Age-related differences in mechanical and functional properties of knee flexor-extensor musculature

Diferencias asociadas a la edad en las propiedades mecánicas y funcionales de la musculatura flexo-extensora de rodilla

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Received: 18-05-25
Accepted: 16-08-25

How to cite in APA

Parodi-Feye, A., Cappuccio-Díaz, Álvaro, & Magallanes-Mira, C. (2025). Age-related differences in mechanical and functional properties of knee flexor-extensor musculature. *Retos, 72*, 502-513. https://doi.org/10.47197/retos.v72.116164

Abstract

Introduction and Objective. The decline in muscle quality (MQ) with aging is associated with increased morbidity and mortality. Therefore, characterizing MQ in older adults (OA) is essential. The objective of this study was to characterize and compare MQ indicators of knee flexor-extensor muscles across different age groups.
Methodology. A total of 66 volunteers of both sexes were divided into three groups: young adults (22.1 ± 1.6 years), adults (49.9 ± 8.3 years), and older adults (71.0 ± 6.4 years). Maximum radial displacement (Dm) and contraction time (Tc) of the Rectus Femoris (RF) and Biceps Femoris (BF) were assessed, along with dynamometric variables of knee flexor-extensor isometric strength and power. Group differences were analyzed using ANOVA, and correlations between tensiomyographic and dynamometric variables were examined.
Results. Aging was associated with a decrease ($p < 0.05$) in isometric strength and power for both knee extension and flexion, and with a significant increase ($p < 0.05$) in RF Tc and a tendency to increase in BF Tc. Dm values of both muscles did not show significant differences ($p > 0.05$) between groups. For knee extension, a weak negative correlation ($p < 0.05$) was observed between both strength measures and RF Tc, and a weak positive correlation between these measures and RF Dm. For knee flexion, weak negative correlations ($p < 0.05$) were found between both strength modalities and BF Tc, with no correlations with BF Dm.
Conclusions. Tensiomyographic variables, particularly Dm, do not appear to be sensitive indicators for detecting age-related declines in MQ when analyzed in isolation. Additional indicators may be necessary to improve the accuracy of MQ assessment in older adults.

Keywords

Muscle quality; older adults; aging; knee flexor-extensor capacity.

Resumen

Introducción y Objetivo. La pérdida de calidad muscular (CM) con el envejecimiento está asociada a un aumento de la morbi-mortalidad. Por lo tanto, su caracterización en adultos mayores (AM) resulta esencial. El objetivo de este estudio fue caracterizar y comparar indicadores de CM de músculos flexo-extensores de rodilla en diferentes grupos etarios.
Metodología. Sesenta y seis voluntarios de ambos sexos se dividieron en tres grupos: adultos jóvenes (22,1 ± 1,6 años), adultos (49,9 ± 8,3 años) y adultos mayores (71,0 ± 6,4 años). Se evaluaron el desplazamiento radial máximo (Dm) y el tiempo de contracción (Tc) del recto femoral (RF) y bíceps femoral (BF), junto con las variables dinamométricas de fuerza isométrica y potencia máximas de flexo-extensión de rodilla. Las diferencias entre grupos se evaluaron mediante ANOVA, y se analizaron las correlaciones entre los dos tipos de variable.
Resultados. El envejecimiento se asoció con una disminución ($p < 0,05$) de la fuerza isométrica y la potencia para la extensión y flexión, con un aumento significativo ($p < 0,05$) del Tc RF y una tendencia al aumento del Tc BF. La Dm de ambos músculos no mostró diferencias ($p > 0,05$) entre los grupos. Para la extensión, se observó una correlación negativa débil ($p < 0,05$) entre ambas modalidades de fuerza y el Tc RF, y una correlación positiva débil entre estas medidas y el Dm RF. Para la flexión, se encontraron correlaciones negativas débiles ($p < 0,05$) entre ambas modalidades de fuerza y el Tc BF, sin correlaciones con el Dm BF.
Conclusiones.Las variables tensiomiográficas, en particular Dm, no parecen ser sensibles para detectar el deterioro de CM cuando se analizan de forma aislada. Sería necesario incorporar nuevos indicadores para mejorar la precisión de la evaluación.

Palabras clave

Calidad muscular; adultos mayores; envejecimiento; capacidad flexo-extensora de rodilla.

Introduction

The World Health Organization has recognized population aging as one of the most pressing public health challenges of the 21st century (Frontera, 2017). Old age is associated with loss of muscle mass and strength, a consequence of structural and functional changes of the muscle fibers. (D'Antona et al., 2003). In addition, older adults (OA; age ≥ 65 years) represent the fastest-growing demographic group (Axelrod et al., 2023). As a result, generating knowledge about the morpho-functional characteristics of the muscular system in this population becomes increasingly relevant.

