Stiffness of Muscles and Tendons of the Lower Limb of Professional and Semiprofessional Athletes Using Shear Wave Elastography

Claudia Romer, MD, MPH, Julia Czupajllo, Enrico Zessin, Thomas Fischer, MD, Bernd Wolfarth, MD, Markus H. Lerchbaumer, MD

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Address correspondence to Claudia Romer, MD, MPH, Department of Sports Medicine, Charité—Universitätsmedizin Berlin, Campus Charité Mitte, Charitéplatz 1, 10117 Berlin, Germany.

E-mail: claudia.roemer@charite.de

Abbreviations

AT, Achilles tendon; PG, professional group/athletes; PT, patellar tendon; QT, quadriceps tendon; SG, semiprofessional group/athletes; SM, soleus muscle insertion; SWE, shear wave elastography; SWS, shear wave speed; US, ultrasound; VM, vastus medialis muscle

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Objective—Shear wave elastography (SWE) allows assessment of muscle and tendon stiffness and can be used to diagnose soft tissue pathologies such as tendinopathies. In sports medicine, SWE may have the potential to uncover structural changes early on before they lead to functional impairment. To systematically analyze possible differences in tendon and muscle stiffness of the lower limb between professional (PG) and semiprofessional female athletes (SG) using SWE and to compile reference values for developing preventive medicine approaches for professional athletes.

Methods—Standardized SWE of both lower limb tendons and muscles (Achilles tendon [AT], soleus muscle insertion [SM], patellar tendon [PT], quadriceps tendon [QT], vastus medialis muscle [VM]) in the longitudinal plane was performed with the tendons in relaxed position in 24 healthy professional female athletes (PG) in comparison with 24 healthy semiprofessional female athletes (SG).

Results—Median tendon and muscle stiffness was significantly higher in professional athletes (AT:PG, 11.12 m/s vs SG, 7.33 m/s, $P < .001$; SM: 1.77 m/s vs 1.14 m/s, $P < .001$; VM: 1.63 m/s vs 0.87 m/s, $P < .001$; QT: 3.31 m/s vs 2.61 m/s, $P < .05$). There was no significant difference in patellar tendon stiffness between PG and SG (PT: 2.57 m/s vs 3.21, $P = .25$).

Conclusion—Professional female athletes have higher stiffness values than semiprofessional female athletes in lower limb muscles and tendons, except for the patellar tendon. Knowledge of such differences is necessary for diagnosing tendinopathy and injuries. Musculoskeletal SWE could offer great benefits in sports medicine as well as in rehabilitation and preventive medicine.

Key Words—elastography; muscle; shear wave elastography; tendon; ultrasound

Introduction

The application of shear wave elastography (SWE) is rising in musculoskeletal imaging. Not only qualitative but also quantitative tissue evaluation is possible by using SWE.[1,2] Measuring shear wave speed in m/s allows tissue assessment for stiffness, with a low speed for soft tissue and higher speed values for stiffer tissue.[3,4] SWE can be used to assess muscle and tendon stiffness and to identify injuries like rupture or tendinopathy.[5–7]

Dirrichs et al studied SWE to investigate Achilles tendon (AT) stiffness in semiprofessional athletes and nonexercising individuals.[8] They found SWE values to be significantly higher in physically active versus inactive individuals.[8] In two other studies, altered stiffness measured by SWE was found to WLYJ-760elate with pain or restricted mobility, suggesting that SWE is a good diagnostic tool to detect pathological changes.[7,9] Selcuk et al reported significant differences in AT and PT stiffness between inactive subjects and semiprofessional athletes; however, the inactive group also differed significantly in bodyweight.[10] Patellar tendon stiffness showed significantly higher SWS values in subjects with patellar tendinopathy, which means an inverse stiffness change compared with the AT.[11] At the same time, there is a lack of data on differences in tendon and muscle stiffness between female semiprofessional and professional athletes, especially for the muscle-tendon units of AT and SM, but also for PT, QT, and VM. In view of the higher risk of knee injuries of female athletes compared with male athletes,[12] we conducted a study with the focus on muscles and tendons stiffness of the lower limb of female professional and semiprofessional athletes using SWE.[12]

Objective

To systematically analyze differences in tendon and muscle stiffness of the lower limb of female professional and semiprofessional athletes using SWE and to compile reference values for developing preventive medicine approaches for professional athletes.

