MUSCLE CONTRACTILE PROPERTIES AND FATIGUE CHARACTERISTICS AFTER SPINAL CORD INJURY

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AFTER SPINAL CORD INJURY

By

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A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree

Masters of Science

McMaster University

MASTERS OF SCIENCE (2009) McMaster University

(Kinesiology) Hamilton, Ontario

TITLE: Muscle Contractile Properties and Fatigue Characteristics after Spinal Cord Injury

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NUMBER OF PAGES: xi, 123

Abstract

Paralyzed skeletal muscle undergoes several changes after spinal cord injury (SCI) that lead to alterations in contractile properties and a decrease in fatigue resistance. In this thesis, SCI-induced changes in the muscle length-tension relationship were explored first through the identification of the optimal joint angles for force generation in the ankle dorsiflexor and plantarflexor muscles. The length-tension relationship in the dorsiflexor muscles was not found to differ between SCI and able-bodied (AB) participants, while the plantarflexor muscle group showed a significant shift to shorter muscle lengths (and thus smaller joint angles) for force generation after SCI.

In the second part of this thesis, muscle fatigue characteristics in the ankle dorsiflexors were examined to determine if a decline in muscle excitability contributed to increased muscle fatigue after SCI. The protocol consisted of a 2 minute trial of intermittent tetanic bursts at 30Hz delivered to the peroneal nerve. There were no changes in M-wave amplitude or area observed over the course of the fatigue trial, despite significant loss in force generating capacity, suggesting the maintenance of muscle excitability during fatigue. Participants with SCI showed a greater degree of fatigue than the AB controls, with a decline of 57% and 43% in PT and TT, respectively. In comparison, the AB group showed an increase of 13% in PT and a decline of 22% in TT at the end of the fatigue trial..

In both studies, there were no significant differences in rates of muscle contraction or relaxation between SCI and AB groups, suggesting the possible preservation of type I muscle fibres in our participants. There was, however, a greater slowing of relaxation rate after fatigue in the SCI group, suggesting some potential impairment in Ca^{2+} re-uptake. Furthermore, there was a significant increase in the twitch-tetanus ratio noted in the SCI group in both studies, suggesting increased muscle stiffness and decreased elastic compliance after SCI. These results have contributed to our understanding of the effects of paralysis on muscle properties; future work should focus on the identification of the mechanisms of muscle fatigue after SCI and the possible role of spasticity in the maintenance of muscle contractile dynamics and fibre composition in paralyzed muscle.

Acknowledgments

I am very appreciative of everyone at McMaster who has helped me with the completion of my Master's degree. I would especially like to thank my supervisor, Audrey Hicks, for her guidance and support. I have really enjoyed work with her for the past two years and I look forward to four more!

I would also like to thank all great new friends I have made here and to my fellow classmates who are always willing to lend a hand. In particular, thanks to Courtney and Jen, for helping keep my sanity in and out of the lab and for teaching me so much. Thanks as always to my family for their patience and support. Finally, thanks to John Moroz and Dam Nguyen for helping me with all of my equipment and software issues.

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List of Abbreviations

½ RT	Half Relaxation Time
AB	Able-bodied
ANOVA	Analysis of Variance
ASIA	American Spinal Injury Association
CSA	Cross Sectional Area
DF	Dorsiflexion
IMF	Intramuscular Fat
MHC	Myosin Heavy Chain
MVC	Maximal Voluntary Contraction
PAP	Postactivation Potentiation
PF	Plantarflexion
PT	Peak Torque
PTP	Posttetanic Potentiation
RTD	Rate of Torque Development
RTR	Rate of Torque Relaxation
SCI	Spinal Cord Injury
SD	Standard Deviation
SDH	Succinate Dehyrogenase
SE	Standard Error
SR	Sarcoplasmic Reticulum
TA	Tibialis Anterior
TPT	Time to Peak Torque
TT	Tetanic Torque

Chapter I: Literature Review

1.1 Spinal Cord Injury

There are currently an estimated 40 000 Canadians living with a spinal cord injury (SCI), an impairment occurring at a rate of approximately 900 per year (Canadian Paraplegic Association, 2008). SCI commonly results from a traumatic accident, such as car collisions or falls, and results in a loss of motor, sensory, and/or autonomic function below the level of lesion (Maynard et al., 1997). The degree of impairment depends on both the level and severity of the injury and is typically classified according to the American Spinal Cord Injury Association scale (ASIA; Maynard et al., 1997). There are five recognized categories of neurological impairment, ranging from A-E, which provide an indication of the amount of sensory and motor function observed below the neurological injury level. ASIA level A indicates a complete SCI, with no motor or sensory function preserved in the sacral segments S4-S5. Level B represents an incomplete injury where some sensory but no motor function is preserved below the neurological level of injury, including S4-S5. Level C also indicates an incomplete injury where some motor function is preserved below the level of injury, and at least half of the muscles have a functional grade below level 3. Level D is described as an incomplete injury where motor function is maintained and at least half of muscles have a grade greater than 3. Level E signifies normal sensory and motor function (Maynard et al., 1997). Injuries that occur in the cervical region (C1-7) typically result in tetraplegia, with limitations being noted in the arms, trunk, and legs. Paraplegia typically results from injuries to the thoracic, lumbar or sacral region of the spinal cord and primarily involves limitations of the legs and hips.

The loss of control over physiological functions varies with both the level and severity of injury and can greatly impact quality of life. Typically, impairments in bowel, bladder, thermoregulatory, and sexual function are experienced. Other secondary complications include pressure sores, increased rates of osteoporosis, autonomic dysreflexia, and chronic pain. Also, and possibly most prominent, are changes in skeletal muscle structure and function subsequent to the loss of voluntary control. Muscle changes after SCI are a result of disuse attributed to a lack of descending motor nerve conduction. Most notably, paralyzed muscle experiences rapid atrophy and a significant decrease in fatigue resistance. As we gain further insight into the muscle adaptations after SCI and the respective mechanism, it will become easier to develop efficient training and rehabilitation strategies in order to prevent or improve the decline in muscle function associated with paralysis.

1.2 Muscle Changes after SCI

The paralysis associated with SCI results in notable changes in skeletal muscle below the level of the lesion. Most prominent is a rapid and significant loss of muscle mass. Also observed is a transformation to the fast fatiguable fibre type (Type IIa, IIx), and changes in muscle contractile properties.

1.2.1 Atrophy

Paralyzed muscle experiences a well documented and significant amount of muscle atrophy, which is characterized by both a decrease in the number of muscle fibres and a shrinking of the remaining fibres. Overall, this leads to a decrease in muscle cross-sectional area (CSA). It has been reported that muscle CSA after complete SCI is only 45-80% of that of age and sex match able-bodied (AB) controls (Castro et al., 1999b, Giangregorio et al., 2005). This atrophy has been shown to occur rapidly, with the CSA of individuals with SCI being only 60% of AB controls at 6 weeks post injury (Castro et al., 1999b). The loss of muscle mass is believed to stabilize 11 months following injury (Round et al., 1993) and is also found to vary between incomplete and complete injuries in the vastus lateralis (Stewart et al., 2004).

Castro *et al.* (1999b) showed a 27-56% atrophy of the vastus lateralis muscle 24 weeks post injury using muscle biopsies. The rate of atrophy slowed with time, with a 22% decrease in CSA occurring between weeks 6 and 11, and a further 10% decrease between weeks 11 and 24. After correcting for intramuscular fat (IMF) accumulation, Gorgey and Dudley (2007) reported a 33% decrease in vastus lateralis CSA 6 weeks following injury. The association between muscle atrophy and increases in IMF was further examined; with a 126% greater absolute IMF and a three-fold increase in relative IMF being noted 6 weeks post injury. IMF was also found to increase in the 3 month follow-up period. A higher percentage of IMF is not desirable, as it has been associated with increased glucose intolerance and a possible increased risk of type II diabetes after SCI (Elder et al., 2004).

The amount of muscle atrophy has also been found to vary with the neurological level of injury. In a group of participants with incomplete SCI, Gorgey and Dudley (2008) used MRI technology to compare muscle CSA between individuals with high (C5-C7) and low (T12-L1) level injuries. Thigh muscle CSA was found to be 22.5% greater in the high level injury group, with a 40% lower relative IMF. Spasticity was found to be six times higher in the high level injury group and a significant linear relationship was noted between muscle CSA and spasticity.

In addition, the amount of muscle atrophy has been shown to very between different muscles. While the vastus lateralis is most commonly biopsied, some studies have examined changes in the tibialis anterior, gastrocnemius, and soleus muscles. Castro *et al.* (1999a) showed decreases in CSA of 24% and 12% in the gastrocnemus and soleus muscles, respectively, while the tibialis anterior showed no significant change in muscle CSA 24 weeks following injury. Contrary to this finding, Rochester *et al.* (1995a), reported some muscle atrophy of the tibialis anterior muscle in participants with chronic injuries; however, it was not a universal finding across all participants. Also in participants with chronic SCI, Martin *et al.* (1992) found a significantly smaller tibialis anterior CSA when compared to able-bodied controls.

Using MRI technology, Shah *et al.* (2006) found an overall decrease of 24-31% in leg muscle CSA among a group of participants with incomplete SCI. It was also noted that decreases in CSA were greater in muscles of the upper leg then the lower leg with the quadriceps femoris showing the greatest loss of muscle CSA at 31% and the tibialis anterior the least, 24%.

1.2.2 Fibre Type Conversion

There are three recognized categories of muscle fibres that compose human skeletal muscle, related to their different metabolic and contractile properties: fast gylcolyctic (FG), fast oxidative gylcolytic (FOG), and slow oxidative (SO; Fitts, 1994; MacIntosh, Gardiner & McComas, 2006). FG and FOG are considered fast twitch fibres and are composed of high adenosinetriphosophate (ATPase) activities, with corresponding short isometric twitch duration at high velocity making them less resistant to fatigue (Fitts, 1994; MacIntosh et al., 2006). SO fibres are considered slow twitch and are generally slower to contract and relax, with slower twitch velocity and low ATPase activity, resulting in an increased fatigue resistance (Fitts, 1994; MacIntosh et al., 2006). Muscle fibres are also frequently classified based on myosin ATPase activity as type I (slow) or type II (fast). Type II muscle fibres in humans are further divided into type IIa and IIx. Fibre classification can be further divided based on myosin heavy chain (MHC) isoforms, type I have MHC I or slow isoforms, and type II fibres have fast isoforms (MHC II), with type IIx expressing both (Fitts, 1994; MacIntosh et al., 2006).

In addition to the significant decreases in total muscle CSA following spinal cord injury, skeletal muscle undergoes a transition where the percentage of muscle tissue represented by type II fibres increases and the amount of type I decreases. Muscle fibre composition has been found to remain relatively stable in the first month post injury, with a transition period occurring between months 1 and 20 in the vastus lateralis after complete SCI (Burnham et al., 1997). This transition period is characterized by a drop in the percentage of MHC I isoforms and an increase in the percentage of muscle fibres that expressed MHC IIx (Burnham et al., 1997). At about 70 months (5.8 years) post injury, a steady state is reached and the muscle is composed exclusively of fast MHC isoforms (Burnham et al., 1997). It has also been reported that there is no significant difference between individuals with complete and incomplete SCI in terms of muscle fibre composition of the vastus lateralis (Malisoux et al., 2007).

Ditor *et al.* (2004) compared muscle fiber composition and area of the paralyzed vastus lateralis and with the unaffected deltoid in a group of participants with complete paraplegia, finding that a smaller mean fibre area in the vastus lateralis could be attributed primarily to differences in type II fibres. There was no difference noted in the mean fibre area of type I fibres, however, the mean fiber area of type IIa fibers was significant smaller in the vastus lateralis and there was a trend towards a smaller type IIx mean fiber area.

In a group of subjects with complete SCI, Talmadge *et al.* (2002) analyzed biopsies of the vastus lateralis at 6 and 24 weeks post injury. Results indicated an increasing percentage of MHC IIx fibres with values of 14% and 16% at 6 and 24 weeks, respectively. MHC IIx fibres represented only 1% of AB vastus lateralis muscle. There was no difference in the percentage of MHC type I fibres between groups or within the SCI group at either time point. Castro *et al.*(1999b) found similar results, showing a decrease in type IIa and an increase in type IIax+IIx CSA and MHC isoforms 24 weeks post injury. There were no changes observed in type I fibre percentage, total fibre number, or MHC isoform percentage. Malisoux *et al.*, (2007) also found smaller proportions of type I (11% in SCI, 34% in AB) and type IIa fibres (11% in SCI, 31% in AB) when compared to controls, while type IIx fibres occurred more frequently in participants with SCI when compared to controls(40% vs. 7%, respectively).

In the tibialis anterior muscle, both Rochester *et al.* (1995a) and Martin *et al.* (1992) found a significant decrease in type I fiber number and CSA when compared with AB controls. Rochester *et al.* (1995a) found that while muscle atrophy did not occur in all of the participants, atrophy of type I fibers was found to occur in 20/28 of the biopsies taken before and after muscle stimulation training.

While the majority of studies do identify a shift from type I to type II muscle fibres after SCI, Gerrits *et al.* (2003) found a considerable amount of variation in the composition of vastus lateralis muscle in a group of participants with complete SCI. Three participants had MHC I values ranging between 36% and 63%, which are similar to the approximately 50% MHC I found in AB muscle. The proposed muscle fibre type transformation after SCI is not yet clear and appears to be highly unpredictable with no clear mechanism identified. This is potentially due to the relatively small number of studies completed to date and the highly variable nature of SCI. The presence or absence of spasticity may also play a role (see below).

1.2.3 Contractile Properties

Another outcome of SCI is a change in muscle contractile properties. Typically, these changes mirror the transformation to fast fatiguable muscle fibers, with faster rates of contraction and relaxation being observed. Typically, the properties that are examined include peak evoked twitch torque (PT), tetanic torque (TT), rate of torque development (RTD), rate of torque relaxation (RTR), time to peak torque (TPT), and half-relaxation time (½ RT).

There have been only a few studies that have examined changes in muscle contractile speed after SCI. In the vastus lateralis, Gerrits *et al.* (1999) found faster rates of contraction and relaxation in a group of people with chronic SCI (>1 year). Maximal rate of force rise (RTD) was significantly faster and ½ RT was significantly slower. Some conflicting results have shown ½ RT to be faster in the quadriceps femoris after SCI in fatigue and at rest (Scott et al., 2006), however, most have shown relaxation rates to be slower. Changes with fatigue have also been noted, as the quadriceps femoris in participants with SCI has been shown to contract 14% faster in nonfatigued conditions and 25% faster in a fatigued condition when compared with AB controls (Scott et al., 2006).

In the soleus muscle, several studies have demonstrated changes in contractile properties following chronic SCI. Indices of muscle relaxation,½ RT and RTR, have been shown to be significantly slower in a group of participants with chronic SCI (> 3 years) when compared with acute injuries (< 5 weeks; Shields, 1995). In the tibialis anterior, rise time for both twitch and tetanic stimulation has been shown to be faster in participants with complete SCI, while ½ RT has been found to be widely scattered around the mean values of the AB control participants (Rochester et al. 1995b). The predicted increase in the percentage of type II muscle fibres after SCI has not been found to be positively correlated with an increased speed of muscle contraction in the tibialis anterior (Rochester et al. 1995 ab).

The paralyzed quadriceps femoris muscle has been shown to produce 62% of the PT produced in non-paralyzed muscle during electrical stimulation at 40 Hz (Scott et al., 2006). Tetanic stimulation of the vastus lateralis at 100 Hz has also resulted in torque deficits in a group of participants with SCI, while stimulation at 10 Hz did not (Gerrits et al., 2003). Contrary to this, the soleus muscle has shown no significant torque deficits during electrical stimulation (Jayaraman et al., 2005). During voluntary muscle contraction participants with incomplete SCI are able to produce 24% of the knee extensor torque and 26% of the plantar flexor torque when compared to AB controls (Jayaraman et al, 2005). Similarly, Stein *et al.* (1992) found no difference in PT or TT achieved between the SCI and control groups during electrical stimulation of the tibialis anterior. In the thenar muscles, stronger twitch force has been found in participants with SCI when compared to controls, while tetanic force is weaker (Hager-Ross et al., 2006).

The force-frequency curve is used to assess the relative torque produced at different stimulation rates and varies with muscle fibre type. In predominantly slow muscles, the steep proportion of the curve occurs at relatively low frequencies (shift to the left), while fast muscles will demonstrate a shift to the right, with higher frequencies needed for the greatest torque production (MacIntosh et al., 2006). SCI would predictably alter the force-frequency relationship, shifting it to the right, however a paradoxical shift to the left has been observed in the quadriceps (Gerrits et al., 1999; Scott et al., 2006) and tibialis anterior (Rochester et al., 1995b) muscles. The mechanism behind this finding remains unknown, however, studies have suggested that it may be an intrinsic property of paralyzed muscle and it may be related to a decreased compliance of the muscle fibres to high frequency stimulation (Gerrits et al., 1999; Scott et al., 2006).

The twitch-tetanus ratio provides an indication of muscle stiffness, with an increased ratio indicating increased stiffness resulting in an enhanced peak twitch torque. An increased twitch-tetanus ratio has been noted in the quadriceps femoris muscle in participants with SCI when compared to AB controls, with values of 0.26 and 0.14, respectively (Scott et al., 2006). These values have also been shown to remain elevated following fatigue (Scott et al., 2006). In the tibialis anterior, values of 0.22 and 0.10 have been reported in SCI and AB groups, respectively (Rodrigues, 2007). Enhanced twitch-tetanus ratio is also observed in the thenar muscles with values of 0.21 in SCI and 0.09 in AB (Thomas, 1997).

