Spor Hekimliği Dergisi, 59(3):99-104; 2024
Turkish Journal of Sports Medicine
Turk J Sports Med. DOI: 10.47447/tjsm.0806

Research Article / Araştırma Makalesi

Associations of passive muscle stiffness and muscle echo-intensity with muscle strength

Pasif kas sertliği ve kas ekojenitesinin kas kuvveti ile ilişkisi

Merve Karapınar[1], Veysel Atilla Ayyıldız[2],

[1]*Department of Physiotherapy and Rehabilitation, Faculty of Health Sciences, Süleyman Demirel University, Isparta, Türkiye*

[2]*Department of Radiology, Faculty of Medicine, Süleyman Demirel University, Isparta, Türkiye*

ABSTRACT

Objective: Muscle tissue parameters including composition and stiffness of muscle can have an important effect on muscle strength. In this study, we aimed to investigate the relationships between muscle echo-intensity (EI), tendon stiffness and muscle strength in young men and women.

Methods: Ultrasound B-mode images of the Rectus Femoris (RF), Vastus Medialis (VM) and Patellar Tendon (PT) were acquired in fifty-two healthy subjects (mean age; 27.43±5.3 years). RF, VM and PT stiffness were characterized by shear-wave elastography measurements. Quantitative evaluations were performed, including measurement of muscle and tendon thickness and muscle EI. Isometric knee extension muscle strength was measured using hand-held dynamometer.

Results: RF stiffness had a good correlation with muscle strength ($r=-0.46$, $p<0.05$) and had a fair correlation with EI_{RF}($r=-0.37$,$p<0.05$), VM stiffness had a good correlation with muscle strength ($r=0.42$, $p<0.05$) and had a fair correlation with EI_{VM} ($r=-0.43$,$p<0.05$) in women. RF stiffness had a good correlation with muscle strength ($r=-0.54$, $p<0.05$), had a good correlation with EI_{RF}($r=-0.41$,$p<0.05$) in men.VM stiffness had a good correlation with muscle strength($r=-0.50$; $p<0.05$), and had a good correlation with EI_{VM}($r=-0.60$,$p<0.05$) in men. EI_{RF} and EI_{VM} had a good relation with muscle strength in men and women (For EI_{RF}; $r=-0.46$; $r=-0.54$; for EI_{VM}; $r=-0.42$; $r=-0.50$ $p<0.05$, respectively)

Conclusions: This study demonstrates that there is a relationship between isometric muscle strength and passive muscle stiffness, muscle EI. Additionally, muscle EI affects muscle stiffness in healthy men and women. Our results should be considered in elite athletes for whom the strengthening program is important.

Keywords: *Echointensity, ultrasonography, muscle stiffness, shear-wave elastography, muscle strength*

ÖZ

Amaç: Kas composiziyonu ve kas sertliği gibi kas dokusu parametreleri kas kuvveti üzerinde önemli bir etkiye sahip olabilir. Bu araştırmada, sağlıklı genç erkek ve kadınlarda kas eko-intensitesi (EI) ile kas ve tendon sertliğinin izometrik kas kuvveti ile arasındaki ilişkiyi incelemeyi amaçladık.

Yöntem: Elli-iki sağlıklı katılımcının (ortalama yaş: 27,43±5,3 yıl) Rektus Femoris(RF), Vastus Medialis(VM) ve Patellar Tendon(PT)'unun B-Mod ultrason görüntüleri elde edildi. RF, VM ve PT sertliği shear-wave elastografi ölçümleri ile karakterize edildi. Kas ve tendon kalınlığı, EI ölçümü gibi nicel değerlendirmeler yapıldı. İzometrik diz ekstansiyon kas kuvveti hand-held dinamometre kullanılarak ölçüldü.

Bulgular: Kadınlarda RF kas sertliği ile kas kuvveti arasında iyi bir korelasyon ($r=-0.46$, $p<0.05$), EI_{RF} ile orta derecede bir korelasyon vardı ($r=-0.37$, $p<0.05$). VM sertliği ile kas kuvveti arasında iyi bir korelasyon ($r= 0,42$, $p<0,005$), EI_{VM} ile orta derecede bir korelasyon ($r=-0,43$, $p<0,05$) vardı. Erkeklerde RF sertliği ile kas kuvveti ($r=-0,54$, $p<0.05$) ve EI_{RF} ($r=-0.41$, $p<0.05$) ile iyi bir korelasyon vardı. VM sertliği ile kas kuvveti ($r=-0.50$; $p<0.05$) ve EI_{VM}($r=-0.60$, $p<0.05$) ile iyi bir korelasyona sahipti. Kadın ve erkeklerde, EI_{RF} ve EI_{VM}'nin kas kuvveti arasında negatif korelasyon bulundu (sırasıyla EI_{RF} için; $r=-0.46$; $r=-0.54$; for EI_{VM}için; $r=-0.42$; $r=-0.50$ $p<0.05$)

