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Technical and measurement report

Measurement of Achilles tendon loading using shear wave tensiometry: A reliability study

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ABSTRACT

Background: Shear wave tensiometry is a recent promising technology which can be used to evaluate tendon loading. Knowing the clinimetric features (e.g., reliability) of this technology is important for use in clinical and research settings.

Objectives: To evaluate the inter-session reliability of a novel shear wave tensiometer for the assessment of Achilles tendon loading. A further aim was to test the construct validity of this device by evaluating its precision in detecting Achilles tendon loading changes induced by a plantar flexor isometric contraction of increasing intensity.

Method: Ten healthy participants were recruited. Five measurements were performed at different time points to evaluate inter-session reliability. Shear wave speed along the Achilles tendon was evaluated during different isometric contractions using a shear wave tensiometer composed of an array of four accelerometers fixed on the tendon, ranging from 4 to 8.5 cm from the calcaneal insertion of the tendon. Test-retest, intra- and inter-session reliability were determined using intraclass correlation coefficient ($ICC_{3.1}$). Absolute reliability was calculated using the standard error of measurement and minimal detectable change.

Results: Test-retest reliability was good to excellent ($ICC_{3.1}$ 0.87–0.99) for each of the contraction levels examined. Intra-session reliability was good to excellent ($ICC_{3.1}$ 0.85–0.96) and inter-session reliability was also good to excellent ($ICC_{3.1}$ 0.75–0.93) for each of the contraction levels.

Conclusions: This study confirms the reliability of this novel device. Future studies analyzing participants with Achilles tendinopathy are needed to evaluate the capability of shear wave tensiometry to detect transient changes in loading due to pathology.

1. Introduction

Increased mechanical stimuli on tendinous structures may lead to changes in the mechanical, material and morphological properties of the tendon; tendon stiffness appears to be modified by changes in the material rather than morphological properties of the tendon (Bohm et al., 2015). A recent study evaluating tendon responses to unloading, loading, and aging showed that tendon tissue is highly adaptable, with increased stiffness when loaded and decreased stiffness when unloaded (Magnusson and Kjaer, 2019). Some authors suggest that tendinopathic changes in the Achilles tendon (AT) leads to decreased tendon axial stiffness (Arya and Kulig, 2010; Chang and Kulig 2015; Child et al., 2010; Helland et al., 2013) and shear stiffness as measured with elastography (Aubry et al., 2015; Coombes et al., 2018).

Different loading protocols have demonstrated an effect on tendon adaptation, with the intensity of the exercise (high loading magnitude) and the length of the intervention (>12 weeks) contributing the most to improvements in tendon mechanical properties (Bohm et al., 2015).

Different assessment techniques have been developed in response to clinical and research interests in evaluating tendon mechanical properties to be able to characterize tendon response to loading and tendon health status. Recently, a promising technology known as shear wave tensiometry, has been developed and validated (Martin et al., 2018). This technology uses accelerometers to measure wave propagation

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along the tendon generated by a tapping device in order to measure muscle-tendon loading. The principle behind this technology is based on the concept that squared tendon wave speed varies in proportion to the axial stress in the tissue (Martin et al., 2018). Recent studies have demonstrated a relationship between AT wave speed and ankle kinetics during locomotion (Martin et al., 2018; Keuler et al., 2019) and different tendon loading between older and younger adults during walking (Ebrahimi et al., 2020).

Evaluation of the inter-session reliability of this device is important to apply this measure with confidence in a clinical setting and in longitudinal studies. Therefore, the aim of this study was to evaluate the inter-session reliability of a novel shear wave tensiometer for the assessment of AT loading. An additional aim was to test the construct validity of this device by evaluating its precision in detecting transient changes in tendon loading induced by a plantar flexor isometric contraction of increasing intensity.

