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Plantarflexor muscle-tendon properties are associated with mobility in healthy older adults

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Running page headline: Muscle, tendon and mobility in old age

Abstract

Background. Muscle mass, strength and power are known determinants of mobility in older adults but there is limited knowledge on the influence of muscle architecture or tendon properties on mobility. The purpose of this study was to examine the relationship between mobility and plantarflexor muscle-tendon properties in healthy older adults.

Methods. A total of 52 subjects (age 70-81 years) were measured for six-minute walk test (6MWT), timed “up and go”-test (TUG), isometric plantarflexion strength, Achilles tendon stiffness, triceps surae muscle architecture, lower extremity lean mass, isometric leg extension strength and leg extension power. Partial correlations and multivariate regression models adjusted for sex, age, body mass and height were used to examine the relationship between mobility (6MWT and TUG) and lower limb muscle-tendon properties.

Results. Multivariate regression models revealed that Achilles tendon stiffness (p=0.020), plantarflexion strength (p=0.022) and medial gastrocnemius fascicle length (p=0.046) were independently associated with 6MWT. Plantarflexion strength (p=0.037) and soleus fascicle length (p=0.031) were independently associated with TUG.

Conclusions. Plantarflexor muscle-tendon properties were associated with mobility in older adults independent of lower extremity lean mass, leg extension strength or power. Plantarflexion strength was a stronger predictor of mobility than leg extension strength or power. The novel finding of this study was that muscle architecture and tendon properties explained inter-individual differences in mobility. This study highlights the importance of the plantarflexors for mobility in older adults and provides understanding of possible mechanisms of age-related decline in mobility.

Introduction

Poor mobility in older age is linked to several adverse health outcomes such as increased risk of mortality, incidence of cardiovascular disease and mobility disability (1-3). In previous literature, lower extremity lean mass (4), leg extension strength (5) and power (6) have been proposed to be causal factors leading to a decline in mobility with aging. Muscle architecture (geometrical arrangement of muscle fibers) and tendon mechanical properties are factors that have received less attention in relation to mobility even though these factors are one of the main determinants of muscle function (7, 8). In addition, muscle architecture and tendon properties have been found to be significantly different between young and old adults (9, 10) making these factors potential contributors of age-related decline in mobility.

Muscle architecture and tendon mechanical properties have an effect on muscle fiber length and velocity hence affecting muscle's force and power production capacity according to force-length (11) and force-velocity (12) relationships. For example, a muscle with longer fibers can produce greater force and power with the same muscle shortening velocity due to lower sarcomere velocity. Longer fibers also reduce the amount of sarcomere shortening per muscle shortening enabling muscle to produce greater force and power throughout a certain joint rotation if operating around optimal length or at ascending limb of force-length relationship (8).

Pennation angle may also have an effect on muscle function. Pennation angle reduces the amount of force applied to a tendon (and to a bone) by a factor of cosine of the pennation angle (13). However, this negative effect is counterbalanced by a mechanism called muscle belly gearing. As muscle fibers shorten they also rotate, amplifying the shortening of the muscle by a factor of 1/cosine of the pennation angle (13) if constant muscle thickness is assumed. The result is a reduced shortening velocity of the individual fibers for a given whole-muscle shortening velocity. Muscle belly gearing increases with increasing pennation angle and as a result, pennation angle has been shown to be related to maximal angular velocity of a limb (14). Finally, greater pennation angle of the muscle fibers allows a larger number of parallel sarcomeres to be arranged in a given muscle volume increasing physiological cross-sectional area of the muscle (8).

Elastic tendon modulates muscle fiber behavior and may decouple length changes of the muscle-tendon unit from length changes of the muscle fibers (15). Recently, Farris and Sawicki showed that medial gastrocnemius force production capacity is impaired with increasing walking speed due to increasing shortening velocity of the muscle fascicles (surrogate of fiber behavior) at the instant of peak force production (16). In this study, Achilles tendon was elongating at the same time as gastrocnemius muscle fascicles were shortening and thus a stiffer (less extendable) Achilles tendon could decrease the amount and velocity of the muscle fascicle shortening. Another recent study by Panizzolo et al. showed that soleus muscle fascicle operating length shifted to a shorter length with increasing walking speed in older adults (17) who reportedly have lower Achilles tendon stiffness (9). This shift in operating length was due to greater Achilles tendon elongation since ankle joint dorsiflexion range of motion did not change. The shift in operating range could impair force production capacity since soleus may typically operate at the ascending limb of the force-length relationship (18). To conclude, with increasing walking speed, a stiffer Achilles tendon may decrease muscle fiber shortening velocity during the peak force production in gastrocnemius and preserve fiber operating length closer to optimal in soleus therefore enhancing force production potential.

