Research paper

Cite as: Ebihara B, Miyasaka H, Fukaya T, Mutsuzaki H: Quantitative evaluation of the effects of several weeks of static stretching on the flexibility of the rectus femoris using shear wave elastography: a before–after study. J Ultrason 2024; 24: 25. doi: 10.15557/JoU.2024.0025.

Submitted: 28.02.2024
Accepted: 05.06.2024
Published: 23.08.2024

Quantitative evaluation of the effects of several weeks of static stretching on the flexibility of the rectus femoris using shear wave elastography: a before–after study

Bungo Ebihara[1], Hayato Miyasaka[1,2], Takashi Fukaya[3], Hirotaka Mutsuzaki[4,5]

[1] *Department of Rehabilitation, Tsuchiura Kyodo General Hospital, Tsuchiura, Japan*
[2] *Graduate School of Health Sciences, Ibaraki Prefectural University of Health Sciences, Ami, Japan*
[3] *Department of Physical Therapy, Faculty of Health Sciences, Tsukuba International University, Tsuchiura, Japan*
[4] *Center for Medical Science, Ibaraki Prefectural University of Health Sciences, Ami, Japan*
[5] *Department of Orthopedic Surgery, Ibaraki Prefectural University of Health Sciences Hospital, Ami, Japan*

Corresponding author: Bungo Ebihara; e-mail: bun.hirakata@gmail.com

DOI: 10.15557/JoU.2024.0025

Keywords
Young's modulus; healthy volunteer; shear wave elastography; static stretching; rectus femoris muscle

Abstract

Aim: The study aimed to quantitatively clarify the effects of several weeks of static stretching on the flexibility of the rectus femoris muscle using shear wave elastography. **Material and methods:** Fifteen healthy men (age: 26.4 ± 2.2 years) were instructed to perform 5 min of voluntary static stretching of their right rectus femoris muscles five times a week for four weeks. The participants adjusted their stretching intensity to a point immediately before experiencing discomfort or pain. The Young's modulus of the rectus femoris muscle and the knee-flexion range of motion were measured as indicators of flexibility. The Young's modulus was measured using shear wave elastography. Measurements were performed at baseline, as well as at two and four weeks after the stretching program started. A generalized linear mixed model was used to assess the change in the Young's modulus after the stretching program and the effects of the Young's modulus on the knee-flexion range of motion. **Results:** The Young's modulus of the rectus femoris muscle decreased after two and four weeks of stretching compared with the baseline ($p = 0.0004$ and $p < 0.0001$, respectively). The Young's modulus of the rectus femoris muscle and the four-week duration of stretching affected the knee-flexion range of motion ($p = 0.0242$ and 0.0016, respectively). **Conclusions:** Shear wave elastography quantitatively revealed that several weeks of static stretching increased the flexibility of the rectus femoris muscle in healthy men. A four-week static stretching regimen reduced the Young's modulus of the rectus femoris muscle and increased the knee-flexion range of motion.

Introduction

Sports-related injuries include muscle injuries, and the rectus femoris muscle is a frequently injured site[1]. One of the risk factors for rectus femoris muscle injury is decreased flexibility, so increasing flexibility can help prevent rectus femoris muscle injury[2–4]. Therefore, quantitative measurement of the flexibility of the rectus femoris muscle is valuable in preventive health care.

Static stretching is an effective exercise to improve joint range of motion, i.e. flexibility[5]. Mechanical theories of increasing flexibility involve muscle viscoelasticity[6]. Shear wave elastography (SWE) is a technique that makes it possible to quantitatively measure elasticity as a value such as the Young's modulus[7] and is expected to be useful for determining the effectiveness of stretching[8]. SWE has been used to examine the immediate effects of static stretching. Static stretching immediately decreases muscle elasticity; however, these effects disappear over time[9–11]. Little is known about the effects of several weeks of static stretching on the rectus femoris muscle, as measured by SWE.

This study was aimed to quantitatively clarify the effects of several weeks of static stretching on the flexibility of the rectus femoris muscle using SWE. The hypothesis was that several weeks of static stretching would reduce the Young's modulus of the rectus femoris muscle and increase the knee-flexion range of motion. Clinically, the study revealed the duration of static stretching required to increase the flexibility of the rectus femoris muscle and the knee-flexion range of motion.