2. Materials and methods

The study was conducted between May and July 2021 at the University of Applied Sciences and Arts of Southern Switzerland. The study was approved by the Ethics Committee of Canton Ticino (ID:2021–00611/CE3844) and written informed consent was provided by the participants. Reporting of this study adheres to the Guidelines for Reporting Reliability and Agreement Studies (Kottner et al., 2011).

2.1. Participants

Ten (5 male and 5 female) healthy, asymptomatic participants were prospectively recruited. Participants were excluded if they had a history of foot or tendon injury or surgery, metabolic, connective tissue or endocrine disease. Participants with systemic inflammatory disorders, spondyloartropathy, rheumatoid arthritis, or hypercholesterolemia were excluded.

The size of the sample was estimated according to Walter et al., (1998) using the following parameters: five replicates, $\rho0 = 0.6$, $p1 = 0.9$, $\alpha = 0.05$, and $\beta = 0.2$. The ideal sample size was 6.4. Given the choice of healthy participants and the non-invasive procedures, 10 were recruited. p0 was selected according to the clinical relevance threshold for the reliability measurement in clinics (0.6) (Munro 2005) whereas p1 of 0.9 was chosen after a structured pilot study involving four healthy participants.

2.2. Study procedures

A test-retest without repositioning of the participant and the device (test-retest) followed by a third measure where the participants were asked to stand up and come back to the examination bed (intra-session) was performed on the first day.

Two between day measures were performed following 1 week and 2 weeks (inter-session).

Participants were asked to maintain the same activity level throughout the entire study.

Wave speed along the AT (m/s) was measured using four accelerometers placed longitudinally on the AT during a ramp of isometric contractions with a randomized level of intensity corresponding to 0–1.75–3.5 - 7–17.5–35 Nm of the ankle joint torque. The participants were positioned in prone with the foot secured within a dynamometer with the ankle in 0° of dorsiflexion/plantarflexion (Fig. 1).

Prior to the first session, the participants attended a practice session to learn how to perform the isometric contraction and familiarize themselves with the visual feedback. The instruction 'push on the board as if you want to reach a tip-toe position' was given. Detachment of the heel from the dynamometer was monitored by the investigator and a tight fixation of the foot and ankle was ensured by two belts.

The detection software acquired a set of 10 repeated measures for each of the contraction levels for both the left and right AT for each participant. The mean of these 10 measurements were used to determine the reliability values. The same test location and times were maintained throughout the study.

Fig. 1. Image of the experimental setup. The participant was positioned in prone with the foot secured within a dynamometer with the ankle in 0° of dorsiflexion/plantarflexion. Force feedback was presented to the participants in real time. The bottom right box shows a detailed image of the tapping device and accelerometers.

2.3. Equipment

2.3.1. Accelerometers

The shear wave tensiometer was composed of an array of four accelerometers (Analog Devices, ADXL202JE) which were fixed with double adhesive tape on the tendon, equally spaced at a distance of 15 mm (Fig. 1). The most distal accelerometer was positioned 4 cm to the calcaneal insertion of the tendon (previously identified with ultrasound imaging - US). US was also used to check whether all the accelerometers were placed on the tendon and not on the musculotendinous junction.

The signals were acquired using a Sessantaquattro (OTBioelettronica, Torino, Italy) with a sampling frequency of 10 kHz. The signals were analyzed in order to identify the propagation velocity of the mechanical waves on the tendon, based on the delay between the waves.

Since the four accelerometers were equally spaced and given the hypothesis that the wave propagates at a constant speed, the delay between the waveforms detected by adjacent accelerometers was expected to be constant. The technique for propagation velocity estimation is based on the estimation of this delay using the cross-correlation function between pairs of signals. Once the average delay from each possible pair of signals was determined, the propagation velocity was calculated as the ratio between the inter-accelerometer distance and the average delay (Farina et al. 2001).

The algorithm is the same used in the field of surface electromyography for the computation of muscle fiber conduction velocity (Farina et al. 2001; Farina et al., 2004). The outcome variable was one propagation speed value (m/s) for each tap provided to the tendon (Fig. 2).