The potential role of age-related alterations in muscle architecture and tendon properties on age-related impairments in mobility has received only a limited amount of research interest. It is not known whether differences in muscle architecture or tendon stiffness can explain inter-individual differences in mobility in older adults and therefore possibly contribute to the age-related decline in mobility. To clarify this issue, the aim of the study was to examine the relationship between mobility and plantarflexor muscle-tendon properties in a sample of healthy older adults. Plantarflexors were chosen to be studied since the role of muscle architecture and tendon mechanical properties for mobility may be most notable in plantarflexors. It has been observed that during walking, age-related loss of joint moment and power occur at the ankle joint but not at the knee or hip joints in walking (19). In addition, triceps surae muscle group has a long elastic Achilles tendon attached to a relatively short muscle fascicles facilitating use of tendon elasticity during locomotion (7). This study also compares plantarflexor muscle-tendon properties to lower extremity lean mass, leg extension strength and power as predictors of mobility.

The hypothesis of this study was that plantarflexor muscle-tendon properties contribute to mobility in older adults and a relationship will exist between muscle-tendon properties and mobility. Better performance in mobility tests, i.e. faster movement speed, was assumed to require a greater force and power production from the plantarflexors and subsequently would be associated with greater plantarflexion strength, longer fascicle length and greater pennation angle in triceps surae muscles and greater Achilles tendon stiffness.

Methods

Subjects

This study was performed as part of a European wide cross-sectional study called MyoAge. Details of the recruitment of the subjects, inclusion and exclusion criteria have been reported previously (20) and only a short description is given here. Twenty-six women and 26 men (70 to 81 year old, 26) were measured for plantarflexor muscle-tendon properties (data collected in Finland). Mobility and other muscle related measurements were performed in total of 91 women and 81 men (data collected in Finland, UK and France). Care was taken to standardize measurement protocols and devices between different measurement sites (20). All subjects were moderately socially active (participating in social or group activities to improve one's knowledge or skills two times or more in a month), free from major diseases and did not have mobility limitations, which would prevent them from walking 250 m without assistance. The local ethical committees of the respective institutions approved the study. Informed consent was obtained from all participants and permission for participation was obtained from a medical doctor. The study was conducted according to the standards set by the latest revision of the Declaration of Helsinki.

Measurements

Detailed information about the measurements can be found from the supplementary material.

Subjects' height and body mass was measured and body mass index (BMI) was calculated. Habitual physical activity level was assessed using the Voorrips physical activity questionnaire (21). Mobility was assessed using the 6-minute walk test (6MWT) (22) and timed "up and go"-test (TUG) (23). Maximal voluntary isometric plantarflexion strength was measured with a custom-built dynamometer. Muscle fascicle length and pennation angle were measured at rest using ultrasonography from medial gastrocnemius and soleus. Muscle thickness was assessed from the same ultrasound images as a measure of muscle size. In order to account for differences in subject's leg length, fascicle lengths were normalized dividing fascicle length by tibia length. Achilles tendon stiffness was measured from several isometric plantarflexions using a method that combines ultrasonography, motion analysis and force measurement (9). Lower extremity lean mass (excluding bone mass) was measured using dual-energy X-ray absorptiometry. Leg extension strength was measured by performing an isometric maximal voluntary contraction with knee extensors in a dynamometer. Leg extension power was measured from a countermovement jump performed on a force plate. Instantaneous power was calculated and peak value during concentric phase was considered to represent leg extension power (24).

Statistical analysis

Data was first carefully checked for coding and measurement errors. Descriptive statistics were checked to verify normality of distributions. Differences between men and women were tested using Student's two-tailed independent samples t-test.

