Short communication

Muscular strength and power are correlated with motor unit action potential amplitudes, but not myosin heavy chain isoforms in sedentary males and females

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ABSTRACT

It remains unclear if the sizes of higher-threshold motor units (MU) are associated with muscular strength and power. Therefore, the purpose of this study was to examine sex-related differences in muscle cross-sectional area (mCSA), percent myosin heavy chain (%MHC) isoform expression, and the MU action potential amplitudes ($MUAP_{AMPS}$)-recruitment threshold (RT) relationships of the vastus lateralis and isometric peak torque, isokinetic peak torque and mean power at 1.05 rad·s^{-1} of the leg extensors. Surface electromyographic decomposition techniques were used to quantify $MUAP_{AMPS}$ recorded during isometric muscle actions at 70% of maximal voluntary contractions and regressed against RTs with the slopes calculated. Ultrasound images were used to measure mCSA. Males had greater slopes from the $MUAP_{AMP}$-RT relationship than the females ($P < 0.05$). The greater slopes likely reflected larger higher-threshold MUs for the males. The mCSAs and slopes from the relationships were strongly correlated with isometric and isokinetic peak torque and isokinetic mean power (r = 0.78–0.82), however, type I %MHC isoform was only moderately correlated with isometric peak torque (r = −0.54). The results indicated that sex-related differences in muscular strength and power were associated more so with the sizes of the higher-threshold MUs (slopes) and mCSA than MHC isoforms. The amount of cross-bridge activity within muscle fibers that comprise higher-threshold MUs may be the primary contributor to muscular strength and power rather than the contractile properties of the muscle.

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1. Introduction

On average, females are weaker and possess lower muscular power than males (Danneskiold-Samsoe et al., 2009; Lee et al., 2017) with the differences typically attributed to muscle cross-sectional area (mCSA) (Schantz et al., 1983). Underlying mechanisms related to mCSA, such as, contractile properties of the muscle and sizes of higher-threshold motor units (MUs) may further explain sex-related differences in muscular strength and power. Myosin heavy chain [MHC] isoform composition is a valid measure of contractile properties of skeletal muscle and is correlated with histochemical derived percentage of fiber type area (Fry et al., 1994; Andersen and Aagaard, 2000; Staron et al., 2000). Typically, males display a greater percentage of type II MHC isoform (Staron et al., 2000) that may explain greater muscular strength and power in comparison to females (Aagaard and Andersen, 1998). However, mixed results are reported when examining the influence of MHC isoform composition and/or fiber type area on muscular strength and power during isokinetic muscle actions (Thorstensson et al., 1977; Ivy et al., 1981; Schantz et al., 1983; Froese and Houston, 1985). Conceivably, there may be other factors that better explain sex-related differences in muscular strength and power than MHC isoform composition.

Increases in excitatory synaptic input to the MU pool results in orderly recruitment of MUs that possess larger diameter fibers, action potential (AP) amplitudes, and twitch forces (Hakansson,

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1956; Milner-Brown et al., 1973; Milner-Brown and Stein, 1975; Goldberg and Derfler, 1977). Presumably, larger diameter fibers located in higher-threshold MUs possess more cross-bridge activity that creates greater twitch forces (Trappe et al., 2003). The orderly recruitment of larger MUs can be quantified on a subject-by-subject basis via the slope from the MUAP amplitude-recruitment threshold relationship (Pope et al., 2016; Trevino et al., 2018). Trevino et al. (2018) reported that the sex-related differences in the slopes from the MUAP amplitudes-recruitment threshold relationships were correlated with mCSAs of the vastus lateralis (VL). Therefore, the increase in MUAP amplitudes with increments in recruitment thresholds was greater for the males and was associated with larger higher-threshold MUs. Thus, the sizes of higher-threshold MUs significantly contribute to mCSA and may explain a greater portion of the variance in muscular strength and power than the MHC isoform composition of the muscle.

Therefore, the purpose of this study was to measure mCSA, MHC isoforms, slope from the MUAP amplitude-recruitment threshold relationship, isometric peak torque, and isokinetic peak torque and mean power during an isokinetic muscle action at 1.05 rad·s^{-1} for males and females. It is hypothesized that size of higher-threshold MUs, or the slopes from the relationships, will better explain sex-related differences in muscular strength and power than MHC isoform composition.

