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Motor unit firing rates of the first dorsal interosseous differ between male and female children aged 8–10 years

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ABSTRACT

The purpose of this study was to examine possible differences in motor unit action potential amplitudes ($\text{MUAP}_{\text{AMPS}}$) and firing rates of the first dorsal interosseous (FDI) in male and female children aged 8–10 years. Eight male (mean ± SD, age = 8.8 ± 0.7 yrs; BMI = 16.5 ± 1.3 kg/m^2) and eight female (age = 9.3 ± 0.9 yrs; BMI = 16.1 ± 1.5 kg/m^2) children volunteered to complete isometric trapezoidal muscle actions of the first dorsal interosseous at 50% of maximal voluntary contraction (MVC). Electromyographic signals were decomposed to yield $\text{MUAP}_{\text{AMPS}}$ and mean firing rates (MFR) at the targeted force. An exponential model was fitted to the $\text{MUAP}_{\text{AMPS}}$ vs. recruitment threshold (RT) while linear models were fitted to the MFRs vs. RT relationships for each subject. Ultrasonography determined the muscle cross-sectional area (CSA) of the FDI. Independent samples *t*-tests were used to examine possible differences between the male and female children for MVC strength, CSA, and the coefficients from the MU relationships. There were no differences in MVC strength, CSA, or the MUAP_{AMP} vs. RT relationships between the male and female children ($P < 0.05$). Males, however, had greater MFRs of lower-threshold MUs as evident by significantly larger y-intercepts ($P = 0.019$) and more negative slopes ($P = 0.004$) from the MFR vs. RT relationships. Despite no differences in muscle strength, CSA, and $\text{MUAP}_{\text{AMPS}}$, differences in firing rates existed between male and female children aged 8–10 years. Neural mechanisms may primarily contribute to sex-related differences in firing rates.

1. Introduction

There is evidence that young male and female children differ in fine motor control tasks of the hand (Poole et al., 2005; Rueckriegel et al., 2008). Rueckriegel et al. (2008) reported higher automation and lower variability in hand movement for young female children. In addition, Poole et al. (2005) reported that female children possessed better fine motor dexterity via quicker times in the 9-hole Peg test and times improved with age regardless of sex. Therefore, limited evidence suggests that fine motor control of the hand may differ as a function of biological sex in young children. The activation of motor units (MUs) are responsible for the movements to complete these tasks, however, no investigations have examine potential differences in motor control at the motor unit

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(MU) level in young male and female children.

During submaximal isometric voluntary efforts in humans the lower-threshold MUs are reported to have greater firing rates at targeted forces when reported on a contraction-by-contraction basis (Carpentier, Duchateau, & Hainaut, 2001; Farina et al., 2009; Holobar, Farina, Gazzoni, Merletti, & Zazula, 2009; Kamen, Sison, Du, & Patten, 1995; Masakado, Noda, Chino, Nagata, & Kimura, 1995; Nawab, Wotiz, & De Luca, 2008; Person & Kudina, 1972). Therefore, reporting the MU firing rates in relation to force at recruitment (recruitment threshold) and the calculation of y-intercepts and slopes provides detailed information regarding the MU firing rate scheme of the muscle at a targeted force (Contessa, De Luca, & Kline, 2016; De Luca & Contessa, 2012; De Luca & Hostage, 2010; Hu, Rymer, & Suresh, 2013b). The y-intercept would indicate the firing rates of the recorded lower-threshold MUs while the negative slope provides an estimate of the rate of decline in the firing rates with increments in recruitment thresholds. An examination of potential differences in the firing rate scheme of the muscle may provide further evidence that motor control does differ between young male and female children.

Recently, it was reported that the first dorsal interosseous (FDI), the primary contributor to abduction of the index finger, of young children achieved greater MU firing rates to complete the same relative isometric force trajectory in comparison to adults (Miller, Sterczala, Trevino, & Herda, 2018). The authors hypothesized that for the children a greater level of co-contraction of antagonist muscles during the same relative force trajectory led to greater activation of the primary agonist muscle (FDI) to complete the task. The greater activation would increase the MU firing rates of the muscle (De Luca & Contessa, 2012; De Luca & Hostage, 2010). Therefore, the reported (Poole et al., 2005) poorer fine motor dexterity in children likely led to greater activation of agonist and antagonists (co-contraction) muscles during the isometric force trajectory task in comparison to the adults. It is plausible that MU firing rates of the FDI may be greater in young male children as a function of poorer fine motor dexterity in comparison to young female children.

