Increased Cross-sectional Area and Reduced Tensile Stress of the Achilles Tendon in Elderly Compared With Young Women

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The Achilles tendon cross-sectional area (CSA), tensile force, and stress during an isometric contraction were examined in healthy young (n = 9, age = 29 ± 1 years, mean ± SEM) and elderly (n = 10, 79 ± 2 years) women. CSA area was obtained with magnetic resonance imaging 3 cm proximal to the insertion, and tendon force was obtained from the isometric ankle moment. The moment of force about the ankle joint was greater in young women (95 ± 17 N m) than in elderly women (51 ± 5 N m; p < .05). The Achilles tendon CSA was significantly greater in elderly women (56.3 ± 3.0 mm²) than in young women (46.0 ± 1.9 mm²; p < .01). These data show that young women can exert a greater force than elderly women on the Achilles tendon during voluntary contraction, although elderly women have an increased (22%) tendon CSA, and a lower tendon force than young women. The greater tendon size combines to lower the stress on the tendon markedly, which may reduce the risk of injury to the tendon.

The Achilles tendon is subjected to considerable loads during human locomotion. In fact, the Achilles tendon may reach tensile forces of up to 2600 N during walking (1,2) and up to 5330 N during running (1). Repetitive tensile force is considered to be a principle factor in the etiology of tendinopathies (3–5), and it appears that the Achilles tendon may be particularly susceptible to injury (6,7). Additionally, the incidence of tendon disorders is evidently related to age (8–10). Animal data demonstrate that the aging process is associated with connective tissue modifications that result in changes in tendon properties, such as reduced hysteresis, elasticity, and strength, and increased stiffness (Δ force/Δ deformation) in the tendon (11–14). Naturally, the intensity of physical activity and associated tensile load on the tendon is reduced with age, which may explain the reduced incidence of injury past 40–50 years of age. However, there is a lack of information on human data on the potential intrinsic changes that may occur with aging.

The average stress (measured in newtons per square meter, or in pascals) imposed on the tendon during loading can be expressed as the force transmitted to the tendon divided by its cross-sectional area (CSA). It has been suggested that the fracture stress for the tendon is ~100 MPa, and that the safety factor, that is, the tensile fracture stress divided by the stress during strenuous activity, is ~8 for a majority of tendons (15,16). However, it was recently shown that, during maximal isometric contraction, the human Achilles tendon has a safety factor of only ~2.4 in untrained subjects and ~4 in trained subjects (17). The difference between untrained and trained subjects was attributed to a larger CSA in the trained individuals. Reducing the average tendon stress for a given load by augmenting its CSA (in response to physical activity) would be advantageous from an injury standpoint. Interestingly, animal data suggest that aging is associated with an increase in tendon CSA (18,19), although it remains to be confirmed in a human model. On the basis of these findings we hypothesize that the CSA of the human Achilles tendon increases with aging. Our purpose in the present study was to investigate the imposed stress of the Achilles tendon by obtaining maximal isometric tendon tensile force and tendon CSA, and thereby calculating the tensile stress of the tendon in healthy elderly and young women.

METHODS

Subjects

Nine young healthy women (29 ± 1 years, 167 ± 3 cm, 71 ± 4 kg, mean ± SEM) and 10 elderly healthy women (79 ± 2 years, 163 ± 3 cm, 62 ± 4 kg) gave written informed consent to participate in the study. The study was approved by the local Human Subject Ethics Committee of Copenhagen and Fredriksberg municipality. We previously showed that physical activity may influence the Achilles tendon CSA (20); therefore, we made an attempt to control for level of physical activity. None of the subjects in either group had participated in regular sports activities throughout their lives, and their current physical activity level was confined to activities of daily living. None of the subjects in either group had any history of known Achilles tendon pathology, including acute or chronic tendinopathy and tendon rupture.
Isometric plantarflexion moment.—Left side maximal isometric plantarflexion moment was measured in a custom-made frame. Each subject was seated in a rigid steel frame with the knee fully extended and the hip flexed to 90° (Figure 1). The foot rested at a neutral position (90°) against an adjustable plate of steel. The heel of the foot rested on a surface that could be adjusted so that the mechanical axis of rotation approximately corresponded to the lateral malleolus. Force (in newtons) was registered with a strain gauge load cell attached between the plate and the steel frame. After positioning, the subjects performed three to five forceful plantarflexion efforts that served as warm-up contractions. Thereafter, two separate maximal voluntary contractions were performed. Each effort lasted approximately 4 seconds with a 1-minute rest between efforts. The trial with maximal peak force was used for data analysis. The force signals were sampled at 50 Hz by use of an analog-to-digital converter (DT 2801A, Data Translation, Marlboro, MA), and they were stored on a computer for subsequent analysis.