2. Methods

2.1. Subjects

Twenty-two healthy individuals (age = 20.4 ± 2.1 yrs; height = 172.3 ± 10.3 cm; mass = 70.8 ± 17.0 kg) who reported no participation in any structured exercise for the previous 3 years volunteered. All subjects read and signed an informed consent form.

2.2. Ultrasound

During the first visit, ultrasound images were used to measure anatomical mCSA of the vastus lateralis in accordance to Dimmick et al. (2018). Distance from the anterior superior iliac spine to the superior border of the patella on the right leg was measured and a mark was placed at 50% of total leg length. The participants laid in a supine position for 10 min to allow fluid shifts to occur. A portable brightness mode (B-mode) ultrasound imaging device with a multi-frequency linear-array probe (12 L-RS; 5–13 MHz; 38.4-mm field of view) in conjunction with GE logiq e Logic View software was used to generate real-time images. A probe support was positioned perpendicular to the longitudinal axis of the thigh and fastened with a strap to ensure the probe movement in the transverse plane. The scan depth was set to 4.5 cm, gain was 68 dB, and transducer was 10 MHz to optimize image quality. The panoramic function was used to obtain a mCSA image. Ultrasound images were assessed using ImageJ software (National Institutes of Health, Bethesda, MD). The muscle was outlined using the polygon function.

2.3. Leg extension measurements

Participants were familiarized to the isometric and isokinetic testing (Biodex Medical Systems, Shirley, NY) during visit 1 and completed the experimental testing during visit 2. Participants performed three isometric maximal voluntary contractions (MVCs) with strong verbal encouragement for motivation followed by sub-maximal isometric trapezoid muscle actions at 70% MVC. For the isometric trapezoid muscle actions, the torque was increased at 10% MVC/s to the desired torque level, where it was held during 10 s plateau and then decreased to baseline at a rate of 10% MVC/s (Herda et al., 2015).

For the isokinetic muscle actions, the range of motion for the isokinetic leg extension muscle actions was set from 0° to 90°, with 0° representing full extension. Each subject performed submaximal warm-up isometric leg extension muscle actions followed by three maximal voluntary muscle actions at 1.05 rad·s^{-1}. Isokinetic peak torque (N m) was calculated as the highest mean value for any consecutive 50 data points (25 ms) during the load range and mean power (W) was calculated as the product of the average torque × velocity during the load range (Jenkins et al., 2015).