It is well understood that MUs are recruited according to action potential amplitudes with the earlier recruited (*lower-threshold*) being smaller in amplitude than the later recruited (*higher-threshold*) MUs (Goldberg & Derfler, 1977; Martinez-Valdes, Negro, Falla, De Nunzio, & Farina, 2018; Milner-Brown & Stein, 1975). In addition, the action potential amplitudes are associated with the twitch forces generated by the MU (Goldberg & Derfler, 1977; Milner-Brown & Stein, 1975; Milner-Brown, Stein, & Yemm, 1973). Therefore, MUs with smaller action potential amplitudes are recruited earlier and generate less force than the larger later recruited MUs. The relative increase in MU action potential amplitudes relative to recruitment threshold is correlated with muscle cross-sectional area (CSA) (Trevino et al., 2018). The slopes from the MU action potential amplitude vs. recruitment threshold relationships indicated that the difference in sizes between the lower- and higher-threshold MUs was greater for the males (more positive slope value) than females (Trevino et al., 2018). The authors suggested that the greater disparity in sizes between the lower- and higher-threshold MUs was a result of larger diameter skeletal muscle fibers within the higher-threshold MUs for the males. Therefore, the greater CSAs in males was a function of larger diameter skeletal muscle fibers that comprise the higher-threshold MUs in comparison to females. In addition, Herda et al. (2019) reported that the relative increase in MU action potential amplitudes relative to recruitment threshold significantly contributed to greater muscular strength and power in males in comparison to females. Subsequently, these non-uniform differences in MU action potential amplitudes may partially explain the reported sex-related differences in MU firing rates between adult males and females (Peng, Tenan, & Griffin, 2018). Therefore, mechanical mechanisms (MU twitch forces) partially explain differences in firing rates between adult males and females.

The central nervous system (CNS) provides excitation to the MU pool to match a task and adjustments to excitation will occur to accommodate changes in the MU twitch forces (Contessa et al., 2016). Non-uniform differences in MU action potential amplitudes between young female and male children similar to adults could result in differences in excitation from the CNS that could explain differences in firing rates during the targeted force trajectory. However, previous research has reported similar strength and CSA of various muscles between young male and female children < 10 years of age (Grosset, Mora, Lambertz, & Perot, 2005; Hager-Ross & Rosblad, 2002; Kanehisa, Yata, Ikegawa, & Fukunaga, 1995; Lambertz, Mora, Grosset, & Perot, 2003; Rauch et al., 2002; Wind, Takken, Helders, & Engelbert, 2010) that suggests that there would be similarities in the MU action potential amplitudes and twitch forces. It is speculated that there will be no sex-related differences in strength, CSA, or MU action potential amplitudes of the FDI. Subsequently, any potential differences in MU firing rates would primarily be neural (co-contraction) rather than mechanical (MU twitch forces) in origin.

Therefore, the purpose of this study was to examine MU action potential amplitudes and firing rates for the FDI during an isometric trapezoid force trajectory that reaches 50% of maximal voluntary contraction (MVC) of young male and female children aged 8 to 10 years. The 50% MVC was chosen as the majority ($> 99\%$) of the MUs would be recruited prior to that targeted force (De Luca & Contessa, 2015). Ultrasound images will be taken to measure CSAs of the FDI. The results from this study could provide support for the inclusion of MU recordings during isometric trapezoid force trajectories to assess fine motor dexterity in young female and male children.

