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Original Article

Discipline-specific Torque-Velocity Profiles and Musculotendinous Morphology in Athletes

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Abstract

Objectives: The aim of this study was to compare torque-velocity profiles, muscle architecture, tendon dimensions, and bilateral-symmetry between competitive cyclists (CY), competitive runners (RN), ice-hockey players (IH), basketball players (BP), and physically-active individuals (CN) (n=10 for each group). **Methods**: Vastus lateralis (VL) muscle and patellar tendon (PT) structures were determined with B-mode ultrasonography, and maximal knee extensor isokinetic torque was assessed at three different velocities. **Results:** Optimal torque and velocity were lower in runners than CY, BP and IH ($p<0.05$). Maximal power was similar between the athlete groups but greater than CN ($p<0.05$). Furthermore, RN and BP reached their peak-torque at longer muscle lengths compared to IH and CY ($p<0.05$). RN had the lowest VL muscle thickness and the greatest fascicle length, while CY had the greatest pennation angle ($p<0.05$). CY had the greatest PT thickness, particularly at the proximal and medial sites, while BP at the distal point ($p<0.05$), with similar trends observed for PT cross-sectional-area. **Conclusions**: Our findings show that even if power generating capacity is similar between athletic disciplines, there are discipline-specific muscle adaptations, where particularly runners appear to have muscles adapted for speed rather than torque development, while in cyclists, velocity is sacrificed for torque development.

Keywords: Isokinetic, Muscle Mechanics, Physical Performance, Skeletal Muscle, Strength

Introduction

Skeletal muscle can modify its structure in response to various stimuli, demonstrating remarkable plasticity[1]. Studies involving different athlete populations or examining responses to different mechanical inputs suggest that the specific exercise to which the musculotendinous structures are exposed dictate distinct structural changes, which are manifested in modifications to the structural and functional properties of both muscles and tendons[2–8].

The vastus lateralis (VL) muscle, due to its ease of access, has traditionally been one of the main muscles to investigate morphological adaptations to training[5]. For instance, Brughelli et al. found that Australian football players had greater VL fascicle length (Lf) and smaller pennation angle (PA) than competitive cyclists, and that the force-length relationship of knee extensors and flexor muscles differed between the two groups[3]. Competitive cyclists also have a different VL muscle architecture from runners (i.e., greater PA_{VL} and shorter Lf_{VL}), including greater torque generating capacity of the knee extensor muscles[8]. Furthermore, varying levels of bilateral asymmetry have been observed among athletes involved in different sports, which may contribute to the risk of injury[9,10]. However, it has been reported that elite athletes show no bilateral asymmetries, neither in terms of morphological nor functional neuromuscular properties[11].

In general, evidence suggests that chronic participation in sport-specific training does induce specific morphological and functional musculotendinous adaptations[3,8,12]. For

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instance, Lf reflects the number of sarcomeres arranged in series and has a positive impact on the muscle's maximal contractile velocity and capacity to produce force at high contractile velocity[13]. In contrast, a greater fiber PA allows for thicker fibers to be packed on the aponeuroses, and hence an increased number of sarcomeres arranged in parallel, therefore being positively associated with a higher force capacity for a given muscle volume, but at the expense of shortening velocity[13]. Consequently, chronic training-induced morphological muscle adaptations are reflected by specific functional properties.

Tendons, akin to muscles, must meet specific structural demands based on their peak operating stress to ultimate stress ratio, known as the safety factor[14]. This safety factor, however, varies across tendons, influenced by daily stresses and cyclic loading-induced fatigue damage. Hence, tendon structure must align with loading conditions to withstand such damage[4]. Research indicates that athletes experiencing impactful stresses like ground forces, as seen in runners and ski jumpers, exhibit larger tendons compared to those in sports with lower stress, such as water polo, or in sedentary individuals[4]. Therefore, tendon size seems adaptable to alterations in loading volume or intensity, potentially serving to maintain ultimate strength and fatigue resistance. Expanding these findings to broader athlete populations could further illuminate this adaptive process.

In summary, the morphology of muscles and tendons most likely align with the demands imposed by specific exercises, particularly when performed consistently and at high performance levels[13,15]. These morphological adaptations, in turn, can impact muscle function, such as maximal torque, velocity, power and the torque-velocity profile[16]. Enhancing our comprehension of sport-specific musculotendinous morphology and functionality could inform interventions to optimize performance in athletes or rehabilitation programs.

To test the assumption that musculotendinous adaptations are discipline-specific, the aim of the present study was to compare in a cross-sectional study the torque-velocity profiles, muscle architecture, tendon dimensions, and bilateral symmetry among experienced athletes from various disciplines. To do so, we selected four different sports with distinct movements, physical performance features, and loads applied to the knee extensor musculotendinous structures: cycling, running, ice hockey, and basketball. We hypothesized that the knee extensor torque-velocity profile and musculotendinous structure differs among athletes exposed to impact forces and stretch-shortening cycles (i.e., runners and basketball players) also due to the specific muscle-tendon unit operating lengths imposed by the exercise, compared to athletes who are less or not exposed to impact forces and characterized by different loads and contractile activity of the knee extensors (i.e., cyclists and ice hockey players). Furthermore, we anticipated that muscles engaged in sports requiring fast movements and high contraction speeds (e.g., runners) would exhibit longer fascicles. Conversely, we expected muscles in athletes from disciplines emphasizing high force production over speed (e.g., cyclists) to display greater pennation angles. Additionally, we hypothesized that power athletes (e.g., ice hockey and basketball players) would demonstrate a balanced architecture, benefiting from both high contraction speed and force generation capacity.

Methods

Study design

Fifty healthy adult men participated in the present cross-sectional observational study. The study population included 10 competitive cyclists (CY) [national and international level], 10 competitive long-distance runners (RN) [national level], 10 ice hockey players (IH) [national and international level first leagues], 10 basketball players (BP) [first and second national league level], and 10 physically-active individuals (CN) [not involved in any specific sport discipline]. Table 1 summarizes the characteristics of the study population. The CY group consisted of athletes who were part of two continental *Union Cycliste Internationale* teams and one amateur national level team. They had an average of 12 ± 4.5 years of experience and covered an average distance of 14684 ± 6473 km/y, resulting in an average of 10 to 15 hours of training per week. The RN group included national level half-marathon and marathon finishers, with an average of 8.5 ± 3.3 years of experience and covering an average distance of 3928 ± 2044 km/y, resulting in an average of 8 to 12 hours of training per week. The IH group consisted of Lithuanian national team members preparing for the first division World championships, while the BP group included individuals from both a first league team participating in international competitions and a second league team. In terms of experience, both groups had athletes with an average of 10 ± 4.7 years of engagement in their respective sports, dedicating 8 to 12 hours per week to training. CN participants were sourced from the local community in Kaunas, Lithuania, and the Lithuanian Sports University. They did not have any specific sport discipline but reported engaging in 100 to 200 minutes of moderate-intensity recreational exercise each week.

