Human Achilles tendon plasticity in response to cyclic strain: effect of rate and duration

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Introduction

Tendons are highly sensitive for their mechanical environment and adapt to cyclic strain by changing either their material and/or morphological properties [1,2,4]. From a mechano-biological point of view, the magnitude, frequency, rate and duration of the applied strain affect the adaption of tendons. Earlier intervention studies of our research group showed that a high strain magnitude and low strain frequency applied to the Achilles tendon (AT) induced pronounced adaptive responses [3,4]. To the best of our knowledge, the effect of a controlled modulation of the strain rate and duration on human tendon adaptation in vivo has not been investigated yet and, therefore, was the purpose of the present study.

Methods

Two exercise interventions were conducted featuring a modification of the strain rate (n=14) and strain duration (n=12) of the AT in vivo. The participants exercised (14 weeks, 4 times a week, 5 sets, fig. 1D) on one leg according to a reference protocol, possessing a high strain magnitude (~6.5%) and a low strain frequency (0.17 Hz, 3 s loading, 3 s relaxation (4 times); fig. 1A), which was similiar to the protocol that induced the most superior adaptive effects of the AT mechanical and morphological properties in our earlier studies [3,4]. The other leg was either trained with a ~3 times higher strain rate (72 one-legged jumps, fig. 1B) or 4 times longer strain duration (1x 12s loading, fig. 1C) compared to the reference protocol. The strain magnitude and loading volume were similar in all three protocols (fig. 1A-C). A matched control group (n=13) remained inactive.

Before and after the interventions we examined the AT stiffness (mechanical property), Young's modulus (material property) and cross-sectional area (morphological property) by means of magnetic resonance imaging (fig. 2), ultrasonography and dynamometry to assess human tendon adaptive responses in vivo. The cross-sectional area was displayed for 10% intervals along the free AT length (fig. 2) to consider region-specific changes of the tendon morphology [1,3].