Sonuçlar: Bu çalışma, izometrik kas kuvveti ile pasif kas sertliği ve EI'si arasında bir ilişki olduğunu göstermektedir. Ayrıca, kas EI'nin sağlıklı erkek ve kadınlarda kas sertliğini etkilediğini göstermektedir. Çalışma sonuçlarımız kuvvetlendirme programının önemli olduğu elit sporcularda mutlaka dikkate alınmalıdır.

Anahtar Sözcükler: *Ekointensite, ultrasonografi, kas sertliği, shear-wave eleastografi, kas kuvveti*

INTRODUCTION

Normal skeletal muscle stiffness is related to active tension resulting from muscle contraction and passive tension created by connective tissue (1). Both passive and active muscle stiffness contribute to physical function. Passive stiffness plays a role in muscle performance and exercise compliance (2). It is suggested that muscle stiffness is closely related to decreased joint range of motion and increased muscle stiffness is associated with joint stiffness. So, passive muscle stiffness has been reported as an important factor for sports injuries. (3). Isometric and isokinetic muscle st–

Received / Geliş: 26.07.2023 · **Accepted / Kabul:** 18.12.2023 · **Published / Yayın Tarihi:** 27.08.2024

Correspondence / Yazışma: Merve Karapınar · Süleyman Demirel Üniversitesi, Tıp Fakültesi, Fizyoterapi ve Rehabilitasyon Bölümü, Isparta, Türkiye · mervekarapinar1306@gmail.com

Cite this article as: Karapinar M, Ayyildiz VA. Associations of passive muscle stiffness and muscle echo-intensity with muscle strength. *Turk J Sports Med.* 2024;59(3):99-104; https://doi.org/10.47447/tjsm.0806

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes (http://creativecommons.org/licenses/by-nc/4.0/).

rength are known to closely related with muscle thickness or muscle size (4).

Qualitative changes in skeletal muscle tissue are caused by a decline in type II fibre size (5). It has also observed that intramuscular and intermuscular fat deposition increases with aging or inactivity (6). Skeletal muscle fat infiltration is related with impaired muscle strength and mobility, making it an important marker for muscle health (7). Palmer et al. (8) indicated that increased muscle echo-intensity may contribute to the prominent passive muscle stiffness in older adults. Due to fat infiltration in the muscles, the ratio of intramuscular adipose tissue increases and the muscle/fat ratio decreases (9). It is thought that changes in muscle composition attributed to fat infiltration might cause changes in viscoelastic properties of muscles and tendons. Understanding the mechanical properties and parameters of muscles and tendons that affect their ability to generate force makes significant contributions to the improvement of physical activity and athletic performance and prevention of joint and muscle injuries (10). Therefore, factors affecting the force-generating ability of skeletal muscle and tendon structures have been a topic of current research (11). Since muscle mechanical properties cause changes in tendon stiffness, it has become even more important to explain the responsible parameters (12).

Muscle and tendon stiffness is defined as an internal resistance to changes in muscle and tendon shape caused by an external force. Muscle strength production takes place with the help of the elastic behavior of the muscles and tendons (13). Passive stiffness is a critical determinant of muscle performance during sportive activities and/or functional movements. It can have a profound effect on muscle strength and force production by influencing the velocity of the contractile component (14). Tissue stiffness is also associated with repetitive stress and strain injuries.

Ultrasonography (US) has been reported to be a valid and reliable tool for estimating muscle mass by measuring muscle cross-sectional area and muscle thickness, as well as predicting muscle quality by gray-scale analysis of muscle echo-intensity (EI). On the other hand, shear wave elastography (SWE) is an ultrasound-based technique that can characterize the viscoelastic properties of muscles and tendons based on the propagation of remotely induced shear waves (15). Increased EI refer to higher infiltration of fibrotic tissue and/or adipose tissue in the muscle (16). Intramuscular fat leads to a reduction in maximum isometric tension in animal models. Similarly, increases in intramuscular fat have been reported to result in lower specific forces (force/physiological cross-sectional area) in muscle simulation applications (17). This is why estimating intramuscular fat accumulation recently gained attention. The effect and mechanism of intramuscular fat on the stiffness of muscle and tendon is still unclear. Indeed, increased tissue stiffness (i.e., the relationship between a given force and the amount of strain the tissue is subjected to) can increase strength production. Therefore, tendon and muscle stiffness and adaptations of structures within the muscle such as muscle echo-intensity may affect muscle strength.

