Immediate Effect of Cumulative Transverse Strain via Exercise on the Achilles Tendon in Individuals with and Without Flat Feet

Serkan Taş, PhD, PT*
Murat Fatih Koçyiğit, MSc, PT†
Ayça Aracı, PhD, PT‡
Muhammed Taha Tüfek, MSc, PT§

Background: Flat feet change lower-extremity alignment, and they may change the load distribution on the Achilles tendon during exercise. The purpose of this study was to investigate the immediate effect of cumulative transverse strain via resistive ankle plantarflexion exercise on the Achilles tendon in individuals with flat feet.

Methods: Fourteen individuals with flat feet and 14 age-matched individuals with normal foot posture were enrolled. Achilles tendon thickness was measured by an ultrasonography device with a linear probe at three points: 1, 2, and 3 cm proximal to the superior aspect of the calcaneus. Ultrasonography measurements were performed before and after participants completed 90 repetitions of double-leg calf raise exercises, which included moving the foot from full ankle dorsiflexion to full ankle plantarflexion.

Results: Achilles tendon thickness at all three points measured was thinner in the flat feet group at preexercise and postexercise conditions compared with that of the control group ($P < .05$). Achilles tendon thickness at all three points decreased after the exercise in both groups ($P < .001$). The differences in Achilles tendon thickness at all three points measured between preexercise and postexercise conditions were lower in individuals with flat feet than in those of the control group ($P < .05$).

Conclusions: There was a significant decrease in Achilles tendon thickness after exercise in both groups; however, tendon thickness markedly diminished in individuals with normal foot posture. The findings are thought to result from changes in tendon structure and load distribution on the Achilles tendon. (J Am Podiatr Med Assoc 115(3), 2025; doi:10.7547/22-230)

Flat feet (FF), also known as pes planus, are one of the most prevalent foot abnormalities in adults, characterized by decreased medial longitudinal arch height and the dorsiflexed and abducted forefoot.[1] A variety of factors cause FF, including body composition,[2] foot intrinsic and extrinsic muscle weakness,[3] foot and ankle injuries,[4] hereditary features,[5] iatrogenic variables,[6] pregnancy,[7] and neurologic problems.[8] On the other hand, FF could lead to insufficient foot function, such as failure in body weight support or alteration in force distribution,[9] and it is associated with foot pathologic conditions such as metatarsalgia[10] or plantar fasciitis[11] as well as Achilles tendinopathy.[12] There are some biomechanical approaches to explain the relationship between FF and Achilles tendon (AT) pathologies. Excessive foot pronation related to FF creates a torsional or whipping action on the AT as the foot rotates quickly from a supinated position at heel strike to an excessive pronated position in midstance.[13] This recurrent whipping phenomenon could cause microtears in the tendon, and it could trigger an inflammatory process in the AT.[14,15] In

*Department of Physical Therapy and Rehabilitation, Faculty of Health Science, Toros University, Mersin, Turkey.

†Department of Therapy and Rehabilitation, Vocational School of Health Services, Alanya Alaaddin Keykubat University, Antalya, Turkey.

‡Department of Physical Therapy and Rehabilitation, Faculty of Health Science, Alanya Alaaddin Keykubat University, Antalya, Turkey.

§Department of Therapy and Rehabilitation, Vocational School of Health Services, Toros University, Mersin, Turkey.