The optimal angle for force generation is dependent upon the length-tension relationship, a relationship that is dictated by the overlap of actin and myosin filaments. Prolonged periods of immobilization have been shown to result in a loss of sarcomeres and shortened muscle tissue (Williams & Goldspink, 1978), suggesting that the length-tension relationship may be altered after SCI. There have been only two studies to date that have specifically examined the length-tension relationship after SCI. In the quadriceps muscle, the optimal angle for force generation was not found to differ between SCI and AB groups, yet the SCI group demonstrated significantly less torque at extreme angles (Gerrits et al., 2005). The tibialis anterior muscle has shown no change in the force-angle relationship after SCI, while the gastrocnemisus/soleus muscles have shown a significant shift into plantar flexion, meaning optimal angles for torque were achieved at shorter muscle lengths, when compared to AB controls (McDonald et al., 2005).

Spasticity has been shown to be an important variable that could affect the changes that occur to skeletal muscle after SCI. Hidler *et al.* (2002) examined the response to various frequencies of muscle stimulation in the plantar flexor muscles of participants with SCI and with varying levels of spasticity. Participants with the lowest amount of spasticity presented the greatest change in contractile dynamics when compared to controls, having significantly faster rates of muscle contraction. Participants with higher levels of spasticity were found to have slower rates of muscle contraction when compared to controls, while participants with medium spasticity fell in between with only modest increases in contractile speed. In a similar examination of the role of spasticity in muscle function after SCI, Gorgey and Dudley (2008) found muscle spasticity to account for 54% of the variation found in the CSA of participants with high (C5-C7) and low (T12-L2) level injuries. Spasticity was found to occur more frequently in the high level injury group, with this group also showing a significantly higher muscle CSA and lower IMF.

1.2.4 M-wave Characteristics

M-waves (muscle compound action potential) represent the summation of motor unit potentials in response to a maximal stimulus. A reduction in M-wave size is considered an indirect measure of muscle atrophy or weakness (Thomas, 1997). A smaller M-wave amplitude indicates fewer muscle fibres; therefore, less overall muscle tissue. While there have been only a few studies to examine changes in M-wave characteristics after SCI, a smaller amplitude has been reported in several muscles.

In the thenar muscles, M-wave amplitude has been found to be highly variable after SCI with some participants showing no change when compared to AB (Thomas, 1997). Rodrigues (2007) found M-wave amplitudes to be greater in AB (9.3 mV) compared to SCI (6.9 mV); however, these differences did not reach statistical significance.

Rodrigues (2007) reported significantly smaller M-wave amplitudes in the soleus and tibialis anterior muscles after SCI. Values of 13.5 mV in AB and 5.5 mV in SCI were reported in the soleus muscles, with corresponding values of 8.3 mV and 4.2 mV in the tibialis anterior. Other studies have also noted decreases in M-wave amplitude in the tibialis anterior after SCI (Stein et al., 1992). A positive relationship has been noted between M-wave amplitude and evoked twitch and tetanic force (Thomas, 1997).

In a comparison between participants with acute and chronic SCI, Shields *et al.* (1998) reported M-wave amplitude values of 5.7 mV and 4.8 mV in the soleus muscle, respectively. M-wave area and duration were also found to be greater among the participants with acute injuries. These finding suggest a relationship between time post injury and M-wave characteristics, similar to what is seen with other muscle properties.

1.2.5 Metabolic Enzymes

Muscle oxidative capacity provides an indication of the potential for aerobic metabolism in skeletal muscle and has important implications for muscle fatigue. There have been a few studies that have examined oxidative capacity in muscle following SCI. The majority of these studies have examined succinate dehyrogenase (SDH) activity.

Rochester *et al.* (1995a) found significantly reduced SDH activity in the tibialis anterior muscle among all fiber types in participants with complete SCI. The participants with the lowest SDH activity also demonstrated the greatest percentage of type IIb fibers, a reduced capillary/fibre ratio, and showed the least resistance to fatigue. Also in the tibialis anterior, Martin *et al.* (1992) showed a significantly reduced SDH activity in participants with SCI when compared to controls, with a more pronounced decrease being noted among type II muscle fibres.

In the vastus lateralis muscle, Gerrits *et al.* (2003) found a significant difference in SDH and glycerophosphate dehydrogenase (GPDH) activity between fibre types and a significant relationship between SDH and fatigue after SCI. Some contrary findings were reported by Castro et al. (1999b), who reported an independence of muscle fibre type and enzyme activity, with a substantial decrease in muscle CSA being observed but only a 10% decrease in SDH activity from 6 to 24 weeks post injury. Also, at the end of 24 weeks, SDH activity was actually found to increase in the participants with SCI and approached the values of control subjects. The authors suggested that the decreases in enzyme activity after SCI may occur only after long-term inactivation, and may not be apparent at 24 weeks post injury.

1.2.6 Na^+/K^+ ATPase

The role of the sodium-potassium pump (Na^+/K^+ ATPase) is to maintain concentration gradients of Na^+ and K^+ across the sarcolemmal membrane. This ensures muscle excitability can be maintained during repetitive activation. The Na^+/K^+ ATPase acts to pump 3 Na^+ ions out and 2 K^+ into the cell and thus, contributes to the negative resting membrane potential. There has only been one study to examine changes in the Na^+/K^+ pump concentration after SCI in humans, while more have been conducted with animal models.

Ditor *et al.* (2004) examined skeletal muscle Na^+/K^+ ATPase concentration in the vastus lateralis in a group of individuals with complete paraplegia. Results demonstrated a significantly smaller concentraton of Na^+/K^+ ATPase in the participants' vastus lateralis when compared to either their own healthy deltoid or when compared to the vastus lateralis of able-bodied controls. There was also a significant negative correlation noted between vastus lateralis Na^+/K^+ ATPase concentration and time since injury in the SCI group, suggesting a progressive reduction which continues for at least 20 years post injury.

Jebens *et al.* (1995) noted a decrease of 39% in Na^+/K^+ pump density following a 9 week period of immobilization in the sheep vastus lateralis. There was also a linear increase in muscle K^+ concentration during both the immobilization and remobilization period, occurring independently from decreases in Na^+/K^+ pump concentration. The authors concluded muscle activity was an important regulator in Na^+/K^+ pump density. A decrease in Na^+/K^+ pump activity has been suggested as a mechanism of muscle fatigue in AB muscle, however, it is not know how the decrease in Na^+/K^+ pump concentration after SCI affects muscle fatiguabiliy.

1.2.7 Blood Flow/Capillarization

There is a general decrease in blood flow to the lower limbs reported after SCI. This is shown by a combination of decreased capillarization, decreased artery diameter, and a decreased blood flow rate. Olive *et al.* (2003a) examined femoral artery diameter and maximal hyperemic blood flow in participants with chronic complete SCI. Findings indicated smaller femoral artery diameter and blood flow when compared to AB controls; however, there was no difference between groups when either variable was expressed per unit of muscle mass. Recovery from ischemia was also found to be prolonged in the SCI group.

In a group of individuals with chronic incomplete SCI, Olive *et al.* (2002) completed a protocol to assess femoral artery size and response to cuff occlusion. Femoral artery size and blood flow at rest were not found to be significantly different between SCI and AB groups. Recovery time after 2, 4, and 10 minutes of ischemia was 50% longer for SCI vs. AB. These findings suggest that a variation in vascular adaptations may exist between incomplete and complete SCI, although evidence of reduced vascular control is evident in both conditions.

1.3 Muscle fatigue characteristics after SCI

One of the major clinical implications of the transformation occuring in skeletal muscle after SCI is a decrease in fatigue resistance (Castro et al.,2000; Gerrits et al., 1999; Shields, 1995). This can impact the ability to complete activities of daily living, inhibit rehabilitation programs, and decrease overall quality of life. The fatigue resistance of paralyzed muscle has been found to decrease rapidly for the first 1.7 years post injury, with minimal changes noted after this point (Shields et al., 2006). There have been many mechanisms suggested for this increased fatiguability such as atrophy, increased percentage of type II muscle fibres, decreases in blood flow, decreases in oxidative capacity, and changes in muscle excitability and neuromuscular propagation.

Castro et al. (2000) examined responses to an electrical stimulation protocol in the quadriceps femoris muscle at 6, 11, and 24 weeks post injury. Decreases in force during the protocol were greater in SCI than AB (95 % and 27%, respectively), with no changes being noted during the 18 weeks. There was no change in twitch rise time during the fatigue protocol in either group or throughout the 18 week experimental period. ½ RT was found to be slower in people with SCI, with a slowing noted during the fatigue protocol at 24 weeks, but not at 6 weeks. The authors suggest the decreases in relaxation time at 24 weeks post injury may be due to deficits in Ca^{2+} handling.

Similarly, Gerrits *et al.* (1999) examined muscle fatigue characteristics of the vastus lateralis in a group of subjects with complete and incomplete SCI. The participants with SCI were found to fatigue faster than in the AB group. The participants in the AB group were able to maintain over 30% maximum MVC torque for the entire 10 min protocol. The SCI group was able to maintain over force over 30% maximum for less than 4 min average, with a significant difference in force decline noted after 2 min of the protocol. ½ RT was also found to increase 335% from the baseline value in the SCI group, which was significantly greater than the slowing observed in the control group.

In the soleus muscle, Shields (1995) examined changes in M-wave size during a 4 minute modified Burke protocol consisting of a 330 ms tetanus at 20 Hz every 1 sec. Results showed significant reductions in M-wave amplitude at 185 and 245 sec compared to initial values in the chronic but not acute SCI group. Significant decreases in M-wave amplitude were also noted at 2, 3, and 4 min of the fatigue protocol. Torque decline occurred early in the fatigue protocol, with a significant reduction observed 30sec into the trial in the participants with chronic SCI. ½ RT time was also found to be significantly slower at 30 sec. It was concluded that changes in muscle membrane excitability were not solely responsible for muscle fatigue as significant decreases in M-wave amplitude occurred after the decreases in torque.

Shields *et al.* (1998) showed a 20% decrease in M-wave amplitude, a 40% increase in M-wave duration, and no change in M-wave area in the soleus of participants with chronic SCI during fatigue. M-wave amplitude was found to completely recover 5 minutes after the stimulation trial, while peak torque remained depressed. It was concluded that the decreased M-wave amplitude and increased M-wave duration were the result of an alteration in the muscle membrane and a slowing of action potential conduction in the participants with chronic SCI and did not appear to influence force generating capacity.

Klein *et al.* (2006) examined single thenar motor units during 2 minute fatigue protocol in a group of individuals with cervical SCI. Results indicated a rapid and significant decrease in force of 8-60% in the paralyzed muscle and increases in M-wave amplitude and area were noted at the beginning of each train. This suggested that muscle fatigue was the result of an impairment in the muscle fibres and not with neuromuscular transmission or muscle excitability. ½ RT and contraction times were slower after fatigue in the SCI group and the paralyzed motor units were found to be significant more fatiguable than controls.

Thomas *et al.* (2003) examined the fatigue response to various stimulation patterns by using 4 stimulation protocols involving variable and constant frequency patterns in paralyzed thenar muscles. Significant force declines of 20-25% of initial force were seen in all stimulation patterns and at both high and low frequency stimulation in the SCI group. The control group experienced a less pronounced decrease in force, which was also not dependent on stimulation protocol. Decreases in force were also accompanied by increases in ½ RT, suggesting a slowing of relaxation with fatigue.

Changes in blood flow have also been suggested as a contributor to the decreased fatigue resistance after SCI. Olive *et al.* (2003b), examined the blood flow response to various electrical stimulation bouts of different durations in participants with chronic SCI. At rest, blood flow was not found to be significantly different between SCI and AB groups, despite a smaller muscle CSA in the SCI group. Fatigue was found to be significantly greater in the participants with SCI, increasing progressively with increasing workload (low, moderate, high) in both groups. Both groups experienced a similar increase in blood flow in response to stimulation; however, half time to peak blood flow was prolonged in SCI. Recovery of blood flow after exercise was also found to be slower in SCI. It was concluded that muscle fatigue in the participants with SCI was not associated with any deficits in blood flow, although the delayed blood flow response at the onset of exercise may represent some vascular impairment.

Another likely cause of muscle fatigue after SCI is a change in oxidative capactity. Gerrits *et al.* (2003), examined muscle fibre type variability and metabolic enzymes during an electrical muscle stimulation protocol in the vastus lateralis.

Interestingly, percentage of MHC I isoform was not found to be significantly related to muscle fatigue. Muscle oxidative capacity, measured by SDH activity, was found to account for 65% of the fatigue resistance in participants with SCI.

Although all of these studies have identified a decrease in fatigue resistance in paralyzed muscle, there has been no identification of the mechanisms of neuromuscular fatigue. Increased relaxation times have been reported in several studies, suggesting a possibly decrease in Ca^{2+} handling. Changes in M-wave characteristics have no revealed any deficits in muscle excitability, however, there has only been two studies conducted to date. Decreases in oxidative capacity after SCI have also been shown to contribute to muscle fatigue after SCI.

1.4 Mechanisms of Muscle Fatigue

In the able-bodied population, there are numerous theories used to explain the muscle fatigue that is experienced during periods of repeated activity. These vary from failure at the level of the brain, whole muscle, or at the cellular/molecular level. Several of these theories may have implications or offer possible explanations for the increased fatigability after SCI.

1.4.1 Muscle Fibre Type

Human skeletal muscle is composed of three main fibre types: type I (slow twitch), Type IIa and IIx (fast twitch). Each muscle typically contains each fibre type in various percentages depending mostly on the particular function and load of each muscle. For example, the soleus muscle, which is used mostly for postural control, consists of approximately 80% type I muscle fibres making it highly resistant to fatigue (Fitts et al., 1994; Johnson et al., 1973). Type I muscle fibres contain a high concentration of mitochondrial enzymes, are rich in capillary networks and are able to perform efficient aerobic metabolism, making them highly fatigue resistant (McIntosh et al, 2006). Type IIx muscle fibres are considered highly fatiguable, perform non-aerobic metabolism and are used for brief high intensity effort (MacIntosh et al., 2006). Type IIA fibres have intermediate properties, are able to perform activities at moderate intensity and exhibit fatigue resistance (MacIntosh et al., 2006). Thus, the fatigue resistance of a particular muscle depends in large part on its fibre type composition, which can be altered by training, or various neuromuscular diseases.

1.4.2 Potassium Hypothesis

The excitation of muscle fibres and subsequent muscle contraction typically result in an increase in Na+ influx and K+ efflux, thus altering the cells membrane potential and decreasing excitability. The sodium-potassium pump (Na^+/K^+ ATPase) is largely responsible for maintaining concentration gradients of Na^+ and K^+ across the sarcolemmal membrane to counteract the ionic changes associated with repeated action potentials and allowing for muscle excitability to be maintained. During periods of repeated contractions, it is suggested that the Na^+/K^+ ATPase becomes unable to keep up with increasing demands and the alterations in ion gradients and membrane potential contribute to a decrease in muscle excitability and muscle fatigue. While the activity of the pump is increased with increased action potential frequency (Hicks & McComas, 1989), there is a growing scientific base to support the limitation of this transport mechanism. A current theory of neuromuscular fatigue involves a decrease in muscle excitability due to an increase in extracellular K^+ which results from decreased Na^+/K^+ ATPase efficiency (Clausen & Nielsen, 2007; Fowles et al., 2002; Nielsen & Clausen, 1996).

This theory has been supported in numerous studies that have examined concentrations of both Na+ and K+ ions and Na^+/K^+ ATPase activity both in vivo and in vitro using animal and human models. Interstitial K+ concentration has been shown to increase 3-5 minutes into dynamic muscle contraction, and is positively related to exercise intensity (Green et al., 2000). It has also been shown that altering the Na^+ and K^+ ion concentrations results in a 54% decrease in M-wave area and a 50% decrease in torque, a deficiency that can be corrected with stimulation of the Na^+/K^+ pump (Overgaard et al., 1999). Also, strong correlations have been noted between muscle membrane excitability and muscle torque as elicited though nerve stimulation (Overgaard et al., 1999). There have been several studies conducted that have shown a dose-response relationship between the inhibitory effect of an increase in K^+ concentration and a decrease in torque (Clausen, 1996). Animal studies have further demonstrated that decreases in contractile endurance can be counterbalanced with increases in intracellular Na^+ loading or the addition of stimulants of the Na^+/K^+ ATPase (Clausen & Nielson, 2007).

Lower maximum tetanic force and muscle endurance have been associated with a decrease in the concentration of active Na^+/K^+ pumps, with the rate of torque decline showing a strong relationship with the concentration of functional pumps (Nielsen & Clausen, 1996). It has been shown that muscles with a 54% reduction in Na^+/K^+ pump concentration displayed a 110% reduction in force decline during 30s of nerve stimulation at 60Hz (Nielsen & Overgaard, 1996). There is also some evidence indicating a relationship with fibre specific muscle fatigue, with a greater influx of Na^+ noted in predominantly fast twitch muscles (Nielsen & Clausen, 1996).

While fewer in number, there have been several human studies conducted examining the role of Na^+/K^+ ATPase in muscle fatigue. The majority of these studies have used M-wave amplitude as an indirect measure of Na^+/K^+ pump activity (Cupido et al., 1996; Hicks & McComas, 1989). M-wave potentiation has been suggested to be an indicator of elevated Na^+/K^+ pump activity and has been observed during periods of tetanic stimulation of the thenar, extensor digitorum (Hicks et al, 1989), and biceps brachii muscles (Cupido et al., 1996). The increased activity of the Na^+/K^+ pump is only observed and can only be maintained under certain conditions and varies with muscle groups. During fatiguing voluntary isometric exercise, results have shown a 38% reduction in Na^+/K^+ ATPase activity in the human vastus lateralis (Fowles et al., 2002). This decrease in Na^+/K^+ ATPase activity has also been associated with decreases in M-wave amplitude and area (Fowles et al., 2002). Cupido *et al.* (1996) observed that the Na^+/K^+ pump is capable of maintaining membrane excitability for almost a minute when stimulated at 20Hz under ischemic conditions, while enlarged action potentials and M-wave amplitude could be sustained for at least 3 minutes with stimulation at 3 or 10Hz. Similarly, muscle excitability, as measured with M-wave amplitude, has been shown to be maintained for 1 min at up to 30 Hz in both human dorsi and plantar flexor muscles (Galea, 2001).

