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Human Kinetics
SCHOLARLY REVIEW

Age-Related Changes in Achilles Tendon Stiffness and Impact on Functional Activities: A Systematic Review and Meta-Analysis

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Achilles tendon stiffness determines calf muscle functioning during functional activities. However, contrasting evidence was found in studies comparing Achilles tendon stiffness in older and younger adults. Therefore, this systematic review compares Achilles tendon stiffness and elastic modulus in older and younger adults and reviews functional implications. Studies revealed by systematic bibliographic searches were included if healthy older adults were investigated, and if Achilles tendon stiffness was measured using ultrasound and dynamometry. Meta-analyses were performed to compare Achilles tendon stiffness and elastic modulus in older and younger adults. Achilles tendon stiffness (weighted standardized mean difference = 1.40, 95% confidence intervals [0.42–2.38]) and elastic modulus (weighted standardized mean difference = 1.74, 95% confidence intervals [0.99–2.49]) were decreased in older compared with younger adults. Decreased Achilles tendon stiffness was related to walking performance and balance. Possibly, decreased Achilles tendon stiffness is caused by altered elastic modulus in older adults. Training interventions increasing Achilles tendon stiffness could improve functional capacity.

Keywords: Achilles tendon properties, functional performance, older adults, training interventions, ultrasound

In the human body, the forces produced by muscle-tendon units are transmitted to the skeleton through tendons. Because of their elastic properties, they allow energy storage and return during functional activities. As a result, the tendon decouples the muscle fascicle length changes from the total muscle-tendon unit length changes (Fukunaga et al., 2001; Lichtwark, Bougoulias, & Wilson, 2007). This mechanism can optimize the muscle force production through the force–length and force–velocity relationship (Alexander, 2002; Biewener & Roberts, 2000; Lichtwark & Barclay, 2010). The mechanical tendon properties are, therefore, expected to significantly influence the mechanics, energetics, and neural control of a wide range of functional activities (Roberts & Azizi, 2011).

Altered elastic tendon properties possibly contribute to the age-related decline of muscle performance. One of the contributors to this decreased muscle performance in older adults is an age-related loss of muscle mass or sarcopenia (Bautmans, Van Puyvelde, & Mets, 2009). However, previous research reported that the age-related decline of muscle performance occurs at higher rates compared with the age-related decline of muscle mass (Clark & Manini, 2012; Goodpaster et al., 2006). As such, other mechanisms are expected to interfere. Because muscle forces are transferred to skeletal bones by elastic tendons, it has previously been suggested that altered elastic tendon properties contribute to the age-related decline of muscle force and functional performance (Narici, Maffulli, & Maganaris, 2008).

Because the Achilles tendon is the longest tendon in the human body, its pronounced energy storage capacity and its important influence on the gastrocnemius and soleus muscle work could impact functional performance. For instance, Achilles tendon stiffness was found to be associated with the energy cost of walking and running in both experimental (Arampatzis et al., 2006; Kubo, Kanehisa, Kawakami, & Fukunaga, 2000) and simulation studies (Lichtwark & Wilson, 2007, 2008; Orselli, Franz, & Thelen, 2017). It also determines the muscle work needed to maintain postural balance (Loram, Maganaris, & Lakie, 2009). It is suggested that these associations are explained through the important role of the gastrocnemius and soleus muscle-tendon units during walking (Neptune, Kautz, & Zajac, 2001; Neptune, Sasaki, & Kautz, 2008) and maintaining postural balance (Riemann, Myers, & Lephart, 2003).

Remarkably, older adults are both faced with increased energy cost of walking and postural instability (Malatesta et al., 2003). Moreover, it has previously been suggested that altered tendon stiffness contributes to the age-related decline of muscle performance during functional activities (Narici et al., 2008). Therefore, several studies have investigated Achilles tendon stiffness in older adults. For instance, one study reported that Achilles tendon stiffness is decreased in older compared with younger adults (Stenroth, Peltonen, Cronin, Sipila, & Finni, 2012), whereas another did not report any differences (Karamanidis & Arampatzis, 2005, 2006). Furthermore, it has been reported that decreased Achilles tendon stiffness influences postural balance in older adults (Onambélé, Narici, & Maganaris, 2006; Onambélé, Narici, Rejc, & Maganaris, 2007). Remarkably, other studies did not confirm that decreased Achilles tendon stiffness influences postural balance during functional tasks in older adults (Arampatzis, Karamanidis, & Mademli, 2008). These contrasting results on Achilles tendon stiffness and its functional impact in older adults indicate the need for a systematic review.

Therefore, the first aim is to determine the difference in Achilles tendon stiffness between older and younger adults. We hypothesize that Achilles tendon stiffness is decreased in older compared with younger adults. The second aim is to compare Achilles tendon elastic modulus in older and younger adults. Altered Achilles tendon elastic modulus possibly explains alterations in Achilles tendon stiffness in older compared with younger adults. We hypothesize that Achilles tendon elastic modulus is decreased in older compared with younger adults. The third aim is

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to compare Achilles tendon stiffness between middle-aged and younger adults as no evidence exists with respect to the onset of possible age-related changes in Achilles tendon stiffness. We hypothesize that Achilles tendon stiffness is also decreased in middle-aged adults compared with younger adults. To conclude, it is an aim to establish the functional consequences of the possible differences in Achilles tendon stiffness between older and younger adults. We hypothesize that decreased Achilles tendon stiffness is associated with the age-related decline in functional activities characterized by high force production in the calf muscles.

Methods

Literature Search

A systemic literature search was conducted on May 17, 2017. The electronic bibliographic databases PubMed, Embase, Web of Science, and SPORTDiscus were searched. The search terms represented the concepts (a) ultrasound imaging, (b) older adults, (c) Achilles tendon, and (d) stiffness. These concepts were applied using the search operator "AND" in the title and the abstract. The specific search terms and addressed Boolean operators are provided as Supplementary Material [available online]. Bibliographies of relevant papers were screened, and authors were contacted for missing outcomes if necessary.

