Published in final edited form as:

Med Eng Phys. 2015 July ; 37(7): 712–716. doi:10.1016/j.medengphy.2015.04.004.

Achilles tendon displacement patterns during passive stretch and eccentric loading are altered in middle-aged adults

Laura Chernak Slane^a and Darryl G Thelen^{a,b,c}

Laura Chernak Slane: laura.c.slane@gmail.com; Darryl G Thelen: thelen@engr.wisc.edu

^aDepartment of Biomedical Engineering, 1550 Engineering Drive, Madison, WI 53706

^bDepartment of Mechanical Engineering, 1513 University Ave, Madison, WI 53706

^cDepartment of Orthopedics and Rehabilitation, 1300 University Ave, Madison, WI 53706

Abstract

The purpose of this study was to investigate middle-age effects on Achilles displacement patterns under passive stretch and eccentric loading. Healthy young (24.1 ± 1.4 years, $n=9$) and middle-aged (49.0 ± 3.1 years, $n=9$) adults were positioned prone and the ankle was cyclically (0.5 Hz, 25 deg range) dorsiflexed during passive stretch and active lengthening. Achilles displacements were tracked in cine ultrasound using 2D speckle tracking. Displacements were found to be non-uniform, with mid and deep portions of the tendon displacing more than superficial portions. However, the degree of non-uniformity was significantly reduced in middle-aged adults, suggesting a potential age-related reduction in inter-fascicle sliding or a shift in loading sharing between plantarflexors. Eccentric loading reduced displacement magnitudes, likely reflecting distal tendon stretch induced via active muscle contractions. Changes in tendon displacement with active loading were greater in middle-aged adults, which could reflect greater tendon compliance. The observed age-related changes in Achilles tendon behavior may have implications for both plantarflexor performance and injury risk.

Keywords

ultrasound speckle tracking; non-uniform motion

© 2015 IPEM. Published by Elsevier Ltd.

Corresponding author: Laura Chernak Slane, Present Address: 1513 University Avenue, Mechanical Engineering Room 3046, Madison, WI 53706, Tel.: +1-608-262-2690, laura.c.slane@gmail.com.

Declarations

The authors have no competing interests to report. Ethical approval for this study was received from the University of Wisconsin-Madison Health Sciences Institutional Review Board. The application reference number is 2012–0206.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Introduction

Achilles tendinopathies increase in incidence in middle-age [1], yet the underlying causes remain unclear. A recent hypothesis suggests that aging may reduce sliding between tendon fascicles [2], potentially due to increased collagen cross-linking [3]. Such a change could alter localized tissue deformations, having implications for muscle performance, injury potential and tissue mechanobiological responses [4]. Thus, an improved understanding of age-related changes in tendon deformation is relevant to both understanding the causes of tendinopathy and for objectively designing conservative treatments to enhance performance and promote healing. For example, although eccentric loading has shown some success in treating Achilles tendinopathies [5–7], the underlying mechanisms are not understood and it remains challenging to predict who will benefit *a priori*.

There is increasing evidence that the Achilles tendon undergoes complex, non-uniform deformations *in vivo*. Various studies have demonstrated that the Achilles and gastrocnemius aponeurosis undergo different amounts of stretch during loading [8, 9]. There is also evidence of mechanical heterogeneity along the Achilles length [10, 11] and within its cross-section [12, 13]. Such spatial variations may contribute to the tendency for injuries to emerge at specific locations; most notably mid-substance Achilles tendinopathies which commonly originate 3–6 cm proximal to the calcaneus [14].

Aging processes significantly alter Achilles behavior at both micro- and macro-scales. Comparative studies have observed a variety of age-related microstructural changes to collagen type III content [15], elastin content [16], collagen fibril diameter [17] and crimp angle [18, 19]. Although the link between these microstructural changes and macro-scale tendon mechanics is not fully understood and may be non-intuitive [20, 21], *in vitro* studies suggest that macro-scale tendon compliance increases during senescence [16, 20, 22, 23]. The progression of these age-related changes, and the specific effects during middle-age are less well studied. In humans, a few recent studies have evaluated the effects of aging on gross tendon strain and compliance, but have reported conflicting results [24–28]. This discrepancy may arise from a methodological limitation of computing tendon strains over large portions of the lower limb, potentially masking localized variations.