2.4. Electromyography (EMG) recording and decomposition

During the isometric muscle actions, surface EMG signals were recorded from the VL using a 5-pin surface array sensor (Delsys, Boston, MA). The Precision Decomposition (PD) III algorithm (version 4.1.1.0) was used for decomposition of EMG signals (Nawab et al., 2010). The 70% MVC was chosen for the study as the PD III algorithm yields MUs with a wide range of recruitment thresholds and action potential amplitudes. The PD III algorithm provides 4 unique MUAP action potential waveforms for the 4 EMG channels. Only MUs with >90% accuracies assessed via the Decompose-Synthesize-Decompose-Compare test were used for further analysis (Nawab et al., 2010) and a spike trigger average (STA) technique was applied to validate MUs action potential waveforms generated via the PD III algorithm as previously described (Hu et al., 2013; McManus et al., 2015). For each MU using for analyses, recruitment threshold (RT) and MUAP amplitude (Fig. 1) were calculated
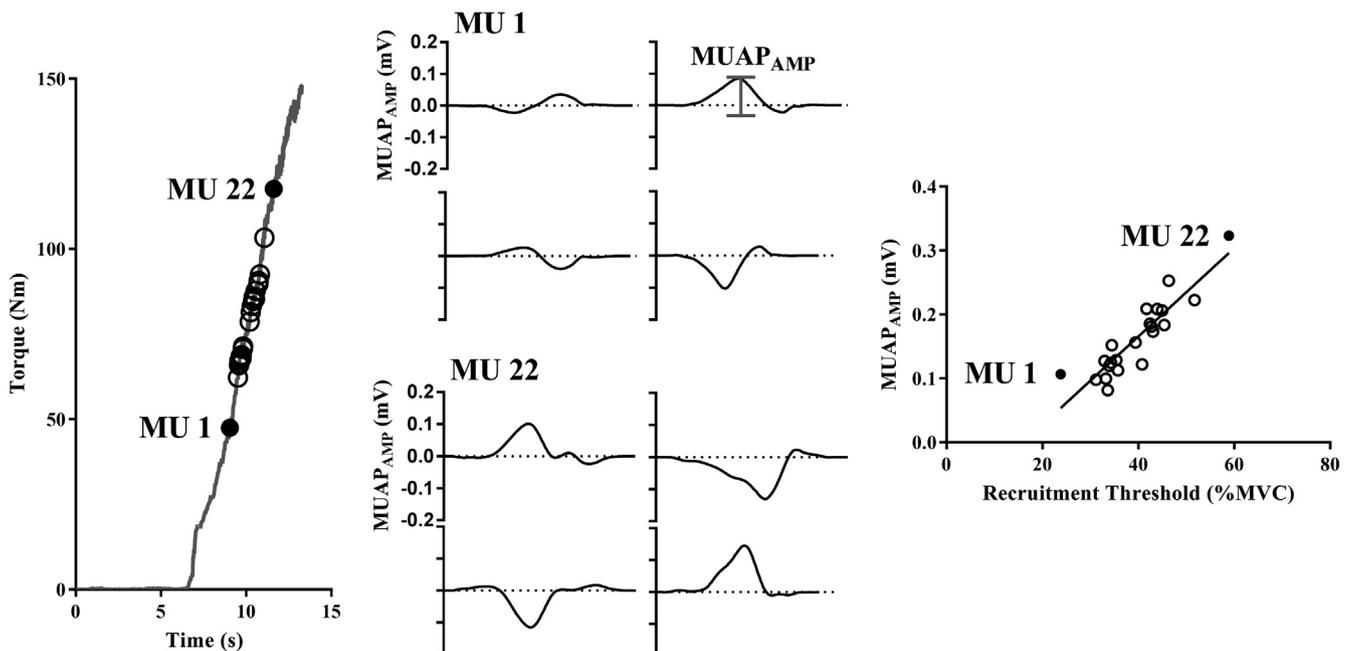
Fig. 1. Left graph: the recorded motor units (MU) (circles) overlaid on the torque tracing of the linear increasing segment of the isometric trapezoidal muscle action (gray line) for one subject. Middle graphs: the plotted MU action potential waveforms (MUAP) for channels 1–4 for the first recruited recorded MU (MU 1) and last recruited recorded MU (MU 22). The gray bracket represents the calculated MUAP$_{AMP}$ for that channel. Right graph: the plotted the MUAP amplitude (MUAP$_{AMP}$) vs. recruitment threshold (expressed as a percentage of maximal voluntary contraction [%MVC]) relationship with the line of best from the calculated linear regression model for the selected subject.

as described by Trevino et al. (2018). For each MUAP, the average of the peak-to-peak amplitude (MUAP$_{AMP}$) for each of the four, unique action potential waveform templates were used for further analysis (Fig. 1) (Trevino et al., 2018). Linear regression models were fitted to the MUAP$_{AMP}$-RT relationships for each subject with the slopes calculated. A small recorded RT range of MUs for a subject could result in spurious coefficients from the regressions because of minimal changes in the peak-to-peak amplitudes and would lack physiological meaning (Pope et al., 2016). In addition, recording only lower-threshold MUs with RTs <30% MVC will not allow for interpretation of the amplitudes of the higher-threshold MUs (Pope et al., 2016), which are the MUs of interest for the present study. Therefore, for a contraction to be used for statistical comparisons, the RT ranges for each subject must be >30% MVC and included MUs with RTs >45% MVC. Seven males (age = 19.6 ± 0.5 yrs) and seven females (age = 21.4 ± 3.0 yrs) met the inclusion criteria for the MUAP$_{AMP}$-RT relationships.

2.5. Muscle biopsy

Muscle biopsies were taken from the VL with the percutaneous needle biopsy methods of Bergstrom (1962) utilizing the double-chop and suction method (Staron et al., 1990) following the isometric and isokinetic testing during visit 2. For detailed information regarding subject preparation and follow-up, and biopsy storage, and SDS-PAGE methods to examine MHC isoforms, refer to Trevino et al. (2018). The MHC isoforms (types I, IIA, and IIX) were identified according to their molecular masses and expressed as a percentage (Staron and Hikida, 1992).