Decreased knee muscle strength is associated with worsened mobility and performance, and increased knee problems and injuries (18). Considering the relationship of muscle strength with various qualities, it seems important to know how muscle strength can be improved and the basic physiological factors that affect muscle strength. If practitioners want to increase the muscle strength of healthy individuals or patients with poor muscle strength, or professional athletes, they need to understand which parameters are more important in terms of muscle strength. Therefore, we investigated the relationship between isometric muscle strength and muscle EI and muscle and tendon stiffness in young healthy adults using shear wave elastography (SWE). We hypothesized that 1) participants with less muscle EI exhibit higher muscle and tendon shear modulus, as fat is less stiff than muscle tissue. 2) Muscle EI and stiffness are related with isometric muscle strength in healthy men and women.

MATERIAL and METHODS

This study was reported following the "Strengthening the Reporting of Observational Studies in Epidemiology" (STROBE) (19).

Subjects

Fifty-two (36 female, 16 male) healthy young and sedentary adults were included. Sedentary individuals who were not involved in any sports and did not exercise regularly for at least 6 months were included in the study. Exclusion criteria were as follows: (a) participating in any form of intense physical activity or sporting activity in the past 72 hours, (b) individuals who had orthopaedic or neurologic or rheumatologic disease related to the lower extremity (c) had lower extremity surgery or major trauma history, (d) participants with history of major trauma or surgery in the upper and/or lower extremity or cardiopulmonary diseases.

Ultrasonographic Assessment

All participants were examined with grey-scale US and SWE (Philips Medical Systems EPIQ5 Release5.0.2, Amsterdam) that was equipped with a high resolution linear-array probe (8-12 MHz, code: eL18-4). A radiologist with over 15 years musculoskeletal experience evaluated and imaged the pa–

tellar tendon and skeletal muscles of each participant. The participants were allowed to rest for 10 minutes in order to evaluate the mechanical properties of the muscles and tendons at resting status. Dominant side of participants was used for ultrasonographic assessments. The leg of dominance was determined by asking the subject to kick a ball. To evaluate vastus medialis (VM) stiffness, transducer was placed at 50% of the distance between the greater trochanter and the medial condyle of the femur. To evaluate Rectus Femoris (RF), transducer located on the midpoint of the line connecting the anterior superior iliac spine with the superior edge of the patella (20). During this assessment, subjects were lying in supine position with their legs extended and relaxed. In order to asses Patellar Tendon (PT) stiffness, the probe was placed at the inferior pole of patella and aligned with the patellar tendon. Scanning of PT was performed with the subject in supine position with knee at 30° of flexion (21). Once a clear image of the muscles and tendon has been captured, the shear wave elastography mode was activated. Minimal force was applied to avoid pressure artifact during the ultrasonographic examination. The probe was held steady for about 10 seconds during SWE map acquisition. The data were expressed in kPa and median and mean values were also presented. The kilopascal (kPa) unit was used to assess the muscle stiffness (Figure 1). US screen displays a color-coded elastogram. High shear wave velocity (SWV) represents higher stiffness, low SWV represents low stiffness, and SWV is directly related to tissue stiffness (22) . Image J software (Version 1.48v, National Institutes of Health, Bethesda, MD, USA) was used to evaluate muscle end tendon echo-intensity. The average echo-intensity of the muscles were ranged from between 0 (black) to 255 (white) arbitrary units (a.u). Values approaching 0 indicate more intramuscular fat, while values approaching 255 indicate more muscle tissue or contractile structure. (23). Lastly, muscle and tendon thickness was measured as the distance between the internal borders of the superficial and deep aponeuroses (24). All ultrasonographic measurements were made three times and the average of the values was recorded for statistical analysis.