2.3.2. Tapper

The mechanical impulse was generated by a custom developed tapper based on an electromagnetic transductor. A current impulse was used to activate an electromagnet, which attracts the iron arm connected to a wooden stick. In its rest position the wooden stick was held a few millimetres away from the tendon. The tapping frequency was set to 4 Hz. The opening and closing of the switch was controlled by a microcontroller (Arduino UNO, Italy) programmed to provide intermittent

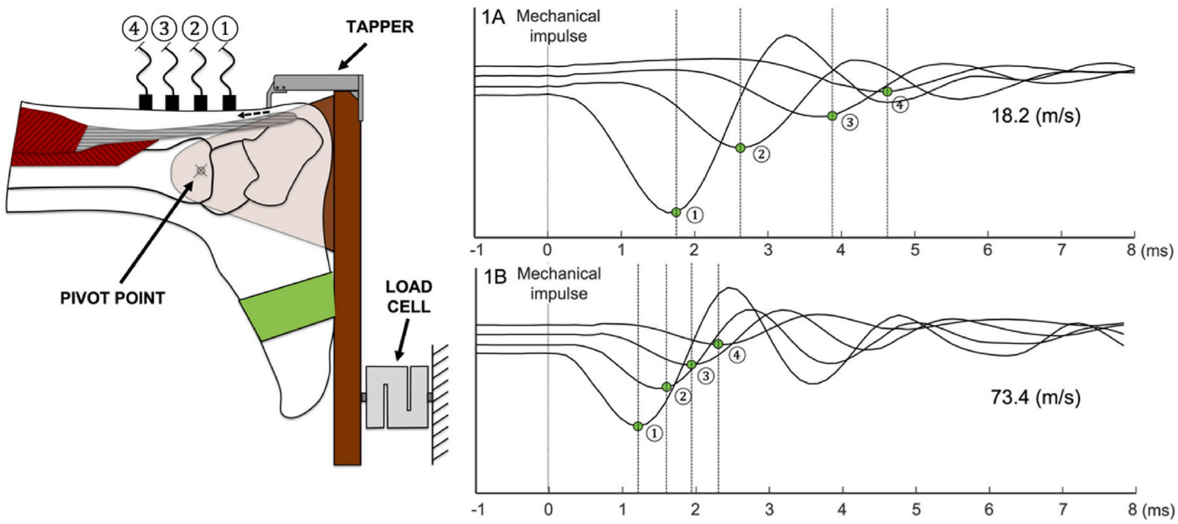

Fig. 2. Schematic of the shear wave tensiometer. The tapper device was mounted on the dynamometer and placed on the Achilles tendon at 2 cm from the calcaneus insertion. The four accelerometers (1–4) were attached to the skin in series with a 15 mm inter-accelerometer distance. Shear wave speed signals of the Achilles tendon at 0 Nm (1A) and at 35 Nm of isometric ankle torque (1B). The propagation velocity of the wave was calculated based on the delay between the waves passing from the accelerometers.".

pulses with constant time intervals (250 ms). The tapper was positioned 2 cm proximally from the end of the calcaneal bone. This location was checked by means of US.

2.3.3. Force feedback

Participants performed different intensities of isometric contractions of the plantar flexors (0–1.75–3.5 - 7–17.5–35 Nm). The torque of the ankle was assessed using a dynamometer connected to a force sensor that operated linearly in the range between 0 and 100N (Mod. TF2/S; CCT Transducers, Turin, Italy). The force sensor was attached to a wooden board connected to a hinge that allowed natural dorsiflexion and plantar flexion of the ankle. The board was fixed in order to permit isometric contractions only at a fixed angle of 0° dorsiflexion. The force measured by the force sensor was proportional to the torque exerted at the ankle level. Force signals were amplified using MISO-II (OT Bioelettronica, Turin, Italy; bandwidth 0–80 Hz) and presented to the participants as real time visual feedback. A practice phase prior to the recording was conducted in order to familiarize the participant with the visual feedback and practice the contractions.