Corresponding author: Serkan Taş, PhD, PT, Department of Physical Therapy and Rehabilitation, Faculty of Health Science, Toros University, 33140, Mersin, Turkey. (E-mail: serkntas@gmail.com)

addition, this whipping phenomenon is thought to result in vascular blanching of the midportion of the AT, and it results in vascular damage and degenerative processes in the AT.[15] Furthermore, FF cause an increase in hindfoot valgus because of reduced medial longitudinal height, and they change the load distribution on the AT.[16,17] It is widely believed that tendinopathies are overuse injuries caused by the inability of the tendon to adapt to loading conditions.[18] Theoretically, the previously mentioned changes in the tendon have the potential to alter the AT structure and/or morphology over time. There are very limited studies investigating the changes in AT morphology in individuals with FF. These studies reported that adults[19] and children[20] with FF had lower AT thickness compared with a control group. The decrease in AT thickness is thought to result from decreased load on the AT.[19,20] However, to our knowledge, there is no study that investigated the immediate response of the AT to cumulative transverse strain via exercise in individuals with FF. Changes in tendon thickness due to loading via exercise provide important information about changes in tendon structure, such as deficiency in tendon extracellular matrix or collagen fibril disorganization.[21-24] In theory, tendon structure changes impair fluid movement with the application of tensile load, and fluid movement impairment is manifested by less reduction in tendon thickness against loads via cumulative transverse strain.[21,25-27] The immediate response of the AT that occurs in the tendon against loads via cumulative transverse strain can provide important information about the abnormal loads in the AT and/or change in the tendon structure in individuals with FF. Therefore, the aim of the present study was to investigate the immediate effect of cumulative transverse strain via resistive ankle plantarflexion exercise on the AT and to compare the results with those of individuals with normal foot posture. Another aim of the study was to expose the effects of FF in morphological features of the AT. We hypothesize that 1) AT thickness will be lower in individuals with FF and 2) the amount of decrease in AT thickness will be less after cumulative transverse strain via exercise in participants with FF compared with the control group.

Materials and Methods

Participants

A total of 28 individuals (six males and 22 females) aged 20 to 38 years (mean ± SD age, 23.5 ± 5.1 years) were included in this study. The navicular drop test (NDT) and the Foot Posture Index (FPI) were used to decide whether individuals had FF. The NDT and the FPI were reported as reliable and valid in identifying FF in adults.[28-30] Participants with an FPI score between 0 and 5 were considered to have normal foot posture, and an FPI score of 6 or higher indicated that the individual has FF.[28,29] The NDT was performed to measure the difference in distance between the navicular tuberosity and the floor during sitting (both feet flat on the ground with hips and knees flexed at 90˚) and standing (placing equal amounts of body weight on each leg) positions. Individuals with a navicular drop of 1 cm or more were considered to have FF.[31] Based on the NDT and FPI findings, 14 individuals (11 females and 3 males) were determined to have a normal foot posture, and 14 individuals (11 females and 3 males) as having FF. Individuals were excluded from the study if they met any of the following criteria: 1) having a systemic or neurologic disease; 2) having a lower-extremity orthopedic disorder such as Achilles tendinitis, ligament injuries, or meniscopathy; 3) having a history of lower-extremity surgery or major trauma; 4) having a marked postural deformity in the lower extremities, such as genu valgum, genu recurvatum, or coxa vara; 5) performing strenuous exercises within 24 hours before measurements; or 6) having a body mass index greater than 30 (the weight in kilograms divided by the square of the height in meters). This study was performed in line with the principles of the Declaration of Helsinki. Ethical approval was obtained from Toros University Ethics Committee (Mersin, Turkey). An informed consent form was signed by each participant.

Ultrasonographic Measurements

The measurements of AT thickness were performed using an ultrasonography device with a linear probe (5–12 MHz) (MicrUs Scanner; Telemed, Vilnius, Lithuania). The measurements were performed by an operator (S.T.) with 6 years of experience in musculoskeletal ultrasonography. The operator was blinded to group allocations. Measurements were performed only on the dominant extremity. The dominant leg of the participants was determined by questioning the leg that they used to kick a ball.[32] All of the measurements were performed between 9 AM and 11 AM. In accordance with previous studies,[23,33] ultrasonographic assessments were performed while the participants were in a prone position with their feet hanging over the end of the examination table. Before the ultrasonographic measurements, the individuals

