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Influence of bone mineral density, age, and strain rate on the failure mode of human Achilles tendons

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Abstract

Objective. To examine the influence of strain rate, bone mineral density, and age in determining the mode by which human Achilles tendons fail.

Design. Dual-energy X-ray absorptiometry and mechanical testing of excised Achilles tendon-calcaneus specimens.

Background. The Achilles tendon can fail by tendon rupture or bony avulsion. These injuries are caused by similar loading mechanisms and can present similar symptoms. It is important to understand when each mode of injury is likely to occur so that accurate diagnoses can be made and appropriate treatments selected.

Methods. Excised human Achilles tendons were loaded to failure at strain rates of 1% s^{-1} and 10% s^{-1} following dual-energy X-ray absorptiometry examination to determine bone mineral density near the tendon insertion. Calcaneal bone mineral density, donor age, and strain rate were compared between specimens that failed by avulsion and those that failed by tendon rupture.

Results. While strain rate was not observed to affect failure mode, the calcaneal bone mineral density of specimens that failed by avulsion was significantly lower than the bone mineral density of specimens that failed by tendon rupture ($P = 0.004$). There was a significant decrease in bone mineral density with age ($P = 0.004$), and the difference in age between the avulsed and ruptured specimens was close to statistical significance ($P = 0.058$). For the avulsed specimens, there was a significant linear relationship between failure load and bone mineral density squared ($P = 0.002$). Logistic regression indicated that the effect of age on failure mode is secondary to the primary effect of bone mineral density.

Conclusions. The avulsions were primarily "premature" failures associated with low bone mineral density. Since bone mineral density decreases with age, older individuals are more likely to experience avulsions while younger individuals are more likely to experience tendon ruptures.

Relevance

Since Achilles tendon rupture and avulsion of the posterior tuberosity of the calcaneus can present similar symptoms but require different treatments, the physician should understand when each type of injury may occur so accurate diagnoses can be made and appropriate treatments selected. Published by Elsevier Science Ltd.

Keywords: Achilles tendon; Rupture; Avulsion; Failure mode

1. Introduction

Failure of the Achilles tendon can occur by rupture of the tendon or by avulsion of the posterior tuberosity of the calcaneus where the tendon inserts. Both types of injuries can be caused by similar loading mechanisms. Strong contraction of the triceps surae combined with external loading of the foot can lead to Achilles tendon rupture [1] or calcaneal avulsion [2,3]. Since the same loading mechanisms can cause both types of injuries, what determines whether the tendon or the bone will fail first?

Previous studies have suggested that strain rate may be one factor that affects how a tendon or ligament will fail. Noyes et al. [4] found that 57% of human anterior cruciate ligaments failed by avulsion when loaded at a rate of 0.0066 s^{-1} while only 34% failed by avulsion when loaded at 0.66 s^{-1}. Crowninshield and Pope [5] also observed more avulsions at slower strain rates for rat medial collateral ligaments loaded at four strain

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rates between 0.0008 and 510 s^{-1}. In that study, all specimens tested at the slowest strain rate failed by avulsion. In contrast, Woo and colleagues [6,7] found no effect of strain rate on the failure mode of rabbit medial collateral ligaments, anterior cruciate ligaments, and patellar tendons tested over four decades of strain rate. It appears that for some tendons and ligaments, strain rate affects failure mode while for other tendons and ligaments it does not.

Previous studies have also suggested that age may affect the mode by which a tendon or ligament fails. Woo et al. [7,8] found that medial collateral ligaments from immature rabbits always failed by avulsion while ligaments from mature rabbits failed primarily in the ligament substance. Noyes and Grood [9] found that anterior cruciate ligaments from middle-aged and elderly humans (age 48–86 yr) failed by avulsion more frequently than anterior cruciate ligaments from younger individuals (age 16–26 yr). Haut et al. [10], on the other hand, found no relationship between age and the failure mode of patellar tendons from dogs aged 6 months to 15 yr. As with strain rate, it appears that age can affect failure mode but that it does not have an effect in all cases.

