Motor Unit Recruitment Patterns in Traditional Strength Loading and Peak Average Power Loading Protocols

by

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Bachelor of Science in Kinesiology (University of New Brunswick, 2019)

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Kinesiology

in the Graduate Academic Unit of Kinesiology

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This thesis is accepted by the
Dean of Graduate Studies

THE UNIVERSITY OF NEW BRUNSWICK

August 2019

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ABSTRACT

Peak average power (PAP) and traditional strength (TS) loading methods demonstrate similar strength responses. Motor unit recruitment strategies of PAP loading have yet to be explained. The purpose of this study was to 1) understand if isotonic and isokinetic contractions have similar responses, and 2) compare PAP and TS loading methods. A total of 30 (15M, 15F) healthy participants (23.1 ± 3.0 yrs.; 173.3 ± 7.9 cm; 76.6 ± 13.6 kg) were recruited. There were three testing sessions: baseline and two experimental data collection sessions (isokinetic contractions (isokinetic dynamometer) and isotonic contractions (back squats)). For the isokinetic condition, TS loading used a speed of 30 deg/s (85% of maximal torque capacity), while PAP loading used a speed of 120 deg/s (100% maximal torque capacity). For the isotonic contraction condition, TS loading used a load of 85% 1-RM, while PAP loading used a load of 67% 1-RM. Muscle activity was measured using high-density electromyography (EMG). Spatial EMG parameters were found not to be significantly different between the two contraction conditions. TS and PAP loading methods do not differ in their motor unit recruitment patterns. Therefore, PAP loading may be a viable method to reduce the strain on the musculoskeletal system, while still stimulating the high threshold motor units.
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Chapter 1: Introduction

1.1 Background Information

Motor unit activation and recruitment patterns for various muscular loading strategies has been an area of interest in recent years, though there is still limited research. To date, a lot of our knowledge is theorized using the size principle (Henneman, 1957; Henneman & Mendell, 1981). According to this theory, motor unit recruitment occurs in an ascending order in that motor units that are weaker and least fatigable (type I muscle fibres) are recruited first, followed by increasingly stronger and more fatigable fibres (type IIa and type IIx muscle fibres) (Burke, Levine, Tsairis, & Zajac, 1973; Fuglevand, Macefield, & Bigland-Ritchie, 1999; Thomas, Johansson, & Bigland-Ritchie, 1991). However, although these categories appear to be distinct and separate from each other, they actually are thought to reside along a continuum (Heckman & Enoka, 2012).

Traditional surface electromyography (EMG) has a limited ability to measure muscle activity at the motor unit level (Stegeman, Kleine, Lapatki, & Van Dijk, 2012) therefore, high-density electromyography (HD-EMG) was developed in hopes of correcting this limitation. The most prominent difference between HD-EMG and traditional EMG methods is that, HD-EMG provides information regarding the spatial distribution, otherwise known as spatial mapping. Additionally, HD-EMG uses electrode grids that are much larger and contain more electrodes, than traditional EMG methods. This consequently enables the researcher or clinician to gain an understanding regarding a larger cross-section of the muscle.
Factors such as fatigue have been suggested to alter the recruitment patterns of muscle fibres during physically demanding tasks. Potvin and colleagues (2017), developed a computer model to explain motor unit activity during various intensities of force application. This model was developed under the basis of physiological theories surrounding recruitment patterns and fatigue, so that the model provided accurate representations of muscle activity. It is theorized that during a sustained 50% maximum voluntary contraction (MVC), all low frequency muscle fibres maintain their motor unit force capacity for 95 seconds, moderate frequency muscle fibres show a slight decline during that same time frame, and highest frequency muscle fibers gradually increase in motor unit force until about 95 seconds, where they then begin to drop off. At 100% MVC, all motor units are recruited initially, with the highest frequency muscle fibres fatiguing the fastest, followed by moderate frequency muscle fibres and then low frequency muscle fibres. This model undoubtedly produced some insight regarding motor unit recruitment during various loading intensities, however little focus has been paid to the recruitment strategies of motor units during activities that require moderate force and high velocity (i.e. power training methods). With the development of HD-EMG, it may be possible to begin to understand the similarities and differences in motor unit recruitment patterns between peak average power loading methods and traditional force loading methods as explained by Potvin et al., (2017).

Peak average power loading, otherwise known as optimal load loading, occurs when the load that maximizes peak power is used during a training session (De Vos et al., 2005). This type of loading is a form of moderate-load high-velocity resistance training, as it typically involves loads ranging from 65-75% of an individual’s one
repetition maximum (1-RM). Contrary to peak average power loading, traditional strength loading utilizes heavier loads with limited focus on movement velocity, usually about 85% of the 1-RM. Although different loads are used for each strategy, both have been found to elicit similar performance and strength gains (Loturco, Ugrinowitsch, Roschel, Tricoli, & González-Badillo, 2013). However, despite similar performance and strength gains, theoretically, the differences in loading styles should lead to different recruitment strategies and fatigue rates as explained by Potvin and colleagues (2017). To measure and monitor muscle activity patterns over the course of the exercise set, variables such as mean amplitude (magnitude of muscle activity), entropy (the amount of spatial heterogeneity throughout the electrode grid), and conduction velocity (the time it takes for the signal to propagate along the sarcolemma) can be measured.

Earlier data from our lab has assessed a high velocity resistance training intervention using peak average power loading and traditional strength loading methods (Wallace, 2018). It was found that there was no significant difference between traditional strength loading methods (average load over an 8-week period was 87.5%) and peak average power loading methods (average load over an 8-week period was 72.5%) across an 8-week period. However, both groups did significantly improve from pre- to post-intervention, for force, power, body composition, and performance variables. Although it appears clear that the peak average power loading method is a viable means of developing muscular force generating capacity in a healthy population, the mechanism of muscle fiber activation remains undiscovered.
1.2 Statement of the Problem

Based on previous research, it was determined that there were no differences between peak average power and traditional loading protocols for various force, power, and performance measures following an eight-week intervention. The goal of this study is to assess the acute motor unit recruitment strategies across a single set of exercise using both isotonic and isokinetic methodologies during both the peak average power and traditional strength loading protocols. An understanding of the recruitment patterns of these loading protocols could influence the way strength and conditioning coaches develop programs for athletes based on desired muscular activation patterns.

1.3 Purpose of the Study

The purpose of this study was to determine if 1) isokinetic loading methods could be used to simulate isotonic loading for traditional strength (TS) and peak average power (PAP) loading strategies, 2) if the motor unit recruitment strategies differed between PAP and TS loading strategies across a single set of exercise in a healthy population. To accomplish this, activation patterns were monitored throughout each repetition of each loading style using HD-EMG. This consequently allowed us to better understand of the muscle recruitment strategies during the onset and cessation of the set, the magnitude of fatigue experienced throughout the set, and if isokinetic contractions elicit similar recruitment strategies as isotonic contractions (squat) for a respective loading style.

1.4 Delimitations

In the following study, individuals who belonged (students or employees) to the University of New Brunswick, Fredericton campus were recruited to participate.
Additionally, only those who were between the ages of 19-35 years old were recruited. This consequently affects the generalizability of the results. Youths and elderly participants were not allowed to participate in the following study, therefore the results of the following study cannot be generalized to those subsets of populations.

Additionally, another delimitation to the following study is the lack of familiarization sessions to the loading styles using in this study. It was not a requirement that participants have experience using isokinetic dynamometers. Although all participants had resistance training experience and therefore, likely have used a leg extension machine in the past. Being restrained with straps around the shoulders and hips to allow for isolation of the knee joint unilaterally may be foreign to most participants.
Chapter 2: Literature Review

2.1 Peak Average Power Loading Compared to Traditional Loading

The selection of a loading protocol (volume and intensity) is a critical component to exercise programming, as the loading protocol determines what adaptations occur within the muscle tissue. The magnitude of power and force adaptations are important, especially when programming for elite athletes but also for the elderly. Table 1 and table 2 breakdown the adaptations which have been reported for both power and force based on power loading, and resistance loading methodologies.

Table 1 presents the power adaptation training response of each loading strategy when used during a training program. Loaded power training interventions produce a moderate effect size when 80-100% of the participants’ 1-RM is used, while large effect sizes are seen when lower loads (30% 1-RM) are used. Therefore, if power is of interest during loaded power training interventions (i.e. jump squats are used), results suggest that a lower load is more efficient at inducing favorable adaptations. When a resistance training intervention is considered, results suggest that moderate to large effect sizes can be seen. Additionally, the two studies that produced the largest effect sizes, individuals trained at 85-90% of their 1-RM.
Table 1 Summary of studies that applied power training and the effects it had on power.

<table>
<thead>
<tr>
<th>Author</th>
<th>n</th>
<th># of weeks</th>
<th>Load Used to Train</th>
<th>Pre-Peak Power</th>
<th>Post-Peak Power</th>
<th>Effect Size (Cohen’s D)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loaded Power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(McBride, Triplett-McBride, Davie, &amp; Newton, 2002)</td>
<td>9</td>
<td>8</td>
<td>30% 1-RM</td>
<td>3554 ± 207 (W)</td>
<td>3908 ± 235 (W)</td>
<td>1.60</td>
</tr>
<tr>
<td>(Jones, Pyne, Haff, &amp; Newton, 2018) Notes: Used unloaded testing condition</td>
<td>6</td>
<td>6</td>
<td>80-100% 1-RM</td>
<td>62.7 ± 8.6 (W/kg)</td>
<td>68.2 ± 8.1 (W/kg)</td>
<td>0.66</td>
</tr>
<tr>
<td><strong>Resistance Training</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Ronnestad, Kvamme, Sunde, &amp; Raastad, 2008)</td>
<td>6</td>
<td>7</td>
<td>4-6 RM</td>
<td>3399 ± 218 (W)</td>
<td>3775 ± 226 (W)</td>
<td>1.69</td>
</tr>
<tr>
<td>(Maté-Muñoz et al., 2018) Notes: Control was used and PP of Pmax</td>
<td>15</td>
<td>5</td>
<td>60% 1-RM</td>
<td>1397 ± 245(W)</td>
<td>1565 ± 146 (W)</td>
<td>0.83</td>
</tr>
<tr>
<td>(Teo, Newton, Newton, Dempsey, &amp; Fairchild, 2016)</td>
<td>13</td>
<td>6</td>
<td>70% 1-RM</td>
<td>4358 ± 658 (W)</td>
<td>4815 ± 646 (W)</td>
<td>0.70</td>
</tr>
<tr>
<td>(Fatouros et al., 2000)</td>
<td>10</td>
<td>12</td>
<td>70-95% 1-RM</td>
<td>46.5 ± 12.6 (W/kg)</td>
<td>58.0 ± 12.6 (W/kg)</td>
<td>0.91</td>
</tr>
<tr>
<td>(Sayers, Guralnik, Thomsbs, &amp; Fielding, 2005) Notes: Older participants</td>
<td>13</td>
<td>12</td>
<td>40% 1-RM</td>
<td>321.8 ± 133.2 (W)</td>
<td>416.1 ± 164.3 (W)</td>
<td>0.63</td>
</tr>
<tr>
<td>(Jones et al., 2018) Notes: Used unloaded testing condition</td>
<td>13</td>
<td>6</td>
<td>80% 1-RM</td>
<td>324.6 ± 154.3 (W)</td>
<td>397.3 ± 169.6 (W)</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Table 2 displays the effects that the loading protocols have on force adaptations following training interventions. Loaded power training interventions produce small effect sizes when lighter loads are used, while heavier loads produce large effect sizes. Resistance training interventions produce moderate to large effect sizes, however heavier loads have been shown to produce greater effect sizes. There is one exception to these results, which was a study completed by Reeves et al., (2004) but the results could be due to a lack of exercises, sets, and repetitions or factors relating to the participants such as age or previous injuries.

Table 2 Summary of studies that applied training protocols to improve force and the effects it had on force.

<table>
<thead>
<tr>
<th>Force</th>
<th>Author</th>
<th>n</th>
<th># of weeks</th>
<th>Load</th>
<th>Pre-Peak Force</th>
<th>Post-Peak Force</th>
<th>Effect Size (Cohen’s D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loaded Power</td>
<td>(McBride et al., 2002)</td>
<td>10</td>
<td>8</td>
<td>80% 1-RM</td>
<td>2697.7 ± 133.9 (N)</td>
<td>2891.5 ± 124.8 (N)</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>(Cormie, McGuigan, &amp; Newton, 2010) Notes: Trained using body weight jump squats</td>
<td>8</td>
<td>10</td>
<td>0-30% 1-RM</td>
<td>35.1 ± 7.2 (N/kg)</td>
<td>36.0 ± 6.5 (N/kg)</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>(Jones et al., 2018) Notes: Used loaded testing condition</td>
<td>6</td>
<td>6</td>
<td>80-100% 1-RM</td>
<td>2151.5 ± 154.7 (N)</td>
<td>2346.5 ± 221.7 (N)</td>
<td>1.02</td>
</tr>
<tr>
<td>Resistance Training</td>
<td>(Reeves, Narici, &amp; Maganaris, 2004) Notes: Older participants</td>
<td>9</td>
<td>14</td>
<td>60-80% 5-RM</td>
<td>847.9 ± 365.3 (N)</td>
<td>939.3 ± 347.8 (N)</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>(Hakkinen, Alen, &amp; Komi, 1985)</td>
<td>11</td>
<td>36</td>
<td>70-100% 1-RM</td>
<td>3987 ± 1025 (N)</td>
<td>5056 ± 1286 (N)</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>(Cormie et al., 2010)</td>
<td>8</td>
<td>10</td>
<td>75-90% 1-RM</td>
<td>34.0 ± 6.2 (N/kg)</td>
<td>41.3 ± 4.3 (N/kg)</td>
<td>1.37</td>
</tr>
</tbody>
</table>
Based on the results of prior work, it is clear that both traditional resistance training and loaded power training result in similar performance outcomes for force and power. However, the mechanism of motor unit stimulation is still unknown. Based on Henneman’s principle, when considering force only, the lower load power protocols should be recruiting motor units in the same fashion as the resistance loading methods. However, due to the requirement of high velocities during the lower load power protocols, it is hypothesized that a more complete motor unit activation is being employed to allow for the expression of maximal power output. It is therefore suggested that two different strategies are being utilized for traditional resistance training compared to peak average power loading. It is hypothesized that the traditional loading protocol uses a less complete motor unit activation at the onset of the exercise with full recruitment during the final repetition due to accumulated fatigue. While the peak average power protocol uses a maximal motor unit recruitment at the onset of the exercise to allow for the expression of maximal velocity against a moderately heavy load, with a reduction in motor unit recruitment throughout the protocol due to accumulated fatigue.

