Mean Power Frequency of Boys and Men
during a Progressive Isometric Contractions Protocol to Exhaustion

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Abstract

Background: The mean power frequency (MPF) of an electromyographic (EMG) signal is affected by contraction intensity and muscular fatigability but is also a potential indicator of motor unit (MU) recruitment.

Methods: This study is a secondary analysis (Woods et al. 2019) in which participants (17 boys, 20 men) completed a progressive isometric contraction protocol while EMG was recorded from the vastus lateralis (VL), using tripolar surface electrodes. MPF and EMG threshold (EMGTh) were calculated for each completed intensity. The latter reflects the onset of accelerated increased in higher-threshold MU recruitment. Independent t-tests were used to assess differences between groups in demographic variables, mean MPF (MPFmn), peak MPF (MPFpk), force (%1RM) at MPFpk, and MPF range. An ANOVA for repeated measures was used to assess differences between groups in MPF pattern, interpolated over ten stages. A correlation analysis was used to assess the relationship between %1RM at MPFpk and %1RM at EMGTh.

Results: Both MPFmn and MPFpk were higher in the men, but only reached statistical significance when %body fat was used as a covariate in the statistical analysis. 65% of participants displayed an expected (inverted-U shape) MPF pattern. Within this subset, the %1RM at which MPFpk occurred was significantly higher (i.e., occurred later) in the boys compared with the men. Additionally, a moderate correlation was observed between the %1RM at MPFpk and the %1RM at EMGTh (r = 0.51).

Discussion: Overall, the findings of the current analysis provide support for the hypothesis of lower type-II MU activation in children. The high variability in MPF patterns may be a result of the interaction between confounding factors that affect MPF (intensity and fatigue). Future research should use an exercise protocol that examines MPF under the influence of each factor separately.
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Abbreviations & Keywords

- **CSA** = Cross-sectional area
- **EMD** = Electromechanical delay
- **EMG** = Electromyograph(y/ic)
- **EMG\text{th}** = EMG threshold
- **FCR** = Flexor carpi radialis
- **MFCV** = Muscle fibre conduction velocity
- **MDF** = Median frequency
- **MHC** = Myosin Heavy Chain
- **MPF** = Mean power frequency
- **MPF\text{pk}** = Peak MPF
- **MPF\text{mn}** = Mean MPF
- **MUAP** = Motor Unit action potential
- **MU** = Motor Unit
- **MVC** = Maximal voluntary contraction
- **RMS** = Root mean squares
- **RMS\text{contract}** = RMS calculated for the single contraction
- **RMS\text{mean}** = Average of RMS values of the 5 contractions of each load.
- **RTD** = Rate of Torque Development
- **VL** = Vastus Lateralis
- **VM** = Vastus Medialis
- **\text{VO}_2** = oxygen uptake
Introduction

Children and adults display significant differences in their performance and physiological response to exercise. Adults have been shown to have greater muscle strength than children, even when normalizing for muscle size (Falk et al., 2009) and greater muscle power, as reflected by considerably higher rates of torque development in dynamic and isometric contractions (Asai & Aoki, 1996; Dotan et al., 2013). Children typically have greater muscle endurance and recover from exercise faster than adults. This is demonstrated primarily in various performance measures, but also by a faster return to homeostasis after exercise in terms of acid-base balance and cardiopulmonary responses (Hebestreit et al., 1993). These differences can in part, be explained by changes that naturally occur with growth and development, such as the increase in body size, possible changes in muscle fibre composition, increases in musculotendinous stiffness and increases in neurological activation. None of these factors individually, or in combination with each other can account for all of the physiological differences between children and adults in terms of their response to exercise (Dotan et al., 2012).

A proposed hypothesis that is thought to underlie all of these differences relates to the motor unit (MU) activation patterns in children and adults. It suggests that children are unable to activate their higher-threshold (presumably, type II) motor units to the same extent as adults (Dotan et al., 2012). The hypothesis is based on the Henneman size principle (1985), which states that, as contraction intensity increases, larger muscle fibres are activated. Typically, the type I muscle fibres are smaller, and the type II fibres are larger. Maximal MU activation, as assessed using the interpolated twitch technique, has been shown to be lower in children than in adults (O’Brien et al., 2010). Therefore, as an extension of the Henneman size principle, it is hypothesized that the portion of the MU pool which children do not activate is made up mostly of type II MUs.
Since direct measurements of MU activation relies on invasive techniques (needle electrodes), it is unethical to use in children, and therefore there is little to no research directly assessing MU activation in children. The suggestion of lower type II MU activation in children has been studied using indirect methods to assess MU activation patterns, and several studies have supported this idea (e.g., (Long et al., 2017; Pitt et al., 2015; Woods et al., 2019, 2020).

Indirect methods used to assess MU activation involve the use of surface electromyography (EMG). The mean power frequency (MPF) of the EMG signal is the average frequency of the EMG power spectrum. Changes in the MPF can be reflective of increased type-II MU activation under certain conditions. Specifically, MPF decreases during isometric contractions or fatiguing exercise at moderate to high intensities (Arendt-Nielsen & Mills, 1988), and the rate at which it decreases appears to be positively correlated with contraction intensity (Hagberg, 1981). The higher MPF recorded with greater force output is thought to be the result of a greater utilization of type II MUs with increasing contraction intensity (Camic et al., 2013; De Luca et al., 1996). MPF changes during exercise have been shown to be a reflection of changes in muscle fibre conduction velocity (MFCV) (Arendt-Nielsen & Mills, 1985) and type II MUs have a faster conduction velocity than type I MUs. This not only explains the higher MPF values shown with increasing intensity of non-fatiguing isometric or dynamic contractions (Gabriel & Kamen, 2009; Moritani & Muro, 1987; but it also explains the faster rate of MPF decrease with increasing intensity during fatiguing contractions, since MFCV will decrease at a faster rate with the more rapid de-recruitment of more fatigable type II MUs. Moreover, it has also been shown that MPF decreases at a faster rate during fatiguing contractions in individuals who have a greater distribution of type II fibres (Komi & Tesch 1979), providing further support for the connection between MPF and MU activation. MPF changes during contraction have been consistently demonstrated in adults (Arendt-Nielsen & Mills, 1988; Daanen et al., 1990; Hagberg, 1981), but only in a few studies that have involved children (Callewaert et al., 2012; Halin et al., 2002, 2003). Similar results have been found measuring the
median frequency (MDF) of the EMG signal, which is closely related to MPF and has also been shown to reflect fatigue and MU activation (Bilodeau et al., 2003; González-Izal et al., 2009; Kupa et al., 1995). The purpose of the current research is to examine and compare the pattern of MPF in children and adults during a progressive isometric contractions protocol. Such a comparison would shed light on MU activation and possible maturational changes that occur in MU activation.

**Literature Review**

**Child-Adult Differences in Exercise Response and Muscle Performance**

Children typically have lower muscle strength than adults, even when normalizing for body size. These differences can be seen when children and adults perform a maximal isometric contraction (Asai & Aoki, 1996). Size-normalized explosive strength is also lower in children than in adults, as measured by rate of torque development (RTD) during isometric contractions (Falk et al., 2009). Since explosive strength is dependent on activation of type II motor units, it has been suggested that these differences are related to differences in the activation of type II motor units between children and adults.

It has been found that children exhibit greater muscle endurance (Armatas et al., 2010) and faster recovery times after exercise compared to adults (Hebestreit et al., 1993). This has been demonstrated by earlier onset of muscle fatigue in adults during repeated contractions (Armatas et al., 2010) and by a faster performance recovery in children after high intensity exercise (Hebestreit et al., 1993). Children have also been characterized as having faster VO2 kinetics at the onset of exercise (Fawkner & Armstrong, 2003), less lactate production during exercise (Dotan et al., 2003), and a greater motor unit activation deficit during maximal contractions (O’Brien et al., 2010) when compared to adults. These age-related differences may have various possible explanations, as outlined below.
Possible Explanations for Child-Adult Differences

*Body size*

The most obvious explanation for differences in strength between children and adults relates to differences in body size. However, strength differences are still apparent even after size differences are considered (Falk et al., 2009). This has been shown in studies that compare the strength of children and adults while size-normalizing for body mass (De Ste Croix et al., 2003) or for muscle cross-sectional area (CSA) (Grosset et al., 2008). Therefore, other factors must be at play.

*Musculotendinous Stiffness*

The ability to produce power and perform explosive muscle contractions is directly affected by the stiffness of the tendon which attaches the muscle to the bone. The tendons of a child have been shown to be more compliant than those of an adult and appear to increase in stiffness during growth (Lambertz et al., 2003). Increased musculotendinous stiffness is associated with greater explosive strength, which is characterized by a higher RTD and shorter electromechanical delay (EMD) of a contraction (Cavanagh & Komi, 1979). However, musculotendinous stiffness has been shown to affect mainly the early phases of force development (<~50ms), rather than the later phases (~200ms) (Blazevich et al., 2009). Dotan et al., (2013) demonstrated that boys’ relative torque kinetics were considerably slower than that of men’s at both the early and late contraction phases, meaning that musculotendinous stiffness differences can only partially explain the lower RTD and explosive force production of children.

*Muscle Fibre Composition*

Research regarding changes in muscle fibre composition during growth is limited due to the ethical issues involved in direct analysis (i.e., muscle biopsies) in children. There are only a handful of
studies directly examining muscle fibre distribution differences between children and adults and the results are not conclusive. Some studies suggest none or minimal changes in muscle fibre composition with growth (Glenmark et al., 1992; Kanelisa et al., 1995), while others suggest there may be an increase of up to 10% in type II muscle fibres during growth (Jansson, 1996; Lexell & Downham, 1991). A possible 10% difference in fibre composition may explain many but not all the observed functional differences between children and adults, and therefore there must be another underlying factor at play (Dotan et al., 2012).

Neuromuscular Activation

The amount of MUs that can be volitionally activated during a maximal contraction is lower in children than it is in adults (O’Brien et al., 2010). Volitional MU activation can be assessed by using the interpolated twitch technique, which uses magnetic or electrical stimulation during an MVC to activate 100% of the available MU pool of a muscle. This technique allows researchers to compare an individual’s maximal volitional MU activation with their physiological full capacity, thereby determining the activation deficit. This deficit has been shown to be larger in children than in adults (Grosset et al., 2008; O’Brien et al., 2010). This deficit could explain the observed child-adult differences in maximal strength, but it can only partially explain differences in explosive force, muscle endurance and muscle recovery.

It has been hypothesized that children’s lower volitional MU recruitment reflects their lower ability to activate their type II MUs during exercise (Dotan et al., 2012). This suggestion is based on the size principle of MU recruitment, in which smaller (typically, type I) MUs are recruited first, followed by larger and larger MUs, as is required to produce a desired force (Henneman, 1985). Since type II MUs are recruited last, it is reasonable to assume that the inactive portion of a child’s MU pool is mainly the type II variety. There are currently no studies directly assessing differential MU activation in children due to the invasiveness of the necessary research techniques. Despite the lack of direct evidence, there is a
substantial amount of research that indirectly supports this hypothesis (Dotan et al., 2012). The pattern of MPF changes during isometric contractions may provide additional support (Armatas et al., 2010; Halin et al., 2003), as outlined below.

**Relationship between MPF and root mean square (RMS) of the EMG signal**

The root mean square (RMS) amplitude of the surface EMG signal reflects the sum of the action potential amplitudes of MUs which are firing at a given point in time during a contraction. It has been shown to increase with contraction intensity during dynamic or sustained contractions (Moritani & Muro, 1987; Christie et al., 2009) and is inversely related to MPF during fatiguing exercise (Gerdle et al., 2000; Petrofsky & Lind, 1980; Pincivero & Gear, 2000). As MPF decreases during a sustained submaximal contraction, RMS increases as fatigue accumulates (Christensen & Fuglsang-Frederiksen, 1988; Madelaine et al., 2002). The increase in RMS amplitude that occurs during sustained contractions has been attributed to an increase in neuromuscular activation through rate coding and motor unit recruitment, which is required to maintain force as the contraction continues (Bigland-Ritchie & Woods, 1984; Mathur et al., 2005). The increasing amplitude and decreasing frequency values typically seen during sustained contractions are often considered as indicators of muscle fatigue (Hermans et al., 1999; Petrofsky, 1979) and the varying extents to which these patterns occur may be indicative of the types of MUs being recruited. It has been shown that higher-threshold MUs are characterized by larger spike amplitudes and generate twitches of greater peak tension than lower-threshold MUs (Goldberg & Derfler, 1977). Therefore, it has been suggested that greater increases in RMS with increasing force or fatigue could be due, in large part, to a greater recruitment of type II MUs and their contribution to the EMG signal (Moritani & Muro, 1987), especially when a concomitant decrease in MPF is demonstrated (Gerdle & Fugl-Meyer, 1992). More recent research involving the use of surface EMG decomposition,
which allows for the isolation and analyses of the activity of distinct MUs, has supported this suggestion, as it demonstrates that the increase in motor unit action potential (MUAP) amplitude with fatigue is predominantly due to the recruitment of additional large MUs (presumably type II) to compensate for the reduction in the force-generating capacity of the muscle (McManus et al., 2015).