Possible covariates for mobility (anthropometrics, age, sex and habitual physical activity level) were tested using bivariate correlations. Factors correlating with mobility (age, sex, body mass and height) were used as adjusting factors in subsequent partial correlations and multivariate regression models.

Partial correlations were performed to examine the association between mobility (6MWT and TUG) and lower limb muscle-tendon properties adjusted for age, sex, body mass and height. Squared partial correlation coefficients are reposted (table 2) and represent the proportion of the variance in mobility test explained by a given muscle-tendon property adjusted for age, sex, body mass and height.

The muscle-tendon properties having a significant partial correlation with mobility were included in the subsequent multivariate models to determine their independent effect. From the multivariate models, a squared semipartial correlations are reported (tables 3 and 4) which represent the proportion of the variance in mobility tests that was uniquely associated with a given muscle-tendon property in the model.

Consistency of the relationships found between mobility and lower extremity lean mass and leg extension strength and power in the primary analysis (n=52) was tested with a larger sample size using data available from the MyoAge-project (n=172).

The Level of statistical significance was set at $\alpha=0.05$. Statistical tests were performed using IBM SPSS Statistics (version 20.0.0).

Results

Subject characteristics and mean values of the measured variables are summarized in table 1. There was no difference in age or level of physical activity between men and women, but men were taller, heavier, had greater lower extremity lean mass, leg extension strength and power and Achilles tendon stiffness, had larger soleus pennation angle, walked a longer distance during the 6MWT and performed TUG in shorter time. Women had longer normalized soleus fascicle length ($p<0.05$ for all sex differences). 6MWT performance ranged from 420 to 749 m, which is equivalent to an average walking speed of 1.2 to 2.1 m/s. TUG time ranged from 4.53 to 9.29 s.

Partial correlations

Partial correlations between mobility tests and lower limb muscle-tendon properties, adjusted for age, sex, body mass and height, are reported in table 2. Longer distance walked in 6MWT was significantly associated with greater plantarflexion strength, Achilles tendon stiffness, soleus pennation angle, leg extension strength and power and shorter medial gastrocnemius and soleus fascicle lengths ($p<0.05$, table 2).

Shorter TUG time was significantly associated with greater plantarflexion strength, Achilles tendon stiffness, soleus pennation angle and leg extension power and shorter soleus fascicle length ($p<0.05$). Lower extremity lean mass or muscle thicknesses of medial gastrocnemius or soleus were not significantly associated with either mobility test.

Multivariate models

Adjusted multivariate regression models include the lower limb muscle-tendon properties that had significant partial correlation with mobility tests (tables 3 and 4).

The multivariate model predicted 73% of the variance in 6MWT distance (table 3). Plantarflexion strength, Achilles tendon stiffness and medial gastrocnemius fascicle length were independent predictors in this model (figure 1).

The multivariate model predicted 61% of the variance in TUG time (table 4). Plantarflexion strength and soleus fascicle length were independent predictors in this model.

Consistency of the results

The larger sample size (n=172) gave comparable results to the ones obtained from the primary analysis. Longer distance walked in 6MWT was significantly associated with greater leg extension strength (partial $r^2=3\%$, $p=0.034$) and leg extension power (partial $r^2=16\%$, $p<0.001$). Shorter time in TUG was significantly associated with greater leg extension power (partial $r^2=15\%$, $p<0.001$). However, in this larger sample greater lower extremity lean mass was significantly associated with both mobility test (6MWT: partial $r^2=6\%$, $p=0.002$ and TUG: partial

r^2=3%, p=0.033). Leg extension power was the only significant independent predictor of 6MWT distance and TUG time in the adjusted multivariate regression models (p<0.05).

Discussion

This study examined the relationship between mobility and plantarflexor muscle-tendon properties in healthy older adults. The novel finding was that triceps surae muscle architecture and Achilles tendon stiffness were associated with mobility. In addition it was found that plantarflexion strength explained a greater proportion of the variance in the mobility tests compared to lower extremity lean mass, leg extension strength or power. The current study provides evidence that muscle architecture and tendon properties are important factors in mobility in healthy older adults.