2.2 Muscle Physiology

In order to better understand the rationale for these hypotheses, it is important to understand the underlying physiology of muscle.
2.2.1 Muscle Fibre Type Characteristics and Adaptations

There are three types of muscle fibres in human skeletal muscle; Type I, Type IIa and Type IIx. Each muscle fibre possesses their own unique characteristics which are one of the factors that determine how well athletes perform in competition. For example, long- and middle-distance runners have 60-70% slow-twitch muscle fibres, whereas sprinters have 80% fast-twitch muscle fibres (Widrick, Stelzer, Shoepe, & Garner, 2002). In sports requiring a greater aerobic capacity, there is a greater proportion of slow-twitch fibres. This is a noteworthy adaptation in aerobic endurance sports because slow-twitch fibres have a higher mitochondrial volume density and capillary-fibre contact length, which allows them to deliver more oxygen to the working muscle to allow for greater aerobic ATP production (Sullivan & Pittman, 1987). In contrast to athletes that compete in sports requiring a greater aerobic capacity (greater type I muscle fibre percentage), athletes who participate in sports requiring greater amounts of power develop a greater percentage of type IIa and type IIx muscle fibres. This is because type IIa and type IIx muscle fibres are able to produce 6 to 10 times the amount of power, respectively, than type I muscle fibres (Wilk et al., 1996). The larger cross-sectional area (CSA) that type II muscle fibres possess (26% and 39% greater CSA in type IIa and type IIx, respectively, in comparison to type I) also allows them to generate more absolute force (Malisoux, Francaux, Nielens, & Theisen, 2006). Type IIa and type IIx muscle fibres have the ability to generate 3 and 4.4 times greater contractile velocity, compared to type I muscle fibres (Malisoux et al., 2006). Lastly, type II muscle fibres have a greater capacity for exercise-induced hypertrophy (Karp, 2001; Schoenfeld, 2000) and hydrolyze adenosine triphosphate (2-3 times) faster, in comparison to their
type I muscle fibre counterparts, which allows them to regenerate force and velocity at much quicker rates (A. W. Taylor, Essén, & Saltin, 1974).

Strength loading (around 85% 1-RM) protocols have been found to alter muscle fibre composition in both males and females (Adams, Hather, Baldwin, & Dudley, 1993; Staron et al., 1994, 1991, 1989). The favorable muscle fibre adaptations observed with this loading protocol have been thought to occur from absolute and relative increases of fast twitch muscle fibres (Edström & Ekblom, 1972; Gollnick, Armstrong, Saubert, Piehl, & Saltin, 1972). Literature has suggested that there is a transformation of type IIx(IIb) muscle fibres to type IIa muscle fibers following a strength loading protocol (Adams et al., 1993; Hather, Mason, & Dudley, 1991; Hather, Tesch, Buchanan, & Dudley, 1991). This muscle fibre transformation coincides with a proportional significant increase of type IIa MHC activity and a significant decrease of type IIx(IIb) MHC activity. However, the proportion of type I muscle fibres and MHC remained unchanged following a 19-week period where participants followed a heavy strength loading protocol (Adams et al., 1993). This transformation was demonstrated in as little as an 8-week training program (Thorstensson, Hultén, Döbeln, & Karlsson, 1976). The underlying cause of this transformation is thought to occur from the inability of type IIx muscle fibres to meet the required demands of various activities requiring type IIa muscle fibres. This consequently results in a decrease in the number of type IIx muscle fibres and an increase in type IIa muscle fibres, so that the demands of the activity can be met (Adams et al., 1993). Following strength loading interventions, significant positive correlations have also been seen (r=0.31 to r=0.67) between Mg$^{2+}$ stimulated ATPase activity and the percentage of fast twitch muscle fibres (Thorstensson et al.,
This relationship is thought to be a representation of how much actomyosin ATPase activity is present during a contraction (Perry, 1998).

In contrast to strength loading, optimal power loading protocols have become increasingly popular as of late. This type of protocol consists of fast, explosive contractions, such as a jump squats or snatches. Further, there appears to be a relationship between the velocity that someone trains and their subsequent performance during competition. In other words, when an athlete trains at a high-velocity and low-load, torque development improves at and below the specific training velocity (Moffroid & Whipple, 1970). This is an important consideration to understand, because as the velocity increases, a more pronounced transformation between muscle fibres may be seen. Paddon-Jones et al., (2001) discovered that when a 10-week exercise protocol consisting of fast isokinetic contractions is employed, the number of type I muscle fibres decreased 53% to 39%, while the amount of type IIx muscle fibres increased 5.8-12.9%. Liu and colleagues (2003), compared exercise induced muscle fibre transformations in the triceps brachii after a 6-week workout protocol. The two groups being compared were a traditional strength loading group (3RM load for 5 sets, 3 days per week) and a combined group (first day consisted of 3-RM load for 5 sets, second day consisted of 10 ballistic movements at 30% of their 1-RM, and their third day consisted of 10 push-ups). They concluded that within the strength loading group, MHC activity of the type IIx muscle fibres decreased (33.4%-19.5%), while there was a subsequent increase in MHC activity of the type IIa muscle fibres (44.9%-66.7%). MHC activity of type I muscle fibres remained unchanged. In contrast, the combined group did not have a change in MHC type IIx muscle fibre activity, although there was an increase in MHC activity for
the type IIa muscle fibres (47.7%-62.7%) and a 50% reduction in MHC activity of type I muscle fibres. In a study by Ewing and colleagues (1990), a 10-week workout protocol was employed where participants trained at either fast or slow velocities. Following the 10-weeks, those who were allocated to the faster training group saw a reduction in type I muscle fibres (51.4-47.3%) and type IIx (Ilb) muscle fibres (12.9% to 10.8%), though there was an increase in type IIa muscle fibres (35.8% to 41.9%). More importantly however, these results were not significant even though muscle fibre area significantly increased for all muscle fibre types (Ewing, Wolfe, Rogers, Amundson, & Stull, 1990).

Sprint loading methods require greater amounts of anaerobic power, similar to power loading strategies. The primary difference between these two methods is that with sprint training, little to no external load is used. Athletes participating in this loading method have been found to have anywhere between 60% to 80% fast-twitch muscle fibres (Aagaard & Andersen, 1998; Bergh et al., 1978). Andersen and colleagues (1994) found that after a 12-week sprint training program, trained male sprinters had a 34.7% to 52.3% increase in MHC type IIa activity and a subsequent decrease in MHC type I (52-41%) activity. The percentage of type IIx muscle fibres decreased from 18% to 10.5%, which accounted for the increase in type IIa muscle fibres. These results are further supported by Jansson and colleagues (1978), who found that following a 4-6-week sprint training protocol (maximal effort 30-second sprints on a cycle ergometer), type I muscle fibres decreased (57-48%), while there was an apparent 6% increase (32-38%) of type IIa muscle fibres. To further support these findings, Esbjornsson and colleagues (1993), found that a 6-week high intensity sprint training program resulted in a decrease
of type I (7%) and type IIx (6%) muscle fibres, while there was an increase of type IIa muscle fibres (12%).

In conclusion, loading protocols elicit specific training adaptations and literature has suggested that proportional re-distribution between muscle fibre types can be observed. The proportional re-distribution partially dictates how well athletes perform during competition due to the adaptations occurring at the muscle fibre level. Therefore, it is critical to consider the specific sport that an athlete is competing in, as well as the load that they will use during training. This will ensure that optimal and beneficial adaptations are occurring within the muscle.

2.2.2 Motor Unit Recruitment

The underlying neural patterns of motor unit recruitment and recruitment are partly explained by the size principle, which was first theorized by Henneman and colleagues (1957). The size principle governs the idea that recruitment follows an ascending order according to motor unit twitch force and firing rates; weakest, slowest, and least fatigable muscle fibers (type I) are recruited first, followed by stronger, faster, and more fatigable muscle fibers (type IIa and type IIx) (Henneman, 1957; Henneman & Mendell, 1981). There appears to be distinct categories of motor units, however because human skeletal muscle is composed of various percentages of each muscle fiber type, it is better to think of muscle as residing on a broad continuum (Heckman & Enoka, 2012). Although the size principle is a distinguished theory commonly adopted in literature, it has been suggested that there may be exceptions to its underlying mechanisms, though there is controversy surrounding this idea. During movements that require high velocity (plyometric or Olympic lifting), it has been suggested that high threshold muscle fibers
are actually recruited before low threshold muscle fibers, which is termed selective recruitment (Nardone, Romanò, & Schieppati, 1989). Selective recruitment has been suggested to occur because of the abbreviated time available to develop and produce maximal force, which is one of the adaptations seen with heavy resistance training.

The other factor that determines the rate and magnitude of force generation during a contraction is termed rate coding. This is the idea that the nervous system is able to alter the rate of action-potential impulses to either increase or decrease force production (Fuglevand, Winter, & Patla, 1993). During fine movements (i.e. when typing on a keyboard), the excitability of motor neurons may be organized within the hand such that all muscles are recruited at low forces and rate coding is then the primary means of increasing force (De Luca, LeFever, McCue, & Xenakis, 1982b; Kukulka & Clamann, 1981; Milner-Brown, Stein, & Yemm, 1973). Rate coding is notably important during movements that require high explosive activity. When there is an increase in frequency of neural impulses in a muscle that is already active, no further motor units need to be activated to generate the increase in force. High explosive activities consequently may induce adaptations to a muscles ability to rate code, as it results in an increased frequency of stimulation in high threshold muscle fibers (Haff, Whitley, & Potteiger, 2001).

It is believed that both the size principle (recruitment) and rate coding (the rate at which motor units are fired) play a vital role in force production (Deschenes, 1989). The interplay between these two factors depends on the size and fiber-type composition of the muscle of interest. For example, the adductor pollicis (which has a type I fiber composition of approximately 72-91%) relies primarily on motor unit recruitment
between 0-50% of the maximal voluntary contraction. Beyond that intensity threshold, rate coding is the primary means of increasing force (Kukulka & Clamann, 1981). When considering a more heterogenous muscle, such as the deltoid, a different pattern of recruitment is expressed (De Luca et al., 1982b; De Luca, LeFever, McCue, & Xenakis, 1982a; Kukulka & Clamann, 1981). Lastly, when considering contractions that involve maximal or near maximal force generation, high threshold fibre (type IIa and type IIx) recruitment is a prerequisite owing to their high force and power generating capabilities (Haff et al., 2001).

2.2.3 Fatigue

Fatigue is defined as the inability to maintain the required or expected force (Edwards, 1981). The underlying mechanisms of fatigue have yet to be fully established, however it has been supported that fatigue adversely affects athletes, various occupational environments, and elderly populations. Muscle byproducts and alterations to the transmembrane ionic concentrations, which have a direct effect on cross-bridge function and excitation-contraction coupling, have been suggested as underlying mechanisms of fatigue in literature (Allen, Lamb, & Westerblad, 2008; Fitts, 1994; Kent-Braun, Fitts, & Christie, 2012).

Additionally, there are various neural components that are thought to contribute to the volume of fatigue that is experienced. Proposed neural components that could be associated with fatigue include a reduced output of higher motor centers that control motor neurons, an increase of synaptic inhibition controlling motor neurons, and adaptations that contribute to motor neurons being less responsive during an activity that requires sustained contractions (Fuglevand, 1996; Gandevia, 2001; Gandevia, Allen, &
McKenzie, 1995; Taylor, Amann, Duchateau, Meeusen, & Rice, 2016). The volume of fatigue also depends on the composition of the contracting muscle fibre, as well as factors relating to the activity itself (i.e. type, duration, and intensity).

Excitation-Contraction (E-C) coupling, otherwise known as a muscle contraction, is regulated by a number of components; the neural-muscular junction, the surface membrane of the muscle cell, the transverse tubules (T-tubules), and the sarcoplasmic reticulum (SR) membrane, which regulates the release of calcium. Besides the neural-muscular junction, all of the components listed above are thought to contribute to fatigue in some capacity. An increased extracellular potassium (K\(^+\)) concentration and consequently a reduced concentration of intracellular K\(^+\), results in a reduced depolarization capacity. This has been suggested as an important factor that may contribute to the experience of fatigue, because it results in a reduced probability that an action potential, which initiates muscle contraction, propagates throughout the muscle. Thus, it is evident that the sodium-potassium (Na\(^+\)-K\(^+\)) pumps located within the sarcolemma and T-tubule play a vital role during the onset of fatigue.

Another factor regulating the T-tubules functional capacity within the muscle cell is the T-tubular dihydropyridine receptor (DHPR), otherwise known as a charge sensor. The DHPR has been suggested to monitor the voltage within a muscle cell and send signals during surface depolarization of the muscle cell to the ryanodine receptor (RyR). RyR is the pathway that releases calcium (Ca\(^{2+}\)) from the SR (Dulhunty et al., 2002). The DHPR is thought to be a robust mechanism and even during extreme levels of fatigue, its function remains unaffected. During prolonged fatigue, the DHPR actively measures the increased concentration of extracellular Ca\(^{2+}\) (Grabowski, Lobsiger, &
Lüttgau, 1972). This increased concentration of extracellular Ca\(^{2+}\) leads to a reduced amplitude of Ca\(^{2+}\) release, possibly resulting from a blockage within the sarcoplasmic reticulum calcium (SR-Ca\(^{2+}\)) release channel. The diminished amplitude results in a reduced force output, because intracellular Ca\(^{2+}\) is positively correlated with force generating capacity. Although the DHPR is not negatively affected during fatigue, it does play a vital role in monitoring and relaying messages regarding the amount of Ca\(^{2+}\) that will be released and consequently the amount of force that the ensuing contraction will produce.

Intracellular Ca\(^{2+}\) concentration within the SR prior to the initiation of the contraction is another mediator of E-C coupling, as briefly discussed above. During repetitive muscle contractions, it has been suggested that a reduction in SR-Ca\(^{2+}\) activity occurs from either Ca\(^{2+}\) binding with its respective protein (parvalbumin) or the SR pump. Thus, there is reduced activity during the removal process of Ca\(^{2+}\) from the intracellular space, which results in an elevated intracellular Ca\(^{2+}\) concentration. In other words, the removal process of Ca\(^{2+}\) from the muscle cell may also result in fatigue.

Ions and substrates also influence the function of SR-Ca\(^{2+}\) channels, not just Ca\(^{2+}\). Glycogen, adenosine triphosphate (ATP), magnesium (Mg\(^{2+}\)), and hydrogen ions have all been proposed as possible ions and substrates to influence these channels. A hypothesis frequently supported in literature is that SR-Ca\(^{2+}\) release is inhibited during fatigue by the combined effect of increased levels of Mg\(^{2+}\) and a reduction of available ATP (Allen et al., 2008; Allen, Lannergren, & Westerblad, 1995; Allen, Kabbara, & Westerblad, 2002). It is not known how exercise positively influences the effects that substrates and ions have on SR-Ca\(^{2+}\) channels, but it can be theorized that with an
increased number of mitochondria, there will be a reduction in adenosine diphosphate, $P_i$, and $Mg^{2+}$, while an increased level of available ATP will be present.