The purpose of this study was to utilize an ultrasound-based tracking technique to evaluate middle-aged Achilles displacement patterns. We were interested in evaluating how displacements vary through the mid-substance tendon cross-section, change with loading condition (passive stretch vs. eccentric loading), and differ from the patterns observed in young adults [13]. We hypothesized that middle-aged adults would exhibit evidence of increased tendon compliance and more uniform tendon displacements, potentially due to less inter-fascicle sliding.

Methods

Nine healthy middle-aged adults (49 ± 3.1 years) were tested, and compared to prior measurements from healthy young adults (24.1 ± 1.4 years) [13] (Table 1). Subjects provided written consent and then walked for six minutes to precondition the plantarflexors [29].

Subjects were positioned prone, with their knee flexed to 30 deg and right foot secured in a custom inertial loading device [13]. Subjects were asked to cyclically dorsi- and plantarflex their ankles between approximately 0 and 30 deg of plantarflexion (0.5 Hz). Ankle angles were measured via an encoder attached to the footplate and displayed in real-time to guide subjects through the desired range of motion (Table 1). The inertial loading device induced eccentric plantarflexor loading with ankle dorsiflexion, while ankle angle and applied force were simultaneously recorded (1000 Hz). During passive trials, a researcher guided the ankle through the same ROM and cyclic rate. Trial order was randomized and subjects were given one minute of practice.

Ultrasound radiofrequency (RF) data were collected (70 frames/sec) using a 10 MHz linear array transducer (L14-5/38, Ultrasonix Corporation, Richmond, BC) with a spatial resolution of 0.3 (along-fiber) by 0.019 mm (transverse). A rectangular standoff pad [13] was positioned over the tendon and the probe was positioned such that the imaging window was just proximal to the superior edge of the calcaneus, and that it aligned longitudinally with the thickest portion of the Achilles.

Tissue displacements were computed using a previously described 2D speckle-tracking approach [30, 31]. The start of each motion cycle was defined at peak plantarflexion. A region of interest (ROI) was outlined within the tendon in this frame (average: 9.8×3.0 mm), and a rectangular grid of nodes was defined within the ROI (spaced: 0.5×0.2 mm). Frame-to-frame nodal displacements were found that maximized the normalized 2D cross-correlation between rectangular kernels (1×0.4 mm) centered on the nodes. Nodal displacements were regularized with second order polynomials [30].

Depth dependent displacement profiles between the plantarflexed and dorsiflexed postures were determined by averaging along-fiber nodal displacements across the tendon thickness. The displacement range was computed as the difference between the maximum and minimum aspects of the displacement profile (Fig. 1). The displacement range was then divided by the average displacement of the entire ROI (i.e. normalized displacement range) as a measure of relative nonuniformity. We statistically compared displacements between three equally sized portions of the tendon: superficial, mid and deep. Multivariate general linear models (Statistica, StatSoft Inc., Tulsa, OK) were used to separately evaluate the effects of: age (young, middle-aged) and loading condition (passive, eccentric) on superficial, mid and deep displacements; age and loading condition on average ROI displacement and normalized displacement range; age and tendon region (superficial, mid, deep) on the difference in average ROI displacement between passive and eccentric loading conditions. All significant interactions were followed up by Tukey post-hoc analyses ($p < 0.05$).

Results

Young and middle-aged adult populations showed similar physical and performance characteristics (Table 1). In both age groups, and in both loading conditions, mid and deep tendon displacements were significantly larger than superficial displacements (Fig. 2;

$p < 0.0002$). Average passive displacements were also significantly larger than eccentric displacements for young ($p = 0.049$) and middle-aged adults ($p = 0.0002$; Fig. 1).

