properties and rugby player's power measured thought a Wingate Test shows negative correlations between power and Dm, Vd and Td of the VL (r =−0.75, r = −0.70 and r =−0.61, respectively), without finding significant relationships between power developed in the test and contractile properties of RF and VM.[47]

Body composition is another factor that modulates performance in sports, ie, where the athlete weight establishes the competition category. In this sense, it has been determined that elite wrestler less hydrated (<60%) at the pre-competition time showed a lower Dm and a higher Tc, in addition, Vrn was higher in more-hydrated (≥60%) for both sides of VM and VL and on the right side of BF in elite men and women wrestlers.[49] In this line, a significant Tc decrease in VL (−22.2%) and BF (−9.9%) and Dm of BF (−20.7%) has been reported in elite male kickboxing athletes after a 2-week tapering period followed by gradual body mass loss, evaluating at the beginning of the tapering period and 2 days after the competition.[50]

In summary, TMG is presented as an interesting tool to evaluate sports performance, as it is a non-invasive method and does not require physical effort from the athlete. The study's results indicate less strong relationships in situation sports (where there several technical and tactical characteristics that determine performance which are not detected in such specific evaluations) than in continuous sports with more closed skills. This seems to make the TMG to be an especially useful tool in this type of sports. It also seems that the athlete's hydration levels affect their contractile properties, so it is essential to be in optimal conditions so that sports performance is not reduced by having a lower strength capacity. However, it seems that a reduction in body mass in a controlled manner can help the athlete to face competition in optimal muscular level conditions.

Athletes´ mechanical and neuromuscular characterization

There are few studies that have characterized the muscle contractile properties of well-trained athletes from a specific sports discipline using TMG.

Soccer players have been the most studied athletes. The Tc parameter seems to show that the closer the soccer player is to the elite the lesser is Tc in lower limbs musculature, also determining that Tc in children varies strongly with age (higher Tc at puberty).[51] This parameter together with Dm and Td are modified throughout the season as a consequence of the different training loads and competitions.[7] If we compare soccer players with the healthy population, the first ones seem to present a lower Dm in RF, while they are similar in BF.[8]

On the other hand, it has been proposed the analysis of their mechanical and neuromuscular characteristics according to a specific role. It was found that the Tc of the RF was greater in the external defenders than the centrals and the goalkeepers,[8] being only the Tr of BF and the Ts of VM the ones that differs between all the positions.[9] Despite, due to the different measurement protocols used, the comparison between these data must be taken with caution. However, TMG parameters baseline values of professional soccer players at the beginning of the season have been proposed,[9] which would allow baseline values of the TMG parameters and observe the changes throughout the season. (Table 3)

Volleyball players have been another of the most studied athletes, showing in both genders a high Vrn (p<0.05) in VL and VM with respect to RF and BF. The relationship of Vrn between flexors and extensors shows greater difference (p<0.05) between females, with higher values in flexors.[26] This could be caused by possible differences in jumping biomechanics and knee stabilization. There are also significant differences in the left leg between VL and BF (p<0.05) in males and between BF and VM (p<0.05), and BF and VL (p<0.005) in females, which are typical sports adaptations.[26,52] For specific positions the Vrn (BF, RF, VM and VL), shows faster values in liberos (56.38±1.20 mm/ms) and setters (56.38±1.53 mm/ms) while for opposites (53.46 ±1.53 mm/ms) and middles (51.27±1.04 mm/ms) is lower.[27] Beach volleyball players' specialized in the second line have lower Dm (Table 3), probably due to the important isometric action of the reception position, typical of their specific role.[53]

Kayakers have also been studied, where their TMG values can also be seen in Table 3. Female elite kayakers are characterized by 34.8% more Dm, 123.7% more Tc and 11.3% more Td in trapezius (TR) muscles, while in the latissimus dorsi present 34.4% more Tc compared to non-kayaker women. However, practically no significant differences were found by gender when compared with elite male kayakers, except Td in the TR muscles of females, 19.5% lower than males.[18]

Professional cyclists have been evaluated through TMG in the preparatory and competitive periods, obtaining reference values for both periods of the season (Table 3).[15,17] These authors suggest that the Dm of RF and BF can be relevant to track the cyclists' physical shape.

The differences between strength and endurance athletes have also been explored through TMG parameters. Strength sports athletes are characterized by having a lower Tc than

Table 3 Tc, Dm, Vrn and Vc reference values in different sports modalities. Data are presented as mean (SD).

