ADAPTATIONS IN TRICEPS SURAE MUSCLE-TENDON UNIT MECHANICAL PROPERTIES IN ELITE JUMPERS

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The purpose of this study was to analyse the triceps surae (TS) muscle-tendon unit (MTU) mechanical properties (muscle strength, maximal tendon strain and tendon stiffness) in elite track and field jumpers (long jump, triple jump, high jump, pole vault) over several years, in order to examine potential alterations in the uniformity of adaptation within the TS MTU. The findings demonstrated a higher TS muscle strength and tendon stiffness for the take-off leg in comparison to the swing leg, irrespective of the jumping discipline. Similar symmetry indexes for muscle strength and tendon stiffness indicated to a uniform TS MTU adaptation in healthy elite track and field jumpers. Longitudinal investigation demonstrated greater fluctuations in TS MTU properties over one year in elite jumpers compared to age-matched controls, predominantly for the take-off leg, irrespective of the training period (preparation vs. competition period). Nevertheless, athletes with lower adaptive similarities between muscle and tendon adaptation may experience temporary increased demand on the tendon and potentially be at greater risk for tendon injuries.

KEYWORDS: tendon stiffness, muscle strength, training adaptation, elite athletes

INTRODUCTION:

Similar to every other living tissue, also tendons are capable to respond to mechanical loading in order to regulate their homeostasis by changing their material and morphological properties. Accordingly, it is not surprising that repeated exposure of human muscle-tendon units (MTUs) to increased mechanical loading (e.g. resistance exercise) leads not only to improvements in muscle strength but also to accompanied increases in tendon stiffness (Arampatzis et al., 2007, Kongsgaard et al., 2007, Kubo et al., 2001). Due to the relatively constant ultimate strain, the modifications in tendon stiffness can be seen as tendon's protective mechanism to preserve its homeostasis to increased functional demand placed upon them due to greater muscle strength. Nevertheless, the relationship between improved strength and alterations in tendon mechanical properties has repeatedly shown to be rather moderate, which can be explained due to differences between muscle and tendon responsiveness and time course to mechanical stimuli (Arampatzis et al., 2007, Kubo et al., 2012) as well as the generally lower tissue turnover in tendons (Heinemeier et al., 2013). Therefore, external mechanical loading such as training could lead to an imbalance between the exerted force by the muscle and the resistance of the tendon transmitting those forces, placing the latter under a higher mechanical demand (i.e. greater tendon strain).

In particular, the Achilles tendon seems to be predisposed to injuries (Janssen et al. 2018) possibly due to its relatively low safety factor in comparison to other tendons (Ker et al. 1988). Therefore, the aim of the current longitudinal investigation was to monitor exercise-induced alterations in triceps surae (TS) muscle strength and tendon stiffness (and strain) of both legs in elite track and field jumpers (pole vault, long, high and triple jump) over several years of athletic training and competition in order to detect possible non-uniformities within the TS MTU due to habitual loading.

METHODS:

Sixty seven young (mean age and standard deviation: 23±4 yrs) elite international level track and field jumpers (35 male and 32 female; high jumpers, long jumpers, triple jumpers, pole vaulters) took part in a nationwide study on the TS MTU adaptation. In all participating athletes the maximal ankle plantar flexion moment, maximal AT strain and AT stiffness were quantified in both legs using synchronous dynamometry and ultrasonography with a mobile device

(TEMULAB®, Protendon GmbH & Co. KG, Aachen, Germany) as a part of daily training session at their respective training venues. The analysis methods for determining TS MTU mechanical properties have been described more precisely in a previous study (Ackermans et al., 2016). TS MTU intra-limb uniformity was examined by calculating the symmetry indexes in the TS muscle strength and tendon stiffness between the take-off and swing limb as in Robinson et al. (1987):

$$SI = \frac{X_{Takeoff} - X_{Swing}}{\frac{1}{2}\left(X_{Takeoff} + X_{Swing}\right)} \times 100\%$$

where $X_{Takeoff}$ is the parameter from the take-off limb and X_{Swing} the associated parameter from the swing limb. A subset (n=19) of the analysed elite athletes were measured regularly (every ~4 weeks) over a timespan of one year and compared to age-matched young adults. The uniformity of muscle and tendon adaptive changes over the time period were analysed using the individual residuals in muscle and tendon properties and by forming cosine similarity (CS) of the relative changes between the individual measurement sessions (Mersmann et al., 2016). In addition, seven of the analysed elite athletes were monitored over a longer time period (four consecutive seasons) to detect possible differences between the preparation and competition periods. For a cross-sectional investigation a three-way repeated measures analysis of variance (ANOVA) with the leg (swing vs take-off leg) and discipline (high jump, triple jump, long jump, pole vault) and sex (male vs. female) as factors was conducted to investigate potential group- and leg-specific differences in the obtained TS MTU mechanical properties. Bonferroni post hoc comparison was performed in the case a significant main effect or interaction was found.