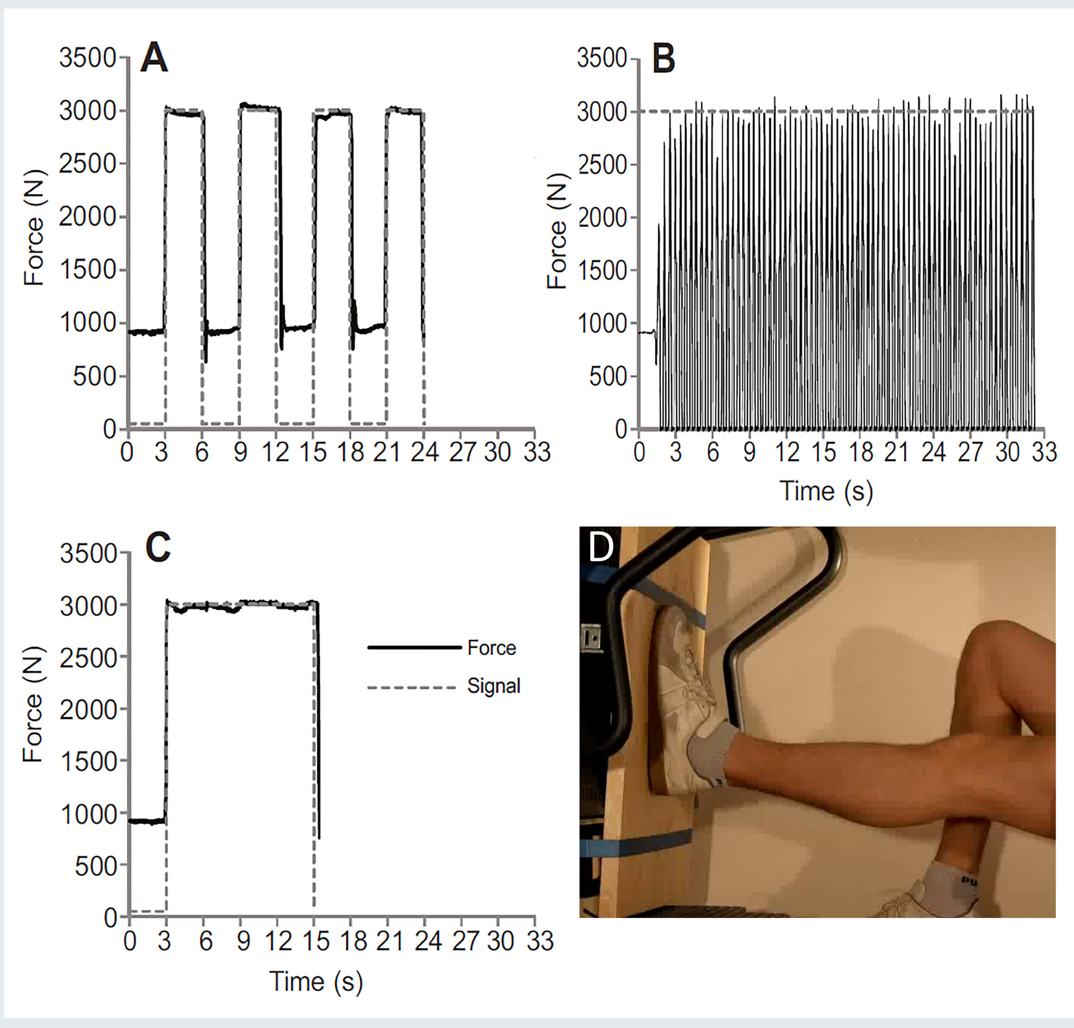

Fig. 1: Loading profiles of the A) reference protocol (4x 3 s loading, 3 s relaxation), B) the high strain rate protocol (72 one-legged jumps) and C) the long strain duration protocol (1x 12 s loading) of the two interventions (14 weeks, 4 d/week, 5 sets) featuring similar magnitude and exercise volume (integral of the plantar flexion force over time). Plantar flexion contractions at 90% maximal voluntary isometric plantar flexion force were used to induce high magnitude strain of the Achilles tendon (D).
Signal: signal displayed to the participants to control the magnitude and volume of loading.
Force: plantar flexion force over time exerted during exemplary exercise for one participant.

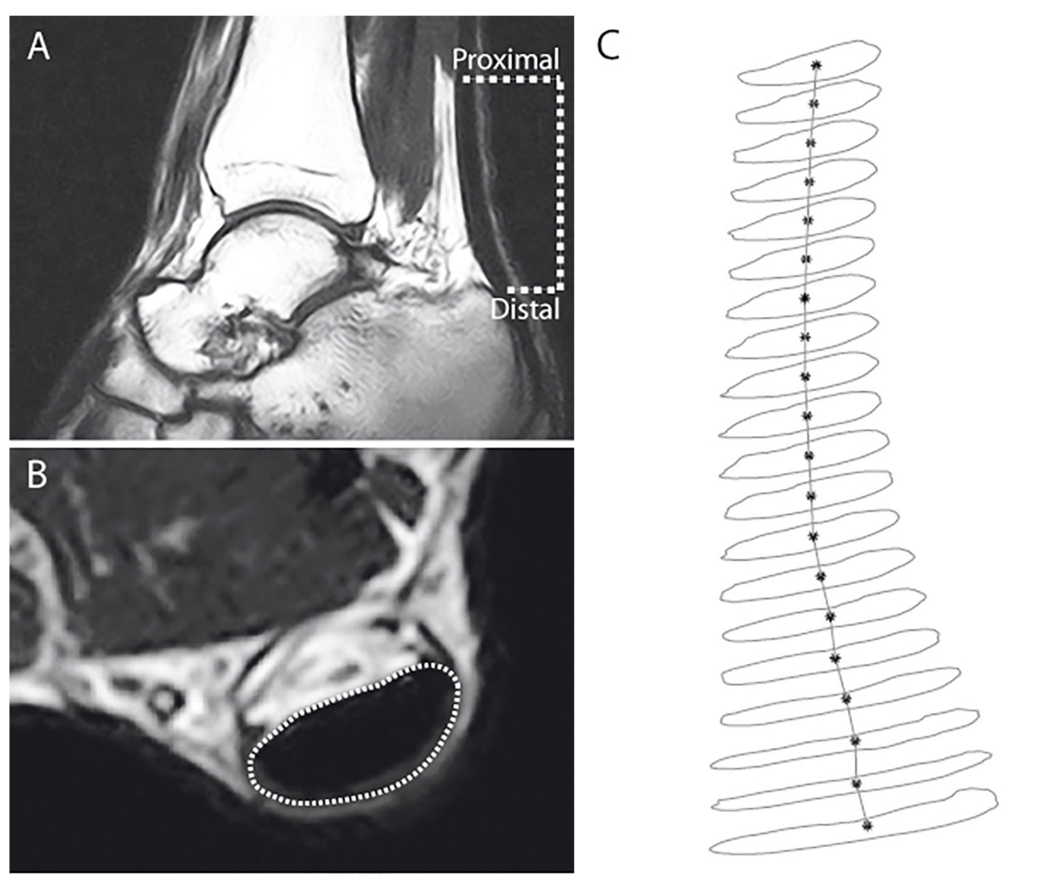

Fig. 2: Sagittal (A) and transverse (B) magnetic resonance images were used to investigate morphological free Achilles tendon properties (i.e. length and cross-sectional area; C).