**Factors that affect MPF**

There are several factors which have been shown to affect the MPF pattern during contractions. These include MFCV, contraction intensity, muscle size and composition, and fatigue. These factors are discussed below. Note that our current knowledge of factors affecting MPF is based on studies in adults (cited below), with very little known about children.

_Muscle Fibre Conduction Velocity_

MFCV affects the frequency content of the EMG signal (Lindström & Magnusson, 1977). Several studies have shown a strong linear relationship between MFCV and MPF during sustained isometric contractions that induce fatigue (Arendt-Nielsen & Mills, 1985; Sadoyama et al., 1983). The average MFCV recorded from sEMG signals during a muscle contraction reflects the average velocity of all the MU action potentials propagating through the recorded location at any given point in time (Farina & Merletti, 2004). Higher-threshold MUs have faster conduction velocities than lower-threshold MUs (Masuda & De Luca, 1991), which explains why MFCV tends to be faster (and MPF higher) during higher-intensity isometric or dynamic contractions (Kupa et al., 1995; Linssen et al., 1991; Pozzo et al., 2004). MFCV also decreases at a faster rate during sustained contractions at higher intensities, which is thought to be due to the de-recruitment of higher threshold, more fatigable MUs (Rainoldi et al., 1999, 2008). Early research suggested that the cause of the reduction in MFCV with fatigue was the accumulation of metabolites (e.g., lactic acid) in the muscle during sustained exercise, which directly slows down the propagation of action potentials along the muscle fibre (Lindstrom et al., 1977; Mortimer et al., 1970).
However, later research points to the accumulation of extracellular potassium ions and subsequent inactivation of extracellular sodium ions during fatiguing exercise as the cause of the reduced membrane excitability that slows down MFCV (Fortune & Lowery, 2009; Mills & Edwards, 1984; Overgaard et al., 1997). Alterations in blood flow have also been shown to influence MFCV during fatiguing exercise (Sjogaard et al., 1988; Zwarts & Arendt-Nielsen, 1988).

While many studies have shown that the decrease in MFCV with fatiguing contractions mirrors the downward shift of the frequency spectrum (Arendt-Nielsen & Mills, 1985; Eberstein & Beattie, 1985; Sbriccoli et al., 2003), others suggest that the MPF decrease cannot be explained by changes in MFCV alone (Bigland-Ritchie et al., 1981; Naeije & Zorn, 1982; Zwarts et al., 1987) Other possible explanations for MPF decreases with fatigue, independent of MFCV, include increased synchronization of MU action potentials (De Luca, 1979; Person & Mishin, 1964) and a decreased discharge rate of fatigued active MUs (Farina et al., 2004). While a full explanation is still unknown, it remains unequivocal that MFCV is the most influential factor directly affecting the frequency spectrum of the EMG signal.

**Contraction Intensity**

MPF has been shown to be highly correlated with force production and contraction intensity (Bilodeau et al., 1990, 1995; Gabriel & Kamen, 2009), as a shift towards higher frequencies of the EMG power spectrum occurs with increasing force of contraction. This can be attributed to the principle of orderly MU recruitment, in which larger MUs, which have faster conduction velocities are recruited to a greater extent with increasing force. Gabriel & Kamen (2009) found that EMG MPF recorded from the biceps brachii increased with contraction intensity up until 80% MVC, with a plateau or slight decrease occurring from 80% to 100% MVC. This plateau in MPF at higher intensities is typically demonstrated when contraction intensity exceeds the recruitment range of the muscle. It was suggested that once all
available MUs are recruited during a high-intensity contraction, any further increases in force are the result of increases in firing rate and MU synchronization (Gabriel et al., 2007). High firing rates and increased MU synchronization increase the probability of temporal overlap between MU action potentials, and the resulting EMG signal would contain larger amplitude spikes with longer durations, thereby potentially decreasing the frequency content of the signal (i.e., leading to a reduction in MPF) (Gabriel & Kamen, 2009; Lenhardt et al., 2009).

Fatigue

The conduction velocity of MU action potentials slows down as a muscle begins to fatigue, affecting the frequency spectrum of the EMG signal. Thus, a reduction in MPF is often regarded as an indicator of muscle fatigue (Arendt-Nielsen & Mills, 1985; Hendrix et al., 2009). Naturally, this decrease in conduction velocity with fatigue emphasizes another aspect of the relationship between contraction intensity and MPF. Since fatigue occurs earlier and develops at a faster rate at higher exercise intensities, due to accumulation of lactate and other metabolites, conduction velocity will slow down more rapidly (Camic et al., 2013; Merletti et al., 1990; Rainoldi et al., 2008). It would therefore be expected that MPF will also decrease at a faster rate during fatiguing higher-intensity contractions. For example, Mastalerz et al. (2012) had professional runners run 400m at four different velocities and found greater decreases in the MPF of both the rectus femoris and the biceps femoris at higher running intensities. These greater decreases occurred despite the fact that running time was shorter with each increase in intensity. It should be noted, however, that only 30 minutes of rest were provided between runs. Therefore, it is possible that cumulative fatigue resulted in a greater decrease in MPF, thus exaggerating the apparent effect of exercise intensity. In an examination of muscle fatigue in the upper trapezius, Bosch et al. (2009) found similar results during prolonged low-intensity repetitive activity. MPF decreased at a greater rate when participants performed contractions during an assembly task at 12% MVC compared to when they performed the same work at 8% MVC, each lasting 3 hours. These
results appear to contradict the work of Arendt-Nielsen et al. (1989), who concluded that during lower intensity (~30% MVC or lower) contractions, MPF would remain stable or slightly increase over time. Arendt-Nielsen et al. (1989) suggested that a small increase in MPF may occur at low contraction intensity, attributed to a progressive recruitment of motor units with higher conduction velocities at a force level that is not sufficiently high to induce significant metabolic perturbations and an associated decrease in MFCV. However, it should be noted that Arendt-Nielsen et al.’s conclusions are based on isometric contractions lasting up to 400 seconds, which may have been too short to induce any metabolic fatigue in their participants. These findings highlight that during sustained exercise, regardless of contraction intensity, changes in MPF appear to reflect fatigue.

**Muscle type and Composition**

EMG studies have shown that MPF is initially higher and decreases at a faster rate during sustained exercise in muscles or individuals with a greater proportion of type II muscle fibres (Goswami et al., 2001; Komi & Tesch, 1979; Kupa et al., 1995; Moritani et al., 1982; Tsuboi et al., 2013). This has been suggested to be explained by the faster conduction velocities of type II MUs, which slow down more quickly during fatigue (Camic et al., 2013; Rainoldi et al., 1999, 2008). The type of muscle examined also appears to influence MPF patterns. While commonly studied arm (e.g., biceps brachii) and leg muscles (e.g., vastus lateralis) tend to respond similarly and according to the patterns described above, other muscles display patterns which sometimes appear contradictory to the above (Farella et al., 2002; Yuen et al., 1989). For example, Farella et al. (2002) found that the EMG MPF of the masseter muscles of young men decreased with increasing bite force, which is contradictory to what is typically seen in larger limb muscles (Bilodeau et al., 1990, 1995; Gabriel & Kamen, 2009). The authors suggest that the findings are likely due to the fact that the type-II fibres of the masseter muscles tend to have smaller cross-sectional areas than the type I muscle fibres (Eriksson & Thornell, 1983). Since MFCV and, by relation, the frequency content of the EMG signal, is highly correlated with muscle fibre CSA and
muscle fibre diameter (Blijham et al., 2006; Methenitis et al., 2016; Sadoyama et al., 1988), it would be expected that the increasing recruitment of smaller type-II MUs of the masseter muscle with increasing bite force would actually lead to a decrease in MPF. It was also noted that the type-1 fibres are located more prominently in the deep masseter muscle, while the majority of type-II muscle fibres, which are increasingly activated with greater bite force, are superficial (closer to recording electrodes) (Farella et al., 2002). These findings are in agreement with the results of Yuen et al. (1989), who examined the masseter and anterior temporal muscles during bite MVCs in men, women, young boys and young girls and found that young girls demonstrated the highest MPF values while adult men had the lowest values. The authors suggested that a gradual conversion of type-II MUs to type I MUs with growth and maturation in the masticatory muscles may explain these results (Yuen et al., 1989).

Other factors affecting the EMG signal

The factors discussed above may affect the pattern of change in MPF. However, there are also several factors which may affect the EMG signal and thereby, also affect the MPF values. These factors include inter-electrode distance, signal rectification and subcutaneous fat, and are discussed in this section.

The thickness of subcutaneous fat under the EMG electrode can have a significant effect on the quality of the EMG signal, as the fat tissue between the muscle and the electrode acts as a filter and determines the transmission distance of the electrical signal (Petrofsky, 2008). A greater skinfold thickness dampens the EMG signal to a greater extent and has been shown to result in lower absolute MPF values (Baniqued et al., 2016; Minetto et al., 2013). Healthy men and boys typically have similar levels of subcutaneous fat (Tanner, 1981). Therefore, subcutaneous fat tissue is generally not expected
to skew the comparison of absolute MPF values between men and boys. However, when groups of differing adiposities are compared (e.g., girls to women), subcutaneous fat tissue must be considered.

The inter-electrode distance in a bipolar configuration has a clear effect on the power spectrum of the EMG signal. Typically, a higher inter-electrode distance shifts the power spectrum towards lower frequencies, thereby decreasing MPF (Elfving et al., 2002). A small inter-electrode distance can capture a wider range of frequencies, including higher frequencies, in the power spectrum, thus resulting in a higher MPF value (Rodriguez-Falces et al., 2015). MPF values are also affected by the type of electrode configuration (Roman-Liu, 2016). For example, Ollivier et al. (2005) showed that Laplacian electrodes presented higher MPF values than bipolar electrodes during isometric contractions of the biceps brachii at varying force levels, likely due to a higher spatial resolution of the bioelectrical signal in the Laplacian configuration (Prats-Boluda et al., 2011).

EMG power spectrum analysis is usually preceded by rectification of the EMG signal, with the purpose of highlighting the low frequency oscillations that are initially overshadowed in the raw data output (Negro et al., 2015). In contrast to the power spectrum of a raw interference EMG signal, the power spectrum of a rectified EMG signal is not equal to the sum of the power spectra of the rectified trains of motor unit action potentials (Farina et al., 2013), and is therefore influenced by a phenomena called amplitude cancellation (Farina et al., 2014). Amplitude cancellation occurs when positive and negative phases of motor unit action potentials overlap, thereby cancelling each other out and reducing the amplitude of the EMG signal (Farina et al., 2014; Keenan et al., 2005). The overall effect is a reduction of the contribution of smaller action potentials to the signal output. These are generally associated with low-threshold MUs (Dideriksen & Farina, 2019; Farina et al., 2008, 2014). While amplitude cancellation is enhanced with increasing neural drive to the muscle (Farina et al., 2008; Keenan et al., 2005), the extent to which the rectified EMG power spectrum is distorted is not yet fully understood (Dideriksen & Farina, 2019).
Relationship between MPF and MU Recruitment

The use of surface EMG variables to investigate MU recruitment strategies, although imperfect, has shown promising results. The most frequently discussed argument for its use points to MFCV as the link between MPF and MU recruitment. In the investigation of sprinters and distance runners, Sadoyama et al. (1988) concluded that muscle fibre composition could be estimated from MFCV, measured with surface electrodes. Since MFCV is so closely related to the frequency spectrum of the EMG signal (Arendt-Nielsen & Mills, 1985; Eberstein & Beattie, 1985; Sadoyama et al., 1983; Sbriccoli et al., 2003; Stulen & De Luca, 1981), it has been suggested that MPF patterns during exercise may offer some insight into MU recruitment strategies as well (Bernardi et al., 1999; Qi et al., 2011; Solomonow et al., 1990).

