Evidence of imbalanced adaptation between muscle and tendon in adolescent athletes

F. Mersmann1,2, S. Bohm1,2, A. Schroll1,2, H. Boeth2,3, G. Duda2,3, A. Arampatzis1,2

1Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Berlin, Germany, 2Center for Sports Science and Sports Medicine, Berlin, Germany, 3Julius Wolff Institute, Charité – Universitätsmedizin Berlin, Berlin, Germany

Corresponding author: Adamantios Arampatzis, PhD, Department of Training and Movement Sciences, Humboldt-Universität zu Berlin, Philippstr. 13, Haus 11, 10115 Berlin, Germany. Tel: +49 30 2093 46045, Fax: +49 30 2093 46046, E-mail: a.arampatzis@hu-berlin.de

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Adolescence may be regarded as a critical phase of tissue plasticity in young growing athletes, as the adaptation process of muscle-tendon unit is affected by both environmental mechanical stimuli and maturation. The present study investigated potential imbalances of knee extensor muscle strength and patellar tendon properties in adolescent compared with middle-aged athletes featuring long-term musculotendinous adaptations. Nineteen adolescent elite volleyball athletes [(A), 15.9 ± 0.6 years] and 18 middle-aged competitively active former elite volleyball athletes [(MA), 46.9 ± 0.6 years] participated in magnetic resonance imaging and ultrasound-dynamometry sessions to determine quadriceps femoris muscle strength, vastus lateralis morphology and patellar tendon mechanical and morphological properties. There was no significant age effect on the physiological cross-sectional area of the vastus lateralis and maximum knee extension moment (P > 0.05) during voluntary isometric contractions. However, the patellar tendon cross-sectional area was significantly smaller (A: 107.4 ± 27.5 mm²; MA: 121.7 ± 39.8 mm²) and the tendon stress during the maximal contractions was significantly higher in adolescent compared with the middle-aged athletes (A: 50.0 ± 10.1 MPa; MA: 40.0 ± 9.5 MPa). These findings provide evidence of an imbalanced development of muscle strength and tendon mechanical and morphological properties in adolescent athletes, which may have implications for the risk of tendon overuse injuries.

The mechanical and morphological properties of muscles and tendons have been shown to influence athletic performance (Arampatzis et al., 2006; Stafilidis & Arampatzis, 2007) and relate to the risk of injury (Arya & Kulig, 2010; Couppé et al., 2013; Hansen et al., 2013). As the maximum strain of tendon tissue cannot be significantly altered (LaCroix et al., 2013), the increase of force as a result of physical exercise (Kongsgaard et al., 2007; Arampatzis et al., 2007a) has to be accompanied by an increase of tendon stiffness to maintain physiological ranges of strain during maximum muscle contractions. This increase of stiffness may be a result of an increase of Young’s modulus (i.e. changes of material properties) (Arampatzis et al., 2007a, 2010) and/or an increase of the tendon’s cross-sectional area (Kongsgaard et al., 2007; Arampatzis et al., 2007a; Couppé et al., 2008; Seynnes et al., 2009; O’Brien et al., 2010b), whereupon the former may be considered an early mechanism leading to an increased stiffness and the latter, a rather long-term effect of mechanical loading (Heinemeier, 2011). However, there is evidence that on the transcriptional level of growth factors in response to loading tendons feature delayed responses compared to muscles (Heinemeier et al., 2011). Further, the mechanical stimuli eliciting adaptation may be different for tendon than for muscle tissue (Arampatzis et al., 2010). Thus, it is reasonable to argue that the development of the muscle-tendon unit within the course of athletic training may be characterized by imbalances of muscle capacity and tendon properties, resulting in episodes of high tendon strain and stress. Besides environmental mechanical stimuli, maturation affects the properties of muscle and tendon (O’Brien et al., 2010a, 2010b). Therefore, it may be argued that young athletes are in a critical phase of muscle and tendon plasticity, as they are subjected to high mechanical loads as well as the physical growth that accompanies adolescence. The above argumentation can be supported by clinical evidence that early manifestations of overload injuries like patellar tendinopathy concern adolescent athletes (Le Gall et al., 2006). While the long-term effects of athletic training with different loading histories on muscle and tendon properties in adults have been investigated previously (Rosager et al., 2002; Kongsgaard et al., 2005; Arampatzis et al., 2007b; Kubo et al., 2011), there is little information about the morphological and mechanical
properties of muscle and tendon in adolescent athletes. Imbalances between muscle strength and tendon loading capacity in adolescent athletes might increase the risk of tendon injury. However, possible differences of the training induced long-term adaptation within the muscle-tendon unit in young compared with adult athletes have to date not been investigated. The identification of differences between the early and later phases of the athletic career would deepen the understanding of adaptational processes that are associated with long-term athletic engagement and, more importantly, shed light on the composition of muscle-tendon unit properties that are crucial for health and performance in a dynamic phase of tissue development (i.e. adolescence).