Results

After the training using the reference and long strain duration protocol we found a significant increase ($p<0.05$) of the AT stiffness of 57% and 25% (fig. 3B), of the cross-sectional area of 4.2% and 5.3% (fig. 5B) and of the Young's modulus of 51% and 17% (fig. 4B), respectively. The increase of Young's modulus was more pronounced following the reference compared to the long strain duration protocol ($p<0.05$, fig 4B). Although a region-specific hypertrophy of the AT was also detected after the high strain rate training (fig. 5A), AT stiffness (fig. 3A) and Young's modulus (fig. 4A) increased only by tendency ($p=0.08$ and $p=0.09$, respectively). The control group did not show any changes ($p>0.05$,

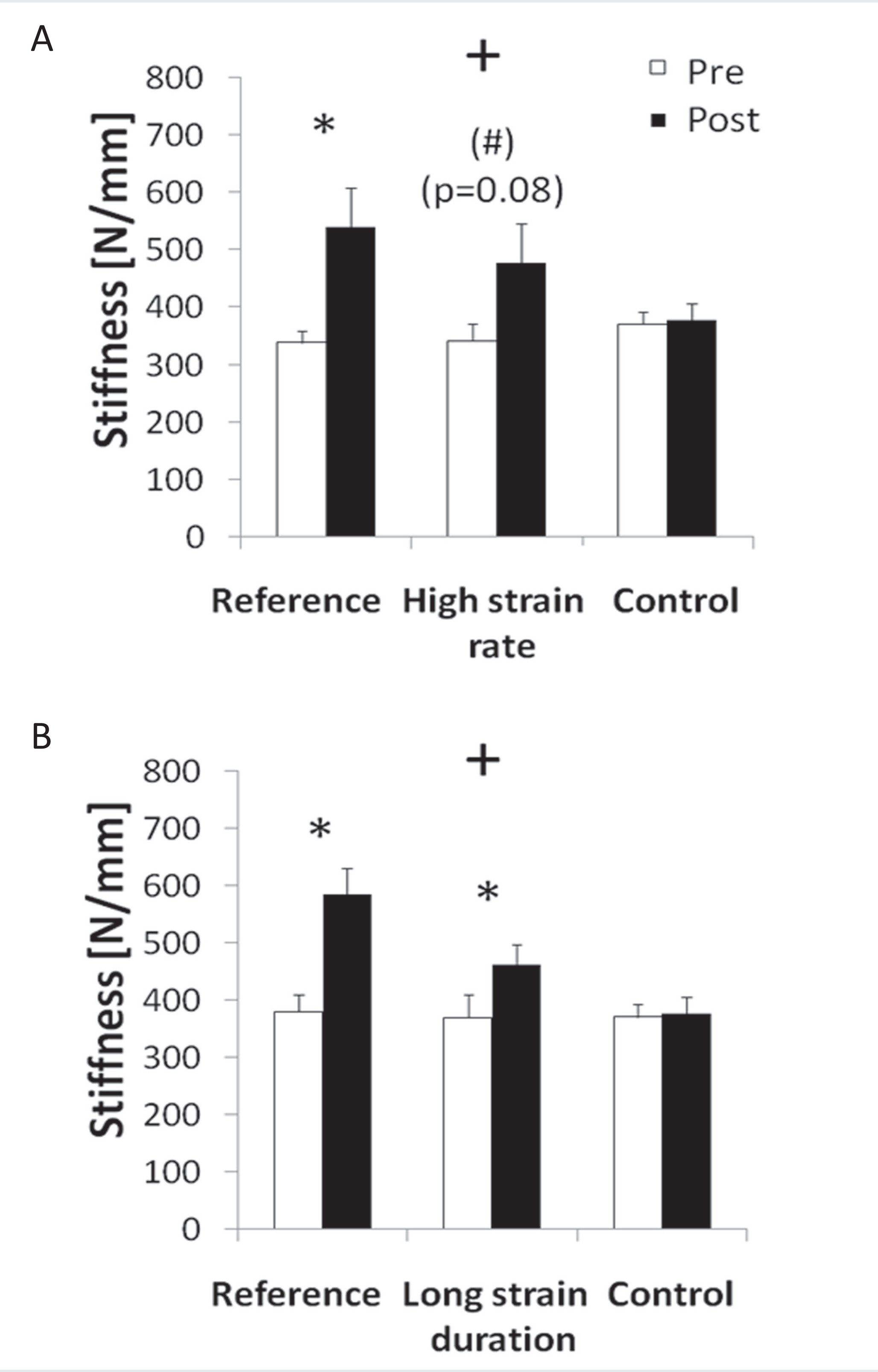

Fig. 3: Mean stiffness values and s.e.m. (error bars) of the Achilles tendon before (Pre) and after (Post) the A) intervention I featuring the reference and high strain rate protocol and B) the intervention II possessing the reference and long strain duration protocol as well as for the control group (A and B).
