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Sports Training's Effects on Muscle and Tendon Characteristics at Different Stages of Development

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Abstract: *This study aimed to investigate the influence of sprint training on muscle and tendon properties across different developmental stages, specifically focusing on pre-adolescent children, adolescent boys, and young men. It is well-established that adults show higher force production, rate of force development, and effective re-use of elastic energy during the stretch-shortening cycle (SSC) compared to children due to different muscle and tendon properties. Thus, it is important to classify the interaction between age and the training process on muscle-tendon system. Participant's tendon properties were assessed using two 10 seconds ramp isometric contractions(increasing the force level every 2'') with an ultrasound probe stabilized on muscle-tendon junction. Moreover, two maximal isometric plantar flexions were performed to evaluate maximal isometric force. Both force capacity and tendon stiffness was evaluated. Our results showed significant increases in height, body mass, and strength levels through maturation ($p<0.05$). Moreover, significant changes were found in tendon stiffness and produced force in athletes compared with non-athletes groups ($p<0.05$). On the other hand, significant differences were found in relative stiffness and force between young adults and non-athletes with the athletes ($p<0.05$). Our results revealed that both maturity and sprint training imposes the tendons to a greater mechanical load through the higher produced force and strain. These stimuli lead to adaptive responses and changes in Achilles tendon properties. Moreover, our data support the importance of training in young adults to maintain tendon properties at the level of adolescence. This study provides valuable insights into the interaction between age, sprint training, and tendon adaptations to prevent tissue imbalances in male individuals engaged in sports activities.*

Keywords: Sprinting, adolescent, pre-adolescent, young adults, stiffness, force

I. INTRODUCTION

Adults always show higher performance in force production, higher rate of force development and better use of elastic energy during the stretch-shortening cycle (SSC) compared to children. These differences could attribute to several differences, such as muscle architecture, neural activation, and tendon properties. Adults and older adolescents demonstrated greater muscle thickness compared to children (Kubo et al., 2014; O'Brien et al., 2010). Recent evidence suggested that development changes in muscle size occur through fiber hypertrophy rather than hyperplasia (Folland& Williams, 2007). Despite the 15 year- old adolescents' fascicle length does not differ from adults (Kubo et al., 2001a), longer fascicle length of lower limbs has been found in adults compared to children in both sexes (Kubo et al., 2014; O'Brien et al., 2010). In contrast, pen nation angle alteration seems to be muscle-specific, with this knee extensors remaining consistent during maturation while medialis gastrocnemius increases from birth to peak height velocity (PHV) (Kannas et al., 2010; Kurihara et al., 2008). As maturation and muscle force capability are the main indicators of tendon stiffness, it is of great interest to record their possible interaction effects on these properties. Adolescence is a critical period of life characterized by fast muscle-tendon and neuromuscular alterations (Dotan et al., 2012; Radnor et al., 2018). During that period, the rapid increase in height (Peak Height Velocity, PHV) is accompanied by significant increases in body mass (Malina 2004) and strength levels (Chalatzoglidis et al., 2021). The increased force capability during human locomotion suggests a greater strain on the tendon (Lefevre et al., 1990). Thus, several adaptive changes in tendon properties occur such as an increase in collagen fibril diameter, density, and intra-fibrillary cross-linking (Lefevre et al., 1990; Radnor et al., 2018) leading to an increased tendon stiffness (Waugh et al., 2012a) to assist the greater strength capacity. A previous study (Thomas D. O'Brien et al., 2010) showed that the patellar tendon is less stiff