2. Methods

2.1. Subjects

Eight male (mean ± SD, age = 8.8 ± 0.7 yrs; body mass = 31.8 ± 4.4 kg; height = 138.7 ± 7.5 cm; BMI = 16.5 ± 1.3 kg/m^2) and eight female (age = 9.3 ± 0.9 yrs; body mass = 32.4 ± 4.8 kg; height = 141.8 ± 8.6 cm; BMI = 16.1 ± 1.5 kg/m^2) children with no current/recent musculoskeletal injuries volunteered to participate. The parents completed the Children's Physical Activity Questionnaire. Male children were reported to participate in 4.2 ± 2.2 hrs/wk of physical activity while the females participated in 4.8 ± 2.4 hrs/wk of physical activity. This study was approved by the University's institutional review board for human subject research, with each parent providing written consent and child providing verbal assent.

2.2. Research design

The participants visited the laboratory two times separated by at least 24 h. The first visit was for familiarization followed by an experimental trial. During the first visit the participants practiced the maximal and submaximal isometric contractions that would be performed during the experimental trial. Ultrasonography scans of the FDI were completed during the familiarization trial in order to determine the muscle anatomical CSA and subcutaneous fat (sFAT).

2.3. Ultrasound images

Ultrasound images were taken of the right FDI according to previous methods (Miller et al., 2017) using a LOGIQe ultrasound-imaging device (GE Healthcare UK, Ltd., Chalfont, Buckinghamshire, UK). For each scan ultrasound brightness mode (B-mode), the musculoskeletal preset, and a GE 12L-RS Linear Ultrasound Transducer (5–13 MHZ), with a 42 × 7 mm footprint was used. The scan depth was set to 2 cm, gain was 38 dB and transducer frequency was 12 MHz. The midway point between the origin and insertion was measured and considered the site for the mid CSA. Once the mid CSA site was determined, a cross section of the muscle belly was scanned with the probe oriented perpendicular to the 2nd metacarpal. Muscle anatomical CSA (cm^2) and sFAT (mm) were determined using the image analysis program ImageJ (National Institutes of Health, Bethesda, Maryland). sFAT was measured from the bottom of the cutaneous layer to the top of the superficial fascia of the muscle, using the mid-point of the cross-section of the muscle as a reference point. The periphery of the muscle was carefully outlined using the polygonal tool and the CSA was calculated from this outlined area.

2.4. Isometric strength

The subject's right forearm was pronated and positioned on a table with the hand open. The forearm, wrist, and third to fifth fingers were immobilized with a Velcro strap. The thumb was restrained with a strap that allowed for a 90° angle between the index finger and thumb during the isometric contractions. The muscle action of the FDI was isolated and measured by instructing the participants to abduct the index finger against a small flat piece of metal connected to the force transducer (MB-100; Interface, Inc., Scottsdale, AZ). Subjects performed three maximum voluntary isometric muscle actions (MVCs) with strong verbal encouragement. Two minutes of rest between each contraction. The peak force from the three MVCs was used to determine the target force amplitude for the 50% MVCs. For each submaximal isometric muscle action force was increased at a rate of 10% MVC/s to the target force, and decreased at a rate of 10% MVC/s back to baseline (Fig. 1). The target force was maintained for 10 s for the 50% MVCs. Each participant was given at least two minutes of rest between the contractions. During the isometric contractions participants maintained their force output as close as possible to the force template displayed digitally on a computer monitor.

2.5. EMG recording

During the trapezoid muscle actions, surface EMG signals were recorded using 5-pin surface array sensor (Delsys, Inc., Natick, Massachusetts). The diameter of each pin is 0.5 mm that are placed at the corners of a 5 × 5-mm square, with the fifth pin in the center of the square. Before sensor placement, the surface of the skin was prepared by shaving, removing superficial dead skin with adhesive tape (3M, St. Paul, Minnesota) and sterilized with alcohol. The sensor was secured by adhesive tape. The reference electrode was placed over the elbow of the right arm.