Methods

Study Population

The prospective study included 24 healthy professional and 24 semiprofessional female athletes, who underwent SWE from June through August 2021. Inclusion criteria were a) age ≥18 years, b) healthy female professional or semiprofessional athletes, c) no acute or chronic (>6 months) musculoskeletal, rheumatic, or vascular comorbidities and no previous injuries of the AT, and IV) written informed consent to participate in the study. The study was conducted in accordance with the Declaration of Helsinki and with the approval of the local ethics committee of Charité—University Medicine of Berlin.

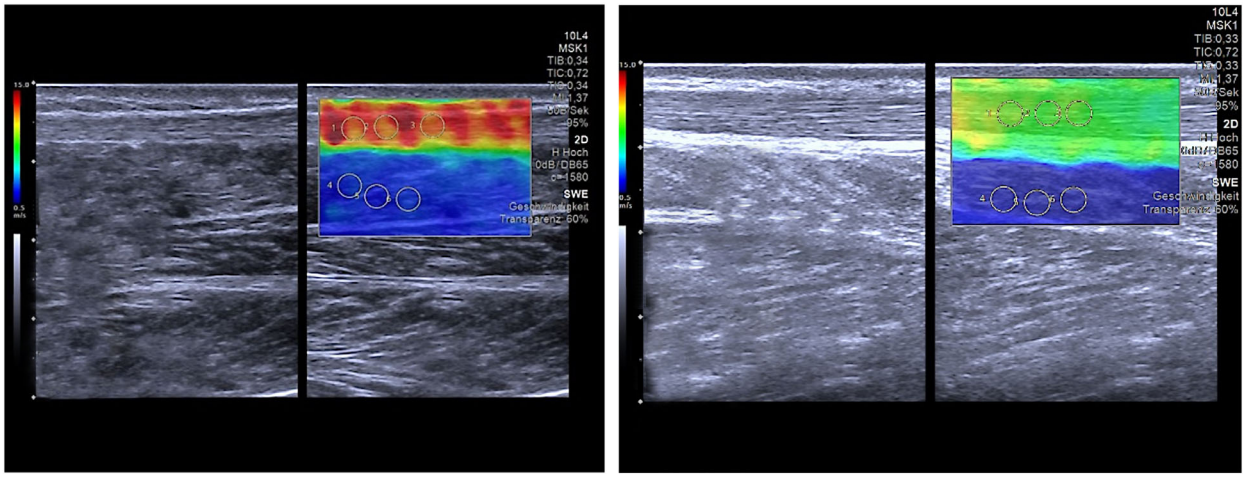
Baseline characteristics of study participants were documented at the time of the examination. Subjects were asked to abstain from exercising on the day of the SWE examination. Professional athletes (German national volleyball team and German professional handball league) mainly trained more than 10 hours/week (79.2%), 20.8% trained 5 to 10 hours/week. Semiprofessional athletes (different and mixed sports types, eg, running, Crossfit workout, yoga) trained 5 to 10 hours/week.

Ultrasound Shear Wave Elastography Examination

All ultrasound shear wave elastography (US-SWE) examinations were performed using a standardized protocol. For SWE of the AT (mid-portion), participants were examined in prone position with both feet hanging in relaxed position shortly over the examination couch. For examination of patellar and quadriceps tendons, patients were re-positioned in a relaxed supine position with a small roll under the knee (20° flexion). Prior to US-SWE, gray-scale B-mode US was performed in transverse and longitudinal planes for orientation to ensure adequate assessment of tendons and probe position. All examinations were performed using a high-end US system with a 4 to 10 MHz multifrequency linear array transducer and a center frequency of 7 MHz (Acuson Sequoia, Siemens Healthineers, Erlangen, Germany). The US-SWE software (Virtual Touch™) supports real-time measurement using Acoustic Radiation Force Impulse (ARFI) imaging technology for quantitative evaluation of shear wave speed.