+ : statistically significant interaction of intervention and protocol ($p<0.05$). The post hoc comparison regarding intervention I showed a significant increase ($p<0.05$) only in the reference protocol (A) and for intervention II an increase following both exercise protocols and a pronounced increase following the reference protocol ($p<0.05$, B)
* : statistically significant difference from the Pre values ($p<0.05$)
(#) : tendency towards a difference to the Pre values ($p=0.08$)

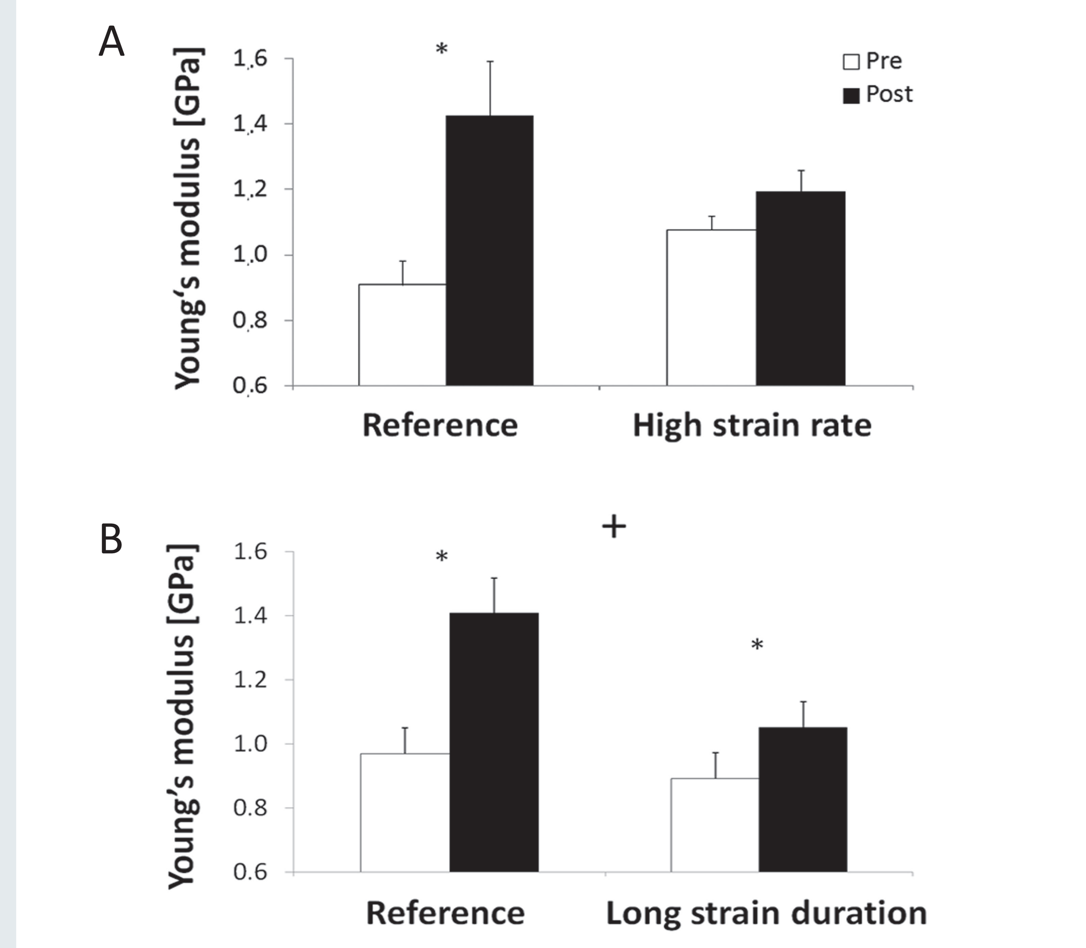

Fig. 4: Mean Young's modulus values and s.e.m. (error bars) of the Achilles tendon before (Pre) and after (Post) intervention I (A) and II (B).
+ : statistically significant interaction of intervention and protocol ($p<0.05$). The post hoc comparison indicated a significant increase ($p<0.05$) only in the reference protocol (B)
* : statistically significant difference from the Pre values ($p<0.05$)

