Phase-contrast MR imaging reveals age-associated differences in plantarflexor fascicle and aponeurosis behavior in isometric contractions

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Target Audience: Researchers of Sarcopenia, Muscuoskeletal Radiologists, Muscle Physiologists, Imaging Physicists.

PURPOSE: Musculoskeletal remodeling processes, affecting the internal arrangement of skeletal muscle fascicles and mechanical properties of collagenous tissues, such as tendons and aponeuroses, have been recognized as important determinants of significant muscle weakness at older age [1]. Our group has used velocity-encoded phase contrast (VE-PC) MRI for the simultaneous acquisition of morphological data and spatially registered functional information, to study human muscle-tendon units *in vivo*. Towards elucidating the causes behind the dramatic reduction of force in sarcopenia, this study aimed to assess and compare between young (*YW*) and senior (*SW*) women, using VE-PC techniques: (i) Contraction-associated changes in gastrocnemius medialis (GM) Muscle architecture, (ii) Aponeurosis strains and (iii) Achilles tendon material properties to elucidate the mechanics of aging in terms of the musculo-tendinous tissue dynamics.

METHODS: The lower (dominant) leg of six young (*YW*: age: 26.1±2.3 yrs) and six senior (*SW*: age: 76.7±8.3 yrs) female volunteers were scanned on a 1.5T GE MRI scanner in a supine, feet-first position. An MR-compatible foot pedal device allowed for computer-controlled plantar-flexions (PF) of the foot and measurement of force exerted [2]. These experiments were performed under isometric conditions during which subjects cyclically contracted (35% of MVC at ~2.5s) and relaxed their PF muscles at a fixed joint position of 10° of PF. The exerted force was (i) digitized and recorded for subsequent analysis, (ii) projected onto the magnet bore face as bio-feedback for the subject for better consistency of force production and, (iii) electronically differentiated to produce an EKG like trigger fed into the scanner for gating the ~70 phase-encoding repetitions required for image acquisition. High-resolution FSE images (TE/TR:: 12.9 / 925ms, NEX: 4, FA: 20°, slice thickness: 3 mm, contiguous, FOV: 30 × 22.5 cm, 512 × 384 matrix), covering (1) the GM from its origin to insertion into the myotendinous junction and (2) the Achilles tendon in its entire length, were acquired in the oblique sagittal plane under static conditions (Fig. 1). Subsequently, two single VE-PC slices (TE/TR:: 7.7 /16.4 ms, NEX: 2, FA: 20°, slice thickness: 5 mm, FOV: 30 × 22.5 cm cm, 256 × 192 matrix, 1 slice, 22 phases per cycle, 10 $cm \cdot s^{-1}$ 3D velocity encoding) were obtained in the same sagittal oblique planes with isometric contractions. Using the proximal FSE image, ROIs, denoting the endpoints of GM fascicles, were placed along the superficial and deep aponeurosis and then superimposed onto the corresponding VE-PC slice. The position of these ROIs was **tracked across all phases** of the contraction-relaxation cycle using an in-house MATLAB algorithm. Based on these coordinates, (i) fascicle lengths, (ii) aponeurosis segment lengths and strains and (iii) fascicle pennation angles were automatically calculated. The values measured in different positions along the GM's superior-inferior dimension were averaged to represent the GM behavior in its distal, middle and proximal region.

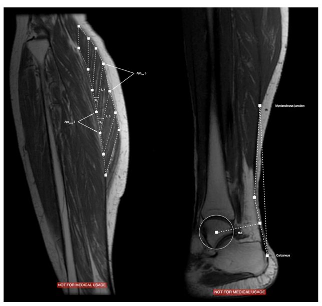
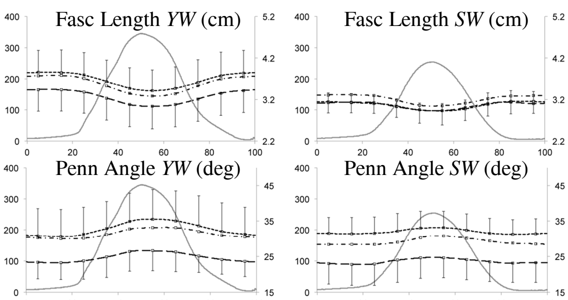
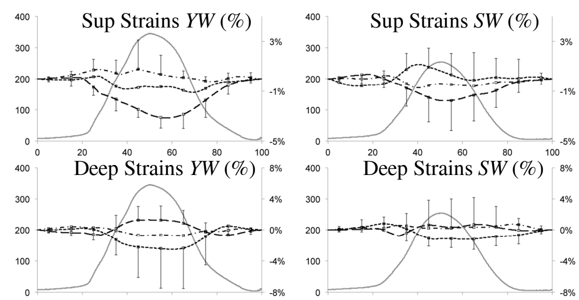


