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Tendon structural and mechanical properties do not differ between genders in a healthy community-dwelling elderly population.

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Tendon Structural and Mechanical Properties Do Not Differ between Genders in a Healthy Community-Dwelling Elderly Population

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ABSTRACT: Elderly women are reportedly at higher risk of falling than their male counterparts. Postural balance is highly associated with fall risk and is also correlated with tendon structural and mechanical properties. Gender differences in tendon properties could partly explain the discrepancy in fall risk. Thus the purpose of this study was to investigate the possible gender difference in tendon properties in the elderly. The properties of the patellar tendon of 55 elderly (men $n = 27$, aged 72 ± 1 years, women $n = 28$, aged 70 ± 1 years) participants were tested. Tendon stiffness (K), length (L), and cross-sectional area (CSA) were measured using B-mode ultrasonography, dynamometry, and electromyography during ramped isometric knee extensions. There were no significant differences ($p > 0.05$) between men and women in tendon stiffness (elderly men 550.9 ± 29.2 vs. women 502.9 ± 44.9 Nmm^{-1}) or in Young's modulus (elderly men 0.32 ± 0.02 vs. women 0.36 ± 0.04 GPa). This elderly group had similar tendon structural and mechanical properties. The comparable characteristics in gender-specific tendon properties in an elderly population exhibiting similar lifestyle characteristics to the current sample may not explain the reports in the literature regarding increased fall risk in elderly women relative to that seen in men of a similar age.

Keywords: aging; gender differences; patellar tendon; stiffness; Young's modulus

In the last 30 years the proportion of the population aged 65 years or more has increased to 16% in the UK and this increase is set to continue (The Office for National Statistics, 2006). Approximately one-third of people aged over 65 fall at least once a year, and about half of these do so recurrently, leading to injury and subsequent decrease in quality of life, and in many cases death.[1] Elderly women exhibit a higher risk of falling than their male counterparts,[2,3] and most falls occur after a loss of stability in a forward direction such as tripping while walking.[2] In order to maintain balance individuals require information concerning the orientation of the body in space and the geometry of the body. In humans this information is obtained via the complex interactions of sensory systems (primarily the somatosensory, visual, and vestibular systems) and motor systems.[4] Aging results in a decline in the function of these systems and their interaction, which has been related to reduced balance ability and thus increased fall risk.[5–7]

One of the major proprioceptive mechanisms involved in maintaining balance is the stretch reflex (the reflex contraction of a muscle in response to an increase in muscle length detected by the muscle spindles).° With aging the latency of this reflex (initiated via a tendon tap) has been seen to increase, which can cause delayed action for postural control.[9,10] Previous authors[11] have demonstrated that in response to a perturbation in the surface on which they are standing, the latency of muscle response was greater in older individuals than their younger counterparts. One of the possible mechanisms behind these delayed responses with aging is through the reported increased compliance of tendon structures in the elderly,[12] whereby more compliant tendons would cause an increase in the time taken to detect and respond to changes in muscle length.

The ability to maintain balance or stability has previously been associated with lower limb tendon structural and mechanical properties, with stiffer tendon structures associated with increased balance ability.[12] A proposed explanation for this finding is related to the tendon's primary function of force transmission. Stiffer tendon structures enable more rapid force transfers than compliant systems and thus increase the speed at which the muscle tendon complex corrects the "catch and throw" actions involved in maintaining balance[13] and consequently improves balance performance.[14] Tendon properties also have the capacity to affect muscle force output and function, as muscle follows a hyperbolic force-velocity relationship. All things being equal, a more compliant tendon would allow greater initial muscle shortening velocity as well as greater degrees of muscle shortening, both of which could adversely affect force production, especially in the early stages of muscle contraction. This has been demonstrated practically as (a) tendon stiffness has been related to rate of force development[15] and (b) tendon stiffness at low force levels has been shown to affect the magnitude of resting and potentiated muscle twitches.[16]

In vivo tests have shown aging to be associated with a reduction in tendon stiffness and Young's modulus,[12,17] and thus to be detrimental to fall risk, muscle output, and function. Potential mechanisms for the reduction in tendon stiffness and Young's modulus with ageing likely include: a reduction in collagen fibril diameter, a reduction in the packing density of longitudinally aligned collagen fibers, and an alteration in any number of molecular factors. In young populations gender differences in tendon and aponeurosis properties have been reported, with men having greater stiffness and Young's modulus than women.[18,19] If this difference is also present in the elderly population it would partly explain the discrepancies in fall risk between genders.