Data Collection and Analysis

Study selection. Following the database search, two independent reviewers (T. Delabastita and S. Bogaerts) evaluated the titles and the abstracts for initial inclusion. The full text of the initially included studies was used to confirm the inclusion. In case of disagreement, a third independent reviewer (B. Vanwanseele) was consulted. Full-text original research articles were included (a) if the article was written in English, (b) if Achilles tendon stiffness or Achilles tendon elastic modulus was experimentally measured using a combination of ultrasound imaging and isokinetic dynamometry, and (c) if it was reported that healthy older adults or healthy middle-aged adults were included in the study population. Cross-sectional as well as longitudinal studies could be included in this systematic review.

Assessment of methodological quality and risk of bias. To be able to assess the methodological quality of observational studies investigating Achilles tendon properties (and not patellar tendon properties), adaptations were made to a quality scale used in a previous systematic review on tendon adaptations following training interventions in younger subjects (Bohm, Mersmann, & Arampatzis, 2015). An overview of the criteria to assess the methodological quality and of the scoring system is presented in Table 1.

Furthermore, to be able to assess the risk of bias in the included studies, adaptations were made to the Cochrane Risk of Bias tool (Higgins & Green, 2011). These adaptations were based on other assessment tools for methodological quality in cross-sectional studies (Downes, Brennan, Williams, & Dean, 2016; Sterne et al., 2016; U.S. Department of Health & Human Services, 2014). An overview of the criteria to assess the risk of bias and of the scoring system is presented in Table 2. All studies were independently assessed by two reviewers (T. Delabastita and S. Bogaerts). In case of disagreement, a third independent reviewer (B. Vanwanseele) was consulted.

Data extraction and management. From all of the studies that fulfilled the inclusion criteria, one of the authors (T. Delabastita) extracted data on (a) the subject characteristics (age, sex, and physical activity level), (b) Achilles tendon stiffness, and (c) Achilles tendon elastic modulus. If a study included measurements of one of these outcomes on multiple time points, only the baseline

Table 1 Criteria to Assess Methodological Quality in the Included Studies and Detailed Information on Scoring Criteria

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	"Y"—criterion is fulfilled "N"—criterion is not fulfilled or no description is available "NA"—criterion is not appropriate to the study
1. Stiffness	Is Achilles tendon stiffness included as a study outcome?
2. Elastic modulus	Is Achilles tendon elastic modulus included as a study outcome?
3. Gravitational forces	Were gravitational forces taken into account in the measurement of plantar flexion moment?
4. Axes misalignment	Was axis misalignment taken into account in the measurement of plantar flexion moment?
5. Antagonistic activation	Was antagonistic muscle activation taken into account in the Achilles tendon force calculations?
6. Synergistic activation	Was muscle activation of different plantar flexor muscles taken into account in the Achilles tendon force calculations?
7. Moment arm measured	Was the plantar flexor's moment arm directly measured?
8. Joint angle changes	Were joint angle changes taken into account in the measurement of Achilles tendon elongation?
9. Multiple trials average	Were multiple trials used to calculate Achilles tendon stiffness?
10. Sex methods	Was sex addressed as a confounding variable by the inclusion criteria or in the statistical methods?
11. Physical activity level	Was physical activity level addressed as a confounding variable by the inclusion criteria or in the statistical methods?
12. Effect sizes	Were effect sizes calculated and reported?
13. Power estimations	Was the study sample size justified by reporting statistical power estimations?
14. Age	Is the study sample described in detail by reporting the study subjects' age?
15. Sex reported	Is the study sample described in detail by reporting the study subjects' sex?
16. Body height	Is the study sample described in detail by reporting the study subjects' body height?
17. Body weight	Is the study sample described in detail by reporting the study subjects' body weight?
18. Activity level	Is the study sample described in detail by reporting the study subjects' physical activity level?

Table 2 Criteria to Assess the Risk of Bias in the Included Studies and Detailed Information on Low Risk Scoring Criteria

In general	"LR"—risk of a specific type of bias is estimated to be low "HR"—risk of a specific type of bias is estimated to be high "UC"—insufficient information is provided to judge the specific type of bias
1. Study population definition	"LR" was assigned if the authors reported objective inclusion criteria with regard to the participant's sex and physical activity level for all subject groups or if subjects were prospectively excluded when specific criteria were met.
2. Selection process	"LR" was assigned if the authors reported for all subjects how the participants were contacted and how they were screened before inclusion in the study.
3. Nonresponders	"LR" was assigned if the authors reported that measures were taken to address and categorize nonresponders.
4. Blinded personnel	"LR" was assigned if the authors reported that measures were taken to blind the study personnel.
5. Blinded outcome assessment	"LR" was assigned if the authors reported that measures were taken to blind assessment of the outcome measures.
6. Incomplete data	"LR" was assigned if no outcomes are missing or if the number of analyzed subjects is added to the tables and figures.
7. Selective reporting	"LR" was assigned if the authors reported the study protocol in detail including all of the primary and secondary outcomes of interest.

data were extracted. If Achilles tendon stiffness or elastic modulus was calculated within several intervals of the force–elongation or stress–strain curve, only the values from the highest intervals were used (Bohm et al., 2015). Furthermore, the included studies were screened to identify correlations between measures of functional performance and Achilles tendon stiffness or group differences with respect to functional performance measures that could be explained by group differences with respect to Achilles tendon stiffness.

Statistical analysis. Meta-analyses were conducted to investigate differences in Achilles tendon stiffness and elastic modulus between older and younger adults. Only studies where the outcome of interest was reported for both older and younger adults could be included. In addition, a meta-analysis was performed to investigate the difference in Achilles tendon stiffness between middle-aged and younger adults. There were two studies with four subject groups that were included in the meta-analyses. First, younger nonactive or younger trained adults were compared with, respectively, older nonactive or older trained adults (Karamanidis & Arampatzis, 2006). Second, younger male or younger female adults were compared with, respectively, older male or older female adults (Stenroth et al., 2012). These meta-analyses were performed using Review Manager 5.3 (The Cochrane Collaboration, 2014). A random effects model was used to calculate a weighted average effect size for each meta-analysis by calculating the standardized mean difference for every study in a specific meta-analysis. As such, the reported group differences are standardized and weighted with the corresponding standard deviation and the number of study subjects (Higgins & Green, 2011). Therefore, only studies that included both younger adults and middle-aged or older adults could be included in these analyses (Higgins & Green, 2011). From all the longitudinal studies, only the baseline measurements of the outcome of interest were included in the meta-analyses. Furthermore, the inconsistency between the included studies was quantified using the I^2 statistic (Higgins & Green, 2011).