The muscular system plays a fundamental role in health and well-being at all ages, with its importance being particularly evident in OA. From age 30, a progressive loss of strength is observed, averaging about 10% per decade, with an accelerated decline after age 60. In addition, from age 50, a gradual loss of muscle fibers occurs, resulting in a reduction of approximately 50% by age 80, even in highly physically active individuals (Faulkner et al., 2007). This condition, often underdiagnosed, is associated with an increased risk of falls, cognitive and metabolic disorders, loss of functional independence, and higher mortality rates (Larsson et al., 2019). In this context, the assessment of muscle quality (MQ), operationally defined as muscle strength relative to muscle mass, has become increasingly important in clinical and gerontological research, as it more accurately captures functional capacity and health status than either parameter in isolation (Fragala et al., 2015).

To address this need, tensiomyography (TMG) has emerged as a particularly suitable tool for the evaluation of MQ in OA, offering the advantages of being non-invasive, rapid, and highly reproducible (Macgregor et al., 2018; Wilson et al., 2019). Through parameters such as maximum radial displacement (Dm) and contraction time (Tc), TMG provides valuable insights into muscle composition, architecture, and the early detection of atrophic changes (Pišot et al., 2008; Šimunič et al., 2019). These characteristics make it a relevant method for monitoring neuromuscular deterioration in this population, thereby facilitating timely preventive and rehabilitative interventions (Narici & Maffulli, 2010).

Despite its potential, the current body of evidence in OA is both limited in scope and characterized by considerable methodological heterogeneity. The most recent systematic review identified only eight studies, spanning different muscles and heterogeneous clinical populations, thereby precluding meta-analytic synthesis and hindering the establishment of muscle-specific reference values (Pus et al., 2023). Notably, the review underscored critical research gaps, such as the complete absence of investigations on the Rectus Femoris (RF) in this age group, and emphasized that the relationship between Tc/Dm alterations and functional performance remains insufficiently understood. These limitations highlight the need for more studies to clarify the functional implications of TMG-derived parameters in older populations.

The purpose of the present study was to compare MQ indicators in OA, adults (AD), and young adults (YA) by assessing the TMG and dynamometric properties of the knee flexo-extensor muscles. While acknowledging the relevance of the muscular system in other regions, particular emphasis is placed on this area due to its critical role in activities that sustain functional independence, its contribution to the prevention of osteoarthritis, and its involvement in mitigating the risk of metabolic conditions such as type 2 diabetes (Mohajer et al., 2022; Pedersen & Febbraio, 2012).

Based on existing evidence, we hypothesized that older age groups would exhibit a marked decline in isometric strength and muscle power. These changes were expected to be concomitant with increased Dm, linked to muscle atrophy (Pišot et al., 2008; Šimunič et al., 2019), and prolonged Tc, associated with the loss of fast-twitch fibers (Šimunič et al., 2011). Such differences were anticipated to be particularly pronounced in OA.

Method

The present study was approved by the ethics committee of the Instituto Superior de Educación Física (ISEF), Universidad de la República, Uruguay (resolution 26/2023). It was conducted following the STROBE checklist for cross-sectional studies. The authors follow the principles outlined in the Declaration of Helsinki as revised in 2013.

Participants

Sixty-six healthy and physically active participants were divided into three groups: young adults (YA) aged 18 to 35 years, adults (AD) aged 40 to 60 years, and older adults (OA) aged ≥ 65 years. Each group consisted of 11 females and 11 males. The following inclusion criteria were applied: (i) no intense physical activity performed within 48 hours prior to the assessments; (ii) absence of pathologies affecting the morpho-functional characteristics of the muscular system being assessed; (iii) no pathologies that could be exacerbated by the efforts required in the present study; (iv) moderate or high physical activity levels (category II or III of the IPAQ questionnaire); (v) no obesity (body mass index [BMI] < 30 kg/m^2 for subjects < 65 years, BMI < 32 kg/m^2 for subjects ≥ 65 years), considering the potential effect of adipose tissue thickness on Dm (Calvo-Lobo et al., 2018); and (vi) not taking medications (such as anabolic agents, corticosteroids, muscle relaxants, or other drugs affecting neuromuscular function) that could influence the study outcomes.

Participants were instructed not to consume high-caffeine beverages at least 90 minutes before the study, as caffeine could significantly affect TMG variables (Pakosz et al., 2024). In the case of female participants, assessments were scheduled on days when they were not in the menstrual phase.