Therefore, the purpose of the current study was to determine the tendon mechanical properties in elderly men and women to quantify any gender differences. We hypothesized that elderly men have greater tendon stiffness than their female counterparts.

METHODS

Participants

Elderly adults volunteered to participate in the current study having responded to advertisements and posters sent to various local societies. Participants with known cardiovascular, neurological, inflammatory, and myopathic diseases were excluded. Medical consent was given by each participant's general practitioner. Thus the current study participants were relatively healthy, semirural community dwelling persons with no recent history of structured resistance training. These individuals were classified as habitually active, as they regularly partook in physical activities (ascertained through a modified version of the Allied Dunbar Fitness Survey[20] as sufficiently high to make them out of breath in their daily routine [men 289 ± 29 min per week, women 314 ± 46 min per week, mean ± SEM]). Thus there was no significant difference in the reported activity levels between genders ($p > 0.05$). None of the participants were master or ex-elite athletes, nor had they any history of physically demanding jobs such as farming or construction work. All in all, 55 individuals participated in the study and were categorized into elderly women (n =28, mean age 70 ± 1 years [SEM], height 1.59 ± 0.01 m, and body mass 69.5 ± 2.6 kg) versus elderly men (n = 27, mean age 72 ± 1 years, height 1.75 ± 0.02 m, and body mass 80.8 ± 2.0 kg). The investigation was approved by the local Ethics Committee and all subjects gave their written informed consent to participate. The study conformed to the principles of the World Medical Association's Declaration of Helsinki. Participants visited the laboratory prior to the test session to allow familiarization with the protocols.

Measurement of Patellar Tendon Forces

Torque output during isometric knee extension was determined using a dynamometer (Cyber NORM, NY). The knee was fixed at 90° flexion (full extension =0°) and hip at 85° (supine =0°). The centre of rotation of the dynamometer lever arm was aligned with the knee joint centre, and straps were fixed across the chest, as well as hip and thigh of the test limb to prevent any extraneous movement. A lever attachment cuff was placed on the lower leg at ~3 cm above the medial malleolus. Three maximal isometric knee extension efforts were carried out to ensure tendon preconditioning prior to the test. Participants were instructed to perform ramped isometric knee extensions to maximum over a 3–4 s time period. Six trials of the test were performed with 180 s rest between contractions. Tendon force was calculated as $F_{tend} = (P þ P_{antag})/T_{arm}$, where F_{tend} = force in the patellar tendon, P = observed knee extensor torque output, P_{antag} = antagonistic (hamstring) cocontraction torque, and T_{arm} = patellar tendon moment arm 44.7 mm computed from the average of previous reports.[21,22]

Estimation of Hamstring Cocontraction during Knee Extension Using Electromyographical (EMG) Activity

The EMG of the long head of the biceps femoris muscle (BF) was measured in order to ascertain the level of antagonistic muscle cocontraction[16] during the isometric knee extension efforts. Assumptions were that BF is representative of its constituent muscle group,[23] and BF EMG relationship with knee flexors torque is generally linear.[24] Two self-adhesive Ag-AgCl electrodes 10 mm in diameter (Medicotest, Rugmarken, Denmark) were placed in a bipolar configuration with a constant interelectrode distance of ~20 mm, at a site corresponding to the distal one-third of the length, in the midline of the belly of the BF. Prior to electrode attachment the skin was prepared by shaving, abrading, and cleaning with an alcohol-based solution in order to minimize its resistance. The reference electrode was placed on the lateral tibial condyle of the test limb. The raw EMG signal was sampled at 2,000 Hz, pre-amplified, and filtered using high- and low-pass filters set at 10 and 500 Hz, respectively (Biopac Systems Inc., CA). All EMG and torque signals were displayed in real time in Acknowledge software (Biopac Systems, Inc.) via a computer (Macintosh G4). A series of three maximal isometric knee flexion contractions were carried out to obtain the EMG at maximal flexion torque. The root mean square (RMS) EMG activity corresponding to the peak torque period was analyzed over 50 ms epochs and averaged for a 1 s period during the plateau of peak torque. This has been previously suggested to be acceptable in terms of signal-to-noise ratio.[25] EMG activity of the BF during knee extension was divided by the maximal BF flexor EMG, and the maximal flexor torque was then multiplied by this value to determine cocontraction torque.