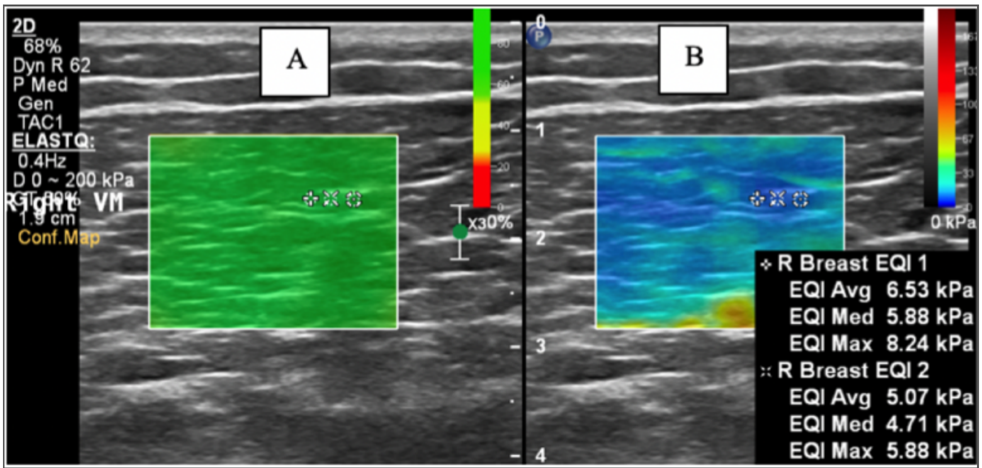

Figure 1. Measurement of elastic property of the Vastus Medialis (VM) in longitudinal view. (A) Longitudinal grey scale sonograms of VM on the identical scan planes. (B) Colour-coded box presentations of the VM elasticity (stiffer areas were coded in red and softer areas in blue) superimposed on a longitudinal grey scale sonogram of the VM

Isometric Muscle Strength

Maximal voluntary isometric quadriceps femoris muscle strengths were evaluated with a Lafayette Hand-Held Dynamometer model 01163 (Lafayette, Sagamore, USA) by the same author. Participants were seated with their knees flexed 60° and their feet on the ground. Dynamometer was placed on the anterior aspect of the distal tibia, just superior to the malleoli. Three assessments with 30 s rest between measurements was performed by the same investigator (25).

Statistical Analysis

All data was analyzed using the SPSS22 (IBM Corp., Armonk, NY) program. Kolmogorov–Smirnov and Shapiro–Wilk and graphical histogram analysis were used to check for normality and the Mann–Whitney U test and Spearman's test were performed. G*Power program was used in order to determine sample size. Based on Tas et al. (26) study, the correlation coefficient between muscle strength and tendon stiffness was at least 0.44 and effect size was seen to be 0.19. According to the power analysis results with Type-I error rates of 0.05 and 90% power, 52 subjects were participated in the study.

RESULTS

This study included fifty-two healthy volunteers (36 women, 16 men) aged 19 to 35 years. The demographic characteristics of subjects are summarized in Table 1. Women had a mean age of 26.5±9.64 years (range, 20–35), and a mean BMI of 25.08±5.59 (range, 17.36 – 40.56) kg/m². Men had a mean age of 28.74±4.32 years (range, 20-32) and a mean BMI of 26.44±4.87 kg/m² (range, 20.66-26.13). There were no significant differences in age, weight, height or BMI between men and women.. RF and VM thickness, VM stiffness, PT stiffness and PT EI were similar between gender ($p>0.05$). Women were found to have a higher RF stiffness, EI_{RF} and EI_{VM} compared to men ($p<0.05$). In addition, women were observed to have a lower PT thickness compared to men ($p<0.05$) (Table 1).

Table 1. Characteristics of the study subjects

Mean±SD (min-max)	Women (n: 36)	Men (n: 16)	p value
Age (years)	26.5±9.64 (20-35)	28.74±4.32 (20-32)	0.231
Height (cm)	165.13±4.69 (156-172)	170.68±6.16 (163-183)	0.342
Weight (kg)	68.31±15.21 (44-120)	75.42±12.32(59-96)	0.085
BMI (kg/m²)	25.08±5.59 (17.36 – 40.56)	26.44±4.87(20.66-26.13)	0.123
Isometric Muscle Strength (kg-f)	22.2±4.85 (16.50-36.20)	24.08±3.18 (21.30-36.40)	0.072
Rectus Femoris			
Thickness (cm)	1.22±0.47 (0.74-3.41)	1.23±0.23(0.98-1.83)	0.249
Stiffness (kPA)	13.50±6.34 (7.06-30.06)	17.10±9.02 (8.24-42.4)	**0.034***
Echo-intensity (a.u)	73.72±11.16 (59.44-102)	62.62±23.14 (40.55-102)	**0.019***
Vastus Medialis			
Thickness (cm)	2.95±0.70 (1.70-4.40)	2.56±0.36 (2.08-3.33)	0.075
Stiffness (kPA)	15.56±7.97 (5.88-39.40)	15.80±2.67 (5.88-34.10)	0.137
Echo-intensity (a.u)	80.27±11.72 (56.26.87-109)	74.43±17.06 (50.19-109.90)	**0.041***
Patellar Tendon			
Thickness (cm)	0.25±0.05 (0.15-0.35)	0.30±0.06 (0.24-0.55)	**0.001***
Stiffness (kPA)	43.93±27.95(24.7-58.8)	55.09±29.04 (31.80-161)	0.089
Echo-intensity (a.u)	72.21±19.49 (22.40-119)	77.13±24.29 (40.36-122.00)	0.285