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in children (prepubertal; about 10 yrs) than in adults indicating that the tendon strain at given stress of children was significantly higher compared to this of adults (Kubo et al., 2001b; O'Brien et al., 2010), while Waugh et al., (2012) did not find any difference in AT strain. The AT mechanical properties and their changes are quite different between the sexes, both in adults (Kubo et al., 2003) and adolescents (Neugebauer& Hawkins, 2012). A recent study(Chalatzoglidis et al., 2021) has presented data that supports the different adaptive models in boys compared twirls. Waugh et al., (2012) found similar changes in tendon properties between the two consequent age stages. They showed that the changes between young and pre-pubertal children are almost the same as those between pre-pubertal children and older adults. Additively, Kubo et al., (2014) compared the tendon properties at three different age stages and concluded that the main developmental changes in tendon properties mostly occur at the early stage of adolescence. As the number of children participating in sports increases, the training procedure might cause imbalances between the muscle, the bone, and the tend nous tissue alteration course. Thus, the training's possible interaction with the maturity process could provide important data to minimize the development of overuse injuries. Training intervention plays an important role regarding tendon properties and strength production, interacting with age. A previous report about adult sprinters showed that knee extensors' tendon stiffness was lower than this in untrained ones (Kubo et al. 2000). Moreover, Arampatzis et al., (2007) showed that Achilles tendon (AT) stiffness was significantly greater in sprinters compared to the non-athletes. Regarding the effects of training during maturity, pre-adolescent children resulted in increased AT stiffness after ten weeks of resistance training (Waugh et al., 2014). Similarly, Mersmann et al., (2017) reported changes in tendon stiffness due to altered structure and collagen alignment (Weide et al., 2015) in adolescent volley-players. Unpublished longitudinal findings showed increased stiffness normalized to force/mass in young athletes with the preceded higher level of produced force stimuli in the tendon properties modulations (Chalatzoglidis et al., under revision). Since sports participation could cause higher increases in strength and tendon stiffness throughout maturation (Chalatzoglidis et al., 2021), it could be easily hypothesized that the appropriate training intervention could prevent the growing children from tissue imbalances. Thus, it is important to identify the interaction between age and the training process, to fully understand the time course of tendon properties throughout human living. The purpose of this paper, therefore, was to determine if sports training influences muscle and tendon properties differently for pre-adolescent, adolescent boys, and young men.

II. MATERIAL AND METHODS

Participants

Twenty-one pre-adolescent (10 athletes and 11 non-athletes), twenty adolescent boys around PHV (13 athletes and 7 non-athletes) and thirty-four young adults (17 athletes and 17 non athletes) were participated in the present study (Table 1). All the pre-adolescent and adolescent non-athlete boys were involved only in the physical education lessons at school. The athletes (pre- and adolescent) were track and field athletes, specifically sprinters, and participated in at least five training sessions per week. Half of Young adults were sprinters (Personal best: > 11s at 100m, five sessions per week). All the participants were healthy, free of any muscular or neurological disease. All the participants or their parents provided their written informed consent to participate in the present study after being informed about the purpose and the risks associated with the present study. The study protocol was approved Local Ethics Research Committee, and the research was conducted under the Declaration of Helsinki guidelines.

Procedure

All the participants completed two sessions in the laboratory. The first session included personal information recording and a familiarization process with submaximal trapezoidal contractions (ramp contractions) and maximal voluntary contractions (MVCs) of the right (dominant) leg. During the second session, the subjects performed maximal voluntary plantar flexions and ramp contractions on a dynamometer using the ultrasound to identify the tendon mechanical properties. The anthropometric data were recorded during the first visit in the lab . The age of Peak Height Velocity (PHV) was calculated using the Mirwald's equation (Mirwald et al., 2002). Moreover, information about the training background and the performance of each participant was collected. Plantar flexion contractions The participants performed 2 ramp isometric plantar flexion contractions (IPF) in the prone position on a dynamometer bench (CybexHumac Norm, CSMI, MA, USA; Figure 1A) to evaluate each participant's strength.