Measurement of Patella Tendon Elongation

Elongation of the patellar tendon was assessed during the graded isometric knee extensions using a 7.5 MHz, 40 mm linear array, B-mode ultrasound probe (AU5; Esaote Biomedica, Italy) with a depth resolution of 49.3 mm. The probe was positioned in the sagittal plane over the patella tendon at either (a) the apex of the patellar (proximal end/origin) or (b) the tibial tuberosity (distal end/insertion) (see Fig. 1).

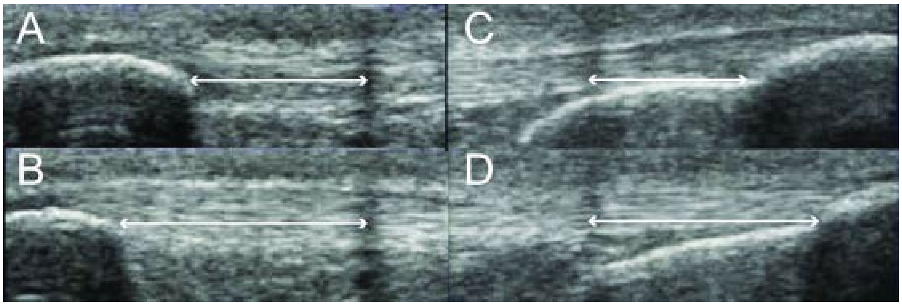


Figure 1. Ultrasound image of the prox- imal (A,B) and distal (C,D) attachments of the patellar tendon, at rest (A,C) and at 100% MVC (B,D). White arrows indicate distance measured between the echo-absorptive marker and the reference point of tendon attachment.

The probe position was alternated between knee extension efforts so that three efforts for both the origin and insertion of the tendon were recorded. An echo-absorptive marker was placed between the probe and the skin to act as a fixed reference from which measures of elongation could be made. Ultrasound images were recorded in real time onto mini DV via S-video output and captured onto PC at 25 Hz using Quintic Biomechanics (9.03 v 11). The ultrasound output was synchronized (using an electronic signal generator) with the force and EMG records to allow temporal alignment. Tendon excursions at both the proximal and distal ends were determined at intervals of 10% of the maximal force (from 0 to 100%) using image J (National Institutes of Health, Bethesda, MD). Corresponding proximal and distal excursions were combined to determine total tendon elongation.

Calculation of Tendon Properties

The tendon force-elongation relationships were fitted with second order polynomial functions forced through zero. Tendon stiffness (K) measures (in Nmm^{-1}) were calculated from the slopes of the tangents at 10% force intervals. In addition, K was also computed at a fixed force level corresponding to the maximum tendon force of the weakest participant (1,200 N). Patella tendon cross-sectional area (T_{CSA}) and resting length (T_L) were also assessed with the knee joint at 90°. T_{CSA} was measured as the average from transverse-plane ultrasound images taken at 25, 50, and 75% T_L with the measure made three times and an average taken. T_L was determined from sagittal-plane ultrasound images and measured from the inferior pole of the patellar to the superior aspect of the tibial tuberosity with the measurement taken twice and the average utilized. Young's modulus (s) was calculated as the product of stiffness and the ratio between T_L to T_{CSA}. Tendon strain (%) was calculated as the ratio of tendon elongation to the T_L. Tendon stress was calculated by dividing force in the tendon by T_{CSA}.

Statistical Analyses

Student's t-tests were performed to determine the effects of gender on tendon properties. Significance was set to $p \leq 0.05$. Effect sizes (r) were calculated for all t-tests where $p \leq 0.05$. All data are presented as mean ± SEM. Intraclass correlation coefficients (ICCs: one-way random effects model) were calculated to estimate reliability of the measures (for knee extension torque the values from the six knee extension trials were compared, for tendon elongation the three combined elongations computed from the six trials were compared, for T_{CSA} the three measured used to calculate the utilized average were compared, and for T_L the two measures taken to calculate the average were compared).