Sport	Muscle	Paper		$Tc_{(ms)}$	$Dm_{(mm)}$	Vrn (mm/s)	Vc $(mm/s)^{-1}$
Male cyclists	VM	A	PP	28.7 (5.5)	7.2 (2.3)		
A - García-García et al[16] n=10			CP	40.6 (14.4)	8.3 (1.5)		
B - García-García et al[13] n=50		B	–	22.9 (2.0)	8.3 (1.3)	35 (3)	
	VL	A	PP	28.3 (4.9)	5.8 (1.6)		
			CP	40.6 (10.2)	5.0 (1.4)		
		B	–	23.4 (2.3)	6.4 (1.3)	34 (3)	
	RF	A	PP	35.9 (6.9)	8.6 (3.0)		
			CP	45.9 (16.2)	7.4 (2.8)		
		B	–	29.0 (4.2)	8.3 (2.0)	28 (5)	
	BF	A	PP	35.9 (9.9)	6.1 (2.3)		
			CP	28.2 (5.2)	5.2 (2.3)		
		B	–	35.6 (7.9)	7.5 (2.2)	23 (4)	
Female rugby	VM			23.4 (3.4)	6.71 (0.97)		
Valenzuela et al[47] n=14	VL			21.5 (2.8)	4.68 (1.61)		
	RF			29.4 (4.1)	9.60 (2.08)		
Male tennis players	RF		D	31.3 (3.9)	8.8 (1.9)		
Wiewelhove et al[10] n=14							
Mountain marathoners	VL			25.8 (5.4)	6.6 (1.7)		
Giovanelli et al[12] n=9							
Male Tumbling gymnasts	VL			22.94 (5.15)	7.38 (2.34)	36.31 (7.18)	
Rojas-Barrionuevo et al[33] n=12	VM			22.71 (2.50)	9.17 (1.39)	35.60 (3.83)	
	RF			31.39 (6.05)	10.11 (1.61)	26.29 (4.70)	
	GM			28.43 (10.64)	3.95 (1.12)	31.27 (10.75)	
Bodyboarders	VL		Left		5.3 (1.6)	31.6 (1.9)	
Rodriguez-Matoso et al[30] n=11			Right		4.7 (1.4)	29.4 (4.1)	
	VM		Left		6.8 (1.6)	28.5 (5.4)	
			Right		6.7 (2.19)	30.1 (5.8)	
	RF		Left		7.4 (2.4)	24.1 (4.2)	
			Right		8.5 (2.2)	24.3 (3.2)	
	BF		Left		6.6 (2.5)	22.4 (7.4)	
			Right		4.8 (2.3)	30.6 (10.8)	
	ST		Left		9.2 (3.5)	17.1 (2.2)	
			Right		7.2 (2.5)	20.6 (4,5)	

(*Continued*)

Table 3 (Continued).

Sport	Muscle	Paper		$Tc_{(ms)}$	$Dm_{(mm)}$	Vrn (mm/s)	Vc $(mm/s)^{-1}$
Ulta-endurance triathlon	BF		Left	59.7	6.8		
García-Manso et al[25] n=19			Right	26.7	4.7		
Acrobatic gymnastics	VM			24.09 (4.53)	8.55 (1.39)	34.2 (6.05)	
Vernetta-Santana et al[34] n=11	VL			23.34 (3.1)	8.43 (2.21)	34.80 (4.52)	
	RF			30.25 (6.73)	10.00 (3.7)	27.58 (5.70)	
	BF			36.38 (1.50)	9.0 (2.01)	23.85 (6.21)	
	GM			22.51 (3.45)	3.74 (1.28)	36.24 (5.18)	
Kayakers top-level	DL		F	15.6 (0.8)	4.4 (0.8)		
García-García et al[18]			M	16.0 (3.2)	5.2 (0.0)		
n=7 Female	TR		F	49.0 (25.4)	5.8 (1.3)		
n=4 men			M	47.8 (31.3)	8.0 (4.7)		
	LD		F	28.5 (5.4)	10.5 (4.)		
			M	25.3 (8.7)	11.6 (2.9)		
Beach volleyball	VM		Left	28.2 (15.5)	8.5 (2.0)		
men			Right	26.4 (10.3)	8.4 (1.5)		
Rodríguez-Ruiz et al[53] n=14	RF		Left	29.2 (4.7)	9.2 (3.2)		
			Right	31.3 (5.5)	9.2 (3.1)		
	VL		Left	26.3 (3.2)	5.6 (1.4)		
			Right	24.7 (4.3)	6.4 (1.1)		
	BF		Left	25.7 (15.6)	3.9 (2.4)		
			Right	24.2 (12.4)	4.3 (2.3)		
Beach volleyball	VM		Left	24.9 (10.8)	7.6 (1.2)		
women			Right	26.4 (11.1)	6.5 (2.0)		
Rodríguez-Ruiz et al[53] n=10	RF		Left	28.3 (5.8)	8.0 (2.3)		
			Right	28.7 (4.4)	8.0 (1.7)		
	VL		Left	24.6 (1.2)	5.6 (1.2)		
			Right	24.4 (2.2)	5.5 (1.0)		
	BF		Left	37.6 (17.5)	5.7 (2.7)		
			Right	32.2 (16.0)	6.4 (2.0)		
Volleyball	VM					52.99/56.67	
M/F	RF					52.24/52.29	
Rodríguez-Ruiz et al[27]	VL					59.79/61.58	
n=83 female	BF					55.28/43.10	
n=83 men							