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The right ankle was in the neutral position while the right foot was positioned in the dynamometer's foot-plate with the knee completely extended and perpendicular to the tibia (Muramatsu et al., 2001, Maganaris, 2002, Muraoka et al., 2004, Kubo et al., 2014). The hips were firmly tied to the seat, while the foot was firmly fastened to the footplate with straps. The ankle joint's rotational axis was carefully aligned parallel to the axis of the dynamometer's lever arm and passed through the middle of the line joining the two malleoli. (De Monte et al., 2006). Participants completed a warm-up exercise before the testing. (Maganaris and Paul, 1999, Rigby et al., 1959, Viidik et al., 1982, Schatzmann et al., 1998). Participants performed two 10-s isometric plantar flexions, increasing the torque from 0% to 100% at a rate of 20% every 2 seconds. The best trial was used to determine the maximal torque values, ensuring that the torque-time curves were linear during the ramp phase. A B-mode ultrasonography (SSD-3500, Aloka, Tokyo, Japan) was used to determine the displacement of the medial gastrocnemius's distal myotendinous junction (MTJ) during ramp IPF (7.5Hz wave frequency; Figure 1B). The probe (60-mm) was positioned longitudinally in the area of the skin surface designated by a marker (Figure). To keep track of any potential probe movement on the skin during the measurement, an echo absorptive marker was placed. Ultrasound images were digitally recorded at a sampling frequency of 25 Hz. The spatial location of the MTJ was digitalized using the Max TRAQ program (Max Traq Lite version 2.09, Innovation Systems, Inc. Columbiaville, Michigan. U.S.A) to generate the MTJ position-time data. The Acknowledge Acquisition & Analysis Software (BIOPAC Systems, Inc., USA) was used to synchronize the torque signal and ultrasound videos. It was suggested that the displacement of the Gastrocnemius MTJ represents the change in the AT's length (Maganaris and Paul, 1999, Muramatsu et al., 2001, Dick et al., 2016). To record plantar flexion motion, a high-speed camera was used to capture (high-speed digital video, JVC 9800, frame rate = 120 Hz) the displacement of MTJ during ramp contractions as a result of unavoidable joint angular rotation (Magnusson et al., 2001b, Arampatzis et al., 2008). On the fifth metatarsal, lateral malleolus, and lower extremity of the heel, five reflectors (2.5-mm radius) were set, along with two markings on the footplate (Figure 1A). Although the foot was stabilized, the ankle joint appeared to move during contraction, leading to a misalignment of the rotation axis of the dynamometer. The position points of the reflectors were captured during ramp isometric plantar flexion, and the coordinate data from the high-speed camera were down sampled to the ultrasound sampling frequency to accurately determine the angle of rotation in two dimensions. To account for the impact of ankle joint rotation, the extra MTJ displacement was deducted from the observed elongation (L) (Arampatzis et al., 2008, Magnusson et al., 2001a). The excursion method was used to estimate the AT moment arm (MA), which was defined as the distance at which the rotating center and the line of AT action are vertical (Fath et al., 2010, Ito et al., 2000). The dynamometer was rotated passively between 20°dorsiflexion and 20° plantar flexion at a speed of 5°/s while the participant's position or the position of the ultrasound probe was not altered. The moment arm is represented by the slope of the curve, which is determined by the first derivative of the polynomial for angle 0° (Fath et al., 2010). The equation used to determine the tendon's force

$F = M / d$, where M is the plantar flexion moment and d is the AT MA length.

The isometric plantar flexion force was evaluated at neutral position. This estimation provides a force that corresponds to the combined force of all the ankle muscles sent through the AT. The linear section of the force-elongation curve's slope, from 60% to 90% of the maximum force, is what is referred to as stiffness (N/mm) (Waugh et al., 2012). This force-elongation curve is what is chosen to be as close to the linear portion as possible (Waugh et al., 2012). Where the slope ($R2=0.9$) of the linear portion of the curve F-L was equal to the k, a first-order polynomial was used. Sagittal imaging was used to determine the tendon boundaries from the point where the AT inserts on the calcaneal tuberosity to the MTJ of the gastrocnemius medial is (GM). Using a DA 100 Bamplifier (Biopac Systems, Inc., Goleta, CA, common mode rejection ratio > 90 db, bandwidth = 0.05 - 500 Hz), analog signals from the dynamometer were amplified and synced with data from the ultrasound system. Torque data were recorded by the dynamometer at a sampling frequency of 100 Hz. Statistical analyses SPSS was used for the statistical analysis (IBM Corp., Version 27.0, Armonk, New York, USA). The means and standard deviations of the descriptive statistics were shown. Levene's test was used to examine the homogeneity of variance and normal distribution.

The independent variables (IVs) for the present study were age groups (pre-adolescents, adolescents, young people) and sport participation (athletes and non-athletes), whereas the dependent variables (DVs) were: peak force (Fpeak), peak force normalized to body mass (Frel), stiffness (k), stiffness normalized to peak force (krelF), stiffness normalized to mass (krelM). A two-way ANOVA test used to compare the effect of IV on DVs. A Bonferroni post-hoc test was

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performed where the interaction was statistically significand. The data is presented as mean ± SD. With a p-value < 0.05, statistical significance was evaluated.

III. RESULTS

The three groups (pre-adolescents, adolescents and adults) showed statistically significant differences both in body mass [F(2,69)=83.6, p<.001] and Body height [F(2,69)=101.1, p<.001]. Post-hoc Bonferroni test showed differences (p<.001) in body mass between pre-adolescents (M= 43.5kg, SD=9.9kg), adolescents (M= 61.1kg, SD=7.3kg) and young adults (M=76.7kg, SD=9.