Procedure

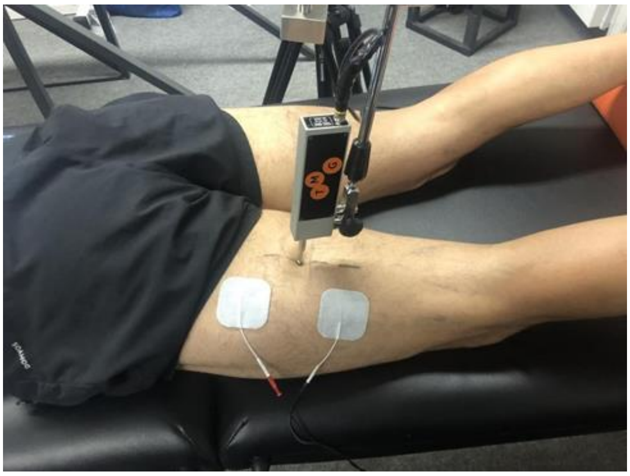
All participants read and signed an informed consent form and then completed the reduced version of the International Physical Activity Questionnaire (IPAQ). Subsequently, body mass (Bioimpedance Scale, HBF-514C, OMRON, Japan) and height (SECA model 213, Germany) were measured. Next, TMG and dynamometric assessments were performed at a standard room temperature of 23ºC.

Tensiomyographic assessment

The contractile mechanical characteristics of the Biceps Femoris (BF) and RF of both lower limbs were analyzed (TMG S2 system; EMF-Furlan and Co., Ljubljana, Slovenia). These muscles were selected because of their relevance to the gait cycle.

For BF assessment, the subject lay ventrally decubitus, with a foam wedge under the leg determining a knee flexion of 150 degrees. The sensor was placed perpendicular to the tangential plane where the muscle belly presented greater volume, directed towards its potential displacement. This point was identified by manual palpation after asking the subject to perform an isometric contraction with the knee at a 90-degree angle. After cleaning the area with 70% ethyl alcohol, the electrodes were placed symmetrically to this point, located 2.5cm distal (negative electrode) and proximal (positive electrode) to it, avoiding tendinous areas. The electrodes were positioned laterally to the sensor rather than aligned longitudinally with it. In this way, it was sought to avoid co-contraction of other adjacent muscles of the posterior thigh loggia, which could increase the Dm value (Macgregor et al., 2018) (Figure 1). Before applying the stimulus, the subject was asked to remain completely relaxed.

Figure 1. Tensiomyographic evaluation of the Biceps Femoris. The electrodes were placed lateral to the posterior surface of the thigh to avoid concomitant stimulation of other muscles in the posterior thigh loggia



The stimuli were applied gradually, starting with 20mA, with successive increments of 10mA. That intensity was selected considering that values less than 10mA can prematurely lead to a plateau in the graph (Macgregor et al., 2018). In agreement with Labata-Lezaun et al. (2023), a rest time of 10 seconds was applied between stimuli, minimizing the possible effect of fatigue and post-activation potentiation.

For the assessment of RF, the subject was placed in dorsal decubitus, with the lower limb supported on a wedge, determining a knee flexion of 120 degrees. The sensor was placed following the same criteria as for the BF, identifying the placement point based on a hip flexion effort with the knee extended. The electrode placement and stimulus application protocol were identical to that used for the BF, except the electrodes were placed in line with the sensor.

In each muscle, only the curve presenting the maximum Dm was considered for subsequent analysis. The variables considered for this study were Tc (in ms) and Dm (in mm).

Dynamometric assessment

Subsequently, peak isometric muscle strength and peak knee flexion and extension power were measured. The choice of these variables responded, in the case of the former, to its relationship with the risk of falls (Valenzuela et al., 2020) and the latter, to its link with performance in activities of daily living in OA (Narici & Maffulli, 2010). Prior to these assessments, participants performed a standardized warm-up sequence lasting approximately 10 minutes. This included joint mobility exercises for the main lower-limb joints (hip, knee, and ankle), consisting of 8 to 10 controlled repetitions per joint in each plane of motion, followed by dynamic and static stretches of the major lower-limb muscle groups, each held for approximately 5 to 8 seconds. The intensity and range of motion were adjusted to prevent fatigue and ensure safety, considering the participants' age group.

For the test, the participants sat on a high bench, with their feet free in the air, without footwear, and with their knees at a 90º angle. A brace was placed at ankle level, connected by an inextensible metal cable to an electromechanical dynamometer (Dynasystem®, DynaBlackbox, Spain). During the effort, the participants were instructed to hold onto the sides of the bench, maintaining their trunks in the most upright position possible. From this position, they performed maximal isometric efforts of right knee extension for 5 seconds, aiming to reach peak strength in the shortest time possible. After a two-minute rest, the effort was repeated with the contralateral limb, alternating for three attempts per limb. The procedure was then repeated for the isometric flexion effort of the same joint, starting from the same position.

Peak knee extension power was assessed after a two-minute rest following the last isometric effort. The dynamometer was set to provide resistance equivalent to 60% of the maximum force achieved during the isometric extension effort in each of the two lower limbs.

From the starting position used in the isometric effort, each participant was instructed to perform three consecutive right knee extension efforts, aiming to achieve the highest possible velocity in each attempt. After a two-minute rest, the procedure was repeated with the left lower limb, alternating sides to complete three sets per limb. Subsequently, the same procedure was repeated, using the same starting position, for knee flexion.

