

## Original Article

# An investigation of the sex-related differences in the stiffness of the Achilles tendon and gastrocnemius muscle: Inter-observer reliability and inter-day repeatability and the effect of ankle joint motion

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## ABSTRACT

**Purpose:** The purpose of the present study was to investigate sex-related differences in the stiffness of the Achilles tendon and gastrocnemius muscle at rest and tensioned state. Another purpose of the study was to investigate the inter-observer reliability and inter-day repeatability of MyotonPRO, a portable myotonometer, in measuring tendon and muscle stiffness.

**Methods:** The study included 73 healthy participants (19 males for the reliability and repeatability study; 24 males and 30 females for the experimental study) with an age range of 19–27 years. The stiffness of the Achilles tendon and medial gastrocnemius muscle was measured with a portable myotonometer (MyotonPRO). The stiffness measurements of the Achilles tendon and medial gastrocnemius muscle were performed at 0° and 10° of ankle joint dorsiflexion. The stiffness measurements were performed by two physiotherapists to determine the inter-observer reliability of the device. For the inter-day repeatability (or between-day precision), the same individuals were reassessed by the same examiner after a 3-day interval.

**Results:** It was found that MyotonPRO has excellent inter-observer reliability and inter-day repeatability in measuring the stiffness of the Achilles tendon and medial gastrocnemius muscle (ICC = 0.83–0.98). The stiffness of the Achilles tendon and gastrocnemius muscle at neutral and 10° joint dorsiflexion was higher in males compared to females ( $p < 0.05$ ); however, the stiffness value of difference between neutral and 10° joint dorsiflexion for the Achilles tendon and gastrocnemius muscle was similar in both groups ( $p > 0.05$ ).

**Discussion:** The obtained results suggest that MyotonPRO is a reliable and repeatable device in measuring the stiffness of the Achilles tendon and gastrocnemius muscle. Furthermore, males have stiffer Achilles tendon and gastrocnemius muscle, compared to females; however, the change in the stiffness of the assessed tissues caused by joint motion was similar in both sexes.

## 1. Introduction

It is well known that the incidence of musculoskeletal disorders (such as foot pain, Achilles tendinopathy or patellofemoral pain syndrome, etc) is higher in females compared to males [1–3]. In recent years, many researchers have extensively studied to determine the sex related differences related to the musculoskeletal system (balance ability, muscle strength, joint stability or joint mobility, etc), which may increase the incidence of musculoskeletal disorders in females [4–7]. On the other hand, sex related differences in muscle and tendon stiffness may be related to a higher incidence of musculoskeletal disorders in females. Tendon and muscle stiffness are an important components of joint stability and/or control [8,9]. Furthermore, muscle-

tendon stiffness could influence the stretch-shortening cycle and it is related to rapid force production during a dynamic movement [10]. Because of these reasons, differences in muscle and/or tendon stiffness in females could cause an increase in the risk of tendon and/or joint injury. More recently, sex-related differences in the passive stiffness of muscle and tendon were investigated by some studies. It was reported that males had stiffer patellar tendon [11], medial gastrocnemius muscle [12], rectus femoris muscle [13], and gastrocnemius muscle [14]. On the other hand, the others found that males and females had similar stiffness of the Achilles tendon [15,16], patellar tendon [17], medial gastrocnemius muscle [18], and biceps brachia muscle [13]. Other studies indicated that the stiffness of the triceps surae [19], and biceps brachia [20] muscle in females was higher compared to males.

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Changes in muscle and tendon stiffness may be different in males and females when the tendon and muscle are exposed to a mechanical stress, such as tension. Tendon and muscle stiffness in tension state could provide important information about the ability of force translation and/or shock absorption of the muscle and tendon [21,22]. There is limited information about sex-related differences in soft tissue stiffness in tensioned state. In a study by Chino and Takahashi [18], it was reported that the change in the stiffness of the medial gastrocnemius caused by joint motion had no significant sex-related differences. On the other hand, Miyamoto et al. [23] suggest that there is a sex-related difference in muscle stiffness in different tension states. It seems that there is no consensus about sex-related differences in soft tissue stiffness. Any insight into sex-related difference in muscle and tendon stiffness between males and females may shed light on the factors causing tendon and muscle disorders, or it may provide important information on the pathomechanics of musculoskeletal disorders.

There are a few methods allowing the measurement of the muscle and/or tendon stiffness such as myotonometry, magnetic resonance elastography, and shear-wave elastography. Myotonometry has some advantages compared to magnetic resonance elastography and shear-wave elastography. For example, a myotonometer is a hand-held device which allows performing measurements in different environments. On the other hand, it is comparatively more economical than magnetic resonance and/or ultrasonography devices. Stiffness measurements by a myotonometer is very simple, which can be easily learned, compared to magnetic resonance elastography and shear-wave elastography. Furthermore, it was reported that myotonometry is a reliable [24–26] and valid [27] method as well as magnetic resonance elastography and shear-wave elastography [28,29]. However, the reliability and repeatability of myotonometry was investigated predominantly in muscle [24–26] by limited studies, and only one study [30] investigated its reliability in measuring the tendon stiffness. The reliability of the MyotonPRO may be different in tension state and/or other soft tissues, such as tendon, and/or ligament.

The purpose of the present study was to investigate the sex-related differences in the stiffness of the Achilles tendon and gastrocnemius muscle at rest position and tensioned state. Another purpose of the study was to investigate the inter-observer reliability and inter-day repeatability of the MyotonPRO in measuring tendon and muscle stiffness. It was hypothesized that (1) the Achilles tendon and gastrocnemius muscle stiffness would be the higher in males compared to females, (2) tension response in the Achilles tendon and gastrocnemius muscle stiffness would be different between males and females, (3) MyotonPRO would be a reliable and repeatable device in measuring tendon and muscle stiffness.