Materials and methods

Study design

This before-and-after study was conducted on healthy volunteers between January and March 2023. The participants were instructed to perform static stretching, and indicators related to flexibility were measured at baseline, i.e. before the stretching program started, as well as two and four weeks later. On the day of measurement, stretching was prohibited until the measurement was completed. The measurements were performed at a hospital in the early evening. All the measurements were done by a single physical therapist with eight years of experience in ultrasonography and SWE measurements.

The study was approved by the ethics committee at our institution (Reference number: 2022FY155) and was conducted following the Declaration of Helsinki. All the participants provided their written informed consent before study entry.

Participants

Fifteen healthy non-athlete males participated in the study. The inclusion criterion was the absence of knee pain or contracture of the knee joint. The exclusion criterion was an 80% or lower completion rate of the stretching program. The age, height, and weight of the participants were recorded, and their body mass index (BMI) was calculated using the measured values.

Static stretching program

The stretching program was developed based on review articles that examined the effects of chronic stretching[8,12]. The participants were instructed to perform voluntary static stretching of the right rectus femoris muscle five times a week for four weeks. Each stretch was conducted five times for 1 min for a total of 5 min, with a 30 s break in between. The participants stood up, grasped their right foot, extended their right hip, and flexed their right knee (Fig. 1)[9]. The participants held a handrail or a table with their left hand to prevent falls. Stretching intensity was applied immediately before the participants started experiencing discomfort or pain[10].

Measurement of static stretching program completion rate

The participants were given a calendar with dates for four weeks after the start of the static stretching program, and they marked the days when stretching was performed in the calendar. Then the calendar was checked, and the completion rate of the stretching program was calculated.

Measurement of the Young's modulus of the rectus femoris muscle and the patellar tendon

The Young's modulus of the right rectus femoris muscle and the patellar tendon was measured using an Aixplorer ultrasound unit in conjunction with a 2–10 MHz linear transducer (Supersonic Imaging, Aix-en-Provence, France). SWE is a reliable technique for measuring soft tissue elasticity around the knee joint[13–15]. Exercises that could cause delayed onset of muscle soreness were avoided two days before the measurement, as they affect muscle stiffness[16].

A preset musculoskeletal and knee setting was selected, and the SWE Opt was set in the penetration mode. The participants rested in a supine position with their legs hanging off the bed, knees bent at 90°, and the upper limbs placed on the sides of the body (Fig. 2). Talking during the measurements was prohibited. The measurer instructed the participants to relax and not to move any of the limbs.

The transducer was placed on the belly of the rectus femoris muscle, 2 cm proximal to the muscle-tendon transition, and on the patellar tendon, 1 cm distal to the patella (Fig. 3). The transducer was placed as parallel to the rectus femoris muscle and the patellar tendon fibers as possible[17]. A large amount of gel was applied between the skin and the transducer to avoid excessive pressure[18]. The measurer recorded three to six five-second SWE videos and saved the video with the most uniform SWE image.

Fig. 1. *Static stretching methods. The participants grasped their right foot, extended their right hip, and flexed their right knee*

Fig. 2. *Measurement position of the Young's modulus. The participants rested in a supine position with their legs hanging off the bed with knees bent at 90°*