For the isometric effort, the best result from the three extension and flexion attempts was selected for analysis. Similarly, for power, the highest value among the nine attempts (performed across three sets of three repetitions) was considered for both extension and flexion. During the tests, the assessors encouraged the participants verbally.

Data analysis

Data are presented as mean ± standard deviation. The sample size (n = 66) was determined a priori using G*Power software (version 3.1.9.7; Heinrich Heine University, Düsseldorf, Germany), based on a statistical power of 0.80, an α level of 0.05, and an expected effect size of 0.4, corresponding to a small-to-moderate magnitude according to Cohen's criteria (Cohen, 1988). To assess potential differences between groups, a one-factor ANOVA without repetition was performed, provided the assumptions of homogeneity of variance (Levene's test) and normality (Shapiro–Wilk test) were satisfied. If these assumptions were not met, the Kruskal–Wallis test was applied. When statistically significant differences were detected ($p < 0.05$), post hoc analysis was conducted using the Bonferroni test.

Additionally, a correlation analysis was conducted between the TMG and dynamometric variables. The Pearson correlation test was applied if the assumptions of normal distribution and homogeneity of variance were met; otherwise, the Spearman correlation test was used. Correlation values were interpreted as follows: 0 to 0.19 indicated no correlation, 0.20 to 0.49 weak correlation, 0.50 to 0.79 moderate correlation, and values above 0.80 indicated strong correlation. Outliers with Z-scores equal to or greater than three standard deviations were excluded from the analysis.

Statistical significance was determined using a 95% confidence level. All analyses were conducted using JASP software (version 0.16.4.0, JASP Team, University of Amsterdam).

Results

The characteristics of the sample, stratified by group and sex, are presented in Table 1.

Table 1. Characteristics of the sample differentiated by age group and sex

	YA (n = 22; 11f, 11m)	AD (n = 22; 11f, 11m)	OA (n = 22; 11f, 11m)
Age (years)	22.1 ± 1.6 (f = 22.2 ± 1.7; m = 22.2 ± 1.5)	49.9 ± 8.3 (f = 50.9 ± 8.4; m = 48.8 ± 8.5)	71.0 ± 6.4 (f = 69.5 ± 4.5; m = 72.6 ± 7.8)
Height (cm)	171.6 ± 9.9 (f = 165.5 ±7.6; m = 177.7 ± 8.1)	168.8 ± 10.6 (f = 160.7 ±7.0; m = 176.8 ± 6.6)	165.0 ± 10.8 (f = 156.7 ±6.3; m = 173.3 ± 7.3)
Mass (kg)	71.4 ± 10.2 (f = 66.7 ±10.0; m = 76.0 ± 8.9)	76.4 ± 14.9 (f = 67.7±11.2; m = 85.0 ± 13.3)	76.1 ± 13.3 (f = 67.4 ± 9.1; m = 84.8 ± 10.9)
BMI (kg/m^2)	24.2 ± 2.8 (f = 24.4 ± 3.3; m = 24.1 ± 2.5)	26.6 ± 3.1 (f = 26.2 ± 3.5; m = 27.0 ± 2.6)	27.8 ± 3.1 (f = 27.5 ± 3.7; m = 28.2 ± 2.5)

Abbreviations: BMI = Body Mass Index; YA = Young Adults; AD = Adults; OA = Older Adults; f = female; m = male.

Results for the tensiomiographic assessment

The TMG values for RF and BF, stratified by group, are presented in Table 2. In the AD group, the Tc data of the left RF of a 48-year-old female subject was excluded because it presented a Z value = 3.8 (62.9ms). A significant difference was observed between groups only in the Tc of the RF for both lower limbs. Post-hoc analysis showed that, although an increase in Tc was observed in both limbs with aging, this difference was only significant ($p < 0.05$) when comparing YA vs. OA and AD vs. OA for the right lower limb. For the left lower limb, significance was found between YA and AD, as well as between YA and OA.

Table 2. Tensiomyography values (Dm and Tc) for Rectus Femoris (RF) Biceps Femoris (BF)

Muscle	Variable	Young	Adults	OA	p-value
			Right Lower Limb		
RF	Dm (mm)	8.0 ± 2.8	7.0 ± 4.1	7.1 ± 2.7	0.517
	Tc (ms)	27.3 ± 7.8	32.1 ± 6.6	37.7 ± 7.9	< .001**
BF	Dm (mm)	3.8 ± 2.6	4.6 ± 3.4	4.4 ± 2.2	0.632
	Tc (ms)	33.7 ± 17.1	37.0 ± 18.2	41.4 ± 18.3	0.376
			Left Lower Limb		
RF	Dm (mm)	7.9 ± 3.0	8.0 ± 3.9	7.0 ± 2.9	0.541
	Tc (ms)	25.3 ± 4.0	32.1 ± 4.2	35.9 ± 6.8	< .001**
BF	Dm (mm)	4.2 ± 2.9	5.2 ± 3.8	5.8 ± 3.8	0.340
	Tc (ms)	33.3 ± 17.9	38.9 ± 22.0	43.6 ± 19.1	0.187^{kw}

Note: * indicates a statistically significant difference for $p < 0.05$; ** indicates a statistically significant difference for $p < 0.01$. kw indicates the Kruskal-Wallis test was used; otherwise, one-factor ANOVA without repetition was used. OA = older adults; Dm = maximum radial deformation; Tc = contraction time.