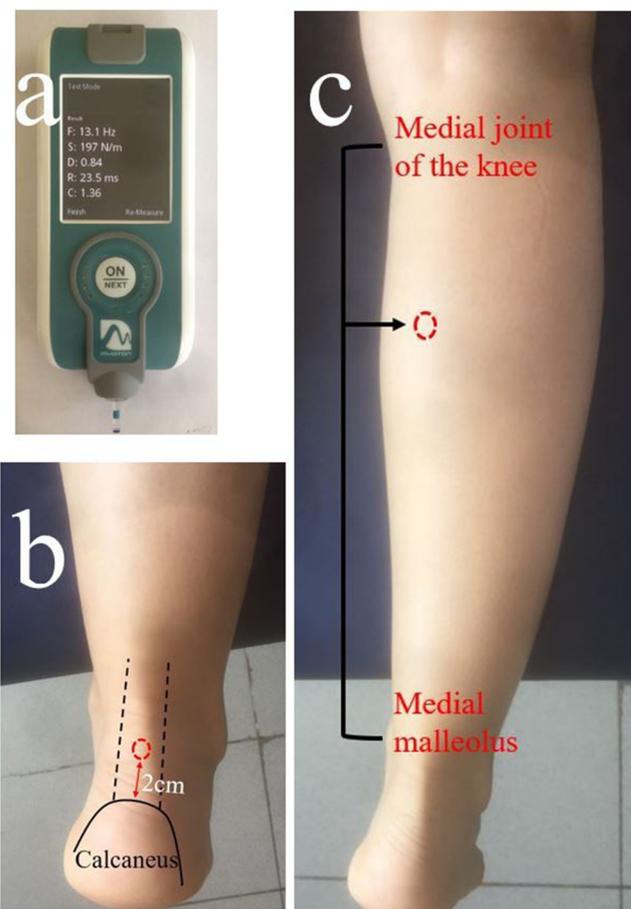
## 2. Material and method

### 2.1. Ethics statements

The present study was approved by the ethics committee of the Toros University. All participants provided oral and written informed consent prior to experiment (2019-05/29).

### 2.2. Stiffness measurements

The stiffness of the Achilles tendon and medial gastrocnemius was measured with a portable myotonometer (MyotonPRO, Muomeetria Ltd., Tallinn, Estonia). The device measures mechanical oscillations of the assessed soft tissues by a mechanical impulse, which is a short duration (15 ms) and involves a constant mechanical force (up to 0.6 N) [31]. The stiffness values of the assessed soft tissue were obtained by calculating the maximum acceleration of the oscillation/maximum displacement of the assessed tissue [31]. The device measures the stiffness value as Newton/meter (N/m). The larger value indicates a stiffer tissue.



**Fig. 1.** (a) MyotonPRO was used for stiffness measurements; (b) the point by 2 cm proximal to the superior aspect of the calcaneus was preferred for measuring the Achilles tendon stiffness; (c) medial gastrocnemius stiffness was measured at 30% of the lower leg length distal in line with lateral malleolus to lateral joint of the knee.

Stiffness of the Achilles tendon and medial gastrocnemius was measured on the subject's dominant leg. The dominant leg was determined by asking the participant to kick a ball [11,32]. Similar to previous studies [18,30], stiffness measurements were performed when the participants were in prone position with neutral ankle position and full knee extension. The point by 2 cm proximal to the superior aspect of the calcaneus was preferred for measuring the Achilles tendon stiffness, because pathological changes in the Achilles tendon is commonly seen in this area [33,34]. According to previous studies [18,35], medial gastrocnemius stiffness was measured at 30% of the lower leg length distal in line with the medial malleolus to medial joint of the knee (Fig. 1). The probe of MyotonPRO was placed perpendicular to the skin above the assessed muscle or tendon to be measured. Stiffness measurements of the Achilles tendon and medial gastrocnemius were performed at 0° and 10° of ankle joint dorsiflexion. The angle of the ankle joint was measured with a universal goniometer. The joint position was kept using an adjustable foot–ankle splint. The stiffness value of the assessed tissues was calculated by taking the average of three successive measurements performed.

### 2.3. Reliability and repeatability study

Reliability study was designed to determine inter-observer reliability and inter-day repeatability of the myotonometer device. The study included 19 asymptomatic males in an age range between 19 and 25 years ( $21.6 \pm 1.6$  years). Participants with a history of knee, ankle, or foot orthopaedic injuries such as plantar fasciitis, tendinopathy,

bursitis, or ligament injuries were excluded from the study.

The stiffness measurements were performed by two physiotherapists to determine the inter-observer reliability of the device. For the inter-day repeatability (or between-day precision), the same individuals were reassessed by the same examiner after a 3-day interval. The measurements were carried out at the same time of the day ( $\pm 1$  h). In order to prevent confounding effects, the participants were asked not to do any strenuous exercises within the 24 h prior to assessments.

2.4. Experimental study

The experimental study was designed to investigate the sex effect on the stiffness of the Achilles tendon and medial gastrocnemius muscle. The study included 54 healthy participants (24 males, 30 females) with an age range of 19–27 years ( $21.4 \pm 1.6$  years). The data obtained from reliability study was not used in the experimental study. Participants with a history of knee, ankle or foot orthopaedic injuries such as plantar fasciitis, tendinopathy, bursitis, or ligament injuries were excluded from the study.