Volleyball players have been found to have greater quadriceps femoris muscle strength and thigh circumference compared to non-active controls and middle-distance runners (Sleivert et al., 1995). On the other hand, volleyball athletes are predisposed to developing patellar tendinopathy (Lian et al., 2005) and, thus, an intriguing subject cohort for the examination of the knee extensor muscle-tendon unit properties and their development. As it has been shown that athletic training has the potential to maintain muscle mass in master athletes (Wroblewski et al., 2011), middle-aged sportsmen seem to be a relevant group to investigate long-term effects of sport-specific training. We further believe that former elite athletes might be more suitable to provide information about a muscle-tendon unit steady-state that develops in response to long-term sport-specific mechanical loading than a younger active elite athlete group, as the latter might be more susceptible to specific plastic changes due to a high rate of adaptation and inhomogeneous training intensity during the season in elite sports.

Our purpose in the present investigation was to provide information about quadriceps femoris muscle strength and morphology as well as patellar tendon mechanical and morphological properties of adolescent and middle-aged elite volleyball athletes. We hypothesized that adolescent athletes feature equivalent muscle capacities due to the rapid development of muscle function, yet lower tendon stiffness and cross-sectional areas (i.e. long-term adaptation), resulting in higher tendon stress and strain. As there is evidence of degraded collagen synthesis in response to mechanical loading in women (Miller et al., 2007), we further hypothesized that these imbalances would be more pronounced in female athletes.

Methods

Experimental design

Thirty-seven volleyball athletes participated in the present study. The adolescent group consisted of 10 male and nine female athletes of the extended pool of the junior national team. The middle-aged group was composed of eight male and 10 female former elite athletes who still engaged actively in volleyball at least twice a week. Anthropometric data of the participants are shown in Table 1. The study has been approved by the university ethics committee and all participants signed informed consent to the experimental procedure, which included (a) the measurement of the maximum knee joint moment during isometric contractions by dynamometry, (b) the assessment of the patellar tendon and vastus lateralis morphology using ultrasonography and magnetic resonance imaging (MRI) and (c) the measurement of the patellar tendon elongation during maximum knee extension contractions by ultrasonography. All measurements were conducted on the jumping leg (i.e. leading leg in the spike jump).

Measurement of maximum knee joint moment

The participants were seated on a dynamometer (Biodex Medical, Inc., Shirley, New York, USA) and fixed with a pelvic strap to prevent trunk flexion of 85° (supine = 0°). Appropriate correction techniques were used to account for the effect of gravitational forces, the misalignment of the joint axis and the axis of the dynamometer during the maximal isometric contractions (Arampatzis et al., 2004) and the antagonistic coactivation (Mademli et al., 2004) on all measured knee extension moments. For this purpose, kinematic, kinetic and electromyographic (EMG) data were recorded during the contractions. Six reflective markers were fixed to the following anatomical landmarks on the leg: anterior iliac spine, greater trochanter, lateral and medial femoral epicondyles and malleoli. Furthermore, two bipolar surface electrodes (2 cm interelectrode distance, 0.8 cm2 pick-up surface, Myon m320RX, Myon AG, Baar, Switzerland) were fixed over the lateral head of the biceps femoris in the direction of the muscle fibers after shaving and cleaning the skin with alcohol to reduce skin impedance (Mademli et al., 2004). Kinematic data was recorded using a Vicon motion capture system (Version 1.7.1., Vicon Motion Systems, Oxford, UK) integrating eight cameras (6x Vicon F20, 2x Vicon T20) operating at 250 Hz. The analog data of the dynamometer as well as the EMG signals were sampled at a rate of 1000 Hz and transmitted to the Vicon system via a 16-channel A-D converter.