1.4.3 Ca^{2+} Handling

Calcium (Ca^{2+}) plays an important role in the excitation-contraction coupling of muscle fibres, acting as a key messenger between the action potential and the contractile process. Following the depolarization of the T-tubules from the incoming action potential, Ca^{2+} is released from the sarcoplasmic reticulum (SR) and binds to troponin, a protein found on the actin molecule. This binding exposes the myosin-binding sites on the actin filaments, allowing for crossbridge cycling to begin. Following contraction, tropomyosin blocks the myosin binding sites, as Ca^{2+} is actively transported back into the SR by the Ca^{2+} ATPase. Proper regulation of Ca^{2+} release and uptake is crucial to ensure muscle contraction and relaxation (Favero et al., 1999; Fitts, 1994))

One current theory of muscle fatigue involves alterations in the ability to control Ca^{2+} in the muscle cell following repetitive contraction. One critical element in the successful transport of Ca^{2+} is the Ca^{2+} ATPase, which occupies approximately 90% of the SR (Cairns et al., 1998). Decreases of 20-60% in Ca^{2+} ATPase activity has been reported during periods of exercise, as well as decreases of 26-70% in Ca^{2+} uptake (Cairns et al., 1998).Other work has shown that the addition of caffeine, a known stimulant of Ca^{2+} channels, reverses the decreases in force associated with fatigue (Cairns et al., 1998; Fitts, 1994).

1.5 Summary and Statement of Purpose

Skeletal muscle experiences a rapid atrophy and possible fibre type transformation after SCI, however, the precise mechanisms behind many of these changes remain unidentified. The first study of this thesis examines the length-tension relationship of the dorsiflexor and plantarflexor muscles after SCI. In order for research on muscle properties after SCI to move forward, it is important that the optimal angles for force generation be quantified. The second study will explore muscle fatigue in the ankle dorsiflexors after SCI, and attempt to determine the role of muscle excitability as a potential mechanism for the decrease in fatigue resistance. In this study the M-wave will be used as a non-invasive indicator of Na^+/K^+ pump activity.

Chapter II: The Length-Tension Relationship of Human Dorsiflexor and Plantarflexor Muscles Following Spinal Cord Injury

The following manuscript has been accepted (July 17, 2009) as presented for publication in the journal *Spinal Cord*

2.1 Abstract

STUDY DESIGN: A cross-sectional design.

OBJECTIVES: To examine the length-tension relationship of dorsiflexion (DF) and plantarflexion (PF) muscle groups in 7 individuals with chronic spinal cord injury (SCI; C2 – T7; age 43 ± 10.1) and compare it to a group of age and sex matched able-bodied (AB) controls.

SETTING: McMaster University, Hamilton, ON, CANADA

METHODS: Isometric single twitch properties, 0.5 sec tetanic contractions (SCI), and maximal voluntary contractions (AB) were measured at 9 joint angles from 20^0 DF to 20^0 PF.

RESULTS: In the DF muscles, peak evoked twitch torque occurred at 20^0 PF for SCI (3.4 ± 1.1 Nm) and AB (3.8 ± 1.4 Nm) with no difference in peak torque between groups, while peak summated force occurred at 10^0PF in AB and 20^0PF in SCI ($p < 0.01$). In the PF muscles, peak evoked twitch torque occurred at15^0 DF in AB (18.6 ± 2.6 Nm) and 5^0 DF (6.8 ± 3.3 Nm; $p < 0.01$) in SCI and peak summated force at 15^0 DF in AB. The SCI group did not demonstrate any change in PF peak summated force with varying joint angles. Rates of contraction and relaxation were not different between groups

CONCLUSIONS: The results suggest a significant change in the length-tension relationship of the PF muscles following SCI, but no change in the DF muscle group. Rehabilitation programs should focus on maintaining PF muscle length in order to optimize muscle strength and function after SCI.

2.2 Introduction

Following spinal cord injury (SCI) it has been established that there are significant changes in skeletal muscle properties below the level of the lesion. These include fibre type transformation, [1, 2] atrophy, [1] faster contractile properties,[2-4] and a decreased range of motion.[5] These changes, which can be attributed to both paralysis and a loss of functional innervation, greatly diminish the force generating capacity of muscle. Another factor known to affect force generation is muscle length. This phenomenon, known as the length-tension relationship, is attributed to the degree of overlap between the actin and myosin filaments within the myofibrils.[6] A major limitation in the majority of studies that have examined various muscle property changes following SCI is the assumption that there is no change in the length-tension relationship. A change in this relationship would not only affect muscle characteristics, but would also imply a change in the optimal angle for force generation.

There is good reason to hypothesize that the length-tension relationship might change in after SCI. Paralysis is associated not only with muscle atrophy; it is also accompanied by increased connective tissue within the muscle belly [7] and possibly a loss of sarcomeres due to prolonged immobilization.[8,9] This increase in connective tissue contributes to a loss of elasticity, an increase in passive tension, and a decrease in range of motion.[7-10]

To date, only two studies have attempted to address changes in the length-tension relationship after SCI. Gerrits et al.[11] found no change in the torque-angle relationship of human knee extensors compared to controls, although the SCI participants produced significantly less torque (relative to their own maximum) at extreme angles. McDonald and colleagues[5] examined length-tension properties of the ankle muscles following SCI and found a significant shift towards plantar flexion in the torque-angle curve of the gastrocnemius/soleus. The tibialis anterior showed no significant shift when comparing the two groups. This study used only single twitch data for an assessment of the torque-angle relationship and did not report findings related to muscle contractile speed. Also, an ideal angle for torque development was not identified in either muscle groups.

The purpose of this study was to determine the optimal angle for force production of dorsiflexor and plantarflexor muscle groups following SCI. It was predicted that the optimal angles for peak twitch and maximal summated force production would occur at shorter muscle lengths for the SCI group versus able-bodied controls. It was also predicted that at all muscle lengths, participants with SCI would produce significantly less torque compared to controls. Finally, given the purported shift towards faster fibre types following SCI, it was predicted that the SCI group would display faster contractile speeds for both the DF and PF muscle groups.

2.3 Materials and Methods

2.3.1 Subjects

Seven male subjects with SCI (43 ± 10.1 years) and seven age and sex matched able-bodied control subjects (AB) were used as participants in this study (42 ± 10.8 years). All participants were recreationally active and none had participated in any form of muscle stimulation training. SCI subject characteristics are summarized in Table 1. Inclusion criteria included: >1 year post injury, upper motor lesion level above T8, American Spinal Injury Association (ASIA) classification A-C, and wheelchair dependent. Testing procedures were approved by the McMaster University Research Ethics Board and informed consent was obtained from each participant.

2.3.2 Apparatus

All measurements were conducted on the right ankle DF and PF muscles. Subjects either remained in their wheelchair (SCI) or sat in a height- adjustable chair (AB) with the right knee flexed at 90^0. The lower leg and foot was secured in an isometric boot apparatus. For the DF muscle group, rubber stimulating electrodes (3cm diameter) were applied to clean abraded skin over the common peroneal nerve just distal to the proximal head of the fibula and on the anterior aspect of the leg, slightly distal to the patella. The PF muscle group was stimulated in the popliteal fossa overlying the tibial nerve with two lead plate stimulating electrodes imbedded in a plastic housing. All electrodes were coated in conducting gel prior to placement on the skin and secured with tape or a Velcro strap. Muscle electrical activity was collected using two surface electromyogram (EMG) electrodes (Kendall Medi-Trace 133) placed 5cm apart on the muscle belly of the tibialis anterior and soleus muscles. A ground electrode was secured on the lateral aspect of the lower leg, between the stimulating and recording electrodes.

A high-voltage constant current stimulator (Digitimer Ltd., Model 3072,) was used to deliver single 50μsec rectangular pulses and 0.5 sec tetanic trains (80 Hz) to the peroneal and tibial nerve for assessment of peak evoked twitch (PT) and peak tetanic torque (TT), respectively. The stimulation frequency (80Hz) was selected based on the force-frequency relationship for the tibialis anterior in people with SCI previously determined in our lab (unpublished). The optimal stimulation intensity was determined at 15^0 PF for the DF muscle group and at 15^0 DF for the PF muscle group. For each participant, stimulation current was gradually increased until there were no further increases in PT. This optimal stimulation intensity was then used for assessment of the PT and TT at different joint angles. Data were acquired using custom designed software (Labview, National Instruments; Austin, TX).

2.3.3 Procedure

After being secured in the boot apparatus and determining optimal stimulation intensity, muscle contractile properties in the PF and DF muscles were measured at 9 joint angles, ranging from 20°DF to 20°PF, in 5° increments. The muscle contractile properties measured were peak evoked twitch (PT), maximum compound action potential amplitude (M-wave), time to PT (TPT), maximum rate of torque development (RTD), ½ relaxation time (1/2 RT) and maximum rate for torque relaxation (RTR). The DF muscle group was assessed first, followed by the PF group and joint angle order was randomized. For determination of maximum summated force generating capacity in the SCI group, a 0.5 sec tetanic train at 80 Hz was evoked at each joint angle following the assessment of PT, to provide peak tetanic torque (TT). Alternatively, in the AB group, subjects were instructed to produce a 5 second maximum voluntary contraction (MVC) at each angle after all the single twitch data were collected to avoid any potentiation effects.

2.3.4 Statistical Treatment

Muscle contractile property data were analysed with a two-way mixed analysis of variance (ANOVA) with one between subjects factor (SCI vs. AB) and one within subjects factor (joint angle). Significance was set at $p < 0.05$, and Tukey A post-hoc tests were used to examine significant differences between means. Throughout the text, values are reported as mean ± standard deviation.

2.4 Results

2.4.1 Effect of joint angle on PT

Table 2 presents the contractile properties for both muscles tested. In the DF muscle group, there were no group differences in PT ($p = 0.49$), nor was there a significant group x angle interaction ($p = 0.71$). Maximal PT occurred at 20^0PF in both the SCI and AB groups with values of 3.4 ± 1.1 Nm and 3.8 ± 1.4 Nm, respectively (Figure 1). Despite the similar PT, the evoked twitches in the SCI group were faster; TPT at the optimal joint angle was 75.4 ± 13.8 ms in SCI compared with 79.9 ± 7.6 ms in AB ($p = 0.037$; Table 2). While there was a trend towards a faster RTD in SCI at some joint angles (eg. 114.8 ± 36.6 ms in SCI and 87.0 ± 36.3 ms in AB at 15^0PF), the difference did not reach significance. Similarly, rates of torque relaxation were not different between groups.

In the PF muscles there were differences between groups in both the magnitude of PT and the optimal angle for evoked force generation ($p < 0.01$; Figure 1). The optimal angle for PT occurred at 5^0DF in the SCI group (6.8 ± 3.3 Nm) and at 15^0DF in AB (18.6 ± 2.5 Nm). As seen in Table 2, TPT was faster in SCI (62.4 ± 18.8 ms) compared with AB (116.2 ± 14.8 ms; $p < 0.00$) due to the significantly smaller PT, while RTD was slower in SCI (229.4 ± 123.6 Nm/s) compared with AB (351.6 ± 60.3 Nm/s; $p = 0.02$).

RTR was also slower in SCI (89.6 ± 52.2 Nm/s) versus AB (142.8 ± 16.4 Nm/s; $p = 0.01$).

2.4.2 Effect of joint angle on M-wave amplitude

In both DF and PF muscle groups, the peak-to-peak amplitude of the M-wave was significantly smaller in the SCI group ($p < 0.05$; Table 3). A significant group x angle interaction ($p < 0.05$) in both muscle groups indicated that the M-wave amplitudes did not change significantly with the different joint angles in the SCI group, but tended to increase at the shorter muscle lengths in the AB group. The M-wave area did not change across joint angles in either group.

2.4.3Effect of joint angle on peak tetanic/MVC torque

The optimal angle for peak summated force in DF and PF muscles was different between groups (see Figure 2). In the DF muscles there was a significant group x angle interaction ($p < 0.01$); peak MVC occurred at 10^0PF for AB (42.2 ± 5.2 Nm), while peak TT occurred at 20^0PF for SCI (12.1 ± 6.5 Nm). In the PF muscles, peak MVC was achieved at 15° DF in the AB group (119.1 ± 61.9 Nm), however there was no significant effect of angle on TT in the SCI group. The twitch: tetanus or twitch: MVC ratio was calculated, revealing a significantly greater ratio ($p < 0.05$) in the SCI vs. AB groups in both the DF (0.36 vs. 0.09) and PF (0.34 vs. 0.19) muscle groups. The DF twitch: tetanus ratio was also found to increase significantly ($p < 0.05$) with increasing muscle length in the SCI group.

2.5 Discussion

The results of the present study gave partial support for our first hypothesis that maximum force would occur at shorter muscle lengths in people with SCI. In the PF muscles, the optimal angle for generation of PT was at a shorter muscle length in the SCI group (5^0DF vs. 15^0 DF in SCI and AB, respectively). These findings support the previous work by McDonald et al.,[5] where the torque-angle relationship in the PF muscles was shifted towards plantar flexion in the SCI group, although no optimal angles were identified in that study. In contrast, there was no evidence of any group differences in optimal angle for peak evoked twitch in the DF muscle group; both groups generated PT at the same joint angle of 20^0PF. It was more difficult to compare the optimal angles for generation of summated force, since tetanic stimulation was used for the SCI group, and MVCs for AB. The significant discomfort associated with 80Hz stimulation, especially in the PF muscles, led to the decision to use MVCs in the AB group.

The results from this study did not support an SCI-induced transformation to faster fibre types. The RTD was not different between groups in the DF muscles, and was significantly slower in the PF muscles of the SCI group. RTD is dependent upon myosin ATPase activity and is directly related to the proportion of Type IIb fibres. [12] Previous studies have shown that muscles undergo a fibre-type transformation towards a greater representation of Type IIb fibres in vastus lateralis [1,13,14] and soleus muscles [2] after SCI. There is some suggestion that the degree of fibre-type transformation may be influenced by the amount of spasticity in a particular muscle after SCI. Previous reports have suggested a preservation of contractile properties and/or an increased expression of slow twitch fibres in muscle that experiences a significant degree of spasticity following SCI. [15,16] Furthermore, Stein et al.[17] suggested that if spasticity occurs more frequently in the extensor muscles (such as the soleus), the tibialis anterior muscle would be placed in a stretched position, thus preserving the torque generating capacity of that muscle. In contrast, the extensor muscles would be exposed to more shortened positions, due to both the prolonged sitting position in a wheelchair and the repeated bouts of spasticity. While this would certainly support the findings of the current study, we did not assess spasticity and cannot attribute the lack of predicted change in contractile speed to levels of spasticity in our subjects. Clearly the role spasticity plays in muscle function and a contractile properties following SCI needs further investigation.

The lack of any observable effect of SCI on the magnitude of PT of the DF muscles confirms previous reports, [3,18,19] and is most likely the result of SCI-induced changes in muscle stiffness. Olsson et al.[10] demonstrated a MHC type IIx dependent increase in muscle stiffness, as measured by passive tension, following SCI. This increase was particularly apparent at long muscle lengths. The significantly greater twitch:tetanus ratio in the SCI group of the present study certainly supports an increase in muscle stiffness, most likely related to a decline in the series elastic component. The increasing twitch: tetanus ratio with increasing ankle angle in the DF of the SCI group lends further support to the contribution of muscle stiffness, as only the twitch torque was found to increase as the muscle was lengthened.

Another noteworthy observation was the inability to generate a muscle twitch in the majority of SCI participants at shortened muscle lengths, particularly in the DF muscle group (see Table 2). While it is possible that the torques generated were too small to be detected by the force transducer, this may also be evidence of sarcomere shortening. At extremely short muscle lengths, thick filaments (myosin) collide with Z-lines, inhibiting adequate binding with actin (thin filaments) and thus, decreasing tension development.[6] In the SCI group, it appears this inability to generate torque occurred at even some neutral muscle lengths, which would suggest sarcomere shortening.

The smaller M-wave amplitude noted in both DF and PF muscle groups following SCI is indicative of the vast muscle atrophy, and confirms previous reports.[2,3,17] Since M-waves represent the summation of motor unit potentials in response to a maximal stimulus, a reduction in M-wave size is considered an indirect indicator of muscle atrophy or weakness.[20] A smaller M-wave would indicate fewer motor units; therefore, less overall muscle tissue. Smaller M-waves have been correlated with a decreased force generating capacity in paralyzed thenar muscles.[20]

The results of this study suggest that when examining changes in muscle properties following SCI, it is important to consider possible changes in the length-tension relationship. While there seems to be a significant change in PF muscles following SCI, such as a shifted length-tension relationship, decreased PT and M-wave size, there does not appear to be the same magnitude of decrease in DF muscle characteristics. In terms of rehabilitation after SCI, interventions and assisted devices should focus on maintaining or increasing muscle length in muscles that sustain long periods in a shortened position. The extended periods of sitting in a wheelchair likely contributes to the shortening (and subsequent loss of force generating capacity) of the PF muscles, so it may be prudent to incorporate full leg extension into the daily routine of persons with SCI.

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2.7 Titles and Legends to Figures

Figure 1. Dorsiflexor **(A)** and plantarflexor **(B)** twitch torque for able-bodied (AB) and spinal cord injured (SCI) participants. Plantar flexion angles are negative, dorsiflexion angles are positive. Error bars represent SEM.