An increased rate of avulsions in young and old individuals may be caused by deficits in bone strength in the insertional region. Woo et al. [7] attributed avulsions of medial collateral ligaments in young rabbits to weakness of the immature bone which was undergoing extensive growth-related remodeling. Similarly, Noyes and Grood [9] observed that avulsions of anterior cruciate ligaments in elderly individuals were associated with decreased cortical thickness and increased trabecular porosity. The changes in failure mode attributed to age may, in fact, be more directly related to bone properties. The relationships between bone properties and the failure mode of tendons and ligaments have yet to be elucidated.

In this study, we examine the influence of strain rate, bone mineral density (BMD), and age on the failure mode of human Achilles tendons. We hypothesize that more avulsions will occur with slower strain rates, lower BMD, and increasing age. Clinically, it is important to understand when each type of injury is likely to occur so appropriate diagnostic tests and treatments can be performed. Our aim is to provide information that will assist the physician in accurately diagnosing Achilles tendon ruptures and avulsions so that the treatments initially administered are appropriate and effective.

2. Methods

Twenty five Achilles tendon specimens with intact calcaneal insertions were procured from 13 human donors aged 35–82 yr (mean 60.5, SD 15.4). The specimens included the posterior half of the calcaneus and extended proximally to the mid-calf. Sources of the specimens included the International Institute for the Advancement of Medicine (Scranton, PA, USA), the Northern California Transplant Bank (San Rafael, CA, USA), and the Stanford University Anatomy Laboratory (Stanford, CA, USA).

Dual-energy X-ray absorptiometry (DXA) examinations were performed on the calcaneus using the fast spine protocol on a QDR-4000 bone densitometer with Hologic scanner software version V9.5 Rev A (Hologic, Waltham, MA, USA). Each specimen was immersed in water 15 cm deep, and the calcaneus was scanned with the X-ray beam aligned in the medial-lateral direction. The areal BMD of each calcaneal specimen was recorded. The region of interest for the BMD measurements was the posterior half of the calcaneus defined on a lateral view as the region posterior to the highest point of the posterior facet (Fig. 1).

The calcaneus was embedded in polymethylmethacrylate (PMMA) in preparation for mechanical testing. The PMMA block containing the calcaneus was secured in an aluminum fixture, and the musculo-tendinous tissue at the proximal end of the specimen was gripped in a liquid nitrogen-cooled freeze clamp [11] (Fig. 2). Testing was performed at room temperature (~24°C) on a servo-hydraulic materials testing machine (MTS, Eden Prairie, MN, USA). Each specimen was assigned a displacement rate of either 1 mm s^{-1} (12 specimens) or 10 mm s^{-1} (13 specimens). For specimens from the same donor, one specimen was randomly assigned the slower rate, and the contralateral was tested at the faster rate. A single unpaired specimen, for which no contralateral was available, was randomly assigned the faster rate. The 1 and 10 mm s^{-1} rates correspond with approximate strain rates of 1% s^{-1} and 10% s^{-1}. The slower rate is considered to be quasi-static, while the faster rate is representative of physiologic activities such as walking.

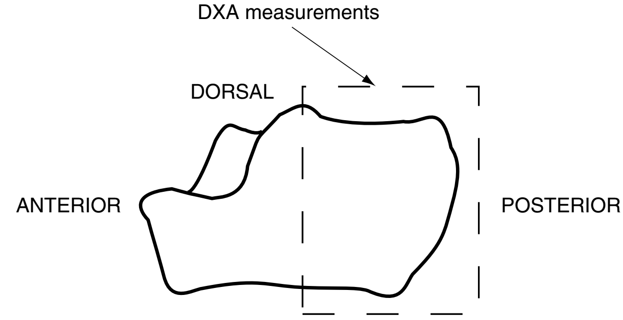

Fig. 1. Region of interest for DXA measurements. BMD was measured for the portion of the calcaneus posterior to the highest point of the posterior facet on a lateral view.

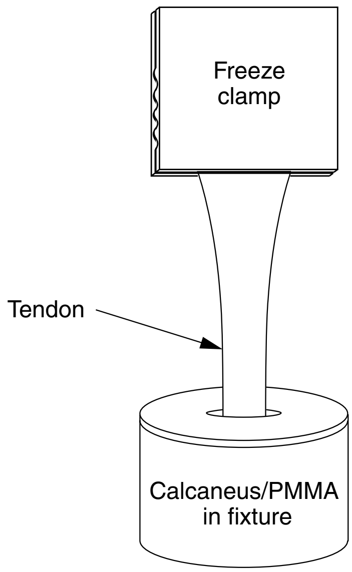

Fig. 2. Mechanical testing setup.