Following a standardized warm-up including 5 min of ergometer cycling and 10 deep squats, 10 submaximal isometric knee extension contractions were used as preconditioning of the tendon and as customizing for the participants. Three to five trials of isometric maximum voluntary knee extension contractions (MVC) were performed starting from a range of resting knee joint angles of 60° to 80° (0° = full knee extension) to measure the maximal

Table 1. Mean values ± standard deviations of age, height and mass of the female and male adolescent and middle-aged athletes, respectively.

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<thead>
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<th>Adolescent</th>
<th>Male</th>
<th>Middle-aged</th>
<th>Male</th>
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<tr>
<td></td>
<td>Female (n = 9)</td>
<td>Male (n = 10)</td>
<td>Female (n = 10)</td>
<td>Male (n = 8)</td>
</tr>
<tr>
<td>Age [years]</td>
<td>15.7 ± 0.5</td>
<td>16.1 ± 0.7</td>
<td>46.9 ± 6.4</td>
<td>46.9 ± 3.3</td>
</tr>
<tr>
<td>Height [cm]</td>
<td>182.3 ± 4.2</td>
<td>194.8 ± 5.6</td>
<td>176.2 ± 4.9</td>
<td>191.6 ± 5.6</td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>69.7 ± 8.4</td>
<td>86.2 ± 7.4</td>
<td>70.2 ± 5.8</td>
<td>97.4 ± 14.9</td>
</tr>
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</table>
on the basis of the behavior of the tracked fascicle portions. A representative reference fascicle (thin dashed line) was then calculated of visible features of multiple fascicles (pointed lines). Subsequently, these features were tracked automatically throughout the upper (upper thick dashed line) and deeper (lower thick dashed line) aponeuroses throughout the whole recording by processing the shift of the brightness profiles. Measurement of fascicle length by a semi-automatic feature-tracking approach, which involved the manual tracking of the upper and deeper aponeuroses throughout the full range of motion driven by the isokinetic device at a speed of 5°/s using a 7.5 MHz ultrasound probe of 10 cm width (My Lab60, Esaote Canada, Georgetown, Canada). The ultrasound probe was positioned over the medial part of the muscle belly and fixed with Velcro straps. The recordings were analyzed by means of a semi-automatic feature-tracking algorithm implemented in a custom written MATLAB interface (Version 2011b, The Mathworks, Natick, Massachusetts, USA). In short, following the manual tracking of the upper and deeper aponeuroses throughout the whole recording, a key-frame in the mid-portion of the recording was selected and the visible features of multiple fascicles were digitalized manually. Subsequently, these features were tracked automatically throughout the recording by processing the shift of the brightness profiles within discrete horizontal lines between the aponeuroses using a non-linear least squares fitting. A representative reference fascicle was calculated on the basis of the tracked fascicle portions (Fig. 1). Hence, fascicle length (FL) was reported as a function of knee angle and was then normalized to femur length (rFL; Mohagheghi et al., 2008). In the following, we present the data measured at 50°, which was the average knee joint angle obtained from the kinematic data where the highest knee joint moment was accomplished during the MVC assessment. The measurement and semi-automatic tracking procedure was tested for reproducibility in a pilot study on the vastus lateralis of six independent male participants (Age: 30.5 ± 3.3 years; body height: 181.8 ± 16.5 cm, body mass: 83.8 ± 21.9 kg) showing an intraclass correlation for absolute agreement between the fascicle lengths at 50° knee joint angle measured on two consecutive days of 0.8 (Day 1: 10.04 ± 1.93 cm; Day 2: 9.97 ± 1.73 cm).