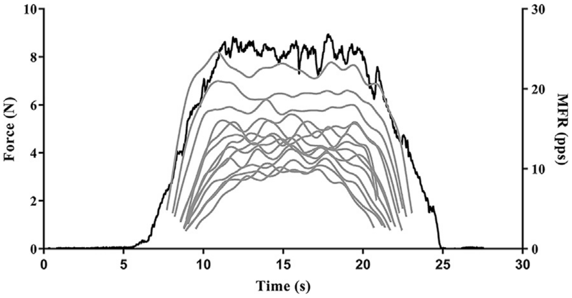

Fig. 1. An example of the mean firing rate (MFR) plots of detected motor units (MU) recorded from the 5-pin surface array sensor during the isometric trapezoidal contraction for one child. The black line is the torque output of the participant (N, left axis) and the gray curves represent the MFR in pulses per second (pps, right axis) across time for each detected MU.

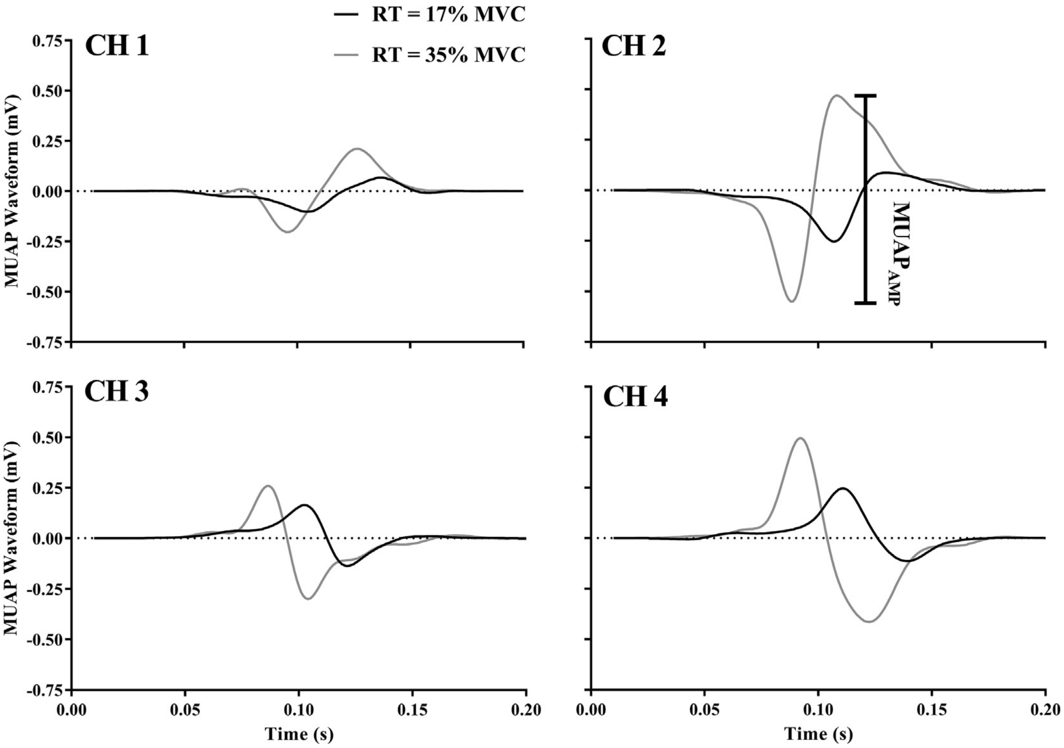

Fig. 2. Motor unit action potential (MUAP) waveforms recorded from the 4 separate electromyographic channels for a lower-threshold MU recruited at 17% of maximal voluntary contraction (MVC) and higher-threshold MU recruited at 35% for one subject. The MUAP amplitude (MUAP$_{AMP}$, mV) was calculated as the average peak-to-peak amplitude, which is illustrated by the dark bracket drawn from peak-to-peak for channel 2.