The main effect of sport participation (not active in sports and track and field athletes) and maturation were significant (p<0.01) indicating that track and field athletes were stronger than not active individuals [F(1,69)=6.116, p=.016] and that plantar flexion strength increased with maturation [F(2,69)=42.497, p<.001]. Furthermore, there was a significant interaction between maturation and sports participation [F(2,69)=4.247, p=.018]. Specifically, a Bonferroni post-hoc test (p<.001) showed that in athletes: adults had greater Fpeak(M=4962.5N, SD=235.9N) than adolescents (M=3322.9N, SD=269.8N) and adolescents had greater Fpeak than pre-adolescents (M=1767.9N, SD=307.6N). Young athletes' Fpeak (M=4962.5N, SD=235.9N) was greater [F(1,69)=19.1, p<.001] than non-athletes (M=3502.9N, SD=235.6N) but not differed in the rest maturation groups. Pre-adolescent non-athletes' Fpeak was lower (p<.01) than adolescents' and young adults' Fpeak

The main effects of age and sport participation were significant (p<0.01) indicating that stiffness (k) increased with maturation [F(2,69)=34.232, p<.001] and that athletes are stiffer than non-athletes [F(1,69)=14.895, p<.001]. Also the interaction between maturation and sports participation was significant [F(2,69)=12.712, p<.001]. A Bonferroni post-hoc test showed in adult athletes had greater k (M=404.6N/mm, SD=16.9 N/mm) than non-athletes (M=230.3N/mm, SD=16.9N/mm) but not differed in the rest maturation groups. Pre-adolescents' k (M=157.7N/mm, SD=15.2N/mm) was lower (p<.01) than adolescents' (M=261.0N/mm, SD=16.3N/mm) and young adults' (M=317.6N/mm, SD=11.9N/mm)

The main effects of sport participation was significant (p<0.01) indicating that stiffness by mass (krel) was greater in athletes [F(2,69)=11.6, p<.001]. Athletes had greater F(1,69)=11.644. p=.001] stiffness normalized by body mass (krel) (M=4.6, SD=.179 Nm-1 kg-1) than non-athletes [M=3.7, SD=.2Nm-1 kg-1], in all maturation stages, while the main effect of maturation wasn't significant (p=.209). Also the interaction between maturation and sports participation was significant [F(2,69)=9.8, p=.001]. Post-hoc analysis showed that there was a significant difference (p<.001) between adult athletes [M=5.4, SD=.3Nm-1 kg-1] and adult non-athletes [M=2.9, SD=.3Nm-1 kg-1]. There was also a significant difference (p<.001) between adolescents [M=4.4, SD=.4Nm-1 kg-1] and young adults in non-athletes population.

IV. DISCUSSION

The present study examined the possible interaction between maturation and sports intervention (sprinting) at the tendon properties. A comparison of three different age groups was made to address the potential differences in properties alteration throughout adolescence and maturity. It was found that age and training process affect both muscle and tendon properties inducing different adjustments throughout time. Specifically, the young adults and the athletes exhibited greater body mass and higher strength capability related to tendon properties modulations. These original data exceed our knowledge and provide new evidence about the time course of the muscle -tendon adjustments during the maturity interacting with the training process. Moreover, both force capacity and stiffness levels were increasing with age leading to the conclusion that young adults are stronger and stiffer than the other two groups, and the pre-adolescents were weaker and less stiff than adolescents.

Our findings showed that pre-adolescent are less stiff compare to adolescents and young adults. These results support previous study indicating that the properties of tendons seem to alter throughout maturation, with a lower level of stiffness in children compared to pre-adolescents and adults (Kubo et al., 2014). It was reported that patella tendon stiffness reaches adult stiffness values by the age of 15 years, suggesting that the significant period is around the peak height velocity period (Kubo et al., 2001). As the body and the muscle mass increase, during PHV, the loading in tendons increases (Malina et al., 2004). The body mass and the force capacity, additively, are correlated with almost

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78% of tendon stiffness in humans (Waugh et al., 2012a), suggesting that age-related body mass changes affect tendons' properties through greater loading during weight-bearing tasks. The additional weight, during PHV, provides the trigger stimulus for the adaptations in both the dimension and material properties of the tendon.