In an MRI session, sagittal and transversal plane images were obtained from the jumping leg of every participant between the pelvic spine and the tibial tuberosity (sagittal: 2D-MESE, slice thickness 3 mm, interslice spacing 3.51 mm, transversal: 3D-MEDIC, slice thickness 1.2 mm, inter-slice spacing 0 mm) lying supine with the knee fully extended in a 1.5 Tesla Magnetom Avanto scanner (Siemens, Erlangen, Germany). To assess vastus lateralis volume (VLvol), the boundaries of the muscle were tracked manually in the transversal plane images between the origin at the linea aspera and the insertion at the patella using Osirix (Version 4.0, 64 bit, Pixmeo SARL, Bernex, Switzerland). Muscle volume was calculated as the sum of the products of the respective cross-sectional areas multiplied by slice thickness. The vastus lateralis physiological cross-sectional area (VLPCS A) was then calculated as the quotient of VLvol to FL at a knee joint angle position of 50° (Lieber & Fridén, 2000).

The patellar tendons cross-sectional areas (PTCSA) were also digitalized manually in the transversal plane MRI between the caudal pole of the patellar and the insertion at the tibial tuberosity. Unfortunately, not all the transversal plane recordings included the most distal part of the tendon. Thus, the reported PTCSA values relate to mean cross-sectional area of the longest common relative length, which was 0–70% of the patellar tendon length. The digitized PTCSA were transformed perpendicular to the line of action of the patellar tendon, which in turn was defined as the line of best fit through the geometrical centers of the respective cross-sectional areas. The patellar tendon moment arm at full knee extension (PTMA) was measured in a three-dimensional coordinate system as the perpendicular distance of the tendon’s line of action to the rotation axis of the knee. The rotation axis of the knee joint was determined by outlining the lateral and medial femoral epicondyles in the sagittal MRI scans and connecting the centers of the respective best fitting circles according to Churchill et al. (1998). Subsequently, the tendon moment arm as a function of knee joint angle was calculated by processing moment arm changes in relation to joint angle on the basis of the data reported by Herzog and Read (1993).

Determination of the mechanical properties of the patellar tendon

The measurement of the patellar tendon elongation during isometric contractions was performed in the same experimental setup as described earlier (in the section measurement of maximum knee joint moment) following the MVC assessment and using the same considerations for joint moment calculation. The ultrasound probe was fixed in a modified knee brace covering the tendon in the sagittal plane. The knee joint angle for the subsequent contractions was adjusted according to the resting knee joint angle where the

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**Fig. 1.** Measurement of fascicle length by a semi-automatic feature-tracking approach, which involved the manual tracking of the upper (upper thick dashed line) and deeper (lower thick dashed line) aponeuroses throughout the whole and the manual digitalization of visible features of multiple fascicles (pointed lines). Subsequently, these features were tracked automatically throughout the recording by processing the shift of the brightness profiles. A representative reference fascicle (thin dashed line) was then calculated on the basis of the behavior of the tracked fascicle portions.
highest individual joint moments were accomplished during the MVC assessment. Based on the findings from Schulze et al. (2012) regarding the reliability of patellar tendon elongation measurements, five trials of isometric ramp contractions were performed by every participant increasing the force steadily from rest to maximum effort in about 5 s. The shank was fixed to the lever arm of the dynamometer with a Velcro strap to allow full relaxation and accurate tendon resting length assessment.