The plantarflexors have a crucial role in age-related decline in mobility. Plantarflexors produce most of the positive mechanical work in walking (25) and there is an age-related reduction at ankle but not at knee or hip joint moment and power in walking and running in older adults compared to young (19). It has been estimated that among older adults plantarflexors are used near their maximal force production capacity in walking (26). In the current study, it was found that plantarflexion strength explained a higher proportion of variance in mobility (19-23 %) compared to lower extremity lean mass (2%), leg extension strength (8-13 %) or leg extension power (18-20 %). Furthermore, plantarflexion strength was significantly associated with mobility when controlling for other measured muscle-tendon properties including leg extension strength and power. Our results emphasize the important role of plantarflexors for mobility and support the previous findings of a strong relationship between mobility and plantarflexor muscle function (27, 28). Plantarflexion strength may be a limiting factor for walking speed in healthy older adults. This has been proposed by previous studies among populations, such as stroke (29) and heart failure patients (30). However, plantarflexion weakness can be compensated, at least to some extent by redistributing the work from the ankles to the hips (25).

Supporting our hypothesis, it was found that better performance in the mobility tests was associated with greater pennation angle in the soleus muscle and greater Achilles tendon stiffness. Interestingly, shorter fascicle length in the triceps surae muscles was associated with better mobility. In the following paragraphs possible mechanism explaining the observed relationships between mobility and muscle architecture and tendon properties are discussed.

In the soleus muscle a greater pennation angle was associated with better walking performance but when controlling for the other muscle-tendon properties in the multivariate regression models this association was not significant. This result may indicate that the greater pennation angle was associated with better performance in mobility tests due to its effect on increasing muscle physiological cross-sectional area (31) and this effect is taken into account by the plantarflexion strength in the model.

The Achilles tendon is responsible for most of the length changes in triceps surae muscle-tendon unit during the stance phase of walking (15) and thus long muscle fascicles may not provide further advantage for force or power production. Instead, shorter fascicles may reduce the energy cost of a given force production due to lower activated muscle mass compared to a similar muscle with longer fascicles (37). This may permit force production to be carried out in prolonged walking with relatively less metabolic load and fatigue. Short fascicles may also help to minimize muscle mass and thus overall energy requirements of swinging the lower leg during walking. Tendon stiffness dictates tendon length changes under loading and thus affects muscle fascicle behavior. A modeling study by Lichtwark and Wilson (32) showed that the Achilles tendon stiffness value measured from young men (180 N/mm) (33) provides an efficient muscle fascicle behavior in walking and the efficiency was decreased markedly with lower stiffness values. Older adults have been shown to have lower Achilles tendon stiffness compared to young adults (9, 34) and in the current study the average Achilles tendon stiffness was 140 N/mm. This may explain why our data suggest that greater Achilles tendon stiffness is associated with better mobility performance especially in constant fast speed walking such as that required in the 6MWT.

A strength of this study is that two distinct functional tasks were used to describe mobility, one that required fast-paced walking for a very short time (around 7 sec) and another that required prolonged walking for 6 min. 6MWT that requires sustained high workloads may benefit from Achilles tendon stiffness that is well tuned for efficient force production and elastic energy utilization. TUG on the other hand is more complex test that sets high demand on balance and may challenge for example hip abductor muscles that were not examined in this study. A sample of older adults with varying levels of physical activity but free from comorbidities were recruited allowing us to generalize the results to the healthy older population. In addition, insights into the muscle-tendon properties were provided by the measurements of muscle architecture and tendon stiffness. The limitation of this study is its inability to reveal cause-effect relationships due to the cross-sectional study design and by not measuring muscle-tendon interaction during locomotion.

In conclusion, this study increases our understanding of the age-related loss of mobility. Plantarflexion strength was shown to be an important factor determining mobility in the elderly population. In addition, muscle architectural features and tendon mechanical properties were found to explain inter-individual differences in mobility to a high degree. More research is needed to examine the role of age-related changes in muscle architecture and tendon properties regarding the etiology of age-related loss of muscle function and physical functioning. The important role of plantarflexors warrants attention when planning interventions for improving or maintaining mobility in the elderly.

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Figure caption

Figure 1. Scatter plots showing the relationship between mobility and the independent predictors from the adjusted multivariate regression models. For illustrative purposes plantarflexion strength was normalized to body mass. Body mass was treated as covariate in the regression models. Fascicle length values were normalized to tibia length.