Aging effects were also observed. During passive loading, average tendon displacements were significantly larger for middle-aged adults (Fig. 1; $p = 0.0002$). Likewise, the difference in average ROI displacement between passive and eccentric loading conditions was significantly larger in middle-aged adults (Fig. 3; $p = 0.03$). For both age groups, this difference was significantly larger in the mid and deep portions of the tendon ($p < 0.01$), with no interaction observed between age group and tendon region.

Finally, we measured significantly smaller normalized displacement ranges in middle-aged adults (Fig. 4; $p = 0.001$), thus demonstrating more uniformity in tendon displacement.

Discussion

We consistently observed non-uniform tendon motion, with mid and deep portions of the tendon undergoing significantly greater displacement than superficial portions (Figs. 1 and 2). These non-uniform tendon displacements are consistent with previous observations during passive [12, 13] and eccentric [13] loading. It is possible that this non-uniformity may reflect sliding between the fascicle bundles that comprise the Achilles [32]. The mid and deep regions of the tendon are likely composed of fascicles originating in the soleus muscle, whereas the medial gastrocnemius fascicles likely comprise the superficial region [32, 33]. Smaller superficial displacements would occur if fascicles originating in the medial gastrocnemius undergo greater distal stretch than fascicles originating in the soleus. The gastrocnemius tendon is longer than the soleus tendon [33], such that this architectural difference could contribute to greater compliance and thus more stretch. Alternatively, differential loading of the soleus, medial gastrocnemius and lateral gastrocnemius [34] could also induce the non-uniform tendon deformations exhibited within the tendon cross-section.

Although both young and middle-aged adults exhibited non-uniform displacement patterns, the magnitude of non-uniformity was smaller in middle-aged adults, with less variation in tissue displacements observed over the tendon thickness. There are two potential explanations for this observation. First, age-related changes in the relative loading of the gastrocnemius and soleus could result in more equal stretch of the fascicle bundles. Changes in plantarflexor muscle coordination patterns with age have been observed [35] and could affect tendon displacement patterns in active conditions. However, we observed more uniform displacement profiles in middle-aged adults under passive dorsiflexion as well, which would only reflect muscle-tendon loading due to passive stretch. Thus, it is more likely that passive tissue properties play a role. One such possibility is that adhesions between fascicle bundles diminish the capacity for inter-fascicle sliding to occur [2], which may result from an age-related increase in collagen cross-linking [3].

In both age groups, we observed smaller tendon displacements during eccentric loading, with a significantly greater difference between passive and eccentric loading tasks arising in middle-aged adults (Fig. 3). This result would suggest that middle-aged tendons underwent greater stretch when loading was applied. This result is consistent with previous *in vivo*

studies which have observed a significant increase in compliance between young and middle-aged [25], and young and older [25, 27, 28] adults. However, it is important to recognize that recent evidence demonstrates significant variation in tendon mechanical properties along the tendon length [8, 10, 11, 36]. Thus, future studies should consider regional variations both within the cross-section and along the tendon length.

It is increasingly recognized that Achilles tendon elasticity affects both the mechanics and performance of the plantarflexors. For example, during the stance phase of walking, the gastrocnemius muscle fascicles remain relatively isometric while the tendon lengthens and stores energy to be released during push-off [37]. Models suggest that variations in tendon compliance can alter tendon and muscle fascicle stretch, which in turn can affect the length and force capacity of the gastrocnemius [38]. Soleus muscle fascicles exhibit kinematic behavior that is distinct from the gastrocnemius [39], which may depend on sliding between the gastrocnemius and soleus tendon fascicles. Hence, an age-related reduction in fascicle sliding may affect proximal muscle fascicle excursions and alter tendon strain patterns. Such mechanical interactions would have an effect on energy storage-return behavior while also influencing injury potential due to localized tendon strains. Future imaging and modeling studies are clearly needed to consider the complexity of 3D muscle-tendon mechanics, and the effects of age-related architectural changes [40] on these mechanics.