Type II MUs not only generate greater amounts of force, but they also consist of muscle fibers with higher propagation velocities than type I MUs (Andreassen & Arendt-Nielsen, 1987), which can explain why both MFCV and MPF increase with increasing force (Bilodeau et al., 1990, 1995; Gabriel & Kamen, 2009). Both MFCV and MPF have been shown to decrease during fatiguing exercise or sustained contractions (Arendt-Nielsen & Mills, 1985; Hendrix et al. 2009; Sbriccoli et al., 2003), and these parameters are reduced more rapidly and to a greater extent during activities of higher intensities (Broman et al., 1985; Hagberg, 1981; Mathur et al., 2005; Zwarts & Arendt-Nielsen, 1988). It has been proposed that since a higher intensity contraction is utilizing a greater proportion of type II MUs, the rapid de-recruitment of these MUs as the muscle fatigues, leads to a greater loss of the recorded average MFCV, thereby decreasing MPF to a greater extent (Camic et al., 2013; Rainoldi et al., 1999, 2008) (see also section on Fatigue, above). The greater twitch force potentiation displayed in type 2 MUs which would be counteracted by equally greater decreases in firing frequency in order to maintain a constant force output during an isometric contraction, offers another possible explanation for the differences in the rate of MPF decrease with different contraction intensities (De Luca et al., 1996). More direct evidence for the relationship between MPF and MU recruitment was provided by Seki &
Narusawa (1998) who showed a strong positive correlation between the MPF, maximal amplitude, and maximal twitch tension of a given MU during a sustained low intensity contraction of the first dorsal interosseus (FDI) muscle, indicating a direct relationship between the size of a MU and the spectral characteristics of its MUAPs. The authors concluded that the spectral characteristics of the MUAPs reflect the size of the MUs from which they originate, with larger, presumably type II MUs, displaying higher maximal amplitudes, larger twitch tensions, and higher MPF values (Seki & Narusawa, 1998).

The EMG frequency spectrum during a sustained isometric contraction appears to follow a similar pattern during both maximal and submaximal contractions, in which MPF progressively decreases. While the mechanisms by which this pattern occurs appears to be different in the two types of contractions, in both cases it has been suggested that MU recruitment and fibre type affect the rate at which the MPF reduction occurs. Arendt-Nielsen et al., (1989) argued that during isometric contractions below 30% MVC, MFCV and MPF tend to remain constant or even increase, likely because these low forces are insufficient to induce fatigue to the extent that measurable changes in conduction velocity occur. However, at fatiguing submaximal exercise, above 30% MVC, MPF tends to decrease, and this is thought to be a result of the progressive recruitment of larger and more fatigable MUs, in an attempt to maintain force, whereby greater amounts of lactate and metabolic by-products accumulate, causing a decrease in membrane excitability and slowing down of conduction velocity in active MUs (Arendt-Nielsen & Mills, 1985; Gerdle & Fugl-Meyer, 1992; Gonzalez-Izal et al., 2009; Hill et al., 2018; Kato et al., 1981; Krogh-Lund & Jorgensen, 1991).

In contrast to a sustained submaximal contraction, in which the effort needed to maintain a target force is progressively increasing thereby resulting in a need for recruitment of additional MUs, a maximal isometric contraction is characterized by complete volitional activation of the functional MU pool at the onset of contraction. During a sustained MVC, maximal effort is theoretically maintained but force inevitably begins to decrease, due to the de-recruitment of fatigable high-threshold MUs. The
inactivation of MUs during a sustained MVC is likely the result of the same accumulations of interstitial potassium ions and losses in membrane excitability that would occur during a submaximal contraction (Camic et al., 2013; Fortune & Lowery, 2009; van Dieën et al., 2009) and this explains why decreases in EMG MPF occur during both maximal and submaximal contractions, regardless of whether more, fresh MUs are being recruited or more fatigued MUs are being de-recruited. For example, Gerdle & Fugl-Meyer (1992) tested the plantar flexors of ten healthy female subjects during both a maximal and a submaximal fatiguing exercise protocol. The authors found that MPF decrease was significantly more prominent during the maximal test than the submaximal test in all muscles tested, and this may be attributed to the quicker fatigue and greater losses in MFCV, or the greater tendency for synchronization of firing and temporal overlap of MUAPs at maximal and near-maximal intensities (Gabriel & Kamen, 2009; Gabriel et al., 2007; Gerdle & Fugl-Meyer, 1992; Lenhardt et al., 2009).

While there is a substantial amount of evidence demonstrating the repeatability of MPF patterns during sustained or intermittent isometric contractions at a constant force, as well as a general understanding of the mechanisms that underlie the observed patterns, much less is known about MPF patterns during progressively increasing contraction intensities. Camic et al. (2009) measured MPF of the vastus lateralis during a cycle ergometry test that began at 80 W and increased by 30 W every 2 minutes, until voluntary exhaustion, reporting a decline in EMG frequency with an increase in exercise intensity. This pattern is in line with previous findings, where the reduction in MPF during fatigue was greater during contractions of higher intensities (Petrofsky, 1979; Gerdle & Fugl-Meyer, 1992). The results of Camic et al. (2009) are in contrast to the results of Jansen et al. (1997), who implemented a similar incremental cycling protocol but found a slight linear increase in MPF with an increase in exercise intensity in the majority of their participants. The MPF pattern in dynamic exercise can be very variable (Gamet et al., 1996). For example, Gamet et al. (1993) used an incremental cycling protocol and reported that among 40 young adults, there were no specific, consistent patterns, although in 7
endurance-trained participants a slight increase in MPF with exercise intensity was observed. The studies described above utilized progressive dynamic exercise protocols in which there is simultaneous increases in intensity and fatigue. To our knowledge there is no study which examined MPF patterns during sustained or intermittent progressive isometric contractions. It is expected that, with isometric contractions, there will be less variability in the signal and thus, more identifiable pattern of MPF.

While the notion that the frequency spectrum of the EMG signal is more sensitive to the activation of type II MUs, with faster conduction velocities, is generally supported (Komi & Tesch, 1979; Kupa et al., 1995; Linssen et al., 1991; Moritani et al., 1985; Orizio & Veicsteinas, 1992; Taylor et al., 1997), these findings are not uniform throughout the literature. For example, Beck et al. (2009) found that differences in fibre-type characteristics were not manifested in the patterns of the EMG spectrum MPF responses of resistance-trained and aerobically-trained individuals during a sustained leg extension at 50% MVC. Despite the fact that the resistance-trained individuals were characterized primarily by type II myosin heavy chain (MHC) expression, when compared to the aerobically-trained individuals, who had a primarily type I MHC expression, they did not demonstrate the expected greater MPF decrease during a fatiguing task. The findings of Beck et al., (2009) may be explained by specific training adaptations of muscle fibres. Several resistance training studies demonstrate a transition from fast-glycolytic type-IIx muscle fibres to more oxidative type-IIa fibres (Aagaard et al., 2011; Hostler et al., 2001; Putman et al., 2004), and the muscle biopsies of the resistance-trained group in the Beck et al., (2009) study support these findings. It has also been found that type I muscle fibres may be capable of hypertrophy (Alway et al., 1988; Andersen et al., 2008), can be just as large, and even larger than type IIa muscle fibres (Sadoyama et al., 1988; Simoneau & Bouchard, 1989), and that both fibre types have a relatively high oxidative capacity and are smaller compared to type-IIx fibres (van Wessel et al., 2010). Since muscle fibre CSA is highly correlated with MFCV (Blijham et al., 2006; Methenitis et al., 2016; Sadoyama et al., 1988), it is possible that despite significant differences in muscle fibre composition, the
activated MUs of both the endurance-trained and resistance-trained group in the Beck et al., (2009) study were of similar size and demonstrated similar propagation velocities, thereby producing a similar MPF response. It is also possible that the moderate intensity contraction (50% MVC) was not sufficient to induce the recruitment of larger MUs with faster conduction velocities, and that a higher intensity contraction may have resulted in the manifestation of the fibre-type differences through the EMG frequency spectrum.

MU characteristics and recruitment patterns can vary between different muscles, and this has implications for the MPF response to exercise. It has been shown that muscles of similar size and function tend to display similar spectral characteristics (Rodriguez-Falces et al., 2014; Yuen et al., 1989). For instance, surface recordings of the VL and the VM have revealed nearly identical EMG activity during both step-wise and ramp contractions at various intensities (Rodriguez-Falces et al., 2014). It is well documented that muscles of different size, function, fibre composition and recruitment thresholds can produce dissimilar MPF patterns, even at similar intensities (Hill et al., 2018; Portero et al. 1996; Roman-Liu, 2016). A meta-analysis by Roman-Liu (2016) found that in most cases, MPF increased with increasing force up to a certain force level, and that this subsequent plateau tended to be higher in larger muscles than in smaller muscles. Differences in the frequency spectrum plateau between muscles may be explained by differences in MU recruitment strategies. For example, it has been suggested that MU recruitment is completed by 30–40% MVC in small hand muscles, but at higher force levels (70–80% MVC) in larger arm muscles (Moritz et al., 2005). Since increases in spectral parameters are mainly caused by the gradual recruitment of larger MUs with faster conduction velocities (Roman-Liu, 2016), it is conceivable that the force at which MPF values would reach a plateau is related to the force at which MU recruitment of the muscle is complete. This expectation is supported by the findings of Roman-Liu (2016), in which spectral parameters increased up to 60-80% MVC in the biceps brachii, while only increasing up to 40% MVC in both the abductor digiti minimi and extensor digitorum muscles in most
cases. Roman-Liu (2016) also suggested that differences in average MPF plateau between muscles may be related to muscle fibre composition. For example, frequency values for the biceps femoris were highest at 50% MVC, while the gastrocnemius, which contains a higher proportion of type-II muscle fibres (Alway et al., 1988), generally showed continuous increase in spectral parameters up to 100% MVC during ballistic contractions (Roman-Liu, 2016). However, this explanation is not in line with the previously mentioned findings in the extensor digitorum muscle. This muscle is comprised of a relatively high proportion of type-II fibres (Clamann, 1993; Johnson et al., 1973), yet it demonstrated an MPF plateau at only 40% MVC (Roman-Liu, 2016). Data regarding the upper limit of recruitment of the extensor digitorum is quite scarce, but it would be reasonable to assume that it would demonstrate similar recruitment strategies as neighbouring small hand muscles. This would suggest that greater activation of type II MUs due to a wider recruitment range has a greater influence on MPF reaching its highest value at higher force levels, rather than having a higher type II muscle fibre composition.

**MPF in Children**

All the above discussion is based on studies in adults. Studies in which MPF is assessed in children are rare compared to the extensive research that has been conducted in adults and are summarized in Table 1. Most of the available findings support the idea that MU activation, as reflected in the MPF pattern, is different between children and adults. For example, Halin et al. (2003) compared boys and men during 30s of a maintained maximal voluntary contraction (MVC) of the elbow flexors and showed that the decrease in both MPF and MFCV of the biceps brachii during the isometric contraction was significantly greater in the men than in the boys. The authors suggested a greater participation of type II MUs in men that led to greater lactic acid and metabolic by-product accumulation during fatigue. Armatas et al. (2010) found a similar pattern in the VL and VM of boys and men who performed
repeated 5s maximal isometric knee extensions, with 5s rest between repetitions, until force declined to 50% of MVC. In this study, the MPF of the VL in boys and men decreased to 82.5% (±6.7) and 60.7% (±8.6) of initial value, respectively. This is in line with the findings of Halin et al. (2003), where MPF of the biceps brachii decreased to ~74% and ~58% of initial value in boys and men, respectively. It is interesting to note that while the decrease in MPF were similar in the two studies, force reduction was smaller in the study by Halin and colleagues (2003) (declined to ~73% and 67% of initial value in boys and men, respectively), compared with the study by Armatas and colleagues (2010) (declined to 50% in both boys and men). This discrepancy in the MPF/force ratio may be explained by differences in exercise protocol. The intermittent nature of the Armatas et al. (2010) study may have resulted in lesser blood flow occlusion (BFO) than would occur in a continuous maximal contraction (Sjogaard et al., 1988), despite a longer exercise time and greater force decline. It has been suggested that higher-threshold (type II) MUs are recruited earlier when there is BFO, due to the decreased availability of oxygen to the working muscle (Moritani et al., 1992). The earlier recruitment of type II MUs would result in a faster reduction in conduction velocity with fatigue, and therefore, a greater decrease in MPF (Mortimer et al., 1970).