2.5. Statistical analysis

Statistical analyses were performed with a statistics software (SPSS version 22 software, IBM Corporation, Armonk, NY). The reliability of the MyotonPRO was tested by intraclass correlation coefficient (ICC) test with 95% confidence interval. ICC<sub>3,1</sub> (two-way mixed model, consistency) was used to determine inter-day repeatability, and ICC<sub>2,2</sub> (two-way random affect model, absolute agreement) was used to examine inter-observer reliability. For every comparison, the standard error of measurement (SEM) was calculated using the following formula:  $[SEM = SD \times \sqrt{(1 - ICC)}]$ . Coefficient of variation (CV) for every comparison was calculated according to the formula:  $[CV = (\frac{SEM}{Mean}) \times 100\%]$ . Minimum detectable change (MDC) was calculated using the following formula:  $[MDC = \sqrt{2} \times 1.96 \times SEM]$ . Correlation analysis results were classified as follows: 0.00–0.20 (poor), 0.21–0.40 (fair), 0.41–0.60 (moderate), 0.61–0.80 (good), and 0.81–1.00 (excellent) [36].

Independent T-test was used to compare the assessed parameters between male and female groups. Paired-samples T-test was used to compare the stiffness values of the Achilles tendon and gastrocnemius muscle between neutral and 10° dorsiflexion position. An overall 5% Type 1 error level was accepted for inter statistical significance.

3. Results

3.1. Inter-observer reliability and inter-day repeatability

Mean height, weight, and body mass index of the assessed individuals in the reliability study were  $1.80 \pm 0.05$  m,  $74.7 \pm 10.7$  kg, and  $23.1 \pm 3.2$  kg/m<sup>2</sup>, respectively. Inter-observer reliability of the Achilles tendon at 0° and 10° of ankle joint dorsiflexion was excellent (ICC = 0.87–0.94): SEM less than 44 N/m, MDC less than 122 N/m, and CV less than 4%. Similarly, inter-day repeatability of tendon stiffness measurements was excellent (ICC = 0.83–0.90): SEM less than 37 N/m, MDC less than 102 N/m, and CV less than 4%. On the other hand, inter-observer reliability of the gastrocnemius at 0° and 10° of ankle joint dorsiflexion was excellent (ICC = 0.93–0.98): SEM less than 15 N/m, MDC less than 78 N/m, and CV less than 7%. Inter-day repeatability of gastrocnemius muscle stiffness measurements at 0° and 10° of ankle joint dorsiflexion was excellent (ICC = 0.87–0.91): SEM less than 31 N/m, MDC less than 85 N/m, and CV less than 8% (Table 1) (Fig. 2).

**Table 1** The inter-observer reliability and inter-day repeatability of MyotonPRO for measuring in the stiffness of the Achilles tendon and medial gastrocnemius (n = 19).

Parameters	Inter-observer reliability				Inter-day repeatability							
	Observer 1 (N/m)	Observer 2 (N/m)	ICC (95%)	SEM (N/m)	CV (%)	MDC (N/m)	Test point 1 (N/m)	Test point 2 (N/m)	ICC (95%)	SEM (N/m)	CV (%)	MDC (N/m)
Achilles tendon stiffness												
At neutral	846.3 ± 79.8	843.5 ± 90.8	0.94 (0.83–0.98)	20.3	2.4	56.3	846.3 ± 79.8	841.9 ± 77.9	0.83 (0.56–0.94)	29.9	3.5	82.9
At 10° dorsiflexion	1160.6 ± 131.7	1210.8 ± 124.0	0.87 (0.56–0.95)	43.8	3.7	121.4	1160.6 ± 131.7	1144.6 ± 110.6	0.90 (0.74–0.96)	36.6	3.2	101.5
Gastrocnemius muscle stiffness (N/m)												
At neutral	371.0 ± 111.9	377.0 ± 99.5	0.98 (0.94–0.99)	14.8	4.0	41.0	371.0 ± 111.9	363.4 ± 84.9	0.91 (0.78–0.97)	28.5	7.8	79.0
At 10° dorsiflexion	427.8 ± 96.1	443.1 ± 120.4	0.93 (0.81–0.97)	27.	6.4	77.1	427.8 ± 96.1	433.1 ± 86.2	0.87 (0.65–0.95)	30.6	7.1	84.8