The participants provided information, including self-reported indications of their dominant and non-dominant limbs, during anamnestic interviews conducted during the first meeting. At this time, the experimental procedures were explained in detail, and the subjects had the opportunity to become familiar with the testing procedures. The exclusion criteria included self-reports of knee injuries that impeded maximal muscle contraction, a history of anterior knee pain, Osgood-Schlatter disease, cardiovascular disorders, medical history of diabetes, respiratory and neuromuscular diseases, or disclosure of anabolic drug abuse. The subjects were contacted either by text or verbally and were informed about the experimental procedures, purposes, risks and benefits.

Procedures

All participants were instructed to abstain from vigorous physical activity for 24 hours prior to the testing session and maintain their regular diet. The tests were conducted randomly on either leg. The same group of investigators conducted all measurements for consistency. The testing protocol consisted of collecting anthropometric measurements, including body mass and body composition using a Tanita-305 body-fat analyzer (Tanita Corp.). B-mode ultrasound (Telemed) was then performed on the vastus lateralis (VL) muscles and patellar tendons (PT). Subsequently, after a standard warm-up procedure on a stationary bike, the participants performed maximal isokinetic knee extensions of both limbs using a calibrated Biodex System 4 dynamometer (Biodex Medical Systems).

Musculoskeletal ultrasound imaging

Images of the VL muscle and PT tendon were obtained using a grayscale B-mode ultrasonography linear array transducer (10- to 15-MHz transducer, Echoblaster 128, UAB; Telemed). The settings of the ultrasound system were standardized (kept identical) for all participants and recorded using EchoWave II video-based software (Telemed), following the recommendations of the European Society of Muscoloskeletal Radiology and a recent literature review on ultrasound imaging application in sports[17,18]. Water-soluble transmission gel was used to coat the transducer, which was positioned with minimal pressure over the skin. Each subject was asked to lie in the supine resting position on a physiotherapy bed with the probe applied at 50% and 70% of the femoral length from the knee joint space to the greater trochanter on the VL, respectively (Figure 1). Parallel fascicle alignment was presumed when the transducer produced an image in which the aponeuroses and the fascicle perimysium trajectory were identified clearly with no visible fascicle distortion at the image edges. This position was chosen to minimize measurement errors associated with the posterior thigh muscles' concave orientation and PT extension[19–21]. The linear transducer was placed first longitudinally to evaluate tendon thickness (long axis) and then in the transverse plane to measure the tendon cross-sectional area (CSA) (short axis), at the proximal, medial and distal point of the tendon[20]. The images were later imported into ImageJ (version 1.46, US National Institutes of Health) and Tracker (version 5.1.5; https://physlets.org/tracker), to measure the VL muscle architecture and PT dimensions[18]. After identifying the desired positions, short (5–10 s) ultrasound videos of the CSA of the PT (CSA_{PT}) were captured. All captured videos were then converted into frames, and in each video, the frame with the best visibility of the tendon was selected for digitalization and CSA analysis.

Isokinetic tests

Maximal isokinetic knee extensions of each leg were performed using a Biodex System 4 dynamometer (Biodex Medical Systems), which recorded instantaneous muscular torques at three pre-set constant angular velocities: 90°/s, 180°/s and 300°/s[22]. The participants underwent a standardized warm-up procedure consisting of pedaling for 10 minutes at 100 W while maintaining 55-65 rpm. They were seated with 90° of flexion at the hip and the dynamometer axis of rotation was aligned with the femoral lateral epicondyle, with the lower leg fixed to the lever arm of the dynamometer just above the medial malleolus (Figure 1). To minimize hip and knee joint movement and vertical displacement between the lower back and the backrest during muscular force exertion, each participant was securely fastened to the dynamometer with transverse shoulder-to-hip belts fixing the trunk, a hip belt, and a belt at the distal thigh. The range of motion tested was 90° with full extension of the leg identified as 0°[22]. Prior to the test, a familiarization session was conducted where participants performed three submaximal trials at each preset velocity. During the test, the participants were instructed to perform concentric extensions as fast and forcefully as possible on a given signal from the test supervisor. Verbal encouragement was provided by the supervisor during the test[23,24]. The return movement was passive at a speed of 300°/s. Each participant performed three repetitions at each speed, interspersed by 1-min recovery. Each velocity trail was separated by a 3-minute rest period. The trial presenting the highest peak torque at each preset velocity was used for analysis.

Ultrasound images analysis

Ultrasound images were analyzed using Tracker (v.5.1.5) software to assess the VL muscle architecture and PT dimensions of both limbs[25]. The Lf_{VL}, PA_{VL}, and MT_{VL} (muscle thickness) were measured as the length of the fascicular path between the superficial and deep aponeuroses, the angle between the fascicular path and deep aponeurosis, and the distance between superficial and deep aponeurosis, respectively[25]. The patella tendon thickness (TT_{PT}) and cross-sectional are (CSA_{PT}) were analyzed at three anatomical landmarks, namely proximal (inferior to the apex of the patella), medial (tendon mid-point), and distal (superior to the tibial tuberosity)[20]. The CSA_{PT} was measured by defining the tendon borders inferior to the first hyperechoic region between the subcutaneous tissue and the deep fascia layer in the transverse plane image. Three ultrasound images were recorded and analyzed for each participant in the different anatomical landmarks and for both limbs, and the measured values were averaged. MT_{VL}, TT_{PT} and CSA_{PT} data were analyzed as absolute, but they were also normalized by the participant's body mass[26,27] raised to the power of 2/3 while the Lf_{VL} was normalized by the participant's height raised to the power of 1/4. This was done to account for possible anthropometric differences between the athlete groups. A bilateral symmetry index (BSI) for all parameters was calculated by: $\frac{(dominant\text{-}non\ dominant)}{(dominant)} \times 100$ [28]. This index provides information on the symmetry of the muscle architecture and PT dimensions between the dominant and non-dominant legs. Intra-rater repeatability was calculated for all variables, and the values ranged from ICC=0.96 to ICC=0.98 and CV=1.72% to CV=3.98%[8].