Explaining muscle fatigue has been a difficult and complex task due to the number of proposed mechanisms that induce fatigue. To help comprehend the rate of fatigue, phenomenological models are becoming increasingly popular (Fuglevand et al., 1993; Potvin & Fuglevand, 2017). Potvin et al., (2017) constructed a computer model with hopes of better understanding the rate of fatigue during submaximal (20, 50, 80%) and maximal (100%) force trials (Potvin & Fuglevand, 2017). During the 80% submaximal contraction, it was shown that the high threshold muscle fibres were not fully recruited until the lower threshold muscle fibres were, which demonstrates the ‘onion skin’ organization. The phenomenon where higher threshold muscle fibres are recruited during the onset of a contraction, but below their maximal capacity, is explained by: (a) an ‘onion skin’ organization where, high threshold fibers are unable to generate maximal firing rates before low threshold muscle fibres (De Luca et al., 1982a; De Luca & Erim, 1994), and (b) high threshold fibers have abbreviated contraction times, which consequently leads to lower forces. In other words, during maximal contractions, a reserved capacity is identified during the initiation of contraction. Additionally, during the following isometric submaximal contraction, the higher threshold muscle fibres began ramping up their force generating capacity, until they were depleted after 4-5 seconds. Meanwhile, the lower threshold muscle fibres maintained much of their force generating capacity for the entire contraction. In contrast, the 100% maximal contraction saw the recruitment of the lower threshold and higher threshold muscle fibres during the onset of the contraction. However, the higher
threshold muscle fibres fatigued almost immediately and consequently lost their force generating capacity. Meanwhile, the lower threshold muscle fibres maintained much of their force generating capacity. The results of the 80% submaximal contraction are what we would expect to see with traditional strength loading in that, the lower threshold muscle fibres will be recruited during the onset of exercise, followed by higher threshold muscle fibres upon the onset of fatigue. This will consequently lead to a positive incline in force generating capacity throughout a set of traditional strength loading. In contrast, the 100% maximal contraction is expected to recruit all muscle fibres initially, with the higher threshold muscle fibres fatiguing almost immediately. This is expected to produce a negative incline for force generating capacity.

2.3 Muscle Activity Assessment Techniques

Electromyography (EMG), which is defined as the recording of the electrical activity of muscle tissue, is used to measure skeletal muscle activity. There are, however, a number of EMG techniques that can be used to measure such activity; intramuscular, bipolar surface, and high density (HD) surface EMG to be specific. Each technique is unique in that it can be used to measure muscle activity at various musculoskeletal levels. In other words, intramuscular EMG can measure skeletal muscle activity using a fine wire electrode inserted into the muscle belly, while surface EMG, measures underlying muscle activity from an electrode adhered to the skin surface overtop of a muscle.

2.4.1 Intramuscular Electromyography

Intramuscular needle EMG and wire EMG are two common EMG techniques used to measure muscle activity at the motor unit level. Both of these techniques are
suggested to be an accurate way of measuring activity at the motor unit level (Merletti & Farina, 2008). This is because the researcher can isolate and recognize individual motor units’ waveforms. Despite this profound advantage, it is an invasive approach and can induce pain for participants (Drost, Stegeman, van Engelen, & Zwarts, 2006). Secondly, when multiple time points of (such as pre and post intervention) intramuscular recordings are taking place within the same muscle and participant, it is difficult to insert the electrode into the exact location session to session. In other words, the reliability of results is very difficult from subsequent data collection sessions (Stegeman et al., 2012).

2.4.2 Surface Electromyography

Surface electromyography (sEMG), which is a noninvasive approach used to measure muscle activity within a muscle or group of muscles, involves placing electrodes on the skin and measuring the ensuing muscle activity of the underlying muscle tissue (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000). However, there are various divisions of sEMG; monopolar sEMG, bipolar sEMG, and HD-EMG. Monopolar sEMG and bipolar sEMG are traditional methods used to measure muscle activity. Monopolar sEMG involves placing electrodes on the skin and amplifying the signal to one reference. In contrast, bipolar sEMG involves placing two electrodes on the muscle of interest and the potential difference is amplified to a reference. HD-EMG, measures muscle activity using a number of monopolar electrodes located on the same electrode grid.

More detection points are one of the many advantages to HD-EMG, as it allows for variables of interest to be more accurately calculated by providing a larger cross-
sectional assessment of the activity in the active muscle. Additionally, a number of channels provides more detection points within the same timeframe, which has been suggested to be beneficial during larger compound movements (Disselhorst-Klug, 1997; Rau, Disselhorst-Klug, & Silny, 1997). In the past, a major limitation of surface EMG analysis was the inability to identify and isolate single motor units based on the summation of electrical muscle activity that is collected by the surface electrode (Disselhorst-Klug, 1997). However, modern approaches are being developed to address this disadvantage through mathematical techniques known as signal decomposition that can isolate signals from single motor units. At this time these techniques are limited to static submaximal contractions and are not appropriate during dynamic motions (De Luca, Adam, Wotiz, Gilmore, & Nawab, 2006). Another concern of surface EMG is movement artifact of the skin overlaying the muscles of interest (Day, 2002). Movement artifact could result in unreliable results if trying to measure muscle activity across a number of sessions, therefore the placement of the electrode grid is an important consideration during study design. In addition, the quality of electrode-skin contact is very important. This consequently implies that further steps need to be taken to ensure that the contact between both surfaces is exceptional.

HD-EMG is considered to be the gold standard approach for surface EMG today (Blok, van Dijk, Drost, Zwarts, & Stegeman, 2002; Farina, Arendt-Nielsen, Merletti, Indino, & Graven-Nielsen, 2003; Stegeman, Blok, Hermens, & Roeleveld, 2000). This approach uses a 2-dimensional (2D) grid, which is comprised of electrodes placed 3-10 mm center-to-center from each other. This unique characteristic enables researchers to measure the spatial distribution (difference of muscle activity intensities) of muscle
activity over the electrode grid area, which is considered one the main advantages in comparison to other techniques. HD-EMG has also been suggested to have high intra-session reliability, in comparison to invasive techniques such as fine needle electromyography (EMG) and wire EMG (Stegeman et al., 2012). Despite the number of advantages there are some disadvantages to HD-EMG. The main disadvantage is the detection depth, which has been suggested to be 1-2cm below the skin. Thus, HD-EMG recordings are restricted to superficial muscle and skin folds need to be considered as an important inclusion criterion consideration (Merletti, Holobar, & Farina, 2008). Lastly, because there are a significant number of electrodes placed on the same grid, it collects a large amount of data and therefore, data processing and storage considerations need to be anticipated prior to the commencement of studies (Merletti et al., 2008).

2.4.3 HD-EMG Electrodes

The design of the electrode grid has been illustrated to be one of the more challenging aspects to overcome while using HD-EMG. It has been frequently noted that there are four common factors relating to the electrode grid design; speed of application, comfort for the subject, signal quality, and price (Stegeman et al., 2012). Additionally, there are a number of grid arrangements that are available, which is important when considering what muscle will be studied. Stegeman and colleagues (2012), highlighted that a dry electrode principle was first adopted, whereby electrodes were constructed from printed circuit board testing probes. This was because of their relatively favorable impedance or resistance (Merletti, 2010). Despite this considerable advantage, it has been suggested that they are uncomfortable and should not be used in locations that are sensitive, such as the face. Further, without the use of electrode gel,
This may contribute to less than optimal contacts between the electrode and skin, which affects the signals that are retrieved (Stegeman et al., 2012).

More modern electrode grids are required to have exceptional electrode-skin contact, which is partially attributed to the electrode gel used during the application process (Stegeman et al., 2012). Due to their highly flexible grid design, they can be used in more sensitive areas such as the face and on anatomical structures that possess uneven areas, such as on the mandible bone. Their flexible design however leads to a more time-consuming application process, as it requires the application of electrode gel. Depending on the grid size, this process usually takes 5-10 minutes. Furthermore, their flexible design results in a smaller chance that they can be repositioned during a data collection session. Nonetheless, their advantages arguably outweigh the disadvantages in that, the signal to noise ratio is dramatically lower in the more modern methods. The current electrode grids also allow for the measurement of muscle activity during dynamic conditions.

2.4.4 Directions of Observation HD-EMG

Due to the 2D design of HD-EMG there are various rows and columns of monopolar electrode arrangements available for assessment purposes. An indisputable advantage to this arrangement is that muscle activity can be analyzed in more directions; parallel and perpendicular to muscle fibres. In literature that uses HD-EMG as a measurement tool, most analyses are performed along the direction of muscle fibres. In other words, bipolar schemes are usually formed by subtracting signals from two adjacent monopolar electrodes running in the direction of muscle fibres. However, researchers and clinicians are also able to visualize how the magnitude of MUAPs
change across the muscle (perpendicular in direction), which provides information regarding motor unit firing (Stegeman et al., 2012). This arrangement was first reported by Monster and Chan (1980), who were interested in MUAP amplitude and MU location relationships.

2.4.5 Spatial Derivation of HD-EMG

As previously discussed, HD-EMG uses monopolar electrodes to retrieve EMG data. This consequently permits for the retrieval of additional information and flexibility during post-hoc signal processing (Roeleveld, Stegeman, Vingerhoets, & Van Oosterom, 1997). This is a result of being able to form any combination of two or more electrodes and spatially filtering those signals (Stegeman et al., 2012).

Monopolar recordings were first introduced in alternative electrophysiology instruments (electrocardiogram and electroencephalogram), before being used in surface EMG techniques (Stegeman et al., 2012). Stegeman and colleagues (2012) indicated that this is partly owed to the high impedences that the electrodes experience during the collection process. However, in today’s technology, this is typically avoided by using technologically advanced amplifiers.

In a study completed by Farina et al., (2003), various derivations were compared during tibialis anterior contractions, while using HD-EMG. It was suggested to use the longitudinal double differential (LDD) derivation, a lower order filter, as it led to shorter MUAP separation distances. In contrast, higher order filtering was shown to lead to the opposite, with increased separations of MUAP firings due to its high selectivity. In other words, they demonstrated that a higher order filter, called the Laplacian derivation, produced the greater separation distances. This is a benefit, because increasing the
number of electrodes during the derivation process, decreases the chance that an electrode experiencing suboptimal skin contact is included in the analysis. Additionally, Staudenmann et al., (2010) stated that increasing the selectivity of a filter resulted in a decreased analysis. In other words, there was a loss of deep MUs in comparison to more superficial MUs. This undoubtedly leads to a disoriented representation of the signal, especially when considering MUs that are located deep within the muscle tissue.

2.4.6 Decomposition of HD-EMG

Decomposition is a process where individual motor units (MU) and their respective action potentials are retrieved from processed raw HD-EMG signals (Kleine, van Dijk, Lapatki, Zwarts, & Stegeman, 2007). This technique is commonly explained as “spike-sorting,” where “spikes” or action potentials that contribute to the overall contraction are retrieved (Buzsáki, 2004). This consequently leads to suggestions about the underlying muscular physiology of an individual. Two notable conclusions that can be made are the following. First, motor unit action potential (MUAP) waveforms allow the researcher or clinician to gain insight about the motor unit type. Secondly, the timing of motor unit firing becomes available, which provides information about when MU’s are recruited or dismissed throughout the contraction.

The decomposition of raw HD-EMG signal has been proposed to provide similar information to that of indwelling wire EMG regarding individual MUs, though this is still limited to static contractions and not dynamic contractions (De Luca et al., 2006). This implies that HD-EMG could provide researchers with considerable advantages, considering it is a noninvasive technique to measure motor units. However, it is important to realize that research has not identified a technique that thoroughly analyzes
individual motor units while using HD-EMG, though significant steps have been taken in recent years to achieve this goal.

For the most part, decomposition techniques use the following steps to carry out the decomposition process; first, signal segmentation occurs (which is where various peaks that contribute to the contraction are segmented), followed by peak classification (clustering), then MUAP identification, and ending with the resolution of MUAP superimpositions (Kleine et al., 2007). The latter steps pose significant problems for researchers. When MUAPs overlap in time, it becomes significantly more difficult to separate them from each other. This occurs quite frequently when a number of MUs are active, because they will fire synchronously with each other. This results in something known as a time-shifted summation (Kleine et al., 2007). Algorithms that are used for decomposition purposes have the assumption that MUAPs of two different MU’s, differ more from each other than two MUAPs from the same MU. When intramuscular EMG is used, this dilemma is eliminated, however a solution to this problem in HD-EMG is still a work in progress.

2.5 Variables of EMG Analysis

2.5.1 Amplitude

Mean amplitude (Equation 1) is the average magnitude of electrical activity across the electrode grid. A definition that has been commonly used in literature is that amplitude is a time-varying standard deviation of the random process (Clancy, Bouchard, & Rancourt, 2001). Additionally, this value is used to quantify the spatial
distribution across an electrode grid, also known as a heat map. To calculate amplitude, Equation 1 can be used.

The magnitude of amplitude is influenced by a number of factors; motor unit properties (Clancy et al., 2001; Merletti, Rainoldi, & Farina, 2001; Stegeman et al., 2000), the thickness of subcutaneous tissue overlying the muscle of interest (Merletti et al., 2001), the number of motor units that are activated throughout the duration of the contraction (Merletti et al., 2001; Stegeman et al., 2000), MFCV (Merletti et al., 2001), and the electrode alignment in relation to the direction of the muscle fibres (Merletti et al., 2001). Motor unit properties and the affect that they have on amplitude are important to understand because, the larger the motor unit (high threshold muscle fibres are larger), the higher the amplitude and vice versa for low threshold muscle fibres.

Amplitude can also be used to make inferences about the amount of fatigue being experienced by the muscle(s) of interest (Merletti, Knaflitz, & De Luca, 1990). In other words, during fatigued states, amplitude is expected to rise due to an increase in the number of muscle fibres being recruited during a fatigue task (Merletti et al., 2001; Stegeman et al., 2000). Merletti and colleagues (1990) also concluded that, MFCV is the highly correlated to the magnitude of amplitude, in that if MFCV declines (lack of high threshold muscle fibres being activated), you would expect to see the same response in amplitude. In conclusion, amplitude is an important variable to consider in almost all EMG research studies, as it ultimately provides information about the muscle fibres being activated throughout a contraction and it is related to other variables as well.
2.5.2 Entropy

Signal entropy (referred to as entropy throughout the document), which is defined as the measure of uniformity across the electrode grid, is represented in Equation 2 (Farina, Leclerc, Arendt-Nielsen, Buttelli, & Madeleine, 2008). Where $p^2(i)$ is the square of the root mean square value at electrode $i$, which is normalized by summation of the 51 root mean square values when using a 64 monopolar electrode grid. In short, entropy has been commonly used in literature to explain the heterogeneity of the muscle being analyzed, which is related to what muscle fibre types are being recruited throughout a contraction. This can be further used to provide some insight about fatigue.