2.6. Statistical analysis

Independent samples *t*-tests were used to examine possible differences in mCSA, isometric and isokinetic peak torque, isokinetic mean power, and the slopes from the MUAP$_{AMP}$-RT relationships between sexes. A two-way mixed factorial ANOVA (sex [male vs. female] × MHC [I vs. IIA] was used to examine possible differences in %MHC isoforms between sexes. Type IIX %MHC isoform was not included in the ANOVA model as it is not statistically independent of the other MHC isoforms. Pearson's product moment correlations were calculated comparing the slopes from the MUAP$_{AMP}$-RT relationships and type I, IIA, and IIX %MHC isoforms with mCSA, isometric and isokinetic peak torque, and isokinetic mean power. Finally, Pearson's product moment correlations were calculated comparing mCSA with isometric and isokinetic peak torque and isokinetic mean power. The level of significance was set at P ≤ 0.05.

3. Results

Descriptive information regarding recorded MUs and the MUAP$_{AMP}$-RT relationships are presented in Table 1.

The males had significantly greater mCSA (P = 0.004), isometric peak torque (P = 0.001), isokinetic peak torque (P = 0.002), isokinetic mean power (P = 0.013) (Table 2), and slopes from the MUAP$_{AMP}$-RT relationships (P = 0.003) than the females (Fig. 2).

For %MHC, there was a two-way interaction (P = 0.015). There were no significant sex-related differences for type I %MHC isoform (P = 0.118), however, males had significantly greater type IIA % MHC isoform (P = 0.018) (Table 2). Type IIX %MHC isoform is presented in Table 2.

3.1. Correlations

The slopes from the MUAP$_{AMP}$-RT relationships were significantly correlated with mCSA (r = 0.66, P = 0.010), isometric peak

Table 1
The mean (SD) for the number of motor units (MU) recorded, the lowest- and highest-recruitment threshold (RT, expressed as a percentage of maximal voluntary contraction) of the recorded MUs, and the r values from the MU action potential amplitude versus RT relationships for the males and females.

	MU count	Lowest-RT	Highest-RT	r
Male	26.3 (5.9)	19.2% (2.8%)	55.7% (6.6%)	0.80 (0.10)
Female	19.4 (6.4)	23.6% (6.3%)	62.0% (6.1)%	0.80 (0.07)

Table 2
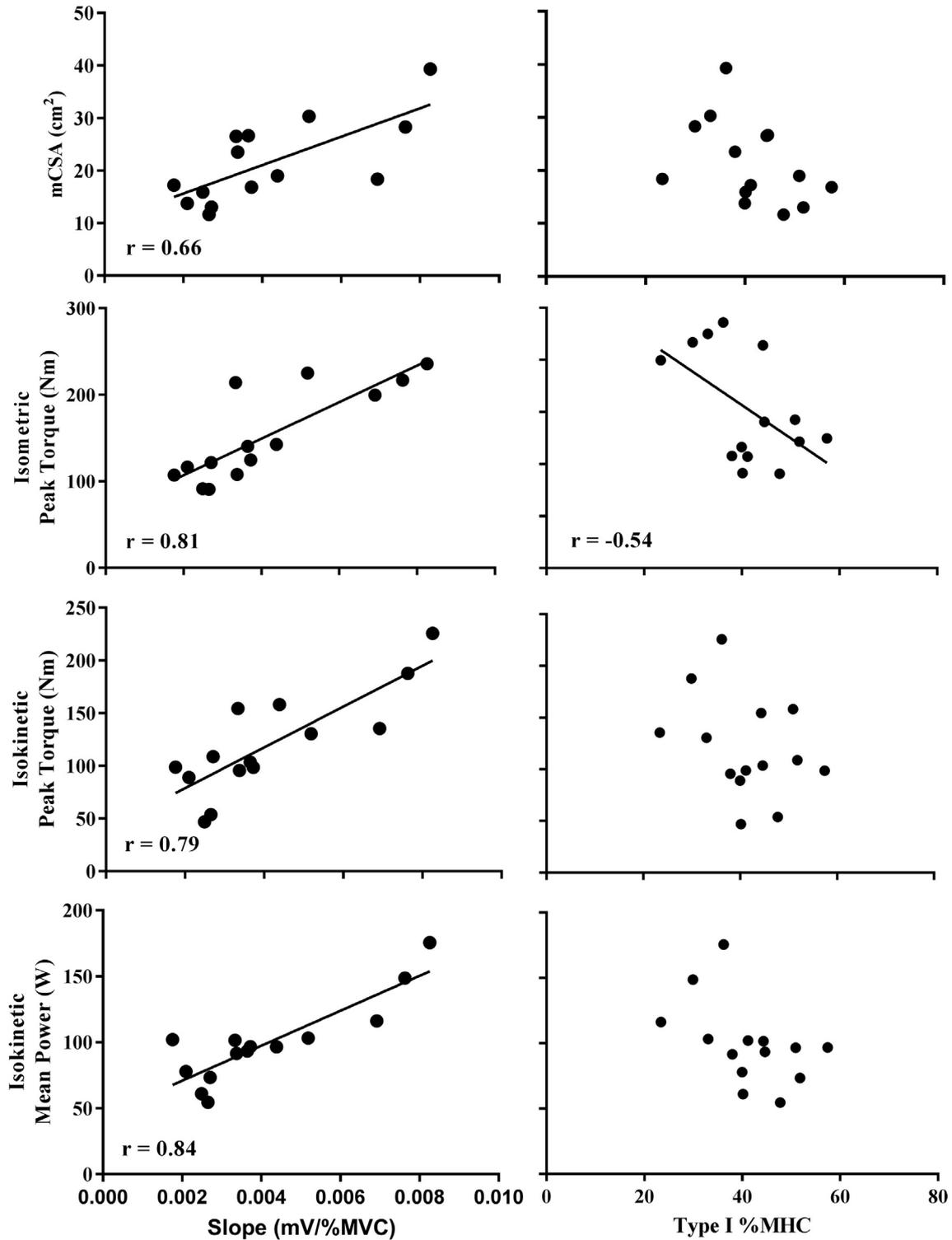The mean (SD) for muscle cross-sectional area (mCSA, cm^2), isometric and isokinetic peak torque (N m), isokinetic mean power (W), and the percent myosin heavy chain (%MHC) isoforms for the males and females.