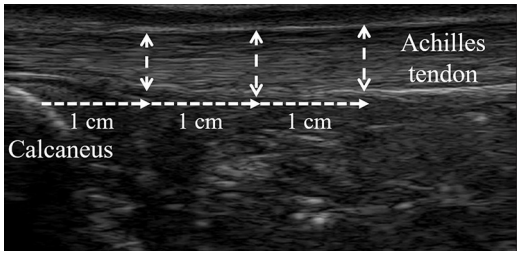

Figure 1. Measurements of Achilles tendon thickness 1, 2, and 3 cm proximal to the superior aspect of the calcaneus.

were allowed to have 10 min of rest in this position. Ultrasonographic measurements were made parallel to the longitudinal axis of the AT. The ultrasound probe was placed on the skin with light pressure to avoid any deformation in the tendon thickness. Ultrasonic images recorded the tendon that included the superior aspect of the calcaneus and the distal AT. The images were analyzed with a software package (RadiAnt DICOM Viewer; Medixant, Poznan, Poland). The analyses were performed by a researcher who was blinded to group allocations. In accordance with previous studies,[23,33-35] the AT thickness was measured using ultrasonic images recorded at three different points, 1 cm (AT-1), 2 cm (AT-2), and 3 cm (AT-3) proximal to the superior aspect of the calcaneus (Fig. 1).

Exercise Protocol

After ultrasonographic measurements, the participants completed the exercise protocol. Similar to previous studies,[22,23,33] the exercise protocol consisted of 90 repetitions of double-leg calf raise exercises, which included moving the foot from full ankle dorsiflexion to full ankle plantarflexion at a rate of approximately 1 Hz. It was reported that the exercise causes a resistance of between 100% and 150% of body weight on the AT, which is similar to the tensile loads exerted by AT during gait.[22,23,33] The ultrasonographic measurements were repeated immediately after the exercise protocol.

Statistical Analyses

A statistical software package was used to perform statistical analyses (IBM SPSS Statistics for Windows, Version 22.0; IBM Corp, Armonk, New York). To decide whether the assessed parameters were normally distributed, analytical methods (Shapiro-Wilk test or Kolmogorov-Smirnov test) and visual methods (probability plots and histograms) were used. Demographic data and the assessed parameters are presented using mean ± SD. The independent Student t test was used to compare the assessed parameters between the FF and control groups. The paired Student t test was used when comparing preexercise and postexercise AT thickness. A $P < .05$ was considered statistically significant.

Results

Both groups were similar in age ($P = .537$), height ($P = .679$), body mass ($P = .752$), and body mass index ($P = .943$) (Table 1). The AT thickness at the points of AT-1, AT-2, and AT-3 were significantly lower at preexercise and postexercise conditions in individuals with FF compared with the control group ($P < .05$). Thickness at AT-1, AT-2, and AT-3 decreased after exercise in both groups ($P < .001$). The differences in thickness at AT-1, AT-2, and AT-3 between preexercise and postexercise were higher

Table 1. Demographic Data of Individuals with Flat Feet and the Control Group

Parameter	Flat Feet Group (n = 14)	Control Group (n = 14)	*P* Value
Age (mean ± SD [years])	22.9 ± 3.9	24.1 ± 6.2	.537
Height (mean ± SD [m])	1.69 ± 0.1	1.71 ± 0.1	.679
Mass (mean ± SD [kg])	61.2 ± 14.6	63.2 ± 17.4	.752
Body mass index (mean ± SD)	21.2 ± 3.0	21.3 ± 3.0	.943
Foot Posture Index score (mean ± SD)	7.5 ± 1.3	2.4 ± 1.7	<.001[a]
Navicular drop (mean ± SD [cm])	1.3 ± 0.2	0.5 ± 0.2	<.001[a]
Sex (No. [%])			
Male	3 (21)	3 (21)	
Female	11 (79)	11 (79)	
Dominant limb (No. [%])			
Right	14 (100)	13 (93)	
Left	0	1 (7)	

[a] $P < .05$, Student t test.

in the control group compared with individuals with FF ($P < .05$) (Table 2).