Research in adults suggests that increased utilization of type II MUs results in a steeper decrease in MPF during a sustained contraction (Gerdle & Fugl-Meyer, 1992; Komi & Tesch, 1979). The findings of Halin et al. (2002) suggest that the same could be said for children. The study examined the MPF pattern in 10 year-old boys who were either untrained or competitive gymnasts, during a 25s maintained MVC of the elbow flexors. Both groups demonstrated a decrease in the MPF of the biceps brachii over the 25s isometric MVC, but the gymnasts displayed a significantly steeper downshift towards the lower end of the power spectrum. The authors attributed these differences to a possibly enhanced recruitment of more fatigable fast MUs in the gymnasts, which may have been inherent in these boys, or a result of adaptations to training.
If greater utilization of quickly fatiguing type II MUs results in a greater MPF decrease during a sustained contraction, then by the same token, it would be expected that greater utilization of fatigue-resistant type I MUs would result in a lesser MPF decline. This reasoning was supported by the results of Callewaert et al. (2012), who compared endurance-trained youth sailors and untrained boys during sustained bouts of submaximal (30 to 40% MVC) isometric knee-extensions. The MPF of the VL decreased linearly in the untrained boys but remained steady through 11 bouts of 90s sustained contractions in the endurance-trained boys. Only in the 12th and final bout did the MPF of the trained boys begin to decrease, but it still decreased to a significantly lesser extent than in the untrained boys. These results may be explained by endurance training adaptations in the young sailors that resulted in a greater proportion of slow twitch type I muscle fibres with a higher oxidative capacity being activated during the exercise protocol, leading to lower lactate and ionic accumulation, less de-recruitment of fatigued motor units and therefore a much smaller, if any, decrease in conduction velocity. This explanation is also supported by the greater increase in deoxygenated haemoglobin and myoglobin concentration shown in the trained boys throughout the exercise protocol, as this suggests that the trained boys had a higher increase in capillary oxygen (O₂) extraction, presumably by recruiting primarily their type I MUs. Moalla et al. (2006) also found a strong positive correlation between muscle oxygenation and MPF in a study that had young boys perform an isometric knee extension at 50% MVC for as long as volitionally possible or until they could no longer maintain the required force and torque fell below 90% of the target value. The boys exhibited a decrease in MPF that became more rapid near the end of the contraction, likely indicating enhanced recruitment and de-recruitment of the higher-threshold, more powerful and fatigable MUs, to maintain the required force.

Most studies reporting MPF patterns in children focus on elbow flexors or knee extensors. However, the trends in MPF patterns found during isometric contractions, especially in terms of how they differ between children and adults, are similar in various muscles. Tanina et al. (2016) recorded the
EMG response of the erector spinae muscles in young adult men and women and in pre-pubertal boys and girls during an unsupported horizontal isometric trunk hold until exhaustion. The erector spinae muscles differ from muscles such as the more commonly studied VL or BB, in that the former are postural muscles and have a relatively higher proportion of type I muscle fibres (Mannion et al., 1997). Nevertheless, it was found that the decrease in MPF during the contraction was still significantly greater in adults than in children of both sexes, suggesting a greater activation of type II MUs in the adults. The authors suggest that a gradual increase in motor neuron impulse frequency during maturation could be a factor responsible for the increasing utilization of type II MUs in these muscles with growth.

Despite some consistencies of MPF patterns during exercise in children, there still exist some conflicting findings within the limited literature, when comparing with adults. For example, Bax et al., (2021) measured the MPF of the flexor carpi radialis (FCR) during intermittent isometric wrist flexion contractions and found no significant differences in the extent to which MPF decreased in children and adults, in both a blood flow occlusion and a control condition, despite finding age-related differences in the RMS pattern. It was suggested that perhaps the exercise protocol, in which 25 contractions were performed for 3s, with 3s rest intervals, at 35% MVC, did not elicit sufficient fatigue to produce significant differences in MPF decrease between children and adults (Bax et al., 2021).

Previous studies examining MPF in children utilized an exercise protocol in which intensity remained constant. No study has examined MPF in children using a progressive (increasing intensity) contraction protocol. The adult studies that used progressive exercise protocols employed dynamic contractions and the MPF patterns were highly variable (Camic et al. 2010; Gamet et al., 1993; Jansen et al., 1997). An MPF pattern comparison between children and adults during a progressively increasing intensity could provide insight into the interaction between intensity and fatigue in terms of their role in affecting MPF, and how it may differ in children and adults, possibly supporting previous findings (Armatas et al., 2010; Halin et al., 2003). It may also help to determine whether an isometric-based
exercise protocol results in less variability (and therefore clearer patterns) of the MPF response during exercise.
Table 1: Summary of Studies Examining MPF in Children

<table>
<thead>
<tr>
<th>Reference</th>
<th>Participants</th>
<th>Agonist Muscle(s)</th>
<th>Exercise Protocol</th>
<th>MPF (Hz) response</th>
<th>Proposed Explanation*</th>
<th>Other Main Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armatas et al. 2010</td>
<td>• All participants untrained but physically active</td>
<td>• Vastus Lateralis • Vastus Medialis</td>
<td>• 5s repetitions of maximal isometric knee extensions, with 5s interval between contractions. • Trial was stopped when torque declined to %50 of initial MVC.</td>
<td>• Significantly greater decrease in men than in boys Men • Initial MPF VM = 97.3 ± 9.7 VL = 92.8 ± 10.5 • Avg MPF at end of protocol (% of initial value) VM = 58.7 ±6.0 VL = 60.7 ± 8.6 Boys • Initial MPF VM = 90.5 ± 10.6 VL = 88.3 ± 8.1 • Avg MPF at end of protocol (% of initial value) VM = 90.7 ± 13.8 VL = 82.5 ± 6.7</td>
<td>• Assumed higher type II motor units in men. • Higher metabolite accumulation observed in men compared with boys possibly causes higher presynaptic inhibition of alpha motoneuron by activating type III and IV afferents to a greater extent. • Incomplete activation of the available motor units (type 2) in boys.</td>
<td>• More rapid torque decrease in men. • Faster torque and MPF recovery in boys.</td>
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<tr>
<td>Bax et al. 2021</td>
<td>Men (n=16) • 24.4 ± 2.5 yrs</td>
<td>Flexor Carpi Radialis</td>
<td>• 25 isometric wrist flexion contractions held for 3s each, with 3s between</td>
<td>• Both, boys and men showed larger decreases in the occlusion condition than the control condition</td>
<td>• Changes in RMS and MPF may reflect changes within the muscle, other than MU</td>
<td>• Occlusion led to a decreased MVC for both boys and men but the magnitude of change in maximal</td>
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<td>Callewaert et al. (2012)</td>
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<td><strong>Two groups of boys</strong></td>
<td><strong>12 bouts of 90s submaximal (30-40% MVC) bilateral knee extensions, separated by 6s recovery periods.</strong></td>
<td><strong>Significant decrease in untrained boys and no change in youth sailors</strong></td>
<td><strong>Endurance training adaptations in youth sailors resulted in the activation of a greater proportion of slow twitch (type 1) fibres with a higher oxidative capacity, leading to lower additional motor unit recruitment and less fatigue development.</strong></td>
<td><strong>MVC torque similar in both groups.</strong> <strong>Endurance-trained boys show a higher increase in deoxygenated haemoglobin and myoglobin concentration (Deoxy[Hb + Mb]) as well as a lower Reoxygenation Index (RI), compared to untrained controls.</strong></td>
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<td><strong>Sailors</strong> <em>(n=10)</em></td>
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<td><strong>Avg MPF at end of protocol: 99.3% of initial value</strong></td>
<td><strong>Avg MPF at end of protocol: 88.9% of initial value</strong></td>
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<td><strong>Untrained</strong> <em>(n=10)</em></td>
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<td><strong>Avg MPF at end of protocol: 99.3% of initial value</strong></td>
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<td><strong>Rate of change similar in boys and men. No difference in initial MPF values between groups</strong></td>
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<td><strong>Exercise protocol did not go until task failure and used a low load. Therefore, it is possible that there was insufficient fatigue to result in significant differences in MPF response</strong></td>
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<td><strong>BFO may not induce large enough effect in boys due to their reliance on lower threshold MUs.</strong></td>
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<td><strong>torque was not different between groups</strong></td>
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<tr>
<td>Study (Year)</td>
<td>Participants</td>
<td>Age</td>
<td>Muscles</td>
<td>Max Effort</td>
<td>Changes in Activations</td>
<td>Results</td>
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<td>Halin et al. (2003)</td>
<td>All participants untrained but physically active</td>
<td>Men (n=12)</td>
<td>21.5 ± 4.5 yrs</td>
<td>Biceps Brachii</td>
<td>Max effort isometric elbow flexion contraction (30s)</td>
<td>Significantly greater decrease in men than in boys</td>
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<td>Boys (n=15)</td>
<td>10.5 ± 0.9 yrs</td>
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<td>Men: Higher initial values</td>
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<td>Boys: Rate of change: -0.76 Hz/s</td>
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<td>Range of values: ~95-75Hz</td>
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<td>A greater percentage of initially activated type II MUs in men generates greater metabolite and ion accumulations, which slows down MFCV and MPF to a greater extent.</td>
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<tr>
<td>Halin et al. (2002)</td>
<td>Two groups of boys</td>
<td>Gymnasts (n=6)</td>
<td>10.5 ± 0.6 yrs</td>
<td>Biceps Brachii</td>
<td>Max effort isometric elbow flexion contraction (25s)</td>
<td>Significantly greater decrease in gymnasts than in untrained boys</td>
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<td>Untrained (n=6)</td>
<td>10.5 ± 0.5 yrs</td>
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<td>Gymnasts: 21.6% decrease from initial value</td>
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<td>Untrained: 12.9% decrease from initial value</td>
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<td>Moalla et al. (2006)</td>
<td>12 untrained but physically active boys</td>
<td>Vastus Lateralis</td>
<td>12.5 ± 1.2 yrs</td>
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<td>Isometric knee extension contraction at 50% of MVC until failure.</td>
<td>Decreased progressively and linearly until exhaustion.</td>
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<td>Abrupt, accelerated decrease during the final quarter of contraction.</td>
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<td>Restriction of blood volume and reduction of oxygen during sustained isometric</td>
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</table>
| Souissi et al. 2012 | **Boys** (n=22)  
• 11 ± 0.5 yrs  
• Vastus Lateralis  
• Vastus Medialis  
• Rectus Femoris | **Wingate Anaerobic test**  
• 30-s maximal cycling sprint against a constant braking resistance (relative to body mass) | **Higher initial MPF in the evening (102.14 ± 18.15) vs the morning (92.38 ± 12.39)**  
• Rate of MPF change similar in morning and evening. | **Diurnal increase in body temperature increase nerve conduction velocity, joint suppleness, and muscle strength via the enhancement of Ca2+ released by the sarcoplasmic reticulum.**  
• Speculated that increased activation of ‘fatigue-sensitive’ type II motor units in the evening following the onset of sprint cycling  
Peripheral mechanisms could be a main source of diurnal variation during short-term anaerobic performances rather than alteration in    | **RMS values unaffected by time of day.** |
| Tanina et al. (2017) | Boys (n=14)  
8.5 ± 1.6 yrs | Erector Spinae muscles at L1 level  
Unsupported horizontal isometric trunk hold until failure. | No significant difference between groups in initial MPF values  
Significantly greater decrease in males than in females for both age groups.  
Significantly greater decrease in young adults than in pre-pubertal children for both sexes.  
**Boys**  
Rate of change: −16.6 ± 5.6%/min  
**Girls**  
Rate of change: -10.3 ± 4.4%/min  
**Men**  
Rate of change: −27.4 ± 9.5%/min  
**Women**  
Rate of change: −17.0 ± 5.5%/min | MPF more sensitive to type 2 muscle fibres than type 1 muscle fibres.  
A Greater drop-off in type 2 motor units occurs in adults than in children during a fatiguing task due to greater recruitment or higher composition of type 2 MUs.  
Lagging maturation of glycolytic metabolism in children.  
A gradual increase in motorneuron impulse frequency during maturation a factor responsible for increasing utilization of type 2 motor units and/or transformation of type 1 to type 2 muscle fibres during growth | Endurance time ranged from 47 to 253 seconds.  
Differences in MVC between sexes only apparent in adults (higher in men). |
|-------------------|----------------|-----------------|----------------------------------|-------------------------------|-------------------|
| Girls (n=13)  
8.2 ± 1.4 yrs | Men (n=14)  
24.5 ± 2.5 yrs | Women (n=13)  
24.5 ± 4.1 yrs | |
| **Boys**  
8.5 ± 1.6 yrs | **Girls**  
8.2 ± 1.4 yrs | **Men**  
24.5 ± 2.5 yrs | **Women**  
24.5 ± 4.1 yrs | ||
| Yuen et al. (1989) | **Boys** (n=10)  | Anterior temporal and masseter muscles | Men had lowest MPF values and girls had highest MPF values.  
- Range of values (across muscles):  
  **Boys**: 183-225Hz  
  **Girls**: 200-231Hz  
  **Men**: 170-196Hz  
  **Women**: 176-227 Hz  
- Higher proportion of slow twitch fibers in men than in other groups in masseter and temporal muscles due to conversion of fast twitch to slow twitch during growth.  
- Results were reproducible between sessions. |  |
|-------------------|-----------------|--------------------------------------|-------------------------------------------------|---|
| **Girls** (n=10)  | 11.2 ± 1.6 yrs  | 6 total trials of 5s MVC isometric clenches at maximal intercuspal position.  
- 2 minutes of rest between trials.  
**Men** (n=10)  | 10.8 ± 1.8 yrs  |  |
| **Men** (n=10)  | 22.8 ± 2.7 yrs  |  |
| **Women** (n=10) | 22.5 ± 2.1 yrs  |  |  |

* Explanation proposed by authors
**Purpose**

This study is a secondary analysis of Woods et al. (2019), in which the EMG RMS response was examined during progressive isometric contractions of the knee extensors (25% MVC to exhaustion) in boys and men. In that study, it was demonstrated the EMG RMS increases non-linearly with an increase in contraction intensity. The point of accelerated increase in the EMG RMS response (EMG threshold) occurred later (i.e., at higher relative contraction intensity) in boys compared with men. These results were interpreted to reflect a later (or lesser) activation of type-II MUs among the boys.