2.6. EMG decomposition

Action potentials were extracted into firing events of single MUs from the 4 separate EMG signals via the precision decomposition (PD) III algorithm (De Luca, Adam, Wotiz, Gilmore, & Nawab, 2006). The accuracy of the decomposed firing instances was initially examined with the reconstruct-and-test procedure (Nawab, Chang, & De Luca, 2010). MUs that possessed $>$ 90% accuracies from the reconstruct-and-test procedure were included for analysis. In addition, a secondary validation of the MU firing events and action potential waveforms derived from the PD III algorithm was measured with a spike trigger average (STA) technique. The output from the PD III algorithm consisted of firing times and 4 unique waveforms corresponding to four pairs of electrode channels for each MU. Using the PD III derived firing times the STA technique was performed on each surface EMG signal that resulted in four representative action potential waveforms for each MU (Hu et al., 2013b, 2013c; McManus, Hu, Rymer, Lowery, & Suresh, 2015). The coefficient of variation of the peak-to-peak amplitude from STA derived MU action potential waveforms were calculated over time. This procedure followed the methods of Hu, Rymer, and Suresh (2013a) in that the window length was 4 s and shifted over the surface EMG signal using a *step size* of 1 s. In addition, the maximum correlation coefficients were calculated between the STA and PD III derived action potential waveforms. For the STA derived MU action potential waveform, the composite of the waveform created from all the firing events was used for the correlation with the waveforms generated via the PD III algorithm (Hu et al., 2013b, 2013c; McManus et al., 2015). In accordance with Hu et al. (2013b), MUs included for further analyses must have a correlation coefficient $>$ 0.7 and coefficient of variation $<$ 0.3 across all four channels. For each MU, three parameters were extracted from the firing rate data: (1) the recruitment threshold (RT) expressed relative to percent MVC (%MVC), (2) MUAP amplitude (MUAP$_{AMP}$, mV), and (3) the mean firing rate (MFR) at the targeted contraction level (pps). The RT was the average of 0.10 ms epoch of force that began at the first discharge of the MU. For each MUAP, the average of the peak-to-peak amplitude (MUAP$_{AMP}$) between the peak-to-peak amplitude values for each of the four, unique action potential waveform templates were used for further analysis (Miller et al., 2018) (Fig. 2). The MFR was calculated as the average value of the MFR trajectory during a 10 s epoch at the force level. The coefficient of variation (CoV) of steady force was calculated over the same epoch that MFRs were selected (Adam, De Luca, & Erim, 1998). For each subject, linear regressions were applied to the MFR vs. RT relationships with the slope and y-intercept values used for statistical analysis (Miller et al., 2018) (Fig. 3). In addition, exponential models were fitted to the MUAP$_{AMP}$ ($\text{MUAP}_{\text{AMP}} = Ae^{B(\text{RT})}$) vs. RT relationships for each subject in accordance to Miller et al. (2018) Sterczala, Miller, Trevino, Dimmick, and Herda (2018) (Fig. 3). A small recorded RT range of MUs ($<$ 10% MVC) for a subject could result in spurious coefficients from the regressions that lack physiological relevance. In the present study, the recorded MU RT range from the 50% MVC for each subject exceeded 20% MVC.

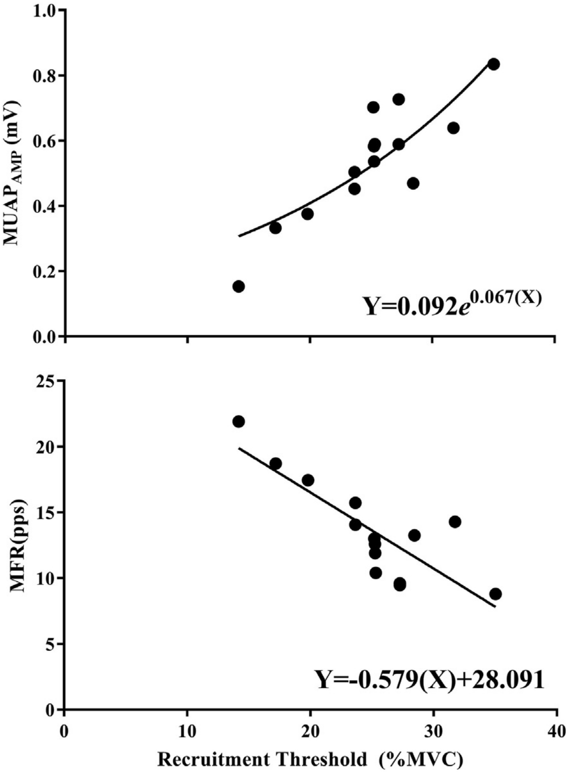

Fig. 3. (Top) The plotted motor unit action potential amplitudes (MUAP$_{AMP}$, mV) and (bottom) mean firing rates (MFR, pps) at steady force vs. recruitment threshold (expressed as percentage of maximal voluntary contraction [%MVC]) relationships for one subject. The equations from the regression models are presented for each relationship.