RESULTS

The within-session ICCs were 0.906 for tendon elongation, 0.959 for knee extension torque, 0.911 for T_{CSA}, and 0.937 for T_L.

The analyses revealed no significant differences between genders for either stiffness or Young's modulus ($p > 0.05$). See Table 1 for a summary of the measured variables.

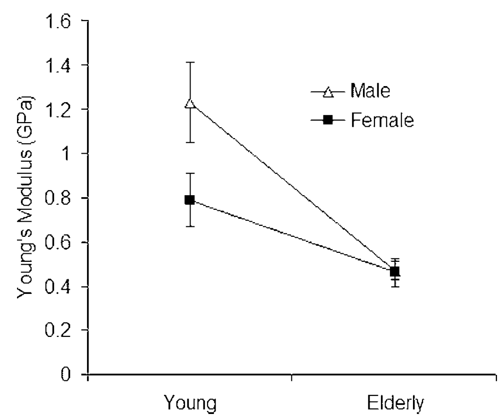
Elderly women had tendons, which, although similar in length compared with those of the male participants, had a smaller cross sectional area ($p < 0.05$, r=0.999) (see Table 1). Even though elderly men produced significantly greater maximal tendon forces than women (men 2,949 ± 173 N vs. women 1,940 ± 112 N, p<0.05, r =0.998), there was no significant difference between genders in K or in s calculated at relative force levels (%MVC) ($p > 0.05$). In addition, when calculated at an absolute force level (1,200 N) no gender differences in K or s were observed ($p > 0.05$). The force-elongation (Fig. 2A) and stress-strain (Fig. 2B) graphs illustrate the similar loading profiles for both elderly genders.

There were no significant differences in maximal tendon elongation between genders in the study population. However, a trend can be seen for greater elongation in men, likely due to their greater force-generating capacities (men 7.3 ± 0.3 mm vs. women 6.2 ± 0.4mm, p=0.06, r=0.469). Consequently, due to their similar tendon lengths, there were no significant differences in maximal strain (men 15.3 ± 0.8% vs. women 13.9 ± 1.0%, $p > 0.05$) in the study group. Similarly, when calculated at an absolute force level (1,200, there were no significant differences between genders in either elongation or strain ($p > 0.05$). Conversely, although there was no significance between genders in maximal stress ($p > 0.05$), stress at the absolute force level of 1,200 N was significantly greater in women than men (men 14.31 ± 0.59 MPa vs. women 18.29 ± 0.62 MPa, $p < 0.05$, r =0.988) due to the smaller CSA in the women.

Table 1. Mechanical and Structural Properties of Tendon in Elderly Men and Women

	Gender	
Variable	Male	Female
Stiffness at 100% MVC (Nmm^{-1})	791.0 ± 51.4	640.6 ± 67.8
Stiffness at 1,200 N (Nmm^{-1})	550.9 ± 29.2	502.9 ± 44.9
Young's modulus at 100% MVC (GPa)	0.47 ± 0.04	0.46 ± 0.05
Young's modulus at 1,200 N (GPa)	0.32 ± 0.02	0.36 ± 0.04
T_L (mm)	48.3 ± 1.0	45.9 ± 1.0
T_{CSA} (mm^2)	87.1 ± 3.3	67.0 ± 1.8*

Asterisk indicated women significantly different from men ($p < 0.05$).