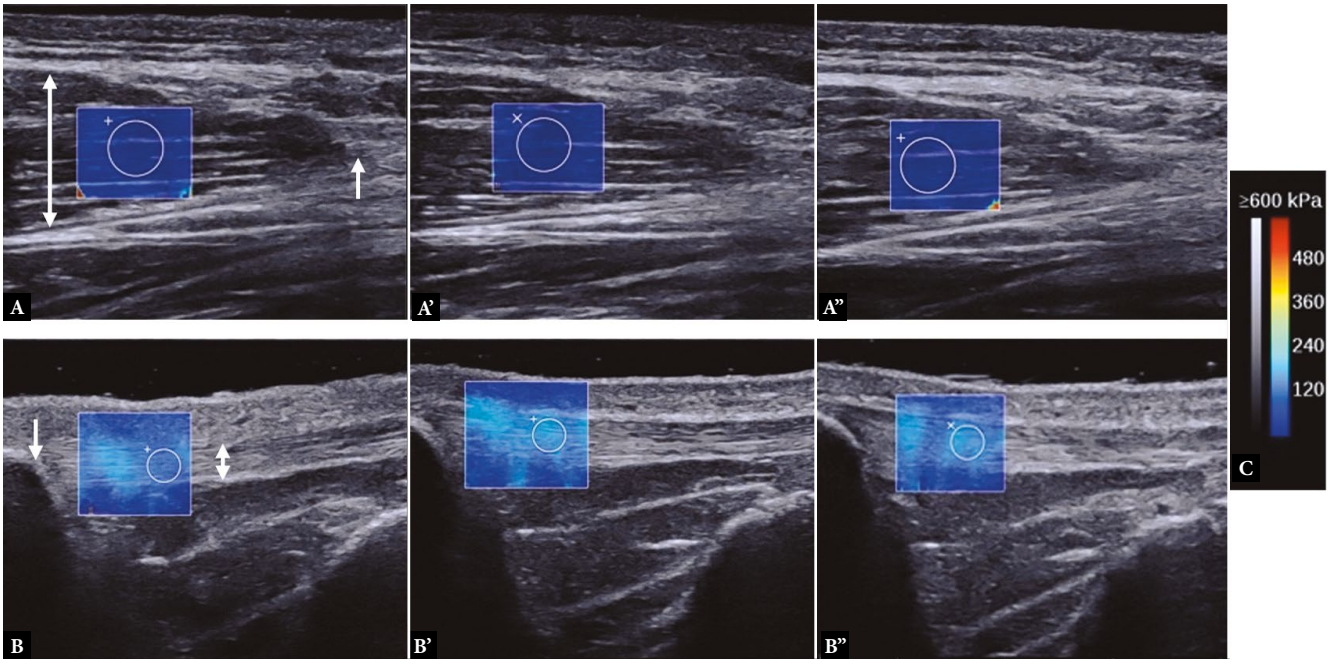

Fig. 3. *Measurement sites for the Young's modulus. The measurement sites for the Young's modulus were the rectus femoris muscle belly 2 cm proximal to the muscle-tendon transition (***A***, ***A'***, and ***A"***) and the patellar tendon 1 cm distal to the patella (***B***, ***B'***, and ***B"***). No quotation marks denote before the stretching program started, (') denotes after two weeks of stretching, and (") denotes after four weeks of stretching. The double arrow indicates the rectus femoris muscle and the single arrow indicates the muscle tendon transition in (***A***). The double arrow indicates the patellar tendon, and the single arrow indicates the patella in (***B***). The left side of each SWE image is proximal, and the right side is distal. (***C***) Grey and color scale*

The Young's modulus was measured in a blinded manner. An individual other than the measurer selected one of the saved videos to conceal the measurement date and the identity of the participant. The measurer played the selected video, paused when the SWE image was most uniform, and measured the Young's modulus. The measurement range was a circle with a diameter of 5 mm for the rectus femoris muscle, and as large as possible to fit within the tendon for the patellar tendon. The mean Young's modulus value within the measurement range was recorded[18]. The same process was repeated until all the videos were measured.

Measurement of the knee-flexion range of motion

The knee-flexion range of motion of the right leg was measured using goniometry. The participants were instructed to lie prone with their left leg lifted off the bed and their left hip joint flexed at 120° (Fig. 4). The measurer passively bent the participant's right knee until the participant experienced pain. The intersection angles of the thigh and lower leg axes were recorded as the knee-flexion range of motion. The thigh axis was defined as the line connecting the greater trochanter and the lateral epicondyle of the femur, and the lower leg axis was defined as the line connecting the fibular head and the lateral malleolus of the fibula.

Fig. 4. *Measurement position of the knee-flexion range of motion. The participants were instructed to lie prone with their left leg lifted off the bed and their left hip joint flexed at 120°*

Statistical analysis

A generalized linear mixed model (GLMM) with individuals as a random effect was used to analyze changes in the knee-flexion range of motion and the Young's modulus of the rectus femoris muscle and the patellar tendon at baseline and then two and four weeks after the stretching program started, since there were individual differences in the values measured before the stretching program. Furthermore, the GLMM was used to analyze the effect of the stretching duration and the Young's modulus of the rectus femoris muscle and the patellar tendon on the knee-flexion range of motion.

The GLMM was performed with the Satterthwaite method, using the GENLINMIXED command of IBM SPSS statistics (version 28.0; IBM Corp., Armonk, New York, USA). Statistical significance was set at p <0.05.

Results

Physical characteristics of the participants

The physical characteristics of the participants are summarized in Tab. 1. The mean (±standard deviation) age of participants was 26.4 (±2.2) years. None of the participants met the exclusion criterion of the stretching program completion rate of <80%.