Figure 2. Dorsiflexor **(A)** and plantarflexor **(B)** tetanic torque and MVC torque for spinal cord injured (SCI) and able-bodied (AB) participants, respectively. Plantar flexion angles are negative, dorsiflexion angles are positive. Error bars represent SEM.

Figure 1.

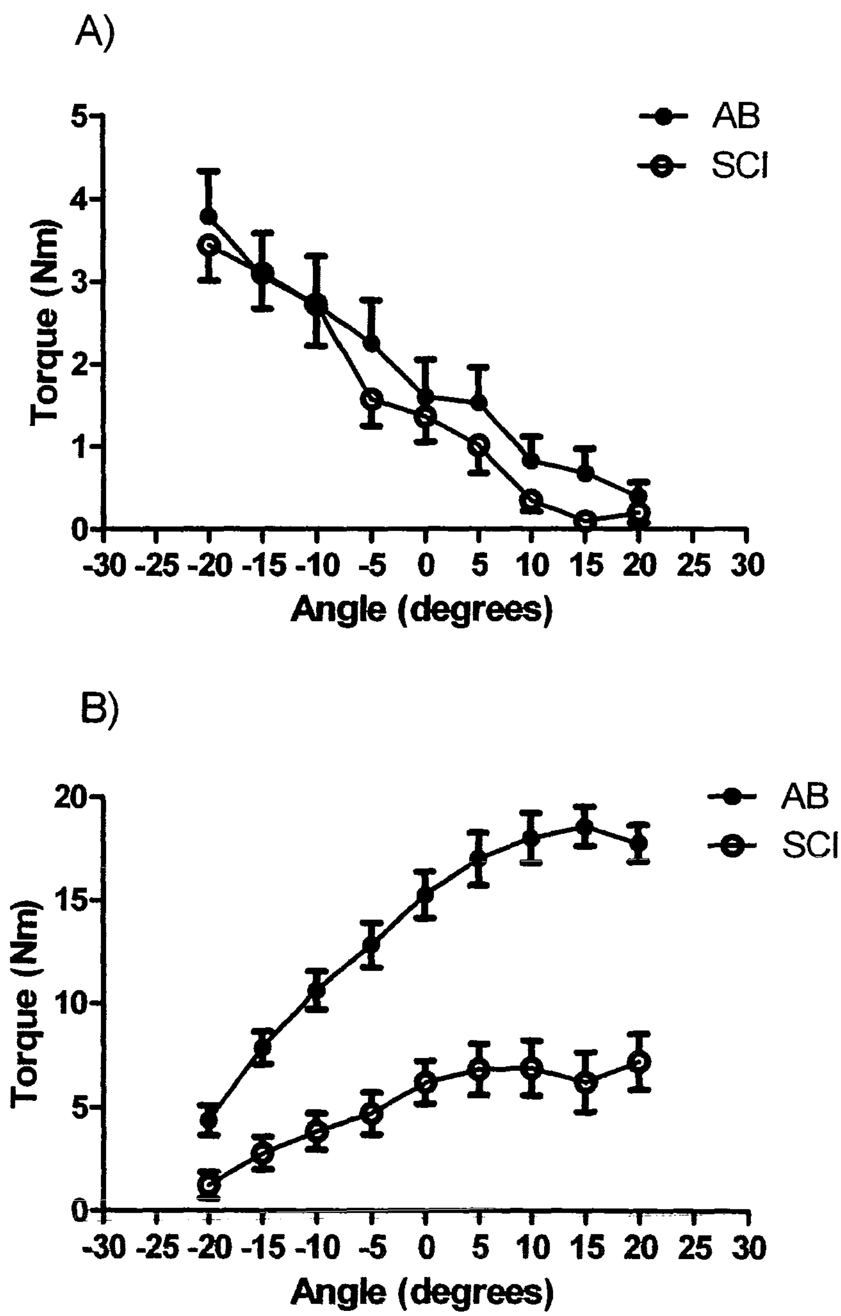
A)
AB
SCI
Torque (Nm)
0
1
2
3
4
5
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30
Angle (degrees)
B)
AB
SCI
Torque (Nm)
0
5
10
15
20
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30
Angle (degrees)

Figure 2.

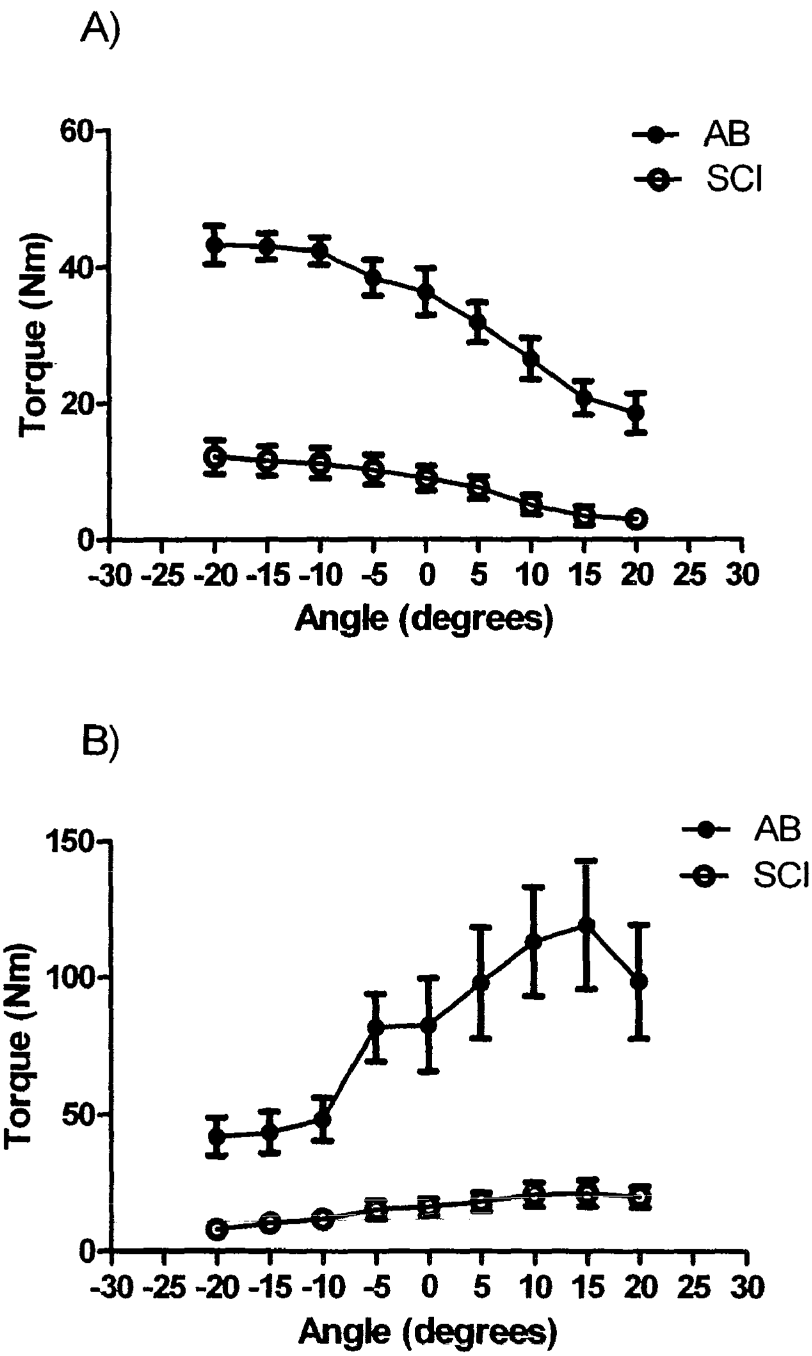
A)
AB
SCI
Torque (Nm)
60
40
20
0
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30
Angle (degrees)
B)
AB
SCI
Torque (Nm)
150
100
50
0
-30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30
Angle (degrees)

Table 1. SCI participant characteristics

Participant	Age	SCI Level	ASIA	Years Post Injury
1	42	T7	A	3
2	51	C2	C	13
3	57	C5-C6	C	21
4	54	C3	C	13
5	35	C4	C	11
6	32	C6-C7	A	13
7	32	C5	A	9

Table 2. Contractile speed characteristics for able-bodied (AB) and spinal cord injured participants (SCI) at various joint angles.

Dorsiflexors								
	AB				SCI			
	TPT (ms)	½RT (ms)	RTD (Nm/s)	RTR (Nm/s)	TPT (ms)	½RT (ms)	RTD (Nm/s)	RTR (Nm/s)
20DF	97.4 ± 77.5	47.6 ± 16.4	27.6 ± 15.2	42.1 ± 39.9	-	-	-	-
15DF	93.4 ± 42.9	78.6 ± 49.3	28.9 ± 7.6	51.7 ± 60.2	-	-	-	-
10DF	58.4 ± 28.2	42.5 ± 14.4	31.8 ± 12.6	31.3 ± 12.9	37.7 ± 12.3	35.0 ± 15.4	37.2 ± 7.6	46.6 ± 2.9
5DF	69.9 ± 14.7	51.6 ± 8.3	63.6 ± 28.1	41.6 ± 14.4	53.1 ± 14.7	53.3 ± 28.9	59.4 ± 27.9	34.5 ± 16.4
0	80.4 ± 16.1	58.3 ± 14.2	65.1 ± 23.7	35.6 ± 10.7	51.5 ± 17.6	51.1 ± 29.0	58.5 ± 26.3	41.2 ± 21.2
5PF	75.5 ± 6.9	56.7 ± 12.0	71.9 ± 41.1	37.9 ± 10.5	67.0 ± 13.1	80.5 ± 25.7	56.9 ± 28.1	30.4 ± 11.7
10PF	78.1 ± 7.8	62.5 ± 8.3	74.7 ± 40.0	38.8 ± 13.0	70.5 ± 13.5	77.7 ± 23.1	107.8 ± 53.4	46.0 ± 18.5
15PF	80.0 ± 7.2	71.1 ± 5.4	87.0 ± 36.3	38.9 ± 12.9	75.6 ± 17.7	78.9 ± 22.4	114.8 ± 36.6	47.8 ± 28.4
20PF	79.9 ± 7.6	79.3 ± 8.9	107.8 ± 41.4	44.3 ± 9.2	75.4 ± 13.8	80.6 ± 14.7	106.1 ± 40.2	44.6 ± 14.0

Values are mean ± SD (only means from complete data sets are included)

TPT, time to peak torque; ½ RT, ½ relaxation time; RTD, maximum rate of torque development; RTR, maximum rate of torque relaxation

Table 2. Contractile speed characteristics for able-bodied (AB) and spinal cord injured participants (SCI) at various joint angles.

Plantarflexors	AB				SCI			
	TPT (ms)	½RT (ms)	RTD (Nm/s)	RTR (Nm/s)	TPT (ms)	½RT (ms)	RTD (Nm/s)	RTR (Nm/s)
20DF	115.9 ± 13.0	111.0 ± 11.7	354.4 ± 85.6	133.4 ± 15.0	53.6 ± 19.3	84.9 ± 38.3	270.9 ± 147.8	103.7 ± 49.7
15DF	116.2 ± 14.8	109.9 ± 17.7	351.5 ± 60.3	142.8 ± 16.4	86.1 ± 33.8	102.4 ± 34.5	189.1 ± 113.5	70.5 ± 45.4
10DF	113.4 ± 12.5	109.2 ± 17.4	398.9 ± 71.9	139.2 ± 16.7	58.2 ± 17.1	81.8 ± 33.1	234.0 ± 127.9	94.3 ± 62.0
5DF	112.4 ± 10.6	106.3 ± 21.5	376.1 ± 62.1	134.2 ± 15.5	62.4 ± 18.8	82.9 ± 32.6	229.4 ± 123.6	89.6 ± 52.2
0	106.8 ± 12.4	102.7 ± 17.1	403.2 ± 134.8	139.2 ± 31.6	61.2 ± 18.5	70.6 ± 21.2	235.2 ± 121.8	85.9 ± 47.5
5PF	107.1 ± 15.6	95.5 ± 10.6	290.1 ± 41.3	119.8 ± 20.8	70.3 ± 13.5	98.4 ± 61.8	134. 8± 77.2	56.9 ± 31.5
10PF	108.0 ± 12.5	89.2 ± 12.1	217.0 ± 51.8	104.7 ± 21.5	64.0 ± 13.1	82.3 ± 53.9	139.8 ± 102.4	51.1 ± 22.9
15PF	104.3 ± 11.8	90.2 ± 11.7	150.7 ± 32.8	76.3 ± 17.7	60.4 ± 11.9	63.9 ± 42.5	96 4 ± 67.6	44.9 ± 23.1
20PF	106.5 ± 10.1	83.2 ± 10.5	90.2 ± 30.2	52.1 ± 11.3	58.5 ± 30.3	51.7 ± 27.3	56.4 ± 50.6	34.1 ± 21.9

Values are mean ± SD (only means from complete data sets are included)

TPT, time to peak torque; ½ RT, ½ relaxation time; RTD, maximum rate of torque development; RTR, maximum rate of torque relaxation

Table 3. M-wave amplitude (mV) at various joint angles for able-bodied (AB) and spinal cord injured (SCI) participants.

Dorsiflexors		
	AB	SCI
20DF	8.2 ± 4.6	2.3 ± 1.3
15DF	7.2 ± 3.8	2.2 ± 1.2
10DF	6.4 ± 2.8	2.1 ± 1.0
5DF	6.3 ± 2.9	2.4 ± 1.1
0	7.1 ± 3.7	2.6 ± 1.2
5PF	6.2 ± 3.3	2.2 ± 1.1
10PF	6.1 ± 3.6	2.4 ± 1.1
15PF	5.7 ± 3.6	2.5 ± 1.2
20PF	5.6 ± 3.6	2.5 ± 1.2
Plantarflexors		
20DF	16.6 ± 4.3	3.2 ± 3.0
15DF	17.4 ± 4.0	3.9 ± 3.5
10DF	17.4 ± 4.4	3.9 ± 3.5
5DF	18.1 ± 4.8	3.8 ± 3.0
0	18.1 ± 5.0	3.9 ± 3.6
5PF	19.8 ± 4.8	4.1 ± 3.4
10PF	20.5 ± 4.7	4.0 ± 3.8
15PF	20.9 ± 4.8	3.4 ± 3.0
20PF	21.5 ± 4.8	3.3 ± 2.9

Values are mean ± SD

Chapter III: Muscle Fatigue Characteristics of the Paralyzed Tibialis Anterior after Spinal Cord Injury

This manuscript has been prepared and formatted for publication in the journal *Spinal Cord*

3.1 Abstract

STUDY DESIGN: Cross-sectional study design.

OBJECTIVES: To examine muscle characteristics and the role of muscle excitability during fatigue of the tibialis anterior in 6 individuals with chronic spinal cord injury (SCI) and compare it to a group of age and sex matched able-bodied (AB) controls.

SETTING: McMaster University, Hamilton, ON, CANADA

METHODS: M-wave characteristics, muscle twitch properties, and summated force were examined during a 2 minute fatigue protocol of intermittent bursts at 30Hz (4 sec tetanus, 2 sec rest) or maximal voluntary contraction (MVC). A 15 minute recovery period followed.

RESULTS: M-wave amplitude and area did not change during fatigue in either group. M-wave amplitude was smaller in SCI (2.5 ± 1.59 mV in SCI, 5.7 ± 3.18 in AB) at baseline. There was an increase in M-wave duration during the course of recovery in the SCI group. PT was not different between groups at baseline (3.8 ± 1.80 Nm in SCI, 3.7 ± 0.59 Nm in AB), but there was potentiation of PT in the AB group during the fatigue trial. There was significantly greater fatigue of both PT (43% decline) and summated force (57% decline) in the SCI group compared with the AB group (13% increase and 22% decline for PT and MVC, respectively).

CONCLUSIONS: Decreases in muscle excitability do not appear to be a significant contributor to the increased fatiguability after SCI. The mechanisms behind the increased fatigue must be distal to the muscle membrane.

3.2 Introduction

One of the most important implications of the changes that occur to skeletal muscle after spinal cord injury (SCI) is a decreased fatigue resistance in the paralyzed muscle. [1-3] This results in many functional limitations and can inhibit rehabilitation efforts. This loss in fatigue resistance has been shown to happen fairly rapidly, with a noticeable decrease occurring at 1.7 years post injury.[4]

While the mechanism for this increased fatiguability in the SCI population is unknown, a current theory of neuromuscular fatigue in the able-bodied (AB) population involves a decrease in muscle excitability due to increased extracellular K^+. The sodium-potassium pump (Na^+/K^+ ATPase) is largely responsible for maintaining concentration gradients of Na^+ and K^+ across the sarcolemmal membrane, allowing for muscle excitability to be maintained during repetitive activation. When an action potential arrives at the membrane, depolarization is required in order to elicit a contraction. Given the small extracellular space around the muscle fibres, repeated depolarization can quickly lead to significant changes in the extracellular concentration of K^+, which would be predicted to affect membrane excitability.[5]

The compound muscle action potential (M-wave) represents the summated action potential response to a single maximal electrical stimulus applied to a particular muscle group and is commonly used to assess muscle excitability. Furthermore, changes in M-wave amplitude and area can be used as an indirect measure of Na^+/K^+ ATPase activity. Hicks and McComas [6] concluded that increased Na^+/K^+ ATPase activity was solely responsible for enhanced action potentials and M-wave amplitude during repeated stimulation of rat soleus muscle. Increases in M-wave size have also been noted during periods of intermittent maximal contractions, suggesting increased Na^+/K^+ ATPase activity. [5, 6] Previous work has demonstrated a substantial decrease in Na^+/K^+ ATPase concentration in the paralysed vastus laterals of people with complete SCI, [7] however, it is not known if this decrease in pump concentration has any significant effect on membrane excitability or fatigue resistance.