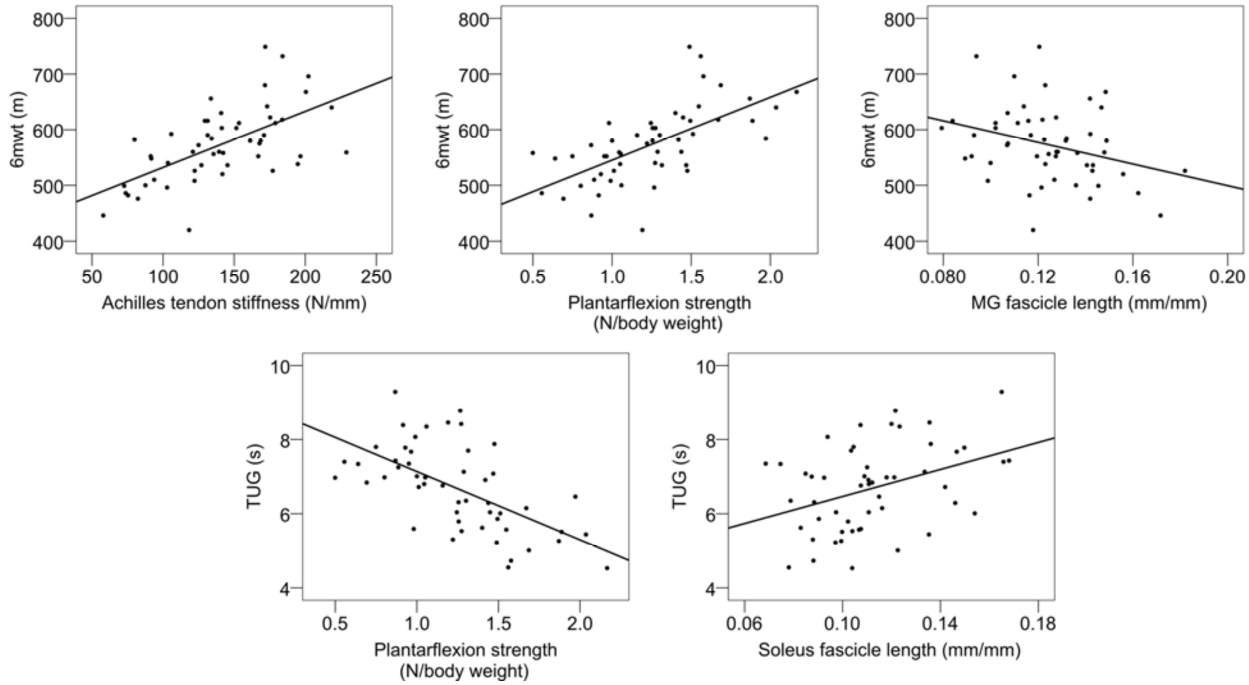

Table 1. Subject characteristics (mean ± standard deviation).

	Women (n=26)	Men (n=26)	Total (n=52)
Age (years)	74.5 ± 3.1	75.2 ± 3.6	74.8 ± 3.3
Height (cm)	158 ± 5	174 ± 5*	166 ± 9
Body mass (kg)	61.8 ± 8.5	76.3 ± 7.3*	69.0 ± 10.7
BMI (kg/m^2)	24.6 ± 3.0	25.3 ± 2.3	24.9 ± 2.7
Physical activity score (points)	9.8 ± 6.4	11.6 ± 5.9	10.7 ± 6.2
Mobility			
6MWT (m)	547 ± 50	599 ± 73*	573 ± 67
TUG (s)	7.19 ± 0.98	6.18 ± 1.10*	6.69 ± 1.15
Plantarflexor muscle-tendon properties			
Plantarflexion strength (N)	669 ± 226	1021 ± 237*	845 ± 290
Achilles tendon stiffness (N/mm)	120 ± 38	160 ± 33*	140 ± 41
MG fascicle length (mm/mm)	0.130 ± 0.022	0.118 ± 0.021	0.124 ± 0.022
MG pennation angle (°)	23.4 ± 3.4	23.8 ± 4.1	23.6 ± 3.7
MG thickness (mm)	16.8 ± 2.0	17.7 ± 3.5	17.3 ± 2.8
Soleus fascicle length (mm/mm)	0.122 ± 0.025	0.103 ± 0.020*	0.112 ± 0.024
Soleus pennation angle (°)	16.8 ± 3.3	21.1 ± 4.0*	18.9 ± 4.3
Soleus thickness (mm)	11.7 ± 2.9	13.3 ± 2.7	12.5 ± 2.9
Lower limb muscle properties			
Lower extremity lean mass (kg)	11.8 ± 1.3	16.7 ± 1.4*	14.2 ± 2.8
Leg extension strength (Nm)	85 ± 19	140 ± 26*	112 ± 36
Leg extension power (W)	1206 ± 209	1960 ± 385*	1583 ± 489

