Evidence that ageing does not influence the uniformity of the muscle-tendon unit adaptation in master sprinters

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Abstract

Differences in the adaptation processes between muscle and tendon in response to mechanical loading can lead to non-uniform mechanical properties within the muscle-tendon unit (MTU), potentially increasing injury risk. The current study analysed the mechanical properties of the triceps surae (TS) MTU in 10 young (YS; 22 ± 3 yrs) and 10 older (OS; age 65 ± 8 yrs; i.e. master) (inter)national level sprinters and 11 young recreationally active adults (YC; 23 ± 3 yrs) to detect possible non-uniformities in muscle and tendon adaptation due to habitual mechanical loading and ageing. Triceps surae muscle strength, tendon stiffness and maximal tendon strain were assessed in both legs during maximal voluntary isometric plantarflexion contractions via dynamometry and ultrasonography. Irrespective of the leg, OS and YC in comparison to YS demonstrated significantly ($P < 0.05$) lower TS muscle strength and tendon stiffness, with no differences between OS and YC. Furthermore, no group differences were detected in the maximal tendon strain (average of both legs: OS 3.7 ± 0.8%, YC 4.4 ± 0.8% and YS 4.3 ± 0.9%) as well as in the inter-limb symmetry indexes in muscle strength, tendon stiffness and maximal tendon strain (range across groups: –5.8 to 4.9%; negative value reflects higher value for the non-preferred leg). Thus, the findings provide no clear evidence for a disruption in the TS MTU uniformity in master sprinters, demonstrating that ageing tendons can maintain their integrity to meet the increased functional demand due to elite sports.

Introduction

Running maximally requires high mechanical power and energy outputs at the lower extremity joints (Bobbert et al., 1986; Stefanyshyn and Nigg, 1998). Accordingly, enhanced capacities of the leg-extensor muscle-tendon units (MTUs), in which muscle and tendon act as a functional powering unit, are needed to improve performance at maximal running intensity. These leg-extensor MTU capacities are however directly influenced by various age-related structural and functional degenerative changes (Kjaer, 2004; Komatsu et al., 2004; Noyes and Grood, 1976; Stenroth et al., 2012; Vogel, 1991).

In general, long-term exercise-induced gains in muscle strength are usually accompanied by similar increases in tendon stiffness in both younger (Arampatzis et al., 2010, 2007a, 2007b; Bohm et al., 2014; Kongsgaard et al., 2007; Kubo et al., 2012, 2001) as well as in older adults (Epro et al., 2017; Karamanidis et al., 2014; Reeves et al., 2003). Such similar modifications in tendon stiffness could be a protective mechanism in response to the increased functional demand due to higher muscular forces. Nevertheless, the adaptation processes between muscle and tendon differ in the responsiveness to mechanical loading (Arampatzis et al., 2010, 2007a). Muscles respond to a large range of mechanical stimuli (Moss et al., 1997; Schoenfeld et al., 2016), whereas tendon adaptation occurs predominantly through high mechanical load causing high tendon strain over extended time durations (Arampatzis et al., 2010, 2007a; Bohm et al., 2014). Therefore, tendon strain duration is suggested to be the central aspect for tendon adaptation (Arampatzis et al., 2020). This is relevant for sprinting athletes who experience high mechanical loads during their daily exercise regime and competition. In essence, sprint running is a form of high magnitude mechanical loading; however, the high forces may occur over too short contact times to lead always an effective tendon adaptation, i.e. to increase its stiffness. Further, a lack of adaptation in the tendinous tissue has been displayed in response to plyometric loading regimens (Burgess et al., 2007; Kubo et al., 2007), especially in adolescent athletes (Mersmann et al., 2016). Arguably, from a biomechanical perspective, an improvement in muscle strength without accompanied adaptive changes in tendon stiffness (non-uniform adaptation) may heighten the experienced tendon strain and hence increase the mechanical demand on the tendon (Arampatzis et al., 2020; Mersmann et al., 2017), which could potentially lead to a higher risk for tendon overuse injuries.