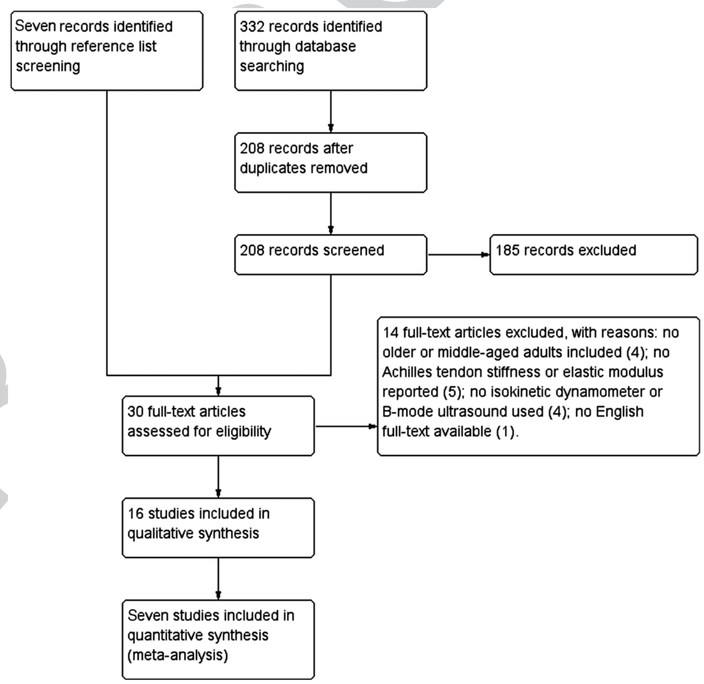

Figure 1 — Q4

Results

Literature Search

The literature search in the four selected bibliographical databases identified 332 records (Figure 1). After removal of duplicates, 208 records were assessed for eligibility through the initial screening (title and abstract). Based on this initial screening, the inclusion criteria were fulfilled in 23 articles. Screening these articles' reference lists resulted in seven additional records. As such, 30 articles were assessed for eligibility through a second screening (full text). This led to the additional exclusion of 14 articles. As such, in total 16 studies were included in the qualitative synthesis of this systematic review. Furthermore, seven studies were included in the quantitative synthesis of this systematic review because at least one of the outcomes of interest was reported for both older or middle-aged and younger adults in these studies.

Description of the Included Studies

From the 16 studies included in the current systematic review, 10 studies are cross-sectional studies, measuring Achilles tendon stiffness at only one time point (Arampatzis et al., 2008; Karamanidis & Arampatzis, 2005, 2006; Karamanidis, Arampatzis, & Mademli, 2008; King, Vanicek, & O'Brien, 2016; Onambélé et al., 2006, 2007; Stenroth et al., 2012, 2015, 2016). By contrast, six studies in the current review measured Achilles tendon stiffness at multiple time points before and after prolonged running (Ackermans et al., 2016), a fatiguing protocol (Mademli & Arampatzis, 2008), or an exercise intervention (Epro et al., 2017; Han et al., 2017; Karamanidis, Oberländer, Niehoff, Epro, & Brüggemann, 2014; Onambélé et al., 2008).

Important differences are observed among the different study participant samples (Table 3). First, the selected study samples varied with respect to the study subjects' sex. Only male subjects were included in seven studies (Ackermans et al., 2016; Arampatzis et al., 2008; Karamanidis & Arampatzis, 2005, 2006; Karamanidis et al., 2008; Mademli & Arampatzis, 2008; Stenroth et al., 2016). Only female subjects were included in three studies (Epro et al., 2017; Han et al., 2017; Karamanidis et al., 2014). Both male and female subjects were included in six studies (King et al., 2016; Onambélé et al., 2006, 2007, 2008; Stenroth et al., 2012, 2015). Second, the selected study samples varied with respect to the study subjects' age. Middle-aged subjects were included in two studies, whereas the other studies included older subjects. The mean age of the middle-aged subjects in the included studies was 46 years (Onambélé et al., 2006) and 56 years (Ackermans et al., 2016). The mean age of the older subjects in the included studies varied from 62 years (King et al., 2016) to 75 years (Stenroth et al., 2012, 2015, 2016). Third, the selected study samples varied with respect to the study subjects' physical activity level. Sedentary subjects were included in five studies (Karamanidis & Arampatzis, 2005, 2006; Onambélé et al., 2007; Stenroth et al., 2012, 2016). Other studies also included subjects generally active in recreational sports (Mademli & Arampatzis, 2008; Stenroth et al., 2012) or subjects active in recreational endurance running (Ackermans et al., 2016; Karamanidis & Arampatzis, 2005, 2006; Karamanidis et al., 2008), in competitive endurance running (Stenroth et al., 2016), or in competitive explosive running disciplines (Stenroth et al., 2016). Finally, it was reported in one study that the study subjects differed regarding their ability to recover from a balance perturbation (Karamanidis et al., 2008).