(*Continued*)

Table 3 (Continued).

Sport	Muscle	Paper		$Tc_{(ms)}$	$Dm_{(mm)}$	Vrn (mm/s)	Vc $(mm/s)^{-1}$
Male soccer players	VM	F		25.0 (1.4)	9.1 (1.3)		0.29 (0.04)
A - Alenton-Geli et al[54] n=38		C	D	22.9 (2.0)	7.7 (1.5)		
B - Alenton-Geli et al[55] n=38			ND	22.5 (2.1)	8 (1.9)		
C - Alvarez-Diaz et al[19] n=38		K	D	25.25 (2.96)	8.29 (1.49)		
E - García-García et al[7] n=37			ND	25.45 (2.66)	9.01 (1.57)		
F - García-García et al[9] n=16		E	AT	35.2 (5.4)	8.4 (1.4)		
G - García-Manso et al[31] n=12			PP	28.7 (6.7)	7.2 (1.1)		
H – Gil et al[21] n=20		B		22.5 (2.1)	7.8 (1.7)		
I – Loturco et al[56] n=24	RF	F		30.9 (3.3)	10.4 (2.3)		0.27 (0.06)
J – Rey et al[24] n=31		C	D	26.6 (4.1)	13.6 (28.9)		
K - Rojas-Valverde et al[57] n=23			ND	27 (5.7)	8.8 (2.9)		
		I	D	27.7 (7.9)	7.99 (3.44)		0.154 (0.067)
			ND	26.7 (6.0)	7.31 (3.25)		0.140 (0.053)
		H	D	19.74 (3.16)	6.16 (1.90)		
			ND	21.27 (3.61)	6.98 (2.50)		
		K	D	29.95 (2.32)	8.42 (3.15)		
			ND	30.84 (5.17)	9.49 (2.43)		
		E	AT	38.3 (3.3)	9.8 (2.4)		
			PP	31.5 (5.8)	8.6 (2.4)		
		J		28.2 (2.6)	11.1 (3.9)		
				29.1 (4.0)	11.2 (2.3)		
		B		26.8 (59)	11.2 (20.5)		
	VL	F		26.1 (3.0)	7.2 (2.2)		0.22 (0.07)
		C	D	22.1 (2.3)	5.5 (1.6)		
			ND	23 (3.2)	6 (2.3)		
		K	D	24.68 (4.0)	7.29 (2.47)		
			ND	23.70 (4.0)	7.29 (2.51)		
		E	AT	36.9 (4.4)	5.9 (1.5)		
			PP	28.5 (7.2)	5.5 (1.8)		
		B		22.6 (2.8)	5.8 (2)		
		G		26.31 (3.04)	5.12 (2.27)		22.08 (9.63)

(*Continued*)

Table 3 (Continued).