Where HD-EMG allows for the quantification of spatial distribution, it is consequently possible to measure entropy across the confined space of the electrode grid. If each electrode on the electrode grid presents the same value, it is considered to have uniform distribution and therefore, maximal homogeneity. Higher values of entropy represent maximum homogeneity among the root mean square values (intensity), whereas lower values correlate to a decrease in uniformity among the maps. Holtermann and colleagues (2005), stated that heterogeneity occurs from either the distribution of motor units across the muscle belly, or from the strategy of motor unit recruitment within the muscle. The amount of force being produced within the muscle has been one mechanism shown to change the uniformity within the muscle, due to the motor unit recruitment changes that come with changes of force (Hermans & Spaepen, 1997).
In the study by Farina et al., (2008) they looked at muscle activity within the trapezius muscle during a sustained contraction. The protocol involved the participant maintaining 90 degrees of shoulder abduction, until it was no longer possible. In their study, it was found that the amount of shift in the spatial distribution is related to the time in which the static contraction is maintained. This consequently indicates that changes in spatial distribution, which is partly estimated by changes in the magnitude of entropy, plays an important role in determining how much heterogeneity is present throughout a contraction. Entropy was found to significantly decrease (less homogeneous map) as the contraction time increased. These changes are thought to result due to peripheral and central physiological mechanisms (Farina et al., 2008). Some of the mechanisms have been found to be related to mean amplitude and muscle fibre conduction velocity (MFCV). One mechanism that is thought to affect the rate of heterogeneity within spatial distribution is the recruitment/derecruitment of motor units, because motor unit types and diameters within most muscles is not homogeneous (Lindman, Eriksson, & Thornell, 1991). It was suggested that participants who were shown to have a reduced entropy value, had a longer endurance time, which consequently means that there are muscle fibre modifications going on within the muscle to achieve longer endurance times. The changes occurring within the motor unit pool may suggest one mechanism used to cope with fatigue. An alternative suggestion as to why there is a correlation between endurance time and spatial distribution changes may be explained by different activation levels during the onset of the muscle contraction, in comparison to later stages (Farina et al., 2008). In conclusion, entropy allows the researcher to gain a better understanding about the fatigue being experienced
by the muscle of interest. An increase in spatial heterogeneity results in a decrease in entropy, which consequently suggests that there are musculoskeletal alterations within the muscle to cope with fatigue.

2.5.3 Muscle Fibre Conduction Velocity

Muscle fibre conduction velocity (MFCV) is best explained as the time it takes for the action potential to propagate along the sarcolemma of a muscle fibre over a set electrode distance (Farina, Ferguson, Macaluso, & De Vito, 2007). The velocity of the action potential has been suggested to be constant across the entire length of the muscle (Blok et al., 2002). The magnitude of MFCV has also been proposed to allow for the estimation of a number of variables relating to the contracting muscle; various contractile properties (Andreassen & Arendt-Nielsen, 1987), muscle fatigue (Merletti et al., 1990), and proportion of muscle fibres (Sadoyama, Masuda, Miyata, & Katsuta, 1988). MFCV values have also been suggested to have similar trends as mean frequency across time when the number of MUs and their discharge patterns remain constant (Lindström & Magnusson, 1977). Across a single set of exercise, the initial MFCV value during the first repetition can be used to estimate the proportion of muscle fibres within the contracting muscle (Sadoyama et al., 1988). This is because during the first repetition, the muscle is not experiencing fatigue. In contrast to the initial value, the MFCV slope across an entire set of exercise provides information regarding the magnitude of peripheral fatigue (Farina, Zagari, Gazzoni, & Merletti, 2004).

Recently, literature has suggested that there is a relationship between MFCV magnitude and muscle fibre type characteristics. This concept was first introduced and supported by Methenitis and colleagues (2016). It was proposed that large muscle fibres,
such as Type IIx muscle fibres, demonstrate faster action potential propagation because of their lower cytoplasmic resistance. Lower cytoplasmic resistance then results in greater MFCV values. The following suggestion was supported, where Type IIx muscle fibres had a higher correlation to MFCV values in comparison to Type IIa and Type I muscle fibres, because Type IIx muscle fibres have the largest cross-sectional area. The vastus lateralis was the muscle of interest and the correlation was seen in both sedentary and active individuals. In addition to this finding, a high correlation was found between intramuscular MFCV and muscle power during countermovement jumps and an isometric leg press contraction.

Another factor that has been suspected to affect the rate of action potential propagation is the sodium-potassium (Na\(^+\)-K\(^+\)) pump (Clausen, 2003). Kossler and colleagues (1991), suggested a similar phenomenon during sustained contractions, where MFCV decreased due to the increase in interstitial potassium concentration. A greater MFCV value is thought to result from a greater presence of Na\(^+\)-K\(^+\) pumps. Therefore, because Type IIx muscle fibres have been suggested to have more of these pumps, MFCV values are thought to greater in this subset of muscle fibres. This consequently reinforces the idea that Type IIx muscle fibres have higher MFCV magnitudes.

One noteworthy disadvantage to MFCV however, is the sensitivity of the measurement. MFCV calculations are extremely sensitive to electrode placement. Rainoldi and colleagues (2001), reported poor interclass correlation coefficients relating to the measurement of MFCV. One method to counter this disadvantage is to increase the number of channels on the electrode grid, which has been shown to slightly improve
the MFCV calculation (Farina et al., 2004). Therefore, it is best to think of electrode placement, when MFCV is of interest, as an extremely tedious and specific process. Farina and colleagues (2004), explained their method of electrode placement, which is the approach commonly used and accepted in literature when MFCV is a variable of interest. To start, the innervation zone, which is the area of the muscle belly with the greatest amount of muscle activity, is determined. To complete this task, the researcher will visually analyze the multichannel signal as the point of inversion of propagation of the MUAP (Masuda, Miyano, & Sadoyama, 1983). An alternative method would be to stimulate the muscle every (start at the distal tendon) 1cm while moving more proximal from the distal tendon. The researcher can be confident that the innervation zone has been found when the greatest muscle twitch is visually seen. The location of the muscle matrix is determined next, which is halfway between the innervation zone and the distal tendon. When a study consists of multiple data collection sessions, it has been suggested to outline the corners of the electrode grid. This is to ensure that the grid is placed in the same location during subsequent data collection sessions. It is important to note that there is not a standard optimal location for electrode grid placement, because it ultimately depends on which muscle is of interest and the individual and their respective height for the most part. For example, short muscles within the hand require distances of 5-10 mm between detection points, whereas larger muscles require a greater distance.

2.5.3.1 Cross-Correlation Analysis – Muscle Fibre Conduction Velocity Calculation

There are various methods used to estimate MFCV noninvasively using HD-EMG. Before discussing the methods used to calculate MFCV while using HD-EMG, it is important to note that more traditional sEMG methods can measure MFCV as well.
To do this, two electrodes are separated by a known distance on the skin. During a contraction, the time delay between the two signals is recorded, which is the MFCV value. However, using HD-EMG makes this process much easier, because two electrodes are chosen at separate ends of the same column on the electrode grid. The distance between the two arbitrary chosen electrodes remains constant, therefore the time it takes for the action potential to propagate along the column is recorded by the HD-EMG system.

To calculate MFCV, the values that are retrieved from the HD-EMG system are inputted into an algorithm. Various algorithms have been proposed to calculate MFCV. The cross-correlation analysis of two delayed signals, which was first explained by Naeije and Zorn (1983), is the most common approach that is used in literature. Farina and colleagues (2001), based their calculation method of MFCV on this approach, however a few changes were made. This approach calculates the cross-correlation between two signals located within the electrode grid. If the propagation direction is known, it is reasonable to assume that the delays should be between 2-7 ms, which are the physiological limits. Most MFCV calculations now use Farina and colleagues (2001) approach, as it was developed to be used with modern EMG measurement techniques.

2.6 Power Spectrum Analysis

Mean frequency (MNF) and median frequency (MDF) are two frequency variables that are regularly reported in literature. MNF is the average frequency across an electrode grid, while MDF is calculated by dividing the total signal spectrum intensity by two (Stolen, De Luca, & De Luca, 1981). MDF is therefore the lowest
frequency that is retrieving the cumulative intensity, but this value is bigger than half of the total intensity (OTBiolab+ User Manual v.1.0).

A technique that is used to calculate the frequency spectrum of EMG signals is called a Fast Fourier Transformation (FFT) (Güler & Koçer, 2005). The most common FFT is called a discrete FFT, which is a reversible mapping operation for a time series. It is beneficial to use due to its time efficient computing process, as well as the limited round-off errors associated with the calculation, in comparison to other techniques (Cochran et al., 1967). This approach has been frequently used in literature to detect muscle fatigue, force production, and MFCV (Bigland-Ritchie, Donovan, & Roussos, 1981). Thus, this analysis method can provide a discrete-time, discrete-frequency representation

2.8 Literature Review Conclusion

HD-EMG can undoubtedly be used to fill in existing gaps currently present in literature that focus on muscle fibre recruitment strategies using traditional compared to peak average power loading techniques. The greatest advantage that HD-EMG provides researchers and clinicians, is its ability to provide information regarding spatial distribution patterns within the muscle of interest. Additionally, HD-EMG may provide an accurate representation as to which threshold of muscle fibres are being recruited during a repetition and across a single set of exercise. HD-EMG can be used to provide insight about the magnitude of fatigue being experienced by the muscle of interest.

There is little research focusing on motor unit recruitment strategies during common loading protocols used in athletic populations. Traditional strength loading and peak average power loading protocols have been thoroughly studied in applied research.
looking at force and power improvements. However, little research has focused on motor unit recruitment strategies during single sets of exercises. Theoretically, each approach could be expected to recruit motor units in different ways, though to our knowledge, research has not studied the differences between each strategy. Being able to understand these recruitment strategies through the use of HD-EMG would fill in existing gaps currently present in literature. This may ultimately change the way strength and conditioning professionals program athletes and healthy adults.

2.9 Hypotheses

**Hypothesis 1 (Traditional Load Activation Pattern: Isokinetic vs. Isotonic):**

Isokinetic and isotonic loading methods will not differ in their response across a set of contractions of traditional strength loading for entropy, amplitude, muscle fiber conduction velocity, or median frequency. Hypothesis 1 will be supported by the lack of a significant Method x Repetition interaction effect.

**Hypothesis 2 (Peak Average Power Load Activation Pattern: Isokinetic vs. Isotonic):**

Isokinetic and isotonic loading methods will not differ in their response across a set of contractions of peak average power loading for entropy, amplitude, muscle fiber conduction velocity, or median frequency. Hypothesis 2 will be supported by the lack of a significant Method x Repetition interaction effect.

**Hypothesis 3 (Method: Peak Average Power vs. Traditional Load):**
Entropy, amplitude, muscle fibre conduction velocity, and median frequency, will be significantly different between the peak average power loading method compared to the traditional loading method across the set of knee extensions. Hypothesis 3 will be supported by a significant Loading x Repetition interaction effect.

**Hypothesis 4 (Isotonic Method: Peak Average Power vs. Traditional Load):**

Entropy, amplitude, muscle fibre conduction velocity, and median frequency, will be significantly different between the peak average power loading method compared to the traditional loading method across the set of squats. Hypothesis 4 will be supported by a significant Loading x Repetition interaction effect.
Chapter 3: Methods

3.1 Participants

Prior to the onset of the research project, ethical approval for research performed with human participants was obtained from the University of New Brunswick research ethics board (REB 2019-027). Thirty-two participants volunteered to participate in the study. Of the thirty-two, thirty participants (15 males and 15 females) (23.1 ± 3.0 yrs.; 173.3 ± 7.9 cm; 76.6 ± 13.6 kg) completed the study. Two of the participants withdrew from the study. One participant aggravated a pre-existing knee injury although not an injury that occurred within the past 2 years, while the other participant withdrew due to time constraints. Inclusion criteria for participation in the research was strictly adhered to.

Inclusion criteria:

1. Between the ages of 19 and 35 years old.
2. Minimum of six months of resistance training experience.
3. Ability to perform a back squat with proper technique and be able to achieve an average velocity during the ascent portion of the squat of at least 1.0 m/s.
4. No previous knee injuries within the last two years.
5. No known diagnosis of knee osteoarthritis.
6. A skinfold thickness around the thigh of the dominant leg that is less than 30mm.
The participants in the following study had an average skinfold thickness of 17 ± 5 mm. Additionally, males and females had an average back squat estimated 1-RM of 148 ± 23 kg and 93 ± 22 kg, respectively. The strength to weight ratio for males and females was 1.7 ± 0.16 kg and 1.4 ± 0.29 kg, respectively.

3.2 Experimental Protocol

Participants were asked to report to the laboratory on three occasions; one session was for the collection of baseline measures, while the two subsequent data collection sessions included experimental data collection. Participants were asked to refrain from consuming caffeine and/or alcohol 24 hours prior to each of the three sessions. Additionally, participants were asked to refrain from lower-body strength training sessions 48 hours before any of the three data collection sessions. Study procedures (Table 3) were addressed before the commencement of the baseline data collection session, then participants were asked to sign a consent form indicating that they understood the procedures and they voluntarily agreed to participate in the study. A Get Active Questionnaire (GAQ) was then completed. The GAQ is a health screening questionnaire that is used and accepted by the Canadian Society of Exercise Physiology. During the baseline measurement session, bodyweight and height were measured using a valid measurement scale (Weigh Beam Eye-Level, Detecto, Webb City, MO). Following that, participants performed a standardized warm-up used within the lab (Table 4). This standardized warm-up was used in the following two sessions, before the collection of data.
**Table 3** Schedule for three days of data collection.

<table>
<thead>
<tr>
<th>Day</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day 1</strong></td>
<td></td>
</tr>
<tr>
<td>Height + Weight</td>
<td>2 minutes</td>
</tr>
<tr>
<td>Warm-Up</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Innervation Zone Identification</td>
<td>10 minutes</td>
</tr>
<tr>
<td>1-RM Back Squat</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Maximal Voluntary Contraction – Become Familiar with 85% of Maximal Torque</td>
<td>10 minutes</td>
</tr>
<tr>
<td><strong>Day 2/3</strong></td>
<td></td>
</tr>
<tr>
<td>Warm-Up</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Three Maximal Voluntary Contraction’s at both 30 deg/s and 120 deg/s</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Two sets of either isokinetic or isotonic contractions (randomized)</td>
<td>20 minutes</td>
</tr>
</tbody>
</table>

**Table 4** Standardized warm-up protocol.

<table>
<thead>
<tr>
<th>Exercise</th>
<th>Sets</th>
<th>Repetitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-minute jog</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking Inseam Lunge</td>
<td>1</td>
<td>6/leg</td>
</tr>
<tr>
<td>Inchworm</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Drop Step Lunge</td>
<td>1</td>
<td>6/leg</td>
</tr>
<tr>
<td>Tuck Jumps</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Jump Regressions</td>
<td>2</td>
<td>5 per phase (3 phases)</td>
</tr>
</tbody>
</table>
After the warm-up was completed, participants were asked to complete a back squat. Male participants completed this using 95 pounds, while female participants completed this using 65 pounds. The squat was videotaped and compared to the National Strength and Conditioning Association back squat teaching video (https://www.nsca.com/education/videos/exercise-technique-high-bar-back-squat/). In addition, participants had to obtain an average mean propulsive velocity of 1.0 m/s during the ascent portion of the squat. The velocity throughout the ascent portion of the squat was monitored by the Power Analyzer V-314 (Tendo Sport Machines UK LTD, Docklands, London). This was a requirement of the protocol so that an accurate prediction of the participants back squat 1-RM could be calculated. If proper form was met, they were allowed to continue to participate in the study. If proper form was not met, they were not allowed to participate in the study due to an increased risk of injury.