2.4. Statistical analysis

Descriptive statistics, mean ± SD, were determined to characterize the demographics of the sample. Statistical Package for Social Sciences (SPSS v. 26) was used for statistical analysis.

Test-retest, intra-session and inter-session reliability was calculated using intraclass correlation coefficient ($ICC_{3.1}$) based on a single-rater (k = 1), absolute agreement, 2-way mixed effect model. Absolute reliability was calculated using the standard error of measurement (SEM) and minimal detectable change (MDC) (Atkinson and Nevill 1998). An ICC >0.6 was used to consider the clinical relevance of the measurements (Munro 2005). Inter-measurement variability was calculated using the coefficient of variation % (CoV%) of the 10 measurements for each participant and contraction level.

The distribution of the data was determined using Shapiro-Wilk test and non-parametric independent samples, Mann-Whitney test was performed to assess significant differences in AT wave speed between men and women and between the dominant and non-dominant leg.

A linear regression model was used for each participant to test the linear relationship between squared wave speed and ankle joint torque to determine construct validity. The goodness of fit of the subject specific model was assessed using the coefficient of determination (R^2).

Wave speed values are presented as median and IQR.

3. Results

Data from 10 healthy participants (5 female) were analyzed. Their mean (±SD) age, height and weight were 31 (6.9) years, 173 (8.2) cm and 65 (9.3) kg respectively.

Data were pooled and analyzed across the entire sample given that no significant difference in AT wave speed was observed between men and women ($p = 1.000$) or between the left and right side ($p = 0.853$). Wave speed values at the different contraction levels and inter-measurement variability are reported in Table 1.

Test-retest reliability was good to excellent with a minimum value of $ICC_{3.1}$ 0.87 and a maximum of $ICC_{3.1}$ 0.99 considering all contraction levels. Intra-session reliability was good to excellent with a minimum value of $ICC_{3.1}$ 0.85 and a maximum of $ICC_{3.1}$ 0.96 considering all contraction levels. Inter-session reliability was also good to excellent with a minimum value of $ICC_{3.1}$ 0.75 and a maximum of $ICC_{3.1}$ 0.93 considering all contraction levels. The measure at 17.5 Nm showed good reliability but the lower limits of 95% CI were below the cut-off point of >0.6 considered to be the clinically relevant threshold. Reliability data with 95% CI and absolute reliability calculated with SEM and MDC are reported in detail in Table 1.

Linear regression models showed that squared wave speed was quite accurately predicted by ankle joint torque for each of the participants ($R^2 = 0.991 \pm 0.01$ and 0.992 ± 0.01, mean ± SD, for the left and right tendon respectively) (Fig. 3) For every Nm of torque increase, the squared wave speed increased by 139 (m^2s^{-2}) on average among the participants. The ankle joint torque-wave speed relationship was however variable across participants, ranging from a minimum value of 84.9 to a maximum of 211.7 (m^2s^{-2}).

4. Discussion

The purpose of this study was to evaluate the reliability of a shear wave tensiometer for the evaluation of AT loading at different contraction levels. The results showed that this device is highly reliable (ICC>0.75) not only when a test-retest without repositioning of the accelerometers was performed but also with the repositioning (intra-session) and between different sessions (inter-session).

Table 1
Shear wave speed values of the sample, inter-measurement variability, absolute and relative reliability values for the different contraction levels.