It was reported in 14 studies that the possible influence of the study subjects' sex was taken into account (Ackermans et al., 2016; Arampatzis et al., 2008; Epro et al., 2017; Han et al., 2017; Karamanidis & Arampatzis, 2005, 2006; Karamanidis et al., 2008, 2014; Mademli & Arampatzis, 2008; Onambélé et al., 2007, 2008; Stenroth et al., 2012, 2015, 2016). It was reported in 10 studies that the possible influence of the study subjects' physical activity level was taken into account (Ackermans et al., 2016; Epro et al., 2017; Han et al., 2017; Karamanidis & Arampatzis, 2005, 2006; Karamanidis et al., 2008; Mademli & Arampatzis, 2008; Stenroth et al., 2012, 2015, 2016). Surprisingly, the study subjects' physical activity level was not reported in detail in seven of these studies (Arampatzis et al., 2008; Epro et al., 2017; Han et al., 2017; Karamanidis et al., 2014; King et al., 2016; Onambélé et al., 2008).

All the included studies reported Achilles tendon stiffness as an outcome. Achilles tendon stiffness was quantified by calculating the force–elongation curve (Ackermans et al., 2016; Epro et al., 2017; Han et al., 2017; Karamanidis et al., 2014; King et al., 2016; Onambélé et al., 2006, 2007, 2008; Stenroth et al., 2012, 2015, 2016) or the force–strain curve (Arampatzis et al., 2008; Karamanidis & Arampatzis, 2005, 2006; Karamanidis et al., 2008; Mademli & Arampatzis, 2008) of the Achilles tendon. Achilles tendon elastic modulus was only reported in five of the included studies (Epro et al., 2017; King et al., 2016; Onambélé et al., 2006; Stenroth et al., 2012, 2016).

Assessment of Methodological Quality and Risk of Bias

The assessment of the methodological quality of the studies shows that there is great variation with respect to the addressed methods to quantify Achilles tendon mechanical, morphological, and material properties (Table 4). Remarkable differences exist with respect to different correction methods to calculate Achilles tendon force. It was reported in six studies that the moment around the ankle joint was corrected for misalignment between the ankle axis of rotation and the axis of rotation of the dynamometer (Arampatzis et al., 2008; Karamanidis & Arampatzis, 2005, 2006; Karamanidis et al., 2008, 2014; Mademli & Arampatzis, 2008). Furthermore, it was reported in five studies that the moment around the ankle joint was corrected for synergistic muscle activation (Han et al., 2017; King et al., 2016; Onambélé et al., 2006, 2007, 2008). Additionally, it was reported in four studies that multiple trials were used to calculate Achilles tendon stiffness (Epro et al., 2017; Stenroth et al., 2012, 2015, 2016). Remarkably, none of the included studies reported a priori statistical power estimations or a posteriori calculations of effect sizes.

With respect to the risk of bias, it was difficult to perform the assessment because the addressed items were not reported in sufficient detail in many of the studies (Table 5). A detailed description of the study subject selection process was provided in only four studies (Han et al., 2017; Onambélé et al., 2006; Stenroth et al., 2012, 2016). Moreover, it was reported in only one study that the assessment of the study outcomes was blinded (Epro et al., 2017). The identification of nonresponders or blinding of study personnel was never reported in any of the studies.

Does Achilles Tendon Stiffness Differ Between Older and Younger Adults?

Achilles tendon stiffness was decreased in older compared with younger adults (Figure 2). The weighted standardized mean difference was 1.40 with 95% confidence intervals being 0.42 and 2.38. The inconsistency across the studies included in the analysis was very high ($I^2 = 92\%$).

Achilles tendon elastic modulus was decreased in older compared with younger adults (Figure 3). The weighted standardized mean difference was 1.74 with 95% confidence intervals being 0.99 and 2.49. The inconsistency across the studies included in the analysis was high ($I^2 = 73\%$).

Does Achilles Tendon Stiffness Differ Between Middle-Aged and Younger Adults?

Achilles tendon stiffness was also decreased in middle-aged compared with younger adults (Figure 4). The weighted standardized mean difference was 1.41 with 95% confidence intervals being 0.35 and 2.48. The inconsistency across the studies included in the analysis was high ($I^2 = 75\%$). As such, the weighted standardized mean differences as computed with the

Table 3 Data Extraction From the Included Studies

		Age					Stiffness		Elastic Modulus		
	Group	Mean	*SD*	*N*	Sex	Physical activity	Mean	*SD*	Mean	*SD*	Functional implications
Ackermans et al. (2016)[d]	Young	26	3	22	M	Recreational marathon running	1,390.4	597.2			
	Middle aged	56	5	27	M		983.1	233.1			
Arampatzis et al. (2008)	Older stable[a]	64	3	10	M	NR	**28.1**	**8.8**			ATS differences do not explain postural control differences
	Older unstable[a]	64	3	28	M		**26.0**	**8.1**			
Epro et al. (2017)	Older control	66	8	13	F	NR	499.3	121.0	1.31	0.31	
	Older training	65	7	21	F		513.3	183.6	1.27	0.39	
Han et al. (2017)	Older control	69	4	15	F	Physically ready to follow training	23.6	10.0			
	Older training[b]			13	F		19.6	7.9			
	Older training[b]			12	F		20.4	6.0			
Karamanidis and Arampatzis (2005)	Younger	29	3	10	M	Nonactive subjects	**FIG**	**FIG**			
	Older	64	2	10	M		**FIG**	**FIG**			
	Younger	27	4	9	M	Endurance running	**FIG**	**FIG**			
	Older	64	3	20	M		**FIG**	**FIG**			
Karamanidis and Arampatzis (2006)[d]	Younger	29	3	10	M	Nonactive subjects	**35.7**	**26.8**			
	Older	64	2	10	M		**23.9**	**7.1**			
	Younger	27	4	9	M	Endurance running	**26.4**	**11.0**			
	Older	64	3	20	M		**26.1**	**8.4**			
Karamanidis et al. (2008)[d]	Younger	27	4	9	M	Endurance running	**27.0**	**11.4**			ATS is not associated with postural control
	Older	64	3	9	M		**26.0**	**10.5**			
Karamanidis et al. (2014)	Older	69	4	12	F	NR	51.4	3.8			
King et al. (2016)	Healthy controls	62	4	10	MF	NR	184.3	65.5	0.48	0.22	
Mademli and Arampatzis (2008)[d]	Younger	30	7	12	M	Recreational sports	**39.1**	**8.0**			
	Older	65	3	14	M		**27.4**	**5.9**			
Onambélé et al. (2006)[d]	Younger	24	1	24	MF	NR	53.3	7.5	0.36	0.05	ATS is associated with single-leg and tandem stance performance
	Middle aged	46	1	10	MF		39.5	3.9	0.26	0.03	
	Older	68	1	36	MF		32.5	4.1	0.26	0.03	
Onambélé et al. (2007)[d]	Younger	24	1	20	MF	Community leaving	59.1	9.1			ATS is associated with single-leg stance performance
	Older	68	1	28	MF		31.6	4.1			
Onambélé et al. (2008)	Older training[c]	70	2	12	MF	NR	26.0	12.8			ATS predicts single-leg stance performance
	Older training[c]	70	1	12	MF		25.0	5.5			
Stenroth et al. (2012)[d]	Younger	24	2	18	M	Sedentary or active in recreational sports	18.6	3.7	0.86	0.20	
	Younger	25	3	15	F		15.1	2.9	0.71	0.18	
	Older	75	4	33	M		16.4	4.7	0.59	0.17	
	Older	74	3	34	F		12.0	3.9	0.48	0.18	
Stenroth et al. (2015)	Older	75	4	26	M	Able to walk 250 m or more	16.0	3.3			ATS is associated with functional walking capacity
	Older	75	3	26	F		12.0	3.8			
Stenroth et al. (2016)	Younger	24	2	18	M	Untrained	18.6	3.7	0.86	0.20	
	Older	75	4	33	M		16.4	4.7	0.59	0.17	
	Older	74	3	10	M	Endurance running	17.2	3.9	0.56	0.22	
	Older	74	3	10	M	Sprinting	16.6	3.5	0.48	0.19	