SD; standard Deviation, *; Mann-Whitney U test, p<0.05, BMI; Body Mass Index, cm; centimeters, kg; kilogram, kg-f; kilogram-force, kPA; kilopascal, a.u; arbitrary unit

The correlation analysis revealed that RF stiffness had a good correlation with muscle strength ($r= -0.46$, $p<0.05$) and had a fair correlation with EI_{RF} ($r=-0.37$, $p<0.05$). VM stiffness had a good correlation with muscle strength ($r= -0.42$, $p<0.05$) and had a fair correlation with EI_{VM} ($r=-0.43$, $p<0.05$) in women. It was also found that RF stiffness had a good correlation with muscle strength ($r=-0.54$, $p<0.05$) and had a good correlation with EI_{RF} ($r=-0.41$, $p<0.05$). VM stiffness had a good correlation with BMI ($r=-0.51$, $p<0.05$), had a good correlation with muscle strength ($r=-0.50$; $p<0.05$), and had a good correlation with EI_{VM} ($r=-0.60$, $p<0.05$) in men. PT stiffness was not associated with muscle strength in women and men ($p>0.05$) (Table 2). EI_{RF} and EI_{VM} had a good relation with muscle strength in men and women (For EI_{RF}; $r=-0.46$; $r=-0.54$; for EI_{VM}; $r=-0.42$; $r=-0.50$ $p<0.05$, respectively).

Table 2. Correlations between patellar tendon stiffness, patellar tendon echo-intensity and isometric muscle strength in women and men

WOMEN	Rectus Femoris Stiffness	Vastus Medialis Stiffness	Patellar Tendon Stiffness
BMI	-0.086	-2.72	-0.220
Isometric Extensor Muscle Strength	-0.463**	-0.421**	-0.009
Rectus Femoris Echo-Intensity	-0.374**	-0.147	-0.187
Vastus Medialis Echo-Intensity	-0.030	-0.437**	-0.002
Patellar Tendon Echo-Intensity	-0.093	-0.010	0.036
Rektus Femoris Thickness	-0.072	-0.104	-0.054
Vastus Medialis Thickness	-0.430	-0.200	0.067
Patellar Tendon Thickness	-0.171	-0.331	0.167
MEN	**Rectus Femoris Stiffness**	**Vastus Medialis Stiffness**	**Patellar Tendon Stiffness**
BMI	-0.258	-0.516*	-0.419
Isometric Extensor Muscle Strength	-0.544*	-0.500*	0.604
Rectus Femoris Echo-Intensity	-0.410 *	0.498	0.461
Vastus Medialis Echo-Intensity	-0.428	-0.608*	0.159
Patellar Tendon Echo-Intensity	0.180	-0.558	-0.461
Rektus Femoris Thickness	-0.483	0.352	0.697
Vastus Medialis Thickness	-0.068	-0.350	-0.038
Patellar Tendon Thickness	-0.093	-0.270	-0.228

DISCUSSION

The major findings of the present study were that (1) the RF and VM muscle stiffness had a good relation with EI_{RF} and EI_{VM} whereas had no relation with patellar tendon stiffness (2) EI_{RF} and EI_{VM} and muscle stiffness were closely related with isometric muscle strength. Our primary results were consistent with our hypothesis.