There are some limitations to consider when interpreting our results. First, we measured tendon displacements relative to a hand-held transducer rather than a fixed anatomical landmark (e.g. calcaneus insertion [41–44]). Also, tendon displacements were measured relative to a fixed ankle angle for which the overall state of loading and strain are not known. For these reasons, the displacements we compute during motion cannot be directly interpreted in terms of tendon stretch. Second, inter-subject variation in tendon architecture [33] makes it challenging to identify precise delineations of tendon fascicles, thus the superficial-deep categorization provides only an approximation of soleus and gastrocnemius fascicle behavior. Finally, we focused our study on the free mid-Achilles where mid-substance tendinopathies commonly occur [45, 46]. Future studies will consider distal deformations to understand insertional tendinopathies which are also common in middle-aged adults.

In conclusion, this study provides evidence that the Achilles undergoes complex deformation patterns with passive stretch and active eccentric loading. Further, we showed that middle-aged adults exhibit more uniform tendon displacement patterns when stretched with evidence of greater tendon compliance. These observations may have implications for plantarflexor performance and the increased risk for Achilles injury with aging.

Acknowledgments

We gratefully acknowledge the support of NIH F31AG043216, R01AR056201, the American Society of Biomechanics Grant-in-Aid, the International Society of Biomechanics Matching Dissertation Program, and the contributions of Dan Volk, Dave Bunger, Nathan Kleinhans, Tanner Marshall and Alex Ehlers to this research.