The purpose of this secondary analysis is to examine the MPF pattern during this progressive isometric contraction protocol and compare the pattern between children and adults. It is expected that the MPF pattern will be similar in both groups (i.e., initial increase in MPF, followed by a decrease), reflecting progressive fatigue. However, based on previous literature which demonstrates lower fatigability in children, it is expected that the decrease in MPF will occur later (i.e., at higher relative contraction intensity) in boys compared with men.

**Specific Hypotheses**

We hypothesize the following:

1) MPF will initially increase with increasing contraction intensity, followed by a decrease towards exhaustion in both boys and men.

2) MPF$_{mn}$ and MPF$_{pk}$ will be higher in men compared with boys.

3) The MPF$_{pk}$ and subsequent decrease will occur earlier (i.e., at lower relative exercise intensity) in men than in boys.

4) The intensity at which MPF$_{pk}$ occurs will be related to the intensity at which the EMG RMS threshold occurs in both boys and men.
Significance

This analysis will provide a better understanding of the factors that affect MPF and how their interaction may affect the MPF response during an exercise protocol. If MPF responds in the way that is hypothesized, this analysis would support previous literature that has examined the effects of intensity and fatigue separately on the EMG power spectrum (Bilodeau et al., 2003; Bosch et al., 2009; Hussain et al., 2020). This analysis can also highlight differences between children and adults in surface EMG response and its reflection of MU recruitment patterns. Since MPF has been shown to be higher in EMG recordings from type-II MUs (Sadoyama et al., 1988; Seki & Narusawa, 1998), a higher mean and MPF_{PK} in men could suggest a higher utilization of type-II MUs in men.

Children have been shown to have greater endurance and less fatigability than adults when exercising at the same relative intensity (Birat et al., 2018; Bontemps et al., 2019; Hebestreit et al., 1993), which has been suggested to be related to MU activation patterns (Dotan et al., 2012). MPF_{PK} and subsequent decrease that occurs later and at a higher relative intensity in children would support previous findings that suggest a greater reliance on type-I MUs in children (Armatas et al., 2010; Halin et al., 2003; Tanina et al., 2017). A later MPF “threshold” in boys would also compliment the findings of Woods et al., (2019), who found a later RMS threshold in boys than in men. The information provided by this analysis could aid in the development of more suitable training or exercise rehabilitation programs in children in comparison with protocols used in adults.
Methods

The current analysis was performed on a data set from a previously conducted cross-sectional study which examined the onset of accelerated activation of higher-threshold motor units, as reflected in the EMG threshold (EMGth), in boys and men (Woods et al. 2019). That is, the present study examines in the same participants, muscle force and EMG response, but focuses on the mean power frequency response in the boys and men.

Participants

Twenty-two boys (10.13 ± 1.07 years) and 22 men (23.29 ± 2.67 years) volunteered to participate in the study. Participants were excluded from the study if they; 1) had consumed any medications in the previous year which may have affected neurological function, 2) had any prior injuries or medical diagnoses associated with altered neuromuscular function, 3) had a lower limb injury or an injury that would limit the movements required for the test, and 4) had answered “Yes” to any of the questions on the Medical Screening Questionnaire (Appendix A). None of the participants met any of the exclusion criteria. Data from three of the boys were excluded from the original analysis because the participants were not able to complete the testing procedures (e.g., did not reach volitional exhaustion or could not hold an isometric contraction for the required amount of time). Data from two of the men were also excluded from the analysis, because their 1RM could not be detected due to technical/weight limitations of the dynamometer. Data from two more of the boys were excluded from the current analysis due to loss or corruption of the data files. Thus, 17 boys and 20 men are included in the present analysis.
Table 2 below describes the participants’ physical characteristics. All 17 boys included in the current analysis self-assessed their Tanner pubertal stage as either stage 1 (n=5) or stage 2 (n=11; pre- or early-pubertal, respectively). One boy did not feel comfortable completing the questionnaire. The boys habitually participated in significantly more physical activity than the men (p < .001). Fifteen of the boys were part of a competitive soccer club which met 2-4 times per week, 12 months of the year for practices and games. The boys also participated in various recreational activities (i.e. hockey, lacrosse, swimming), and none were trained endurance athletes. Many of the men had engaged in competitive sports in the past (e.g., hockey, soccer, baseball, running and bodybuilding), but none were trained endurance athletes. Around the time of testing most of the men were recreationally active, and engaged in regular strength training programs (2-3 x per week).

Table 2. Participants’ Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Boys</th>
<th>Men</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>17</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>10.3 ± 1.2</td>
<td>23.3 ± 2.7</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Years from PHV (years)</td>
<td>-3.0 ± 0.7</td>
<td>NA</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>143.4 ± 7.9</td>
<td>177.8 ± 7.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>34.2 ± 7.7</td>
<td>77.8 ± 11.1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Body Fat Percentage (%)</td>
<td>10.1 ± 7.5</td>
<td>17.1 ± 5.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Muscle CSA (cm²)</td>
<td>2.3 ± 1.1</td>
<td>7.0 ± 4.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Physical Activity (Score)</td>
<td>126.9 ± 51.3</td>
<td>63.2 ± 44.9</td>
<td>&lt;0.001</td>
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<tr>
<td>1RM (Nm)</td>
<td>103.9 ± 23.4</td>
<td>286.7 ± 75.5</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>1RM (Nm kg⁻¹)</td>
<td>0.31 ± 0.06</td>
<td>0.41 ± 0.07</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Procedures

All tests and measurements were performed during two visits to the Applied Physiology Laboratory, at Brock University. During the first visit, participants (and guardian if they were under the age of 18) were verbally informed of all the tests and procedures involved in the study and provided written consent to participate in the study. Participants (or their guardians) also provided consent that their data obtained during their visits could be used for further analysis at a later date. Then, after completing a series of questionnaires regarding medical history, athletic training history, physical activity habits, and pubertal stage (boys only), an anthropometric assessment was performed. The latter included height, seated height (boys only), and body compositional measurements using the Bioelectrical Impedance Assessment (BIA). EMG sensors were applied to the participant’s skin over the Vastus Lateralis (VL) muscle, using double-sided tape. Once the sensors were secured, the dynamometer was fit to the participant’s size (e.g., height, leg length). All the settings were recorded to ensure the same setup was used for the second visit. Once participants were ready, they completed a warm-up consisting of repeated leg extensions. The warm-up included 4 sets of 10, 8, 5, and 3 repetitions at increasing loads. The boys started at a load of 2.5 lbs and increased by 2.5 lbs every set. Men started at a load of 15 lbs and increased by 5-10 lbs each set. After a short rest (1-2 minutes) the participant started the knee extension 1RM protocol (see protocols section for more details). Lastly, following 4-6 minute recovery period, the progressive protocol for the determination of the EMGTh was performed. Following this protocol, participants completed a cool down by cycling for ~2 minutes. One to two weeks later participants returned for visit 2. During the second visit, participants repeated all the procedures they completed in visit 1, with the exception of the questionnaires and the anthropometrics listed above. Prior to 1RM and EMGTh determination, muscle diameter was measured using ultrasound. Following these measurements, the EMG sensors were placed at the same locations as in visit 1 (based on the measurements from visit 1). Next, as with the first visit, the participants completed a warm-up and a
short habituation period before the re-assessment of maximal leg strength. Once the participants were ready, they performed the EMG₇₀ protocol as they did in visit one (see below for protocol).

**Measurements**

All physical measurements were performed by the same investigator, thus eliminating interobserver variability.

**Body Stature**

Standing and seated (boys only) height were measured to the nearest 0.1cm, using Ellard Instrumentation Ltd. Stadiometer.

**Mass**

When determining the mass of the participants, they first removed shoes and all clothing that may significantly affect their weight (e.g. sweater, jacket, sweat pants). Using a digital scale (InBody 520, Biospace CO., Ltd), body mass was measured to the nearest 0.1 kg.

**Bio-Electrical Impedance (BIA)**

Body composition (i.e., body fat percentage) was assessed using BIA (InBody520, Biospace Co. Ltd.). The BIA device measures various body compositional characteristics by creating a weak electrical current (800μA, 50kHz) that passes from electrodes situated on the hands to electrodes on the feet. Based on the speed at which these signals pass through the body the compositional measurements can be estimated. When participants arrived, they were asked about their hydration status. If they had not hydrated before arrival, they were provided with a bottle of water, and asked to void before BIA measurements.
**Muscle Diameter**

Muscle diameter (depth) of the VL was measured using an 8L-RS MHz linear-array probe on a real-time ultrasound system (Vivid-1, GE Medical Systems, Horten, Norway). Muscle diameter was used to calculate muscle cross-sectional area. Participants were asked to lie in a relaxed supine position with their toes pointed upwards for the measurements. The imaging site for measurement of the VL were the same locations for the placement of the EMG electrode (i.e., SENIAM guidelines). Muscle diameter was measured as the distance between the deepest aspect of the subcutaneous fat tissue and superficial aspect of muscle connective tissue of the vastus intermedius. The site was imaged 3 times and the median value was used for analysis. In cases where a measurement was beyond 1 mm of the others, an additional measurement was made.

**Questionnaires**

**Medical History**

The Brock Applied Physiology Research Group Medical Screening Questionnaire was used to screen for the participant’s ability to participate in the study (see Appendix A).

**Leisure-Time Physical Activity**

The participants habitual physical activity was determined using the Godin-Shephard leisure-time exercise questionnaire (Godin-Shephard, 1985; see Appendix B).

**Training History**

Participants who reported a previous history of sports training, were asked to complete an additional questionnaire to determine the level and extent of their current sport training. The training
questionnaire is a fillable chart which asks the participants about the specific sports they have played in the past and present, how many hours they have contributed to these sports, and whether their participation was competitive or recreational in nature. At times, further questions were asked by the researcher to clarify the nature of these training practices (see Appendix C).

**Pubertal Stage**

Pubertal status was self-assessed by the boys, based on secondary sex characteristics (i.e., pubic hair) as outlined by Tanner (1962). The questionnaire was completed in a private space to avoid embarrassment. Once complete, the questionnaire was placed in an envelope by the child and handed to the researcher (see Appendix D).

**Exercise Protocols**

All exercise protocols (1RM and progressive isometric contractions protocol) were performed on the same purpose-built dynamometer (see Appendix E for details). This dynamometer was built to allow for the small increases in resistance needed for the progressive protocol, specifically for the children.

**Maximal Strength (1RM) Protocol**

Participants were positioned and secured in the Biodex chair with their right leg secured to the dynamometer. The resting hip was at 90° and the knee was at 110-120° angles. The initial load was set as the load at the last warm-up set (i.e., ~ 15 lbs for children and ~ 50 lbs for adults). Once the participants were ready, they were asked to extend their right knee to a height sufficiently high to lift the weight box from its resting platform (~5-10°; see Appendix E). Weight was added or eliminated from the weight box of the dynamometer until participants could only perform one repetition of the motion.
A rest of 1 minute was provided between repetitions. The maximal strength (1RM) was determined within 3-6 repetitions.