Note. N = number of subjects; ATS = Achilles tendon stiffness. NR indicates that the value of interest was measured but not reported in the corresponding study; FIG indicates that the value of interest was measured but only reported in a figure in the corresponding study; empty cells indicate that the value of interest was not measured in the corresponding study. M indicates that only male subjects were included in the corresponding subject group; F indicates that only female subjects were included in the corresponding subject group; MF indicates that both male and female subjects were included in the corresponding subject group. Bolded Achilles tendon stiffness values indicate that Achilles tendon stiffness was quantified by calculating the Achilles tendon force–strain curve and not the Achilles tendon force–elongation curve. [a]Subjects were assigned to the (un)stable group based on the ability to recover from a balance perturbation task. [b]Subjects were assigned to an intensity-modulated training group (above) or an exposure-time modulated group (below). [c]Subjects were assigned to a conventional training group (above) or a flywheel-resistance training group. [d]The corresponding study is included in the meta-analyses of the current review.

Table 4 Assessment of Methodological Quality of the Included Studies

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	Stiffness	Elastic modulus	Gravitational forces	Axes misalignment	Antagonistic activation	Synergistic activation	Moment arm measured	Joint angle changes	Multiple trials average	Sex methods	Physical activity level	Effect sizes	Power estimations	Age	Sex reported	Body height	Body weight	Physical activity level
Ackermans et al. (2016)	Y	N	Y	N	N	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y
Arampatzis et al. (2008)	Y	N	Y	Y	Y	N	N	Y	N	Y	N	N	N	Y	Y	Y	Y	N
Epro et al. (2017)	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y
Han et al. (2017)	Y	N	N	N	N	Y	N	Y	N	Y	Y	N	N	Y	Y	Y	Y	N
Karamanidis and Arampatzis (2005)	*Y*	N	Y	Y	Y	N	N	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y
Karamanidis and Arampatzis (2006)	*Y*	N	Y	Y	Y	N	N	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y
Karamanidis et al. (2008)	*Y*	N	Y	Y	Y	N	N	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y
Karamanidis et al. (2014)	Y	N	Y	Y	Y	N	N	Y	N	Y	N	N	N	Y	Y	Y	Y	N
King et al. (2016)	Y	Y	N	N	Y	Y	Y	N	N	N	N	N	N	Y	Y	Y	Y	N
Mademli and Arampatzis (2008)	*Y*	N	Y	Y	Y	N	N	Y	N	Y	Y	N	N	Y	Y	Y	Y	Y
Onambélé et al. (2006)	Y	Y	N	N	Y	Y	Y	Y	N	N	N	N	N	Y	Y	N	N	N
Onambélé et al. (2007)	Y	N	N	N	Y	Y	Y	Y	N	Y	N	N	N	Y	Y	N	N	N
Onambélé et al. (2008)	Y	N	N	N	Y	Y	N	N	N	Y	N	N	N	Y	Y	N	N	N
Stenroth et al. (2012)	Y	Y	N	N	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y
Stenroth et al. (2015)	Y	N	N	N	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y
Stenroth et al. (2016)	Y	Y	N	N	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y

Note. Roman "Y" indicates that the corresponding criterion is fulfilled; N indicates that the corresponding criterion is not fulfilled; NA indicates that the corresponding criterion is not appropriate to the specific study; italics "*Y*" indicates that Achilles tendon stiffness is quantified calculating the Achilles tendon force–strain relationship.

meta-analysis comparing older adults and younger adults (1.40; Figure 2) and the meta-analysis comparing middle-aged adults and younger adults (1.41; Figure 4) were almost equal. By contrast, it was reported that Achilles tendon stiffness is decreased more in older adults than in middle-aged adults compared with younger adults (Onambélé et al., 2006). It was calculated that the standardized mean difference in Achilles tendon stiffness between older and younger adults was 3.60 with 95% confidence intervals being 2.76 and 4.45 (Figure 2). The standardized mean difference in Achilles tendon stiffness between middle-aged and younger adults was only 2.02 with 95% confidence intervals being 1.12 and 2.91 (Figure 4).