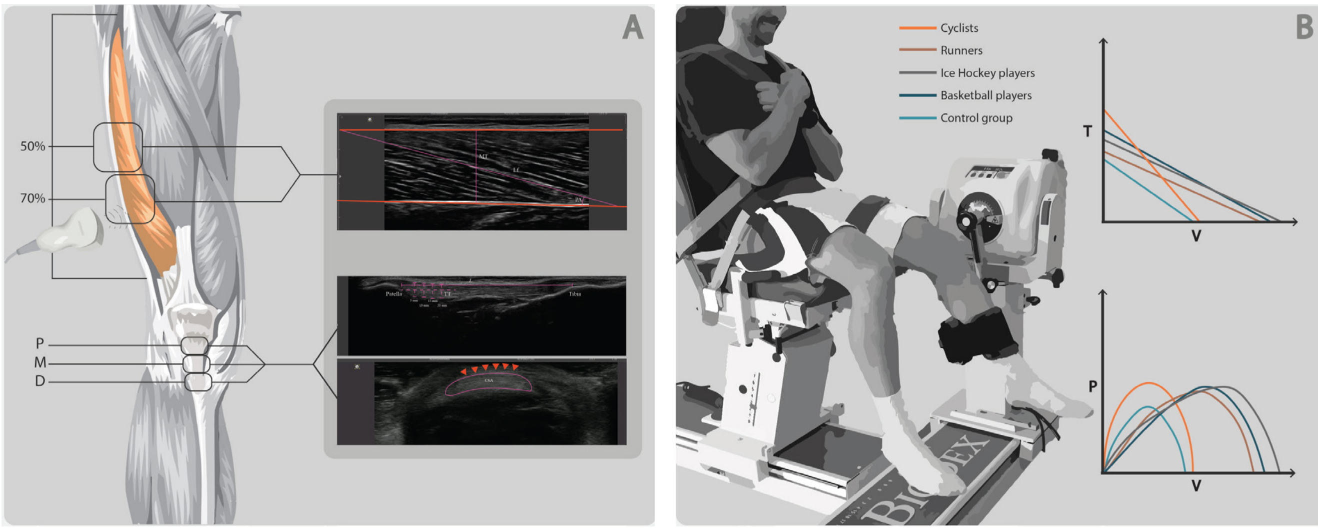

Figure 1. Graphical representation of the study protocol. Left side representing the details of the ultrasound imaging procedures and right side representing the isokinetic test and force velocity profiling.

Torque-velocity analysis

The peak torque was identified as the highest value attained during the period of constant preset velocity. To normalize the data, torque values were divided by the participant's body mass[26] raised to the power of 2/3, and velocity was converted to radians per second (1° × π/180 = 0,01745 rad). Torque-velocity relationships were derived using a linear regression model of the form: $T(V)=T_p-aV$, where T_p represents the torque intercept (i.e., theoretical maximal torque), a is the slope that corresponds to T_p/V_p, and V_p is the velocity intercept (i.e., the theoretical maximal velocity). The torque-velocity relationship was considered valid and used for data extraction only if R-squared (R^2) was greater than or equal to 0.95. As a direct result of the linear relationship between torque and velocity, the instantaneous peak power (P_{max}) was calculated as the product of the optimal torque (T_0) and the corresponding angular velocity (V_0)[22,29]. The optimal angle (OA) was defined as the angle at which the isokinetic torque peaked. P_{max} data were normalized by the participant's body mass raised to the power of 2/3[26]. A BSI for all parameters was calculated by: $\frac{(\text{dominant-non dominant})}{(\text{dominant})} \times 100$ [28]. This index provides information on the symmetry of the muscle isokinetic torque-velocity characteristics between the dominant and non-dominant legs.

Statistical analysis

All data were analyzed using IBM SPSS Statistics (version 21.0; IBM Corp., Armonk, NY, USA), and data graphs produced using GraphPad Prism (version 7.0; GraphPad Software, San Diego, CA, USA). The critical level of statistical significance was set at an α level of 0.05. Descriptive statistics (mean±SD) were calculated for each variable, and data were stratified according to exercise modality that the participant was undertaking (CY, RN, IH, BP, CN). The Shapiro–Wilk test was used to assess the normality of the distribution of the samples. Accordingly, between-group differences for all tested variables and within group differences between the dominant and non-dominant legs were analyzed with a two-way analysis of variance (ANOVA) (fixed factor: discipline; within factor: leg). A one-way ANOVA was conducted to examine the disparities in BSI among the groups. Furthermore, an additional two-way ANOVA was employed to assess the combined effect of discipline (fixed factor) and anatomical landmark (within factor) on the independent variables encompassing muscle architecture and tendon dimensions. In case of a significant between-group effect, a Tukey corrected post hoc test was performed to assess statistical significance of differences between mean values of the five groups. Effect size was defined according to Cohen[30], with the standardized effect (η^2) being small for η^2>0.1, medium for η^2>0.25, and large for η^2>0.4.

Results

Table 1 presents the characteristics of the study population. Among the anthropometric variables, significant differences were observed for body mass (F=6.564; p<0.001; η^2: 0.182) and height (F=13.885; p<0.001; η^2: 0.382). Tukey's post-hoc analysis revealed that RN had lower body mass than CY, IH, and BP, while BP were taller

Table 1. Descriptive data (mean ± SD) of the study population.

	CY (n=10)	RN (n=10)	IH (n=10)	BP (n=10)	CN (n=10)
Age (years)	27 ± 5	30 ± 5	24 ± 3	24 ± 3	26 ± 3
Body mass (kg)	82 ± 7[a]	71 ± 9[b,c]	84 ± 8	89 ± 11	76 ± 7
Body fat (%)	11 ± 4	10 ± 4	11 ± 3	12 ± 3	13 ± 3
Height (cm)	184 ± 4[c]	179 ± 6[c,b]	186 ± 4[c,d]	194 ± 5[d]	179 ± 6
BMI (kg/m²)	24 ± 3	22 ± 2	24 ± 2	24 ± 2	24 ± 1

Notes: [a], p<0.05 RN; [b], p<0,05 IH; [c], p<0.05 BP; [d], p<0.05 CN.