2.7. Signal processing

The force (N) signal from was recoded with a NI cDAQ (National instruments, Austin, TX, US) during each isometric muscle action. The sampling frequency was 2000 Hz for all signals. The force signal was low-pass filtered with a 10-Hz cutoff (zero-phase fourth order Butterworth filter).

2.8. Statistical analysis

Independent samples t-tests were performed to examine potential sex-related differences in age, BMI, CSA, sFAT, and MVC force, the number of recorded MUs, RT ranges, slopes and y-intercepts from the MFR, vs. RT relationships and *A* and *B* terms from the MUAP$_{AMP}$ vs. RT relationships. In addition, an independent samples *t*-test was performed to examine possible differences in force (% MVC) and CoV of force at which MFR data was obtained during the contraction.

Cohen's *d* effect sizes were calculated in addition to each to provide further interpretation of the data. A small effect size was considered $d = 0.2$, a medium effect size $d = 0.5$, and large effect size $d \geq 0.8$ (Miller et al., 2018).

3. Results

There were no sex-related differences for age (P = 0.232, $d = 0.62$), BMI (P = 0.582, $d = 0.28$), MVC force (P = 0.950,

Table 1
Maximal voluntary contraction (MVC) force (N), cross-sectional area (CSA, cm^2), and subcutaneous fat (sFAT, cm) of the first dorsal interosseous.

		MVC Force	CSA	sFAT
Male	Mean	14.64	1.19	0.26
	SD	2.00	0.14	0.03
Female	Mean	14.53	1.06	0.25
	SD	4.51	0.14	0.11

Table 2
Motor unit (MU) count, recorded recruitment threshold (RT) range (expressed as percentage of maximal voluntary contraction), and *r* values from the relationships for males and females.

		MU counts	RT Range		$\text{MUAP}_{\text{AMP VS RT}}$	MFR vs RT
			Low	High		
Males	Mean	13.4	9.6%	38.5%	0.86	−0.90
	SD	6.2	4.8%	9.7%	0.10	0.05
Females	Mean	15.8	11.5%	37.5%	0.90	−0.91
	SD	5.5	3.3%	6.4%	0.06	0.06

MU action potential amplitude = MUAP_{AMP}; mean firing rate = MFR.

d = 0.03), CSA (P = 0.082, *d* = 0.94), and sFAT (P = 0.763, *d* = 0.015) (Table 1). No significant differences in sFAT provides confidence that the filtering effect of fat was not a confounding variable when interpreting $\text{MUAP}_{\text{AMPS}}$. Table 2 contains the number of recorded MUs, RT ranges, and *r* values from the relationships for the males and females. Each subject's MUAP_{AMP} vs. RT and MFR vs. RT relationships were significant. Composites of these relationships for the male and female children are presented in Fig. 4 and were calculated from each subject's regression coefficients. For each subject, MUs were recorded between the RT ranges of 16% to 30% MVC. Therefore, the predictions presented in Fig. 4 include the RT ranges of MUs recorded for all subjects (i.e., 16% to 30% MVC).

There were significant differences in the slopes and y-intercepts from the MFR vs. RT (P = 0.019, *d* = 1.32; P = 0.004, *d* = 1.70) relationships (Table 3, Fig. 4). The y-intercepts from the MFR vs. RT relationships were greater for the males (35.8 ± 4.1 pps) than females (29.2 ± 3.6 pps). The slopes from the MFR vs. RT relationships were more negative for the males (-0.70 ± 0.15 pps/%MVC) than females (-0.49 ± 0.16 pps/%MVC). There were no significant differences for the *B* and *A* terms from the MUAP_{AMP} vs. RT (P = 0.516, *d* = 0.64; P = 0.699, *d* = 0.20) relationships (Table 3, Fig. 4).