Ankle torque	Shear wave speed values (m/s)	Inter-measurement variability	Test-retest reliability			Intra-session reliability			Inter-session reliability		
Nm	Median (IQR)	Cov (%)	ICC	SEM	MDC	ICC	SEM	MDC	ICC	SEM	MDC
0	21.53 (4.4)	2.3%	0.99 (0.98–0.99)	0.3	0.8	0.96 (0.91–0.99)	0.6	1.8	0.93 (0.86–0.97)	0.9	2.5
1.75	27.24 (6.3)	2.8%	0.95 (0.87–0.98)	0.8	2.3	0.92 (0.79–0.97)	1.2	3.4	0.83 (0.65–0.93)	1.9	5.1
3.5	31.3 (5.8)	2.6%	0.94 (0.84–0.98)	1.0	2.7	0.95 (0.86–0.98)	0.9	2.6	0.84 (0.65–0.93)	1.9	5.3
7	36.08 (6.8)	2.4%	0.96 (0.89–0.98)	1.0	2.7	0.85 (0.62–0.94)	2.0	5.4	0.81 (0.60–0.92)	2.3	6.4
17.5	54.6 (9.2)	2.5%	0.93 (0.83–0.97)	1.7	4.6	0.90 (0.75–0.96)	2.0	5.7	0.75 (0.48–0.89)	3.4	9.5
35	76.33 (22.6)	2.1%	0.87 (0.67–0.95)	4.7	13.1	0.90 (0.75–0.96)	3.7	10.3	0.84 (0.66–0.93)	4.7	12.9

Abr.: ICC, intraclass correlation coefficient; CI, coefficient interval; SEM, standard error of measurement; MDC, minimal detectable change; CoV, coefficient of variation; IQR, interquartile range.