Changes in the knee-flexion range of motion and the Young's modulus of the rectus femoris muscle and the patellar tendon

The changes in the knee-flexion range of motion and the Young's modulus of the rectus femoris muscle and the patellar tendon at two and four weeks after the stretching program started are summarized in Tab. 2. The knee-flexion range of motion increased after two and four weeks of stretching compared to the baseline (p = 0.0003 and p <0.0001, respectively). The Young's modulus of the rectus femoris muscle decreased after two and four weeks of stretching compared to the baseline (p = 0.0004 and p <0.0001, respectively).

Effect of stretching duration and the Young's modulus of the rectus femoris muscle and the patellar tendon on the knee-flexion range of motion

The effects of the Young's modulus and the stretching duration on the knee-flexion range of motion are summarized in Tab. 3. Model 1 used the Young's modulus of the rectus femoris muscle and the patellar tendon, as well as the stretching duration, as fixed effects. The results revealed significant fixed effects of the Young's modulus of the rectus femoris muscle (p = 0.0210) and the four-week stretching duration (p <0.0001) on the knee-flexion range of motion. The conditional Akaike information criterion (AICC) and the Schwarz Bayesian information criterion (BIC) were 314.626 and 317.679, respectively.

Model 2 used the Young's modulus of the rectus femoris muscle, the stretching duration, and their interaction as fixed effects. Similar to Model 1, there were significant fixed effects of the Young's modulus of the rectus femoris muscle (p = 0.0242) and the four-week stretching duration (p = 0.0016) on the knee-flexion range of motion. Furthermore, the interaction between the Young's modulus of the rectus femoris muscle and the four-week stretching duration was also significant (p = 0.0481). The AICC and BIC values were 307.634 and 310.628, respectively.

Discussion

The results of the study support our hypothesis that performing static stretching for several weeks decreases the Young's modulus of the rectus femoris muscle and increases the knee-flexion range of motion.

Our findings show that the Young's modulus of the rectus femoris muscle decreased two weeks after the initiation of static stretching. Furthermore, the GLMM model in this study revealed that the Young's modulus of the rectus femoris muscle affected the knee-flexion range of motion. Several weeks of static stretching can decrease the Young's modulus of muscle and increase the joint range of motion. Modified sensation seems to be primarily responsible for the increase in flexibility with stretching within eight weeks, while the muscle properties do not seem to change[8]. However, this study indicates a change in the Young's modulus of muscle. Other studies have also reported changes in muscle properties after four to five weeks of stretching, determined by SWE[19–21]. These are interesting findings about increasing flexibility. Further studies using SWE are necessary to quantitatively demonstrate the effects of several weeks of stretching on muscle properties.

Our GLMM model found that a four-week duration of static stretching, not a two-week regimen, was required to increase the knee-flexion range of motion. A four-week duration of stretching reduced the Young's modulus of the rectus femoris muscle and increased the knee-flexion range of motion. Therefore, at least four weeks of static stretching are recommended to improve flexibility.

Tab. 1. Physical characteristics of the participants

Physical characteristics	Participants (n = 15)
Age (years)	26.4 ± 2.2[a]
Height (m)	1.73 ± 0.03[a]
Body weight (kg)	66.0 ± 6.9[a]
BMI (kg/m^2)	22.0 ± 1.9[a]

BMI – body mass index
[a]Values are presented as the mean ± standard deviation

Tab. 2. Changes in measured values

	Pre		2w		4w		Pre-2w		Pre-4w	
	Mean	95% CI	Mean	95% CI	Mean	95% CI	t	p value	t	p value
Young's modulus of the rectus femoris muscle (kPa)	35.6	31.0–40.2	29.5	24.9–34.1	28.0	23.4–32.6	−4.028	0.0004*	−5.027	<0.0001*
Young's modulus of the patellar tendon (kPa)	162.9	118.0–207.8	144.8	99.9–189.7	143.9	99.0–188.8	−1.354	0.1864	−1.422	0.1660
Knee-flexion range of motion (°)	122.6	113.9–131.4	130.3	121.5–139.0	137.5	128.7–146.2	4.118	0.0003*	7.986	<0.0001*

* Statistically significant
pre – before the stretching program started; 2w – after 2 weeks of stretching; 4w – after 4 weeks of stretching; 95% CI – 95% confidence interval

Tab. 3. Effect of the Young's modulus and stretching duration on the knee-flexion range of motion