**Progressive Isometric Contraction (EMGth Protocol)**

The progressive, intermittent, isometric contraction protocol for the original study was as follows: The initial load was 25% 1RM, at which participants completed five repetitive isometric contractions at a rate of 5 seconds on and 3 seconds off. This was followed by a 30 second rest during which the load was increased by 3% 1RM. Participants completed this pattern until volitional exhaustion.

**EMG/Goniometer Set-up and Signal Recording**

EMG was recorded using tripolar surface electrodes located on the VL. Signals were collected using a Computer-Based Oscillograph and Data Acquisition System (EMGworks Acquisition, Delsys Inc., Boston, MA). EMG data were collected at a rate of 1000Hz and bandpass filtered (20–450 Hz) using the Bagnoli-4 bioamplifier (Delsys Inc., Boston, MA). Before placement of the electrodes, the skin was prepared by shaving (if necessary) and rubbing the skin around the electrode placement sites with alcohol and an exfoliant gel to remove any dirt or oil. Once the skin was cleaned, the sensors were placed according to SENIAM guidelines for the VL. Specifically, the sensor for the VL was placed 2/3 the distance between the superior border of the patella and the anterior superior spina iliaca. Sensors were held in place by double-sided adhesive tape placed directly on the skin and over the electrodes casing. The reference electrode was placed over a boney process located on the seventh cervical vertebrae. An electro-goniometer (S700/S720 Joint Angle SHAPE SENSOR, Measurand Inc., Fredericton, NB, Canada) was used to collect data on the participants’ leg position. The device was fastened to the base and the arm of the purpose-built dynamometer (see Appendix F). Traditionally, the electro-goniometer is placed directly on the participant’s leg. However, we chose to place it directly on the testing device to minimize
interference and so that it is standardized for all participants. Similar to the collection of EMG signal, goniometer data were collected using a Computer-Based Oscillograph and Data Acquisition System (EMGworks Acquisition, Delsys Inc., Boston, MA). Goniometer data were collected at 1000Hz and band-pass filtered (20–450 Hz) using the Bagnoli-4 bioamplifier (Delsys Inc., Boston, MA).

**Data Analysis**

**Original Analysis - EMG Threshold Determination**

Data reduction for the original analysis is described below and summarized in Fig 1. Further details appear in Woods et al. 2019. Once the data were collected, the original reduction and analysis of the raw EMG data was completed using MATLAB v. 2017a. All data (i.e., EMG and goniometer) were filtered with a fourth-order Butterworth filter. Once filtered, the EMG and goniometer trace was cut to only include the isometric contraction protocol. Next, the function ‘Peakfinder’ (Yoder, 2011) was run through the goniometer data to determine the start of each isometric contraction. The root mean square (RMS) of each contraction (RMScontract) was then calculated over a 2 second window where the goniometer data were the most stable (i.e., lowest variance). All RMScontract values were then exported to Microsoft Excel for further reduction. Once in Excel, RMScontract values greater than ± 2 standard deviations (SD) away from the mean of the other four points in the respective load were eliminated (five contractions were performed at each load). RMScontract values were averaged within each load. If the last RMSmean value was lower than the previous value, it was eliminated. Using RMSmean values, 2 to 3 potential EMG75’s in each test were visually identified. The RMSmean and the respective %1RM’s values were then imported into Prisms GraphPad software, where a segmental regression was used to determine the lowest sum of squares. A segmental regression creates two linear regression lines around a set constraint point (visually identified thresholds). Once all potential
thresholds and points ± 2 %1RM around the visually identified threshold had been examined, the data series with the lowest sum of squares was used for the determination of the threshold. The lowest sum of squares is a numerical representation which describes the regression which results in the smallest sum of squares residuals. Next, the data were plotted in Excel and two linear regressions were determined around the point which presented the lowest sum of squares, as found by GraphPad. EMG$_{Th}$ was determined at the point at which the 2 regression lines cross.

*Figure 1. EMG$_{Th}$ determination process. A) An RMS point distribution (5 points/contractions per load) of a typical participant; B) plot of mean RMS per load and the point of the determined lowest sum of squares; C) EMG$_{Th}$ determination as the intersection of the two bi-segmental regression lines. Figure from Woods et al. 2019.*

**Current Analysis - MPF Calculation**

The current reduction and analysis of the raw EMG data was completed using MATLAB v. 2019a. All data (i.e., EMG and goniometer) were filtered with a low pass, fourth-order Butterworth filter at 20 to 450 Hz. Once filtered, the EMG and goniometer trace was cropped to only include the isometric
contraction protocol. Next, each isometric contraction was manually determined from the goniometer data by one observer for all contractions and was characterized as the initial peak or as the plateau after the rapid increase in force. The mean power frequency (MPF) of each contraction was then calculated over a 1 second window, where the goniometer data was the most stable (i.e., lowest variance). Contraction were removed from the analysis if a stable 1s plateau could not be identified. The MPF$_{mn}$ of each stage (5 contractions) was then calculated. The number of stages each participant completed varied widely (range: 10-22). To standardize the MPF pattern throughout the protocol between participants, the mean MPF values for each stage over the total number of stages was interpolated to the lowest number of stages that any participant completed (10 stages), using the LaGrange polynomial (Gabriel et al., 2002). All MPF values were exported to Microsoft Excel for further reduction.

In Excel, each participant’s MPF data were reduced and examined in two ways: a) over the total number of stages, and b) over the interpolated 10-stages. In both cases, the MPF$_{PK}$ value was then determined in MATLAB, using a 2$^{nd}$ order polynomial equation. The %1RM at which the MPF$_{PK}$ occurred was compared to the %1RM at which EMG$_{Th}$ occurred. Further calculated outcome variables included the interpolated stage at which MPF$_{PK}$ occurred, the interpolated stage at which EMG$_{Th}$ occurred, the range (highest to lowest) of the ten interpolated mean MPF values and the mean interpolated MPF for all participants.

Based on previous literature, the expected MPF pattern over the progressively increasing workload was one of an inverted-U shape (Figure 2; see also Literature Review; Mastalerz et al. 2012; Bilodeau et al. 1990). The MPF patterns observed in this study were mostly as expected (11 boys, 13 men, 65%), although some were not. Indeed, in some participants a linear increasing (n= 7) or irregular pattern (n= 6) was observed.
Figure 2. Example of the typical MPF pattern demonstrated in this study from an adult (top), displayed in raw form (left) and interpolated form (right), and a child (bottom), displayed in raw form (left) and interpolated form (right)
Statistical Analysis

Statistical analyses were performed on the whole sample, as well as on the subset of participants who displayed the expected MPF pattern.

All data were assessed for normality by considering the skewness and kurtosis ± 3 prior to parametric assessment. All variables met the assumptions of normality. Independent t-tests were used to assess differences between groups in demographic variables, MPF<sub>mn</sub>, MPF<sub>PK</sub>, force (%1RM) at MPF<sub>PK</sub>, MPF range, interpolated MPF<sub>PK</sub> stage, interpolated EMG<sub>Th</sub> stage, and average difference in %1RM between MPF<sub>PK</sub> and EMG<sub>Th</sub>. An ANOVA for repeated measures was used to assess differences between groups in interpolated MPF over ten stages. Both the independent t-tests and repeated measures ANOVA were also performed using %body fat as a covariate. A correlation analysis was used to assess the relationship between %1RM at MPF<sub>PK</sub> and %1RM at EMG<sub>Th</sub>. All data appear as mean ± standard deviation. Significance was determined at p < 0.05.

Results

Table 3 below describes the participants’ performance characteristics during the progressive isometric contractions protocol. The boys completed a similar number of progressive stages but the average EMG<sub>Th</sub> of the boys occurred at a significantly higher %1RM, or later in the exercise protocol than the men, as previously reported (Woods et al., 2019). Both, the MPF<sub>mn</sub> and MPF<sub>PK</sub> were higher in the men, but neither of these differences reached statistical significance. However, when %body fat was used as a covariate in the statistical analysis, the difference in both, MPF<sub>mn</sub> and MPF<sub>PK</sub> between boys and men was significant. The %1RM at which MPF<sub>PK</sub> occurred was not statistically different between boys and men. The range of MPF values was significantly greater in men compared with boys.
Table 3. Results of Progressive Resistance Protocol to Exhaustion – All participants

<table>
<thead>
<tr>
<th></th>
<th>Boys</th>
<th>Men</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>17</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Stage at Exhaustion (n)</td>
<td>17.1 ± 2.5</td>
<td>16.0 ± 3.4</td>
<td>0.27</td>
</tr>
<tr>
<td>Load at Exhaustion (%1RM)</td>
<td>80.4 ± 6.9</td>
<td>71.5 ± 10.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Torque at Exhaustion (Nm)</td>
<td>83.6 ± 17.4</td>
<td>214.9 ± 34.9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EMG_{Th} (%1RM)</td>
<td>56.8 ± 9.0</td>
<td>46.2 ± 6.8</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Mean MPF (Hz) *</td>
<td>109.7 ± 17.6</td>
<td>118.2 ± 20.3</td>
<td>*&lt;0.001</td>
</tr>
<tr>
<td>Peak MPF (Hz, 2nd order polynomial) *</td>
<td>113.8 ± 17.9</td>
<td>124.1 ± 22.0</td>
<td>*&lt;0.001</td>
</tr>
<tr>
<td>Peak MPF (Hz, integrated polynomial) *</td>
<td>113.7 ± 17.8</td>
<td>125.2 ± 22.2</td>
<td>*&lt;0.001</td>
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<tr>
<td>Peak MPF (%1RM)</td>
<td>58.3 ± 22.1</td>
<td>51.9 ± 15.6</td>
<td>0.31</td>
</tr>
<tr>
<td>MPF Range (Hz, integrated)</td>
<td>13.3 ± 6.4</td>
<td>18.5 ± 8.1</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

* Outcomes were analyzed for child-adult difference with %body fat as a covariate.

Table 4 describes the performance characteristics of only the participants who displayed an expected MPF pattern during the isometric contraction protocol. When analyzing this subset of the participant pool, the pattern of results was similar to the analysis of the whole group. Notably, in this subset, the %1RM at which MPF_{PK} occurred was significantly higher (i.e., occurred later) in the boys compared with the men.
Table 4. Results of Progressive Resistance Protocol to Exhaustion – Participants with Expected MPF pattern

<table>
<thead>
<tr>
<th></th>
<th>Boys</th>
<th>Men</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
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<td>13</td>
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<tr>
<td>Stage at Exhaustion (n)</td>
<td>17.82 ± 2.6</td>
<td>15.5 ± 2.9</td>
<td>0.05</td>
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<tr>
<td>Stage at Exhaustion (%1RM)</td>
<td>82.4 ± 7.4</td>
<td>70.7 ± 9.7</td>
<td>&lt;0.001</td>
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<tr>
<td>Torque at Exhaustion (Nm)</td>
<td>84.6 ± 16.3</td>
<td>216.3 ± 32.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>EMGth (%1RM)</td>
<td>58.1 ± 10.1</td>
<td>44.4 ± 5.6</td>
<td>&lt;0.001</td>
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<tr>
<td>Mean MPF (Hz)*</td>
<td>107.9 ± 18.6</td>
<td>117.8 ± 22.7</td>
<td>*0.008</td>
</tr>
<tr>
<td>Peak MPF (Hz, 2nd order polynomial)*</td>
<td>112.6 ± 19.6</td>
<td>123.4 ± 24.7</td>
<td>*0.009</td>
</tr>
<tr>
<td>Peak MPF (Hz, integrated polynomial)*</td>
<td>112.5 ± 19.4</td>
<td>123.7 ± 25.0</td>
<td>*0.009</td>
</tr>
<tr>
<td>Peak MPF (%1RM)</td>
<td>60.4 ± 20.6</td>
<td>46.7 ± 10.7</td>
<td>0.05</td>
</tr>
<tr>
<td>MPF Range (Hz, integrated)</td>
<td>15.7 ± 6.6</td>
<td>20.3 ± 6.9</td>
<td>0.11</td>
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</table>

* Outcomes were analyzed for child-adult difference with %body fat as a covariate.