Results for the dynamometric assessment

The results of the isometric strength and power tests for knee extension and flexion are presented in Table 3. Significant differences ($p < 0.01$) were observed for isometric strength, power, flexion, and extension in both lower limbs across all groups. In the post-hoc analysis for knee extension and flexion, statistically significant differences ($p < 0.05$) were observed for both movements when comparing YA vs. OA; and only for right lower limb isometric extension strength when comparing YA vs. AD. When comparing AD vs. OA, significant differences were found in right lower limb extension power, left lower limb isometric strength and extension power, and flexion power in both lower limbs.

Table 3. Isometric and dynamic force (power) values for knee extension and flexion

		Young	Adults	OA	p-value
			Right Lower Limb		
Extension	Isometry (N)	521.8 ± 123.0	393.2 ± 142.5	306.5 ± 96.5	< .001kw **
	Power (W)	464.3 ± 113.9	380.4 ± 191.2	197.4 ± 89.2	< .001kw **
Flexion	Isometry (N)	270.2 ± 75.1	246.1 ± 87.1	191.2 ± 57.2	0.003 **
	Power (W)	157.5 ± 50.2	131.2 ± 59.1	84.9 ± 36.1	< .001kw **
			Left lower limb		
Extension	Isometry (N)	509.9 ± 138.8	415.9 ± 141.5	307.2 ± 86.0	< .001kw **
	Power (W)	464.7 ± 128.4	377.1 ± 180.1	210.4 ± 85.6	< .001kw **
Flexion	Isometry (N)	262.5 ± 65.5	235.0 ± 87.5	181.9 ± 58.8	< .001kw **
	Power (W)	161.0 ± 43.2	122.5 ± 63.3	77.5 ± 32.7	< .001kw **

Note: * indicates a statistically significant difference for $p < 0.05$; ** indicates a statistically significant difference for $p < 0.01$. kw indicates the Kruskal-Wallis test was used; otherwise, one-factor ANOVA without replication was used. OA = Older Adults; Isometry = Peak Isometric Strength.

Correlation between tensiomyographic and dynamometric variables

The correlations between Tc and Dm of the RF with isometric strength and power for both knee extension and flexion, respectively, in both lower limbs, are presented in Table 4. Regarding extension, a weak negative but significant ($p < 0.05$) correlation was observed between the Tc of the RF and both maximum isometric strength and power in both lower limbs. A weak positive correlation was also found between RF Dm and both strength modalities in both limbs; however, only the correlation between the first variable and isometric strength for the right lower limb reached statistical significance.

Regarding flexion, and similar to what was observed for extension, weak but significant ($p < 0.05$) negative correlations ($p < 0.05$) were found between the Tc of BF and the maximum isometric strength and power in both lower limbs. No correlation was observed between BF Dm and either strength modality.

Table 4. Correlation between tensiomiographic and dynamometric variables

Variable		Isometric Strength (N)	Power (W)
		Right Lower Limb	
Extension	RF Tc (ms)	-0.341 (p = 0.005) Sp*	-0.396 (p = 0.002) Sp*
	RF Dm (mm)	0.313 (p = 0.011) *	0.247 (p = 0.053)
Flexion	BF Tc (ms)	-0.414 (p < .001) *	-0.486 (p < .001) *
	BF Dm (mm)	-0.090 (p = 0.488) Sp*	-0.022 (p = 0.861)
		Left Lower Limb	
Extension	RF Tc (ms)	-0.334 (p = 0.010) *	-0.438 (p < .001) Sp*
	RF Dm (mm)	0.198 (p = 0.132)	0.219 (p = 0.095)
Flexion	BF Tc (ms)	-0.367 (p = 0.004) Sp *	-0.388 (p = 0.002) Sp*
	BF Dm (mm)	-0.059 (p = 0.653) Sp	-0.083 (p = 0.523) Sp

Note: Sp indicates Spearman's rho statistic; otherwise, Pearson's r was used. * indicates a statistically significant difference ($p < 0.05$). RF = Rectus Femoris muscle; Tc = contraction time; Dm = maximum radial displacement.