Discussion

One of the aims of this study was to investigate the effect of foot posture on AT morphology. We hypothesized that AT thickness will be lower in individuals with FF compared with individuals with normal foot posture. Consistent with the hypothesis, it was found that individuals with FF had a thinner AT compared with those with normal foot posture. There are a few studies investigating the effect of foot posture on AT morphology. Similar to the present findings, Murley et al[19] found that AT thickness was lower in adults with FF compared with adults with normal foot posture. Furthermore, Gonul et al[20] indicated a decrease in AT thickness in children with FF. The reduction in AT thickness is thought to result from decreased load on the AT during gait.[19,20] There are some potential reasons for a decrease in load on the AT. It was reported that FF increased the valgus hindfoot moment arm and caused a reduction in the moment arm of the AT as well as in the load on the AT while standing.[16,17] Moreover, increased hindfoot valgus causes insufficient foot rigidity during locomotion and propulsion.[36] Insufficient foot rigidity causes an impairment or inefficiency in load transfer from the hindfoot to the forefoot during the propulsion phase of gait,[19,36] and it decreases the lever arm of the AT as well as the load on the AT.[19] The mechanical loading is very important to ensure tendon hemostasis. The decreased mechanical loading could cause a decrease in new extracellular matrix formation and collagen fiber synthesis, and it could cause a decrease in tendon thickness over time.[37-39] On the other hand, a decrease in AT thickness may cause an increase in predisposition to AT pathologies such as tendinopathy or rupture. It was suggested that tendon ruptures more easily in a thinner tendon because of the increased stress concentration compared with the thicker tendon.[40,41]

To our knowledge, this is the first study investigating the immediate effect of resistance exercise on the AT in individuals with FF. The findings from the present study demonstrate that AT thickness significantly decreased after double-leg calf raise exercises in individuals with and without FF. There are several studies that reported the immediate effects of intense or prolonged ankle exercises on AT thickness in healthy or asymptomatic individuals. Similar to the present results, these studies reported a 15% to 20% reduction in AT after intense or prolonged ankle exercises in healthy individuals.[21-23,33] The decrease in AT thickness is thought to result from the movement of fluid out of the tendon due to loading and tension on the tendon after the exercises.[22,23,33] On the other hand, it was hypothesized that the response of AT will be different against cumulative transverse strain via exercise in individuals with and without FF. In line with

Table 2. Preexercise and Postexercise Conditions in Individuals with and Without Flat Feet

Parameter	Flat Feet Group (n = 14)	Control Group (n = 14)	*P* Value
AT-1			
Preexercise (mm)	3.6 ± 0.5	4.3 ± 0.6	.001[a]
Postexercise (mm)	3.3 ± 0.4	3.7 ± 0.5	.007[a]
Difference (mm)	0.3 ± 0.2	0.6 ± 0.3	.009[a]
Difference (%)	9.1 ± 3.4	13.4 ± 6.0	.028[a]
AT-2			
Preexercise (mm)	3.7 ± 0.5	4.5 ± 0.6	.001[a]
Postexercise (mm)	3.3 ± 0.4	3.7 ± 0.5	.041[a]
Difference (mm)	0.4 ± 0.2	0.8 ± 0.3	.001[a]
Difference (%)	11.1 ± 4.6	17.5 ± 5.9	.003[a]
AT-3			
Preexercise (mm)	3.9 ± 0.4	4.6 ± 0.5	.003[a]
Postexercise (mm)	3.5 ± 0.4	3.8 ± 0.5	.061
Difference (mm)	0.5 ± 0.2	0.7 ± 0.3	.010[a]
Difference (%)	11.3 ± 5.1	15.8 ± 5.9	.038[a]

Note: Data are given as mean ± SD.