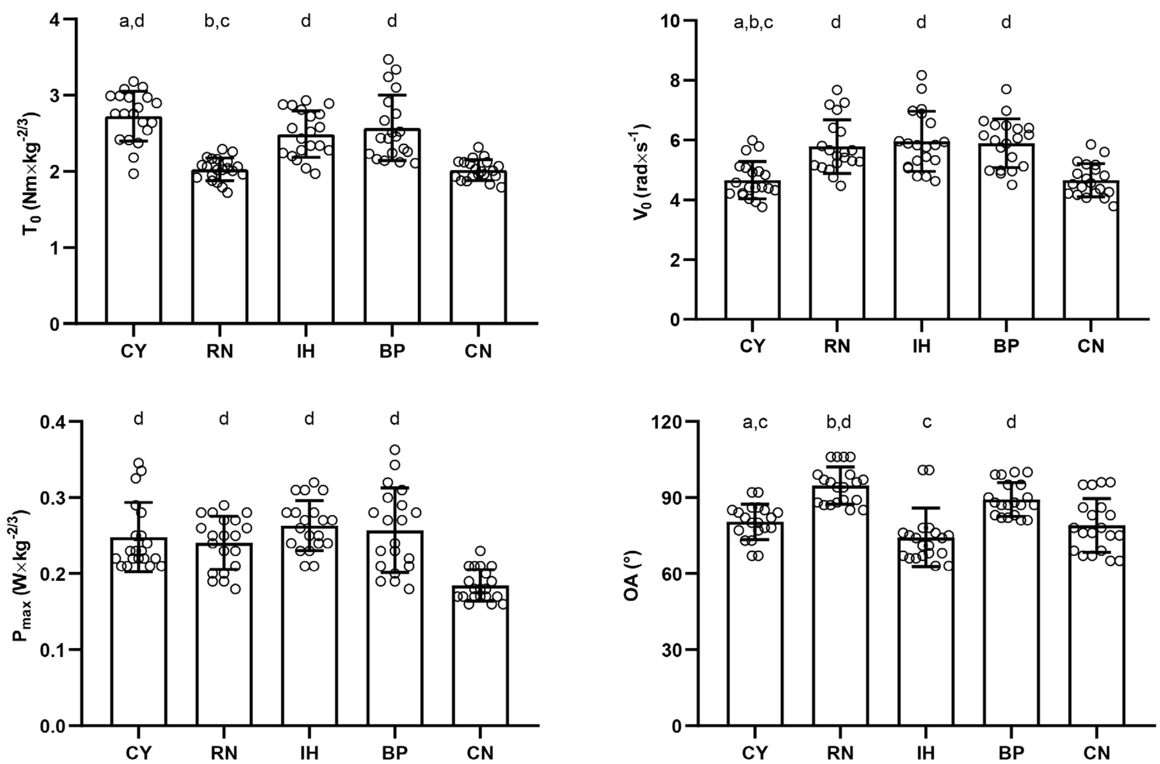

Figure 2. Between-groups differences for isokinetic torque-velocity profile markers. Notes: T_0, optimal torque; V_0, optimal velocity; P_{max}, maximum power; OA, optimal angle; [a], p<0.05 RN; [b], p<0,05 IH; [c], p<0.05 BP; [d], p<0.05 CN.

than CY, RN, IH, and CN. IH players were also taller than RN and CN. However, no significant differences were found for the other comparisons.

Between-groups differences in BSI

Non-significant differences emerged for the comparisons between the BSI values for all parameters analyzed (Supplementary Table 1).

Between-groups differences in torque-velocity profile

Significant between-group differences were observed for the isokinetic torque-velocity profile, as shown in Figure 2. Delving deeper, distinct significance was noted in the T_0 ($F=23.752$; $p<0.001$; η^2: 0.514), with CY registering higher values compared to RN and CN ($p<0.001$), and BP and IH showcased higher T_0 compared to RN ($p<0.01$). There was also a main effect of discipline

Table 2. Between-groups differences for VL muscle architecture absolute data.

		CY (n=10)	RN (n=10)	IH (n=10)	BP (n=10)	CN (n=10)	F	*p*-value	η^2
50%	MT_{VL} (mm)	25.9 ± 4.38[a,d]	21.4 ± 3.94[b,c]	28.1 ± 3.08[d]	26.7 ± 2.07[d]	21.4 ± 3.02	16.144	<0.001	0.418
	PA_{VL} (°)	20.8 ± 1.88[a,c,d]	15.0 ± 1.36[b,c]	19.5 ± 1.98[c,d]	16.7 ± 1.21	15.4 ± 1.42	49.667	<0.001	0.688
	Lf_{VL} (mm)	78.5 ± 3.69[a]	87.3 ± 5.71	83.6 ± 7.72	83.4 ± 6.82	83.7 ± 8.31	4.176	0.004	0.157
70%	MT_{VL} (mm)	20.8 ± 3.54[b,c]	18.0 ± 3.32[b,c,d]	25.5 ± 3.01[d]	24.6 ± 1.83[d]	21.1 ± 3.75	17.992	<0.001	0.444
	PA_{VL} (°)	22.9 ± 1.99[a,c,d]	16.8 ± 1.54[b,c]	23.3 ± 2.57[c,d]	19.9 ± 1.46[d]	18.4 ± 1.77	40.426	<0.001	0.642
	Lf_{VL} (mm)	73.2 ± 3.42[a,b,c,d]	83.6 ± 5.29	85.7 ± 7.86	85.7 ± 6.87	86.1 ± 7.85	13.572	<0.001	0.376

Notes: MT_{VL}, muscle thickness; PA_{VL}, pennation angle; Lf_{VL}, fascicle length; [a], p<0.05 RN; [b], p<0,05 IH; [c], p<0.05 BP; [d], p<0.05 CN.