Table 5 Assessment of Risk of Bias in the Included Studies

	1 Study population definition	2 Selection process	3 Nonresponders	4 Blinded personnel	5 Blinded outcome assessment	6 Incomplete data	7 Selective reporting
Ackermans et al. (2016)	LR	UC	UC	UC	UC	LR	LR
Arampatzis et al. (2008)	UC	UC	UC	UC	UC	LR	LR
Epro et al. (2017)	LR	UC	UC	UC	LR	LR	LR
Han et al. (2017)	LR	LR	UC	UC	UC	UC	LR
Karamanidis and Arampatzis (2005)	LR	UC	UC	UC	UC	LR	LR
Karamanidis and Arampatzis (2006)	LR	UC	UC	UC	UC	LR	LR
Karamanidis et al. (2008)	LR	UC	UC	UC	UC	LR	LR
Karamanidis et al. (2014)	LR	UC	UC	UC	UC	UC	LR
King et al. (2016)	LR	UC	UC	UC	UC	UC	LR
Mademli and Arampatzis (2008)	LR	UC	UC	UC	UC	LR	LR
Onambélé et al. (2006)	LR	LR	UC	UC	UC	UC	LR
Onambélé et al. (2007)	LR	UC	UC	UC	UC	UC	LR
Onambélé et al. (2008)	UC	UC	UC	UC	UC	LR	LR
Stenroth et al. (2012)	LR	LR	UC	UC	UC	LR	LR
Stenroth et al. (2015)	LR	UC	UC	UC	UC	LR	LR
Stenroth et al. (2016)	LR	LR	UC	UC	UC	LR	LR

Note. LR indicates that the risk of a specific type of bias is estimated to be low. HR indicates that the risk of a corresponding type of bias is estimated to be high. UC indicates that insufficient information is provided to judge the corresponding type of bias.

What Are the Functional Consequences of the Possible Differences in Achilles Tendon Stiffness Between Older and Younger Adults?

It was found that Achilles tendon stiffness is related to functional walking capacity in older adults (Stenroth et al., 2015). Contrasting results were found regarding the association of Achilles tendon stiffness with postural balance. Achilles tendon stiffness was associated with single-leg stance performance (Onambélé et al., 2007) and tandem stance performance in older adults (Onambélé et al., 2006). Moreover, Achilles tendon stiffness independently predicted single-leg stance performance in older adults (Onambélé et al., 2008). By contrast, it was found that Achilles tendon stiffness was not related to postural control as measured by the ability to recover from a forward fall (Karamanidis et al., 2008) and that differences in Achilles tendon stiffness did not explain differences in the ability to recover from a forward fall in older adults (Arampatzis et al., 2008).

Discussion

The current systematic review aimed to compare Achilles tendon stiffness between older and younger adults. It was found that Achilles tendon stiffness is decreased in older compared with younger adults. In addition, it was found that Achilles tendon stiffness is also decreased in middle-aged compared with younger adults. With respect to the functional consequences of the possible differences in Achilles tendon stiffness between older and younger

Study or subgroup	Weight	Standardized mean difference IV, Random, 95% CI
Karamanidis and Arampatzis (2006)	12.3%	0.58 (−0.32 to 1.47)
Karamanidis and Arampatzis (2006)	12.6%	0.03 (−0.76 to 0.82)
Karamanidis et al. (2008)	12.2%	0.09 (−0.83 to 1.02)
Mademli and Arampatzis (2008)	12.3%	1.63 (0.72 to 2.54)
Onambélé et al. (2006)	12.5%	3.60 (2.76 to 4.45)
Onambélé et al. (2007)	11.9%	4.07 (3.05 to 5.10)
Stenroth et al. (2012)	13.1%	0.49 (−0.09 to 1.08)
Stenroth et al. (2012)	13.0%	0.84 (0.21 to 1.47)
Total (95% CI)	**100.0%**	**1.40 (.42 to 2.38)**

Heterogeneity: $\tau^2 = 1.82$; $\chi^2 = 84.90$, $df = 7$ ($P < .00001$); $I^2 = 92\%$
Test for overall effect: $Z = 2.79$ ($P = .005$)

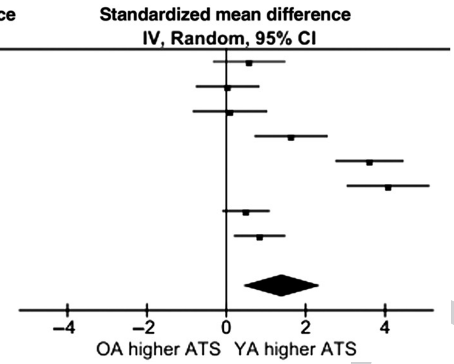

Figure 2 — CI = confidence intervals; OA = older adults; YA = younger adults; ATS = Achilles tendon stiffness; *df* = degrees of freedom.

Study or subgroup	Weight	Standardized mean difference IV, Random, 95% CI
Stenroth et al. (2012)	33.5%	1.26 (0.60 to 1.92)
Stenroth et al. (2012)	33.9%	1.47 (0.82 to 2.12)
Onambélé et al. (2006)	32.6%	2.52 (1.82 to 3.22)
Total (95% CI)	**100.0%**	**1.74 (.99 to 2.49)**

Heterogeneity: $\tau^2 = .32$; $\chi^2 = 7.54$, $df = 2$ ($P = .02$); $I^2 = 73\%$
Test for overall effect: $Z = 4.56$ ($P < .00001$)

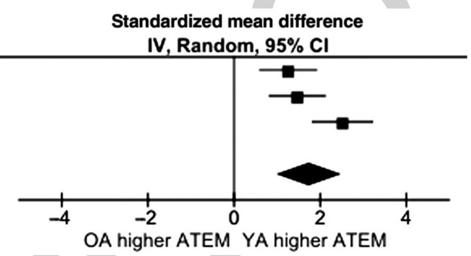

Figure 3 — CI = confidence intervals; OA = older adults; YA = younger adults; ATEM = Achilles tendon elastic modulus; *df* = degrees of freedom.