Abbreviations: AT-1, Achilles tendon thickness 1 cm proximal to the superior aspect of the calcaneus; AT-2, Achilles tendon thickness 2 cm proximal to the superior aspect of the calcaneus; AT-3, Achilles tendon thickness 3 cm proximal to the superior aspect of the calcaneus.

[a]$P < .05$, Student *t* test.

the hypothesis, it was found that the amount of decrease in AT thickness after double-leg calf raise exercises in individuals with FF (~11% reduction) was less than that of the control group (~15% reduction). There may be some reasons for the difference in the exercise response of the tendon between groups. The AT may be exposed to less load during exercises in individuals with FF because of the previously mentioned changes, such as the decrease in the moment arm of the AT, and it might cause less movement of fluid out of the tendon because fluid movement usually occurs with tendon loading.[25-27] Less fluid out of the tendon will cause less reduction in tendon thickness in individuals with FF. Moreover, less fluid movement may be related to changes in collagen structure due to changes in the load of the AT in individuals with FF. Previous studies hypothesized that changes in collagen structure, such as collagen fibril disorganization or thinning, reduce the interfibrillar space and could cause a decrease in intratendinous fluid mobility and/or movement of fluid out of the tendon when the tendon is under tension or load.[21,24,25] On the other hand, intratendinous fluid mobility is considered to play an important role in tendon homeostasis,[42] and a reduction in intratendinous fluid mobility may cause an impairment in nutritional pathways in tendon.[43] Speculatively, reduced intratendinous fluid mobility may cause an increase in the predisposition to AT pathology observed in individuals with FF.

The present study has a few limitations. First, AT thickness measurements were conducted only in the longitudinal plane. Use of the horizontal plane for cross-sectional area measurements would provide more information about the effect of FF on AT. Second, the present study included only young and asymptomatic individuals. The effect of resistive ankle plantarflexion exercises may be different in middle-aged and/or older adults because age can cause changes in AT structure.[44,45] Third, ultrasonographic measurement was performed only before and after eccentric ankle exercises. In future studies, additional measurements may be performed at some intervals after eccentric exercises to investigate time-dependent changes. Finally, in the current investigation, changes in the morphological features of the AT in individuals with FF were compared with those of healthy people. Further research is needed to increase clarification of morphological changes in AT thickness in patients with varying levels of FF severity, which may have more practical significance for FF management.

Conclusions

It was found that individuals with FF had a thinner AT compared with individuals with normal foot posture. In addition, there was a significant decrease in AT thickness after exercise in both groups; however, the reduction in AT thickness was lower in individuals with FF (~11%) than in the control group (~15%). This finding is thought to result from structural changes in the AT and/or decreased load on the AT that might cause a decrease in interstitial fluid movement during loading on the tendon. These changes may be related to the higher prevalence of AT pathologies in individuals with FF. Therapeutic approaches such as orthoses and exercises, which maintain normal medial arch height, may help prevent structural changes in the tendon or AT pathologies in individuals with FF.

Financial Disclosure: None reported.
Conflict of Interest: None reported.