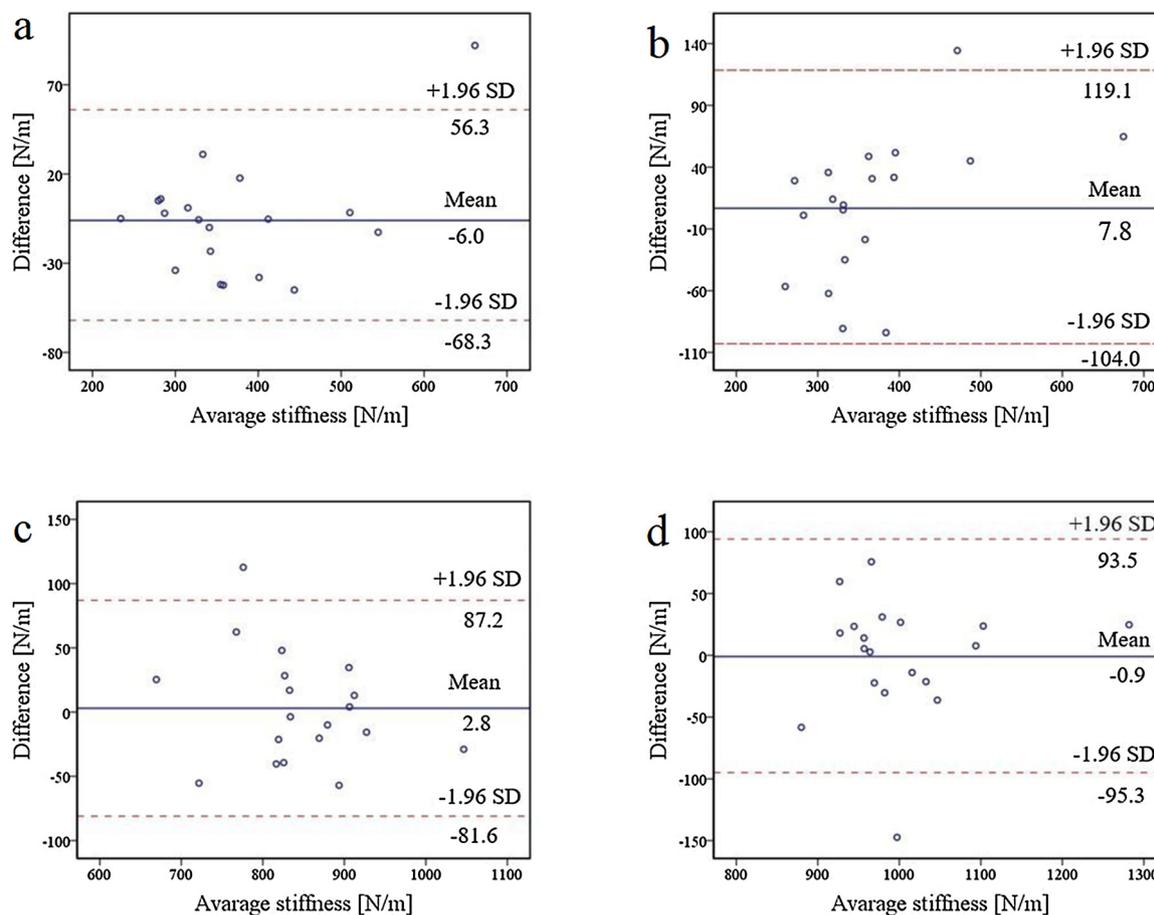


Fig. 2. Bland and Altman plots of the inter-observer reliability and inter-day repeatability of the Achilles tendon and medial gastrocnemius muscle at neutral position. (A) Inter-observer reliability of the medial gastrocnemius, (B) inter-day repeatability of medial gastrocnemius, (C) inter-observer reliability of the Achilles tendon, (D) inter-day repeatability of the Achilles tendon.

### 3.2. Effect of joint motion

Gastrocnemius muscle stiffness at 10° dorsiflexion position was significantly higher in both females and males compared to the neutral position ( $p < 0.001$ ). Similarly, Achilles tendon stiffness at 10° dorsiflexion position was higher in both sexes compared to the neutral position (Table 2).

### 3.3. Sex effect on the stiffness of the Achilles tendon and gastrocnemius muscle

Both groups were similar in age ( $p = 0.595$ ), while males had higher height, weight and body mass index compared to females ( $p < 0.001$ ) (Table 2). The stiffness of the Achilles tendon and gastrocnemius muscle at neutral and 10° joint dorsiflexion in males was higher compared to females ( $p < 0.05$ ); however, differences in stiffness values between neutral and 10° joint dorsiflexion for the Achilles tendon and gastrocnemius muscle were similar in both groups ( $p > 0.05$ ) (Table 3) (Fig. 3).

Table 2 Demographic data of females and males (n = 54).

	Male (n = 24) Mean ± SD	Female (n = 30) Mean ± SD	p
Age (years)	21.5 ± 1.6	21.3 ± 1.6	0.595
Height (m)	1.81 ± 0.06	1.66 ± 0.05	< 0.001
Body mass (kg)	77.3 ± 11.8	55.4 ± 6.0	< 0.001
Body mass index (kg/m <sup>2</sup> )	23.8 ± 3.7	20.2 ± 1.9	< 0.001

Table 3

Comparisons of the stiffness of the Achilles tendon and gastrocnemius muscle between neutral and 10° of ankle joint dorsiflexion (n = 54).

Parameters	Male (n = 24) Mean ± SD	Female (n = 30) Mean ± SD	p
Achilles tendon stiffness			
At neutral (N/m)	856.1 ± 82.5	781.0 ± 98.1	<b>0.004</b>
At 10° dorsiflexion (N/m)	1197.4 ± 200.9	1075.2 ± 79.0	<b>0.004</b>
Difference (N/m)	341.3 ± 202.1	300.0 ± 108.5	0.347
Difference (%)	40.8 ± 26.3	40.9.0 ± 22.3	0.994
Gastrocnemius muscle stiffness			
At neutral (N/m)	370.8 ± 104.4	257.0 ± 52.5	< <b>0.001</b>
At 10° dorsiflexion (N/m)	422.2 ± 90.5	292.2 ± 59.2	< <b>0.001</b>
Difference (N/m)	51.4 ± 50.2	35.2 ± 22.4	0.118
Difference (%)	16.0 ± 14.3	14.0 ± 9.3	0.545

## 4. Discussion

The purpose of the present study was to investigate the differences in the stiffness of medial gastrocnemius muscle and Achilles tendon related to the ankle joint motion and sex. Another purpose of the study was to determine the inter-observer reliability and inter-day repeatability of quantifying the stiffness of medial gastrocnemius muscle and Achilles tendon. Our results support that the MyotonPRO device has excellent inter-observer reliability and inter-day repeatability in measuring the stiffness of the medial gastrocnemius muscle and Achilles tendon. In addition, the results of this study indicate that the stiffness of the medial gastrocnemius muscle and Achilles tendon is higher in males compared to females; however, stiffness changes in the gastrocnemius