Following the squat assessment, the innervation zone on the dominant leg was determined. This served as a reference point for the placement of EMG electrodes in the subsequent data collection sessions. To determine leg dominance, the Waterloo Footedness Questionnaire (see Appendix A) was used (Methenitis et al., 2016), which has been shown to have an ICC value of 0.92 (Elias, Bryden, & Bulman-Fleming, 1998). To find the innervation zone, the distal tendon of the vastus lateralis was located. From the distal tendon of the vastus lateralis, a muscle stimulator (Digitimer STIMULATOR model DS7A, Ft. Lauderdale, FL) stimulated the muscle (moving distally to more proximal) every centimeter. The muscle was stimulated using 80 mA from a Digitimer (Ft. Lauderdale, FL) at a compliance voltage of 300 V and a pulse width of 100 microseconds. When the location with the greatest muscle activity was
identified, a line was marked on the skin using a permanent marker. The line served as a reference point in subsequent data collection sessions. The electrode grid was placed halfway between the innervation zone (the middle of the line) and the distal tendon of the vastus lateralis when the participant was sitting upright in a chair with a knee angle of 90 degrees. The knee angle was confirmed with a goniometer. Electrode grid placement needs to be precise for accurate MFCV calculations. Participants were given a permanent marker to recopy the location of this line throughout the study (i.e. after showers, exercise, etc.). This was to ensure that it was not removed during the duration of the study and that the placement of the electrode grid was consistent for all sessions.

After the innervation zone was identified, participants completed a velocity based 1-RM estimation for the back squat (Banyard, Nosaka, & Haff, 2017). In the study by Banyard et al., (2017), it was found that as the weight increases, the Pearson correlation increases as well. For the 90%, 80% and 60% IRM, the Pearson correlations were r=0.93, r=0.87, and r=0.78, respectively (Banyard et al., 2017). This test uses four different loads to meet four different target mean propulsive velocities ($\geq 1.0 \text{ m/s}$, $\sim 0.8 \text{ m/s}$, $\sim 0.6 \text{ m/s}$, $\leq 0.4 \text{ m/s}$). At least two repetitions occurred for each weight, while the fastest mean propulsive velocity during each set was used to calculate the estimated 1-RM. Three minutes of rest was granted between each set. The resulting fastest mean propulsive velocity for each set was used to form a regression line on Microsoft Excel (Redmond, WA). Previous research has found that the average propulsive velocity during the 1-RM of a back squat is 0.24 m/s, therefore the linear regression equation was solved using this value (Banyard et al., 2017; Zourdos et al., 2016). The resulting estimated 1-RM value was used to calculate the loads during the isotonic contraction
session. Additionally, participants had to obtain a knee flexion angle of 90 degrees or greater during the following estimation process and isotonic contraction condition.

After the 1-RM was determined, participants were asked to complete a maximal voluntary contractions (MVC) at 30 degrees per second (deg/s) on the isokinetic dynamometer. Following that, they performed six repetitions where they practiced producing 85% of their maximal torque capacity consistently across a single set of exercise. This was to ensure that a learning effect took place, so that they could effectively perform the traditional strength loading protocol during the isokinetic contraction condition. Pilot work within the laboratory demonstrated that individuals who learned how to fulfill this expectation during the baseline data collection session, were more likely to consistently hit 85% of their maximal torque capacity during the experimental data collection session. Following this, the baseline testing session was completed.

The subsequent two sessions (experimental data collection sessions) involved a three-tiered randomization in that, the contraction type (isokinetic and isotonic), loading protocol (peak average power and traditional strength), and MVC (30 deg/s or 120 deg/s) order was randomized. The purpose of the randomization was to reduce the chance that a learning effect would influence data collection (Table 3). Participants had two to four rest days between sessions and all trials took place around the same time of day (± 3 hours). For each experimental session, regardless of the condition (isokinetic or isotonic), the beginning of the session was as follows. The same standardized warm-up (Table 4) that was performed during baseline testing session was performed again. Following the warm-up, EMG electrodes were placed on the participant.
A wireless high-density EMG system (Trentadue, OT Bioelettronica, Italy, input impedance: >1000 MΩ, CMMR: >96 Db, filter: 15 Hz low cut-off, 500Hz high cut-off, noise: <2µV\text{RMS}) with a semi-disposable 32-channel electrode grid (ELSCH032, OT Bioelettronica, Italy) was placed on the same area of the vastus lateralis during all testing sessions (Figure 1). The sampling rate was 1000 Hz. The grid consisted of 8 rows and 4 columns of electrodes (10mm interelectrode distance in both directions) and a double-sided adhesive foam grid was placed over the electrode grid. The adhesive foam grid was layered with conductive cream. The area between the innervation zone (marked on day 1) and the distal tendon of the vastus lateralis, as well as the patella, was shaved and an alcohol swab was used to decontaminate the area of the muscle where the electrode grid was placed. These steps and the palpation of the vastus lateralis that occurred during day 1, follow the suggested guidelines from The Seniam Project (1999). The Seniam Project (1999) guidelines were initially developed to be used during bipolar EMG. During the electrode grid placement, participants were sitting in an upright chair with the knee in 90 degrees of flexion. After the electrode grid was placed, the upper right corner and bottom left corner of the grid was marked. This ensured that the same placement occurred during the second experimental data collection session. Participants were asked to recopy these lines, in addition to the one that was placed on the skin during the baseline data collection session. Hypafix tape was used to ensure that electrodes did not move during data collection.

After the placement of the EMG electrodes, six MVC’s were performed on the isokinetic dynamometer (HUMAC NORM, CASMI, Massachusetts, United States). This took place during both experimental data collection sessions. The MVC’s were
used to normalize the data during the ensuing loading style sets (Merletti, 1999). Three MVC’s occurred at 30 deg/s, while the other three MVC’s occurred at 120 deg/s. Whether participants completed the 30 deg/s or 120 deg/s MVC’s first was randomized. Participants were asked to maximally contract, during the full range of motion (ROM) of the knee extension and verbal encouragement was provided. Two minutes of rest was granted between each MVC. The best MVC for each velocity was selected for normalization purposes.

Following the steps above, the rest of the experimental data collection session was randomized, as previously stated (Table 3). One of the two experimental testing sessions involved two sets of isokinetic contractions at different speeds; one set with an angular velocity set at 30 deg/s (performed at 85% of the subject’s maximal torque capacity), while the other set was performed at 120 deg/s (performed at 100% of the subject’s maximal torque capacity). The slower speed will simulate traditional strength loading, while the faster set will simulate peak average power loading. The set order was randomized, and verbal encouragement was provided during the peak average power loading set, because maximal effort was required. Through pilot work within the lab, 120 deg/s was chosen because as the load that maximizes peak power during a back squat, participants extended their knee at a rate of 120 deg/s in the squat during a peak average power loading protocol. Each set involved six repetitions, with five minutes of rest between each set. If participants were not consistent (~±15 N/m) at hitting 85% of their maximal torque capacity across the six repetitions during the traditional strength loading set, they were asked to repeat this set following five minutes of rest. All isokinetic contractions were performed on the isokinetic dynamometer.
The other experimental data collection session consisted of two sets of isotonic contractions. To complete isotonic contractions, subjects performed back squats. One set involved the subject performing six repetitions at 85% of their 1-RM, while the other set involved the subject performing six repetitions at 67% of their 1-RM. The heavier set simulated traditional strength loading, while the lighter set simulated peak average power loading. The set order was randomized, and verbal encouragement was provided during both sets. Five minutes of rest was granted between sets. At least five repetitions were required during the traditional strength loading set. If participants couldn’t meet this expectation, the weight was reduced appropriately. Furthermore, during the isotonic contraction condition, both the traditional strength loading, and peak average power loading sets were videotaped using a 2017 Apple iPad Pro (Cupertino, CA). Video was captured at 60 frames per second. The purpose of videotaping both of these sets was to ensure that the HD-EMG data was synced with the location of the participant’s body in space throughout the ROM of the squat. This was an important component during the EMG data analysis, because the researcher was most interested in the muscle activity around the 90-degree knee flexion position during the concentric phase. Peak muscle activity occurs roughly at a knee angle of 90 degrees (Marchetti et al., 2016; Wilk et al., 1996). Without this video, the researcher would not be able to sync the HD-EMG data with the knee joint angle during the squat. Unfortunately, during the analysis, it came to our attention that during a number of isotonic sets, the HD-EMG device had lagged and therefore the video could not be used for syncing purposes. This consequently resulted in the data being analyzed around the area that exhibited peak muscle activity during each contraction.
Subject debriefing and the removal of the HD-EMG equipment followed all baseline and experimental data collection sessions.

**Figure 1** High-density electromyography system.

**Figure 2** Isokinetic dynamometer.
Figure 3 Isotonic contraction condition. Pictured here is the HD-EMG system and electrode grid on the vastus lateralis.

3.3 Data Analysis

Raw EMG data were retrieved from the HD-EMG device during all of the MVC (three contractions at 30 deg/s, while the other three were at 120 deg/s) sets and two loading style sets for each of the experimental data collection sessions (day two and three).

During the isokinetic contractions, torque values were retrieved from the isokinetic dynamometer (HUMAC NORM, CASMi, Massachusetts, United States), while average velocity during the ascent portion of the squat was retrieved from the Power Analyzer V-314 (Tendo Sport Machines UK LTD, Docklands, London).

3.3.1 Data Processing

Raw EMG data will be processed using OTBiolab (OT Bioelettronica, Torino, Italy) software and the HD-sEMG Analysis Tool (Version 1.1; Pradhan, 2018). The HD-sEMG Analysis Tool (Version 1.1; Pradhan, 2018) code was used to calculate mean amplitude (Equation 1), entropy (Equation 2) and median frequency (Equation 3). These values were retrieved from the traditional strength loading and peak average power loading sets for each of the conditions. OTBiolab was used to calculate the multichannel MFCV for each repetition of the traditional strength loading and peak average power loading during both contraction conditions.

Similar to the approach used by Watanabe and colleagues (2012), 27 bipolar surface EMG signals along each row were made from a 32-channel electrode grid. This method is called single differentiation. The following approach was used when
computing amplitude (Equation 1), entropy (Equation 2), and MDF (Equation 3) with the HD-sEMG Analysis Tool (Version 1.1; Pradhan, 2018). OTBiolab and the HD-sEMG Analysis Tool (Version 1.1; Pradhan, 2018) both use fourth order Butterworth bandpass filters of 20-450 Hz to analyze raw EMG data. Noise was eliminated by using single differentiation, whereby two monopolar electrodes that are side by side are subtracted from one another.

**Equation 1** Estimation of RMS.

$$\text{RMS} = 1000 \sqrt{\frac{1}{N} \sum_{k=1}^{N} x_k^2} [\mu V]$$

(OTBiolab+ User Manual v.1.0)

Where:
- ‘N’ is the number of samples per epoch.
- ‘x_k’ is the amplitude of the signal at the input of the amplifier in mV.
- ‘1000’ allow to obtain the result in μV.

**Equation 2** Entropy calculation.

$$E = - \sum_{i=1}^{64} p(i)^2 \log_2 p(i)^2$$

(Farina et al., 2004)

Where:
- $p(i)^2$ is the square of RMS value of channel $i$ divided by the sum of the squares of all the 64 RMS values at the definitive force level.

So, $p(i)^2$ represents the normalized power of each channel.

**Equation 3** Estimation of MDF.

$$f(i) = \frac{\sum_{k=0}^{n} \lambda_k \cdot f_k}{\sum_{k=0}^{n} \lambda_k} [\text{Hz}]$$

(OTBiolab+ User Manual v.1.0)
Where:

- ‘n’ is the number of frequency bins in the spectrum.
- ‘\(f_k\)’ is the frequency of spectrum at bin k of n.
- I\(_k\) is the intensity of spectrum at bin k of n.

The collected EMG data for the traditional strength loading and peak average power loading sets were normalized to the MVC with the highest amplitude value for the 30 deg/s and 120 deg/s MVC contraction, respectively. For isokinetic contractions, data was windowed around the peak isokinetic torque value for each repetition. Meanwhile, for the isotonic contractions, data was windowed around the area that exhibited the greatest muscle activity. An epoch of 250 ms was used for all calculations.

During the analysis, it came to light that some of the frames from the recorded video did not match with their respective contraction. This was a limitation to the following study, because the wireless connection between the HD-EMG device and computer where the data was being collected lagged. Unfortunately, this went unnoticed during the data collection session, unless it occurred during a contraction(s) in which the trial was repeated (it went unnoticed when the lag occurred between contractions). This consequently resulted in the data being windowed around the area with peak muscle activity for all isotonic contractions, rather than when the knee joint was in 90 degrees of flexion. This process was performed carefully to ensure that noise was not being analyzed during the selected window.

MFCV velocity was calculated using a multichannel MFCV calculation, whereby all 31-channels (it is a 32-channel electrode grid, however one of the channels
is substituted for torque) are used during the calculation. As previously noted, an epoch of 250 ms was used. The peak MFCV value during each contraction was considered. However, only values between 2-7 ms were considered because they have been suggested to be the physiological limits of human skeletal muscle. Values out of this range were not considered.

Some of the participants in the following study could only complete five repetitions during the isotonic TS loading condition. This consequently resulted in a pair-wise data removal process during the statistical analysis procedures resulting in unacceptably low sample size for all assessments using repetitions during TS. Therefore, to increase the power during the statistical analyses, only the first five repetitions of TS loading conditions were considered to allow for a more robust sample size. It was felt that this approach would be appropriate as the goal of this work was to assess the pattern across the set rather than the absolute values within the set.

3.4 Statistical Analysis

Data was analyzed using IBM SPSS Statistics version 25.0 (SPSS, INC, Chicago, IL). The Shapiro-Wilk test was used to assess normality prior to statistical analyses. When all repetitions of a variable were identified as being non-normally distributed, a non-parametric statistic Friedman’s analysis was used to analyze the data for hypothesis one and two, while the Wilcoxon Signed Ranks Test was used for hypothesis three and four. Based on the use of five comparisons a Bonferroni correction was applied during the Wilcoxon Signed Ranks Test assessment adjusting the alpha to p<0.01. For variables where the majority of the repetitions were identified as normally distributed, a two-factor mixed model between-within analysis of variance
(ANOVA) was used to assess between and within group differences for hypotheses 1-4 (Norman, 2010). For all significant main and interaction effect differences, a Bonferroni Correction Test was used as during post hoc analysis. The main effects that were assessed for were: Loading, Repetitions, and Method (Table 5). For hypothesis one and two a model including Method x Repetition were used. For hypothesis three and four a model including Loading x Repetition were used. All of the independent and dependent variables are listed in table 5. Significance level was accepted at p<0.05 for all variables aside from those assessed with a Wilcoxon test. Effect size values were calculated using the partial ETA squared method.