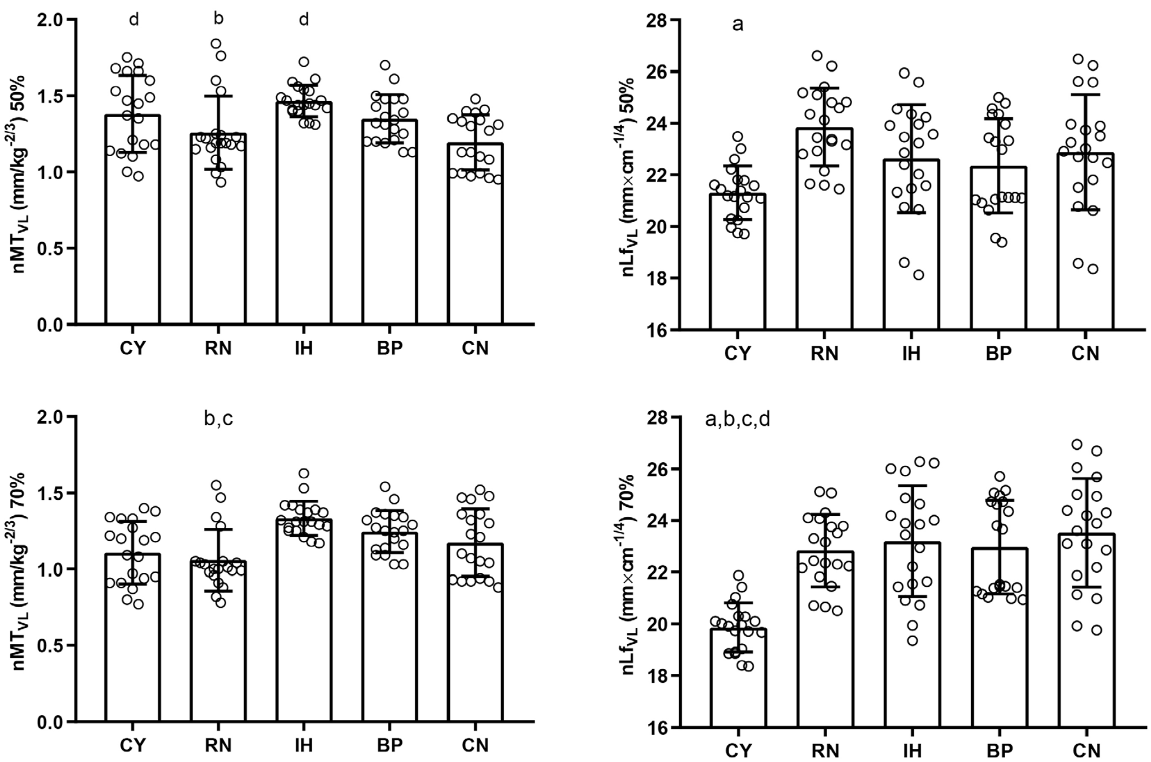

Figure 3. Between-groups differences for VL muscle architecture relative data. Notes: nMT_{VL}, normalized muscle thickness; nLf_{VL}, normalized fascicle length [a], p<0.05 RN; [b], p<0,05 IH; [c], p<0.05 BP; [d], p<0.05 CN.

on V_0 (F=13.536; *p*<0.001; η^2: 0.376). Post-hoc analysis revealed that CY and CN had a lower V_0 compared to RN, IH, and BP (p<0.01). The P_{max} of all athlete groups was higher than that in CN (F=12.028; *p*<0.001; η^2: 0.348). The OA of RN was higher than that of IH, CY, and CN (F=15.104; *p*<0.001; η^2: 0.402) and BP had a higher OA than that of IH and CN (p<0.01).

Between-groups differences in vastus lateralis muscle architecture

There were significant group effects for MT_{VL} (50%: p<0.001; 70%: p<0.001), PA_{VL} (50%: p<0.001; 70%: p<0.001) and Lf_{VL} (50%: p<0.004; 70%: p<0.001), and significant interactions between discipline and anatomical landmark for MT_{VL} (F=5.848; p<0.001; η^2: 0.206), PA_{VL}

Table 3. Between-groups differences for tendon dimensions absolute data.

	CY (n=10)	RN (n=10)	IH (n=10)	BP (n=10)	CON (n=10)	F	*p*-value	η^2
TT_P (mm)	4.84 ± 0.67[a,b,c,d]	3.80 ± 0.56[c]	3.97 ± 0.46	4.29 ± 0.24[d]	3.54 ± 0.39	19.714	<0.001	0.467
TT_M (mm)	4.38 ± 0.65[a,b,d]	3.52 ± 0.49[c]	3.59 ± 0.42[c]	4.24 ± 0.24[d]	3.50 ± 0.39	16.409	<0.001	0.422
TT_D (mm)	3.43 ± 0.53[c]	3.26 ± 0.45[c]	3.21 ± 0.28[c]	4.20 ± 0.23[d]	3.46 ± 0.39	19.379	<0.001	0.463
CSA_P (mm^2)	99.6 ± 9.50[a,b,d]	90.4 ± 8.85[d]	90.7 ± 11.5[d]	96.4 ± 4.25[d]	81.1 ± 9.86	11.398	<0.001	0.336
CSA_M (mm^2)	96.1 ± 10.3[d]	89.2 ± 8.24[d]	88.8 ± 10.8[d]	95.4 ± 4.18[d]	79.6 ± 9.25	10.607	<0.001	0.320
CSA_D (mm^2)	86.2 ± 10.3[c,d]	86.0 ± 9.91[c,d]	82.2 ± 10.9[c]	94.4 ± 3.97[d]	76.1 ± 8.83	10.627	<0.001	0.321

Notes: TT, tendon thickness; CSA, cross-sectional area; P, proximal side; M, medial side; D, distal side; [a], p<0.05 RN; [b], p<0,05 IH; [c], p<0.05 BP; [d], p<0.05 CN.