Discussion

The present study aimed to characterize and analyze the impact of aging on the mechanical and functional properties of the knee flexor-extensor musculature. As hypothesized, a significant decrease in Tc at the RF level, as well as in isometric strength and power, was observed in the older groups compared to the younger groups. However, no significant differences were found between the groups regarding Tc in BF and Dm in both RF and BF.

In all groups and for both lower limbs, the Tc value was consistently higher in BF compared to RF. This is consistent with the different proportions of fiber types in both muscles. In this regard, in the work of Šimunič et al. (2018), the lowest Tc was observed in the Vastus Lateralis (VL) (26.1 ± 4.2ms), followed by the Gastrocnemius Medialis (GM) (30.0 ± 7.7ms) and the BF (43.1 ± 11.3ms), coinciding with differences in the proportion of type I fibers in those muscles (50%, 54%-63%, and 67%, respectively).

Consequently, the higher proportion of slow fibers in the BF could underlie the lower contraction velocity (higher Tc) observed in the latter muscle.

Effect of aging on tensiomyographic variables

In the present study, we observed a marked trend toward an increase in Tc for both RF and BF when comparing each group with their corresponding younger counterparts. While this could reflect different factors, including a decrease in tendon stiffness (Pišot et al., 2008), it is generally accepted that it represents a change at the level of the predominant muscle fiber type, to the detriment of the faster ones. Šimunič et al. (2019), using muscle biopsies at the VL level from subjects aged 20 to 83 years (similar to the range in the present study), reported a positive correlation ($p < 0.01$) between Tc and the proportion of MHC-I, implying that the higher the Tc, the lower the percentage of fast fibers. In this regard, the results of the present study align with the aforementioned selective loss of fast fibers associated with aging. The statistical significance ($p < 0.05$) observed at the RF level but not at the BF level could be explained by the fact that, with aging, the center of gravity tends to shift forward. This shift increases the work of the knee flexor musculature, potentially helping to delay the loss of fast fibers (Asaka & Wang, 2008).

The effect of training on lower limb Tc of YA, AD, and OA was studied by Šimunič et al. (2018), comparing samples of non-athletes, power athletes, or endurance athletes. In all cases, and similar to the present work (performed in active non-athlete subjects), a sustained trend towards increasing Tc with aging was found; the lowest values were observed in power athletes and the highest in endurance athletes. The values of BF Tc observed in OA in the present study are comparable to those reported for master power athletes, which is striking, considering that the latter is a sample of high-level competitors. These values were also significantly lower than those reported for endurance athletes. This finding, along with the more pronounced increase in Tc with advancing age in this population, could be explained by the process of sports selection favoring individuals with a higher percentage of type I fibers, which are more affected by glycation processes of myosin molecules associated with aging.

Regarding Dm, the present study did not find a significant increase in its values ($p > 0.05$) with advancing age. The only trend observed was an increase in the BF of the left lower limb, although it did not reach statistical significance. Therefore, the hypothesis was not confirmed.

There is evidence that muscle hypertrophy with a concomitant increase in tone leads to a decrease in Dm (Rodríguez-Matoso et al., 2012), while atrophy processes are associated with an increase in these values. Regarding the former, in another work, a decrease ($p < 0.001$) in RF Dm, associated with an increase in muscular mass, was observed after six weeks of strength training in previously untrained men (Wilson et al., 2019). Regarding the latter, in the work of Pišot et al. (2008), in which young men were subjected to 35 days of bed rest, an increase ($p < 0.01$) in the Dm of BF (26%), VM (24%), and GM (30%) was observed. The negative correlation found ($r = -0.70$, $p < 0.01$) between the loss of muscle mass post-intervention and the mentioned increase leads the authors to suggest that the latter would reflect a lower muscle tension, which is associated with possible changes in the visco-elastic properties of the intramuscular fascia and tendon.

Considering the muscle atrophy associated with aging, as well as the usual lower involvement of OA in strength training, it would have been expected in the present work that Dm would have increased in that group, particularly at the level of non-postural muscles, more prone to volume and MQ loss, given their higher percentage of type II fibers (Deschenes et al., 2013). However, the results obtained did not show such an increase. A possible explanation could be the infiltration of fatty deposits, increased fibrosis, and a reduced capacity for muscle excitation-contraction coupling associated with aging.

Additionally, the increase in type I fibers would lead to a loss of muscle elasticity since they are less elastic than type II-x fibers. The sum of these factors would favor the reduction in Dm values, compensating for the tendency to increase caused by muscle atrophy (Pus et al., 2023). This could explain the unexpected finding of a lower Dm in lower limb muscles of OA compared to YA females (Chai et al., 2022), as well as that reported by Vidnjevič et al. (2017), who observed practically identical Dm values between active vs. sedentary adults, both middle-aged (46.7 ± 5.6 years) and elderly (64.2 ± 6.5 years).