Deficits in the active component are more easily recognized because of their adverse effects on daily functioning, whereas similar changes in the passive component are more difficult to identify. SWE provides information about the mechanical and viscoelastic properties of the region in question by generating shear waves in muscle and tendon tissue and then measuring the velocity of the propagating shear waves (27). The velocity of these shear waves is related to the shear modulus of the muscle. Shear waves travel faster in hard tissues and slower in soft tissues. Therefore, the softer the tissue the slower the SWE and the smaller the Young's modulus. It is approved that adipose tissue is softer than skeletal muscle tissue (28). The shear modulus is expected to be higher in the muscle tissue which contains lower muscular fat than in the muscle which contains higher muscular fat. Rahemi et al. (17) showed that the accumulation of intramuscular fat or increased EI resulted in increased muscle tissue stiffness in their a finite element modeling study. In our study, these assumptions were confirmed by detecting increased fat ratio or EI_{RF} and EI_{VM} was associated with increased muscle stiffness in healthy participants.

Alfuraih et al. (29) reported that decline in skeletal muscle stiffness positively correlates with muscle weakness in their study conducted with healthy young, middle-aged and older individuals. Several studies have demonstrated relation between age-related increase in passive muscle stiffness and declined muscle strength (30,31).

Since the decrease in muscle strength due to sarcopenia increase mortality, deterioration in muscle strength and power should be taken into consideration. Hirata et al. (32) showed that younger participants had greater muscle stiffness (i.e. harder) than older participants. Our study indicated that passive muscle stiffness also closely related with isometric muscle strength in healthy individuals. Differences in muscle stiffness imply that it is proportional to the ratio of contractile and non-contractile tissues. Soft tissue composition differs between men and women. Passive gastrocnemius muscle stiffness was 6% lower in women compared to men (33). We observed stiffness in RF was %21 lower in healthy women when compared to healthy men. Also, we showed that echo-intensity was higher in women. On the other hand, Chino et al. (34) showed that no gender difference was observed in the medial gastrocnemius muscle stiffness and also, Tang et al. (35) pointed no significant difference in SWE values of the RF between men and women in the relaxed position. However, these studies did not have any information on muscle echointensity. In our study, while there was no difference in muscle and tendon stiffness between men and women, it was found that muscle echo density differed according to gender.

Musculoskeletal tissue is stiffer than fat tissue so the shear modulus is expected to be lower in muscle containing more intramuscular fat than muscle with lower intramuscular fat. Young et al (36) indicated that intramuscular fat was positively correlated with BMI. Hoffman et al. (37) showed no relation between BMI and gastrocnemius muscle stiffness in different situations such as resting position and during muscle contraction. Thus, we consider that VM elastic properties may be affected by sex and difference in intramuscular fat distribution. Demographic characteristics, such as gender can influence both muscle stiffness and of muscles EI. Furthermore, muscle echogenicity should be considered when assessing muscle stiffness in men and women.

We investigated the relationship between isometric knee extensor muscle strength and muscle EI. There was a relationship between EI_{RF} and isometric muscle strength in women and there was a relationship between EI_{RF} and $EI_{VM}$and isometric muscle strength in men. Echo-intensity was associated with isometric muscle strength in older and younger subjects ($r = 0.27–0.64$) (38). Muscular fat infiltration also has relationship with jumping and sprint performance in younger healthy people besides relation with muscle strength (39). Strength training and explosive movements produce improvement in power by recruiting type II fibers. Slow fibers seem to be stiffer than fast muscle fibers (40). Considering these findings, our results possibly indicate that greater fat infiltration into the muscle and lower passive muscle stiffness are associated with lower isometric muscle strength in healthy men and women. In future studies, it would be useful to investigate how to reduce intramuscular fat or muscle EI and improve the quality of muscle composition.

Our study had several limitations. Firstly, age group of individuals in our study do not correspond to children or older age groups. Secondly, we included healthy participants with no musculoskeletal problems. Lastly, there was only one measurement site.

CONCLUSION

Our study denoted infiltration of adipose tissue in muscle tissue may manifest as changes in muscle stiffness and changes of muscle strength in healthy men and women. The results of this study demonstrated that significant correlations existed among muscle EI and muscle stiffness in healthy participants. Moreover, RF and VM muscle EI and muscle stiffness were negatively correlated with isometric muscle strength.

Ethics Committee Approval / Etik Komite Onayı

This study was approved by the Suleyman Demirel University University Faculty of Medicine Scientific Research Ethics Committee (Decision number: 258, Date: 28.09. 2022).

Conflict of Interest / Çıkar Çatışması

The authors declared no conflicts of interest with respect to authorship and/or publication of the article.