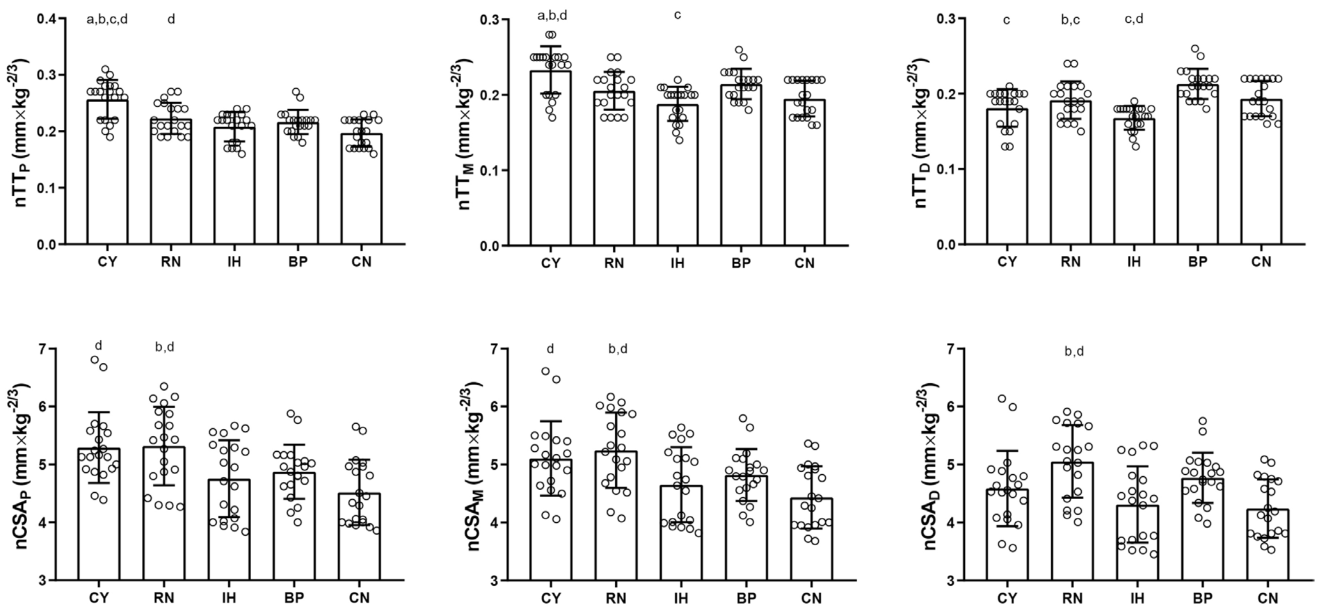

Figure 4. Between-groups differences for PT dimensions relative data. Notes: nTT, normalized tendon thickness; nCSA, normalized cross-sectional area; P, proximal side; M, medial side; D, distal side; [a], p<0.05 RN; [b], p<0,05 IH; [c], p<0.05 BP; [d], p<0.05 CN. [a], p<0.05 RN; [b], p<0,05 IH; [c], p<0.05 BP; [d], p<0.05 CN.

($F=3.048$; $p=0.009$; η^2: 0.119), and Lf_{VL} ($F=5.232$; $p<0.001$; η^2: 0.188). The interaction indicates that the impact of discipline differed between the 50 and 70% locations of the VL (Table 2). Specifically, at the 50%-point, IH, BP, and CY exhibited notably higher MT_{VL} values compared to RN and CN ($p<0.001$), while at the 70%-point, IH and BP demonstrated higher MT_{VL} figures in contrast to CY, RN, and CN ($p<0.001$). CY and IH emerged with the largest PA_{VL} at both anatomical locations ($p<0.001$). At both 50 and 70%, CY displayed lower Lf_{VL} compared to all other groups (50%: $p<0.004$; 70%: $p<0.001$).

After normalization for anthropometric parameters, significant interactions between discipline and anatomical landmark were observed for nMT_{VL} ($F=3.317$; $p<0.001$; η^2: 0.128) and nLf_{VL} ($F=3.741$; $p<0.001$; η^2: 0.142) (Figure 3). The between-group differences remained statistically significant, although the effect size was reduced at both the VL 50% [nMT_{VL}: $F=5.721$; $p<0.001$; $\eta^2=0.203$]; [nLf_{VL}: $F=5.015$; $p<0.001$; $\eta^2=0.182$], and 70% anatomical landmark [nMT_{VL}: $F=7.006$; $p<0.001$; $\eta^2=0.381$]; [nLf_{VL}: $F=13.876$; $p<0.001$; $\eta^2=0.381$] (Figure 3). At the 50%-point, it's notable that CY and IH exhibited higher nMT_{VL} values compared to CN (p<0.001). Furthermore, CY demonstrated superior nMT_{VL} values compared to RN (p<0.001). At the 70%-point, RN displayed lower nMT_{VL} relative to CY, IH, and BP (p<0.001). The nLf_{VL} was lower in CY than in RN at both, 50 and 70% location (p<0.001) and at 70% CY had the lowest nLf_{VL} compared to all other groups (p<0.001).

Between-groups differences in patellar tendon dimensions

Significant interactions between discipline and anatomical landmark were observed for TT (F=3.834; p<0.001; η^2: 0.185) and CSA (F=3.125; p=0.003; η^2: 0.122), indicating that the discipline-specific adaptations differed between the proximal, middle and distal location of the tendon (Table 3). Significant between-group differences in PT dimensions were observed for both TT and CSA at each of the three different anatomical landmarks, as shown in Table 3. More in detail, CY, followed by BP, exhibited the highest TT_p and TT_M values (p<0.001). However, when considering the TT_D point, BP had greater values compared to the other groups (p<0.001). This pattern concerning various anatomical landmarks was also observed in the case of the PT CSA.

After normalization for two-third power body mass significant interactions between discipline and anatomical landmark remained for nTT (F=3.917; p<0.001; η^2: 0.188) and nCSA (F=3.246; p=0.002; η^2: 0.126) (Figure 4). The between-group differences remained significant, although the effect size was reduced for PT TT, [TT_p: F=13.319; *p*<0.001; η^2=0.372; TT_M: F=9.589; *p*<0.001; η^2=0.299; TT_D: F=10.831; *p*<0.001; η^2=0.325]; and for CSA [CSA_P: F=6.385; *p*<0.001; η^2=0.221; CSA_M: F=5.969; *p*<0.001; η^2=0.210; CSA_D: F=6.322; *p*<0.001; η^2=0.219] (Figure 4). Moreover, the post-hoc analysis corroborated analogous trends to those observed for the absolute values of PT TT and CSA across the three different anatomical landmarks.

Discussion and Implications

Our findings demonstrate that chronic training, irrespective of discipline, leads to a significant increase in maximal power production of knee extensors when compared with non-specifically trained physically active subjects. This enhancement can be attributed to a higher optimal velocity, maximal torque, or a combination of both, depending on the discipline and its exercise-specific requirements and resulting remodeling stimuli. Specifically, RN produced a high power through a greater knee extensor velocity, while CY exhibited larger torques. BP and IH benefitted from a combination of both factors. Such specific functional adaptations were to some extent explicable by specific musculotendinous structural adaptations, such as a smaller MT and larger Lf_{VL} in the RN, and a larger PA, resulting in a lower shortening velocity but higher torque per muscle volume, in the CY.