References

1. De Jonge S, Van Den Berg C, De Vos RJ, Van Der Heide HJ, Weir A, Verhaar JA, Bierma-Zeinstra SM, Tol JL. Incidence of midportion achilles tendinopathy in the general population. *Br J Sports Med.* 2011; 45:1026–8. [PubMed: 21926076]
2. Thorpe CT, Udeze CP, Birch HL, Clegg PD, Screen HRC. Capacity for sliding between tendon fascicles decreases with ageing in injury prone equine tendons: A possible mechanism for age-related tendinopathy? *Eur Cells Mater.* 2013; 25:48–60.
3. Couppe C, Hansen P, Kongsgaard M, Kovanen V, Suetta C, Aagaard P, Kjaer M, Magnusson SP. Mechanical properties and collagen cross-linking of the patellar tendon in old and young men. *J Appl Physiol* (1985). 2009; 107:880–6. [PubMed: 19556458]
4. Arnoczky SP, Lavagnino M, Egerbacher M. The mechanobiological aetiopathogenesis of tendinopathy: Is it the over-stimulation or the under-stimulation of tendon cells? *Int J Exp Pathol.* 2007; 88:217–26. [PubMed: 17696902]
5. Alfredson H, Pietila T, Jonsson P, Lorentzon R. Heavy-load eccentric calf muscle training for the treatment of chronic achilles tendinosis. *Am J Sports Med.* 1998; 26:360–6. [PubMed: 9617396]
6. Fahlstrom M, Jonsson P, Lorentzon R, Alfredson H. Chronic achilles tendon pain treated with eccentric calf-muscle training. *Knee Surg Sports Traumatol Arthrosc.* 2003; 11:327–33. [PubMed: 12942235]
7. Maffulli N, Longo UG. Conservative management for tendinopathy: Is there enough scientific evidence? *Rheumatology* (Oxford). 2008; 47:390–1. [PubMed: 18281691]
8. Magnusson SP, Hansen P, Aagaard P, Brond J, Dyhre-Poulsen P, Bojsen-Moller J, Kjaer M. Differential strain patterns of the human gastrocnemius aponeurosis and free tendon, in vivo. *Acta Physiol Scand.* 2003; 177:185–95. [PubMed: 12558555]
9. Muramatsu T, Muraoka T, Takeshita D, Kawakami Y, Hirano Y, Fukunaga T. Mechanical properties of tendon and aponeurosis of human gastrocnemius muscle in vivo. *J Appl Physiol.* 2001; 90:1671–8. [PubMed: 11299254]
10. Dewall RJ, Slane LC, Lee KS, Thelen DG. Spatial variations in achilles tendon shear wave speed. *J Biomech.* 2014 in press.
11. Finni T, Hodgson JA, Lai AM, Edgerton VR, Sinha S. Nonuniform strain of human soleus aponeurosis-tendon complex during submaximal voluntary contractions in vivo. 2003; 95:829–37.
12. Arndt A, Bengtsson AS, Peolsson M, Thorstensson A, Movin T. Non-uniform displacement within the achilles tendon during passive ankle joint motion. *Knee Surg Sport Tr A.* 2012; 20:1868–74.
13. Slane LC, Thelen D. Non-uniform displacements within the achilles tendon observed during passive and eccentric loading. *J Biomech.* 2014; 47:2831–5. [PubMed: 25150898]
14. Astrom M, Rausing A. Chronic achilles tendinopathy. A survey of surgical and histopathologic findings. *Clin Orthop Relat Res.* 1995:151–64. [PubMed: 7634699]
15. Birch HL, Bailey JV, Bailey AJ, Goodship AE. Age-related changes to the molecular and cellular components of equine flexor tendons. *Equine Vet J.* 1999; 31:391–6. [PubMed: 10505954]
16. Vogel HG. Influence of maturation and aging on mechanical and biochemical properties of connective tissue in rats. *Mech Ageing Dev.* 1980; 14:283–92. [PubMed: 7206819]
17. Nakagawa Y, Majima T, Nagashima K. Effect of ageing on ultrastructure of slow and fast skeletal muscle tendon in rabbit achilles tendons. *Acta Physiol Scand.* 1994; 152:307–13. [PubMed: 7872008]
18. Tuite DJ, Renstrom PA, O'brien M. The aging tendon. *Scand J Med Sci Sports.* 1997; 7:72–7. [PubMed: 9211607]
19. Patterson-Kane JC, Firth EC, Goodship AE, Parry DA. Age-related differences in collagen crimp patterns in the superficial digital flexor tendon core region of untrained horses. *Aust Vet J.* 1997; 75:39–44. [PubMed: 9034498]
20. Dressler MR, Butler DL, Wenstrup R, Awad HA, Smith F, Boivin GP. A potential mechanism for age-related declines in patellar tendon biomechanics. *J Orthop Res.* 2002; 20:1315–22. [PubMed: 12472246]