There were no significant differences between groups (P = 0.914) for force (male: 48.7 ± 2.3%, female: 48.3 ± 2.6%) at which the MFR data was obtained during the steady force contraction. In addition, there was no significant differences (P = 0.508) in CoV

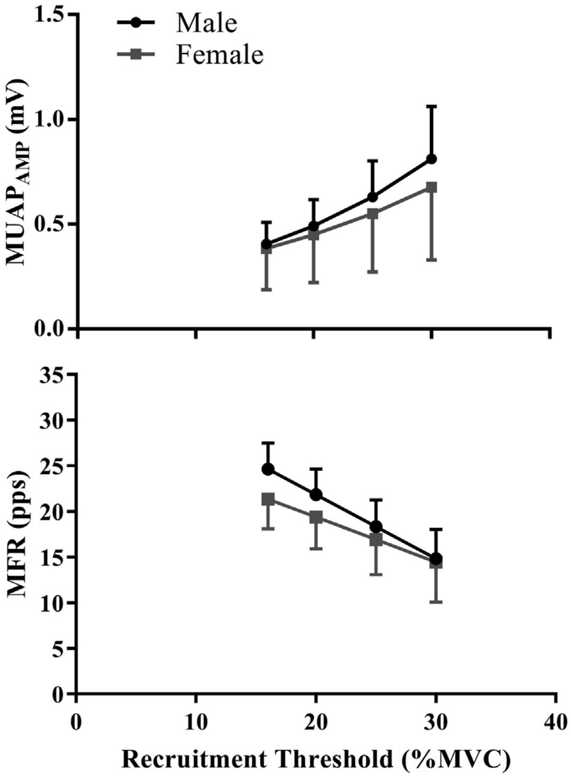

Fig. 4. (Top) The composite (mean ± SD) motor unit action potential amplitude (MUAP_{AMP}, mV) and (bottom) mean firing rate (MFR, pps) at steady force vs. recruitment threshold (expressed as percentage of maximal voluntary contraction [%MVC]) relationships for the male and female children. The composite relationships were calculated via each subject's calculated coefficient values. For each subject, MUs were recorded between the RT ranges of 16% to 30% MVC.

Table 3
The mean (SD) of the coefficients from the motor unit action potential amplitude ($MUAP_{AMP}$) and mean firing rate (MFR) vs recruitment threshold (RT) relationships for the male and female children.

		$MUAP_{AMP}$vs RT		MFR VS RT	
		B Terms	A terms	Slopes	Y-intercepts
Male	Mean	0.049	0.190	−0.700*	35.823*
	SD	0.014	0.067	0.154	4.130
Female	Mean	0.040	0.208	−0.491	29.218
	SD	0.015	0.114	0.160	3.628

* Indicates significant difference between the males and females ($P < 0.05$).

of force between the groups (male: 3.2 ± 2.1%; female 4.0 ± 2.6%). For the FDI, Adam et al. (1998) reported that there were differences in firing rates and CoV of force as a function of hand dominance. In the present study, the similar CoV of force between groups provides evidence that a systematic difference in right hand dominance was not the primary factor in the sex-related differences in firing rates.

4. Discussion

A novel finding was that male children achieved greater MU firing rates than female children during the steady force segment of the trajectory. This was particularly evident for the lower-threshold MUs recorded in the present study (Fig. 4). In contrast, there were no differences in strength, CSA, or the $MUAP_{AMPS}$. Although speculative, a plausible explanation for the differences in firing rates could be neural in origin and related to co-contraction.

Greater excitation or neural drive results in the simultaneous increase in firing rates and recruitment of MUs. For the present study, the majority of MUs of the FDI (> 90%) were likely recruited prior to 30% MVC in the young children (Miller et al., 2018). Therefore, increase in firing rates was the primary mechanism to increment force from 30% to 50% MVC. A potential explanation for the males achieving higher firing rates at the targeted force was the result of greater co-activation of antagonist muscles. For example, the force output of an antagonist muscle will increase with activation. In response, greater activation of the agonist muscle will be required to maintain the target force trajectory. The greater activation or excitation to the agonist muscle, the FDI, in the present study would primarily result in the increase of firing rates (De Luca & Contessa, 2015).