The external moment of force (N·m) about the ankle joint was obtained by multiplying the registered force by the external lever arm, which in turn can be converted to tensile force of the Achilles tendon ($F_t$) by the following equation: $F_t = M_a/a$, where $M_a$ is the moment of force (N·m) about the ankle, and $a$ is the internal Achilles tendon moment arm (meters).

Calculation of Achilles tendon moment arm.—Sagittal plane magnetic resonance (MR) images (GE Signa horizon LX 1.5T, T2-weighted fast spin echo (FSE), TR/TE [time to repeat/echo time]: 4000/88; field of view 12; matrix 256 × 192, slice thickness 3 mm) were obtained with the ankle in the neutral position (90°) to estimate the Achilles tendon moment arm, using a modified Reuleaux method (21). Briefly, the method assumes that the joint surface of the talus is circular and, by using geometric rules, obtains a center of rotation at a specific point distal to the joint surface of the talus. The tendon moment arm was obtained by measuring the perpendicular distance from the Achilles tendon to the center of rotation. The measurement of the moment arm from the MR images was performed three times for each subject and a mean was used as an estimate for the moment arm. The mean coefficient of variation for repeated measures across subjects has been shown to be 1.9% (17).

Measurement of tendon CSA.—Tendon CSA was obtained from MR images (T1 weighted SE, TR/TE: 400/15; field of view 12; matrix 512 × 512, slice thickness 6 mm), as shown in Figure 2. The CSA of the Achilles tendon was measured 3 cm proximal to the Achilles tendon insertion onto the calcaneus. This measurement site was chosen because it typically corresponds to the narrowest portion of the Achilles tendon (21). The measurement was performed three times for each subject and the mean was used as the CSA. The mean coefficient of variation for repeated measures across subjects was 3.4%.

Statistical analysis.—Two-tailed unpaired Student’s $t$ tests were used to examine if differences existed between the groups. An alpha level of 0.05 was considered significant. Results are reported as sample means ± SEM.

RESULTS

There were no significant differences between young and elderly women in either height or weight. The moment of force about the ankle joint was greater in young women (95 ± 17 N·m) than in elderly women (51 ± 5 N·m, $p < .05$). Achilles tendon CSA was significantly greater in elderly women than in young women; $p < .01$ (Figure 3A).
Achilles tendon stress in elderly women

The moment arm was similar in the young women (50.1 ± 0.13 mm) and in the elderly women (52.3 ± 1.3 mm). The absolute and weight-adjusted Achilles tendon force (p < .05) and stress (p < .01) were significantly lower in elderly women (Figures 3B and 3C). Tendon CSA was positively correlated to weight (r = .67, p < .05), and it approached a significant relationship to tendon force (r = .65, p = .056) for young women. The corresponding relationships could not be demonstrated for the elderly women (r = .24, r = .36).

Discussion

The principle findings of the present study were that young women were stronger than elderly women, as indicated by the greater maximal plantarflexion moment about the ankle joint. Correspondingly, the tensile force of the Achilles tendon was also greater in young women than in elderly women. However, despite the greater strength in the young women, the CSA of the Achilles tendon was larger in the elderly women, which also resulted in a markedly reduced tendon stress during maximal isometric loading of the triceps surae muscles. To our knowledge, the combination of reduced strength and a greater tendon CSA to yield a lower tendon stress in the Achilles tendon of elderly subjects has not previously been observed.