Table 5 Independent and dependent variables of interest.

<table>
<thead>
<tr>
<th>Independent Variables</th>
<th>Dependent Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading (Traditional, Peak Average Power)</td>
<td>Mean Amplitude</td>
</tr>
<tr>
<td>Repetitions (1, 2, 3, 4, 5, 6)</td>
<td>Median Frequency</td>
</tr>
<tr>
<td>Method (Isokinetic, Isotonic)</td>
<td>Conduction Velocity</td>
</tr>
<tr>
<td></td>
<td>Entropy</td>
</tr>
</tbody>
</table>
Chapter 4: Results

4.1 Assumption Assessment for a Mixed Model Analysis of Variance

Tests for normality were conducted using the Shapiro-Wilk test for normality. It was found that all values for entropy during each condition and loading strategy were not normally distributed. Additionally, the following values during the isokinetic contraction PAP condition were deemed to not be normally distributed; repetitions three (p=0.044) and five (p=0.031) for MFCV, and repetitions three (p=0.003), four (0.015) and six (p=0.028) for frequency. For the isokinetic TS condition, the following values were not normally distributed; repetitions two (p=0.03), three (p=0.047) and five (p=0.002) for amplitude, and repetitions one (p=0.04) and six (p=0.025) for frequency. For the isotonic PAP contraction condition, the following values were not normally distributed; repetition five (p=0.018) for MFCV and repetition four (p=0.023) for frequency. Lastly, repetition six (p=0.024) for frequency during TS loading during the isotonic contraction condition was not normally distributed. Besides entropy, a two-factor mixed model between-within ANOVA was still used. Previous research has indicated that when the majority of the points are normally distributed and the sample size is large (n ≥ 15), an ANOVA is still the most appropriate statistic for analysis (Norman, 2010) However, non-parametric tests were consequently used for all statistical analyses involving entropy, because all repetitions were found to be non-normally distributed. All normality statistics can be found in Appendix B. Mauchly’s test of sphericity were also assessed and all data was found to display sphericity for both the main effect of Repetition and the interaction effect.
4.2 Peak Torque during Isokinetic Contractions

The average peak torque values during the isokinetic contraction condition for both loading methods are presented in Figure 4.

![Figure 4](image)

**Figure 4** Peak torque values during isokinetic contractions across a single set of exercise for traditional strength loading and peak average power loading. Error bars represent standard deviation.

4.3 Average Velocity during Isotonic Contractions

The average propulsive velocity during the isotonic contraction condition for both loading methods are presented in Figure 5.
Figure 5 Average velocity values during isotonic contractions across a single set of exercise for traditional strength loading and peak average power loading. Error bars represent standard deviation.

4.4 Hypothesis 1

Isokinetic and isotonic loading methods will not differ in their response across a set of contractions of traditional strength loading for entropy, amplitude, muscle fiber conduction velocity, or median frequency. Hypothesis 1 will be supported by the lack of a significant Method x Repetition interaction effect.
Table 6 Summary of results for hypothesis 1 for each of the variable, main effect, and interaction effect. F-statistic, p-value, and effect size are presented. Bold print indicates a significant difference.

<table>
<thead>
<tr>
<th>Hypothesis 1 – TS Loading Comparing Isokinetic and Isotonic Contractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Entropy</td>
</tr>
<tr>
<td>Amplitude</td>
</tr>
<tr>
<td>MFCV</td>
</tr>
<tr>
<td>Frequency</td>
</tr>
</tbody>
</table>

4.4.1 Entropy

The Freidman’s analysis indicated that there were no significant differences across the set of isokinetic (\( \chi^2(4, N = 30) = 3.036, p=0.694 \)) and isotonic contractions (\( \chi^2(4, N = 30) = 2.130, p=0.712 \)) during TS (Figure 6). The Friedman’s analysis does not assess for an interaction effect of Method x Repetition.
4.4.2 Amplitude

Amplitude demonstrated a significant main effect for Method ($F(1,29) = 14.442$, $p=0.001$, $\eta_{p}^2=0.332$) with the isotonic condition resulting in higher amplitude compared to the isokinetic condition (Figure 7). The main effect for Repetition ($F(4,26) = 5.027$, $p=0.004$, $\eta_{p}^2=0.436$) was also found to be significant (Figure 8). The interaction effect was not significant.

* indicates a significant change at a p-value of <0.05.
According to the pairwise comparisons, repetition one was significantly lower than repetitions two (p=0.026), three (p=0.006), four (p=0.002), and five (p=0.002) (Figure 8).

**Figure 8** Normalized amplitude for isokinetic and isotonic contractions during traditional strength loading. Error bars represent standard deviation. * indicates values that are significant different from repetition one, p<0.05.

### 4.4.3 Muscle Fibre Conduction Velocity

MFCV had a significant main effect for Method (F(1,29) = 12.75, p=0.005, \(\eta_p^2=0.338\)) with isokinetic demonstrating a higher MFCV compared to isotonic contractions (Figure 9), however the main effect for Repetition and the interaction effect were found not to be significant.
Figure 9 Muscle fibre conduction velocity for isotonic and isokinetic contractions during traditional strength loading. Error bars represent standard deviation.

* indicates a significant change at a p-value of <0.05.

4.4.4 Frequency

Frequency demonstrated a significant main effect for Repetition ($F(4,26) = 13.8$, $p<0.001$, $\eta_p^2=0.680$) during traditional strength loading (Figure 10). Repetition one was significantly greater than repetitions three ($p=0.021$), four ($p<0.001$), and five ($p=0.001$). The main effect for Method and the interaction effect were deemed to not be significant.
**Figure 10** Frequency during isokinetic and isotonic contractions during traditional strength loading. Error bars represent standard deviation. * indicates values that are significant different from repetition one, p<0.05.

### 4.5 Hypothesis 2

Isokinetic and isotonic loading methods will not differ in their response across a set of contractions of peak average power loading for entropy, amplitude, muscle fiber conduction velocity, or median frequency. Hypothesis 2 will be supported by the lack of a significant Method x Repetition interaction effect.

**Table 7** Summary of results for hypothesis 2 for each of the variable, main effect, and interaction effect. F-statistic, p-value, and effect size are presented. Bold print indicates a significant difference.

| Hypothesis 2 – PAP Loading Comparing Isokinetic and Isotonic Contractions |
|---|---|---|---|
| Variable | Method Main Effect | Repetition Main Effect | Interaction Effect |
| Entropy | See Friedman’s Statistic – all comparisons are non-significant | | |
| Amplitude | $F(1,27) = 9.28, \eta^2=0.256, p=0.005$ | $F(5,23) = 11.22, \eta^2=0.709, p<0.001$ | $F(5,23) = 1.088, \eta^2=0.191, p=0.394$ |
| MFCV | $F(1,21) = 0.180, \eta^2=0.008, p=0.676$ | $F(5,17) = 0.429, \eta^2=0.112, p=0.822$ | $F(5,17) = 1.333, \eta^2=0.282, p=0.298$ |
| Frequency | $F(1,27) = 12.73, \eta^2=0.320, p=0.001$ | $F(5,23) = 6.77, \eta^2=0.595, p=0.001$ | $F(5,23) = 2.615, \eta^2=0.282, p=0.052$ |

#### 4.5.1 Entropy

The Freidman’s analysis indicated that there were no significant differences across the set of isokinetic ($\chi^2(4, N = 29) = 2.544, p=0.770$) and isotonic contractions ($\chi^2(4, N = 29) = 2.544, p=0.770$).
N = 29) = 1.131, p=0.889) during PAP (Figure 11). The Friedman’s analysis does not assess for an interaction effect of Method x Repetition.

![Figure 11](image)

**Figure 11** Entropy values for isokinetic and isotonic contractions peak average power loading. Error bars indicate standard deviation.

### 4.5.2 Amplitude

Amplitude demonstrated a significant main effect for Method (F(1,27) = 9.28, p=0.005, $\eta_p^2=0.256$) with the isotonic condition resulting in a higher amplitude (Figure 12). There was also a significant main effect for Repetition (F(5,23) = 11.22, p<0.001, $\eta_p^2=0.709$) (Figure 13). The interaction effect was not significant. Repetition two, during the isotonic contraction condition appears to be erratic, however, the data was further visually analyzed and deemed to be correct with no outlier’s present.
Figure 12 Normalized amplitude for isotonic and isokinetic contractions during peak average power loading. Error bars represent standard deviation. * indicates a significant change at a p-value of <0.05.

According to the pairwise comparisons, repetition one was significantly lower than repetitions two (p=0.002), three (p<0.001), four (p<0.001), five (p<0.001), and six (p<0.001). Repetition two was also found to be significantly greater than repetitions five (p=0.002) and six (p=0.008).
Figure 13 Normalized amplitude for isokinetic contractions and isotonic contractions during peak average power loading. Error bars represent standard deviation. * indicates values that are significant different from repetition one, p<0.05. @ indicates values that are significant different from repetition two, p<0.05.

4.5.3 Muscle Fibre Conduction Velocity

There were no significant main effects for Method or Repetition, as well as the interaction effect (Figure 14).
Figure 14 Muscle fibre conduction velocity for peak average power loading during isokinetic and isotonic contractions. Error bars indicate standard deviation.

4.5.4 Frequency

Frequency had a significant main effect for Method ($F(1,27) = 12.73$, $p=0.001$, $\eta_p^2=0.320$) where the isokinetic condition was greater than the isotonic condition (Figure 15). There was also a significant main effect for Repetition ($F(5,23) = 6.77$, $p=0.001$, $\eta_p^2=0.595$) (Figure 16). The interaction effect was not significant.
Figure 15 Frequency for isotonic and isokinetic contractions during peak average power loading. Error bars represent standard deviation. * indicates a significant change at a p-value of < 0.05.

According to the pairwise comparisons, repetition one was significantly greater than repetition six (p=0.023). Repetition two was also significantly greater than repetition four (p=0.001), five (p=0.007), and six (0.002). Lastly, repetition three was significantly greater than repetition four (p<0.001), five (p=0.009), and six (p=0.026).
**Figure 16** Frequency for isokinetic and isotonic contractions during peak average power loading. Error bars represent standard deviation.

* indicates values that are significant different from repetition one, p<0.05.
@ indicates values that are significant different from repetition two, p<0.05.
$ indicates values that are significant different from repetition three, p<0.05.

### 4.6 Hypothesis 3

Entropy, amplitude, muscle fibre conduction velocity, and median frequency, will be significantly different between the peak average power loading method compared to the traditional loading method across the set of knee extensions.

Hypothesis 3 will be supported by a significant Loading x Repetition interaction effect.
Table 8 Summary of results for hypothesis 3 for each of the variable, main effect, and interaction effect. F-statistic, p-value, and effect size are presented. Bold print indicates a significant difference.

<table>
<thead>
<tr>
<th>Hypothesis 3 – Isokinetic Contractions Comparing PAP and TS Loading</th>
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<tbody>
<tr>
<td>Variable</td>
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<tr>
<td>----------</td>
</tr>
<tr>
<td>Entropy</td>
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<tr>
<td>Amplitude</td>
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<td>MFCV</td>
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<td>Frequency</td>
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</table>

4.6.1 Entropy

The Wilcoxon Signed Ranks Test indicated that there were no significant differences between the two loading styles for each repetition during isokinetic contractions (Figure 17). See Appendix C for further details.
Figure 17  Entropy for traditional strength loading and peak average power loading during isokinetic contractions. Error bars represent standard deviation.

4.6.2 Amplitude

Amplitude had a significant main effect for Load (F(1,28) = 5.271, p=0.029, ηp²=0.158) where PAP loading had a higher amplitude (Figure 18). There was also a significant main effect for Repetition (F(5,24) = 12.931, p<0.001, ηp²=0.729) (Figure 19). The interaction effect was not statistically significant.

![Figure 18](image)

Figure 18 Normalized amplitude for traditional strength loading and peak average power loading during isokinetic contractions. Error bars represent standard deviation. * indicates a significant change at a p-value of <0.05.

According to pairwise comparisons, there was a significant difference between repetition one was significantly lower than repetition two (p<0.001), three (p<0.001), four (p<0.001), five (p<0.001), and six (p<0.001). Repetition two was significantly lower than repetition four (p=0.014), five (p=0.008), and six (p=0.003). Lastly, repetition three was significantly lower than repetition five (p=0.032).
Figure 19 Normalized amplitude for traditional strength loading and peak average power loading during isokinetic contractions. Error bars represent standard deviation. * indicates values that are significant different from repetition one, p<0.05. @ indicates values that are significant different from repetition two, p<0.05. $ indicates values that are significant different from repetition three, p<0.05.

4.6.3 Muscle Fibre Conduction Velocity

MFCV had a significant main effect for Load (F(1,22) = 4.605, p=0.043, \(\eta_p^2=0.173\)) where TS loading had a higher MFCV on average (Figure 20). The main effect of Repetition and the interaction effect were not significant.
**Figure 20** Muscle fibre conduction velocity for traditional strength loading and peak average power loading during isokinetic contractions. Error bars indicate standard deviation.

* indicates a significant change at a p-value of <0.05.

4.6.4 Frequency

Frequency had a significant main effect for Load \((F(1,28) = 42.074, \ p<0.001, \ \eta_p^2=0.600)\) where PAP loading had a higher median frequency on average (Figure 21).

There was also a significant main effect for Repetition \((F(5,24) = 3.483, \ p=0.017, \ \eta_p^2=0.420)\) (Figure 22), as well as the interaction of Load x Repetition \((F(5,24) = 3.088, \ p = 0.027, \ \eta_p^2=0.391)\).
Figure 21 Frequency for traditional strength loading and peak average power loading during isokinetic contractions. Error bars indicate standard deviation. * indicates a significant change at a p-value of <0.05.

According to pairwise comparisons, repetition three was significantly greater than repetition five (p=0.023).

Figure 22 Frequency for traditional strength loading and peak average power loading during isokinetic contractions. Error bars indicate standard deviation. * indicates values that are significant different from repetition three, p<0.05.
According to the pairwise comparison for the interaction effect of Load x Repetition, there was significant difference between the two loading styles for repetition one (p<0.001), two (p<0.001), three (p<0.001), four (p<0.001), five (p<0.001), and six (p<0.001).

4.7 Hypothesis 4

Entropy, amplitude, muscle fibre conduction velocity, and median frequency, will be significantly different between the peak average power loading method compared to the traditional loading method across the set of squats. Hypothesis 4 will be supported by a significant Loading x Repetition interaction effect.

Table 9 Summary of results for hypothesis 4 for each of the variable, main effect, and interaction effect. F-statistic, p-value, and effect size are presented. Bold print indicates a significant difference.