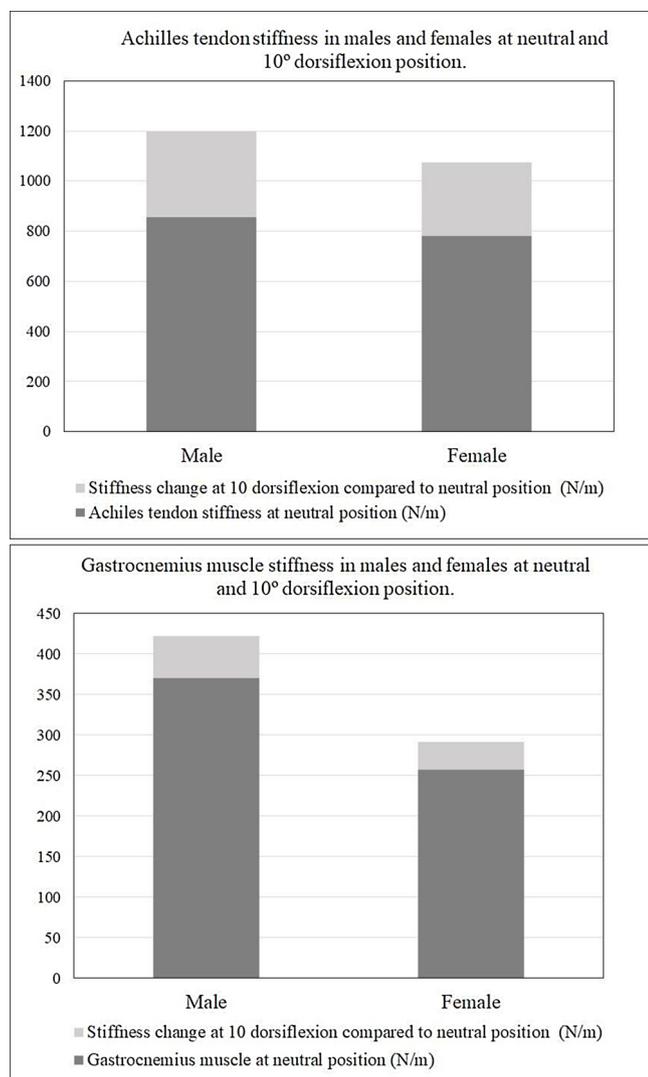


Fig. 3. Stiffness values of the Achilles tendon and medial gastrocnemius muscle at neutral and 10° dorsiflexion positions.

muscle and Achilles tendon depending on joint motion was similar in both sexes.

#### 4.1. Inter-observer and inter-day reliability

The results of the present study revealed that the MyotonPRO device has excellent inter-observer reliability and inter-day repeatability for measuring the stiffness of the Achilles tendon at neutral and 10° dorsiflexion positions. Previous studies predominantly focused on determining the reliability of the MyotonPRO in measuring passive muscle stiffness, but not in tensioned state. The reliability of the MyotonPRO may be different in tension state and/or other soft tissues, such as tendon, and/or ligament. There is only one study that investigated the reliability of MyotonPRO in measuring tendon stiffness. In a study by Liu et al. [30], the stiffness of the Achilles tendon was quantified by a MyotonPRO. Liu et al. [30] found excellent inter- and intra-observer reliability (ICC: 0.88–0.95), corresponding to SEM less than 18.2 N/m, and MDC less than 36.6–44.4 N/m. On the other hand, the results of the present study suggest that MyotonPRO has excellent inter-observer reliability and inter-day repeatability to quantify the medial gastrocnemius muscle. The obtained results are consistent with previous studies focusing on the reliability of MyotonPRO in measuring muscle stiffness [24–26]. Liu et al. [26] examined the inter- and intra-observer reliability of MyotonPRO to quantify the upper trapezius

stiffness in healthy individuals. They found excellent inter- and intra-observer reliability (ICC = 0.97), corresponding to SEM of 9.5 N/m and MDC of 26.2 N/m. Davidson et al. [24] examined the inter- and intra-observer reliability of MyotonPRO in measuring muscle stiffness in the perineal and thenar muscles. Davidson et al. [24] reported that ICC values ranged from 0.70 to 0.91, corresponding to SEM less than 23.8 N/m and MDC less than 66.1 N/m. Lohr et al. [25] investigated the intra-tester reliability and inter-day repeatability of MyotonPRO in measuring lumbar erector spinae in healthy volunteers. Lohr et al. [25] revealed that ICC ranged from 0.91 to 0.97, corresponding to SEM less than 22.9 N/m, CV less than 5.9%, and MDC less than 63.4 N/m. In summary, there seems to be a consensus in the literature that MyotonPRO is reliable and repeatable in measuring the muscle and tendon stiffness.

#### 4.2. Effect of joint motion on muscle and tendon stiffness

Another important finding of the present study is that tendon and muscle stiffness significantly increased when the ankle was brought from neutral to 10° dorsiflexion. However, there was a difference between the tendon and the muscle in terms of this increase. It was found that mean difference at the Achilles tendon stiffness was 40%, while the mean difference at the medial gastrocnemius stiffness ranged from 14% to 16%. On the other hand, standard deviations of this difference were in a wide range. This finding indicates that the effect of joint position on muscle and tendon stiffness was highly variable depending on personal characteristics. Similar to our study, Liu et al. [30] examined the effect of joint motion on Achilles tendon stiffness. They revealed that Achilles tendon stiffness was 1143 N/m at neutral position, and it was 1329 N/m at 30° ankle dorsiflexion. Aubry et al. [37] quantified the difference in Achilles tendon stiffness related to ankle joint motion. They reported that Achilles tendon stiffness increased nearly 5 times at maximum dorsiflexion compared to the neutral ankle position (from 147 kPa to 780 kPa). Furthermore, Huang et al. [22] investigated the effect of ankle joint position on medial and lateral gastrocnemius muscles. They found that mean difference in the stiffness of the medial gastrocnemius muscle increased up to 163 N/m from –50° to 25° of ankle joint rotation. On the other hand, Chino and Takahashi [18] quantified the difference of medial gastrocnemius muscle at different joint angles by shear-wave elastography. They reported that the stiffness value of the medial gastrocnemius muscle at 10° dorsiflexion was almost twice more compared to the neutral ankle position (from 12 kPa to 24 kPa).