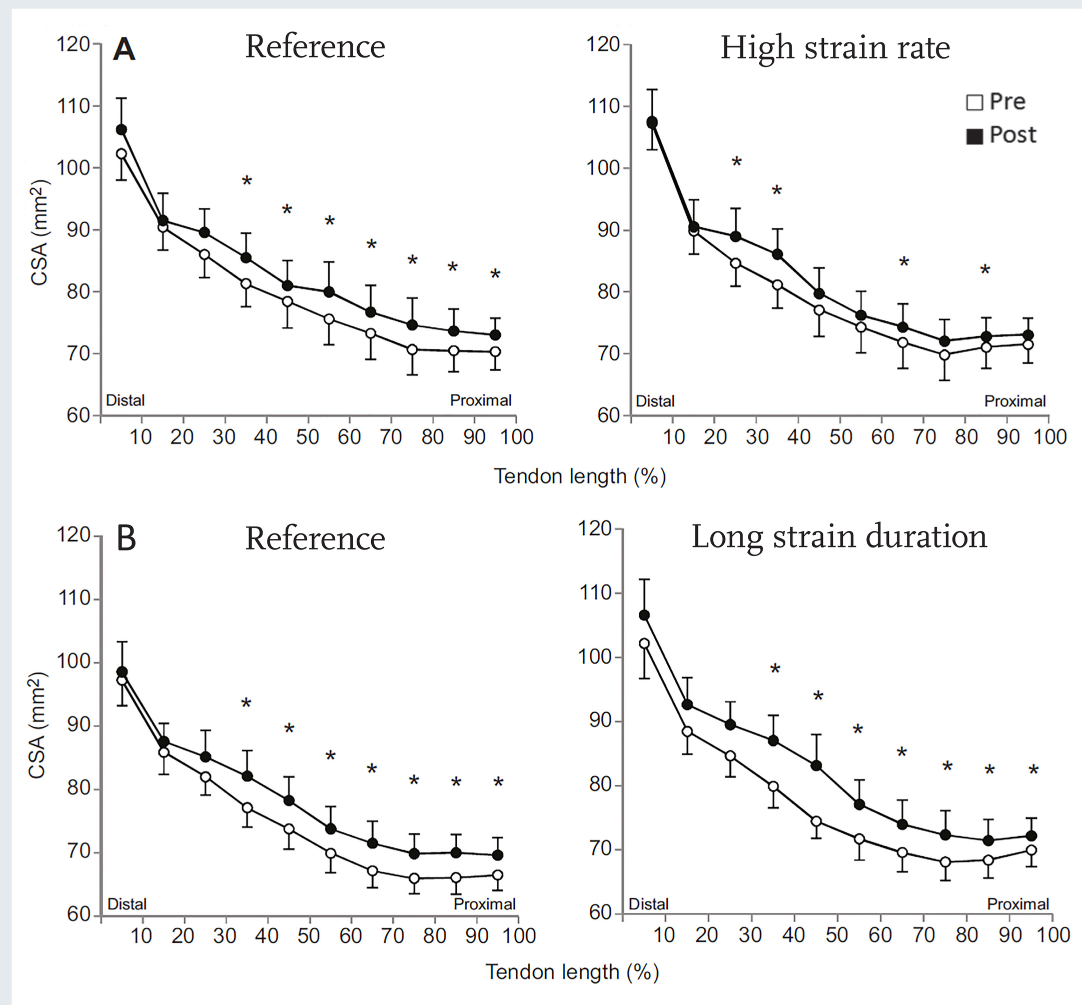

Fig. 5: Mean cross-sectional area and s.e.m. (error bars) of the Achilles tendon in 10% intervals of the tendon length before (pre) and after (post) intervention I (A) and II (B).
* : Statistically significant difference between the pre and post values ($p<0.05$)

Conclusions

Our results provide evidence that repetitive (3s loading, 3s relaxation) high strain magnitude loading causes the most pronounced adaptive responses of the AT material and morphological properties compared to a higher rate and longer duration of strain in young healthy male adults. Therefore, we can conclude that a high strain magnitude, an appropriate strain duration and repetitive loading are essential components of an efficient training stimulus for tendons. This finding may important in the context of athletic performance improvement as well as prevention and rehabilitation of tendon injuries.

References

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