In the soleus muscle, Shields [2] examined changes in M-wave size during a 4 minute modified Burke protocol consisting of a 330 ms tetanus at 20 Hz every 1 sec. Results showed significant reductions in M-wave amplitude at 185 and 245 sec compared to initial values but only in the chronic but not acute SCI group. Despite these changes, it was concluded that changes in muscle membrane excitability were not solely responsible for muscle fatigue as significant decreases in M-wave amplitude did not coincide with decreases in torque. A similar study, also in the soleus muscle, found a 20% decrease in M-wave amplitude, a 40% increase in M-wave duration, no change in M-wave area, and an 80% decrease in peak torque following intermittent tetanic stimulation in people with chronic but not acute (< 6 weeks post injury) SCI.[8] M-wave amplitude was found to completely recover 5 minutes after the stimulation trial, while peak torque remained depressed.[8]

Contrary to the extensive body of literature pertaining to muscle fatigue in AB humans, the various mechanisms behind neuromuscular fatigue have not been fully resolved in paralyzed muscle. The characteristics of muscle fatigue in people with SCI appear to vary with fatigue protocol, stimulation intensity, and the muscle being investigated. The purpose of this study was to examine the potential role of a decline in muscle excitability as a contributor to impaired fatigue resistance in the ankle dorsiflexors in people with SCI, using the M-wave as a non-invasive determinant of Na^+/K^+ ATPase activity. M-wave changes during a period of intermittent tetanic stimulation were assessed in the ankle dorsiflexor muscles of people with SCI, and compared to a similar protocol in AB individuals. It was predicted that the SCI group would show a greater decrease in M-wave amplitude throughout the fatigue protocol when compared to AB controls. It was also predicted that the SCI group would show decreased fatigue resistance as evidenced by a more rapid and significant decline in peak torque and a slower recovery.

3.3 Methods

3.3.1 Participants

Six participants with chronic SCI (5 male, 1 female; age 44 ± 13.9 years) and six age-and -sex matched AB controls (age 45 ± 14.3 years) were used as participants in this study. All participants were recreationally active and none had participated in any form of muscle stimulation training. Characteristics of the study participants with SCI are summarized in Table 1. Inclusion criteria for the participants with SCI included: > 1 yr post injury, upper motor neuron lesion level higher than T8, American Spinal Injury Associatioin (ASIA) classification A-C, and wheelchair-dependent. Informed consent was obtained from all participants and procedures were approved by the McMaster University Research Ethics Board.

3.3.2 Apparatus

All measurements were conducted on the right ankle dorsiflexor muscle (tibialis anterior). Subjects either remained in their wheelchair (SCI) or a height- adjustable chair (AB) with the right knee flexed at 90^0. For both the SCI and AB participants, the ankle was placed at 20^0 PF. This angle has been previously determined as optimal for evoked dorsiflexor torque in the SCI population.[9] The lower leg and foot were secured in an isometric boot apparatus. Rubber stimulating electrodes (3cm diameter) were applied to clean abraded skin over the common peroneal nerve just distal to the proximal head of the fibula and on the anterior aspect of the leg, slightly distal to the patella. Electrodes were coated in conducting gel prior to placement on the skin and secured with tape. Muscle electrical activity was collected using two surface electromyogram (EMG) electrodes (Kendall Medi-Trace 133, Mansfield, Massachusetts, United States) placed 5cm apart on the muscle belly of the tibialis anterior. A ground electrode was secured on the lateral aspect of the lower leg, in between the stimulating and recording electrodes.

A constant current stimulator (Digitimer Ltd., Model 3072, Welwyn Garden City, Hertfordshire, England) was used to deliver single 50μsec rectangular pulses and 4 sec tetanic trains (30 Hz) to the peroneal nerve for assessment of peak evoked twitch (PT) and tetanic torque (TT), respectively. The stimulation intensity (30Hz) was selected based on the force-frequency relationship for the tibialis anterior in people with SCI previously determined in our lab (unpublished). The optimal stimulation intensity was determined for each participant by gradually increasing the current until there were no further increases in evoked twitch torque. This optimal stimulation intensity was then used throughout the fatigue protocol for both the 4 sec tetanus and single twitches.

3.3.3 Procedure

Muscle contractile properties and M-wave characteristics were assessed before, during, and after a 2 minute fatigue trial of intermittent tetanic stimulation in the SCI group, and a similar trial of intermittent MVCs in the AB group. The fatigue protocol consisted of 4 sec tetanus at 30 Hz, followed by 2 sec rest. A single muscle twitch was elicited half way through each 2 sec rest period. A 15 min recovery period followed the fatigue protocol and consisted of 17 addition twitches spaced at decreasing intervals. Specifically, the muscle contractile properties measured were peak evoked twitch (PT), maximum compound action potential amplitude (M-wave Amplitude), area (M-wave Area), and duration (M-wave duration), time to PT (TPT), maximum rate of torque development (RTD), ½ relaxation time (1/2 RT) and maximum rate for torque relaxation (RTR). A fatigue index (% decline in torque) was calculated for both the decline in PT and decline in TT or MVC, using the following formula: $(\text{Torque}_{\text{baseline}} - \text{Torque}_{2\text{min}}) / \text{Torque}_{\text{baseline}} \times 100$.

Each participant attended 2 sessions at the laboratory. The first visit served as the familiarization session, allowing the participants to experience the muscle stimulation and become comfortable with the procedures. The second visit occured approximately 1 week later and consisted of the fatigue protocol.

3.3.4 Statistical Treatment

Muscle fatigue characteristics were analyzed with a two-factor analysis of variance (ANOVA) with one between subjects factor (SCI vs. AB) and one within subjects factor (time). Significance was set at $p < 0.05$, and Tukey A post-hoc tests were used to examine significant differences between means. Throughout the text, values are reported as mean ± standard deviation (SD) and mean ± standard error (SE) in figures.

3.4 Results

3.4.1 M-wave Characteristics

M-wave amplitude was significantly greater ($p < 0.05$) in the AB group at baseline with values of 2.5 ± 1.59 mV in SCI and 5.7 ± 3.18 mV in AB. There was no significant difference in M-wave duration (34.9 ± 9.06 in SCI, 27.8 ± 7.32 in AB) or area noted between groups at baseline. In both the SCI and AB groups, M-wave amplitudes were maintained throughout the fatigue protocol and through recovery. A significantly increasing M-wave area was observed during fatigue in the SCI group. Also in the SCI group, there was a significant increase in M-wave duration over the course of recovery. These results are demonstrated in Table 2 and Figure 1.

3.4.2 Muscle Contractile Properties

Changes in muscle contractile properties from baseline through to the end of the recovery stage are depicted in Table 3. There was no significant difference in PT between groups at baseline (3.8 ± 1.80 Nm in SCI, 3.7 ± 0.59 Nm in AB), however both groups responded differently to the fatigue protocol. There was significant PT potentiation noted in the AB group (Figure 2). In contrast, despite some early potentiation of PT in the SCI group (not statistically significant), values dropped below baseline within 1 minute of the fatigue protocol and were significantly smaller at the end of fatigue. A significantly ($p < 0.05$) greater fatigue index for PT was observed in the SCI group (42.8 ± 41.27% in SCI, -13.2 ± 22.97% in AB). With regard to contractile speed, both TPT and RTD were similar between groups at baseline, however RTD slowed significanly in the SCI group over the course of fatigue (Table 3). Similarly, RTR and ½ RT were not significantly different between groups at baseline, but relaxation rates were markedly slower in the SCI group at the end of fatigue (28.9 ± 28.73 Nm/s in SCI, 71.7 ± 38.67 Nm/s in AB).

3.4.3 Summated Torque

Both groups demonstrated decreases in TT or MVC (Figure 3) from baseline to the end of the fatigue protocol, with a significantly greater fatigue index being observed in SCI compared to AB (57.2 ± 19.89% versus 22.4 ± 13.96%, respectively). Fatigue index results are shown in Figure 4. An evaluation of the twitch-tetanus ratio (Table 4) showed a signficantly greater ratio in the SCI (0.43 ± 0.23) vs. AB (0.11 ± 0.06) groups ($p < 0.01$). There was no effect of fatigue on this ratio in either group.

3.5 Discussion

The findings of this study suggest that changes in muscle excitability do not appear to be a major contributing factor to the decrease in fatigue resistance in the ankle dorsiflexors following SCI. While the SCI group displayed a greater fatigue index for both PT and TT, there was no indication of a decrease in muscle excitability as assessed by changes in M-wave amplitude or area. These findings are similar to previous work that has shown changes in M-waves to be disassociated with changes in muscle torque during fatigue in the paralyzed soleus [8] and thenar muscles. [3, 10]

M-wave amplitude was significantly greater in the AB group at all time points, which supports previous findings [3, 9, 11] and is likely a reflection of the significant muscle atrophy following SCI. The fact that M-wave amplitude and area stayed relatively constant over the course of fatigue in the SCI group suggests that the previously reported decrease in Na^+/K^+ pump concentration after SCI does not affect muscle excitability.[7] Although there was an increase in M-wave area in the SCI group, that was likely a reflection of the increase in M-wave duration rather than increased Na^+/K^+ pump activity, as there was no corresponding increase in M-wave amplitude. The increasing M-wave duration in the SCI group during fatigue and recovery is suggestive of a slowing of action potential conduction across the sarcolemma membrane. This is similar to previous work where a 40% increase in M-wave duration has been reported during a fatigue protocol in the paralyzed soleus muscle.[8]

There was no significant difference in PT between groups at baseline, which has been noted previously in the tibialis anterior. [9, 11] The maintenance of PT after SCI may be the result of increased muscle stiffness taking up a significant portion of the series elasticity in the muscle. Further evidence of the increase in muscle stiffness was seen in the increased twitch-tetanus ratio observed in the SCI group (0.43 versus 0.11). Rates of muscle contraction and relaxation were also not different between groups at baseline. This finding contradicts some previous reports of increased rates of muscle contraction and relaxation in the vastus lateralis[1] and tibialis anterior[12] muscles, however, previous work in our lab has also shown no change or a slowing of RTR and RTD in the dorsiflexor and plantarflexor muscles after SCI.[9]

As predicted, the SCI group demonstrated increased fatigue compared to the AB group with respect to summated force, with a fatigue index of 57% versus 22%, respectively. This was also true when examining the fatigue index for PT values; PT declined by 43% in the SCI group, yet increased by 13% in AB. This increased fatiguability in paralyzed muscle has been widely reported in several different muscle groups. [1-4] Based on the M-wave results of the current study, and from previous work,[8] a failure in neuromuscular propagation does not appear to play a significant role in the reduction in fatigue resistance after SCI. One mechanism that could play a possible role is the potential change in muscle oxidative capactity, which has been previously shown to decrease after SCI and has been correlated with an increase in fatiguability in the tibialis anterior [13, 14] and vastus lateralis.[15] Muscle oxidative capacity provides an indication of the potential for aerobic metabolism and is typically measured through succinate dehyrogenase (SDH) activity. Decreases in SDH activity have been noted in the tibialis anterior after SCI with a more pronounced decrease observed in type II muscle fibres.[13, 14] A decrease in skeletal muscle capillarization is another possible fatigue mechanism, as a lower capillary density and a smaller capillary-to-fibre ratio have been observed following SCI.[16] Finally, another common theory of muscle fatigue involves the impaired control of calcium (Ca^{2+}) release into the sarcoplasmic reticulum. [17, 18] Alterations in the function and concentration of Ca^{2+}ATPase have been suggested following SCI to explain the slowing of relaxation time [19] and changes in sarcoplasmic reticulum Ca^{2+}ATPase

(SERCA) isoform expression. [20] While force relaxation rates were not significantly different between SCI and AB at baseline, the SCI group displayed a slowing of RTR over the course of fatigue and which became significantly slower than AB by the end of fatigue. This slowing in relaxation rate could certainly be indicative of deficits in Ca^{2+}ATPase efficiency after SCI.

The lack of significant M-wave potentiation during the course of fatigue in either the AB or SCI group was an unexpected observation. Previous work has noted increases in both M-wave amplitude and area during periods of similar intermittent MVCs in the thenar, brachioradialis, and tibialis anterior muscles of AB individuals. [5] This potentiation is believed to be the result of increased Na^+/K^+ pump activity in response to the increased activation in the muscle.[5, 6] The absence of any significant M-wave potentiation with the current fatigue protocol may be related to the muscle group being studied; significantly greater potentiation has been observed in the thenar versus extensor digitorum brevis muscle groups.[5] The lack of potentiation may also be related to the intermittent nature of the current fatigue protocol. Potentiation of M-wave amplitude was demonstrated during continuous tetanic stimulation (15Hz or 30Hz for 1min) in the tibialis anterior in people with SCI. [11] In that study, early potentiation was noted in both SCI and AB groups, occurring earlier in AB but more pronounced in SCI.

The phenomenon of enhanced force after a brief maximal summated contraction is known as post-activation potentiation (PAP) or post-tetanic potentiation (PTP), depending on whether the stimulus is voluntary (PAP) or electrical stimulation (PTP). In the present study, there was a significant PAP observed in the AB group during the fatigue protocol that was maintained through recovery, while the SCI group demonstrated only a brief period of potentiation. Potentiation can prevail over muscle fatigue, particularly in muscles with a high percentage of type II fibers.[21, 22] This is evidently what occurred in the AB group, as PT was still potentiated at the end of the fatigue protocol (fatigue index = -13%). Although the human tibialis anterior is composed of approximately 73% slow twitch muscle fibres[23], PAP has been observed in this muscle group previously.[22] Contrary to what was expected, there was less twitch potentiation observed in the SCI compared with the AB group. Although the different fatigue protocols (electrically induced vs. voluntary) may be a contributing factor to the group differences, twitch responses have been shown to be similar regardless of fatigue method.[24] Thus, it appears paralyzed muscle is unable to maintain twitch potentiation and succumbs to fatigue sooner than AB controls during periods of intermittent maximal contraction.

One additional factor that could be contributing to changes in muscle properties after SCI may be spasticity. Spasticity is more likely to occur in muscles of the lower leg, as well, these muscles are more likely to experience more mobility and involvement in daily activities. Recently, spasticity has been shown to attenuate muscle atrophy and prevent against the accumulation of intramuscular fat following SCI. [25] Persistent spasticity may also work to prevent the predicted fibre type transformation after SCI, and this theory has been examined in the animal model. Harris et al. [26] examined muscle spasticity in the paralyzed tail muscle of adult rats and found slowing rates of muscle contraction and relaxation, suggesting a preservation or enhancement of slow twitch fibers. In addition, an increased PT and decreased TT were observed, leading to an increased twitch-tetanus ratio, yet the paralyzed muscles were still more fatiguable when compared to controls. Similarly, in the human model, Hidler et al. [27] reported a slowing of muscle contraction in participants that were highly spastic, where those that were classified as having a low amount of spasticity had the fastest rates of muscle contraction and relaxation. The lack of any group differences in RTD and RTR at baseline in the current study was unexpected given previous reports of an increase in contraction speed [12] and fibre type transformation [14] in the tibialis anterior following SCI. These earlier studies, however, did not include information on the presence or absence of spasticity in their subjects. All of the participants in the present study had upper motor neuron injuries and previous work has shown a greater amount of spasticity in participants with high (C5-C7) versus low (T12-L1) level injuries.[25] The relationship between muscle spasticity and changes in muscle contractile properties is complex and likely highly variable with each individual, warranting further investigation.

The results of this study extend the findings of increased fatiguability in paralyzed muscle following SCI to the ankle dorsiflexor muscle group. A decrease in muscle excitability does not appear to be a significant contributing factor to the decreased fatigue resistance of the tibialis anterior after SCI; the mechanisms more likely relate to changes in excitation-contraction coupling and/or muscle oxidative capacity. It is interesting to note that increases in oxidative capacity have been reported following both electrical stimulation [13, 15] and body-weight supported treadmill training, [28] suggesting that with early intervention of exercise therapy, it may be possible to prevent or minimize the decline in muscle fatiguability after SCI. Further research should look at other possible changes in muscle properties as contributors to increased fatigue after SCI and the development of effective rehabilitation strategies to preserve fatigue resistance and improve functional mobility.

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Titles and Legends to Figures

Figure 1. M-wave amplutude (A), area (B), and duration (C) during a 2 minute fatigue protocol followed by a 15 minute recovery period in AB and SCI groups. The dotted hoizontal line represents the transition between fatigue and recovery. Error bars represent SE.

Figure 2. PT from baseline, during a 2 minute fatigue and 15 minute recovery protocol in AB and SCI groups. The horizontal dotted line represents the end of the fatigue protocol. Error bars represent SE.

Figure 3. TT or MVC during a 2 minute fatigue protocol in AB and SCI groups. Error bars represent SE.

Figure 4. Fatigue index for AB and SCI groups following a 2 minute fatigue protocol. Error bars represent SE.

Figure 1.