21. Narici MV, Maffulli N, Maganaris CN. Ageing of human muscles and tendons. *Disabil Rehabil.* 2008; 30:1548–54. [PubMed: 18608375]
22. Vogel HG. Age dependence of mechanical properties of rat tail tendons (hysteresis experiments). *Aktuelle Gerontol.* 1983; 13:22–7. [PubMed: 6131619]
23. Blevins FT, Hecker AT, Bigler GT, Boland AL, Hayes WC. The effects of donor age and strain rate on the biomechanical properties of bone-patellar tendon-bone allografts. *Am J Sports Med.* 1994; 22:328–33. [PubMed: 8037272]
24. Kubo K, Morimoto M, Komuro T, Tsunoda N, Kanehisa H, Fukunaga T. Age-related differences in the properties of the plantar flexor muscles and tendons. *Med Sci Sports Exerc.* 2007; 39:541–7. [PubMed: 17473781]
25. Onambele GL, Narici MV, Maganaris CN. Calf muscle-tendon properties and postural balance in old age. *J Appl Physiol.* 2006; 100:2048–56. [PubMed: 16455811]
26. Karamanidis K, Arampatzis A. Mechanical and morphological properties of different muscle-tendon units in the lower extremity and running mechanics: Effect of aging and physical activity. *J Exp Biol.* 2005; 208:3907–23. [PubMed: 16215218]
27. Stenroth L, Peltonen J, Cronin NJ, Sipila S, Finni T. Age-related differences in achilles tendon properties and triceps surae muscle architecture in vivo. *J Appl Physiol* (1985). 2012; 113:1537–44. [PubMed: 23042907]
28. Narici MV, Maganaris C, Reeves N. Myotendinous alterations and effects of resistive loading in old age. *Scand J Med Sci Sports.* 2005; 15:392–401. [PubMed: 16293151]
29. Hawkins D, Lum C, Gaydos D, Dunning R. Dynamic creep and pre-conditioning of the achilles tendon in-vivo. *J Biomech.* 2009; 42:2813–7. [PubMed: 19762028]
30. Slane LC, Thelen DG. The use of 2d ultrasound elastography for measuring tendon motion and strain. *J Biomech.* 2014; 47:750–4. [PubMed: 24388164]
31. Chernak LA, Thelen DG. Tendon motion and strain patterns evaluated with two-dimensional ultrasound elastography. *J Biomech.* 2012; 45:2618–23. [PubMed: 22939179]
32. Szaro P, Witkowski G, Smigielski R, Krajewski P, Ciszek B. Fascicles of the adult human achilles tendon - an anatomical study. *Ann Anat.* 2009; 191:586–93. [PubMed: 19734029]
33. Cummins EJ, Anson BJ, et al. The structure of the calcaneal tendon (of achilles) in relation to orthopedic surgery, with additional observations on the plantaris muscle. *Surg Gynecol Obstet.* 1946; 83:107–16. [PubMed: 20988044]
34. Arndt A, Bruggemann GP, Koebke J, Segesser B. Asymmetrical loading of the human triceps surae: I. Mediolateral force differences in the achilles tendon. *Foot Ankle Int.* 1999; 20:444–9. [PubMed: 10437928]
35. Schmitz A, Silder A, Heiderscheit B, Mahoney J, Thelen DG. Differences in lower-extremity muscular activation during walking between healthy older and younger adults. 2009; 19:1085–91.
36. Slane LC, Dewall RJ, Martin JA, Lee KS, Thelen DG. Middle-aged adults exhibit altered spatial variations in achilles tendon shear wave speed. *J Appl Physiol.* 2014 in review.
37. Fukunaga T, Kubo K, Kawakami Y, Fukashiro S, Kanehisa H, Maganaris CN. In vivo behaviour of human muscle tendon during walking. 2001; 268:229–33.
38. Lichtwark GA, Wilson AM. Is achilles tendon compliance optimised for maximum muscle efficiency during locomotion? *J Biomech J Biomech.* 2007; 40:1768–75.
39. Ishikawa M, Komi PV, Grey MJ, Lepola V, Bruggemann GP. Muscle-tendon interaction and elastic energy usage in human walking. *J Appl Physiol* (1985). 2005; 99:603–8. [PubMed: 15845776]
40. Kim PJ, Martin E, Ballehr L, Richey JM, Steinberg JS. Variability of insertion of the achilles tendon on the calcaneus: An mri study of younger subjects. *J Foot Ankle Surg.* 2011; 50:41–3. [PubMed: 21172640]
41. Maganaris CN. Tendon conditioning: Artefact or property? *Proc R Soc A.* 2003; 270 (Suppl 1):S39–42.
42. Maganaris CN. Validity of procedures involved in ultrasound-based measurement of human plantarflexor tendon elongation on contraction. *J Biomech.* 2005; 38:9–13. [PubMed: 15519334]

43. Maganaris CN, Paul JP. Tensile properties of the in vivo human gastrocnemius tendon. *J Biomech.* 2002; 35:1639–46. [PubMed: 12445617]
44. Child S, Bryant AL, Clark RA, Crossley KM. Mechanical properties of the achilles tendon aponeurosis are altered in athletes with achilles tendinopathy. *Am J Sports Med.* 2010
45. Astrom M. Partial rupture in chronic achilles tendinopathy. A retrospective analysis of 342 cases. *Acta Orthop Scand.* 1998; 69:404–7. [PubMed: 9798451]
46. Hanada M, Takahashi M, Suzuki D, Abe M, Matsuyama Y. A biochemical study of the distribution of collagen and its crosslinks in knee ligaments and the patellar tendon. *Connect Tissue Res.* 2014; 55:378–83. [PubMed: 25140988]