The data of the present study strongly suggest that age is accompanied by an increase in human Achilles tendon CSA, which to our knowledge has not been observed previously. Such an age-related hypertrophy of tendon is in accordance with animal data (18,19,22,23). Birch and colleagues (18) demonstrated that both physical activity and aging induced tendon hypertrophy in the horse. Similarly, Nakagawa and associates (19) demonstrated that the Achilles tendon in rabbits underwent hypertrophy with aging. The exact mechanism of such an age-related increase in tendon size remains unclear. It has previously been shown that the width, but not the CSA, of the Achilles tendon was greater in elderly (> 70 years) endurance and power sport athletes compared with that of age-matched controls (24). Further, it was recently shown that endurance-trained young subjects had a greater Achilles tendon CSA than that of untrained subjects (20). Increased tendon CSA in response to physical activity is in accordance with metabolic studies of human peritendinous tissue, in vivo (25,26). Together these studies suggest that physical activity likely results in a net collagen synthesis. The individuals in the present study were sedentary, but there was a significant albeit weak (r = .65) positive relationship between body weight and Achilles tendon CSA in young women, which does not exclude that the loading of activities of daily living influences tendon hypertrophy. However, it might still be somewhat surprising that the CSA of the tendon was greater in the present sample of elderly women compared with young women. It is therefore likely that factors other than mechanical loading influence tendon CSA. The effect of aging on the ratio of synthesis and degradation rate of human tendinous tissue remains unknown, but compensatory increases in collagen formation to counteract for age-related accumulation of advanced glycation end products and reduced tendon strength could play a role.

The safety factor, that is, the rupture stress divided by the stress during high loading activity, is ~8 for a majority of tendons (15), but it may be as low as 1–2 (16). We have recently shown that the safety factor for the Achilles tendon is ~4 for trained and ~2.6 for untrained subjects (20). If a tendon undergoes hypertrophy in response to increased physical activity or aging, it will effectively reduce the stress and thereby improve its mechanical safety factor. In the present study, elderly women had considerably reduced stress on the tendon during maximal isometric contractions. The safety factor for the young women was ~2.5, which is comparable with that of the untrained men. In contrast, the elderly women exhibited a pronounced increase in the safety factor (~5.7). Together the reduced maximal tendon force and the greater CSA lowered the tendon stress to less than 50% of that of young women, which may reduce the risk of tendon injury considerably. Although the intensity of physical activity diminishes with aging, it is plausible that the marked age-related augmentation in the safety factor contributes to the reduced injury incidence in the elderly population.

Figure 3. Mean ± SEM values for elderly (black bars) and young (white bars) women: A, Cross-sectional area of the Achilles tendon; B, Achilles tendon force; C, Achilles tendon stress. Significant difference from young women: *p < .05, **p < .01.

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In addition to reducing the average stress on the tendon, the increased CSA may also increase the stiffness (ΔN/Δm) of the tendon, such that it will require a larger force to produce a given elongation of the tendon. A change in the mechanical properties of the tendon may influence the contractile dynamics of muscle fibers: It has been suggested that increased tendinous stiffness will result in reduced sarcocereal shortening velocity for a given fixed-end (“isometric”) contraction, which in turn may augment force (27), and the rate of force development. Such an age-related change that potentially produces greater contractile force may be beneficial because the aging process is associated with significant muscle loss. It has also been suggested that the tendon contributes significantly to energy conservation during locomotion because muscle contraction force will stretch the tendon, which stores elastic energy that is subsequently released upon unloading (16, 28). An increased tendon CSA and stiffness would reduce tendon strain for a given load, and theoretically it would reduce energy elastic savings and increase the metabolic demand of locomotion.

In the present study the average plantarflexion strength in elderly women was markedly less than that of young women, which is in accordance with previous reports (22, 29). This observed 46% difference in plantarflexion strength is noteworthy, although it was not the primary intention of the study. It is well known that the aging process is associated with a decline in muscle mass, with a reduction in total number of individual muscle fibers, atrophy of surviving individual fibers, and changes in neural components of strength, which together result in loss of strength and function (30, 31). Importantly, such an age-related decline in plantarflexion strength may adversely affect propulsive power for locomotion and increase the risk of falls (31–33).

Conclusions

In conclusion, the present data demonstrate that young women can exert a greater force than elderly women on the Achilles tendon. Conversely, elderly women have an increased (22%) tendon CSA, and the lower tendon force and the greater tendon size combine to markedly lower tendon stress during maximal plantarflexion.

ACKNOWLEDGMENT

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REFERENCES


Received August 21, 2002
Accepted September 30, 2002
Decision Editor: James R. Smith, PhD