Figure 2 displays the MPF pattern (averaged across all participants) at each stage for all stages (top), and during the ten interpolated stages (bottom). Generally, MPFmn initially increased, reaching a plateau, and then decreased until failure. This pattern was clearer when analyzing the subset of participants who displayed the expected trend (Figure 3).
Figure 3. Mean MPF of all participants for each stage for all stages completed (top) and for each of the ten interpolated stages (bottom). Numbers above data points represent the number of participants who completed the corresponding stage. The arrows indicate the mean stage at which the highest MPF occurred for both boys and men. Error bars are standard deviations.
Figure 4. Mean MPF of only the participants with an expected MPF pattern for each stage out of the total amount of stages completed (top) and for each of the ten interpolated stages (bottom). Numbers above data points represent the number of participants who completed the corresponding stage. The arrows indicate the mean stage at which the highest MPF occurred for both boys and men. Error bars are standard deviations.
Table 5 summarizes the statistical results of the repeated measures ANOVA of the interpolated MPF values for a) all participants, b) the subset of participants who exhibited the expected MPF pattern, c) all participants, with % body fat as a covariate, and d) the subset of participants who exhibited the expected MPF pattern, with % body fat as a covariate. There was a significant main effect of interpolated stage in a quadratic pattern for all analyses (p < 0.05). Pairwise comparisons revealed significant differences between the 10th (final) interpolated stage and stages 7 through 9 (p < 0.05), while there were no significant differences between the 10th stage and the first 6 stages. The ANOVA also revealed a significant main effect for group (p < 0.001) when using % body fat as a covariate, with higher MPF values in men than in boys. The stage-by-group interaction did not reach statistical significance (p = 0.194). The stage by % body fat interaction was significant in a linear pattern (p = 0.015).

Table 5a. Results of Repeated Measures ANOVA for MPF during Interpolated Stages (all participants)

<table>
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<tr>
<th>Effect</th>
<th>Degrees of freedom</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Subjects</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>1,35</td>
<td>1.8</td>
<td>0.189</td>
</tr>
<tr>
<td><strong>Within Subjects</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Stage</td>
<td>9,35</td>
<td>5.6</td>
<td><strong>0.005</strong></td>
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<td>Linear</td>
<td>1,35</td>
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<td>0.942</td>
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<tr>
<td>Quadratic</td>
<td>1,35</td>
<td>21</td>
<td><strong>&lt;0.001</strong></td>
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<tr>
<td>Cubic</td>
<td>1,35</td>
<td>9.6</td>
<td>0.004</td>
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<tr>
<td>Stage x group</td>
<td>9,35</td>
<td>1.8</td>
<td>0.472</td>
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</table>
Table 5b. Results of Repeated Measures ANOVA for MPF during Interpolated Stages (subset of participants who exhibited the expected MPF pattern)

<table>
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<th>Effect</th>
<th>Df</th>
<th>F</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Subjects</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>1,22</td>
<td>1.3</td>
<td>0.265</td>
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<tr>
<td><strong>Within Subjects</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td>9,22</td>
<td>11</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Linear</td>
<td>1,22</td>
<td>1.794</td>
<td>0.194</td>
</tr>
<tr>
<td>Quadratic</td>
<td>1,22</td>
<td>45</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Cubic</td>
<td>1,22</td>
<td>9.5</td>
<td>0.006</td>
</tr>
<tr>
<td>Stage x group</td>
<td>9,22</td>
<td>1.8</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 5c. Results of Repeated Measures ANOVA for MPF, with body fat percentage as covariate, during Interpolated Stages (all participants)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Subjects</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>1,34</td>
<td>28.0</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>% fat</td>
<td>1,34</td>
<td>16.9</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td><strong>Within Subjects</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td>9,34</td>
<td>5.2</td>
<td>0.006</td>
</tr>
<tr>
<td>Linear</td>
<td>1,34</td>
<td>5.9</td>
<td>0.021</td>
</tr>
<tr>
<td>Quadratic</td>
<td>1,34</td>
<td>5.7</td>
<td>0.023</td>
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<tr>
<td>Cubic</td>
<td>1,34</td>
<td>1.8</td>
<td>0.184</td>
</tr>
<tr>
<td>Stage x group</td>
<td>9,34</td>
<td>1.7</td>
<td>0.194</td>
</tr>
<tr>
<td>Stage x %fat</td>
<td>9,34</td>
<td>4.2</td>
<td>0.015</td>
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<tr>
<td>Linear</td>
<td>1,34</td>
<td>7.0</td>
<td>0.012</td>
</tr>
<tr>
<td>Quadratic</td>
<td>1,34</td>
<td>0.27</td>
<td>0.61</td>
</tr>
</tbody>
</table>
Table 5d. Results of Repeated Measures ANOVA for MPF, with body fat percentage as a covariate, during Interpolated Stages (subset of participants who exhibited the expected MPF pattern)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Subjects</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group</td>
<td>1,21</td>
<td>382.5</td>
<td>&lt;0.001</td>
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<tr>
<td>% fat</td>
<td>1,21</td>
<td>19.6</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td><strong>Within Subjects</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage</td>
<td>9,21</td>
<td>6.3</td>
<td>0.002</td>
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<tr>
<td>Linear</td>
<td>1,21</td>
<td>3.8</td>
<td>0.064</td>
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<tr>
<td>Quadratic</td>
<td>1,21</td>
<td>14.502</td>
<td>0.001</td>
</tr>
<tr>
<td>Cubic</td>
<td>1,21</td>
<td>3.449</td>
<td>0.077</td>
</tr>
<tr>
<td>Stage x group</td>
<td>9,21</td>
<td>1.8</td>
<td>0.180</td>
</tr>
<tr>
<td>Stage x %fat</td>
<td>9,21</td>
<td>5.384</td>
<td>0.006</td>
</tr>
<tr>
<td>Linear</td>
<td>1,21</td>
<td>8.535</td>
<td>0.008</td>
</tr>
<tr>
<td>Quadratic</td>
<td>1,21</td>
<td>0.942</td>
<td>0.343</td>
</tr>
</tbody>
</table>

A correlation analysis revealed that among participants who displayed the expected MPF pattern, there was a moderate correlation between the %1RM at which MPFpk and EMGTh occurred in boys ($r = 0.41$), a weak correlation in men ($r = 0.19$), and a moderate correlation when combining the two groups ($r = 0.51$).
Figure 5. Scatter plot of correlation between %1RM at MPF \textsubscript{PK} and %1RM at EMG\textsubscript{Th} in boys (top), men (middle) all participants (bottom) with expected MPF pattern
Discussion

This study examined the MPF response during a progressive isometric contractions protocol of the knee extensors to exhaustion in boys and men. It also compared the occurrence of MPF_PK with the occurrence of the EMG_TH in both groups. Overall, MPF values were generally higher in men compared with boys, but the pattern of change with increasing load was not different between groups. There was a variability in the pattern of response in both groups, with about 65% of participants demonstrating the expected inverted-U pattern. Among this subset of participants, MPF_PK occurred at a higher workload (%1RM), or at a later stage, among boys compared with men. These results suggest that the pattern of muscle fatigue during progressively increasing workloads is similar in boys and men, but that fatigue may occur later in boys. This is consistent with the finding of later EMG_TH in the boys. The relative intensities at which MPF_PK and EMG_TH occurred were moderately correlated, although they did not coincide. The overall higher MPF and greater range of values in men may reflect higher type-II fibre composition or activation during the progressive protocol.

The MPF of an EMG signal is considered a reliable reflection of muscle fatigue, with a large body of research demonstrating a shift to lower power spectrum frequencies with an increase in the physiological parameters that are associated with fatigue (i.e. lactate and metabolite accumulation) (Hendrix et al., 2009; Li, 2017). MPF is thought to be directly influenced by, and has been shown to be closely related to MFCV, which slows down during fatiguing exercise (Arendt-Nielsen & Mills, 1985; Fortune & Lowery, 2009; Mills & Edwards, 1984; Sadoyama et al., 1983; Overgaard et al., 1997). Since MFCV increases with higher intensity contractions (Kupa et al., 1995; Linssen et al., 1991; Pozzo et al., 2004), and MPF follows the same pattern (Bilodeau et al. 1990, 1995; Gabriel & Kamen, 2009), it has been suggested that during non-fatiguing contractions, MPF may also reflect relative intensity (Thongpanja et al., 2013). The main determinants of MFCV are contraction intensity and the type of
MUs being recruited (Methenitis et al., 2016). A higher contraction intensity is powered by a greater proportion of type II MUs that conduct MU action potentials at a faster rate, thereby increasing MFCV, and by relation, MPF (Kupa et al., 1995; Linssen et al., 1991; Masuda & De Luca, 1991; Pozzo et al., 2004). The decrease in MFCV and MPF during sustained submaximal contractions indicate an increasing proportion of recruited type II MUs that lose conduction velocity at a greater rate (Houtman et al., 2003), and this is amplified in higher-intensity fatiguing contractions (Rainoldi et al., 1999, 2008). Since MPF increases with intensity and decreases with fatigue, it was hypothesized that in an exercise protocol in which both intensity and fatigue increased simultaneously, the expected MPF pattern would consist of an increasing trend until fatigue would match and eventually outweigh the effect of the increase in intensity, resulting in a plateau and subsequent decrease in MPF. This is the first study to compare EMG MPF in boys and men during an exercise protocol in which both of its main influences, fatigue and intensity, are increasing at the same time. The inverted-U MPF pattern described in this hypothesis was observed in 65% of participants.

One of the main findings of the current analysis is that men demonstrated a significantly higher mean and MPF_{pk} than boys, after accounting for differences in adiposity. Subcutaneous fat has been shown to have consequential effects on the quality of the EMG signal, as the fat tissue creates a filter and a greater transmission distance between the muscle and the electrode (Petrofsky, 2008). An inverse relationship between MPF and skinfold thickness has previously been shown in adults (Baniqued et al., 2016). A higher MPF_{pk} in men than in boys has been shown previously in studies where EMG was recorded during exercise (Armatas et al. 2010; Halin et al., 2003). Since the exercise protocols in these studies used maximum effort contractions, MPF was highest at the start of the contraction, and was higher in men than in boys. The authors suggested that the higher MPF_{pk} in the men may be related to greater use of type-II muscle fibres. This is consistent with previous studies in adults which show that
initial or $\text{MPF}_{\text{PK}}$ is higher in individuals who have a greater proportion of type II MUs, characterized by higher MFCV (Gerdle et al., 1991; Komi & Tesch, 1979; Mannion et al., 1999; Rainoldi et al., 2008).

In line with the above, we observed higher $\text{MPF}_{\text{PK}}$, as well as $\text{MPF}_{\text{mn}}$ in the men compared with the boys. While there is a well-documented inter-individual variability in MPF values (Malek et al., 2006; Ryan et al., 2007), $\text{MPF}_{\text{mn}}$ has been shown to be higher in individuals and in muscles with presumably higher proportion of type II MUs (Akasaka et al., 1997; Bilodeau et al., 1994; Rainoldi et al., 2008; Sadoyama et al. 1988; Seki & Narusawa 1998). Thus, the finding of higher peak and mean MPF values in the men may reflect higher type-II fibre composition or activation during the progressive protocol.

The original analysis of the data compared the EMG RMS threshold ($\text{EMG}_{\text{Th}}$) in boys and men and found that it occurred earlier in men than in boys (Woods et al., 2019). The $\text{EMG}_{\text{Th}}$ is defined as the point at which the RMS amplitude of the EMG signal begins to increase at a greater rate and in a non-linear fashion (Miyashita & Kanehisa, 1980; Moritani & DeVries, 1978; Woods et al., 2019), reflecting an accelerated recruitment of higher-threshold, presumably type II MUs (Taylor & Bronks, 1996). An earlier occurring $\text{EMG}_{\text{Th}}$ in men indicates that they start recruiting their type II MUs at a lower relative exercise intensity, and that they have a greater reliance on type II MUs than boys. The current analysis showed that among participants who displayed the expected MPF pattern, $\text{MPF}_{\text{PK}}$ occurred at a significantly lower relative intensity (earlier) in men than in boys. This, along with the original finding of a lower $\text{EMG}_{\text{Th}}$ in men, suggests that men started utilizing a greater proportion of type II MUs earlier in the exercise protocol and fatigued earlier than boys.

In a progressive intensity exercise protocol to exhaustion, such as the one in the present study, the relative exercise intensities at which the $\text{MPF}_{\text{PK}}$ and the $\text{EMG}_{\text{Th}}$ occur are theoretically related, as they both relate to MU recruitment. Indeed, among the participants with the expected inverted-U
pattern, the relative exercise intensities (%1RM) at which $MPF_{PK}$ and $EMG_{Th}$ occurred were moderately related.