Sport	Muscle	Paper		$Tc_{(ms)}$	$Dm_{(mm)}$	Vrn (mm/s)	Vc $(mm/s)^{-1}$
	BF	F		34.5 (6.6)	7.0 (1.7)		0.16 (0.03)
		C	D	24.9 (6.5)	4.7 (2.1)		
			ND	24.2 (7.0)	4.5 (2.2)		
		I	D	19.2 (3.4)	3.02 (1.64)		0.074 (0.040)
			ND	19.8 (5.5)	3.10 (2.04)		0.073 (0.044)
		H	D	29.53 (11.09)	7.18 (3.39)		
			ND	26.71 (9.89)	6.21 (3.0)		
		K	D	25.96 (6.37)	5.67 (1.88)		
			ND	27.88 (6.85)	6.56 (2.54)		
		E	AT	28.8 (5.9)	5.3 (1)		
			PP	29.8 (4.6)	6.6 (1.9)		
		J		26.7 (4.7)	5.5 (1.7)		
				26.9 (3.6)	5.3 (1.8)		
		B		24.6 (6.7)	4.6 (2.1)		
	ST	C	D	35.8 (5.89)	9.4 (2.7)		
			ND	35.1 (6.2)	9.7 (2.8)		
	GM	C	D	22.3 (2.4)	3.1 (1)		
			ND	21.8 (2.7)	3 (1)		
		K	D	25.91 (4.63)	3.61 (1.61)		
			ND	25.42 (3.65)	3.15 (1.09)		
		A		22.1 (2.5)	3.1 (1)		
	GL	C	D	20.7 (2.4)	3.7 (1.3)		
			ND	21.5 (5.5)	3.8 (1.3)		
		K	D	21.63 (2.92)	3.86 (1.38)		
			ND	22.92 (3.33)	4.17 (1.38)		
		A		21.1 (4.3)	3.7 (1.3)		
	AL	K	D	19.85 (3.89)	3.66 (1.87)		
			ND	19.30 (4.08)	3.73 (2.48)		
	ST	B		35.4 (6)	9.6 (2.7)		

Abbreviations: SD, Standard deviation; Tc, contraction time; Dm, maximal displacement; Vrn, normalized response speed; VM, vastus medialis; PP, preparation period; CP, competition period; VL, vastus lateralis; RF, rectus femoris; BF, biceps femoris; GM, gastrocnemius medialis; DL, deltoideus; F, female; M, male; TR, trapezius; LD, latissimus dorsi; ST, semitendinosus; D, dominant side; ND, non-dominant side; GL, gastrocnemius lateralis; AL, adductor longus.

$$\textbf{Ls} = 0,1 \cdot \frac{\min(Tdr \cdot Tdl)}{\max(Tdr \cdot Tdl)} + 0,6 \cdot \frac{\min(Tcr \cdot Tcl)}{\max(Tcr \cdot Tcl)} + 0,1 \cdot \frac{\min(Tsr \cdot Tsl)}{\max(Tsr \cdot Tsl)} + 0,2 \cdot \frac{\min(Dmr \cdot Dml)}{\max(Dmr \cdot Dml)}$$

$$\textbf{Fs} = 0,1 \cdot \frac{\min(average(Tdr1,Tdr2),average(Tdr3,Tdr4))}{\max(average(Tdr1,Tdr2),average(Tdr3,Tdr4))} + 0,8 \cdot \frac{\min(average(Tcr1,Tcr2),average(Tcr3,Tcr4))}{\max(average(Tcr1,Tcr2),average(Tcr3,Tcr4))} + 0,1 \cdot \frac{\min(average(Tsr1,Tsr2),average(Tsr3,Tsr4))}{\max(average(Tsr1,Tsr2),average(Tsr3,Tsr4))}$$

Figure 2 Algorithm implemented by the TMG-BMC tensomyography® software to determine the lateral (LS) and functional symmetry (FS).

those of resistance sports in RF (22.9±4.0 and 18.3±2.8 ms) and BF (19.4±3.3 and 14.3±2.3 ms).[11,22]

TMG parameters as symmetry measure

TMG allows a symmetry measure comparing the superficial muscles contractile properties between the right and left side (lateral symmetry) and between the muscles that surround a joint (functional symmetry). To establish a measurement based on the TMG parameters, an algorithm has been developed (Figure 2) implemented in the TMG-BCM tensiomyography® software.