The Achilles tendon (AT) in particular is highly susceptible to injury arguably due to its low safety factor, i.e. relationship between ultimate and operating stress (Ker et al., 1988; Magnusson et al., 2001). Thus, it is not surprising that elite sprinters and endurance runners are more susceptible to the onset of Achilles tendinopathy (Janssen et al., 2018), which indicates that the injured athletes may have an increased tendon strain under load and hence lowered tendon stiffness (Arya and Kulig, 2010). Moreover, the occurrence of Achilles tendon injuries (tendinopathies and ruptures) at least in men seems to increase with ageing (Huttunen et al., 2014; Taunton et al., 2002). Indeed, aged tendons seem to be diminished in re-establishing normal cellular tensional homeostasis after exercise-induced increased elongation (Lavagnino et al., 2014), which may alter tendon’s mechanobiological environment and lead ultimately to pathological changes, i.e. tendinopathy (Arnoczky et al., 2007). In agreement with this, Ackermans et al. (2016) findings suggests that the acute adaptive response of the AT following cyclic mechanical loading (e.g. following a half marathon run) may be age dependent in long-distance runners. Even though in general long-term habitual loading in younger sprinters as well as jumpers tends to increase both triceps surae (TS) muscle strength as well as tendon stiffness (Arampatzis et al., 2007b; Epro et al., 2019), there are indications of that this training regime seems ineffective in modifying tendon stiffness with advancing age (Stenroth et al., 2016). Given that ageing affects tendon homeostasis and extracellular matrix remodelling (Guzzoni et al. 2018) and is regarded as a potential risk factor for tendon overuse injuries (Huttunen et al., 2014; Taunton et al., 2002), suggests that ageing in combination with habitual athletic training may interrupt the uniformity within the TS MTU and could have implications for both performance and injury in master (older) athletes.

The purpose of the current study was to investigate TS MTU biomechanical properties in elite healthy young sprinters, master sprinters and recreationally active young adults (young controls) in order to detect potential non-uniformities in muscle and tendon adaptation due to habitual mechanical loading and ageing. It was hypothesised that master sprinters will demonstrate reduced TS MTU capacities and greater non-uniformities in muscle-tendon adaptation in comparison to younger sprinters and young controls.

Materials and Methods

Ten young male adult elite sprinters (age: 22 ± 3 years, body mass: 82 ± 5 kg, body height: 187 ± 6 cm; 100 m best time in the last 2 years: 10.80 ± 0.33 s; mean ± SD) and ten male master sprinters (age: 65 ± 8 years, body mass: 77 ± 8 kg, body height: 177 ± 5 cm; 100 m best time in the last 2 years: 13.78 ± 0.85 s), competing at national or international level for the last 6 years, took part in the study. The personal best time of both groups is similarly approximately 11% lower in relation to the current age-group world record. In addition, eleven young recreationally active male adults (age: 23 ± 3 years, body mass: 81 ± 5 kg, body height: 184 ± 6 cm; 100 m best time in the last 2 years: 13.1 ± 0.7 s hand timing) were recruited as a control group. Exclusion criteria were any previous AT ruptures and problems (tendinopathy etc.) within a 6 month period prior to testing. Ethics approval was obtained from the responsible Ethics Committee of the German Sport University Cologne and all participants provided their written informed consent in agreement with the Declaration of Helsinki. The TS MTU mechanical properties (maximal ankle plantarflexion moment and TS tendon stiffness) of all participants were assessed in both legs, directly before or during the competition period. The lead leg in sprint start was defined as the preferred leg, whereas the contralateral leg was defined as the non-preferred leg.

One week following a familiarisation session, the TS MTU mechanical properties were examined using simultaneous ultrasonography and dynamometry on a custom-made device as described in more detail in a previous study (Ackermans et al., 2016). Briefly, each participant was seated with their lower leg fixed with the foot placed on a custom-made strain gauge type dynamometer (Fig. 1; TEMULAB®, Protendon GmbH & Co. KG, Aachen, Germany). Participants then performed an individualised warm-up, followed by a 2–3 min standardised warm-up program (both sub-maximal and maximal contractions) to pre-condition the tendon (Maganaris, 2003).

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The maximal ankle plantarflexion moment and the force–elongation relationship of the tendon~~,~~ were determined using isometric plantarflexion contractions at different force levels: three maximal voluntary ankle plantarflexion contractions and three sustained contractions with visual feedback at 30, 50 and 80% of the maximal joint moment. The resultant ankle joint moments were calculated using inverse dynamics, considering the gravitational moments from a prior passive measurement. The AT force was determined by dividing the resultant ankle joint moment by the tendon moment arm acquired from previous literature (Maganaris et al., 1998). The elongation of the myotendinous junction of the m. gastrocnemius medialis was analysed during sustained contractions using a linear array ultrasound probe (27 Hz; MyLab™One, Esaote; Genoa, Italy) and TEMULAB® software (Fig. 1). The resultant tendon elongation was then normalised to the tendon's resting length to obtain tendon strain values (Fig. 1). Linear extrapolation of the elongation at 50 and 80% target joint moments were used to calculate the tendon elongation at maximal (100%) ankle joint moment (Ackermans et al., 2016; Epro et al., 2019). The TS tendon stiffness was determined as the ratio between the estimated tendon force and the resultant tendon elongation between 30% and 80% of maximum tendon force.