BMI: body mass index, 6MWT: 6-minute walk test, TUG: timed “up and go” –test, MG: medial gastrocnemius. *Significantly different from women.

Table 2. Partial correlations between mobility and lower limb muscle-tendon properties.

	6MWT (m)			TUG (s)		
	Partial r	Partial r^2 (%)	P-value	Partial r	Partial r^2 (%)	P-value
Plantarflexion strength (N)	**0.482**	**23.2**	**0.001**	**-0.434**	**18.8**	**0.002**
Achilles tendon stiffness (N/mm)	**0.519**	**26.9**	**<0.001**	**-0.381**	**14.5**	**0.007**
MG fascicle length (mm/mm)	**-0.287**	**8.2**	**0.048**	0.093	0.9	0.528
MG pennation angle (°)	0.188	3.5	0.603	0.049	0.2	0.742
MG thickness (mm)	-0.077	0.6	0.603	0.013	0.0	0.931
Soleus fascicle length (mm/mm)	**-0.302**	**9.1**	**0.037**	**0.291**	**8.5**	**0.045**
Soleus pennation angle (°)	**0.422**	**17.8**	**0.003**	**-0.298**	**8.9**	**0.040**
Soleus thickness (mm)	0.073	0.5	0.622	-0.053	0.3	0.719
Lower extremity lean mass (kg)	0.155	2.4	0.292	-0.125	1.6	0.396
Leg extension strength (Nm)	**0.360**	**13.0**	**0.012**	-0.282	8.0	0.053
Leg extension power (W)	**0.443**	**19.6**	**0.002**	**-0.419**	**17.6**	**0.003**

Adjusted for age, sex, body mass and height. 6MWT: 6-minute walk test, TUG: timed “up and go” –test, MG: medial gastrocnemius.

Table 3. Adjusted multivariate regression model with 6-minute walk test as dependent variable and lower limb muscle-tendon properties as independent variables.

	R^2	Adjusted R^2	Standardized β-coefficient	Semipartial r^2 (%)	P-value
6MWT	0.727	0.651			
Plantarflexion strength (N)			0.340	3.9	0.022
Achilles tendon stiffness (N/mm)			0.272	4.0	0.020
MG fascicle length (mm/mm)			-0.208	2.9	0.046
Soleus fascicle length (mm/mm)			-0.121	0.9	0.269
Soleus pennation angle (°)			0.110	0.6	0.358
Leg extension strength (Nm)			0.038	0.0	0.831
Leg extension power (W)			0.321	2.0	0.098

Adjusted for age, sex, body mass and height. P-value for the model <0.001. 6MWT: 6-minute walk test, MG: medial gastrocnemius.

Table 4. Adjusted multivariate regression model with timed “up and go” -test as dependent variable and lower limb muscle-tendon properties as independent variables.

	R^2	Adjusted R^2	Standardized β-coefficient	Semipartial r^2 (%)	P-value
TUG	0.613	0.530			
Plantarflexion strength (N)			-0.335	4.3	0.037
Achilles tendon stiffness (N/mm)			-0.169	1.6	0.193
Soleus fascicle length (mm/mm)			0.245	4.6	0.031
Soleus pennation angle (°)			-0.027	0.0	0.841
Leg extension power (W)			-0.363	2.7	0.096

Adjusted for age, sex, body mass and height. P-value for the model <0.001. TUG: timed “up and go”-test, MG: medial gastrocnemius.