Figure 1. ROIs on FSE images.





On all graphs: x-axis is Cycle (%) and primary y-axis is Force (N). Distal: —— , Mid: — · —, Proximal: - - -

Figure 2 (4 images on left). Changes in fascicle length (top row) and pennation angles (bottom row). *YW* and *SW* shown on left and right, respectively.

Figure 3 (4 images on right). Strains along the superficial (top) and deep (bottom) GM aponeurosis. *YW* and *SW* shown on left and right, respectively.

On the distal image stacks, Achilles tendon length and strains were similarly acquired and used to calculate tendon stiffness and Young's modulus.

RESULTS: The fascicle shortening observed during muscular contraction was significantly greater in *YW* in the distal (*YW* -4 ± 1 mm vs. *SW* -2 ± 1 mm, p = 0.032), middle (*YW* -5 ± 1 mm vs. *SW* -3 ± 1 mm, p = 0.012) and proximal (*YW* -4 ± 2 mm vs. *SW* -2 ± 1 mm, p = 0.021) GM region. This greater fascicle shortening was also reflected in a trend towards greater fascicle strains in *YW* (distal: *YW* -12 ± 5% vs. *SW* -6 ± 5%, p = 0.065; middle: *YW* -12 ± 3% vs. *SW* -8 ± 4%, p = 0.050; proximal: *YW* -11 ± 4% vs. *SW* -7 ± 3%, p = 0.059). As opposed to the decrease in fascicle length, pennation angles increased during active contraction of the plantarflexor muscles in both age groups, with the changes being significantly larger in *YW* in both the distal (*YW* +3.2° ± 1.4° vs. *SW* +1.5° ± 0.9°, p = 0.033) and proximal (*YW* +4.5° ± 1.0° vs. *SW* +1.6° ± 0.9°, p < 0.001) muscle region. Aponeurosis strains were not significantly different between groups but displayed substantial heterogeneity along the GM's proximo-distal length. Some aponeurosis sections were found to elongate (positive strains), while others maintained their length or even shortened (negative strains) during contraction. Achilles tendon stiffness (*YW* 120.2 ± 52.3 $N \cdot mm^{-1}$ vs. *SW* 53.9 ± 44.4 $N \cdot mm^{-1}$, p = 0.040) and Young's modulus (*YW* 340.1 ± 163.3 MPa vs. *SW* 139.7 ± 130.5 MPa), derived as the slopes of the tendon's force-elongation and stress-strain relationships, were significantly larger in *YW*.

CONCLUSION: VE-PC MRI revealed substantial age-associated differences in musculo-tendinous tissue dynamics during isometric contraction of the PF muscles, that might explain the large decrease in force generated by seniors compared to young. Particularly noteworthy is that, at equal relative contraction intensity, changes in GM muscle architecture were smaller in *SW*, in spite of greater Achilles tendon elasticity. This finding challenges the classical view of serial alignment of muscles and tendons and indicates that factors other than tendon compliance (e.g. fascicle slack, architectural arrangement) strongly influence the degree of intramuscular strains during contraction. Moreover, finding of negative aponeurosis strains is unintuitive, since loaded elastic materials are expected to stretch. Modeling studies [3] and animal experiments [4] suggest that heterogeneous aponeurosis behavior may be related to regional differences in fascicle pennation angles and transversal aponeurosis deformation. **References:** [1] Narici, MV et al. (2007). Exerc Sport Sci Rev; [2] Sinha, S et al. (2012). JMRI; [3] Chi, SW et al. (2010). J Biomech; [4] Azizi, E et al. (2009). J Physiol (Lond.)