Study or subgroup	Weight	Standardized mean difference IV, Random, 95% CI
Ackermans et al. (2016)	54.9%	0.92 (0.33 to 1.52)
Onambélé et al. (2006)	45.1%	2.02 (1.12 to 2.91)
Total (95% CI)	**100.0%**	**1.41 (.35 to 2.48)**

Heterogeneity: $\tau^2 = .45$; $\chi^2 = 3.98$, $df = 1$ ($P = .05$); $I^2 = 75\%$
Test for overall effect: $Z = 2.60$ ($P = .009$)

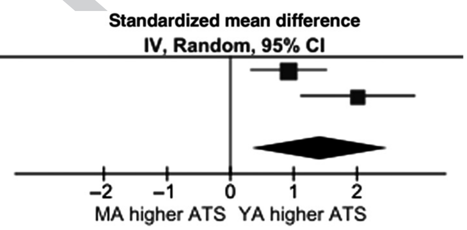

Figure 4 — CI = confidence intervals; OA = older adults; YA = younger adults; ATS = Achilles tendon stiffness; *df* = degrees of freedom.

adults, it was found that Achilles tendon stiffness is related to functional walking capacity in older adults. Contrasting results were found with respect to the association between Achilles tendon stiffness and postural balance in older adults.

Does Achilles Tendon Stiffness Differ Between Older and Younger Adults?

A first meta-analysis on Achilles tendon stiffness confirmed the hypothesis that Achilles tendon stiffness is decreased in older compared with younger adults. Based on the weighted average effect size calculated in this meta-analysis, Achilles tendon stiffness is 24% (Onambélé et al., 2006) to 99% (Karamanidis & Arampatzis, 2006) higher in younger compared with older adults. Based on these results, the Achilles tendon would lengthen much more in older compared with younger adults assuming equal contractile forces in the gastrocnemius and soleus muscles. This influences these muscles' force-producing capacities through the force–length and force–velocity relationship (Alexander, 2002; Biewener & Roberts, 2000; Lichtwark & Barclay, 2010). Therefore, it is highlighted that research investigating gastrocnemius and soleus muscle functioning in older adults should not overlook the influence of this age-related decrease in Achilles tendon stiffness. Moreover, it is suggested that musculoskeletal modeling-based research investigating calf muscle functioning in older adults should integrate musculoskeletal models with individualized Achilles tendon stiffness (Franz & Thelen, 2016; Passmore, Lai, Sangeux, Schache, & Pandy, 2017).

The second meta-analysis showed that Achilles tendon elastic modulus is decreased in older compared with younger adults. Although only two different studies were included in the meta-analysis, this suggests that Achilles tendon stiffness is decreased in older compared with younger adults due to changes in the material properties (Svensson, Heinemeier, Couppé, Kjaer, & Magnusson, 2016). For instance, it has been reported that tendon fascicles (the principal tensile load-bearing unit) in older adults are characterized by reduced collagen content (Couppé et al., 2009) or lipid content (Svensson et al., 2016). This reduced collagen content could be linked to reduced cell proliferation and reduced stem cell presence in tendon tissue with aging (Kohler et al., 2013). Moreover, increased cross-link formation between the collagen molecules has been observed in tendons in older adults. It was reported that this contributes to dehydration of the tendon due to the glycation of collagen molecules (Carroll et al., 2008; Couppé et al., 2014). Furthermore, previous research indicated the important role of the interfascicular tendon matrix to determine the mechanical tendon properties (Thorpe et al., 2015; Thorpe, Riley, Birch, Clegg, & Screen, 2017). For instance, reduced and disorganized elastin content is suggested to decrease the energy storing and interfascicular sliding capacity in older equine tendons (Godinho, Thorpe, Greenwald, & Screen, 2017). Similarly, research also reported that decreased interfascicular sliding capacity is also related to alterations in Achilles tendon stiffness in older adults (Franz & Thelen, 2016). To conclude, these changes in tendon composition, tendon cell function, and interfascicular tendon matrix composition are suggested to support the age-related changes in Achilles tendon elastic modulus.

Unfortunately, a high degree of inconsistency between the studies hinders strong conclusions. In other words, a high proportion of the total variation in study results is attributed to heterogeneity rather than sampling error and chance (Higgins & Green, 2011). The high degree of inconsistency can partly be attributed to the low number of studies included in the meta-analyses. Furthermore, the inconsistency between the studies could also partly exist due to methodological differences in the included studies. For instance, differences exist with respect to the quantification of Achilles tendon stiffness. In general, stiffness of a body is defined as its resistance to deformation, and it is quantified by dividing the force on the body by the displacement in the direction of the force. Achilles tendon stiffness was quantified in some studies by dividing Achilles tendon force by absolute tendon elongation (Onambélé et al., 2006, 2007; Stenroth et al., 2012), whereas it was quantified in other studies by dividing Achilles tendon force by tendon strain or relative deformation (Karamanidis & Arampatzis, 2006; Karamanidis et al., 2008; Mademli & Arampatzis, 2008). These studies calculated Achilles tendon elongation by tracking a cross-point on the medial gastrocnemius' deep aponeurosis during isometric contractions. Achilles tendon elongation was normalized to Achilles tendon resting length because these cross-points' localization influences the measured elongation (Muramatsu et al., 2001). The first approach provides more insight into the functional consequences of the age-related decrease in Achilles tendon stiffness as it is expected that the influence of Achilles tendon elongation on muscle fascicle functioning is independent of Achilles tendon resting length. The assessment of the methodological quality of the included studies indicated some other methodological differences that could further explain the inconsistency between the included studies. Important differences exist between the studies regarding (a) the correction of the ankle joint moment for misalignment between the rotational axis of the ankle joint and the isokinetic dynamometer (Arampatzis et al., 2005), (b) the correction of the ankle joint moment for antagonistic muscle coactivation (Mademli, Arampatzis, Morey-Klapsing, & Brüggemann, 2004; Magnusson, Aagaard, Rosager, Dyhre-Poulsen, & Kjaer, 2001), and (c) the measurement of the Achilles tendon moment arm (Fath et al., 2010). The reproducibility and reliability of the first two methods were not yet reported. By contrast, the tendon excursion method to calculate the Achilles tendon moment arm was found to be reliable and reproducible compared with moment arm determination based on magnetic resonance imaging (Fath et al., 2010). Furthermore, it is expected that the inconsistency between the studies can partly be explained by differences regarding the included subjects. The structured data extraction showed important differences regarding the sex and physical activity level of the included study populations. Although Achilles tendon stiffness may vary with sex (Stenroth et al., 2012) and physical activity level in both younger (Bohm et al., 2015; Bohm, Mersmann, Tettke, Kraft, & Arampatzis, 2014) and older adults (Epro et al., 2017; Han et al., 2017; Karamanidis et al., 2014; Onambélé et al., 2008), it was not always reported that these confounding factors were taken into account through the study design. Additionally, incomplete reporting of both subject recruitment processes and subjects' characteristics hinders the assessment of possible sources of inconsistency and the risk of bias in the included studies. It should be noted that an accurate assessment of the risk of bias in many of the included studies was difficult due to inconsiderate reporting. Therefore, it is advised to consider the addressed issues with regard to the methodology and some aspects of concise writing in future research.