RESULTS:
Regardless of sex and discipline, the take-off leg of the analysed jumpers demonstrated a significantly higher (P<0.05) TS muscle strength and tendon stiffness. Despite these inter-limb differences the symmetry indexes of TS muscle strength (5.9±9.4%) and tendon stiffness (8.1±11.5%) were comparable. These results were accompanied by a significant (r=0.44, P<0.01; n=67) correlation between the symmetry indexes of TS muscle strength and tendon stiffness (Fig. 1).

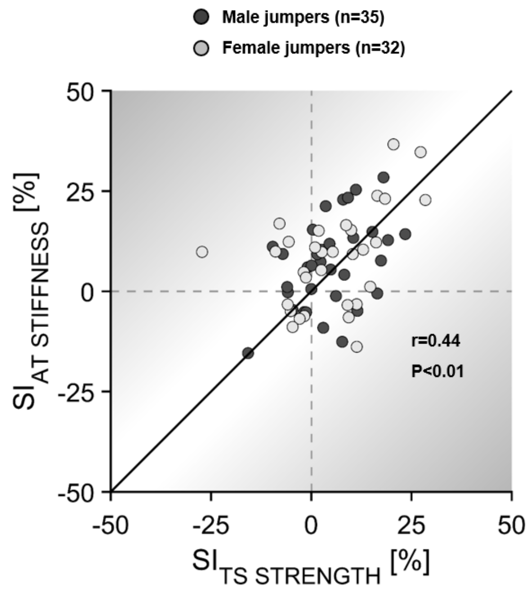

Figure 1: Correlation between the symmetry index of the maximal ankle plantar flexion moment ($SI_{TS\ STRENGTH}$) and Achilles tendon stiffness ($SI_{AT\ STIFFNESS}$) in all analysed athletes. A positive symmetry index demonstrates a higher value for the take-off leg and a negative symmetry index for the swing leg.

Furthermore, in both limbs significantly higher residuals ($P<0.05$) were detected for TS muscle strength over time and tendencies for greater residuals in tendon stiffness and maximal tendon strain for the take-off leg when compared to age-matched controls. In addition, take-off leg showed significantly ($P<0.05$) lower cosine similarity than the controls. No training period (preparation vs competition period) differences were identified in the residuals in TS muscle strength, maximal tendon strain or tendon stiffness.

DISCUSSION:
The results of the current study demonstrate leg-specific differences in both TS muscle strength the AT stiffness to years of habitual training in healthy young elite track and field jumpers, with greater values for the take-off leg in comparison to the swing leg, indicating to a diverse habitual mechanical loading between the limbs. When examining the uniformity of muscle and tendon adaptation, we detected similar symmetry indexes in TS muscle strength and tendon stiffness as well as a supporting significant but moderate correlation ($r=0.44$, $P<0.01$) between these symmetry indexes, independent of sex. This could indicate that intra- and inter-limb alterations in muscle strength throughout the athletic training may not always be followed by comparable adaptive changes in tendon stiffness, thus leading to possible discordances between muscle and tendon properties in some elite athletes (Fig 1).
The longitudinal investigation of the uniformity of adaptation in TS MTU mechanical properties over 1 year demonstrated higher fluctuations in muscle strength over time in both of the limbs and tendencies for greater fluctuations in tendon stiffness and maximal tendon strain for the take-off leg, along with lower adaptive similarities between muscle strength and tendon stiffness. When separating the athletes into two groups based on the cosine similarity, we detected even higher fluctuations of muscle strength and tendon stiffness as well as maximal tendon strain in the low cosine similarity group (low similarity between adaptation in muscle strength and tendon stiffness). This suggests that repetitive plyometric and habitual mechanical loading experienced during athletic training and competitions in elite track and field jumpers may affect the uniformity within TS MTU, possibly leading to a temporary higher demand on the AT. However, when dividing the athletic season in preparation and competitive periods, we did not detect any differences between the periods in the fluctuations in muscle strength and tendon stiffness nor in cosine similarity over time (seven athletes over 4 years), irrespective of the analysed leg.

CONCLUSION:
Habitual mechanical loading during training and competition in elite track and field jumpers leads to inter-limb differences in TS muscle strength and tendon stiffness, however these potentially different mechanical loading profiles between limbs seems not to cause a detectable discordance within the TS MTU. Longitudinal findings suggest that most elite jumpers demonstrate greater fluctuations but similar adaptation in muscle and tendon properties (more pronounced in the take-off leg), irrespective of the training period (preparation vs. competition period). Nevertheless, athletes with a lower adaptive similarities between muscle and tendon adaptation may experience temporary increased mechanical demand on the tendon and potentially be at greater risk for tendon injuries.

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