#### 4.3. Effect of sex on muscle and tendon stiffness

The primary purpose of this study was to investigate the effect of sex on the stiffness of the Achilles tendon and medial gastrocnemius muscle. Similar to our hypothesis, the obtained results indicate that males have stiffer Achilles tendon and medial gastrocnemius muscle compared to females. The difference between males and females was more prominent in the medial gastrocnemius muscle ( $370.8 \pm 104.4$  N/m for males, and  $257.0 \pm 52.5$  N/m for females) compared to the Achilles tendon ( $856.1 \pm 82.5$  N/m for males, and  $781.0 \pm 98.1$  N/m for females). This difference may be related to the hormonal differences between sexes. The estrogen is an important hormone that affects the homeostasis of many musculoskeletal tissues [38–40]. The estrogen level could influence the sensitive estrogen receptors in soft tissue such as tendon and/or muscle, which causes to decrease in the estradiol level and collagen synthesis [38–40]. Any decrease in collagen synthesis could cause a decrease in tendon and muscle stiffness [41,42]. There are several studies which investigated the sex effect in muscle and tendon stiffness; however, the reported results vary immensely. It has been reported that males had stiffer patellar tendon [11], medial gastrocnemius muscle [12], rectus femoris muscle [13], and gastrocnemius muscle [14]. On the other hand, others have found that male and female had similar stiffness of the Achilles

tendon [15,16], patellar tendon [17], medial gastrocnemius muscle [18], and biceps brachia muscle [13]. Other studies have indicated that the stiffness of the soleus [19] and biceps brachia [20] muscles in females was higher compared to males. It seems that there is no consensus about the effect of sex on tendon and/or muscle stiffness, which may be related with the methodological differences of these studies. The differences in the method used to assess tissue stiffness (myotonometry, shear-wave elastography, ultrasonography, etc), the evaluated structures (muscle or tendon), and the evaluated population (athletes, young, middle age, or old individuals, etc.) might cause substantial differences in the results.

Another hypothesis of this study was that changes in tendon and muscle stiffness caused by joint motion would be different in males and females. The hypothesis is based on the idea that there would be differences in tendon and muscle stiffness between males and females, because the concentration of the connective tissue may differ between sexes. Thus, differences in tendon and muscle stiffness between sexes may lead to a significant sex-related difference in tendon and muscle stiffness in tensioned state. Different from our hypothesis, it was found that changes in the stiffness of Achilles tendon and the medial gastrocnemius muscle were similar in both sexes when the ankle was brought from neutral to 10° dorsiflexion. One study by Chino and Takahashi [18] investigated the sex-related differences in medial gastrocnemius stiffness in different ankle joint motions. They found that changes in the stiffness of the medial gastrocnemius caused by joint motion were not significant sex-related difference between sexes. On the other hand, Miyamoto et al. [23] quantified the effect of joint motion in the gastrocnemius by shear-wave elastography. They revealed that dorsiflexion ROM was negatively correlated to passive muscle stiffness in males but not females.

#### 4.4. Limitations

The present study has some limitations. First, only inter-observer reliability and inter-day repeatability were investigated in the present study. Intra-observer reliability, by measurements a few hours apart on the same day, was not investigated. Second, the effect of joint motion in muscle and tendon stiffness was tested only at 10° of ankle joint dorsiflexion. The effect of joint motion may be different at different degree of ankle joint motion such as 20° dorsiflexion, or 10° or 30° plantarflexion. Last, the study included young and healthy individuals. The reliability of the device used, sex effect and joint motion may be different in different populations (middle aged, geriatric, athletes, etc.) or pathological conditions (tendon pathologies or muscle damage).

#### 5. Conclusion

It was found that males have stiffer Achilles tendon and gastrocnemius muscle compared to females; however, changes in the stiffness of the assessed tissues caused by joint motion were similar in both sexes. Lower tendon and muscle stiffness in females may cause the impaired joint stability and/or control compared to males, and it may cause an increase in the musculoskeletal injury risk in females. On the other hand, the obtained results suggest that MyotonPRO has excellent inter-observer reliability and inter-day repeatability in measuring the stiffness of the Achilles tendon and medial gastrocnemius muscle.

#### Brief summary

##### What is known

- Tendon and muscle stiffness are an important component of joint stability and/or control.
- Tendon and muscle stiffness may be different in females because of the differences in hormone concentrations.
- Tendon and muscle stiffness are correlated with the tension on

muscle and tendon.

##### What this study adds

- MyotonPRO has excellent reliability and repeatability in measuring the stiffness of tendon and muscle.
- The stiffness of the Achilles tendon and gastrocnemius muscle is higher in males compared to females.
- Tension effect in tendon and muscle stiffness is similar in both sexes.

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#### Conflict of interest

None.