Discipline-specific adaptations in torque-velocity relationships

Here it was shown that the higher power of the athletes of different sports disciplines than non-athletes may be attributable to a higher maximal torque production capacity and/or contraction velocity of the knee extensors. Such specific adaptations may be related to the different demands on the muscles in various sport disciplines. For instance, the higher T_0 observed in CY, IH and BP, is consistent with the high demands of strength to push high gears in case of CY, and to maintain joint stability and the ability to absorb and distribute forces during athletic movements, such as jumping, change of directions and sprinting in case of IH and BP[31–33]. In contrast, RN does not require high forces, and may explain why RN had a lower torque generating capacity than the other groups.

CY were the athletes with the largest PA_{VL}, consistent with previous observations[3,8]. Muscles with a larger PA can accommodate thicker fibers, and hence more sarcomeres arranged in parallel, resulting in a higher force capacity for a given muscle volume that may contribute to their high torque generating capacity[13]. The CY group also exhibited the lowest V_0, which may be due to the need for the athletes to maintain a steady cadence requiring not as high contraction velocities as seen in quick turns in IH and BP. The high loads (gear combinations) used by CY, combined with the requirements of pedaling biomechanics may therefore explain the greater PA_{VL} observed in CY[34,35].

RN had a smaller MT_{VL} compared to CY, BP and IH, and given that muscle size plays a pivotal role in determining maximal torque production capacity[36] it is not surprising that they had the lowest torque generating capacity of all the athlete groups, further accentuated by their smallest PA. The small PA and long fascicles - Lf reflects the number of sarcomeres arranged in series - has a positive impact on the muscle's maximal contractile velocity and capacity to produce force at high contractile velocity[13,37].

The IH, BP groups had even higher values for optimal contraction velocity than RN, which may reflect the need for quick and explosive movements in their respective sports. This faster contraction velocity in IH and BP than RN cannot be ascribed to differences in Lf or PA, as Lf was similar between RN, and IH and BP, and PA was even higher in the latter two groups. Perhaps the IH and BP may benefit from having a higher proportion of fast type IIx and IIa fibers than RN[38,39]. This, however, should then result in a higher power generating capacity than in RN, but there was no significant difference between RN, and IH and BP. We therefore have no clear explanation for the higher speed of contraction in the IH and BP than RN. Nevertheless, the high PA is beneficial for generation of large forces required during quick explosive movements, such as rapid changes of direction, in these sports.

It is important to note that no significant differences were observed between the groups in terms of maximal power, except when compared to the CN group. This may suggest that while the different sports may require different optimal torque production capacities and contraction velocities, they may ultimately result in similar maximal power outputs. Overall, these findings highlight that the manner in which peak power is generated is discipline-specific, where one group shows a 'velocity' and another more a 'torque' adaptation.

Discipline-specific musculotendinous adaptations

The links between muscle size, architecture and the *in vivo* isokinetic torque-velocity relationship have been studied for a long time and, as discussed above, may contribute to the differences between disciplines in knee extensor torque-velocity relationship[40].

Part of the discipline-specific adaptations may be caused by differences in prevalence of concentric contractions and stretch shortening cycles, as well as the variation in muscle operating lengths that have been reported to elicit different musculoskeletal adaptations[3,8,41]. For instance, concentric contractions -as in cyclists- involve shortening of the muscle fibers, while stretch-shortening cycles -as in RN, but also IH and BP- involve an eccentric contraction followed immediately by a concentric contraction. Eccentric contractions are known to result in a greater stretch of the muscle fibers, and thus may result in hypertrophic adaptations characterized by a lower PA compared to concentric contractions[5]. Therefore, the different prevalence of contraction types utilized in these sports could contribute to the observed differences in PA. Accordingly, the Lf in CY, experiencing only concentric contractions, was smaller than that in RN, IH and BP. From a functional perspective, RN, BP and IH, may benefit from increased Lf, as fibers containing more sarcomeres in series contract at a higher velocity than one containing fewer sarcomeres. This would be reflected in enhanced running, sprinting and jumping performance[2,42]. Taken together and in accordance with previous hypotheses[41,43], these differences may indicate that the structural adaptations of the muscle are dependent on the intensity of the mechanical stimulus, the range of motion utilized during different exercise modalities, and the use of eccentric and/or concentric muscle contractions[41,43].

In further support of this, previous studies have shown that concentric training elicits muscle hypertrophy through a large increase in PA_{VL}, occurring mainly in the central region of the VL, while training with eccentric contractions elicits hypertrophy characterized by an increase in Lf_{VL} and over a larger portion including the distal side[44]. Although the regional hypertrophy and architectural differences observed in our cross-sectional comparisons are not as remarkable as that emerged from interventional studies involving isolated concentric *vs*. eccentric training[44], we still detected differences in experienced athletes belonging to different sports and in turn, exposed to distinct chronic remodeling stimuli. Furthermore, we observed that RN and BP, characterized respectively by increased Lf and the greater MT_{VL} at the distal side of the VL, reached their peak torque at longer muscle lengths compared to IH and CY, which peaked torque at shorter muscle lengths. These findings are consistent with previous observations that have shown lower optimal knee extensor lengths for CY compared to Australian rules football players[3] or RN[41]. These findings lend further support to the potential connections between the noted variations in muscle architecture and the muscle's contractile capacity.

Mechanical loading will not only have an impact on muscle structure and function but will also affect tendons[15]. When normalized for body mass, RN emerged as the group with biggest CSA_{PT}. These observations are consistent with previous cross-sectional comparisons between different athlete populations[4,15]. The need to maintain a sufficient ultimate strength or to reduce operating stresses may drive tendon hypertrophy in athletes exposed to high magnitude or volume of loading. This explains the significantly larger tendon dimensions in CY and RN than the CN group and corresponds with the notion that in CY, the PT and quadriceps tendon are subjected to high loads[45] and the observation that PT dimensions in RN are among the highest compared to other athletes[4,31]. Yet, it is surprising to us that IH, where knee shear stresses seem to be greatest and may contribute to lateral knee pain such as iliotibial band inflammation and lateral collateral knee ligament rupture, among the most prevalent reported injuries[32], had the smallest tendon dimensions of the athletic groups. Whatever the explanation for our observation in IH, taken together our data and the literature suggest that the load intensity and volume as well as the specificity of the stressors applied to the PT do at least partly determine tendon adaptations, where differences in adaptations at different anatomical landmarks may potentially reflect the areas in which peak stress is reached during the different activities.