US-SWE examinations were performed in the longitudinal plane to depict each tendon and the area of interest in one single image (Figure 1). Using the respective 2D SWE approach, the examiner acquired four US images of each tendon and muscle of both legs, corresponding to a total of 96 (including left and right leg) consecutive SWE measurements using a 3-mm circular region of interest (ROI) placed in the center of each target tendon avoiding areas of visible artifacts. Each single elastogram contains three point-measurements of the AT and three point-measurements of the Soleus Muscle beside. Thus, representative tendon stiffness is given as the median of 10 measurements

Figure 1. Images illustrating AT appearance in a volleyball national team player (left) and a semiprofessional athlete (right).



with interquartile range (IQR). Before ROI placement, shear wave speed as a surrogate for tissue stiffness was depicted by color-coded SWE mapping. The standardized penetration depth was adapted to each participant for optimal visualization of the tendon and correct SWE measurement. Gain was not changed to avoid potential effects on US-SWE measurements. The measurements were jointly performed in consensus by a trained sonographer and a highly experienced radiologist specialized on ultrasound imaging following a standardized protocol used for every participant. Both observers were blinded to training status and profession of the participants.

Statistical Analysis

Continuous variables were tested for normal distribution using the Kolmogorov–Smirnov test. Not normally distributed variables are reported as median and interquartile range (IQR). Categorical variables were compared using Student's *t*-test or the χ^2 test, as appropriate, and reported by their proportion (n/N), as absolute values and percentages.

A two-sided significance level of $\alpha = 0.05$ was defined to indicate statistical significance. All statistical analyses were performed using the SPSS software (IBM Corp., released 2019. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY: IBM Corp.).

Results

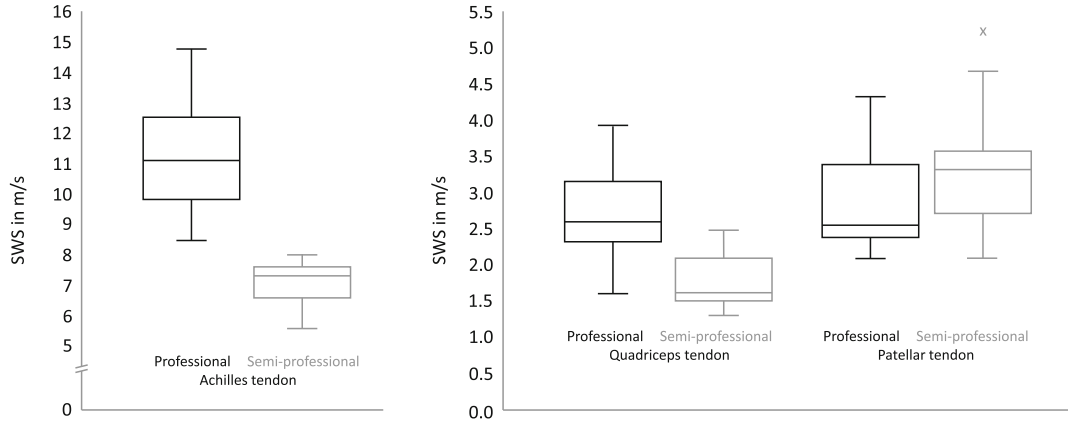
Characteristics of Professional and Semiprofessional Athletes

A total of 24 female professional athletes (volleyball n = 13; handball n = 11) with a mean age of 22 were examined. One professional athlete was diagnosed with hypothyroidism, while no other diseases such as diabetes mellitus, fatigue, hyperlipidemia, rheumatic diseases, or malposition of lower limb joints were known. Overall, 11 athletes reported rupture of lower ligaments, none reported a history of tendon rupture, especially of Achilles, patellar or quadriceps tendon (ligament rupture of the ankle [n = 8], ligament rupture of the knee [n = 7]). Permanent medications taken by subjects at the time of study were L-thyroxine (n = 1) and

Table 1. Characteristics of the Two Groups (Professional Vs Semiprofessional Female Athletes; Normally Distributed, Continuous Variables Given as Median and IQR)

Variable	Professional	Semiprofessional
Age (years)	22 (19–25)	27 (22–31)
BMI (kg/m^2)	22.49 (21.21–23.29)	22.06 (20.12–23.70)
Sport type		
Volleyball	13/24 (54.2%)	0
Handball	11/24 (45.8%)	0
Mixed sports	0	24/24 (100%)
Training workload		
5–10 hours	5/24 (20.8%)	24/24 (100%)
>10 hours	19/24 (79.2%)	0/24 (0%)

Figure 2. Boxplots of tendon stiffness for professional and semiprofessional female athletes.



contraceptives (oral/hormonal [n = 2], hormonal intrauterine device [n = 2]).