<table>
<thead>
<tr>
<th>Hypothesis 4 – Isotonic Contractions Comparing PAP and TS Loading</th>
<th>Load Main Effect</th>
<th>Repetition Main Effect</th>
<th>Interaction Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entropy</td>
<td>See Appendix D – all comparisons are non-significant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude</td>
<td>F(1,28) = 0.000, p=1.000, η²=0.000</td>
<td>F(4,25) = 4.971, p=0.004, η²=0.443</td>
<td>F(4,25) = 0.915, p=0.471, η²=0.128</td>
</tr>
<tr>
<td>MFCV</td>
<td>F(1,28) = 0.014, p=0.907, η²=0.000</td>
<td>F(4,25) = 0.639, p=0.639, η²=0.093</td>
<td>F(4,25) = 1.435, p=0.252, η²=0.187</td>
</tr>
<tr>
<td>Frequency</td>
<td>F(1,28) = 3.109, p=0.089, η²=0.100</td>
<td>F(4,25) = 21.478, p&lt;0.001, η²=0.775</td>
<td>F(4,25) = 1.340, p=0.283, η²=0.176</td>
</tr>
</tbody>
</table>
4.7.1 Entropy

The Wilcoxon Signed Ranks Test indicated that there were no significant differences between the two loading styles for each repetition during isotonic contractions (Figure 23). See Appendix D for further details.

![Figure 23](image)

**Figure 23** Entropy for traditional strength loading and peak average power loading during isotonic contractions. Error bars represent standard deviation.

4.7.2 Amplitude

Amplitude had a significant main effect for Repetition \( (F(4,25) = 4.971, p=0.004, \eta^2=0.443) \) (Figure 24). There was not a significant main effect for Load or for the interaction effect. According to pairwise comparisons, repetition one was significantly smaller than repetition two \( (p=0.048) \), four \( (p=0.021) \), and five \( (p=0.001) \).
4.7.3 Muscle Fibre Conduction Velocity

There were no significant main effects for Load or Repetition, as well as the interaction effect (Figure 25).

**Figure 24** Normalized amplitude values for traditional strength loading and peak average power loading during isotonic contractions. Error bars represent standard deviation.
* indicates values that are significant different from repetition one, p<0.05.

**Figure 25** Muscle fibre conduction velocity for traditional strength loading and peak average power loading during isokinetic contractions. Error bars indicate standard deviation.
4.7.4 Frequency

Frequency had a significant main effect for Repetition \((F(4,25) = 21.478, p<0.001, \eta_p^2=0.775)\) (Figure 26). The main effect for Load and the interaction effect were not significant. According to pairwise comparisons, repetition one was significantly greater than repetitions two \((p=0.028)\), three \((p<0.001)\), four \((p<0.001)\), and five \((p<0.001)\). Lastly, repetition two was significantly greater than repetitions three \((p=0.005)\), four \((p=0.003)\), and five \((p<0.001)\).

![Figure 26](image)

**Figure 26** Frequency for traditional strength loading and peak average powering loading during isotonic contractions. Error bars represent standard deviation. * indicates values that are significant different from repetition one, \(p<0.05\). @ indicates values that are significant different from repetition two, \(p<0.05\).
Chapter 5: Discussion

5.1 Major Findings

The purpose of this study was to determine if 1) isokinetic loading methods could be used to simulate isotonic loading for TS and PAP loading strategies, and 2) if the motor unit recruitment strategies differed between PAP and TS loading strategies across a single set of exercise. Based on the results of this study, hypothesis one and hypothesis two are supported. The absolute values of amplitude and MFCV demonstrated differences in the main effect of Method (i.e. isokinetic and isotonic loading), however; no interaction effects were observed for any of the variables in question. The lack of interaction effect suggests that isokinetic loading methods can be used as a reasonable simulation of isotonic loading for both TS and PAP loading. When considering the second portion of the research purpose, the results suggest that hypothesis three is partially supported with the demonstration of a significant interaction effect for frequency during the isokinetic TS and PAP protocols. All other variables failed to demonstrate a significant interaction effect suggesting that entropy, amplitude, and MFCV demonstrate similar recruitment strategies during the TS and PAP loading conditions during isokinetic contractions. Hypothesis four is refuted as none of the variables of interest demonstrated a significant interaction effect during the isotonic loading method. These results suggest that the TS and PAP loading methods use similar muscle recruitment strategies over the duration of a single set of contractions during isotonic exercise.

Hypothesis one, which analyzed the muscle fibre recruitment strategies during isotonic and isokinetic contractions for TS loading, was supported. It was hypothesized
that across a single set of TS loading, there would be no difference for recruitment patterns between isotonic and isokinetic contractions. The support for this hypothesis is critical, because it would imply that for TS loading, either contraction method (i.e. isotonic or isokinetic) could be used to assess motor unit recruitment strategies. Entropy was the first variable to be assessed. It was found that there were no differences for the main effects of Method and Repetition, as well as the interaction effect. This would suggest that the recruitment patterns during TS loading for both contraction methods, induced either a similar amount or no fatigue. Amplitude was found to have a significant main effect for both Method and Repetition. For the main effect of Method, the isotonic contraction condition on average produced a significantly greater amplitude. However, for the main effect of Repetition, both contraction methods during TS loading demonstrated an increase in amplitude across the set. Next, MFCV was found to have a significant difference for the main effect of Method (isokinetic condition was higher), however for the main effect of Repetition and the interaction effect, the difference was not statistically significant. Based on this result, it can be concluded that on average during the TS loading, the isokinetic contraction condition recruited more higher threshold muscle fibres than the isotonic contraction condition. Lastly, frequency had a significant difference for the main effect of Repetition, but not for the main effect of Method or for the interaction effect. Both contraction methods decreased across the set.

In conclusion, for hypothesis one, it can be concluded that during TS loading, both the knee extensions and squats produce similar motor unit recruitment strategies.

Hypothesis two explored the muscle activation pattern for isotonic and isokinetic contractions during PAP loading. This hypothesis would be supported with a lack of
interaction effects for Method by Repetition. Similar to TS loading, entropy did not have a significant difference between the two contraction methods during PAP loading. Amplitude had a similar response during PAP loading, when compared to TS loading. It was found that amplitude had a significant difference for the main effect of Method and Repetition. Similar to TS loading, the isotonic contraction condition produced a higher amplitude on average, while both methods did increase across the single set of exercise for PAP loading. MFCV did not have a significant difference for either of the main effects or for the interaction effect. This would suggest that motor unit recruitment patterns for each contraction method were similar during PAP loading and did not change across the set. Lastly, frequency had a significant difference for the main effects of Method and Repetition. On average, the isokinetic contraction condition had a greater frequency, however both contraction methods did decrease across the set. In conclusion, due to the lack of interaction effects, it can be concluded that during PAP loading, both contraction methods produce similar recruitment patterns. This consequently implies that either contraction condition (i.e. isotonic or isokinetic) can be used to assess recruitment strategies across a single set of PAP loading.

Hypothesis three, which analyzed the differences between the two loading strategies during isokinetic contractions, was only partially supported. To demonstrate that TS and PAP loading are different from one another during isokinetic contractions, an interaction effect for each variable is required. Entropy did not have a significant difference between the two loading styles for isokinetic contractions. This would partially suggest that neither protocol induced a meaningful amount of fatigue across the single set of exercise. Amplitude had a significant difference for the main effects of
Load and Repetition, though an interaction effect was not present. PAP loading had a significantly higher amplitude on average, in comparison to TS loading. For the main effect of Repetition, both loading styles increased across the set of exercise. MFCV had a significant difference for the main effect of load, where TS loading on average was greater. This would suggest that TS loading recruited higher threshold muscle fibres, when compared to PAP loading during isokinetic contractions. The results of amplitude during knee extensions contradict the results of MFCV when regarding the magnitude of motor recruitment throughout the set. Although this result is perplexing, it is possible that the isokinetic nature of the task, and relative inexperience of the participant may explain some contradiction. Lastly, frequency had a significant difference for each of the main effect (Load and Repetition), as well as the interaction effect. For the main effect of Load, PAP loading produced a higher frequency on average compared to the TS loading method. For the main effect of Repetition, frequency reduced across the duration of the set. When considering the interaction effect, TS loading decreased across the single set of exercise while PAP loading remained relativity constant with only a slight trend toward a decrease. This result is thought to be a result of fatigue, in that during knee extensions, PAP loading did not induce any substantial fatigue, though a trend was starting to begin whereby frequency started to decrease. In comparison, TS loading had a noticeable decline from the beginning of the set as it was a more strenuous task when compared to PAP loading. If more repetitions had occurred for each loading strategy, it is thought that the difference between the two loading strategies would have been much more apparent, especially for PAP loading. In conclusion, because of the interaction effect for frequency, it can be concluded that TS and PAP loading produce
different frequencies across a set of knee extension in an isokinetic situation, though all other variables responded in a similar fashion between the two methods.

Hypothesis four analyzed the differences between the two loading styles during squats. The following hypothesis would be supported by an interaction effect (Load x Repetition) for each variable. Entropy and MFCV did not have a significant difference for either of the main effects or for the interaction effects. This suggests that during squats, both loading methods have similar capacities to recruit higher threshold muscle fibres and neither method (TS nor PAP) altered the recruitment pattern across a set of squats. Amplitude had a significant difference for the main effect of Repetition, with both loading strategies resulting in an increase across the set of exercise. Lastly, frequency had a significant difference for the main effect of Repetition, where both loading protocols resulted in a decrease in frequency across the set. In conclusion, due to the absence of any interaction effects for any of the variables of interest, it is concluded that hypothesis four is refuted. This consequently suggests that both loading strategies during squats have similar recruitment patterns.

5.2 Motor Unit Recruitment

Potvin et al., (2017) investigated motor unit recruitment patterns during various submaximal and maximal static contractions. Their computer model was based on the model that Fuglevand and colleagues (1993) developed, however Potvin et al., (2017) factored in MU responses to fatigue and the affects that it would have on force generation, contraction time, and firing rates. Therefore, with these changes, their study is the most recent, to our knowledge, to investigating force-based motor unit recruitment patterns during submaximal and maximal contractions. This leads to the current study,
which to our knowledge, is the first study to investigate motor unit recruitment patterns in human participants during dynamic PAP loading strategies.

When comparing Potvin and colleagues (2017) findings and the findings of the current study, it is important to take into account two things; 1) Isokinetic and isotonic contractions were used in the this study, whereas Potvin et al., (2017) simulated their findings based on isometric contractions, and 2) In the this study, PAP loading (67% 1-RM) and TS loading (85% 1-RM) methods were used, with the PAP method utilizing a velocity based contraction method not assessed in the work by Potvin et al. (2017). The TS loading condition in the current study is thought to be comparable to the 80% submaximal contraction in the study by Potvin et al., (2017). This is speculated because during the isokinetic contraction condition, participants targeted 85% of their maximal torque capacity, while during the isotonic contraction condition, participants used a load that was equivalent to 85% of their estimated 1-RM. However, for PAP loading, it was hypothesized that the results would be similar to the recruitment patterns during the maximal contraction in the study by Potvin et al., (2017). This was thought because participants performed knee extensions at 120 deg/s using their maximal capacity, while during the squats, each repetition was performed using maximal velocity with a load of 67% of their estimated 1-RM. Based on the results of Potvin and colleagues (2017) study, it is thought that 1) During PAP loading, all muscle fibres will be initially recruited and as the set progresses, high threshold muscle fibres would fatigue and drop off, and 2) During TS loading, low threshold muscle fibres would be initially recruited and as the set progresses, higher threshold muscle fibres will be recruited to allow for the maintenance of the external force of 85% torque or 1-RM.
MFCV is an important variable to consider when motor unit recruitment strategies are of interest. This is because MFCV is primarily affected by the recruitment of high and low threshold muscle fibres. This has been supported by Methenitis et al., (2016) where it was demonstrated that MFCV was found to have a strong correlation with Type IIx CSA (0.943, p<0.001). Sadoyama et al., (1988) also had similar findings showing that there was a strong correlation (0.84, p<0.01) between fast twitch muscle fibres and MFCV. Therefore, it can be assumed that an increase in MFCV is related to an increased recruitment of high threshold muscle fibres. This suggests that during TS loading, MFCV should theoretically increase across the single set of exercise, while during PAP loading, MFCV should decrease across the set.

In the current study, hypothesis three and four aimed to compare the differences between TS and PAP loading during isokinetic and isotonic contractions, respectively. The results of this study do not support hypothesis three and four. This consequently suggests that TS and PAP loading during knee extensions and squats have the same muscle fibre recruitment patterns during a single set of exercise. As previously implied, it is important to acknowledge two differences between the current study and the study by Potvin et al., (2017). The first difference is that in their study, static contractions were carried out to and beyond fatigue (marked by the “endurance limit”), where the current study consisted of a single set of exercise. Therefore, if the vastus lateralis in the current study endured a greater magnitude of fatigue, the results may have been different. Another factor to consider, which was previously discussed, is that PAP loading was hypothesized to recruit motor units similar to the 100% maximal contraction in the study by Potvin et al., (2017). The load that both of these contractions
use are different, because PAP loading used a load that has been found to optimize peak power (67% 1-RM), whereas the maximal contraction in the study by Potvin et al., (2017) was a static contraction performed at 100% maximal capacity. However, during the PAP loading, each repetition was performed at maximal capacity, which is why it was hypothesized that it would show similar recruitment patterns to a 100% maximal static contraction. The results of this study refuted that hypothesis. In conclusion, PAP loading did not show similar recruitment patterns as the 100% maximal contraction, rather it demonstrated similar recruitment patterns as the TS loading condition. However, it would be of interest for future research to ensure more fatigue is induced by adding more sets of each loading strategy. The result of this may change the conclusions of the current study and potentially demonstrate similar motor unit recruitment strategies that Potvin et al., (2017) displayed.

5.3 Fatigue

Entropy has been suggested to provide information regarding the heterogeneity of electrical activity across the muscle (Farina et al., 2008). A lower entropy value implies that the activity across the muscle is more homogeneous (measured muscle activity is similar across the map), which corresponds to less fatigue (Farina et al., 2008). In contrast, a larger value corresponds to a more heterogeneous signal, which consequently suggests that more fatigue is being experienced by the muscle (Farina et al., 2008). Farina et al., (2008) suggested that a meaningful factor that influences the magnitude of entropy, is the recruitment and derecruitment of muscle fibres. It was hypothesized that entropy would increase across a set of contractions for PAP and decrease for TS loading. These outcomes were hypothesized because, with PAP loading,
it was hypothesized that higher threshold muscle fibres would be recruited during the onset of exercise, however they would fatigue and consequently drop off. This would suggest a more heterogeneous muscle activation which correlates to a greater amount of fatigue being experienced by the vastus lateralis. In contrast, TS loading was hypothesized to recruit higher threshold muscle fibres once fatigue began to set in, which corresponds to a more homogeneous muscle activity and a lower entropy value. Interestingly, the hypotheses in this study for both loading methods during each contraction condition were refuted. It was found that TS and PAP loading did not significantly change across the single set of exercise. The results for the variable of entropy suggest that fatigue was not experienced throughout the duration of the single set of exercise for either loading method. This is contrary to the trends for the variables of amplitude and frequency, which suggest that some fatigue was experienced. A previous study by Falla & Farina (2008) found a significant difference for entropy during a 25% submaximal contraction lasting 60 seconds in the upper trapezius. According to that study, entropy values began at 4.4 ± 0.3 and ended at 4.6 ± 0.2 (F = 4.9, p < 0.001) (Falla & Farina, 2008). Therefore, if more repetitions had been included during the isokinetic contraction condition in the current study, a significant difference may have been identified.