Each specimen was loaded to failure at the prescribed displacement rate following 10 preconditioning cycles in which the tendon was stretched between 0% and 2% strain at 0.5 Hz.

The difference in frequency of avulsion at the two strain rates was tested for statistical significance using the Z-statistic. BMD of the avulsed specimens was compared with BMD of the specimens that failed by tendon rupture using a one-tailed t-test. Ages of the avulsed and ruptured specimens were also compared using a one-tailed t-test. For the avulsed specimens, linear regression was performed between failure load and BMD^2 since theory predicts a linear relationship between these two variables [12,13] (see Section 4). Linear regression was also performed between BMD and age for all specimens. A significance level of 0.05 was used for all statistical tests.

In addition, logistic regression was performed to corroborate the Z-statistic and t-test results and to investigate possible interactions between strain rate, age, and BMD as predictors of failure mode. Simple logistic regressions were performed for each of the three variables (strain rate, age, and BMD), and a multiple logistic regression was performed including all three variables. Results of the logistic regressions were evaluated using the G likelihood ratio statistic.

3. Results

Of the 12 specimens tested at 1% s^{-1}, three (25%) failed by avulsion and nine (75%) by tendon rupture. Of the 13 specimens tested at 10% s^{-1}, four (31%) failed by avulsion and nine (69%) by tendon rupture. The difference in frequency of avulsions between the two rates was not statistically significant based on the Z-statistic ($P = 0.741$) suggesting that strain rate did not affect failure mode (Table 1).

The specimens that failed by avulsion had significantly lower BMD than the specimens that failed through rupture of the tendon ($P = 0.004$). The avulsion group had a mean BMD of 0.459 g cm^{-2} (SD, 0.195) while the tendon rupture group had a mean BMD of 0.681 g cm^{-2} (SD, 0.160). For the avulsed specimens, there was a significant linear relationship between failure load and BMD^2 ($P = 0.002$) (Fig. 3).

The difference in age between the avulsed and ruptured specimens was close to statistical significance ($P = 0.058$). The avulsion group had a mean age of 67.1 yr (SD, 17.9) while the tendon rupture group had a mean age of 56.8 yr

Table 1
Data for all specimens

Donor	Age (yr)	Sex	Left				Right			
			Rate (mm s^{-1})	BMD (g cm^{-2})	Failure mode	Failure load (N)	Rate (mm s^{-1})	BMD	Failure mode	Failure load (N)
1	55	M	1	0.602	Rupture	3488	10	0.684	Rupture	4862
2	56	M	1	0.700	Rupture	5604	10	0.695	Rupture	6813
3	52	M	1	0.884	Rupture	6462	10	0.883	Rupture	6786
4	47	F	10	0.614	Rupture	4903	1	0.594	Rupture	3743
5	55	M	10	0.969	Rupture	4961	1	0.972	Rupture	5083
6	35	M	10	0.701	Rupture	7251	1	0.763	Avulsion	7282
7	65	F	10	0.721	Rupture	4373	1	0.736	Rupture	4284
8	79	F	1	0.473	Rupture	3396	10	0.491	Avulsion	4200
9	80	F	10	0.526	Rupture	4275	1	0.514	Rupture	3868
10	44	M	1	0.499	Rupture	5626	10	0.495	Rupture	5988
11	57	M	1	0.592	Avulsion	5493	10	0.521	Avulsion	5912
12	80	F	10	0.314	Avulsion	2157	1	0.359	Avulsion	2158
13	82	F	–	–	–	–	10	0.173	Avulsion	857

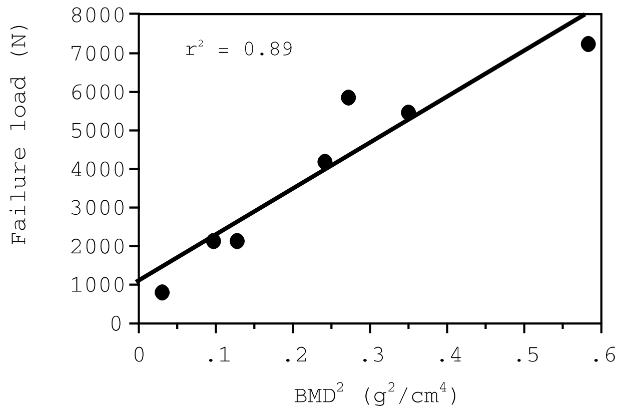

Fig. 3. Linear relationship between failure load and BMD^2 for the avulsed specimens ($P = 0.002$).