References

1. Franco AH: Pes cavus and pes planus: analyses and treatment. Phys Ther **67:** 688, 1987.
2. Wearing SC, Hennig EM, Byrne NM, et al: Musculoskeletal disorders associated with obesity: a biomechanical perspective. Obes Rev **7:** 239, 2006.
3. McKeon PO, Hertel J, Bramble D, et al: The foot core system: a new paradigm for understanding intrinsic foot muscle function. Br J Sports Med **49:** 290, 2015.
4. Blitz NM, Stabile RJ, Giorgini RJ, et al: Flexible pediatric and adolescent pes planovalgus: conservative and surgical treatment options. Clin Podiatr Med Surg **27:** 59, 2010.
5. Mosca VS: Flexible flatfoot in children and adolescents. J Child Orthop **4:** 107, 2010.
6. Pecheva M, Devany A, Nourallah B, et al: Long-term follow-up of patients undergoing tibialis posterior transfer: is acquired pes planus a complication? Foot (Edinb) **34:** 83, 2018.
7. Conder R, Zamani R, Akrami M: The biomechanics of pregnancy: a systematic review. J Funct Morphol Kinesiol **4:** 72, 2019.
8. Dare DM, Dodwell ER: Pediatric flatfoot: cause, epidemiology, assessment, and treatment. Curr Opin Pediatr **26:** 93, 2014.
9. Arachchige SNK, Chander H, Knight A: Flatfeet: biomechanical implications, assessment and management. Foot (Edinb) **38:** 81, 2019.
10. Madjarevic M, Kolundzic R, Trkulja V, et al: Biomechanical analysis of functional adaptation of metatarsal bones in statically deformed feet. Int Orthop **33:** 157, 2009.
11. Wearing SC, Smeathers JE, Urry SR, et al: The pathomechanics of plantar fasciitis. Sports Med **36:** 585, 2006.