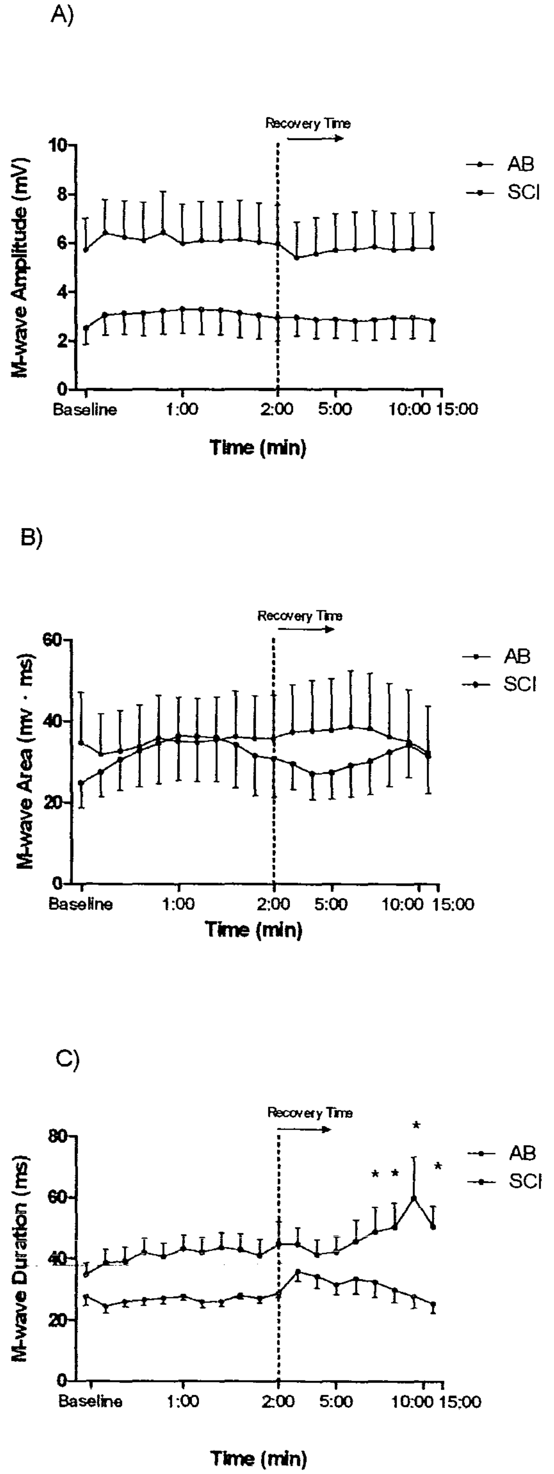
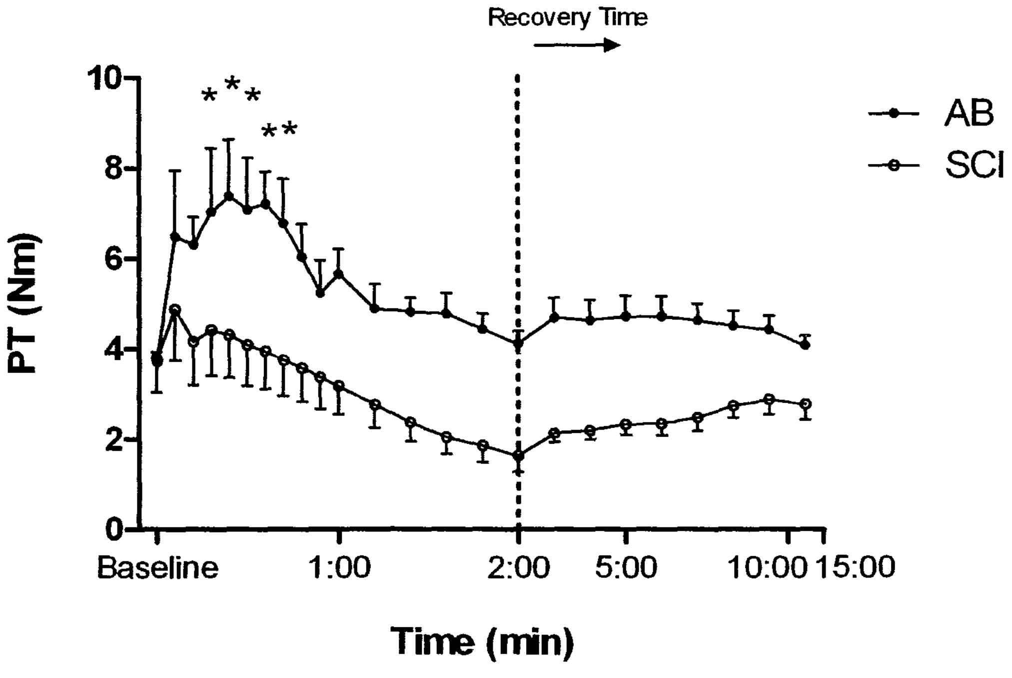

A)
Recovery Time
M-wave Amplitude (mV)
AB
SCI
Baseline
1:00
2:00
5:00
10:00
15:00
Time (min)
B)
Recovery Time
M-wave Area (mv · ms)
AB
SCI
Baseline
1:00
2:00
5:00
10:00
15:00
Time (min)
C)
Recovery Time
M-wave Duration (ms)
AB
SCI
Baseline
1:00
2:00
5:00
10:00
15:00
Time (min)

Figure 2.


Recovery Time
10
8
6
4
2
0
PT (Nm)
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AB
SCI
Baseline
1:00
2:00
5:00
10:00
15:00
Time (min)

Figure 3.

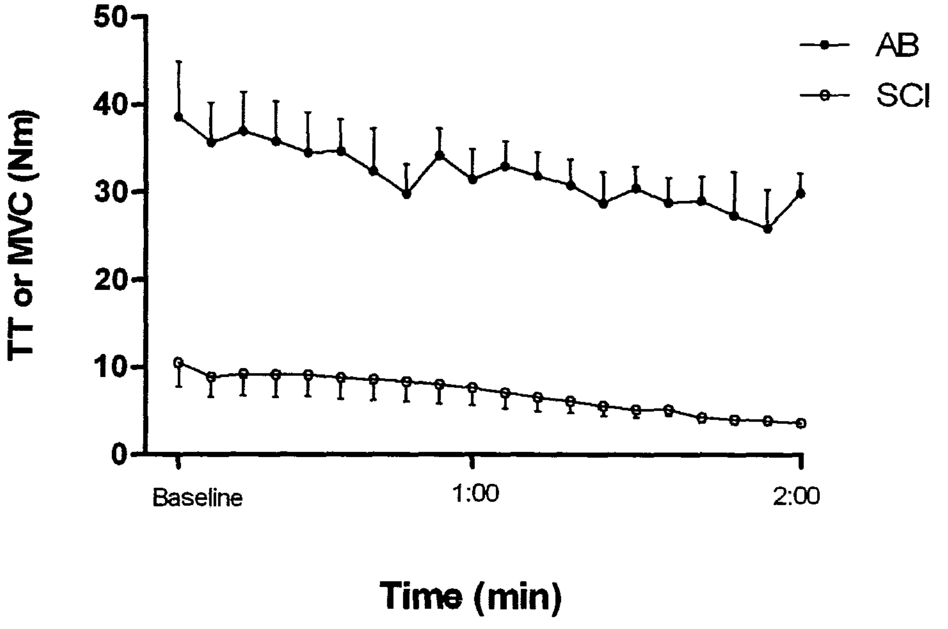

Figure 4.

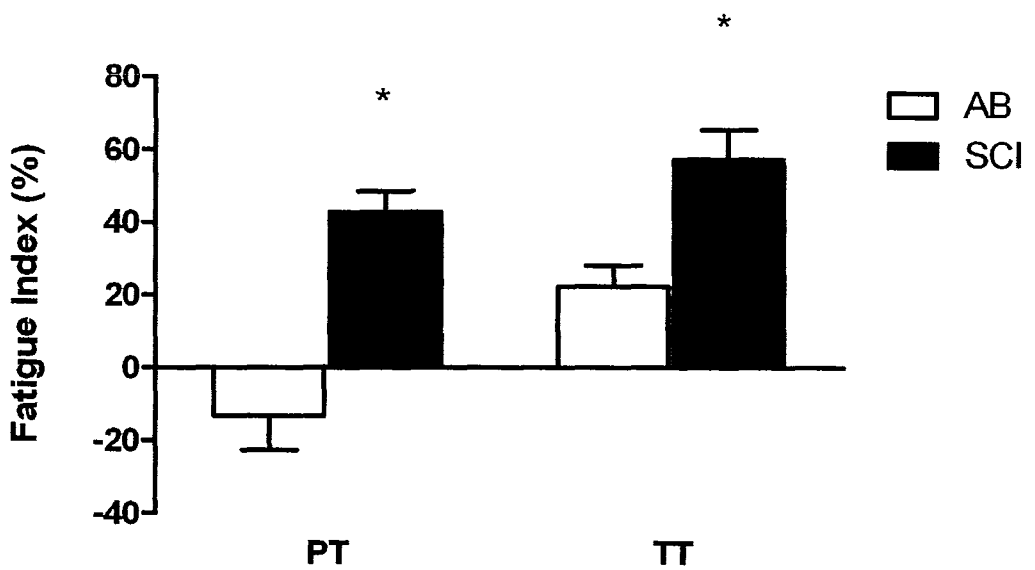

Table 1. SCI subject characteristics.

Participant	Age	Sex	ASIA Classification	Level of Injury	Years Since Injury
1	55	M	C	C3	14
2	33	M	A	C6/7	14
3	42	M	A	T7	4
4	49	M	A	C5/6/7	2
5	24	M	A	C6	1.5
6	61	F	C	T1	1.5

Table 2. M-wave characteristics through fatigue and recovery.

		Baseline	Post-fatigue	1 min Recovery	5 min Recovery	15 min Recovery
Amplitude (mV)	SCI	2.5 ± 1.6	2.9 ± 2.4	2.9 ± 1.9	2.9 ± 2.1	2.7 ± 1.9
	AB	5.7 ± 3.2	5.9 ± 3.8	5.7 ± 3.7	5.7 ± 3.6	5.9 ± 3.4
Area (mV·ms)	SCI	24.9 ± 14.8	30.8 ± 23.2	27.4 ± 15.7	32.0 ± 19.9	29.0 ± 20.6
	AB	34.8 ± 30.5	35.9 ± 26.0	37.8 ± 31.0	34.4 ± 30.4	32.5 ± 28.2
Duration (ms)	SCI	34.9 ± 9.1	44.8 ± 18.2	42.4 ± 12.1	53.9 ± 22.5*	47.3 ± 12.5*
	AB	27.8 ± 7.3	28.9 ± 3.3	31.7 ± 8.1	28.6 ± 9.8	25.5 ± 7.1

* Indicates a significant difference between groups. Values are mean ± SD

Table 3. Muscle contractile properties before and after a 2 minute fatigue protocol and during recovery.

		Baseline	Post-fatigue	1 min Recovery	5 min Recovery	15 min Recovery
PT (Nm)	SCI	3.8 ± 1.8	1.6 ± 0.9*	2.3 ± 0.6	2.7 ± 0.8	2.6 ± 0.9
	AB	3.7 ± 0.6	4.1 ± 0.7	4.7 ± 1.1	4.3 ± 0.7	3.7 ± 0.5
RTD (Nm/s)	SCI	116.6 ± 38.5	67.4 ± 55.4*	94.9 ± 55.0	93.4 ± 50.9	89.0 ± 34.1
	AB	135.2 ± 83.4	178.2 ± 2.5	185.7 ± 4.9	164.5 ± 89.0	128.9 ± 67.3
RTR (Nm/s)	SCI	42.2 ± 18.9	28.9 ± 28.7	35.1 ± 35.9	39.2 ± 33.0	41.9 ± 35.8
	AB	50.0 ± 48.5	71.7 ± 38.7	54.9 ± 29.2	74.0 ± 52.1	67.1 ± 39.8
TPT (ms)	SCI	96.2 ± 26.2	140.7 ± 67.1	119.9 ±59.5	126.0 ± 72.0	107.0 ± 57.0
	AB	94.7 ± 17.7	87.9 ± 18.2	119.8 ± 20.6	115.2 ± 24.5	100.3 ± 18.4
½ RT (ms)	SCI	108.0 ± 28.3	178.2 ± 28.2	145.7 ± 27.5	149.9 ± 35.5	143.7 ± 54.2
	AB	87.0 ± 13.0	110.2 ± 41.4	110.0 ± 13.2	104.2 ± 25.1	88.7 ±18.3
TT or MVC	SCI	10.5 ± 6.6	3.6 ±1.1	-	-	-
(Nm)	AB	38.6 ± 15.6	29.8 ± 5.5	-	-	-

* Indicated a signficant difference between groups. Values are mean ± SD

Table 4. Twitch:tetanus ratio for SCI and AB groups before and after 2 min fatigue protocol.

	Pre-Fatigue	Post-Fatigue
SCI	0.43 ± 0.23*	0.43 ± 0.20*
AB	0.11 ± 0.06	0.14 ± 0.03

* Indicates a significant difference between groups. Values are mean ± SD

Chapter IV: Summary

The studies presented here have attempted to expand the existing body of knowledge on the changes in muscle structure and function after SCI; with an examination of the length-tension relationship and muscle fatigue characteristics. There has been no comprehensive assessment of the length-tension relationship of ankle muscles after SCI and assuming there is no change from AB muscle may be providing misleading information during the assessment of contractile properties. The current study identified optimal angles for PT and TT in the DF and PF muscle groups and showed a significant shift in the length-tension relationship in the PF, but not DF muscle groups, confirming previous reports (McDonald et al., 2005). Decreased fatigue resistance is a well established adaptation after SCI, although the mechanism remains elusive. The present study confirmed these findings and further determined that a decrease in muscle excitability and Na^+/K^+ concentration after SCI is not a significant contributing factor, which supports previous work (Shields, 1998).

Changes in the length-tension relationship in both the dorsiflexor and plantarflexor muscle groups were examined by eliciting a single muscle twitch and either a 0.5 sec tetanus at 80Hz (SCI) or MVC (AB) at 9 angles ranging from 20^0 DF to 20^0 PF. Results indicated no change in the length-tension relationship or optimal angle for force production in the dorsiflexor muscle group after SCI, while there was a shift towards shorter optimum angles after SCI in the plantarflexors. The optimal angle for dorsiflexor PT was found to be 20^0 PF in both groups; with no significant difference in PT noted (3.4 ± 1.1 in SCI, 3.8 ± 1.4 in AB). In the plantarflexors, the optimal angle was found to be smaller in the SCI group (5^0 DF and 15^0 DF, respectively). There was also significantly smaller M-wave amplitude in both muscle groups observed in the participants with SCI. DF rates of muscle contraction and relaxation were found not to differ between AB and SCI, while the PF were found to contract and relax slower after SCI. There was also an increased twitch-tetanus ratio noted in both the DF (0.36 versus 0.09) and PF (0.34 versus 0.19) muscle groups. The twitch-tetanus ratio was found to increases in the DF muscle with increasing muscle length in the SCI group only.

The findings of this study suggest that there is shortening of the PF muscles after SCI, while the DF muscle group maintains length-tension properties. Further, the increase in the twitch-tetanus ratio in both muscle groups suggests stiffening of muscle tissue after SCI, which was particularly apparent in the DF muscles. The results of this study suggest that the PF muscle group may be placed in a shortened position, possibly due to wheelchair positioning and this may alter the structure and force-generating capacity of these muscles (soleus, gastrocnemius etc.).

The potential role of the decreased Na^+/K^+ pump concentration after SCI (Ditor et al., 2004) in muscle fatigue was examined by recording changes in M-wave amplitude and area during a 2 minute protocol of intermittent tetanic stimulation (4 sec burst, 2 sec rest) at 30Hz. A single twitch was elicited during the 2 sec rest for examination of twitch contractile properties. Similar to the previous study; MVCs were used in lieu of tetanic stimulation in the AB group. The results confirmed previous reports of increased fatiguability after SCI, with summated force fatigue index values of 57% and 22% in SCI and AB, respectively. Twitch fatigue index values were 43% in SCI and -13% in AB, indicating the significant potentiation of PT seen in the AB group. M-wave amplitude and area were not found to change in either group during fatigue or recovery, while M-wave duration was found to increase with fatigue in the SCI group only. RTD and RTR were not found to differ between groups at baseline, however, both slowed with fatigue in the SCI group.

Although both of these studies examined different muscle properties, there were some similarities noted in the findings. First, in both studies the PT of the tibialis anterior (dorsiflexor) was found to be similar between SCI and AB. This may be due to increased muscle stiffness and passive tension which can be further supported by the increased twitch-tetanus ratio seen in both studies. Although the current study did not explore possible mechanisms for this increase in muscle stiffness, it may be due to a decrease in the series elastic component. An increase in passive tension has been previously reported in paralyzed muscle, and is particularly apparent at longer muscle lengths in individuals with spasticity (Olsson et al., 2002). This increase in passive tension may serve to enhance PT, while not affecting tetanic force. Further, a high amount of spasticity in our group of participants may help to explain the lack of observable change, or slowing rates of muscle contraction and relaxation. This is contrary to many previous reports and to the predicted transformation to faster type II muscle fibres after SCI. Some papers have indicated that the preservation of MHC 1 isoforms is possible in some participants (Gerrits et al. 2003) and muscle spasticity has been suggested as a significant contributor to the maintenance of muscle properties after SCI (Hidler et al, 2002, Harris 2006). All of our participants had upper motor neuron injuries, and previous reports have shown a greater amount of spasticity to occur in individuals with high versus low SCI (Gorgey and Dudley, 2008). Another common finding is a decrease in M-wave amplitude after SCI in both muscle groups examined. This likely represents the significant muscle atrophy after SCI, as it would indicate fewer motor units. This has been observed previously in the thenar (Thomas et al., 1997), tibialis anterior (Rodrigues, 2007), and soleus muscles (Rodrigues, 2007; Shields et al., 1998).

The two studies presented here examining the length-tension relationship and fatigue characteristics provide information on changes to skeletal muscle properties after SCI. While we have not conducted any intervention or training study, previous work has shown improvements in muscle fatigue resistance, maintenance of type I muscle fibres, and increases in muscle mass after electrical stimulation training protocols (Gerrits et al., 2003; Martin et al., 2002) . Future work should examine the regular use of these programs in the rehabilitation after SCI as well as the long term benefits to muscle structure and function. Also, the apparent increase in muscle stiffness should be further explored, examining issues of a declining series elastic component and increased accumulation of intramuscular fat. The cause for the decrease in fatigue resistance after SCI should also be identified further exploring other possibilities such as a decrease in oxidative capacity, blood flow, and Ca^{2+} handling.