There have been several sports disciplines where the athletes' muscle symmetry has been analyzed with this technique. Lateral asymmetries were found in the Dm and in the Vrn of VL and VM, RF and BF of volleyball players.[26] In addition, TMG has shown excellent reproducibility of lateral symmetry in these athletes.[58] In professional cyclists it has been reported that there are no significant differences in VL, VM, RF and BF between the right side and left the side, in terms of Dm and Tc.[16,17] Similarly, no significant differences have been found between right and left in soccer players.[9,14,19,21,56,57] Furthermore, variations in LS in MV (92.5±2.7% vs 85.1±8.9% vs 89±6.4%, p=0.009) and RF (84.3±9% vs 90.2±6.3% vs 86.7±6.9%, p=0.05) were found in professional soccer players during the three periods of the season, not detecting a variation pattern or asymmetry.[14]

On the contrary, it has also been suggested that soccer players show significant differences in some TMG parameters.[56,57] It was determined that the dominant leg prevails over the non-dominant in Dm of BF, RF and tibialis anterior as in Ts of the adductor longus, considering necessary an individualized analysis of each athlete.[57]

Top-level women kayakers have reported a possible lateral asymmetry detected in the TR (62.8±17.1%) through the algorithm of Figure 2, being this percentage much higher in men (82.5±16.2%).[18]

The functional symmetry determined through the algorithm of Figure 2 has been much less explored in the literature reviewed. In professional cyclists, 73.2±8.8% has been reported for the knee joint in the preparatory period, which is considered to be insufficient.[17]

Finally, a recent research find no relationship between the symmetry percentage detected with TMG and other symmetry tests such as CMJ and SJ (unilateral/bilateral), which seems to indicate that they could be evaluating different parameters that affect muscle symmetry in a different way, being able to be the athlete very symmetric in some capacities and not so much in others.[56]

In summary, there does not seem to be a clear criterion to determine athlete's asymmetry using the TMG-BCM tensiomyography® algorithm. It has been suggested as adequate >80% in lateral symmetry[17] and >65% in functional symmetry.[57] Thus, more research is needed to determine athletes symmetry percentage using this algorithm and explore their relationship with other symmetry tests and their predictive capacity on performance and sports injuries.

Recovery after exercise

On the other hand, TMG has been used in the field of exercise (Table 2) as a tool to detect mechanical fatigue between high-volume and high-load resistance exercises showing subtle differences among them.[42] It has also been used to examine the contractibility effects of Foam Rolling showing no statistically significant effects,[43] being of great help to the coach to monitor muscle adaptation more often at different training or competition periods during the year.[59]

Injury prevention

TMG has been used in several studies (Table 4)[54,55,60] as a useful tool in the prevention of injuries which may have

Table 4 Characteristics of the studies that assessed injuries prevention and rehabilitation

Study (year)	Sample (n)	Mean Age ± SD	Injury	Muscle Group	Results	Conclusions
Álvarez-Diaz et al[60]	40 competitive Soccer players	22.3±6.9	ACLR	VM, VL, RF, ST, BF, GM and GL	↓ Ts and Tr for VL, Tc for RF and Tc and Dm for BF in both sides ↓Tc for VL, ST and GM, Tr for GL and Td for GL in injured side ↑Tr for VM and Ts for Gm in injured side ↓Tr for RF and Td for BF uninjured side ↑% SM in VM, VL, RF, and GM	↑ resistance to fatigue in VL, VM and RF in both sides ↑ Muscle contraction velocity and tone in BF, VL, VM and RF in both sides Changes in gastrocnemius only in the injury side ↑% SM between both sides
Alvarez-Diaz et al[61]	40 Competitive male soccer players	22.3±6.8	ACL	VM, VL, RF, ST, BF, GM and GL	↑Tc for VM, VL, RF ↑Tc and Dm for BF ↑Tc, Tr and Dm and ↓Ts for GM for GM ↑Tc for VM, VL, RF, ST, BF	The vastbmajority of TMG parameters were higher in the injured compared to the control group. Effects were worst in the quadriceps and GM compared to the hamstrings and GL
Alentorn-Geli et al[55]	40 soccer players	22.3±6.8	Complete ACL tear	VM, VL, RF, ST and BF	↑Tr for VL, Tc for FR, Tc, Tr and Ts for RF, and Tr Dm for BF in injury side	↓resistance to fatigue and muscle stiffness (ST and BF), may be an injury risk factor for ACL injury
Alentorn-Geli et al[54]	40 Competive male soccer players	22.3±6.8	ACL tear	GM and GL	↑Tr and Dm for GM in injured group	↓resistance to fatigue and muscle stiffness of GM GM and GL may not be an injury risk factor for ACL
Atiković et al[59]	1 artistic gymnastic Olympic medallist	19	Spinal cord injury	BF, ES, GMx, RF	95% LS for BF, 76% for ES, 92% GMx and 79% for RF	↓LS for ES and RF ↑LS for Gmx ↑values for ES and GMx
Maeda et al[62]	10 (3 men +7 women) with previus ACLR hisotry	Men: 23.9±4.4 Women: 21.6 ±3.1	ACLR	VM, VL, RF, BF	↑Dm for VM compared with non-ACLR side ↑Tr for VM and BF in both sides	↑Muscle contraction velocity and tone in antagonist could prevent ACL injury