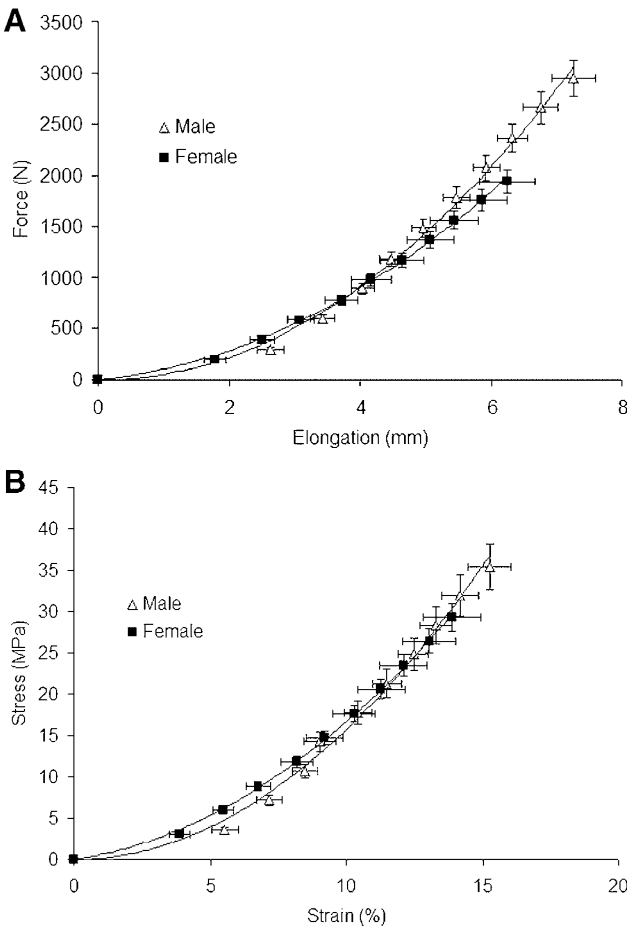


Figure 2. Gender differences in patella tendon properties in healthy elderly persons. (A) Mean force elongation profile. (B) Mean stress-strain relationship. Data are mean ± SEM.

Figure 3. Gender differences in patellar tendon. Young's mod- ulus by age group. The significant differences in the maximal values seen at ~22 years of age have disappeared by the age of ~71. Data are mean ± SEM.

DISCUSSION

The purpose of the current study was to systematically characterize the tendon structural and mechanical properties in the elderly to quantify any gender differences. Our findings have shown that there is no significant difference in stiffness and Young's modulus between genders in the studied elderly population. This is in contrast to the previously reported significant gender differences found in the young.[18]

The reported elderly values in this study for stiffness and Young's modulus (men: 791.0 ± 51.4 Nmm^{-1}, 550.9 ± 29.2 GPa; women: 640.6 ± 67.° Nmm^{-1}, 502.9 ± 44.9 GPa) are lower than those found previously for mixed gender elderly populations (2,1°7.4 ± 713.1 Nmm^{-1}, 1.3 ± 0.3 GPa[26] and 1,375.5 ± °11.2[27]). However, the present study took into account tibial excursions in addition to those of the patellar. This is in contrast to the method used previously,[26–2°] where only patellar excursions were measured when determining tendon elongation. Indeed, the tibial movement has previously been shown to account for up to 45% of overall tibial-patellar displacement.[29] Thus, failure to take tibial motion into account, whilst useful in determining relative differences, results in an underestimation of absolute tendon elongation values, and therefore, higher calculated stiffness values. Previous findings in young individuals comparing both the stiffness calculated from just patellar and patellar plus tibial excursions (i.e., combined methodology) showed that the combined method produced stiffness values that were 50 –60% lower than the methodology that only takes patellar displacement into account.[1°]

As expected the elderly population had lower stiffness and Young's modulus values than previously reported data on younger persons. Interestingly, comparing the current set of data to figures from Onambélé et al.[18] it can be seen that based on group averages, men show a 62% decrease in Young's modulus with aging whereas women show a smaller decrease (i.e., 42%). The differing slopes would suggest that the alignment in tendon mechanical properties between genders with ageing seen in the current study is due to the men experiencing a greater age-related decrement compared with the women. This is also highlighted by the age-gender interaction shown graphically in Figure 3. There is a lack of a significant gender difference in tendon stiffness and Young's modulus in the elderly population (elderly men: 791.0 Nmm^{-1}, 0.47 GPa vs. elderly women: 640.6 Nmm^{-1}, 0.46 GPa) compared to significant differences previously found in the young (young men: 2,919.0 Nmm^{-1}, 1.23 GPa vs. young women: 1,393.6 Nmm^{-1}, 0.79 GPa [1°]).