The 24 semiprofessional athletes included had a mean age of 27 years. No morbidities, especially no injuries of the lower limb, were reported. No permanent medication was taken apart from contraceptives (oral/hormonal [n = 4], hormonal intrauterine device [n = 2]) (Table 1).

Results of US-SWE in Professional and Semiprofessional Female Athletes

In the total study population (n = 48), we obtained different stiffness values for AT, patellar tendon, and leg muscles. The highest stiffness was measured in the AT, followed by the patellar and quadriceps tendon. Compared with the tendons, the soleus and vastus medialis muscles had significantly lower stiffness values ($P < .001$).

Professional athletes had significantly higher SWS values in the AT ($P < .001$), quadriceps tendon ($P < .05$), soleus muscle ($P < .001$), and vastus medialis muscle ($p < .001$; cf. Figures 2 and 3). For the patellar tendon, no significant difference was found between professional and semiprofessional athletes (cf. Table 2).

There was a moderate to strong correlation between PT and VM ($r = .423$; $P = .044$) and between QT and VM ($r = .600$; $P = .002$) in the group of professional athletes. No correlation was shown between AT and SM ($r = .193$; $P = .379$).

In the semiprofessional group, there was no correlation between PT and VM ($r = -.218$; $P = .306$) and between QT and VM ($r = .364$; $P = .081$). Moderate correlation was found between AT and SM ($r = .456$, $P = .025$).

Furthermore, there was no significant difference for BMI ($P = .458$) between groups. The

Figure 3. Boxplot of muscle stiffness for professional and semiprofessional female athletes.

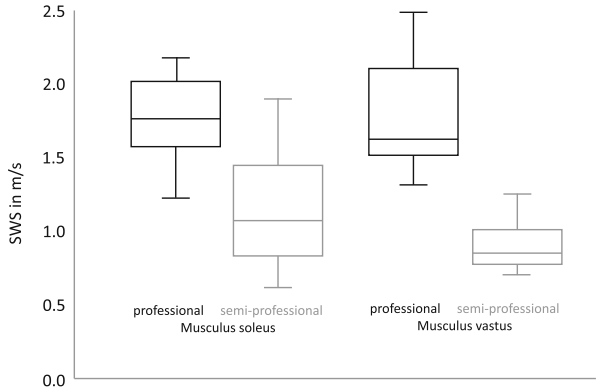


Table 2. Median SWS of Professional and Semiprofessional Female Athletes (Normally Distributed, Continuous Variables Given as Median and IQR)

Tendon/ muscle	SWSprof (m/s); n = 24	SWSsemiprof (m/s); n = 24	*P*-value
AT	11.12 (9.85–12.53)	7.33 (6.60–7.64)	<.001
SM	1.77 (1.58–2.02)	1.14 (0.83–1.49)	<.001
PT	2.57 (2.40–3.40)	3.21 (2.38–3.54)	.25
QT	3.31 (2.72–3.84)	2.61 (2.30–3.34)	.017
VM	1.63 (1.52–2.11)	0.87 (0.79–1.09)	<.001

semiprofessional group was significantly older in comparison to the professional group ($P < 0.001$, see Table 1).

Discussion

Earlier studies have already demonstrated that SWE is a suitable diagnostic method for assessing the stiffness of tendons and muscles.[9,13,14] Specifically, it has been shown that SWE can be used to detect differences between physically active and inactive individuals.[8,10,15] While AT stiffness and tendinopathy are well studied by SWE,[7,8,16–18] fewer data are available on patellar and quadriceps tendons or muscle and tendon stiffness in female professional athletes. For the patellar tendon, greater softness was observed in young and moderately active individuals.[19] In another study, however, resistance training was found to only alter the stiffness of the vastus lateralis muscle but not that of the patellar tendon.[20]

The results of this study show significantly higher SWS values in professional athletes (AT, QT, SM, and VM) compared with semiprofessional athletes. The significantly higher stiffness values in the professional group are attributable to the high rate of jumping phases in volleyball and handball, resulting in high forces acting on the AT forces, which ultimately lead to AT adaptation.[21,22] Most studies of musculoskeletal SWE have focused on male athletes.[8,15] Our results in female professional and semiprofessional athletes are comparable to findings reported for male athletes in terms of tendon and muscle stiffness adaptation.[8,15]