Does Achilles Tendon Stiffness Differ Between Middle-Aged and Younger Adults?

A meta-analysis showed that Achilles tendon stiffness is decreased in middle-aged compared with younger adults. The weighted overall effect size is relatively high. Because the included studies had participants with mean ages of 56 years (Ackermans et al., 2016) and 46 years (Onambélé et al., 2006), it seems that the Achilles tendon stiffness decreases gradually with age and that this age-related decline starts before the age of 46 years. Although it is not supported by the weighted average effect sizes as calculated in the meta-analyses in the current systematic review, research included in these analyses did report that Achilles tendon stiffness is decreased more in older adults than in middle-aged adults compared with younger adults (Onambélé et al., 2006). Possibly, this age-related decline in Achilles tendon stiffness and the age-related decline in muscle strength start approximately at the same age (Larsson, Grimby, & Karlsson, 1979). The association between Achilles tendon stiffness and ankle plantar flexor muscle strength has been reported before in younger (Morrison, Dick, & Wakeling, 2015) and in older adults (Stenroth et al., 2012). Obviously, more research is needed to investigate the onset of the age-related decline in Achilles tendon stiffness and its relation to the age-related decline in ankle plantar flexor muscle strength.

What Are the Functional Consequences of the Possible Differences in Achilles Tendon Stiffness Between Older and Younger Adults?

Decreased Achilles tendon stiffness was found to be associated with decreased functional walking performance in older adults (Stenroth et al., 2015). Possibly, altered Achilles tendon stiffness alters gastrocnemius and soleus muscle fascicle behavior (Fukunaga et al., 2001; Lichtwark et al., 2007). Increased Achilles tendon elongation at a given force level would make the gastrocnemius and soleus muscle fascicles work at lower lengths (Mian, Thom, Ardigò, Minetti, & Narici, 2007) and at higher shortening velocities. Given the force–length and force–velocity relationship, this could increase the energy cost of walking for the gastrocnemius and soleus muscles (Lichtwark & Barclay, 2010; Lichtwark & Wilson, 2007, 2008) in older adults. An interesting simulation study already highlighted that a 25% decrease of Achilles tendon stiffness could decrease soleus and gastrocnemius muscles' efficiency by 15% (Lichtwark & Wilson, 2007). Based on the meta-analyses included in the current systematic review, these differences are highly plausible (see Section 4.1. first paragraph). As such, decreased efficiency and increased energy cost of walking possibly lead to more fatigue during walking in older adults. This mechanism could explain the association between decreased Achilles tendon stiffness and decreased functional walking performance. As such, Achilles tendon stiffness could negatively influence walking performance in older adults through its effect on the gastrocnemius and soleus muscle fascicle work and energy consumption during walking.

The studies included in the current review highlighted that decreased Achilles tendon stiffness possibly disturbs postural balance during single-leg stance and tandem stance, because it delays the feedback loop controlling postural balance and the development of ankle torque to restore postural balance (Onambélé et al., 2006, 2007, 2008). This is supported by research indicating the important role of the elastic Achilles tendon in healthy younger adults during undisturbed standing (Loram, Maganaris, & Lakie, 2005, 2009). By contrast, other research reported that Achilles tendon stiffness is not related to dynamic stability (Karamanidis et al., 2008) and that differences in Achilles tendons do not explain differences in dynamic stability as measured by the response to a sudden release from a fixed forward-inclined body position (Arampatzis et al., 2008). However, the role of the hip and knee extensors is greater compared with the role of the ankle plantar flexors during these recovery tasks (Carty et al., 2012).

Short-term training interventions can increase Achilles tendon stiffness in healthy younger (Bohm et al., 2015) and older adults (Epro et al., 2017; Han et al., 2017; Karamanidis et al., 2014; Onambélé et al., 2008). Possibly, an intervention to increase Achilles tendon stiffness could increase older adults' functional performance and safety during daily life through the association between Achilles tendon stiffness, functional walking performance, and postural balance. Previous research has already reported a decreased energy cost of running after a training intervention to increase Achilles tendon stiffness in long-distance runners (Albracht & Arampatzis, 2013). Certainly, more research is needed to confirm these suggestions. However, the great clinical importance of the findings reported in the current review is clearly highlighted.

Conclusions

To conclude, it is suggested that Achilles tendon stiffness is decreased in older compared with younger subjects through altered Achilles tendon material properties. Strong conclusions are hindered by the limited number of studies in the meta-analyses and by high inconsistency between the studies' results. Second, further research is needed to confirm that the age-related decline in Achilles tendon stiffness already starts before the age of 46 years. Third, the hypothesis that decreased Achilles tendon stiffness is associated with the age-related decline in functional activities characterized by high force production in the calf muscles is partly confirmed. Research reports an association between decreased Achilles tendon stiffness and decreased functional walking performance and postural balance in older adults. More research is needed to reveal the mechanisms behind these associations. Together, these findings offer great opportunities for innovative clinical interventions to increase functional performance and safety in older adults.

Acknowledgments

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