Amplitude has been suggested to provide information about the magnitude of fatigue being experienced by a muscle(s). It has been suggested that during a fatiguing isometric contraction, amplitude will increase across the contraction (De Luca, 1984; Zwarts & Arendt-Nielsen, 1988). This is observed because as fatigue begins, more motor units are recruited and there is an increase in firing frequency to allow force to be
maintained as higher threshold muscle fibers become fatigued (Zwarts & Stegeman, 2003). Higher threshold muscle fibres are also thought to produce a larger amplitude than lower threshold muscle fibres. Additionally, Gallina et al., (2013) concluded that as force increases, amplitude is expected to increase as well. In the current study, it was hypothesized that during PAP loading, amplitude would decrease across the set of six repetitions, whereas TS loading was hypothesized to increase in amplitude. These results were hypothesized because during PAP loading, it was thought that higher threshold muscle fibres would be recruited during the onset of exercise, then, as the set continued, the highest threshold fibers would fatigue and the participant would finish their set of exercise at a lower mean propulsive velocity compared to their initial repetition. The opposite was expected for TS loading, where lower threshold muscle fibres would be initially recruited at the onset of the set, however as fatigue accumulated, higher threshold muscle fibres would be recruited to allow for the sustained internal forces to overcome the external load. The results do not support the proposed hypotheses. During knee extensions, there was a significant difference for the main effects of Load (PAP loading was greater) and Repetition. For the main effect of Repetition, both loading strategies resulted in an increase in amplitude across the single set. The findings for amplitude during knee extensions supported what was hypothesized for TS loading, however were the opposite of what was expected for the PAP loading method. For the isotonic contraction condition (squats), amplitude had a significant difference for the main effect of Repetition. Both loading strategies again increased in amplitude across the set of contractions. Similar to the isokinetic condition, this supported what was hypothesized for TS loading, but not PAP loading where amplitude
was hypothesized to decline. In conclusion, both loading strategies demonstrate similar trends for amplitude across a single set of exercise during isotonic and isokinetic exercise.

Frequency is another variable thought to provide information regarding fatigue. In a study by Komi & Tesch (1979), their results demonstrated that a positive correlation between force decline and decline in frequency during fatigue was present for static contraction MVC tasks. As muscle fatigue increased, high threshold muscle fibres decreased their firing frequency, which resulted in a decline in median frequency (Gydikov & Kosarov, 1974; Komi & Tesch, 1979). Consistent with this, a study by Viitasalo & Komi (1977) showed that there was an increase in low frequency components, while high frequency components declined during a sustained MVC contraction, resulting in an overall decline in median frequency (Viitasalo & Komi, 1977). These results are different during submaximal contractions. It has been demonstrated that during submaximal contractions, low threshold motor units decline in frequency during a sustained contraction, however high threshold motor units increase in frequency (Potvin & Fuglevand, 2017). This would consequently result in an overall increase of frequency during submaximal contractions. In the current study, it was hypothesized that during PAP loading, frequency would decrease across the single set of exercise for both contraction methods due to the maximal nature of these contractions. In contrast, TS loading was hypothesized to increase across the single set of exercise due to the submaximal nature of these contractions. During the set of knee extensions, there was a significant difference for the main effects of Load and Repetition, as well as the interaction effect. The interaction effect identified that during knee extensions, TS
loading decreased across the set of exercise, while PAP loading maintained relatively constant from the start to the end of the set. During the set of squats, there was a significant difference for the main effect of Repetition. Both loading strategies decreased across the set of exercise. In conclusion, the results of frequency did not support what was hypothesized. Similar to the other variables that were analyzed, it would be of interest to add more sets for each loading protocol. This modification could lead to the results being more pronounced, allowing for a better assessment of the study hypotheses.

There are inconsistencies within the literature regarding how many sets an individual should perform for each exercise during a workout. Some studies suggest that a single set of exercise is sufficient for optimal muscular adaptations (Carpinelli & Otto, 1998), while other studies suggest multiple sets are required (Borst et al., 2001; Humburg, Baars, Schröder, Reer, & Braumann, 2007; Kelly et al., 2007). In a meta-analysis completed by Krieger (2010), it was concluded that multiple sets, compared to a single set had an effect size difference of 0.11 ± 0.04 (95% CI: 0.02-0.19, p=0.016) when considering hypertrophy gains. Additionally, it has been widely supported that mechanical loading stimulates muscle protein synthesis (Spangenburg, 2009), however this response plateaus with an increasing load (Kumar et al., 2009). This plateau seems to be around four to six sets. In conclusion, because the current study only used one set or repetitions and there is evidence from the entropy and frequency response during the isokinetic knee extension that sufficient fatigue was not achieved in the PAP group, it would be of interest to see if using more sets would influence the motor unit recruitment patterns as of the muscle for the PAP group.
5.4 Limitations

To our knowledge, this is the only study that addresses acute motor unit recruitment strategies utilized during PAP loading compared to TS loading. Previous work within the same laboratory employed an exercise intervention study comparing PAP loading to TS loading for a back squat (Wallace, 2018). The limitation to that study was that although similar performance outcomes were achieved, little was known about the method of motor unit recruitment that allowed these changes to occur. Potvin et al. (2017) have also provided valuable insight into the mechanism of motor unit recruitment during various loading intensities, yet their study did not address how velocity influences these strategies. This study addressed these limitations by assessing variables from HD-EMG that are associated with motor unit recruitment. However, HD-EMG is a relatively new tool to measure muscle activity, therefore a program or method that can reliably analyze and identify individual motor units during dynamic activity has yet to be made available. Thus, in the following study, individual motor units were not analyzed.

Secondly, during the isotonic contraction condition, EMG activity was analyzed when the knee joint was in 90 degrees of flexion, also considered as the area with peak muscle activity (Marchetti et al., 2016; Wilk et al., 1996). Therefore, it was desirable to synchronize the lower-limb joint angles throughout the range of motion of the squat to the HD-EMG signals. The XSENS (Enschede, Netherlands), which is a full-body motion capture system that participants wear to measure joint angles throughout the body, would be ideal to use. However, through pilot work within the laboratory, it was shown that when the XSENS (Enschede, Netherlands) is synced to the HD-EMG, a lot
of noise was present within the collected EMG signal. This consequently means that in the following study, a camera was used to sync the EMG signal to joint angles, which is not the preferred approach due to a reduced reliability associated with this method.

Despite the effort of trying to sync the knee angle and EMG signal, during data collection it came to notice that the HD-EMG system had difficulty connecting throughout some of the isotonic contractions (squats). This consequently led to parts of the signal not being recorded and therefore, the recorded video could not be synced to the collected EMG signal. In the following study, due to this limitation, isotonic EMG data was windowed and analyzed around the area that had peak muscle activity. Ideally, the isotonic data would have been analyzed around the time that the knee was in 90 degrees of flexion, which has been suggested to be the knee angle that presents peak muscle activity (Marchetti et al., 2016; Wilk et al., 1996). Future studies should address this limitation by ensuring that their connection is optimal and does not lag during the collection of data. A viable solution would be to move the HD-EMG system closer to the computer that is recording the signal. Additionally, using a motion capture system with noise reduction would correct this limitation, though this solution is much more expensive.

Another limitation to the following study is that there was a lack of familiarization. Even though all participants had experience using a bilateral knee extension machine within a gym setting, the isokinetic dynamometer was new to the majority of participants. The difference between the two machines is that, during MVC’s and PAP loading techniques, participants are asked to exert maximal effort against the lever. This contraction method is typically not used during a traditional
bilateral knee extension machine. Most participants did not have experience performing the PAP loading condition during back squats. This condition required the participant to exert maximal velocity during the ascent portion of the squat. A familiarization session focusing on the loading strategies may have been beneficial for all participants. Along with allow the participants to better express power following the familiarization, this may have also led to more accurate estimations of each participant’s 1-RM, where participants had to exert maximal velocity during each repetition. Therefore, more familiarization focused on the two isokinetic loading conditions (30 deg/s and 120 deg/s) and lighter isotonic condition (67% 1-RM) would have been beneficial. Additionally, participants wore the HD-EMG system during the experimental data collection sessions. Although the system and electrode grid are relatively small, it may have caused participants to change the mechanics of their squats and knee extensions due to discomfort. If there was more familiarization, participants may have had different results.

This study only analyzed one of the quadriceps muscles, which was the vastus lateralis, due to equipment limitations (only one available electrode grid sensor). Therefore, another limitation to the following study is that only one muscle was analyzed, rather than multiple muscles. Future research should consider testing multiple muscles and compare the motor unit recruitment patterns between them.

In this study, participants were asked to refrain from lower-body exercise 48 hours prior to any of the testing sessions, as well as caffeine and alcohol 24 hours before. If they did not comply to this recommendation, fatigue and neural muscular factors may have influenced the results of the following study.
Another limitation that should be addressed in future research is that multiple sets should be used to examine the affects that they have on motor unit recruitment patterns during TS and PAP loading. A number of studies, which have been explained in the studies by Krieger (2009) and Krieger (2010), have identified that one set is not enough to induce musculoskeletal alterations in humans. Krieger (2010) stated that as the number of sets increase, effect sizes also increase. Not only would this replicate traditional exercise (typically more than one set is performed during a workout) but inducing fatigue could potentially alter our understanding of the recruitment strategies of TS and PAP loading. Therefore, future research should correct this limitation by adding multiple sets into the testing regimen. This may induce more fatigue within the muscles of interest and consequently better represent the motor unit recruitment strategies for the loading method in question.

The last limitation of the following study is the 1-RM protocol. In the following study, an estimated 1-RM protocol was used to estimate the loads that would be used during the isotonic contraction condition. This protocol was chosen due to the reduced chance of injury and fatigue, in comparison to a traditional 1-RM approach. The limitation is that, not all participants could complete the estimated 85% load for five repetitions (at least five repetitions were needed for analyzing purposes). This consequently led to the load being reduced by the researcher. If an actual 1-RM protocol was used in the following study, participants would have been more likely to lift the 85% 1-RM load for at least five repetitions.
5.5 Directions for Future Research

Future research should try and address the above limitations. In addition to those limitations, it would be of interest to see if the same tissue responses are seen in elderly populations. If the responses are similar, it would be a valuable and compelling recommendation, because a lighter load would not induce as much strain on the musculoskeletal system. It could also improve the quality of life for elderly populations and potentially reduce the chance of falls and other accidents relating to old age.

5.6 Conclusion

In conclusion, the current study found that isokinetic and isotonic contractions have similar recruitment patterns for TS and PAP loading. This consequently suggests that if motor unit recruitment strategies are of interest, either contraction method can be used for TS or PAP loading. However, isolating the muscle(s) of interest may best occur while using an isokinetic dynamometer, as it may eliminate some of the synergistic muscles that otherwise could be used during isotonic contractions, although achieving adequate fatigue during the PAP method is still of concern for the isokinetic method. The current study also suggests that the motor unit recruitment strategies during TS and PAP loading methods are remarkably similar during a single set of exercise. This is an important finding because, if a lighter load has a similar tissue response as a heavier load does, the lighter load could be used as there is less strain on the musculoskeletal system. Although these findings are important and provide great insight to acute motor unit recruitment patterns, future research should focus on increasing the number of sets to better replicate an acute resistance training session. This would lead to a greater accumulation of fatigue in both loading methods, resulting in greater overall muscular...
mechanical strain in the active muscles. Inducing more fatigue may further elucidate the findings of the current study.


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https://doi.org/10.1152/ajpregu.00120.2002

https://doi.org/10.1177/036354659602400418

https://doi.org/10.1519/JSC.0000000000001049

9

Appendices

Appendix A – Waterloo Footedness Questionnaire

Appendix: Waterloo Footedness Questionnaire—Revised

Instructions: Answer each of the following questions as best you can. If you always use one foot to perform the described activity, circle Ra or La (for right always or left always). If you usually use one foot circle Ru or Lu, as appropriate. If you use both feet equally often, circle Eq.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and then mark the appropriate answer. If necessary, stop and pantomime the activity.

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<th>Lu</th>
<th>Eq</th>
<th>Ru</th>
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<td>Which foot would you use to kick a stationary ball at a target straight in front of you?</td>
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<td>If you had to stand on one foot, which foot would it be?</td>
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<td>Which foot would you use to smooth sand at the beach?</td>
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<td>If you had to step up onto a chair, which foot would you place on the chair first?</td>
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<td>5</td>
<td>Which foot would you use to stomp on a fast-moving bug?</td>
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<td>6</td>
<td>If you were to balance on one foot on a railway track, which foot would you use?</td>
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<td>If you wanted to pick up a marble with your toes, which foot would you use?</td>
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<td>8</td>
<td>If you had to hop on one foot, which foot would you use?</td>
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<td>9</td>
<td>Which foot would you use to help push a shovel into the ground?</td>
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<td>10</td>
<td>During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?</td>
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<td>Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities?</td>
<td>YES</td>
<td>NO</td>
<td>(circle one)</td>
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<td></td>
<td>Have you ever been given special training or encouragement to use a particular foot for certain activities?</td>
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<td>NO</td>
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<td>If you have answered YES for either question 11 or 12, please explain:</td>
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Appendix B – ANOVA Outputs

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Appendix C – Hypothesis 3 Wilcoxon Signed Rank Test Results

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## Appendix D – Hypothesis 4 Wilcoxon Signed Rank Test Results

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Curriculum Vitae

Candidates full name: Brandon Jeffrey Richards

Universities attended: Bachelor of Science in Kinesiology

University of New Brunswick

April 2017

Certifications:
- Certified Strength and Conditioning Specialist (CSCS)

Publications: None

Conference Presentations:
- Controlling Lower-Body Fatigue Prior to the Force-Velocity Imbalance Assessment in an Athletic Population: An Assessment of Reliability. Canadian Society of Exercise Physiology 2018 (Niagara Falls, ON)
- Reliability of the Force-Velocity Imbalance Assessment in an Athletic Population. Canadian Society of Exercise Physiology 2018 (Niagara Falls, ON)

- Should Low-Volume Community Practices Be Performing Stapes Surgery? 71st Canadian Society of Otolaryngology – Head & Neck Surgery Conference 2017 (Saskatoon, SK)