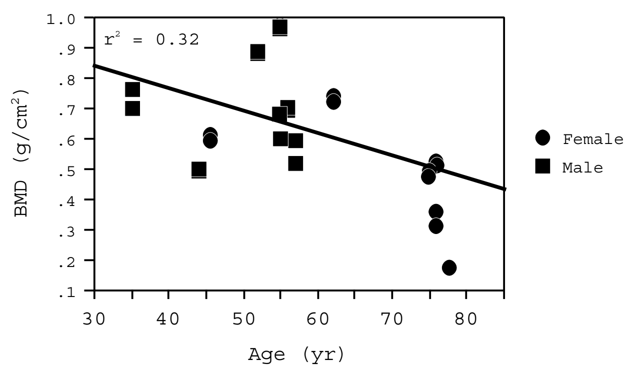

Fig. 4. Linear relationship between BMD and age ($P = 0.004$).

(SD, 12.7). There was a statistically significant decrease in BMD with age ($P = 0.004$) (Fig. 4).

The simple logistic regressions confirmed the Z-statistic and t-test results (Table 2). Strain rate did not affect failure mode ($P = 0.748$). BMD had a strong effect on failure mode ($P = 0.005$). The effect of age on failure mode was close to statistical significance ($P = 0.105$). The multiple logistic regression indicated that BMD was the primary variable influencing failure mode. BMD continued to be a significant influence on failure mode when strain rate and age were taken into account ($P = 0.020$), but the possible age effect disappeared when strain rate and BMD effects were removed ($P = 0.823$).

4. Discussion

Our results clearly showed that BMD of the posterior half of the calcaneus had a strong effect on the Achilles tendon's failure mode. All specimens with BMD <0.4 g cm^{-2} failed by avulsion (three specimens), while all specimens with BMD >0.8 g cm^{-2} failed by tendon rupture (four specimens). Specimens with intermediate BMD tended to fail by tendon rupture although both modes of failure were observed (4 avulsions, 14 ruptures). For the specimens with intermediate BMD, the bone and tendon are very close in strength making it possible for either to fail first. Previous studies have noted that in many cases indications of preliminary bone failure are observed in ruptured ligaments and fiber tearing is observed in avulsed ligaments [4,9].

While either the tendon or bone may fail when both are at peak strength, many avulsions are associated with deficits in bone strength. Previous studies have suggested that the failure load of a bone should be proportional to BMD^2 based on theoretical considerations [12,13]. Since BMD is an areal density (g cm^{-2}), BMD^2 is proportional to $\rho^2 A$, where ρ is a volumetric density (g cm^{-3}) and A is an area (cm^2). Bone failure load is also proportional to $\rho^2 A$ since failure stress is proportional to ρ^2 [14]. BMD^2 and failure load should therefore also be proportional to each other. The current study confirmed this relationship through the linear regression of failure load versus BMD^2 for the avulsed specimens (Fig. 3). This indicates that the avulsions are governed by bone strength which depends, in turn, on BMD. The lower the BMD, the more likely avulsion failure will occur before the tendon ruptures. These avulsions are what Noyes and Grood [9] have called "premature" since they occur at lower load than the tendon or healthy bone would achieve. Because BMD decreases with age, more avulsions are likely to occur in elderly individuals. The effect of age on failure mode may therefore be a secondary effect reflecting the primary effect of BMD on failure mode.

Table 2
Results of logistic regressions testing effects of strain rate, age, and BMD on failure mode[a]

Model	Effect	P-value
Constant + rate	Rate	0.748
Constant + age	Age	0.105
Constant + BMD	BMD	0.005
Constant + rate + age + BMD	Rate (controlling for age and BMD)	0.991
Constant + rate + age + BMD	Age (controlling for rate and BMD)	0.823
Constant + rate + age + BMD	BMD (controlling for rate and age)	0.020

[a] P-values are for G likelihood ratio statistic from logistic regression.