Therefore, the observed increases in tendon stiffness during maturity are mediated by growth- and maturity-related modifications of the material properties of the MTU through the body mass changes. As previously described (Chalatzoglidis et al., 2021; O'Brien et al., 2010), the alterations in the body mass and the maximal force could adjust the Achilles tendon properties in males of different ages. As the Achilles tendon adjustments occur through the cyclic loading during force production (Arampatzis et al., 2007, 2010), tendon properties could be affected by the increased body mass during the daily living activity load or the increased level of force during training (Quatman et al., 2008; Waugh et al., 2013). Our findings agree with and support previous data showing that most of the abovementioned changes occur around PHV (Chalatzoglidis et al., 2021; Radnor et al., 2018). Despite the progressive increases in maximal force found during maturity, our relative force data demonstrates that these alterations are greater from the pre- to the adolescent stage. Additively, our results showed that tendon stiffness increases with age leading to higher tendon stiffness during adulthood. The larger crimp angles of collagen fibers (Kastelic et al., 1978; Kubo et al., 2014) and the greater CSA of the Achilles tendon (Magnusson, Beyer, et al., 2003; Magnusson, Hansen, et al., 2003) explain the decreased stiffness in children. The more compliant tendons found in pre-adolescent and adolescent populations might act as a protective mechanism against the imposed stress during daily activities at young ages. Indeed, it is previously highlighted the imbalance between muscle and tendon tissue adjustments during adolescence (Mersmann et al., 2017). The greater extensibility in children's tendons might act as a buffer of the stress during SSC activities to offset the effects of the immature neuromuscular system. Sprint training consists of several contexts to increase athletes' acceleration, velocity, strength, and power capability (Howatson et al., 2016). Despite that training with short ground contacts, such as sprinting and plyometric, seems inefficient to modify in tendon properties, the strength training provides a suitable stimulus for the tendon to start its adaptations. As the force capacity of the plantar flexors improves, the Achilles tendon experiences greater cyclic loading with greater strain during sprinting, resulting in adjustment in its properties. The higher strain during force production affects the fibroblast deformation and the fluid flow that are tendon's adaptive response determinants (Lavagnino et al., 2008).

Our findings support that isometric strength should be considered s determined indicator of tendon capacities (Waugh et al., 2012b) and correspond well with previous intervention studies (Arampatzis et al., 2007, 2010) showing that tendon adaptive response depends on the strain magnitude. The higher strain during force production is associated with higher tenocyte cell deformation and collagen activity, while the catabolic activity decreases. Thus, the stiffness increases to handle the extensive tendon loading. Short and long-period of sprinting training in adolescence would result in neuromuscular adaptations first (Steib et al., 2017; Williams et al., 2021), leading to greater force capacity accompanied by a delayed response of the tendon tissue (Mersmann et al., 2017; Mersmann et al., 2019). Our recent study (Chalatzoglidis et al., 2021) showed that AT stiffness increases rapidly around PHVs at the neutral position of the ankle in both boys and girls. Kubo and colleagues examined the time course of muscle-tendon adaptations in two separate 3-month training studies on the patellar (Kubo et al., 2010) and the Achilles tendon (Kubo et al., 2012), respectively. These studies showed that a significant increase in muscle strength preceded significant changes in tendon stiffness by 1–2 months (Kubo et al., 2012) or even six months (Chalatzoglidis et al. under revision). The connection between AT stiffness and plantar flexor capacity, especially in boys, has been previously established (Chalatzoglidis et al., 2021). These data showed that the rapid increase in peak force around PHV triggers the increases in AT stiffness, even six months before. Despite the higher produced force of the adult and the adolescents, a greater change in the force level was found between the pre-adolescents and the adolescent groups. The higher alteration rate of produced force by the plantar flexors might provide the trigger stimulus in the local mechanosensitive molecules causing tendon-specific molecular signaling (Chalatzoglidis et al., 2021; Kjær& Hansen, 2008), leading to the consequent properties changes. Given the above, training for sprinters should be considered to provide an effective stimulus leading to significant alterations in tendon properties, which becomes evident as plantar flexors' force capacity increases.

V. CONCLUSION

The results of the present study clearly show that both maturation and training could affect tendon properties throughout time. The increase in body mass is the main factor causing alteration in muscle strength and tendon properties in untrained males. In male sprinters, the increases in muscle strength through the training, lead to increased tendon stiffness. Despite that fast contractions do not provide sufficient stimulus to modify tendon properties, contexts such as strength training might be sufficient enough. Moreover, the increased strain during sprinting, due to greater force during plantar flexion, could result in significant changes in tendon properties. An interesting finding is that AT stiffness similarly decreases in untrained young adults as the relative peak force. These changes lead to the tendon's stiffness at lower levels than the untrained adolescents. This result indicated the usefulness and the necessity of tendon training in young adults to maintain their properties at an efficient level. To conclude, the increases in body mass in untrained males and muscle strength in trained ones are important for the consequent modifications in tendon properties. Considering that the tendon is the optimal tissue to store and re-use the elastic energy, the key factor during maturation and strengthening is to be stiffer to utilize its elastic storage potential.

Conflicts of interest - If the authors have any conflicts of interest to declare.

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