	Model 1		Model 2	
	t	*p* value	t	*p* value
Intercept	17.284	<0.0001*	16.795	<0.0001*
Time (4w)	4.483	<0.0001*	3.393	0.0016*
Time (2w)	1.938	0.0597	0.866	0.3918
Time (pre)	–		–	
Young's modulus of the rectus femoris muscle	−2.402	0.0210*	−2.345	0.0242*
Young's modulus of the patellar tendon	−0.777	0.4419	–	
Young's modulus of the rectus femoris muscle*Time (4w)	–		−2.041	0.0481*
Young's modulus of the rectus femoris muscle*Time (2w)	–		−0.195	0.8461
Young's modulus of the rectus femoris muscle*Time (pre)	–		–	
AICC	314.626		307.634	
BIC	317.679		310.628	

*Statistically significant
pre – before the stretching program started; 2w – 2-week stretching duration; 4w – 4-week stretching duration; AICC – conditional Akaike's information criterion; BIC – Schwarz's Bayesian information criterion

The recommendation could be used in stretching programs to prevent the onset of rectus femoris muscle injury. The target value in prevention programs for soccer players is a knee-flexion range of motion greater than 128° in the prone position with the opposite hip flexed at 90°[2,3]. The measurement posture in this study resembled that in the previous study[3]. The knee-flexion range of motion in the participants in this study increased to the mean of 137.5° (95% CI 128.7–146.2) after four weeks of stretching, thus indicating that the stretching program may be effective.

This study has four limitations. First, it was limited to a small number of healthy men. Therefore, further studies with a larger sample size and female participants would be desirable. Second, we did not use electromyography when measuring the Young's modulus. Muscle contraction affects the Young's modulus; therefore, measuring muscle tone is important[22]. Third, the measurement site of the Young's modulus was localized. Stretching effects will extend beyond the measured region. Fourth, we did not perform measurements three weeks after the stretching program started. Therefore, it is unclear whether a three-week stretching duration can affect the knee-flexion range of motion. Further studies are required to address these limitations.

Conclusion

SWE quantitatively revealed that several weeks of static stretching increased the flexibility of the rectus femoris muscle in healthy men. We confirmed that four weeks of static stretching reduced the Young's modulus of the rectus femoris muscle and increased the knee-flexion range of motion. Clinically, we recommend static stretching for at least four weeks to increase flexibility. SWE is an acceptable method to quantitatively measure changes in muscle properties after stretching.

Conflict of interest

The authors do not report any financial or personal connections with other persons or organizations that might negatively affect the contents of this publication and/or claim authorship rights to this publication.

Acknowledgments

The authors would like to thank Koichi Iwai for advice on the statistical analysis.

Author contributions

Original concept of study: BE, HaMi, TF, HiMu. Writing of manuscript: BE. Analysis and interpretation of data: BE. Final acceptation of manuscript: BE, HaMi, TF, HiMu. Collection, recording and/or compilation of data: BE. Critical review of manuscript: BE, HaMi, TF, HiMu.

References

1. Isern-Kebschull J, Mechó S, Pruna R, Kassarjian A, Valle X, Yanguas X *et al.*: Sports-related lower limb injuries: pattern recognition approach and MRI review. Insights Imaging 2020; 11: 108. doi: 10.1186/s13244-020-00912-4.
2. Mendiguchia J, Alentorn-Geli E, Idoate F, Myer GD: Rectus femoris muscle injuries in football: a clinically relevant review of mechanisms of injury, risk factors and preventive strategies. Br J Sports Med 2013; 47: 359–366. doi: 10.1136/bjsports-2012-091250.
3. Witvrouw E, Danneels L, Asselman P, D'Have T, Cambier D: Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study. Am J Sports Med 2003; 31: 41–46. doi: 10.1177/03635465030310011801.
4. Fousekis K, Tsepis E, Poulmedis P, Athanasopoulos S, Vagenas G: Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: a prospective study of 100 professional players. Br J Sports Med 2011; 45: 709–714. doi: 10.1136/bjsm.2010.077560.
5. Konrad A, Alizadeh S, Daneshjoo A, Anvar SH, Graham A, Zahiri A *et al.*: Chronic effects of stretching on range of motion with consideration of potential moderating variables: A systematic review with meta-analysis. J Sport Health Sci 2024; 13: 186–194. doi: 10.1016/j.jshs.2023.06.002.
6. Weppler CH, Magnusson SP: Increasing muscle extensibility: A matter of increasing length or modifying sensation? Phys Ther 2010; 90: 438–449.
7. Bercoff J: ShearWave elastography. https://www.konicaminolta.jp/healthcare/products/us/aixplorer/pdf/whitepaper_swe_eng.pdf. [Accessed February 9, 2024]
8. Freitas SR, Mendes B, Le Sant G, Andrade RJ, Nordez A, Milanovic Z: Can chronic stretching change the muscle-tendon mechanical properties? A review. Scand J Med Sci Sports 2018; 28: 794–806. doi: 10.1111/sms.12957.
9. Caliskan E, Akkoc O, Bayramoglu Z, Gozubuyuk OB, Kural D, Azamat S *et al.*: Effects of static stretching duration on muscle stiffness and blood flow in the rectus femoris in adolescents. Med Ultrason 2019; 21: 136–143. doi: 10.11152/mu-1859.
10. Nakamura M, Sato S, Murakami Y, Kiyono R, Yahata K, Sanuki F *et al.*: The comparison of different stretching intensities on the range of motion and muscle stiffness of the quadriceps muscles. Front Physiol 2020; 11: 628870. doi: 10.3389/fphys.2020.628870.
11. Taniguchi K, Shinohara M, Nozaki S, Katayose M: Acute decrease in the stiffness of resting muscle belly due to static stretching. Scand J Med Sci Sports 2015; 25: 32–40. doi: 10.1111/sms.12146.