Future directions and limitations

The present study highlighted differences in contractile and morphological musculotendinous properties between different groups of athletes. Future work could assess specific musculotendinous adaptations to discipline-specific training programs in non-athletes. Moreover, a valuable pursuit would involve pinpointing the specific morphological and contractile properties of musculotendinous structures that are associated with optimal athletic performance in different sports. This knowledge could inform tailored training programs and enhance our comprehension of the fundamental mechanisms driving athletic performance. Indeed, an in-depth understanding of the discipline-specific adaptations of musculotendinous structures could inform training programs to enhance athletic performance, minimize risk of injury, and optimal recovery after an athletic event or injury. The application of the information from our study may also benefit the wider population by informing exercise prescriptions to improve musculoskeletal health and physical function across diverse age and patient groups.

While the study examined athletes from a variety of sports, the sample did not include athletes from all possible sports or disciplines. This may limit the generalizability of the findings to other sports or populations and measurements in larger sample sizes that include more heterogeneous sport disciplines may help. One potential limitation of the present study is that we did not study women, but we have no reason to believe that the observed discipline-specific adaptations in the musculotendinous structure and function would differ between men and women. Another potential limitation is that the study focused solely on the knee extensors and did not examine other muscle groups. It is conceivable that different muscle groups will show different discipline-specific adaptations and therefore conclusions about the overall musculoskeletal characteristics of athletes in different sports need further research. Additionally, incorporating antagonist muscles like the knee flexors could have offered further valuable insights into the observed dynamics. We acknowledge that our morphological data were collected at rest with the leg in an extended position. While this approach is commonly used, it could be considered a limitation, because they may not represent the dynamic nature of muscle behavior during active contraction, exercise, or sport performance. Future research should consider employing dynamic ultrasound analysis to provide a more comprehensive exploration of discipline-specific differences in changes in muscle architecture and their influence on muscle function during a contraction. Finally, the study did not include functional performance testing to assess how the observed differences in muscle and tendon properties translate to actual performance in the different sports.

In conclusion, the comparison of torque-velocity profiles, muscle architecture and tendon dimensions underscore the discipline-specific adaptations, where in one discipline velocity is sacrificed for torque (like in cyclists) and in another discipline torque is sacrificed for velocity (runners). These discipline-specific functional adaptations are to a large extent explicable by discipline-specific adaptations in muscle architecture, such as a large pennation angle and short fascicles in cyclists and a high pennation angle (torque adaptation) and long fascicles small pennation angle (velocity adaptation) in runners.

Ethics approval

The research protocol adhered to the Declaration of Helsinki and was approved by the Ethics Committee of the Lithuanian Sports University (NR. MNL-SVA (M)-2023-614).

Consent to participate

All subjects voluntarily signed a written informed consent prior to participating in the study.

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Supplementary Table 1. Between-groups differences for BSI values.

		CY (n=10)	RN (n=10)	IH (n=10)	BP (n=10)	CON (n=10)	$F_{(4,45)}$	*p*-value	η^2
50%	BSI_{VLMT}	2.75 ± 1.68	4.43 ± 0.59	2.03 ± 6.40	3.12 ± 2.50	0.46 ± 2.99	1.796	0.146	0.137
	BSI_{VLPA}	2.75 ± 1.83	2.26 ± 1.99	-2.08 ± 14.1	1.82 ± 3.01	1.16 ± 1.37	0.838	0.509	0.069
	BSI_{VLLf}	-0.38 ± 1.86	-1.36 ± 1.09†	0.96 ± 2.95	-0.82 ± 1.01	-0.77 ± 0.55	2.620	0.047	0.188
70%	BSI_{VLMT}	2.98 ± 1.68	4.62 ± 0.61	2.04 ± 6.65	3.31 ± 2.49	0.61 ± 2.99	1.790	0.148	0.137
	BSI_{VLPA}	2.37 ± 1.11	1.90 ± 2.13	-2.73 ± 14.6	1.50 ± 3.19	0.84 ± 1.40	0.896	0.474	0.073
	BSI_{VLLf}	-0.24 ± 1.71	-1.22 ± 1.49	0.86 ± 2.76	-0.69 ± 1.46	-0.65 ± 1.04	1.919	0.124	0.145
	BSI_{TTP}	1.71 ± 1.49	1.67 ± 1.75	1.64 ± 1.63	1.57 ± 2.01	1.45 ± 0.32	0.044	0.996	0.004
	BSI_{TTM}	1.24 ± 0.93	1.74 ± 0.90	1.15 ± 1.73	1.71 ± 1.62	0.93 ± 0.18	0.849	0.502	0.070
	BSI_{TTD}	1.94 ± 1.37	2.62 ± 0.85	1.48 ± 1.94	2.52 ± 1.29	1.46 ± 0.29	1.868	0.133	0.130
	BSI_{CSAP}	1.77 ± 1.35	2.15 ± 1.29	1.51 ± 0.98	2.39 ± 1.35	1.45 ± 0.32	1.290	0.288	0.103
	BSI_{CSAM}	1.12 ± 1.13	1.71 ± 0.97	1.49 ± 0.94	2.04 ± 1.43	0.93 ± 0.18	1.899	0.127	0.144
	BSI_{CSAD}	1.94 ± 1.37	1.86 ± 1.13	1.44 ± 0.95	2.30 ± 0.99	1.46 ± 0.29	1.252	0.303	0.100
	BSI_{TO}	1.78 ± 10.7	3.17 ± 2.39	-0.85 ± 14.2	3.42 ± 2.83	3.06 ± 3.35	0.482	0.749	0.041
	BSI_{VO}	-1.59 ± 10.8	-0.90 ± 4.63	0.81 ± 18.7	-1.22 ± 5.61	-2.30 ± 4.86	0.124	0.973	0.011
	BSI_{Pmax}	0.04 ± 7.20	1.57 ± 4.50	3.44 ± 8.38	2.14 ± 7.78	0.84 ± 5.76	0.354	0.840	0.030
	BSI_{OA}	-2.80 ± 5.82	-3.03 ± 6.93	-6.34 ± 8.99	-3.28 ± 4.91	-4.27 ± 5.35	0.487	0.745	0.041

Supplementary Table 2. List of abbreviations.

Abbreviation	Definition
BP	Basketball players
BSI	Bilateral symmetry index
CN	Control subjects
CSA	Cross-sectional-area
CY	Cyclists
IH	Ice hockey players
Lf	Fascicle length
OA	Optimal angle
PA	Pennation angle
P_{max}	Peak power
PT	Patellar tendon
RN	Runners
T_O	Optimal torque
TT	Tendon thickness
V_O	Optimal velocity
VL	Vastus lateralis muscle