In absolute values, the elongation and strain values for the elderly population reported here are lower than those previously highlighted in young men and women.[1°] This, however, is not surprising, as the more compliant elderly tendon structures elongate less during maximal voluntary contractions, owing to a reduced maximal force-generating capacity. Results from isolated tissue testing in vitro have shown the mechanical properties at the point of failure for the patellar tendon of a group of older persons (64–93 years) to be: 53.6 ± 10.0 MPa (stress), 15 ± 5% (strain), and 504 ± 222 MPa (modulus).[30] In comparison to the results reported here, the above values are greater for stress and strain. This is to be expected because our measurements using voluntary contraction did not reach tissue failure. What is more, the lower values of tendon modulus in vitro may be due to inherent errors in the in vitro measurement process, such as: specimen slippage,[31] changes in tissue properties due to extraction and storage,[32] and premature specimen failure due to high stress created at the clamping sites,[33] as well as differential physiological factors such as temperature[29] and variance in the magnitude of the applied load and strain rates. In fact, reported failure values for the patellar in vitro have reached: stress ~80 MPa,[30] strain ~30%,[32] and modulus ~850 MPa.[34]

A possible explanation for the reduction of a gender difference in tendon mechanical properties with aging is the changing hormonal milieu. Research has identified estrogen as being important to the homeostasis of many musculoskeletal tissues.[35] Tendon has been found to contain estrogen receptors that are responsive to female sex hormones,[36,37] and it has been suggested that circulating hormonal factors such as estrogen and/or progesterone could affect tendon stiffness.[38] This has been supported by evidence showing that lower limb musculotendinous stiffness varies considerably over the course of the menstrual cycle.[39] In addition, in rat tail tendon, collagen concentration has been reported to decrease after treatment with oestrogen.[40] Women experience a rapid decline in sex hormones (estrogen) expressed with the cessation of menses.[41] It is possible that the reduction in estrogen levels to some degree counteracts the aging effect on tendon through causing women's tendon properties to deteriorate less (where increased compliance is considered a deterioration) with aging than men's.

The similarity between genders in tendon properties in this elderly population implies that the higher fall risk in elderly women is not partly due to differences in tendon mechanical properties, but due to gender differences in other fall risk factors. One possible explanation based on the results presented here is the difference in strength between genders. First, it should be noted here that the strength values presented here are in line with those reported previously for mixed gender and single gender healthy elderly populations.[26,42–44] Second, it is notable that the men produced significantly higher forces than the women. Nevertheless, the relationship between strength and risk of falls remains unclear,[45] with some previous studies reporting positive associations between strength and balance ability[6,12,46] and others showing no association.[47,4°] The contradictory reports may be influenced by the differing elderly populations, ranging from independent individuals living alone to those who are institutionalized and may possess different neuromuscular characteristics owing to decreased functions of self-reliant daily living. In addition it has been proposed that both the most active and inactive individuals could run increased risk of falls, because the active individuals have increased opportunity to fall whilst the inactive individuals possess poor balance ability.[49] The results presented here are thus only representative of a healthy, recreationally active, community-dwelling group of elderly individuals, who showed a slight trend for the women to carry out slightly more (~9%, $p > 0.05$) habitual physical activities compared with the men.

How do we know that the effects observed are due to gender—in other words, are all other variables controlled? If activity level was to cause the alignment in tendon properties it would mean that the females would have had to be considerably (not just slightly!) more physically active than the males. However, the males in fact had significantly greater force-producing capabilities than the females. What is more, the sampled populations were similar in terms of lifestyle and health status. Finally, the greater decline in tendon stiffness with aging in the males is in line with reported greater levels of sarcopenia amongst men compared to women.[50] Although strength has not become aligned, tendon properties have. This is not entirely surprising because recent data[51] have shown that tendon parameters per se appear to be more rapidly sensitive to modulator influences than muscle parameters.

In conclusion, the current data have shown there to be no significant differences in the patellar tendon properties between genders in the studied elderly population. Hence, gender-specific tendon mechanical properties in an elderly population exhibiting similar lifestyle characteristics to the current sample may not explain the reports in the literature regarding increased fall risk in elderly women compared with that in men of a similar age.

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