In order to further analyse the inter-limb symmetry, the symmetry indexes (Robinson et al., 1987) of TS muscle strength, tendon stiffness and maximal tendon strain were calculated between the preferred and non-preferred leg as follows:

$$Symmetry\ Index = \frac{X_{PrefLeg} - X_{NonPrefLeg}}{\frac{1}{2}\left(X_{PrefLeg} + X_{NonPrefLeg}\right)} \times 100\%$$

where $X_{PrefLeg}$ is the parameter from the preferred leg and $X_{NonPrefLeg}$ the corresponding parameter from the non-preferred leg. Symmetry index value close to zero indicates an inter-limb symmetry in the corresponding parameter, with a positive symmetry index denoting a greater value for the preferred leg and negative symmetry index vice versa for the non-preferred leg.

A two-way analysis of variance (ANOVA) was performed to investigate potential leg- and group differences in TS muscle strength, tendon stiffness and maximal tendon strain. Possible group-differences in the symmetry indexes of TS MTU properties were analysed using a one-way ANOVA. In case of a significant interaction a Bonferroni post hoc comparison was performed. In addition, the partial eta squared (η_p^2) as normalised effect size measure was calculated in order to evaluate the strength of potential group-effects, with values higher than 0.01 denoting small, 0.06 moderate and 0.14 large effects (Cohen, 2013). All statistical analyses were done using SPSS (v26.0; IBM Corp., USA) with the level of significance set at $\alpha = 0.05$. All data in the text as well as in the figures are presented as means and standard deviation (SD).

Results

A significant group effect ($P < 0.001$, $\eta_p^2 = 0.555$; Fig. 2) was detected in TS muscle strength, with master sprinters ($P < 0.001$) and recreationally active young adults ($P = 0.001$) demonstrating lower values in comparison to the younger sprinters. Similarly, a significant group effect ($P < 0.001$, $\eta_p^2 = 0.427$; Fig. 2) was revealed for the TS tendon stiffness, with lower values observed in the master sprinters ($P < 0.001$) and recreationally active young adults ($P = 0.003$) in comparison to the young sprinters. However, no significant group differences were detected in the maximal TS tendon strain (average values and SD for both legs: master sprinters 3.7 ± 0.8 % vs. recreationally active young adults 4.4 ± 0.8 % vs. young sprinters 4.3 ± 0.9 % respectively; Fig. 3). Moreover, the above differences between groups were independent of the analysed leg (no evident group x leg interaction). Regarding the analysis of the TS MTU inter-limb symmetry, no significant group-differences were detected in the symmetry indexes of the TS muscle strength (4.7 ± 15.1, –1.0 ± 10.9 % and –0.9 ± 11.5), tendon stiffness (4.9 ± 19.4, 3.4 ± 16.0 and –0.6 ± 15.4 %) and maximal tendon strain (–2.6 ± 16.0, –5.8 ± 17.5 and –2.4 ± 12.1 %) respectively between master sprinters, recreationally active young adults and young sprinters.

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----------------- Insert Figure 3 -----------------

Discussion

The current study examined the TS MTU biomechanical properties in elite healthy young sprinters, master sprinters and recreationally active young adults in order to detect potential non-uniformities in muscle and tendon adaptation due to mechanical loading and ageing. Our hypothesis could not be confirmed as we did not identify any non-uniformities in TS MTU adaptation, because the master sprinters did not display significantly higher tendon strain during the maximum plantarflexion contractions or greater inter-limb asymmetries in MTU mechanical properties.