Financial Disclosure / Finansal Destek

The authors received no financial support for the research and/or publication of this article.

Author Contributions / Yazar Katkıları

Concept – MK, VAA; Design - MK; Supervision – VAA; Materials – Data Collection and/or Processing – MK, VAA; Analysis and Interpretation – MK; Literature Review – MK, VAA; Writing manuscript; MK, VAA; Critical Reviews – MK, VAA. All authors contributed to the final version of the manuscript and discussed the results and contributed to the final manuscript

REFERENCES

1. Eby SF, Song P, Chen S, Chen Q, Greenleaf JF, An K-N. Validation of shear wave elastography in skeletal muscle. *J Biomech.* 2013;46(14):2381–7.
2. Kubo K, Kanehisa H, Fukunaga T. Is passive stiffness in human muscles related to the elasticity of tendon structures? *Eur J Appl Physiol.* 2001;85(3-4):226–32.
3. Green B, Bourne MN, van Dyk N, Pizzari T. Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. *Br J Sports Med.* 2020;54(18):1081–8.
4. Wernbom M, Augustsson J, Thomeé R. The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. *Sports Med.* 2007;37(3):225–64.
5. Lexell J, Taylor CC, Sjöström M. What is the cause of the ageing atrophy?: Total number, size and proportion of different fiber types studied in whole vastus lateralis muscle from 15-to 83-year-old men. *J Neurol Sci.* 1988;84(2–3):275–94.
6. Mizuno T, Matsui Y, Tomida M, Suzuki Y, Nishita Y, Tange C, et al. Differences in the mass and quality of the quadriceps with age and sex and their relationships with knee extension strength. *J Cachexia Sarcopenia Muscle.*2021;12(4):900–12.
7. Manini TM, Clark BC, Nalls MA, Goodpaster BH, Ploutz-Snyder LL, Harris TB. Reduced physical activity increases intermuscular adipose tissue in healthy young adults. *Am J Clin Nutr.* 2007;85(2):377–84.
8. Palmer TB, Thompson BJ. Influence of age on passive stiffness and size, quality, and strength characteristics. *Muscle Nerve.* 2017;55(3):305–15.
9. Hausman GJ, Basu U, Du M, Fernyhough-Culver M, Dodson M V. Intermuscular and intramuscular adipose tissues: bad vs. good adipose tissues. *Adipocyte.* 2014;3(4):242–55.
10. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med.* 2016;46(10):1419–49.
11. Maden-Wilkinson TM, Balshaw TG, Massey GJ, Folland JP. What makes long-term resistance-trained individuals so strong? A comparison of skeletal muscle morphology, architecture, and joint mechanics. *J Appl Physiol.* 2020;128(4):1000–11.
12. Lazarczuk SL, Maniar N, Opar DA, Duhig SJ, Shield A, Barrett RS, et al. Mechanical, Material and Morphological Adaptations of Healthy Lower Limb Tendons to Mechanical Loading: A Systematic Review and Meta-Analysis. *Sports Med.* 2022;52(10):2405–29.
13. Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clin Biomech.* 2001;16(2):87–101.
14. Roberts TJ. Contribution of elastic tissues to the mechanics and energetics of muscle function during movement. *J Exp Biol.* 2016;219(2):266–75.
15. Taljanovic MS, Gimber LH, Becker GW, Latt LD, Klauser AS, Melville DM, et al. Shear-wave elastography: basic physics and musculoskeletal applications. *Radiographics.* 2017;37(3):855–70.
16. Wu J, Luo H, Ren S, Shen L, Cheng D, Wang N. Enhanced echo intensity of skeletal muscle is associated with poor physical function in hemodialysis patients: a cross-sectional study. *BMC Nephrol.* 2022;23(1):186.
17. Rahemi H, Nigam N, Wakeling JM. The effect of intramuscular fat on skeletal muscle mechanics: implications for the elderly and obese. *J R Soc Interface.* 2015;12(109):20150365.
18. Carvalho C, Serrão FV, Mancini L, Serrao PRM da S. Impaired muscle capacity of the hip and knee in individuals with isolated patellofemoral osteoarthritis: a cross-sectional study. *Ther Adv Chronic Dis.* 2021;12:20406223211028764.
19. Von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *Bull World Health Organ.* 2007;85(11):867–72.