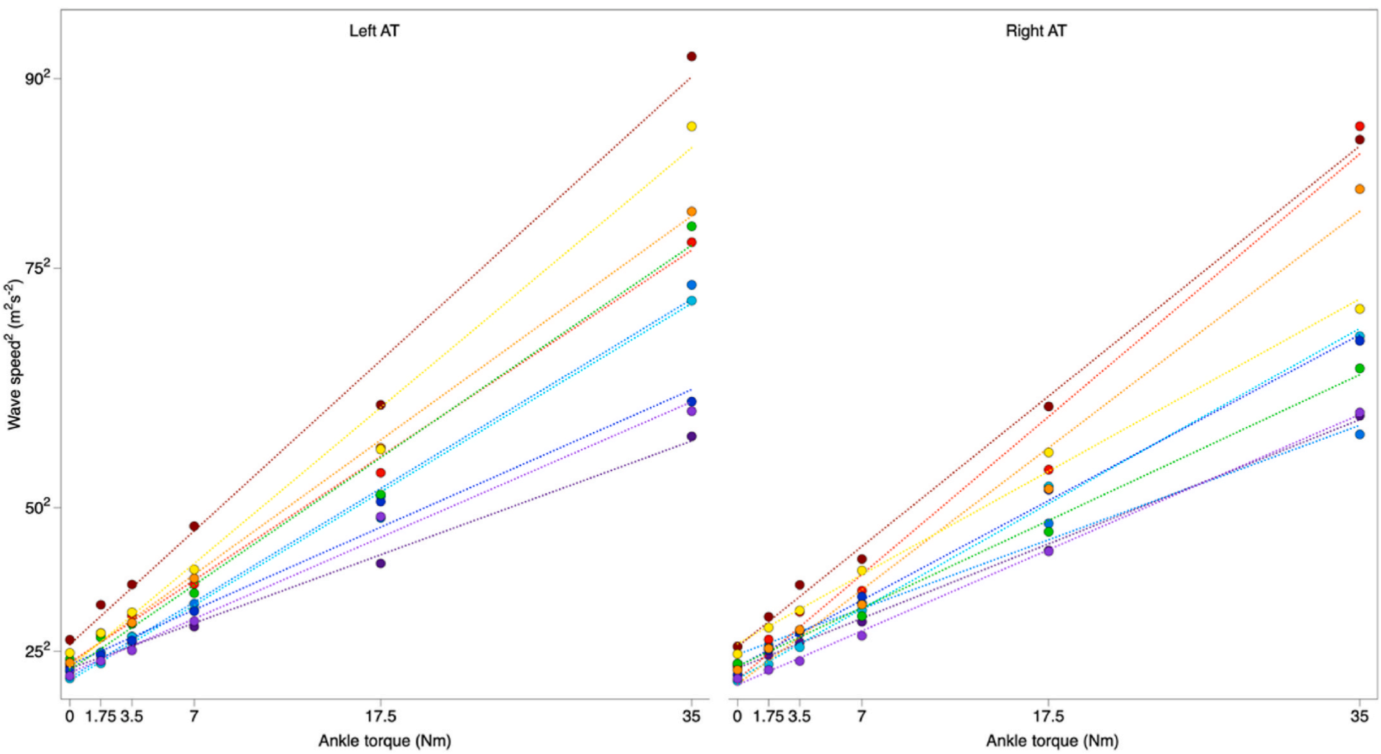

Fig. 3. Scatter plot showing the squared shear wave speed values of each of the participants tendons (n = 20) for the different levels of ankle torque. The two panels show the values of the left and right tendon (AT). Each dot is the average of three sessions and each colour represents a participant. Lines represent the linear regression for each tendon (R^2).(For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article)

Every contraction level assessed in the study (from 0 to 35 Nm) resulted in high reliability values showing that this instrument is precise even when the tendon is under load and is subject to a transient loading change. Moreover, absolute reliability calculated with the SEM and MDC showed a very small error when compared to the shear wave speed values obtained in the different contraction levels.

As the plantar flexor force increase, AT should increase its strain and its stiffness (Kjaer 2004; Magnusson et al., 2003), and therefore an increment in the shear wave speed should be found when the tendon is gradually put under load by isometric contractions to confirm this construct. Construct validity of the measurement was confirmed, and indeed for each participant the coefficient of determination (R^2) was very high ($R^2 = 0.991 \pm 0.01$ and 0.992 ± 0.01, mean ± SD, for the left and right tendon respectively) indicating that the increase in the squared wave speed was strongly correlated with the increase of the ankle joint torque.

Despite this strong relationship, highly variable results were found between participants showing possible individual behavior of the tendon during load. Further studies are needed to better understand these changes.

This novel technology has been previously validated and used to assess AT loading during gait (Martin et al., 2018). Only a few studies (Martin et al., 2018 Keuler et al., 2019) tested this device during isometric contractions and the results are comparable with the present study with a wave speed that varies from 15 to 20 (m/s) when the muscles were relaxed, to 60 to 80 (m/s) when maximal contractions were performed.

In the present study, values ranged from 21.53 m/s (IQR 4.4) with no contraction to 76.33 m/s (IQR 22.6) with a 35 Nm contraction. The device used in the current study consisted of 4 accelerometers in series with an inter-accelerometer distance of 1.5 cm which allows a larger (4.5 cm) portion of the Achilles free tendon to be assessed compared to previous studies which analyzed 1 cm of the tendon. (Keuler et al., 2019; Ebrahimi et al., 2020; Acuna et al., 2019). Considering that it was not possible to assume a constant wave speed between accelerometers pairs, due to possible variation of the tendon cross-sectional area or wave dispersion, a larger spatial sampling with multiple detection points allowed us to average the wave speed.

4.1. Methodological considerations

There are some limitations of this study that need to be acknowledged. Firstly, the study evaluated a novel shear wave tensiometer under controlled conditions, and therefore the results cannot be generalized to other types of shear wave tensiometers. Sample size was estimated for the calculation of the reliability values, therefore values of the correlation between contraction levels with this sample size could be underpowered. Moreover, the results cannot be generalized to other tendons or to different conditions.

5. Conclusions

This study confirms the reliability and construct validity of shear wave tensiometry. Future studies analyzing participants with Achilles tendon pathology (i.e., tendinopathies or tendon rupture) are needed to evaluate the capability of shear wave tensiometry for use in clinical practice.

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Declaration of competing interest

None.

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