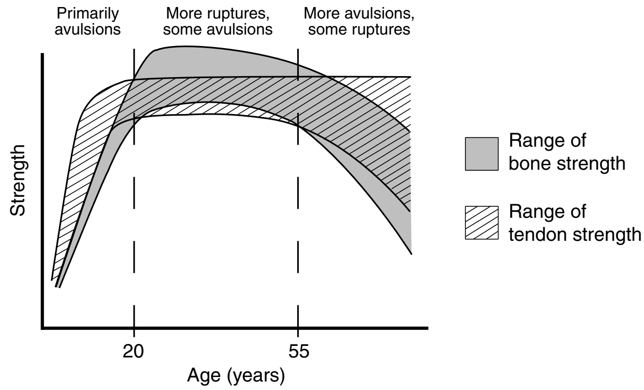

Fig. 5. Schematic describing changes in failure mode with age due to changes in tendon and bone strength. In children, most failures are expected to be avulsions. Both ruptures and avulsions occur in adults. For young adults, more ruptures occur. Avulsions become more common with age.

Tendon and ligament properties appear to be better maintained with age than BMD and bone properties. Most studies have found no changes in the failure stress, failure strain, modulus, and strain energy density of various tendons and ligaments after maturity [8,15–18] although a few studies have found decreases in some of these properties with age [9,17]. To describe age-related changes in tendon and bone properties and their effect on tendon failure mode, we have developed the schematic shown in Fig. 5. This schematic is based on a suggestion by Woo et al. [8]. Our schematic shows ranges of tendon and bone strength as a function of age. For growing individuals below 20 yr of age, failure occurs primarily by avulsion since tendon strength exceeds bone strength. For adults aged 20–55 yr, ruptures predominate although both types of injury can occur. With increasing age, avulsions become increasingly common. Around age 55, the predominant failure mode changes from tendon rupture to bony avulsion due to the pronounced loss of bone strength and better maintenance of tendon strength.

Under the conditions of this study, we found that strain rate did not affect whether the Achilles tendon failed by rupture or avulsion. All specimens but one were paired, and for each pair one specimen was tested at 1 mm s^{-1} and the contralateral at 10 mm s^{-1}. The specimen to be tested at the slower rate was selected randomly so that there was no bias in strain rate between left and right tendons. Within this randomized sample, the difference in frequency of avulsions between the two rates was far from statistical significance ($P = 0.741$). Strain rate might affect failure mode under different testing conditions. However, any rate effect would likely be small compared with the influence of BMD and age. Some previous studies have found that strain rate does affect the failure mode of various tendons and ligaments [4,5] while other studies have found no strain rate effect [6,7]. Strain rate also has little effect on the viscoelastic behavior of tendons and ligaments [19,20]. The influence of strain rate may differ between different tendons and ligaments. A strain rate effect might also be observed with a larger range of rates than the one-decade range we examined. More specimens would need to be tested to conclusively state that strain rate has no effect on Achilles tendon failure mode.

Clinically, Achilles tendon rupture affects primarily middle-aged men [1,21] while avulsion of the posterior tuberosity of the calcaneus affects primarily middle-aged and elderly women [22,23]. The reason for the male predominance in Achilles tendon rupture is not known, but it may be related to higher participation of middle-aged men in recreational sports. We did not specifically investigate the relationship between gender and Achilles failure mode in this study, but the predominance of avulsions in elderly females is likely related to the low BMD in that group. Since women tend to live longer and have an earlier onset of osteoporosis, it would seem that women are more likely to suffer calcaneal avulsions.

Our results suggest that attention should be paid to the mode by which Achilles tendon failure is likely to occur. Achilles tendon ruptures and calcaneal avulsions can present similar functional deficits [1,3]. Nevertheless, different treatment approaches are needed for each type of injury, and diagnostic tests such as radiographs or DXA scans for elderly individuals are not always routinely performed [23]. Correct diagnosis of the injury on initial examination is important since clinical outcomes may be compromised if proper treatment is delayed.

5. Conclusions

Strain rate did not affect the failure mode of human Achilles tendons under the conditions of this study. In contrast, bone mineral density had a significant effect on failure mode. Low BMD increases the likelihood of avulsion. Since BMD decreases with age, older individuals are more likely to suffer avulsions while younger individuals are more likely to experience tendon ruptures. The physician should be aware of these effects when evaluating patients who appear to have suffered Achilles tendon injury.

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