	mCSA	Isometric peak torque	Isokinetic peak torque	Isokinetic mean power	Type I %MHC	Type IIA %MHC	Type IIX %MHC
Male	26.9 (7.1)*	196.4 (39.1)*	156.6 (40.1)*	119.3 (31.1)*	37.5 (9.6)	48.0 (9.6)*	14.5 (13.4)
Female	16.7 (4.5)	108.5 (13.6)	82.2 (23.3)	73.8 (16.0)	45.2 (7.3)	34.2 (9.3)	20.6 (8.2)

* Indicates significant differences between sexes (P < 0.05).
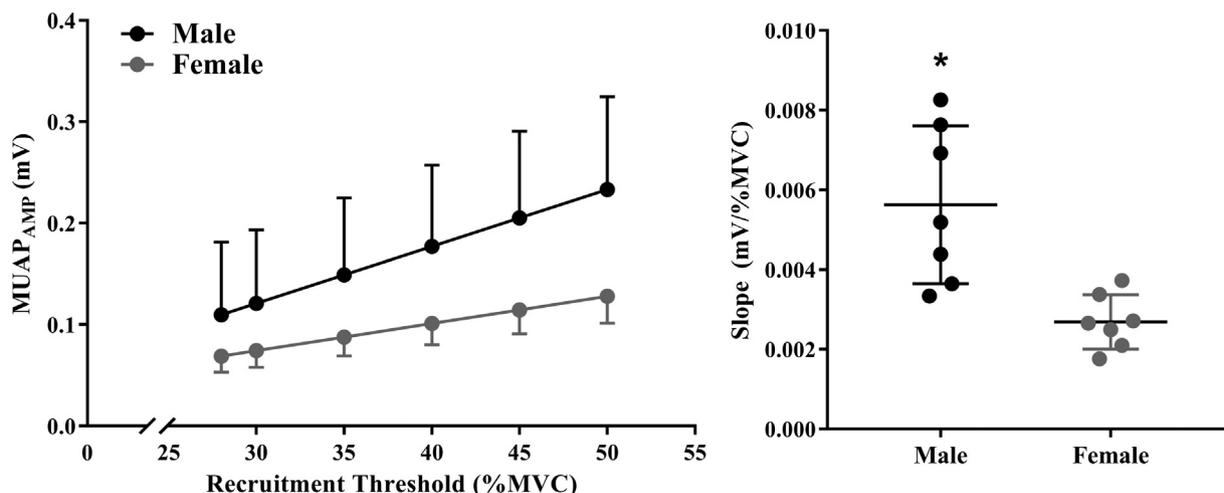
Fig. 2. Left graph: the plotted composite MUAP$_{AMP}$ vs. recruitment threshold relationships calculated via the slope and y-intercept from the linear regression model for each subject. All subjects had MUs recorded for the presented recruitment threshold ranges (i.e., 28–50% MVC). Right graph: the slopes from the motor unit action potential amplitudes (MUAP$_{AMP}$) vs. recruitment threshold (expressed as a percentage of maximal voluntary contraction [%MVC]) relationships for females and males. * indicates significant differences between sexes.