Abbreviations: ACL, anterior cruciate ligament; ACLR, Anterior cruciate ligament reconstruction; AL: adductor longus; VM, vastus medialis; VL, vastus lateralis; RF, rectus femoris, ST, semitendinous; BF, biceps femoris; GM, gastrocnemius medialis; GL, gastrocnemius lateralis; ES, erector spinae, GMx, gluteus maximus; LS, lateral symmetry; % SM, percentage of symmetry; Dm, maximal displacement; Tc, contraction time; Td, delay time; Ts, sustained time; Tr, half-relaxation time; CG, control group.

great potential to improve the prevention and management of musculoskeletal injuries in athletes.[6]

The role of mechanical and contractile properties through TMG as risk factors for anterior cruciate ligament (ACL) injury in competitive male soccer players has been investigated concluding that decreased resistance to fatigue and muscle stiffness in the hamstring muscles may be a risk factor for ACL; also a predominant impairment in TMG characteristics in the quadriceps over the hamstrings may indicate an altered muscular co-contraction (imbalance) between both muscle groups, which might be another factor risk for ACL in this population.[55] However, gastrocnemius muscles (VM and VL) were not detected as significant risk factors for ACL injury in the same population.[54]

The effects of ACL injury on mechanical and contractile characteristics (Table 4) has been also addressed showing a decrease in contraction velocity (VM, VL, RF, semitendinosus (ST), BF and GM), in resistance to fatigue (VM, VL, RF, ST, BF and GM) and in muscle tone/stiffness (ST, BF and GM) compared to healthy control group.[60]

Injury rehabilitation

Recent insights suggest that TMG may be a promising tool for screening, diagnosis and monitoring the response to surgical treatment.[28] An ACL reconstruction and its subsequent rehabilitation can positively impact neuromuscular characteristics of the quadriceps and hamstrings,[61] where the presence of strength and symmetry deficits in the VM and BF may need for long-term training postoperatively.[62]

The usefulness of this method has also been demonstrated (Table 4) after studying for 4 months a high-level gymnast rehabilitation process concluding that TMG can be used as a further contribution to optimizing the process of rehabilitation and physical recovery of athletes with muscle injuries.[59]

Conclusions

TMG presents a good reliability to find the displacement-time curve with the greater Dm in the evaluated muscle. This technique has been used to characterize the muscles contractile properties of athletes from specific sports disciplines to determine the changes that occur in the muscle contractile properties after stimuli of competitions, trainings or recovery. As well to control training effects that occur during a specific period or throughout the competition season. In addition, it has also been used as a lateral and functional symmetry measure and as a monitoring tool for injury prevention and recovery. However, despite showing some usefulness, there are still very few well-characterized sports and it is really necessary to continue advancing in the knowledge of the behavior manifested by the contractile properties due to the training, competition and injuries effects, even in the knowledge of the parameters interpretation obtained through the TMG.

Also, it is necessary to bear in mind that some of the limitations in the use of the TMG will be given by the assessment of the muscles contractile properties exclusively through an isometric contraction. In sports where the mechanical model of performance is determined by a stretch-shortening cycle (ie, team sports, jumps in athletics, etc.), or by a concentric contraction (cycling) it may not be specific enough. In addition, the limited intensity of the stimulus (110 mA) could suppose another limitation to explore the maximum Dm or the Tc in well-trained athletes from sports that demand speed and reactivity, since the fast fibers might not be stimulated at these intensities. Finally, in order to ensure a high relative and absolute reliability, it is necessary for the evaluator to be an expert, which means that he has carried out a good number of previous evaluations.

Disclosure

The authors report no conflicts of interest in this work.

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