Tendon force was then calculated by dividing the knee joint moment by the angle-specific tendon moment arm. The patellar tendon elongation was digitalized by manually tracking the deep insertion of the tendon at the caudal pole of the patella and the tibial tuberosity frame by frame using a custom written MATLAB user interface to navigate through the video images and mark the respective insertion points. Subsequently, the mean force-elongation relationship for each participant was calculated using the highest force value that was reached in all of the five ramp contractions (and the respective elongations) as peak force. The resultant function was fitted by a second-order polynomial and tendon stiffness as well as Young’s modulus was calculated between 50% and 100% of the peak tendon force. For the calculation of the respective stress values, we used the mean patellar tendon cross-sectional area. The data obtained in the ultrasound sessions of four out of the 37 participants had to be excluded due to artefacts in the ultrasound recordings.

Statistics
Statistical analysis was performed in SPSS (SPSS Inc., Version 19.0, Chicago, Illinois, USA). After testing for normal distribution of the data using the Kolmogorov–Smirnov test, the parameters were analyzed by means of a two-way analysis of variance with the fixed factors sex and age. The level of significance was set to \( \alpha = 0.05 \).

Results
Morphology and strength
There was a significant effect of sex and age \( (P < 0.05) \) on the VLvol (Table 2). The male athletes had a greater muscle volume compared with the female, and the adolescent compared with the middle-aged counterparts, respectively. Male athletes showed a greater \( (P < 0.05) \) VLPCSAA of the vastus lateralis muscle and a higher maximal resultant knee extension moment during the MVC compared with the female athletes (Table 2). However, we did not find any age effect \( (P > 0.05) \) on the VTOL and maximal knee joint moment. Further, there was no effect of sex and age on the relative fascicle length of the vastus lateralis muscle (Table 2).

Tendon morphological and mechanical properties
Males showed a greater \( (P < 0.05) \) moment arm, tendon force and resting length of the patellar tendon compared with the female athletes (Table 3). There was no significant effect of sex or age on patellar tendon stiffness and Young’s modulus but a tendency \( (P = 0.07) \) towards higher maximum tendon strain in adolescent compared with middle-aged athletes (Table 3). There was a significant effect of sex and age \( (P < 0.05) \) on the PTCSA and the maximum tendon stress. We found smaller cross-sectional areas, yet higher tendon stress in the female compared with male and the adolescent compared with middle-aged athletes (Fig. 2).

Table 2. Mean values ± standard deviations of vastus lateralis VLvol, physiological cross-sectional area (VLPCSAA), fascicle length relative to femur length (rFL) and maximum knee joint moment (MVC) of female and male adolescent and middle-aged athletes, respectively

<table>
<thead>
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<tbody>
<tr>
<td></td>
<td>Female (n = 9)</td>
<td>Male (n = 10)</td>
<td>Female (n = 10)</td>
<td>Male (n = 8)</td>
</tr>
<tr>
<td>VLvol [cm³]</td>
<td>620 ± 155</td>
<td>862 ± 129</td>
<td>476 ± 68</td>
<td>776 ± 78</td>
</tr>
<tr>
<td>VLPCSAA [cm²]</td>
<td>45.5 ± 8.0</td>
<td>53.4 ± 13.1</td>
<td>36.0 ± 10.0</td>
<td>55.0 ± 10.8</td>
</tr>
<tr>
<td>rFL</td>
<td>0.287 ± 0.047</td>
<td>0.355 ± 0.094</td>
<td>0.309 ± 0.091</td>
<td>0.305 ± 0.71</td>
</tr>
<tr>
<td>MVC [Nm]</td>
<td>248 ± 49</td>
<td>351 ± 39</td>
<td>214 ± 28</td>
<td>340 ± 58</td>
</tr>
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</table>

*significant effect of age \( (P < 0.05) \).
*significant effect of sex \( (P < 0.05) \).