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Appendix A: Participant Information Letter and Consent Form

Chapter II: The Length-Tension Relationship of Human Dorsiflexor and Plantarflexor Muscles Following Spinal Cord Injury

Participant Information Letter

The Length-Tension Relationship in Human Dorsiflexor and Plantarflexor Muscles Following Spinal Cord Injury

You are invited to participate in a research study conducted by:

Student Investigators: **Chelsea Pelletier**
Graduate Student
Department of Kinesiology
McMaster University
(905) 525-9140 ext. 26086
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Principal Investigator: **Dr. Audrey Hicks**
Department of Kinesiology
McMaster University
Hamilton, Ontario, Canada
(905) 525-9140 ext. 24643

What is the purpose of this study?

In this study, we are hoping to gain a better understanding of the changes in muscle following spinal cord injury. We are going to measure the strength of two muscles in your lower leg, while your ankle is placed in different positions. While the effect that ankle angle and muscle length have on muscle strength is known in the able-bodied population, it is unknown in paralyzed muscles. This information will be important for future studies on how muscles function and may contribute towards improved rehabilitation methods. We are also interested in determining the potential effect of leg muscle spasticity on muscle properties following spinal cord injury.

What will my responsibilities be if I participate in this study?

If you participate in this study, you will be asked to come to McMaster University for two visits. During the first visit, you will be shown the equipment that will be needed to measure muscle contractile properties. You will also become familiar with the sensations felt during muscle stimulation. While sitting in a chair, your right foot will be secured on a metal plate with a velcro strap. Electrodes will be placed on your knee and lower leg. The electrodes will cause your lower leg muscles to twitch. This first visit will allow us to find the ideal placement of the electrodes. We will also administer a questionnaire, which consists of 35 questions pertaining to the impact of spasticity on your daily functioning. This questionnaire will take approximately 7 minutes to complete. The questionnaire will ask you whether spasticity has affected such things as how you eat, sleep, dress, and shower, etc. It will also ask whether spasticity symptoms have affected your sex life, your concerns about falling, about getting injured or injuring others.

The second visit will be the experimental session. The electrodes will be placed in the same locations. Your ankle will be moved to various angles in 5^0 increments. At each position, a muscle contraction will be elicited with a single simulation as well as multiple stimulations occurring very close together. The length of stimulation will never be longer than 0.5 second. The electrical activity caused by the twitch will be recorded by one of the electrodes. Both visits will take place in the Ivor Wynne Centre (IWC), McMaster University. Each visit will take up to an hour.

What are the possible risks or discomforts?

If you have some sensation in your legs, the gel placed on the electrodes might feel cold when applied to your skin and you may feel some temporary discomfort when your muscles are stimulated. This discomfort is brief and will last only while your muscle is being stimulated, approximately ½ of a second. The stimulation of your muscle may also induce a spasm/clonus. While there is no danger with these spasms, the test will be stopped until they go away. Please take this into consideration when deciding whether you want to go ahead with the testing. Also, please remember that it is your right to stop the testing or withdraw from the study at any point you wish. There are no physical risks to answering the questionnaire, but there is a possibility that some of the questions may cause you to reflect on symptoms that may cause some anxiety. If this occurs, you will be provided with information/resources to help you cope with these feelings.

What are the possible benefits for me or society?

This research will not benefit you directly. However, when the study is over, you will have access to your results. Your results may provide you with information on your muscle function. We hope that this study will help us to understand more about muscle force generation and limitations after a spinal cord injury. This information could help with future rehabilitation programs.

Will there be any payment or reimbursement if I participate in this study?

If you agree to take part in this study, we will reimburse you for parking or transportation costs.

What information will be kept private?

Your data will not be shared with anyone, except with your consent. The information obtained by me will be kept in a locked cabinet. All personal information such as your name, address and phone number will be kept separate from the data. Your data will be linked to a number. The list linking your number and name, with your personal information, will be kept separate from the data in a secure place. If the results are published, no names or identifying information will be released or published without your specific consent to the disclosure.

What if I change my mind about participating in the study?

Your participation in this study is voluntary. If you volunteer to be in this study, you may withdraw at any time, even after signing the consent form or part-way through the study, including during the familiarization or testing session. In cases of withdrawal your data will be destroyed unless you indicate otherwise. The investigator may withdraw you from this research if circumstances arise which warrant doing so. Your decision whether or not to participate will not affect your continuing access to services at the McMaster Centre for Health Promotion and Rehabilitation.

Will I find out about the study results?

You may obtain information about the results of the study by contacting Chelsea Pelletier by phone, email or in person. The results will be presented to you in the form of a written summary. This summary will include a brief explanation of the results as well as conclusions drawn and will be available August 2008 approximately.

Can I get more information about participating as a study subject?

If you have questions or require more information about the study itself, please contact Chelsea Pelletier by phone or email. Heather McCarrel will be administering and evaluating the questionnaire data as part of a summer research project, and she can be contacted by email. The information mentioned above will be discussed and all questions clarified prior to any involvement in the study.

This study has been reviewed and approved by the McMaster Research Ethics Board. If you have concerns or questions about your rights as a participant or about the way the study is conducted, you may contact:

McMaster Research Ethics Board Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Office of Research Services
E-mail: ethicsoffice@mcmaster.ca

CONSENT

I have read the information presented in the information letter about a study being conducted by Chelsea Pelletier, of McMaster University. I have had the opportunity to ask questions about my involvement in this study, and to receive any additional details I wanted to know about the study. I understand that I may withdraw from the study at any time, if I choose to do so, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Participant

____

Signature of Participant

In my opinion, the person who has signed above is agreeing to participate in this study voluntarily, and understands the nature of the study and the consequences of participation in it.

____

Signature of Researcher or Witness

Chapter III: Muscle Fatigue Characteristics of the Paralyzed Tibialis Anterior after Spinal Cord Injury

Participant Information Letter

Muscle Excitability and Fatigue Following Spinal Cord Injury

You are invited to participate in a research study conducted by:

Student Investigator: **Chelsea Pelletier**
Graduate Student
Department of Kinesiology
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Principal Investigator: **Dr. Audrey Hicks**
Department of Kinesiology
McMaster University
Hamilton, Ontario, Canada
(905) 525-9140 ext. 24643

What is the purpose of this study?

In this study, we are hoping to gain a better understanding of the changes in muscle following spinal cord injury. We are going to measure electrical changes in your lower leg muscles during and after a period of alternating muscle contraction and rest. This information will be important by providing information on the causes of muscle fatigue after SCI and may contribute towards improved rehabilitation methods.

What will my responsibilities be if I participate in this study?

If you participate in this study, you will be asked to come to McMaster University for three visits. During the first visit, you will be shown the equipment that will be needed to measure muscle contractile properties. You will also become familiar with the sensations felt during muscle stimulation. While sitting in a chair, your right foot will be secured on a metal plate with a velcro strap. Electrodes will be taped on to your knee and lower leg. The electrodes will cause your lower leg muscles to contract. This first visit will allow us to find the ideal placement of the electrodes.

The second and third visits will be the experimental sessions. The electrodes will be placed in the same locations. We will conduct two trials, one per session; the first one with the muscles on your shin, the second with the muscles of your calf. The trials will be

2 minutes in length and will consist of 4 sec of contraction from electrical stimulation followed by 2 sec rest. In the rest period a single muscle twitch will be elicited. There will be a total of 20 muscle contractions and 20 twitches. Following the 2-minute protocol your muscle activity will be assessed during a 15-minute recovery period. During the recovery period there will be a total of 15 additional twitches to your muscle at various intervals. Both visits will take place in the Ivor Wynne Centre (IWC), McMaster University. Each visit will take approximately 30 mins.

What are the possible risks or discomforts?

If you have sensation in your legs, you may feel some temporary discomfort when your muscles are stimulated; the degree of discomfort or pain associated with the stimulation varies between individuals and depends on the degree of sensation in your lower legs. This discomfort is brief and will last only while your muscle is being stimulated. The stimulation of your muscle may also induce a spasm/clonus. While there is no danger with these spasms, the test will be stopped until they go away. Please take this into consideration when deciding whether you want to go ahead with the testing. The gel placed on the electrodes might feel cold when applied to your skin.

What are the possible benefits for me or society?

This research will not benefit you directly. However, when the study is over, you will have access to your results. Your results may provide you with information on your muscle function. We hope that this study will help us to understand more about muscle fatigue and limitations after a spinal cord injury. This information could help with future rehabilitation programs.

Will there be any payment or reimbursement if I participate in this study?

If you agree to take part in this study, we will reimburse you for parking or transportation costs.

What information will be kept private?

Your data will not be shared with anyone, except with your consent. The information obtained by me will be kept in a locked cabinet. All personal information such as your name, address and phone number will be kept separate from the data. Your data will be linked to a number. The list linking your number and name, with your personal information, will be kept separate from the data in a secure place. If the results are published, no names or identifying information will be released or published without your specific consent to the disclosure.

What if I change my mind about participating in the study?

Your participation in this study is voluntary. If you volunteer to be in this study, you may withdraw at any time, even after signing the consent form or part-way through the study, including during the familiarization or testing session. In cases of withdrawal your data will be destroyed unless you indicate otherwise. The investigator may withdraw you from this research if circumstances arise which warrant doing so, such as sustained muscle spasm or discomfort. Your decision whether or not to participate will not affect your continuing access to services at the McMaster Centre for Health Promotion and Rehabilitation.

Will I find out about the study results?

You may obtain information about the results of the study by contacting Chelsea Pelletier by phone, email or in person. The results will be presented to you in the form of a written summary. This summary will include a brief explanation of the results as well as conclusions drawn and will be available August 2009 approximately.

Can I get more information about participating as a study subject?

If you have questions or require more information about the study itself, please contact Chelsea Pelletier by phone or email. The information mentioned above will be discussed and all questions clarified prior to any involvement in the study.

This study has been reviewed and approved by the McMaster Research Ethics Board. If you have concerns or questions about your rights as a participant or about the way the study is conducted, you may contact:

McMaster Research Ethics Board Secretariat
Telephone: (905) 525-9140 ext. 23142
c/o Office of Research Services
E-mail: ethicsoffice@mcmaster.ca

CONSENT

I have read the information presented in the information letter about a study being conducted by Chelsea Pelletier, of McMaster University. I have had the opportunity to ask questions about my involvement in this study, and to receive any additional details I wanted to know about the study. I understand that I may withdraw from the study at any time, if I choose to do so, and I agree to participate in this study. I have been given a copy of this form.

____

Name of Participant

____

Signature of Participant

In my opinion, the person who has signed above is agreeing to participate in this study voluntarily, and understands the nature of the study and the consequences of participation in it.

____

Signature of Researcher or Witness

Appendix B: ANOVA Tables

Chapter II: The Length-Tension Relationship of Human Dorsiflexor and Plantarflexor Muscles Following Spinal Cord Injury

n = 7
1 = between factor = group (SCI vs. AB)
2 = within factor = angle (20^0 DF – 20^0PF)
Bold values represent statistical significance ($p < 0.05$)

Peak Twitch Torque (PT)

DF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	3.50	12	6.94	0.51	0.49
2	**8**	**20.69**	**96**	**0.33**	**63.22**	**0.00**
1x2	8	0.22	96	0.33	0.68	0.71

PF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**2265.60**	**12**	**54.96**	**41.22**	**0.00**
2	**8**	**177.08**	**96**	**1.96**	**90.39**	**0.00**
1x2	**8**	**31.59**	**96**	**1.96**	**16.13**	**0.00**

Summated Force Torque (TT or MVC)

DF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**20141.34**	**12**	**243.91**	**82.57**	**0.00**
2	**8**	**600.97**	**96**	**12.29**	**48.87**	**0.00**
1x2	**8**	**129.42**	**96**	**12.29**	**10.52**	**0.00**

PF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**133457.6**	**12**	**7108.16**	**18.78**	**0.00**
2	**8**	**4162.4**	**96**	**212.31**	**19.61**	**0.00**
1x2	**8**	**2215.3**	**96**	**212.31**	**10.43**	**0.00**

M-wave Amplitude

DF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**510.60**	**11**	**59.22**	**8.63**	**0.01**
2	8	2.03	88	1.09	1.86	0.08
1x2	**8**	**5.52**	**88**	**1.09**	**2.31**	**0.03**

* one SCI participant was removed from this analysis due to problems recording M-wave data

PF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**6722.79**	**11**	**139.97**	**48.03**	**0.00**
2	**8**	**10.16**	**88**	**1.22**	**8.33**	**0.00**
1x2	**8**	**11.18**	**88**	**1.22**	**9.16**	**0.00**

* one SCI participant was removed from this analysis due to problems recording M-wave data

½ RT

DF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	1177.85	12	1077.06	1.09	0.32
2	**4**	**1259.66**	**48**	**132.01**	**9.54**	**0.00**
1x2	**4**	**506.36**	**48**	**132.01**	**3.84**	**0.00**

* some angles been removed from analysis due to problems generating full muscle twitches at short muscle lengths in the SCI group

PF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	12366.89	12	2642.21	4.68	0.051
2	**8**	**1976.63**	**96**	**696.87**	**2.84**	**0.01**
1x2	8	556.40	96	696.87	0.80	0.61

RTD

DF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	984.53	12	5952.98	0.17	0.69
2	**4**	**6070.81**	**48**	**258.84**	**23.45**	**0.00**
1x2	**4**	**1619.49**	**48**	**258.84**	**6.26**	**0.00**

* some angles have been removed from analysis due to problems generating full muscle twitches at short muscle lengths in the SCI group

PF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**425718.7**	**12**	**55870.54**	**7.62**	**0.02**
2	**8**	**118817.4**	**96**	**2322.69**	**51.16**	**0.00**
1x2	**8**	**9998.7**	**96**	**2322.69**	**4.30**	**0.00**

RTR

DF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	147.15	12	837.51	0.18	0.68
2	4	251.88	48	108.39	2.32	0.07
1x2	4	155.06	48	108.39	1.43	0.24

PF

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**65643.56**	**12**	**6443.41**	**10.19**	**0.01**
2	**8**	**10381.81**	**96**	**391.91**	**26.49**	**0.00**
1x2	**8**	**1030.26**	**96**	**391.91**	**2.63**	**0.01**

Chapter III: Muscle Fatigue Characteristics of the Paralyzed Tibialis Anterior after Spinal Cord Injury

n = 6
1= between subject factor = group (SCI vs. AB)
2 = within subject factor = time

Bold values indicate statistical significance ($p < 0.05$)

PT

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**571.05**	**10**	**20.66**	**27.64**	**0.00**
2	**37**	**9.18**	**370**	**1.51**	**6.07**	**0.00**
1x2	37	1.15	370	1.51	0.76	0.85

PT- Fatigue Only

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	176.75	10	42.05	4.20	0.07
2	**10**	**5.84**	**100**	**1.36**	**4.30**	**0.00**
1x2	**10**	**2.73**	**100**	**1.36**	**2.0**	**0.04**

TT or MVC

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**42808.49**	**9**	**365.71**	**117.06**	**0.00**
2	**19**	**106.25**	**171**	**9.07**	**11.71**	**0.00**
1x2	**19**	**106.25**	**171**	**9.07**	**2.04**	**0.01**

RTD

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**1598877**	**10**	**247425.4**	**6.46**	**0.03**
2	**37**	**19486**	**370**	**3687.5**	**5.28**	**0.00**
1x2	**37**	**6587**	**370**	**3687.5**	**1.79**	**0.00**

RTR

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	160370.1	10	38604.36	4.15	0.07
2	**37**	**1225.3**	**370**	**346.81**	**3.53**	**0.00**
1x2	37	444.7	370	346.81	1.28	0.13

M-wave Amplitude

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	972.08	10	349.57	2.78	0.13
2	**37**	**0.5728**	**370**	**0.2023**	**2.83**	**0.00**
1x2	37	0.1280	370	0.2023	0.63	0.95

M-wave Area

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	1	1544.90	10	23058.89	0.67	0.80
2	37	36.93	370	28.28	1.31	0.12
1x2	**37**	**44.97**	**370**	**28.28**	**1.59**	**0.02**

M-wave Duration

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**25728.06**	**10**	**3190.18**	**8.06**	**0.02**
2	**37**	**108.23**	**370**	**43.00**	**2.52**	**0.00**
1x2	37	56.60	370	43.00	1.32	0.11

M-wave Duration – Recovery Only

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**12512.97**	**10**	**2384.73**	**5.25**	**0.04**
2	16	32.31	160	41.27	0.78	0.70
1x2	**16**	**111.04**	**160**	**41.27**	**2.69**	**0.00**

Twitch-tetanus Ratio

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**0.549**	**10**	**0.19**	**28.74**	**0.00**

Fatigue Index

PT

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**9415.84**	**10**	**1115.32**	**8.44**	**0.01**

TT or MVC

Effect	df Effect	MS Effect	df Error	MS Error	F	P-level
1	**1**	**6206.66**	**10**	**806.41**	**7.69**	**0.02**

Appendix C. Raw Data

Chapter II: The Length-Tension Relationship of Human Dorsiflexor and Plantarflexor Muscles Following Spinal Cord Injury