12. Wnuk-Scardaccione A, Mizia E, Rutowicz B, et al: Is there a relationship between functional flat foot and prevalence of non-insertional Achilles tendinopathy in joggers? A pilot study. Folia Med Cracov **57:** 77, 2017.
13. Wezenbeek E, Willems TM, Mahieu N, et al: Is Achilles tendon blood flow related to foot pronation? Scand J Med Sci Sports **27:** 1970, 2017.
14. Kvist M: Achilles tendon injuries in athletes. Sports Med **18:** 173, 1994.
15. Clement D, Taunton J, Smart G: Achilles tendinitis and peritendinitis: etiology and treatment. Am J Sports Med **12:** 179, 1984.
16. Arangio G, Rogman A, Reed JF: Hindfoot alignment valgus moment arm increases in adult flatfoot with Achilles tendon contracture. Foot Ankle Int **30:** 1078, 2009.
17. Deforth M, Zwicky L, Horn T, et al: The effect of foot type on the Achilles tendon moment arm and biomechanics. Foot (Edinb) **38:** 91, 2019.
18. Fredberg U, Stengaard-Pedersen K: Chronic tendinopathy tissue pathology, pain mechanisms, and etiology with a special focus on inflammation. Scand J Med Sci Sports **18:** 3, 2008.
19. Murley G, Tan J, Edwards R, et al: Foot posture is associated with morphometry of the peroneus longus muscle, tibialis anterior tendon, and Achilles tendon. Scand J Med Sci Sports **24:** 535, 2014.
20. Gonul Y, Yucel O, Eroglu M, et al: Ultrasonographic evaluation of Achilles tendon in children with flatfoot: a case-control morphometric study. Diagn Interv Imaging **97:** 907, 2016.
21. Wearing S, Smeathers J, Urry S, et al: "The Time-Course of Acute Changes in Achilles Tendon Morphology Following Exercise," in *The Impact of Technology on Sport II*, edited by FK Fuss, A Subic, S Ujihashi, p 65, Taylor & Francis, New York, 2008.
22. Wearing SC, Grigg NL, Hooper SL, et al: Conditioning of the Achilles tendon via ankle exercise improves correlations between sonographic measures of tendon thickness and body anthropometry. J Appl Physiol (1985) **110:** 1384, 2011.
23. Wearing SC, Hooper SL, Grigg NL, et al: Overweight and obesity alters the cumulative transverse strain in the Achilles tendon immediately following exercise. J Bodyw Mov Ther **17:** 316, 2013.
24. Lanir Y, Salant EL, Foux A: Physico-chemical and microstructural changes in collagen fiber bundles following stretch in-vitro. Biorheology **25:** 591, 1988.
25. Wellen J, Helmer KG, Grigg P, et al: Spatial characterization of T1 and T2 relaxation times and the water apparent diffusion coefficient in rabbit Achilles tendon subjected to tensile loading. Magn Reson Med **53:** 535, 2005.
26. Grigg NL, Stevenson NJ, Wearing SC, et al: Incidental walking activity is sufficient to induce time-dependent conditioning of the Achilles tendon. Gait Posture **31:** 64, 2010.
27. Grigg NL, Wearing SC, Smeathers JE: Achilles tendinopathy has an aberrant strain response to eccentric exercise. Med Sci Sports Exerc **44:** 12, 2012.
28. Aquino MRC, Avelar BS, Silva PL, et al: Reliability of Foot Posture Index individual and total scores for adults and older adults. Musculoskelet Sci Pract **36:** 92, 2018.
29. Redmond AC, Crosbie J, Ouvrier RA: Development and validation of a novel rating system for scoring standing foot posture: the Foot Posture Index. Clin Biomech (Bristol, Avon) **21:** 89, 2006.
30. Zuil-Escobar JC, Martínez-Cepa CB, Martín-Urrialde JA, et al: Medial longitudinal arch: accuracy, reliability, and correlation between navicular drop test and footprint parameters. J Manipulative Physiol Ther **41:** 672, 2018.
31. Brody DM: Techniques in the evaluation and treatment of the injured runner. Orthop Clin North Am **13:** 541, 1982.
32. van Melick N, Meddeler BM, Hoogeboom TJ, et al: How to determine leg dominance: the agreement between self-reported and observed performance in healthy adults. PLoS One **12:** e0189876, 2017.
33. Wearing SC, Smeathers JE, Hooper SL, et al: The time course of in vivo recovery of transverse strain in high-stress tendons following exercise. Br J Sports Med **48:** 383, 2014.
34. Del Baño-Aledo ME, Martínez-Payá JJ, Ríos-Díaz J, et al: Ultrasound measures of tendon thickness: intra-rater, inter-rater and inter-machine reliability. Muscles Ligaments Tendons J **7:** 192, 2017.
35. Kulig K, Oki KC, Chang YJ, et al: Achilles and patellar tendon morphology in dancers with and without tendon pain. Med Probl Perform Art **29:** 221, 2014.
36. Van Ginckel A, Thijs Y, Hesar NG, et al: Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: a prospective study. Gait Posture **29:** 387, 2009.
37. Heinemeier KM, Kjaer M: In vivo investigation of tendon responses to mechanical loading. J Musculoskelet Neuronal Interact **11:** 115, 2011.
38. Abate M, Silbernagel KG, Siljeholm C, et al: Pathogenesis of tendinopathies: inflammation or degeneration? Arthritis Res Ther **11:** 235, 2009.
39. Kubo K, Kanehisa H, Fukunaga T: Gender differences in the viscoelastic properties of tendon structures. Eur J Appl Physiol **88:** 520, 2003.
40. Blei CL, Nirschl RP, Grant EG: Achilles tendon: US diagnosis of pathologic conditions: work in progress. Radiology **159:** 765, 1986.
41. Theobald P, Benjamin M, Nokes L: Review of the vascularisation of the human Achilles tendon. Injury **36:** 1267, 2005.
42. Lavagnino M, Arnoczky SP, Kepich E: A finite element model predicts the mechanotransduction response of tendon cells to cyclic tensile loading. Biomech Model Mechanobiol **7:** 405, 2008.
43. Lundborg G, Holm S, Myrhage R: The role of the synovial fluid and tendon sheath for flexor tendon nutrition: an

experimental tracer study on diffusional pathways in dogs. Scand J Plast Reconstr Surg **14:** 99, 1980.
44. Ishigaki T, Kubo K: Mechanical properties and collagen fiber orientation of tendon in young and elderly. Clin Biomech (Bristol, Avon) **71:** 5, 2020.
45. Yan Z, Yin H, Brochhausen C, et al: Aged tendon stem/progenitor cells are less competent to form 3D tendon organoids due to cell autonomous and matrix production deficits. Front Bioeng Biotechnol **8:** 406, 2020.