It has been suggested that an increase in Dm could be an early indicator of muscle atrophy processes, even before other techniques can detect such processes (Šimunič et al., 2019). In contrast, the findings of the present study do not support the use of Dm as an indicator of age-associated atrophy. This variable may be a sensitive indicator in acute atrophy processes (such as those caused by rest secondary to disease or injury), but not in relatively slow and gradual atrophy processes like aging.

Effect of aging on the dynamometric variables

In the present study, consistent with the proposed hypothesis, a marked decrease in isometric strength and peak power, both in extension and flexion, was observed with aging. In many cases, these differences reached statistical significance when comparing each group with the immediately older or younger group.

Some studies suggest that the reduction in power occurs at a more accelerated rate than the reduction in isometric strength. In this regard, Narici and Maffulli (2010), comparing OA ($\bar{x}$ = 74 years) with YA ($\bar{x}$ = 26 years), observed a 40% loss in isometric strength in the former, while the decrease in power was 60%.

In the present study, using the right lower limb as a reference and comparing the OA vs. YA groups, a loss of 41.3% in isometric strength and 57.5% in peak power for knee extension was observed in the former, values that closely resemble those reported by the aforementioned authors. These findings also align with those of Haus et al. (2007), who observed a reduction of 35% in maximum isometric strength and 48% in peak power of the Quadriceps Femoris when comparing OA (78 ± 6 years) with YA (25 ± 3 years).

Regarding knee flexion, in the present study, the percentage difference in strength between YA and OA was significantly lower, possibly due to the greater susceptibility of certain muscles to the effects of aging. However, as seen in extension, the loss was notably more pronounced for power (46.1% decrease) than for isometric strength (29.2% decrease).

It has been reported that in OA, the measurement of isometric knee extensor strength, using protocols similar to that of the present study, has greater predictive power for elevated risk of falls than different variants of the *Timed Up and Go Test* (TUG), commonly used for this purpose. This predictive power was maintained after correcting for potential intervening variables such as age, sex, BMI, and history of previous falls (Valenzuela et al., 2020). Additionally, the assessment of muscle power at the lower limb level is a crucial determinant of functional independence status in OA since its association with the ability to perform everyday tasks, such as getting up from a chair and climbing stairs, as well as walking speed (Reid & Fielding, 2012).

Among the causes underlying the decline in strength and power with aging are atrophy and selective loss of fast muscle fibers (indirectly suggested in the present study by the increase in Tc). Other causes include loss of motor units, altered neuromuscular activation, and increased deposition of intramuscular adipose tissue, all of which prevent full muscle activation during contraction (Yoshida et al., 2012). At the molecular level, this could be related to kinetic changes in the myosin molecular motor, which may explain the 18% to 25% slowing observed in actin filament sliding in type I fibers when comparing YA vs. OA (Höök et al., 2001).

In the present study, the age-associated loss of strength and power was observed, despite all subjects being physically active. Similarly, in the work of Brauer et al. (2023), where middle-aged (53.9 ± 2.5 years) vs. older (64.4 ± 3.5 years) male endurance runners were compared, a significant decrease in cross-sectional area (-16%; $p = 0.03$) and muscle fascicle length (-15%; $p = 0.02$) of the VL, associated with a lower peak isometric torque in knee extension (-18%; $p = 0.02$) and lower echo-intensity (-14%; $p < 0.01$) was observed. Without ignoring all its other benefits, these findings suggest that, in isolation, moderate-intensity aerobic training may not be sufficient to mitigate the decline in MQ associated with aging. In contrast, evidence indicates that muscles retain adaptive capacity due to systematic strength training, even in octogenarian and nonagenarian individuals (Marzuca-Nassr et al., 2023). This highlights the importance of incorporating resistance exercises into the training routine of OA.

Correlation between tensiomiographic and dynamometric variables

The correlation between the TMG and dynamometric variables analyzed was seldom statistically significant ($p < 0.05$), and when significant, the correlation was weak. Regarding Tc, in both lower limbs, for both movements (extension and flexion) and for both force modalities, the correlation was weak ($r < 0.5$) and negative. This negative correlation is likely linked to a higher Tc in older stages of life, which is in turn associated with a selective loss of fast fibers, particularly type II-x. These fibers, compared to type I, are characterized by their ability to develop approximately twice the relative strength (relative to their cross-sectional area) and between four to six times more power (Plotkin et al., 2021), thus explaining the negative nature of this correlation. This finding aligns with the results reported by Fabiani et al. (2021), who, studying older female adults with low physical fitness, observed a positive correlation (rho = 0.456; $p = 0.015$) between the VL Tc and the time taken to complete the TUG test.

The weak nature of the correlation may be attributed to other factors beyond the amount and type of muscle fibers involved in the expression of maximum strength. These factors include neuromuscular activation and coordination, hormonal factors, previous experience, execution technique, and psychological factors such as motivation (Stone et al., 2007).