Fig. 3. Left graphs: the plotted relationships between the slopes from the motor unit action potential amplitudes *vs.* recruitment threshold relationships with muscle cross-sectional area (mCSA), isometric peak torque, isokinetic peak torque, and isokinetic mean power with the line of best from the linear regression model. Right graphs: the plotted relationships between type I percent myosin chain (type I% MHC) with CSA, isometric peak torque, isokinetic peak torque, and isokinetic mean power with the line of best from the linear regression model.

torque (r = 0.81, P < 0.001), isokinetic peak torque (r = 0.79, P = 0.001), and isokinetic mean power (r = 0.84, P < 0.001) (Fig. 3) and mCSA was correlated with isometric peak torque (r = 0.80, P = 0.001), isokinetic peak torque (r = 0.77, P = 0.001), and isokinetic mean power (r = 0.82, P < 0.001).

Type I %MHC isoform was not significantly correlated with mCSA (r = −0.40, P = 0.162), isokinetic peak torque (r = −0.32, P = 0.273), and isokinetic mean power (r = −0.47, P = 0.092), however, type I %MHC isoform was significantly correlated with isometric peak torque (r = −0.54, P = 0.048) and the slopes

(r = −0.59, P = 0.028) from the MUAP$_{AMP}$-RT relationship. Type IIA %MHC isoform was significantly correlated with mCSA (r = 0.66, P = 0.010) and the slopes (r = 0.55, P = 0.040) from the MUAP$_{AMP}$-RT relationships, however, was not significantly correlated with isometric peak torque (r = 0.52, P = 0.058), isokinetic peak torque (r = 0.37, P = 0.190), and isokinetic mean power (r = 0.44, P = 0.118). Type IIX %MHC isoform was not significantly correlated with any of the variables (r = −0.36 to −0.07, P = 0.207–0.841).

4. Discussion

The males possessed larger mCSAs and larger slopes from the MUAP$_{AMP}$-RT relationships, greater muscular strength and power, and greater type IIA %MHC isoform in comparison to the females. Similar to Trevino et al. (2018), the slopes from the MUAP$_{AMP}$-RT relationships were correlated with %MHC isoform and mCSA. A significant and novel finding was that the greater relative increase (greater slopes) in MUAP$_{AMPS}$ in relation to RT of the VL accounted for large portions of the variances in isometric and isokinetic strength and mean power of the leg extensors, unlike for the % MHC isoforms where only type I and IIA %MHC were moderately correlated with isometric peak torque.

The AP$_{AMP}$ has been previously reported to reflect the twitch force of the MU with larger twitch forces generated from MUs with larger AP$_{AMPS}$ (Milner-Brown et al., 1973; Goldberg and Derfler, 1977), which likely is a result of greater cross-bridge activity (Trappe et al., 2003). The greater slope from the MUAP$_{AMP}$-RT relationships indirectly indicates larger higher-threshold MUs that would coincide with greater twitch forces (Milner-Brown et al., 1973, Goldberg and Derfler, 1977). Therefore, the diameter of fibers and cross-bridge activity that comprise the higher-threshold MUs are likely significant contributors to muscle CSA and muscular strength and power.

Previous studies have indicated that fast-twitch fiber area is correlated with peak torque during isokinetic muscle actions (Thorstensson et al., 1977; Ivy et al., 1981; Aagaard and Andersen, 1998) while others have reported no significant relationships (Schantz et al., 1983; Froese and Houston, 1985). Schantz et al. (1983) reported that isokinetic peak torque at velocities from 0.52 to 3.14 rad·s^{-1} were correlated with mCSA, but not with fiber type area and concluded that peak torque during isokinetic muscle actions may not be strictly dependent on muscle fiber area of the VL. The results from the present study support these conclusions and suggests that the sizes of the higher-threshold MUs is of greater importance to maximal muscular strength and power than MHC isoforms in sedentary individuals. A limitation of this study, however, is that MHC isoform and MUAP amplitudes were only analyzed for the VL and could vary slightly amongst the leg extensors (Johnson et al., 1973).

Conflict of interest

The authors declare no conflict of interests, financial or otherwise.

Acknowledgement

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