#### References

- [1] Molgaard C, Lundbye-Christensen S, Simonsen O. High prevalence of foot problems in the Danish population: a survey of causes and associations. *Foot (Edinb)* 2010;20:7–11. <https://doi.org/10.1016/j.foot.2010.03.002>.
- [2] Wezenbeek E, Willems T, Mahieu N, De Muynck M, Vanden Bossche L, Steyaert A, et al. The role of the vascular and structural response to activity in the development of Achilles tendinopathy: a prospective study. *Am J Sports Med* 2018;46:947–54. <https://doi.org/10.1177/0363546517750854>.
- [3] Collins NJ, Oei EHG, de Kanter JL, Vicenzino B, Crossley KM. Prevalence of radiographic and magnetic resonance imaging features of patellofemoral osteoarthritis in young and middle-aged adults with persistent patellofemoral pain. *Arthritis Care Res (Hoboken)* 2019;71(8):1068–73. <https://doi.org/10.1002/acr.23726>.
- [4] Raschner C, Hildebrandt C, Mohr J, Müller L. Sex differences in balance among alpine ski racers: cross-sectional age comparisons. *Percept Mot Skills* 2017;124(6):1134–50. <https://doi.org/10.1177/0031512517730730>.
- [5] Muehlbauer T, Gollhofer A, Granacher U. Associations between measures of balance and lower-extremity muscle strength/power in healthy individuals across the lifespan: a systematic review and meta-analysis. *Sports Med* 2015;45(December (12)):1671–92. <https://doi.org/10.1007/s40279-015-0390-z>.
- [6] Holden S, Boreham C, Delahunt E. Sex differences in landing biomechanics and postural stability during adolescence: a systematic review with meta-analyses. *Sports Med* 2016;46(2):241–53. <https://doi.org/10.1007/s40279-015-0416-6>.
- [7] El-Ashker S, Carson BP, Ayala F, De Ste Croix M. Sex-related differences in joint-angle-specific functional hamstring-to-quadriceps strength ratios. *Knee Surg Sports Traumatol Arthrosc* 2017;25(3):949–57. <https://doi.org/10.1007/s00167-015-3684-7>.
- [8] Stanev D, Moustakas K. Stiffness modulation of redundant musculoskeletal systems. *J Biomech* 2019;85:101–7. <https://doi.org/10.1016/j.jbiomech.2019.01.017>.
- [9] Maganaris CN, Paul JP. In vivo human tendon mechanical properties. *J Physiol* 1999;521 Pt 1:307–13. <https://doi.org/10.1111/j.1469-7793.1999.00307.x>.
- [10] Secomb JL, Lundgren LE, Farley OR, Tran TT, Nimphius S, Sheppard JM. Relationships between lower-body muscle structure and lower-body strength, power, and muscle-tendon complex stiffness. *J Strength Cond Res* 2015;29:2221–8. <https://doi.org/10.1519/JSC.0000000000000858>.
- [11] Tas S, Yilmaz S, Onur MR, Soylu AR, Altuntas O, Korkusuz F. Patellar tendon mechanical properties change with gender, body mass index and quadriceps femoris muscle strength. *Acta Orthop Traumatol Turc* 2017;51:54–9. <https://doi.org/10.1016/j.aott.2016.12.003>.
- [12] Burgess KE, Graham-Smith P, Pearson SJ. Effect of acute tensile loading on gender-specific tendon structural and mechanical properties. *J Orthop Res* 2009;27:510–6. <https://doi.org/10.1002/jor.20768>.
- [13] Agyapong-Badu S, Warner M, Samuel D, Stokes M. Measurement of ageing effects on muscle tone and mechanical properties of rectus femoris and biceps brachii in healthy males and females using a novel hand-held myometric device. *Arch Gerontol Geriatr* 2016;62:59–67. <https://doi.org/10.1016/j.archger.2015.09.011>.
- [14] Morse CI. Gender differences in the passive stiffness of the human gastrocnemius muscle during stretch. *Eur J Appl Physiol* 2011;111:2149–54. <https://doi.org/10.1007/s00421-011-1845-z>.
- [15] Morrison SM, Dick TJ, Wakeling JM. Structural and mechanical properties of the human Achilles tendon: Sex and strength effects. *J Biomech* 2015;48:3530–3. <https://doi.org/10.1016/j.jbiomech.2015.06.009>.
- [16] Fu S, Cui L, He X, Sun Y. Elastic characteristics of the normal Achilles tendon assessed by virtual touch imaging quantification shear wave elastography. *J Ultrasound Med* 2016;35:1881–7. <https://doi.org/10.7863/ultra.16.01052>.
- [17] Burgess KE, Pearson SJ, Breen L, Onambele GN. Tendon structural and mechanical properties do not differ between genders in a healthy community-dwelling elderly population. *J Orthop Res* 2009;27:820–5. <https://doi.org/10.1002/jor.20811>.
- [18] Chino K, Takahashi H. Association of gastrocnemius muscle stiffness with passive