For the FDI, the antagonist muscle during the abduction is the second palmar interosseous. Previous research has indicated activation of the second palmer interosseous via intramuscular electrodes during a similar isometric contraction used in the present study (Burnett, Laidlaw, & Enoka, 2000). Burnett et al. (2000) reported greater activation of the second palmer interosseous with increases in isometric contraction intensity in young and older adults. Activation of the second palmer interosseous can only be measured by intramuscular electrodes. Therefore, intramuscular EMG of the second palmer interosseous was not measured in the present study but could potentially explain the differences in the activation of the primary agonist muscle involved in abduction (FDI) of the index finger. Greater co-contraction could partially explain poorer fine motor dexterity in young male children (Poole et al., 2005).

In the present study, there were no significant sex-related differences in $MUAP_{AMPS}$ in relation to RT, CSA, or isometric strength. However, there was a large and medium effect size for CSA and the slopes of the $MUAP_{AMPS}$ vs. RT relationships. The non-significant differences (13%, 24%) between sexes in the present study does not approach the percent sex-related differences in CSA (~36%) and slopes (~49%) of these relationships in the vastus lateralis for adults presented in Trevino et al. (2019) and Herda et al. (2019). The smaller percent differences in the CSA and slopes of the $MUAP_{AMPS}$ vs. RT relationships between sexes may be a likely reason why it did not manifest into differences in maximal strength in conjunction with the idea that the contribution of firing rates to maximal strength may be overall greater for the FDI in comparison to the vastus lateralis (De Luca & Contessa, 2015). Potentially, sex-related differences in firing rates in adults could be a function of non-uniform differences in the twitch forces of MUs across the recruitment threshold spectrum. For example, MU firing rates are reported to be similar between adult males and females during lower-intensity contractions (Tenan, Peng, Hackney, & Griffin, 2013), however, MU firing rates differ between sexes during higher-intensity contractions (Peng et al., 2018). Trevino et al. (2018) reported similar sizes of lower-threshold, but larger higher-threshold MUs for males in comparison to females. Therefore, at lower contraction intensities similar excitation or neural drive is required to match the same relative force, however, as the intensity of the contraction increases the females would require more excitation or neural drive to overcome the recruitment of progressively smaller MUs in comparison to the males. Therefore, the greater firing rates in adult females at the same relative high-intensity torques as males could be the result of diminishing MU twitch forces with increments in RT and, thus, sex-related differences in firing rates may at least be partially mechanical in origin.

In contrast to adults, the male children possessed greater firing rates than the female children. In addition, these differences existed in absence of significant differences, but slightly larger CSA or $MUAP_{AMPS}$ unlike for the sex-related differences in adults. Therefore, the mechanical properties (*twitch forces*) of the muscle were likely similar or may have favored the males more so than the female children. Subsequently, the results from this study suggest that the greater firing rates in the male children may be neural in origin and related to the reported poorer fine motor dexterity. Future research should simultaneously examine fine motor dexterity of the hand and motor control strategies to match a torque trajectory in children to test this hypothesis.

In summary, there were no differences in FDI strength, CSA, or $MUAP_{AMP}$ vs. RT relationships. In contrast, the male children had greater firing rates of the lower-threshold MUs of the FDI at 50% MVC that contradicts what is reported for adults (Peng et al., 2018). The differences in motor control strategies of the FDI may be related to differences in fine motor dexterity between male and female children. The potential greater co-contraction of antagonist muscles during the isometric trapezoidal muscle action likely resulted in increased neural drive to the FDI to complete the task for the males. Greater neural drive would increase the firing rates of recruited MUs. Further research should focus on co-contraction and neural mechanisms to better understand why differences in firing rates exist in young male and female children and to monitor age-related changes in firing rates from childhood to adulthood.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.04.011.

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