Table 3. Mean values ± standard deviations of the patellar tendon moment arm (PTMA), maximum tendon force (TFmax), maximum strain, stiffness, Young’s modulus and rest length of female and male adolescent and middle-aged athletes respectively

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<tr>
<td></td>
<td>Female (n = 8)</td>
<td>Male (n = 10)</td>
<td>female (n = 7)</td>
<td>male (n = 8)</td>
</tr>
<tr>
<td>PTMA [mm]</td>
<td>55.4 ± 2.9</td>
<td>62.9 ± 2.4</td>
<td>57.4 ± 3.1</td>
<td>63.6 ± 3.8</td>
</tr>
<tr>
<td>TFmax [Nm]</td>
<td>4688 ± 529</td>
<td>5622 ± 639</td>
<td>3994 ± 748</td>
<td>5383 ± 1031</td>
</tr>
<tr>
<td>Strain [%]</td>
<td>8.20 ± 2.27</td>
<td>8.40 ± 2.36</td>
<td>6.16 ± 2.03</td>
<td>7.49 ± 2.26</td>
</tr>
<tr>
<td>Stiffness [N/mm]</td>
<td>1031 ± 285</td>
<td>1258 ± 463</td>
<td>1370 ± 540</td>
<td>1345 ± 480</td>
</tr>
<tr>
<td>Young’s modulus [GPa]</td>
<td>0.64 ± 0.18</td>
<td>0.59 ± 0.25</td>
<td>0.69 ± 0.23</td>
<td>0.54 ± 0.24</td>
</tr>
<tr>
<td>Rest length [mm]</td>
<td>51.2 ± 3.1</td>
<td>56.8 ± 3.0</td>
<td>48.5 ± 3.4</td>
<td>55.5 ± 4.4</td>
</tr>
</tbody>
</table>

*significant effect of sex \( (P < 0.05) \).
Imbalanced adaptation in adolescent athletes

The present study investigated the muscle strength of the knee extensors and the morphological and mechanical properties of the vastus lateralis and patellar tendon in adolescent and middle-aged athletes. While muscle strength of the knee extensors and physiological cross-sectional area (PCSA) of the vastus lateralis muscle were similar between the two groups, the adolescent athletes featured a lower tendon cross-sectional area and, thus, higher tendon stress. Further, tendon stress was greater in female compared to male athletes. Therefore, our hypotheses were partly confirmed.

It is well known that muscle strength increases during maturation (O’Brien et al., 2010b). Although still under debate, it is likely that this increase is mainly due to increases in muscle size (especially the PCSA), moment arm length and activation level and not changes in muscle specific contractile capacity (Bouchant et al., 2011). In the present study, the maximal knee extensor moments did not differ between the adolescent and middle-aged athletes. Further, there were no differences in patellar tendon moment arm and vastus lateralis PCSA. These findings may be interpreted in terms of the adolescents featuring middle-age adult-like muscular capacities in volleyball athletes. As mechanical loading and strength training have been shown to increase muscle strength in adolescents and even pre-pubertal children (Matos & Winsley, 2007) and hormonal changes during puberty facilitate muscle growth (Hulthen, 2001), the developmental status of the muscular capacities of the adolescent athletes in the present study is well explicable. However, the present study provides evidence of considerable differences between adolescent and middle-aged athletes regarding the properties of the patellar tendon, which has the crucial role to transmit the force of the muscle to the bone. A strong muscle acting on a tendon characterized by a low cross-sectional area induces high levels of tendon stress. In the present study, the maximum patellar tendon stress during isometric knee extension contractions was significantly increased (~27%) in adolescent compared with middle-aged athletes and can be explained by an unfavorable relation of muscle strength to tendon cross-sectional area, indicating an imbalance within the muscle-tendon unit of the quadriceps muscle. While muscle strength did not differ significantly between groups, the average cross-sectional area of the patellar tendon was smaller in the adolescents. It has been shown recently that patellar tendinopathy in athletes is associated with tendon stress (Couppé et al., 2013). Thus, the high levels of tendon stress may increase the injury risk of the patellar tendon in the adolescent athletes. Patellar tendinopathy is a well-known phenomenon in sports with a high frequency in jumping and sprinting (Lian et al., 2005; Le Gall et al., 2006) and considerably affects the sporting development in adolescent and young athletes. As there is evidence that the time course of plastic changes of muscle and tendon in response to loading and unloading is different (de Boer et al., 2007; Heinemeier et al., 2011) and that the effective mechanical stimuli eliciting adaptational responses in muscle and tendon might differ as well (Arampatzis et al., 2007a, 2010), it is well possible that adolescent athletes develop imbalances between muscle and tendon. It has been shown that even though maturation is accompanied by a general increase of tendon cross-sectional area (O’Brien et al., 2010b), the shortening of the muscle-tendon unit during growth can be accompanied by episodes of cross-sectional area reductions and increases of tendon stress (Neugebauer & Hawkins, 2012). Furthermore, we found a tendency (P = 0.07) for higher tendon strain in the adolescent compared with middle-aged athletes, which might be interpreted as a mechanical weakening of the patellar tendon (Hansen et al., 2013) and can be explained by a slightly lower average tendon stiffness, due to the lower tendon cross-sectional area, in the adolescent group.