Regarding Dm, a weak or non-existent correlation, with no statistical significance ($p > 0.05$), was observed between the dynamometric and TMG variables, except for the right RF in isometric extension strength. These findings suggest that Dm may not be sufficiently sensitive to detect chronic muscle atrophy associated with strength loss; as such, its variation may not be reflected in the strength values obtained.

In the study by de Paula-Simola et al. (2015), conducted on young men (23.0 ± 1.9 years) trained in strength, TMG variables such as Dm (but not Tc) at the RF level significantly correlated with changes in voluntary isometric maximum strength capacity ($r = 0.64$; $p < 0.05$) from the half-squat position. However, unlike the present study, which was conducted in unfatigued subjects, these researchers assessed participants at 0.5h, 24h, and 48h after completing a five-week strength training protocol. The observed increase in passive structural stress due to induced fatigue, coupled with reduced excitation-contraction coupling efficiency, decreased sarcolemma conductance, and altered regulation of Ca2+ release from the sarcoplasmic reticulum, could explain these findings.

On the other hand, the findings of the present study align with those of Labata-Lezaun et al. (2023), who investigated OA in both sexes (73.7 ± 7.4 years). These authors, using a knee position similar to the one employed in the present study, found a weak positive correlation ($r = 0.220$), although not statistically significant ($p = 0.125$), between the isometric extensor strength of the dominant lower limb and the RF Dm. Similarly, they observed a negative correlation, though weak ($r < 0.1$) and not statistically significant ($p = 0.542$), between this capacity and Tc, which is consistent with the present study's results. Additionally, these authors reported a significant correlation ($p < 0.05$) between the aforementioned TMG variables of RF and VL and two functional tests commonly used in OA populations: the *Short Physical Performance Battery* (SPPB) and the *Five Times Sit to Stand Test* (5xSST). Contrary to what is widely documented in the scientific literature (as well as to the findings of the present study), the positive correlation for the first test (SPPB; rho = 0.491) and the negative correlation for the second test (5xSST; rho = -0.340) would suggest that a higher Dm corresponds to better performance outcomes in these tests.

These findings, as reported by Labata-Lezaun et al. (2023), suggest that while functional tests should remain the primary focus in OA assessments, Dm may be a potentially useful variable for detecting MQ decline, particularly in individuals with limited mobility. However, the results of the present study indicate that Tc could be a more suitable alternative for assessing MQ loss in this context. Nonetheless, the low correlation levels observed in both studies warrant cautious interpretation and highlight the need for further research.

It is important to note that, in the present study, strength assessments were conducted from an initial position of 90 degrees knee flexion, whereas TMG variables were assessed at different joint angles. This discrepancy could have altered the relative alignment of actin and myosin filaments within the sarcomeres, influencing contraction capacity and potentially contributing to the lack of observed correlation (Ditroilo et al., 2011). Nonetheless, this absence of correlation could also suggest that TMG provides complementary and subsidiary information to traditional functional tests, enabling the study of muscle properties from an alternative analytical perspective. As such, TMG may be useful in assessing muscle quality parameters beyond what can be captured through conventional approaches.

Limitations

This study had certain limitations. First, the sample size was relatively small, which may limit the generalizability of the findings. Additionally, participants were assessed at different times of the day due to scheduling constraints, which required adapting the assessment sessions to each participant's availability. This may have influenced the dynamometric assessments, as muscle strength is known to follow a circadian rhythm (Chtourou & Souissi, 2012). To our knowledge, no studies have explored the potential effects of time of day on TMG variables, making this a relevant topic for future research. Another limitation was the lack of prior experience with the strength tasks in some participants, particularly OA. This may have introduced a learning bias, although efforts were made to mitigate this by incorporating familiarization trials before the tests.

For TMG measurements, the lack of fixation of the assessed segment could have influenced the results, as contractions may not have been purely isometric. However, previous research has reported no significant differences ($p > 0.05$) in TMG values for the BF when comparing conditions with and without fixation at the ankle (Schwiete et al., 2023).

Conclusions

The importance of maintaining or improving MQ in OA underscores the critical need for accurate assessment methods and the development of reliable indicators for its evaluation and categorization. The findings of this study, showing weak or non-existent correlations between TMG variables (particularly Dm) and functional indicators such as isometric strength and power, suggest that TMG, when used in isolation, would not be sufficient under certain conditions to detect MQ deterioration processes. These results should be interpreted with caution and point to the need for future research aimed at designing and validating comprehensive MQ indices that could more accurately and sensitively detect changes associated with chronic aging processes. Such advancements could provide more robust tools for identifying early declines in MQ and guiding targeted interventions to preserve physical function and quality of life in OA populations.

Acknowledgements

We would like to thank the 66 volunteers who generously agreed to be part of this study. We are deeply grateful to them for offering their valuable time and effort. We would also like to thank all our colleagues from the Sports and Performance Research Group, Scientific Research Sectorial Commission (CSIC) no. 883101, for their valuable contributions to this project.

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