12. Thomas E, Bianco A, Paoli A, Palma A: The relation between stretching typology and stretching duration: the effects on range of motion. Int J Sports Med 2018; 39: 243–254. doi: 10.1055/s-0044-101146.
13. Wu J, Qian Z, Liang W, Liu J, Ren L, Ren L: In vivo assessment of material properties of muscles and connective tissues around the knee joint based on shear wave elastography. J Mech Behav Biomed Mater 2020; 109: 103829. doi: 10.1016/j.jmbbm.2020.103829.
14. Alfuraih AM, O'Connor P, Tan AL, Hensor E, Emery P, Wakefield RJ: An investigation into the variability between different shear wave elastography systems in muscle. Med Ultrason 2017; 19: 392–400. doi: 10.11152/mu-1113.
15. Schneebeli A, Folli A, Falla D, Barbero M: Reliability of sonoelastography measurements of lower limb tendon properties: a systematic review. Ultrasound Med Biol 2021; 47: 1131–1150. doi: 10.1016/j.ultrasmedbio.2020.12.018.
16. Muanjai P, Mickevicius M, Snieckus A, Jones DA, Zachovajevas P, Satkunskiene D *et al.*: Response of knee extensor muscle-tendon unit stiffness to unaccustomed and repeated high-volume eccentric exercise. Int J Environ Res Public Health 2021; 18: 4510. doi: 10.3390/ijerph18094510.
17. Eby SF, Song P, Chen S, Chen Q, Greenleaf JF, An KN: Validation of shear wave elastography in skeletal muscle. J Biomech 2013; 46: 2381–2387. doi: 10.1016/j.jbiomech.2013.07.033.
18. Kot BC, Zhang ZJ, Lee AW, Leung VY, Fu SN: Elastic modulus of muscle and tendon with shear wave ultrasound elastography: variations with different technical settings. PLoS One 2012; 7: e44348. doi: 10.1371/journal.pone.0044348.
19. Ichihashi N, Umegaki H, Ikezoe T, Nakamura M, Nishishita S, Fujita K *et al.*: The effects of a 4-week static stretching programme on the individual muscles comprising the hamstrings. J Sports Sci 2016; 34: 2155–2159. doi: 10.1080/02640414.2016.1172725.
20. Yamauchi T, Hasegawa S, Nakamura M, Nishishita S, Yanase K, Fujita K *et al.*: Effects of two stretching methods on shoulder range of motion and muscle stiffness in baseball players with posterior shoulder tightness: a randomized controlled trial. J Shoulder Elbow Surg 2016; 25: 1395–1403. doi: 10.1016/j.jse.2016.04.025.
21. Akagi R, Takahashi H: Effect of a 5-week static stretching program on hardness of the gastrocnemius muscle. Scand J Med Sci Sports 2014; 24: 950–957. doi: 10.1111/sms.12111.
22. Shinohara M, Sabra K, Gennisson JL, Fink M, Tanter M: Real-time visualization of muscle stiffness distribution with ultrasound shear wave imaging during muscle contraction. Muscle Nerve 2010; 42: 438–441. doi: 10.1002/mus.21723.