Specific differences between sexes in the capacity and morphology of the muscle tendon unit are well documented (Neder et al., 1999; Westh & Kongsgaard, 2008; O’Brien et al., 2010a) and replicated in the present study (i.e. greater muscle strength, muscle volume, muscle PCSA and tendon cross-sectional area for male compared to female athletes). However, a novel finding of the present study is that the female featured higher maximum tendon stress compared to the male athletes. In previous studies, tendon stress has been found to be similar between sexes (Westh & Kongsgaard, 2008) in runners or higher in males (Onambele et al., 2007) in moderately active individuals. However, the mechanical loading profile of volleyball is characterized by a high frequency of maximum effort muscle contractions and, thus, may be
considered an effective stimulus for increasing muscle strength. Regarding the potentially degrading effect of estrogen on the collagen response to mechanical loading (Miller et al., 2007), it may be possible that the higher tendon stress found in the female volleyball players might be due to a marked imbalance in the development of muscle strength and tendon cross-sectional area as a result of the sport-specific mechanical loading. There might be a sex-related disadvantage regarding the long-term adaptation of the tendon (i.e. tendon hypertrophy) to the developing levels of muscle force. This assumption can be supported by reports of reduced hypertrophic tendon responses to loading and greater risks to develop soft tissue injuries in women compared with men (Magnusson et al., 2007).

The rationale of choosing a group of middle-aged former elite athletes as comparison to the adolescents entails some limitations of the present study. Although there is strong evidence that continuous mechanical loading has the potential to preserve muscle strength (Wroblewski et al., 2011), an effect of age-related degeneration in the middle-aged participants cannot be ruled out completely. However, the isotropic torque production of the middle-aged male athletes (340 Nm) in the present study was similar to those reported from varsity athletes (350 Nm; Sleivert et al., 1995). This is a strong indication that the muscle capacity of the athletes of the present study has been preserved on a very high level and gives reason to believe that this would hold true for the properties of the tendon as well. However, because of a lack of untrained adolescent and middle-aged controls, the effect of maturation and long-term mechanical loading on the properties of the muscle-tendon unit cannot be separated with the current study design.

In conclusion, the present study provides evidence of an imbalanced development of muscle strength and tendon mechanical and morphological properties in adolescent athletes. While muscle strength was similar to that of middle-aged athletes, tendon hypertrophy, as a potential consequence of long-term mechanical loading, was not similarly developed and resulted in greater tendon stress in the adolescent athletes. This imbalance is even more pronounced in female athletes and may, among other factors (Lian et al., 2005), be associated with the development of overuse injuries.

Perspectives

Taking into account recent reports of Couppé et al. (2013) and Hansen et al. (2013), who were able to associate overload injuries to the mechanical properties of tendons, the present findings of high tendon stress in adolescent athletes demonstrate the need for exercise interventions increasing the mechanical strength of tendons to meet the demands placed upon the tissue by the muscle. Facilitating tendon hypertrophy seems to be of particular importance, as it has the potential to reduce tendon stress and has been identified in the present study as a main deficit within the muscle-tendon unit of adolescent compared to long-term adapted middle-aged athletes.

Key words: Tendon morphology, muscle strength, knee joint, muscle morphology.

References


Imbalanced adaptation in adolescent athletes