An important finding of the current analysis is the significantly greater MPF range in the men compared with the boys. Large increases in MPF with increasing intensity are related to greater utilization of type II MUs (Bilodeau et al. 1990, 1995; Gabriel & Kamen, 2009). Likewise, large decreases in MPF with fatigue are associated with enhanced type II MU recruitment (Halin et al., 2003; Komi & Tesch, 1979; Houtman et al., 2003; Rainoldi et al., 1999, 2008). The larger range of MPF values in the men suggests greater variability in the muscle fibre types recruited by the men. This suggestion is in line with previous studies which indicate that the frequency spectrum of the EMG signal is more sensitive to the recruitment of type II MUs than type I MUs (Komi & Tesch, 1979; Kupa et al., 1995; Linssen et al., 1991; Moritani et al., 1985; Orizio & Veicsteinas 1992; Taylor et al., 1997). The greater MPF range in the men is in line with other studies which show larger range of MPF values during exercise in adults than in children (Armatas et al., 2010; Halin et al. 2003; Tanina et al., 2017), and in power-trained or untrained athletes than in endurance athletes (Callewaert et al., 2012; Halin et al., 2002; Rainoldi et al., 2008). For example, Armatas et al. (2010) reported that during a protocol of intermittent 5s maximal isometric knee extensions to fatigue, average MPF values for the VL ranged between 92.8 ± 10.5 Hz and 60.7 ± 8.6 Hz in a group of men, while boys’ MPF values ranged between 88.3 ± 8.1 Hz and 82.5 ± 6.7 Hz. For the VM muscle, MPF values ranged from 97.3 ± 9.7 to 58.7 ± 6.0 Hz in men and stayed relatively steady around the initial MPF of 90.5 ± 10.6 Hz in boys (Armatas et al., 2010). Thus, the greater range of MPF values indirectly support the notion that the men had greater range of recruited MUs.

There are confounding anatomical and physiological factors that are difficult to account for when comparing children and adults. While differences in CSA of whole muscle can be normalized for, it is the size of the individual muscle fibres which influence the MFCV, and therefore, the MPF. Muscle fibre size is different between children and adults (Aherne et al., 1971). Among adults, muscle fiber
diameter has been shown to be positively correlated with conduction velocity (Blijham et al., 2006; Methenitis et al., 2016), but the effect of children’s smaller muscle fibres on the recorded conduction velocity during muscular contraction, and by extension, on the MPF of the EMG signal, is unknown. That is, the difference in the MFCV between children and adults may not be proportional to the differences in whole muscle size. This idea is supported by muscle biopsy studies in which it has been found that children tend to have type I and type II fibres of similar sizes, while the type II fibres of adults are typically larger than their type I fibres (Esbjörnsson et al., 2021). Among adults, MFCV is directly related to the percentage of type II fibres, irrespective of muscle fibre diameter (Sadoyama et al., 1988; Linssen et al., 1991). Nevertheless, it is possible that MPF pattern differences between children and adults reflect not only the composition and recruitment but also the size of the activated muscle fibres. It is also important to note that the extent to which MFCV mirrors MPF is not fully understood, with some authors reporting that the percentage decrease in MPF during fatiguing exercise always exceeds that of MFCV (Broman et al., 1985; Zwarts et al., 1987), while other studies demonstrate proportional relationships between both parameters (Arendt-Nielsen & Mills, 1985; Sadoyama et al., 1983). Halin et al. (2003) found that while both MPF and MFCV decreased to a greater extent in men than in children during a sustained MVC, the age-related difference was more pronounced in MPF. It was previously suggested that the discrepancy between MPF and MFCV change patterns may be explained by central nervous system-controlled firing rate regulation, mediated by metabolite and ionic accumulation in the muscle (Macefield et al., 2000). Firing rate would likely affect EMG parameters to a greater extent than MFCV and is directly related to fibre type composition (Tesch et al., 1979).

It is important to acknowledge that there are a multitude of factors that can affect MPF and the EMG signal is often highly variable, as seen in the present study, making interpretations difficult. The process of EMG signal rectification from the raw data is generally used to overcome the high-pass nature of the raw EMG signal by filtering the neural information with a low-pass transfer function,
allowing for the analysis of low frequency oscillations that are initially blunted in the raw EMG output (Negro et al., 2015). However, it has been argued that rectification may distort the coherence function when studying higher frequencies and introduce peaks that do not correspond to physiological shared input (Negro et al., 2015). EMG signal rectification may also allow for amplitude cancellation to influence the power spectrum by reducing the contribution of low-threshold MUs to the signal output (Farina et al., 2014). The use of MPF to infer details about MU recruitment specifically, has been criticized by some authors who point out that the difference between a surface action potential generated by a given motor unit with relatively high conduction velocity (high-threshold) and that generated by a motor unit with lower conduction velocity (lower-threshold) may be offset by a different distance between the two motor units and the recording electrodes (Farina et al. 2014). Thus, while numerous studies have shown that muscles or individuals with a relatively large proportion of type 2 MUs consistently generate greater increases in MPF with increasing force and greater decreases in MPF with increasing fatigue (Bilodeau et al. 1990, 1995; Gabriel & Kamen, 2009; Halin et al., 2003; Houtman et al., 2003; Komi & Tesch, 1979; Rainoldi et al., 1999; Rainoldi et al., 2008), the MPF pattern and the differences between groups observed in the current study should be interpreted with caution.

Beyond the caution which should be exercised when interpreting the results, the current analysis does have some limitations. The analysis is based on a relatively small sample size, especially that of the sub-sample of participants who displayed the expected MPF pattern. A larger sample size would provide a clearer depiction of the typical MPF patterns in both men and boys and potentially, a clearer difference between groups. The progressive protocol utilized in the present study is consistent with other threshold-related protocols utilized in exercise science (e.g., lactate threshold, ventilatory threshold). Nevertheless, it involved both increasing contraction intensities and onset of fatigue, both of which affect the MPF pattern. Previous studies have examined the effect of intensity and fatigue on MPF separately (Bilodeau et al., 2003; Bosch et al., 2009; Hussain et al., 2020). The simultaneous increase in
fatigue and intensity in the current exercise protocol may partly explain the variability in the MPF pattern observed. Despite the variability in the results, 65% of participants displayed the expected MPF pattern in which MPF increased or stayed stable in a non-fatigued state and with increasing intensity, and eventually decreased as fatigue became more prominent. Within this subset of the participants, the boys’ MPF \text{PK} occurred at a significantly greater relative exercise intensity (later) than in men, suggesting greater endurance and less reliance on higher-threshold (presumably type II) MUs in boys. Additionally, the MPF range was smaller in boys, suggesting that they activated a more homogenous MU pool (presumably type I) than the men. The findings of this analysis, along with the finding of a higher EMG\text{Th} in children (Long et al. 2017, Pitt et al. 2015, Woods et al. 2019, 2020), provide further support to the hypothesis of lower type-II MU activation in children (Dotan et al., 2012).

**Future Directions**

The issue of inter-individual variability in MPF during exercise is highlighted in the current analysis. Such inter-individual variability may be minimized by controlling physiological parameters such as temperature, hydration level, and blood flow, all of which have been shown to influence the frequency spectrum of the EMG signal (Bax et al., 2021; Bigard et al., 2001; Jaafar & Lajili, 2018; Mallette et al., 2018; Petrofsky & Lind, 1980; Souissi et al., 2012).

Participants with unexpected MPF outcomes may have specific commonalities regarding their physiological characteristics during exercise, which could help to explain the variability found in the current analysis and others. A future study’s protocol could separate increasing force from increasing fatigue. One way to do that is by investigating MPF during sustained isometric contractions (e.g. 15s) of increasing intensities, but with sufficient rest intervals to avoid fatigue, and/or in random order. This could help to determine whether the variability is due to inherent physiological differences among
individuals or due to the complexity of the interaction between the progressive contraction intensity and the fatigue.

While the current analysis provided some evidence supporting the hypothesis of lower type-II MUs activation in children, future research should attempt to build on the current findings and use the most prominent MPF determinants, intensity and fatigue, in a more systematic fashion that could clearly differentiate MPF patterns in children and adults. Based on previous research, it is known Type II MUs are increasingly recruited as intensity of contraction increases, and that Type II MUs are recruited to a lesser extent at lower intensities (Andreassen & Arendt-Nielsen, 1987; Fling et al., 2009; Henneman, 1985). If there are specific MU recruitment differences between children and adults, they should only be demonstrated at higher intensities and not at lower intensities. Therefore, a child-adult study that examines MPF during a fatiguing contraction at both high and low intensities in separate sustained contractions could provide more insight into EMG-related differences between children and adults and the possible implications for MU recruitment, which may reinforce the current findings.
References


APPENDIX

Appendix A: Subject Screening and Medical History Questionnaire

APPLIED PHYSIOLOGY RESEARCH GROUP

DEPARTMENT OF KINESIOLOGY, BROCK UNIVERSITY

Your responses to this questionnaire are confidential and you are asked to complete it for your own health and safety. If you answer “YES” to any of the following questions, please give additional details in the space provided and discuss the matter with one of the investigators.

ID: ___________________________ Date: ___________________________

1. Have you ever been told that you have a heart problem?
   YES NO

2. Have you ever been told that you have a breathing problem such as asthma?
   YES NO

3. Have you ever been told that you sometimes experience seizures?
   YES NO

4. Have you ever had any major joint instability or ongoing chronic pain such as in the knee, back or elbow?
   YES NO

5. When you experience a cut do you take a long time to stop bleeding?
   YES NO

6. When you receive a blow to a muscle do you develop bruises easily?
   YES NO

7. Are you currently taking any medication (including aspirin) or have you taken any medication in the last two days?
   YES NO

8. Is there any medical condition with which you have been diagnosed and are under the care of a physician (e.g. diabetes, high blood pressure)?
   YES NO
Appendix B: Godin-Shepard Leisure Time Exercise Questionnaire

GODIN-SHEPHARD LEISURE-TIME EXERCISE QUESTIONNAIRE

ID: __________ Date: __________________________

1. Considering a 7-day period (a week), how many times on the average do you do the following kinds of exercise for more than 15 minutes during your free-time (write on each line the appropriate number)?

   Times Per Week

   (a) STRENUOUS EXERCISE (HEART BEATS RAPIDLY)
   (i.e. running, jogging, hockey, football, soccer, squash, basketball,
cross country skiing, judo, roller skating, vigorous swimming,
vigorous long distance bicycling) __________

   (b) MODERATE EXERCISE (NOT EXHAUSTING)
   (i.e. fast walking, baseball, tennis, easy bicycling, volleyball,
badminton, easy swimming, alpine skiing, popular and folk dancing) __________

   (c) MILD EXERCISE (MINIMAL EFFORT)
   (i.e. yoga, archery, fishing from river bank, bowling, horseshoes,
golf, snow-mobiling, easy walking) __________

2. Considering a 7-day period (a week), during your leisure-time, how often do you engage in any regular activity long enough to work up a sweat (heart beats rapidly)?

   1. OFTEN  2. SOMETIMES  3. NEVER/RARELY

   □          □          □
Appendix C: Training History Questionnaire

ID: ________________________ Date: __________________________

Please fill in the table below to the best of your knowledge. If you have any difficulties, discuss the matter with one of the investigators.

<table>
<thead>
<tr>
<th>Activity/Sport</th>
<th>Level of Competition</th>
<th># of years</th>
<th>Sessions/week</th>
<th>Min/session</th>
<th>Intensity (light, moderate, intense, very intense)</th>
<th>Seasonal length</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swimming</td>
<td></td>
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<td></td>
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<tr>
<td>Hockey</td>
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<td></td>
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<tr>
<td>Gymnastics</td>
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<td></td>
</tr>
<tr>
<td>Running</td>
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<td>Resistance</td>
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<tr>
<td>Other</td>
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<td></td>
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</tr>
</tbody>
</table>
Appendix D: Pubertal Stage Questionnaire (Tanner, 1962)

**Male Pubertal Stage**

This survey will be used to assess the maturational levels of the participant. For each photo choose the appropriate stage and place an X in the corresponding square.

ID: _________________________              Date:        ____________________

- Please circle the box that looks most like you
- Please look at the pubic hair only
- Please circle the box that looks most like you

1  2  3  4  5  6
Appendix E: Dynamometer

Front view

Back view: Apparatus on which weights (resistance) are applied

Side view, with participant seated.
(note pulley system)

Lever and pulley system

Apparatus on which weights (resistance) are applied

Examples of weights (resistance)