Consistent with earlier studies, we found no significant difference in PT stiffness between semiprofessional and professional athletes.[15,23] While earlier studies showed consistent training to highly correlate with AT stiffness, no such effect of load exercise and strength training on stiffness properties was found for the patellar tendon in athletic individuals.[8,20] This may be attributable to a lack of standard measurement of patellar tendon stiffness, which has been shown to vary with the knee angle.[24] Moreover, PT stiffness is also affected by quadriceps contraction.[25] This underlines the importance of a standardized protocol and the need to carefully instruct participants regarding quadriceps muscle contraction and relaxation in order to obtain reproducible and reliable stiffness measurements of the PT and QT.

For standardized SWE measurement, joints, tendons, and muscles need to be in a relaxed position, and the transducer should be positioned without pressure.[26,27] If this is borne in mind, SWE allows reliable measurement of muscle and tendon stiffness.[28,29]

The differences found between professional and semiprofessional athletes need to be taken into account when stiffness is used to diagnose tendon injuries.[8] Establishing SWS reference values for professional athletes may help in developing preventive medicine approaches and to thus avoid acute and chronic tendinopathy and injuries of the legs.

It is also important to be aware that the patellar tendon was not found to adapt in individuals who exercise professionally in comparison to semiprofessional athletes.[20,23] Many professional athletes suffer knee injuries during their career.[30] The risk of knee injuries is up to eight times higher in female athletes than in men who participate in high-performance sports.[12] Thus, it is necessary to put a higher emphasis on preventive training and timely diagnosis in order to reduce knee joint damage in professional athletes in the future.

The results of this study show a significant difference for age between groups, as the semiprofessional athletes were older. Sixteen semiprofessional athletes were between 20 and 30 years, five athletes between 30 and 35 years, which is considerably younger in comparison to studies, which detected muscle and tendon tissue stiffness differences for age.[31–33] At the same time, Liu et al detected stiffness differences in gastrocnemius medialis at a dorsiflexion from 20° and higher between children (6–12 years) and a middle-aged population (30–40 years).[33] Muscle stiffness of gastrocnemius muscle was strongly inverse correlated to age, while stiffness increase rate stayed the same,[34] which should be considered in future studies, examining muscle stiffness changes as a potential risk of injury.

Limitations

Two professional and four semiprofessional athletes in the study cohort took oral contraceptives. Oral

contraceptives affect the natural hormonal fluctuation, as synthetic ethinyl estradiol present a higher receptor affinity in comparison to endogenous estrogen.[35,36] Higher estrogen levels are discussed to lead to higher knee laxity, as estrogen may effect musculoskeletal tissue stiffness.[37] Injury prevalence of the musculoskeletal system, for example, for anterior cruciate ligament (ACL) ruptures, is up to eight times higher in women than in men who participate in high-performance sports.[38] However, evidence is scarce and results are contradictive.[39,40] A more precise injury analysis in female athletes with a wider scope and an interdisciplinary approach should be performed in future studies.[40] Future studies, examining the effect of oral contraceptives, should regard the same dosage of oral contraceptives.

In addition, the menstrual cycle might influence musculoskeletal injury prevalence, as results show an increased occurrence in the preovulatory phase, which is characterized by an increase in estrogen.[39,41] These results also needed to be evaluated in a greater context, as injury prevalence in professional athletes may not only be influenced by menstrual cycle, but also by higher stress and cortisol levels and nutrient deficiency.[40,42] SWE measurements were performed independently of menstrual cycle phase of the athletes, which should be examined in future work, including blood samples.

Overall, SWE seems to be a useful tool to assess tissue stiffness in professional and semiprofessional athletes. Individual serial measurement by SWE in professional sports could detect changes in stiffness and thus reduce the risk of injury. Further studies are necessary to investigate the potential of US-SWE in preventing injury in professional athletes.

Conclusion

Female professional athletes show significantly higher stiffness values of leg tendons and muscles, except for the patellar tendon. The technique of SWE could be used to define reference values for estimating the individual risk of injury. Especially for athletes, a readily available diagnostic tool could help in detecting early stages of injuries and developing algorithms for preventing acute and chronic tendon and muscle injuries.

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