20. Taniguchi M, Fukumoto Y, Kobayashi M, Kawasaki T, Maegawa S, Ibuki S, et al. Quantity and Quality of the Lower Extremity Muscles in Women with Knee Osteoarthritis. *Ultrasound Med Biol.* 2015 Oct 1;41(10):2567–74.
21. Mannarino P, Matta TT da, Oliveira LF de. An 8-week resistance training protocol is effective in adapting quadriceps but not patellar tendon shear modulus measured by Shear Wave Elastography. *PLoS One.* 2019;14(4):e0205782.
22. Bernabei M, Lee SSM, Perreault EJ, Sandercock TG. Shear wave velocity is sensitive to changes in muscle stiffness that occur independently from changes in force. *J Appl Physiol.* 2020;128(1):8–16.
23. Young H, Jenkins NT, Zhao Q, McCully KK. Measurement of intramuscular fat by muscle echo intensity. *Muscle Nerve.* 2015;52(6):963–71.
24. Blazevich AJ, Gill ND, Zhou S. Intra–and intermuscular variation in human quadriceps femoris architecture assessed in vivo. *J Anat.* 2006;209(3):289–310.
25. Mentiplay BF, Perraton LG, Bower KJ, Adair B, Pua Y-H, Williams GP, et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: a reliability and validity study. *PLoS One.*2015;10(10):e0140822.
26. Taş S, Yılmaz S, Onur MR, Soylu AR, Altuntaş O, Korkusuz F. Patellar tendon mechanical properties change with gender, body mass index and quadriceps femoris muscle strength. *Acta Orthop Traumatol Turc.* 2017;51(1):54–9.
27. Blank J, Blomquist M, Arant L, Cone S, Roth J. Characterizing musculoskeletal tissue mechanics based on shear wave propagation: a systematic review of current methods and reported measurements. *Ann Biomed Eng.*2022;50(7):751–68.
28. Chakouch MK, Charleux F, Bensamoun SF. Quantifying the elastic property of nine thigh muscles using magnetic resonance elastography. *PLoS One.* 2015;10(9):e0138873.
29. Alfuraih AM, Tan AL, O'Connor P, Emery P, Wakefield RJ. The effect of ageing on shear wave elastography muscle stiffness in adults. *Aging Clin Exp Res.* 2019;31(12):1755–63.
30. Xu J, Fu SN, Hug F. Age-related increase in muscle stiffness is muscle length dependent and associated with muscle force in senior females. *BMC Musculoskelet Disord.* 2021;22(1):829.
31. Lim J-Y, Choi SJ, Widrick JJ, Phillips EM, Frontera WR. Passive force and viscoelastic properties of single fibers in human aging muscles. *Eur J Appl Physiol.* 2019;119(10):2339–48.
32. Hirata K, Yamadera R, Akagi R. Associations between range of motion and tissue stiffness in young and older people. *Med Sci Sports Exerc.* 2020;52(10):2179-88.
33. Yoshiko A, Ando R, Akima H. Passive muscle stiffness is correlated with the intramuscular adipose tissue in young individuals. *Eur J Appl Physiol.* 2023;123(5):1081-90.
34. Chino K, Takahashi H. Measurement of gastrocnemius muscle elasticity by shear wave elastography: association with passive ankle joint stiffness and sex differences. *Eur J Appl Physiol.* 2016;116(4):823–30.
35. Tang X, Wang L, Guo R, Huang S, Tang Y, Qiu L. Application of ultrasound elastography in the evaluation of muscle strength in a healthy population. *Quant Imaging Med Surg.* 2020;10(10):1961-72.
36. Young H, Southern WM, Mccully KK. Comparisons of ultrasound–estimated intramuscular fat with fitness and health indicators. *Muscle Nerve.* 2016;54(4):743–9.
37. Hoffman LR, Koppenhaver SL, MacDonald CW, Herrera JM, Streuli J, Visco ZL, et al. Normative parameters of gastrocnemius muscle stiffness and associations with patient characteristics and function. *Int J Sports Phys Ther.* 2021;16(1):41-8.
38. Stock MS, Mota JA, Hernandez JM, Thompson BJ. Echo intensity and muscle thickness as predictors Of athleticism and isometric strength in middle–school boys. *Muscle Nerve.* 2017;55(5):685–92.
39. Addison O, Marcus RL, Lastayo PC, Ryan AS. Intermuscular fat: A review of the consequences and causes. *Int J Endocrinol.* 2014;2014:309570.
40. Purslow PP. The structure and functional significance of variations in the connective tissue within muscle. *Comp Biochem Physiol A Mol Integr Physiol.* 2002;133(4):947–66.