Long-term habitual athletic training has generally demonstrated to effectively enhance both TS muscle strength as well as tendon stiffness in younger sprinters (Arampatzis et al., 2007b), but not modify tendon stiffness in master sprinters (Stenroth et al., 2016). One could suggest that the latter may interrupt the uniformity within the MTU, which would be potentially indicated by an increased maximal tendon strain; an established biomechanical marker and main indicator for non-uniform MTU adaptation (Arampatzis et al., 2020; Mersmann et al., 2017). However, the current cross-sectional investigation does not provide evidence to support the assumption that habitual high mechanical loading in master sprinters may lead to an inhomogeneous adaptation within the TS MTU. Although we found a main group effect on TS MTU mechanical properties, no disruption in the uniformity in muscle strength and tendon stiffness adaptation was evident in the master or young sprinters as no subject group differences were detected in the level of tendon strain during maximum plantarflexion contractions. Thus, cumulative habitual loading does not necessarily lead to non-uniform adaptation within the TS MTU and the changes in muscle strength seem to be accompanied with relatively similar modifications in tendon stiffness even in old age, as seen in previous resistance training interventions (Epro et al., 2017; Karamanidis et al., 2014; Reeves et al., 2003). This seems also evident from the average percentage difference in TS muscle strength (~42%) and tendon stiffness (~29%) between the young and master sprinters, which is similar to previous studies analysing non-active younger and older adults (for review see: McCrum et al., 2018). The similar TS MTU properties between master sprinters and young recreational adults indicate that master sprinters seem to partially counteract the typically shown age-related deteriorations in muscle strength and tendon stiffness (McCrum et al., 2018). Moreover, the symmetry indexes were comparatively low for all investigated MTU parameters (range across groups: –5.8 to 4.9%) with no differences between subject groups indicating that habitual athletic training in old age seems not to disrupt the inter-limb adaptive changes in TS MTU mechanical properties. Thus, this rather uniform TS MTU adaptation suggests that tendon's ability to adapt and withstand the increased demand is not necessarily disrupted even due to the two-fold effect of ageing and habitually increased mechanical loading.

The above findings rely on the examinations of both legs and irrespective of the analysed group muscle strength and tendon stiffness did not significantly differ between the preferred and non-preferred leg. Furthermore, the symmetry indexes in muscle strength and tendon stiffness as well as in maximal tendon strain were close to zero across all groups, suggesting that a general transferability from the TS MTU mechanical properties to the contralateral leg (i.e. preferred to the non-preferred leg) seems legitimate when analysing a group of young adult or master sprinters. However, even if on average the symmetry indexes where rather low at the group level, the relatively high standard deviation within each group suggests that potential limb-differences need to be considered when analysing TS MTU mechanical properties, as previously recommended in healthy recreationally active adults (Bohm et al., 2015). Hence, despite the rather cyclic nature of sprinting and relatively uniform inter-limb TS MTU properties at a group-level, from an individual perspective future investigations should consider both limbs also in sprinters, as disruptions in the fine-tuned interactions within the MTU cannot be excluded in elite athletes (Karamanidis & Epro, 2020).

It is important to note that the current study implemented generic AT moment arms at same ankle joint configuration from previous literature (Maganaris et al., 1998), which has direct implications for our calculated tendon stiffness values in absolute terms. However, although we cannot exclude differences in the AT moment arms between the analysed groups, this potential drawback will not affect our observation of similar maximal tendon strain values across groups. In addition, one might argue that the generated maximal moments do not reflect the maximal muscle force potential of the subjects because we did not consider the activation deficit of the TS nor place the MTU at an optimal length to generate its highest force (Creswell et al. 1995). While these drawbacks will affect the measured maximal joint moment (and tendon strain) in absolute terms, we believe they do not significantly affect the main outcomes concerning our subject group comparison, because the difference in activation level of the TS between young and older adults is merely 4% (Mademli & Arampatzis, 2008) and there is no clear evidence for an age-related change in the shape of the joint moment-angular relationship during MVC (Karamanidis and Arampatzis, 2005). One might argue that the study might have been underpowered to detect differences in muscle-tendon uniformity on the group level. However, it is important to note that next to the missing group-differences in tendon strain, the analysis revealed equally high partial eta squared values in TS muscle strength ($\eta_p^2 = 0.555$) and tendon stiffness ($\eta_p^2 = 0.427$) group-comparisons. Furthermore, the current cross-sectional investigation was performed at a specific time period (directly before or during the competition period), therefore missing potential contrasting fluctuations in TS MTU mechanical properties due to different phases in athletic training.

In conclusion, the current findings provide no clear evidence for a disruption in the TS MTU uniformity in master sprinters, demonstrating that ageing tendons can maintain their integrity to meet the increased functional demand due to elite sports. Future studies should investigate whether potential training-induced fluctuations in TS MTU mechanical properties over an athletic season in master athletes may provoke non-uniformities in muscle and tendon adaption, which can have potential implications for MTU overuse injuries.

Conflict of Interest Statement

KK has equity in Protendon GmbH & Co. KG, whose measurement device and software was used for the data processing and analysis in this study. No other authors declare any conflict of interests.

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