- ankle joint stiffness and sex-related difference in the joint stiffness. *J Appl Biomech* 2018;34:169–74. <https://doi.org/10.1123/jab.2017-0121>.
- [19] Saeki J, Ikezoe T, Yoshimi S, Nakamura M, Ichihashi N. Menstrual cycle variation and gender difference in muscle stiffness of triceps surae. *Clin Biomech (Bristol, Avon)* 2019;61:222–6. <https://doi.org/10.1016/j.clinbiomech.2018.12.013>.
- [20] Eby SF, Cloud BA, Brandenburg JE, Giambini H, Song P, Chen S, et al. Shear wave elastography of passive skeletal muscle stiffness: influences of sex and age throughout adulthood. *Clin Biomech (Bristol, Avon)* 2015;30:22–7. <https://doi.org/10.1016/j.clinbiomech.2014.11.011>.
- [21] Zhang LN, Wan WB, Wang YX, Jiao ZY, Zhang LH, Luo YK, et al. Evaluation of elastic stiffness in healing achilles tendon after surgical repair of a tendon rupture using in vivo ultrasound shear wave elastography. *Med Sci Monit* 2016;22:1186–9.
- [22] Huang J, Qin K, Tang C, Zhu Y, Klein CS, Zhang Z, et al. Assessment of passive stiffness of medial and lateral heads of gastrocnemius muscle, Achilles tendon, and plantar fascia at different ankle and knee positions using the MyotonPRO. *Med Sci Monit* 2018;24:7570–6. <https://doi.org/10.12659/MSM.909550>.
- [23] Miyamoto N, Hirata K, Miyamoto-Mikami E, Yasuda O, Kanehisa H. Associations of passive muscle stiffness, muscle stretch tolerance, and muscle slack angle with range of motion: individual and sex differences. *Sci Rep* 2018;8:8274. <https://doi.org/10.1038/s41598-018-26574-3>.
- [24] Davidson MJ, Bryant AL, Bower WF, Frawley HC. Myotonometry reliably measures muscle stiffness in the thenar and perineal muscles. *Physiother Can* 2017;69:104–12. <https://doi.org/10.3138/ptc.2015-85>.
- [25] Lohr C, Braumann KM, Reer R, Schroeder J, Schmidt T. Reliability of tensiomyography and myotonometry in detecting mechanical and contractile characteristics of the lumbar erector spinae in healthy volunteers. *Eur J Appl Physiol* 2018;118:1349–59. <https://doi.org/10.1007/s00421-018-3867-2>.
- [26] Liu CL, Feng YN, Zhang HQ, Li YP, Zhu Y, Zhang ZJ. Assessing the viscoelastic properties of upper trapezius muscle: intra- and inter-tester reliability and the effect of shoulder elevation. *J Electromyogr Kinesiol* 2018;43:226–9. <https://doi.org/10.1016/j.jelekin.2017.09.007>.
- [27] Feng YN, Li YP, Liu CL, Zhang ZJ. Assessing the elastic properties of skeletal muscle and tendon using shearwave ultrasound elastography and MyotonPRO. *Sci Rep* 2018;8:17064. <https://doi.org/10.1038/s41598-018-34719-7>.
- [28] Tas S, Onur MR, Yilmaz S, Soylu AR, Korkusuz F. Shear wave elastography is a reliable and repeatable method for measuring the elastic modulus of the rectus femoris muscle and patellar tendon. *J Ultrasound Med* 2017;36:565–70. <https://doi.org/10.7863/ultra.16.03032>.
- [29] Kishimoto R, Suga M, Koyama A, Omatsu T, Tachibana Y, Ebner DK, et al. Measuring shear-wave speed with point shear-wave elastography and MR elastography: a phantom study. *BMJ Open* 2017;7:e013925. <https://doi.org/10.1136/bmjopen-2016-013925>.
- [30] Liu CL, Li YP, Wang XQ, Zhang ZJ. Quantifying the stiffness of Achilles tendon: intra- and inter-operator reliability and the effect of ankle joint motion. *Med Sci Monit* 2018;24:4876–81. <https://doi.org/10.12659/MSM.909531>.
- [31] Ditroilo M, Hunter AM, Haslam S, De Vito G. The effectiveness of two novel techniques in establishing the mechanical and contractile responses of biceps femoris. *Physiol Meas* 2011;32:1315–26. <https://doi.org/10.1088/0967-3334/32/8/020>.
- [32] Tas S, Bek N. Effects of morphological and mechanical properties of plantar fascia and heel pad on balance performance in asymptomatic females. *Foot (Edinb)* 2018;36:30–4. <https://doi.org/10.1016/j.foot.2018.02.003>.
- [33] Peltonen J, Cronin NJ, Avela J, Finni T. In vivo mechanical response of human Achilles tendon to a single bout of hopping exercise. *J Exp Biol* 2010;213:1259–65. <https://doi.org/10.1242/jeb.033514>.
- [34] Stenroth L, Peltonen J, Cronin NJ, Sipilä S, Finni T. Age-related differences in Achilles tendon properties and triceps surae muscle architecture in vivo. *J Appl Physiol* 2012;113:1537–44. <https://doi.org/10.1152/jappphysiol.00782.2012>.
- [35] 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;116:823–30. <https://doi.org/10.1007/s00421-016-3339-5>.
- [36] Altman DG. *Practical statistics for medical research*. London: Chapman and Hall; 2013.
- [37] Aubry S, Risson JR, Kastler A, Barbier-Brion B, Siliman G, Runge M, et al. Biomechanical properties of the calcaneal tendon in vivo assessed by transient shear wave elastography. *Skeletal Radiol* 2013;42:1143–50. <https://doi.org/10.1007/s00256-013-1649-9>.
- [38] Wentorf FA, Sudoh K, Moses C, Arendt EA, Carlson CS. The effects of estrogen on material and mechanical properties of the intra- and extra-articular knee structures. *Am J Sports Med* 2006;34:1948–52. <https://doi.org/10.1177/0363546506290060>.
- [39] Hart DA, Archambault JM, Kydd A, Reno C, Frank CB, Herzog W. Gender and neurogenic variables in tendon biology and repetitive motion disorders. *Clin Orthop Relat Res* 1998;44–56. PMID: 9646746.
- [40] Yu WD, Panossian V, Hatch JD, Liu SH, Finerman GA. Combined effects of estrogen and progesterone on the anterior cruciate ligament. *Clin Orthop Relat Res* 2001;268–81. <https://doi.org/10.1097/00003086-200102000-00031>.
- [41] Gajdosik RL. Passive extensibility of skeletal muscle: review of the literature with clinical implications. *Clin Biomech (Bristol, Avon)* 2001;16:87–101. PMID: 11222927.
- [42] Purslow PP. Strain-induced reorientation of an intramuscular connective tissue network: implications for passive muscle elasticity. *J Biomech* 1989;22:21–31. PMID: 2914969.