Highlights

- *In vivo* Achilles exhibits non-uniform displacements during stretch
- Middle-aged tendons stretch more uniformly and appear more compliant
- Age-related changes in tendon displacements may affect performance and injury risk

Figure 1.

Ultrasound images were collected of the mid Achilles tendon when passively and actively stretched. In post-hoc analyses, a region of interest (ROI, yellow rectangle) was defined within the tendon from a B-Mode image collected in the most plantarflexed posture. The ROI (average initial position represented by blue line) displaced distally with dorsiflexion as denoted by the average depth dependent ROI displacement profiles for each subject group under the passive and active loading conditions. Displacement range, defined as the difference between the maximum and minimum tissue displacements over the tendon thickness, varied between the young and middle-aged subjects. Average ROI displacements (horizontal bars) were greater under passive loading conditions, with middle-aged adults (M) exhibiting greater tendon displacements than young adults (Y; $p = 0.0002$).

Figure 2.

Average distal displacement (+ standard deviation) in superficial, mid and deep tendon regions for young (Y) and middle-aged (M) adults. Significant regional variation in tendon displacements was observed in both passive and eccentric loading conditions, with the superficial tendon exhibiting significantly smaller displacements than the mid and deep portions of the tendon.

Figure 3.

The difference between the average (+ standard deviation) ROI displacement in passive and eccentric loading is plotted for young and middle-aged adults in the superficial (S), mid (M) and deep (D) regions. For both age groups, the average passive displacement was greater than the average eccentric displacement. The difference in distal displacement between the two loading conditions was significantly larger in middle-aged adults than young adults, and significantly larger in the mid and deep portions of the tendon than the superficial portion, with no interaction between age group and tendon depth. * $p < 0.05$.

Figure 4.

Uniformity of tendon motion was quantified by the normalized displacement range, which was defined as the variation in tendon displacement over the tendon cross-section normalized to the average tendon displacement. Plotted is the average (+ standard deviation) normalized displacement range for young and middle-aged adults in both passive and eccentric loading conditions. There was a significantly smaller normalized displacement range in middle-aged adults compared to the young adults. * $p = 0.001$.

Table 1

Comparison of subject characteristics, ankle ranges of motion and net ankle joint moment for the passive stretch and eccentric loading trials. There were no significant differences between young and middle-aged adult populations in terms of height, tendon thickness or average hours of weekly exercise. Young and middle-aged subjects exhibited similar peak ankle plantarflexor moments and ranges of motion in eccentric loading trials, though peak loading occurred slightly earlier for middle-aged subjects. During passive trials, middle-aged adults demonstrated a slightly smaller average range of motion

	Young Adults	Middle-aged adults
Age:	24.1 ± 1.4 years	49.0 ± 3.1 years
Subjects:	4 M, 5 F	4 M, 5 F
Height:	70.5 ± 5.5 inches	67.3 ± 5.7 inches
Tendon thickness:	4.5 ± 0.5 mm	4.8 ± 0.7 mm
Total exercise per week:	10.2 ± 4.5 hours	9.0 ± 5.4 hours
Ankle range of motion during passive trials:	25.2 ± 1.7 deg	22.7 ± 1.4 deg *
Ankle range of motion during eccentric trials:	25.6 ± 1.7 deg	26.1 ± 1.3 deg
Ankle plantarflexor moment during eccentric trials:	30.1 ± 7.4 Nm	33.5 ± 2.9 Nm
Percent of trial for peak ankle plantarflexor moment:	57.0 ± 3.0 %	52.6 ± 3.7 % *

*
p < 0.05