AB – DF

	Participant	PT	TPT	1/2RT	RTD	RTD	M-wave	TT	IT
20DF	1	0.16	73.50	52.75	14.57	-16.81	1.81	20.35	-0.02
	2	0.34	35.25	31.25	25.41	-100.61	7.25	11.79	0.04
	3	0.38					4.66	10.79	-0.03
	4	0.48	70.00	38.25	20.92	-16.44	5.36	27.77	0.24
	5	1.36	210.75	68.25	49.32	-34.33	12.60	28.03	-0.17
	6	0.07					13.00	20.53	
	7	0.01					12.70	9.89	0.09
	MEAN	0.40	97.38	47.63	27.56	-42.05	8.20	18.45	0.03
	SD	0.46	77.53	16.41	15.18	39.92	4.56	7.78	0.14
15DF	1	0.66	155.25	73.25	23.54	-15.69	1.61	23.47	0.07
	2	1.91	58.50	149.50	33.63	-141.43	6.72	15.96	-0.04
	3	0.02					4.26	14.56	0.03
	4	0.66	72.25	40.00	21.30	-19.06	5.29	33.35	0.16
	5	1.49	87.50	51.50	36.99	-30.64	12.10	18.15	0.01
	6	0.01					10.60	22.82	
	7	0.01					9.87	16.46	0.05
	MEAN	0.68	93.38	78.56	28.87	-51.71	7.21	20.68	0.05
	SD	0.76	42.92	49.26	7.62	60.16	3.80	6.54	0.07
10DF	1	0.54	80.25	55.50	18.31	-17.94	1.74	30.38	0.02
	2	1.27	30.25	56.75	38.86	-44.46	6.48	25.47	-0.01
	3	1.14	62.25	33.75	35.12	-46.33	6.05	15.43	0.02
	4	0.47	73.75	33.50	23.54	-18.31	5.47	38.57	-0.25
	5	2.15	86.50	53.00	51.94	-36.62	11.10	30.17	-0.10
	6	0.04					7.37	27.98	
	7	0.17	17.50	22.50	22.79	-23.91	6.59	17.22	0.05
	MEAN	0.83	58.42	42.50	31.76	-31.26	6.40	26.46	-0.05
	SD	0.74	28.22	14.42	12.63	12.88	2.76	8.02	0.11
5DF	1	1.10	84.25	53.00	28.02	-21.30	1.67	35.54	-0.02
	2	3.53	52.00	65.25	106.12	-60.53	6.08	31.43	0.21
	3	2.02	72.50	46.25	63.89	-47.83	6.18	21.25	0.03
	4	1.85	57.50	49.00	54.18	-40.73	4.27	40.13	0.01
	5	1.76	83.25	44.25	65.76	-37.74	11.40	39.19	-0.08
	6	0.09					7.12	33.19	
	7	0.27					7.22	21.82	0.04
	MEAN	1.52	69.90	51.55	63.59	-41.63	6.28	31.79	0.03
	SD	1.17	14.71	8.33	28.14	14.36	2.98	7.65	0.10

	Participant	PT	TPT	1/2RT	RTD	RTD	M-wave	TT	IT
0	1	1.48	82.25	65.50	39.98	-21.67	1.98	43.18	-0.01
	2	3.51	58.75	77.00	103.50	-49.32	5.91	31.95	0.00
	3	1.25	72.75	42.25	53.06	-28.40	6.17	26.34	-0.02
	4	2.04	102.25	46.25	65.02	-39.61	3.71	39.14	0.00
	5	2.54	86.00	60.50	63.89	-38.86	11.80	51.47	-0.06
	6	0.25					10.00	34.92	
	7	0.07					10.20	26.83	0.12
	MEAN	1.59	80.40	58.30	65.09	-35.57	7.11	36.26	0.01
	SD	1.23	16.12	14.22	23.73	10.73	3.65	9.09	0.06
5PF	1	1.59	82.50	69.25	37.37	-24.66	2.15	43.83	-0.08
	2	4.73	78.25	69.25	148.34	-54.18	4.89	39.13	-0.03
	3	2.95	73.50	62.00	83.70	-44.84	5.82	28.42	-0.12
	4	2.27	63.75	54.00	79.96	-38.86	4.84	40.83	0.17
	5	2.38	79.00	54.25	82.95	-41.10	12.80	46.24	0.10
	6	0.45	69.75	34.25	27.28	-25.03	7.17	41.00	
	7	1.35	82.00	53.75	43.72	-36.99	5.53	28.95	-0.12
	MEAN	2.25	75.54	56.68	71.90	-37.95	6.17	38.34	-0.01
	SD	1.36	6.91	12.04	41.12	10.54	3.29	6.99	0.12
10PF	1	2.01	83.00	69.50	51.19	-31.76	2.16	45.99	0.07
	2	5.27	79.00	73.00	139.75	-58.29	4.61	44.84	-0.05
	3	3.38	80.25	65.00	79.21	-42.22	4.70	34.19	-0.02
	4	2.70	67.00	56.25	96.40	-38.86	4.42	42.80	0.11
	5	3.54	80.00	67.25	93.79	-49.32	13.40	49.77	0.09
	6	0.54	88.75	50.25	20.92	-17.94	6.78	39.89	
	7	1.61	68.50	56.25	41.85	-33.25	6.87	38.15	-0.09
	MEAN	2.72	78.07	62.50	74.73	-38.81	6.13	42.23	0.02
	SD	1.53	7.77	8.33	40.02	13.02	3.58	5.24	0.08
15PF	1	2.13	87.25	71.75	53.81	-29.52	2.26	47.42	-0.09
	2	4.94	84.50	73.75	123.31	-50.07	4.21	41.71	-0.10
	3	3.66	84.50	75.25	96.03	-43.34	4.22	37.23	-0.09
	4	3.29	65.25	62.75	99.39	-46.71	3.68	39.53	-0.34
	5	4.30	79.75	73.50	136.38	-53.43	13.30	51.36	-0.08
	6	1.06	80.50	76.50	42.97	-17.94	6.48	45.27	
	7	2.07	78.25	64.50	57.17	-31.39	5.96	38.41	0.07
	MEAN	3.06	80.00	71.14	87.01	-38.91	5.73	42.99	-0.11
	SD	1.37	7.23	5.37	36.34	12.91	3.62	5.21	0.13
20PF	1	2.23	84.25	89.25	55.67	-31.76	2.43	47.10	-0.03
	2	5.93	86.25	80.50	162.16	-57.92	4.00	40.44	0.15
	3	4.30	83.25	87.75	107.99	-44.84	3.82	37.07	-0.09
	4	3.40	64.75	62.25	108.36	-46.33	4.11	38.78	0.34
	5	5.27	84.00	77.25	155.81	-52.68	13.40	57.73	0.04
	6	2.46	81.50	77.00	60.16	-35.12	5.55	44.62	
	7	2.97	75.00	81.00	104.62	-41.48	5.87	36.89	0.04
	MEAN	3.79	79.86	79.29	107.82	-44.30	5.60	43.23	0.08
	SD	1.42	7.56	8.90	41.35	9.22	3.63	7.45	0.15

SCI – DF

	Participant	PT	TPT	1/2Rt	mxRTD	mxRTR	M-wave	tetT	mxRTD	mxRTR
20DF	1	0.09					2.16	3.65	59.04	-30.27
	2	0.03					4.39	0.78	75.48	-67.26
	3	0.01					1.50	0.37	50.07	-42.97
	4	0.19						4.58	54.18	-71.37
	5	0.91					3.14	3.52	115.83	-90.80
	6	0.06					1.44	7.57	181.59	-205.13
	7	0.10					1.13	0.01	102.01	-78.09
	MEAN	0.20					2.29	2.93	91.17	-83.70
	SD	0.32					1.25	2.73	46.97	57.39
15DF	1	0.15	34.25	42.50	21.67	-13.08	2.14	3.78	60.91	-38.11
	2	0.03					3.99	0.01	75.10	-60.53
	3	0.02					1.09	1.06	35.12	-25.41
	4	0.12						4.75	48.57	-74.36
	5	0.15						3.23	60.53	-38.49
	6	0.17					2.59	10.82	153.20	-157.68
	7	0.03					0.94	0.59	72.49	-67.63
	MEAN	0.10	34.25	42.50	21.67	-13.08	2.15	3.46	72.27	-66.03
	SD	0.07					1.24	3.69	38.22	44.14
10DF	1	0.14	36.00	34.25	30.64	-45.96	2.14	2.54	58.29	-20.92
	2	0.34					3.69	3.87	133.77	-59.78
	3	0.02					1.78	2.58	48.95	-37.37
	4	0.18						5.59	51.19	-85.19
	5	1.01	50.75	50.75	35.50	-49.70	2.89	6.78	124.43	-91.17
	6	0.56	26.25	20.00	45.59	-44.09	1.42	12.57	182.72	-182.34
	7	0.21					0.89	1.51	105.37	-73.98
	MEAN	0.35	37.67	35.00	37.24	-46.58	2.14	5.06	100.67	-78.68
	SD	0.34	12.33	15.39	7.63	2.86	1.02	3.79	50.55	52.23
5DF	1	0.98	73.50	99.75	42.60	-16.07	2.11	4.96	92.67	-65.76
	2	0.01					4.05	9.45	163.66	-105.00
	3	0.09					1.68	4.22	70.25	-51.56
	4	0.43	40.00	23.25	32.51	-23.17		5.51	50.07	-86.31
	5	1.69	61.25	56.50	43.34	-33.25	3.31	9.72	138.62	-103.13
	6	2.24	52.00	37.50	83.32	-57.92	2.08	15.72	202.15	-204.01
	7	1.60	38.50	49.25	95.28	-42.22	0.97	3.54	116.21	-49.70
	MEAN	1.01	53.05	53.25	59.41	-34.53	2.37	7.59	119.09	-95.07
	SD	0.87	14.74	28.88	27.94	16.41	1.12	4.34	53.42	53.10

	Participant	PT	TPT	1/2Rt	mxRTD	mxRTR	M-wave	tetT	mxRTD	mxRTR
0	1	1.42	75.50	113.25	50.82	-22.05	2.17	5.83	89.30	-37.37
	2	0.66	20.75	23.50	55.67	-38.11	3.98	13.98	153.57	-180.85
	3	0.47	56.25	35.00	25.41	-19.06	1.53	5.58	75.48	-59.41
	4	0.76	49.25	44.25	34.75	-21.30		5.47	56.80	-73.98
	5	1.74	59.25	52.75	57.17	-57.92	3.63	11.23	126.67	-106.86
	6	2.82	61.00	41.00	87.81	-60.16	2.95	16.06	369.92	-192.80
	7	1.67	38.75	48.00	97.90	-69.50	1.05	4.35	129.66	-55.30
	MEAN	1.36	51.54	51.11	58.50	-41.16	2.55	8.93	143.06	-100.94
	SD	0.82	17.62	29.00	26.27	21.22	1.17	4.75	105.61	62.50
5PF	1	1.66	80.25	122.00	45.59	-39.98	2.04	4.98	93.41	-19.43
	2	0.60	83.50	103.75	48.20	-23.54	3.73	16.17	136.38	-143.48
	3	0.87	76.25	67.75	24.66	-17.94	1.33	9.17	92.67	-70.25
	4	0.69	53.00	76.75	28.02	-20.55		4.00	67.26	-52.68
	5	1.91	66.50	86.00	68.38	-23.17		13.84	85.94	-139.75
	6	2.87	57.75	47.74	86.31	-46.71	2.98	17.88	197.66	-207.38
	7	2.38	52.00	59.75	97.52	-41.10	1.11	5.25	123.31	-56.42
	MEAN	1.57	67.04	80.53	56.95	-30.43	2.24	10.18	113.80	-98.48
	SD	0.88	13.17	25.73	28.06	11.72	1.11	5.76	43.66	66.46
10PF	1	1.95	87.50	111.75	64.64	-21.67	1.99	5.72	90.80	-25.41
	2	1.53	70.50	109.50	88.56	-43.34	3.07	17.85	190.94	-115.46
	3	1.83	68.75	73.25	56.80	-26.90	1.32	12.19	97.15	-90.42
	4	1.67	83.75	68.25	66.88	-64.64		4.28	88.93	-42.22
	5	3.64	75.75	64.75	122.56	-43.34	3.97	13.66	153.57	-139.37
	6	5.05	57.75	56.00	195.79	-72.86	2.80	17.85	268.28	-192.80
	7	3.35	49.75	60.50	159.18	-49.32	1.30	6.17	136.38	-70.62
	MEAN	2.72	70.54	77.71	107.77	-46.01	2.41	11.10	146.58	-96.61
	SD	1.33	13.47	23.15	53.40	18.49	1.06	5.75	65.59	57.99
15PF	1	2.66	108.00	120.00	88.56	-25.78	2.11	7.14	121.44	-44.09
	2	2.75	69.00	90.00	121.06	-30.64	3.37	18.77	191.68	-146.10
	3	2.07	76.75	87.25	83.32	-25.41	1.14	14.34	102.75	-101.63
	4	2.03	88.50	69.00	70.25	-28.77		4.33	90.42	-42.60
	5	3.00	66.25	59.00	118.45	-93.04	4.13	12.37	170.01	-120.32
	6	5.26	66.75	54.75	166.27	-81.83	2.74	17.30	249.60	-180.47
	7	3.94	54.25	72.75	155.44	-49.32	1.40	6.38	160.67	-65.39
	MEAN	3.10	75.64	78.96	114.76	-47.83	2.48	11.52	155.22	-100.09
	SD	1.15	17.71	22.35	36.55	28.43	1.16	5.66	55.65	52.65
20PF	1	2.53	79.50	93.25	57.92	-29.14	2.17	6.11	104.25	-40.35
	2	3.29	67.50	106.00	116.95	-46.33	3.33	19.64	265.67	-139.37
	3	2.46	88.50	83.00	68.00	-34.75	1.02	18.04	111.35	-114.34
	4	2.18	92.75	68.75	72.11	-32.13		4.10	84.82	-39.23
	5	3.97	79.75	72.50	121.81	-46.71	4.32	12.44	156.56	-115.08
	6	5.17	66.00	64.75	149.46	-68.38	2.70	17.58	278.74	-175.99
	7	4.46	53.50	76.00	156.19	-54.93	1.37	6.73	172.25	-67.63
	MEAN	3.44	75.36	80.61	106.06	-44.62	2.49	12.09	167.66	-98.86
	SD	1.13	13.78	14.66	40.17	13.97	1.23	6.47	77.61	51.72

AB- PF

	Participant	PT	TPT	1/2RT	mxRTD	mxRTR	M-wave	tetT	IT
20DF	1	16.37	131.00	117.75	267.16	-115.46	17.40	53.44	8.31
	2	20.12	123.75	118.00	321.71	-132.27	21.50	61.25	11.83
	3	14.58	123.00	119.00	247.36	-111.72	16.10	28.14	9.06
	4	15.93	98.75	97.50	429.33	-136.38	13.20	97.18	5.26
	5	20.50	98.50	116.00	432.31	-149.46	19.30	168.15	6.54
	6	17.18	124.00	90.75	323.21	-149.46	9.00	168.25	7.19
	7	19.71	112.50	118.00	459.97	-139.00	19.50	112.05	7.84
	MEAN	17.77	115.93	111.00	354.44	-133.39	16.57	98.35	8.00
	SD	2.33	13.00	11.73	85.58	15.00	4.28	55.18	2.09
15DF	1	18.27	130.00	112.00	289.58	-134.51	18.30	66.69	10.22
	2	21.68	125.00	115.25	342.26	-148.34	21.80	72.47	7.81
	3	17.17	126.25	131.75	267.53	-122.18	16.90	52.18	5.43
	4	14.10	90.75	82.50	337.78	-161.42	15.00	105.21	5.32
	5	20.44	100.50	114.00	418.12	-143.48	20.00	211.09	0.35
	6	17.89	122.75	89.75	381.12	-164.03	9.83	186.27	1.30
	7	20.37	118.25	124.00	424.47	-125.55	20.20	139.94	3.36
	MEAN	18.56	116.21	109.89	351.55	-142.79	17.43	119.12	4.83
	SD	2.55	14.78	17.71	60.28	16.43	4.04	61.91	3.49
10DF	1	18.01	126.75	111.25	306.02	-139.75	19.00	61.20	4.11
	2	20.75	121.75	108.75	382.25	-154.32	22.00	67.29	9.22
	3	16.70	125.25	131.25	348.24	-116.58	17.10	55.66	4.90
	4	11.83	95.50	80.00	360.95	-128.91	14.00	112.42	4.22
	5	20.88	98.25	113.50	479.02	-141.24	20.20	158.65	2.60
	6	17.78	112.50	94.75	409.52	-165.53	9.32	185.48	3.65
	7	20.10	113.50	124.75	506.67	-128.16	20.30	150.80	1.34
	MEAN	18.01	113.36	109.18	398.95	-139.21	17.42	113.07	4.29
	SD	3.16	12.51	17.38	71.95	16.66	4.41	52.96	2.47
5DF	1	16.92	124.75	99.50	297.80	-147.97	20.00	48.99	6.16
	2	19.53	121.50	106.00	366.55	-146.85	22.80	59.98	9.53
	3	16.88	121.25	127.50	322.46	-124.05	17.60	32.44	0.68
	4	9.81	102.50	68.50	338.53	-114.71	14.50	105.62	4.25
	5	19.14	97.75	113.75	430.82	-127.79	20.40	146.01	2.40
	6	17.50	113.25	96.00	406.53	-155.07	9.30	179.79	1.33
	7	19.19	106.00	132.50	469.68	-122.93	21.80	112.45	0.30
	MEAN	17.00	112.43	106.25	376.05	-134.20	18.06	97.90	3.52
	SD	3.36	10.55	21.50	62.17	15.47	4.75	53.86	3.37

	Participant	PT	TPT	1/2RT	mxRTD	mxRTR	M-wave	tetT	IT
0	1	14.83	122.75	91.50	278.74	-141.99	20.10	43.91	7.22
	2	18.39	112.25	110.75	394.95	-137.50	23.30	57.50	6.86
	3	15.03	117.25	123.50	357.58	-115.08	18.00	23.87	9.58
	4	9.19	87.00	77.00	319.85	-113.59	12.90	86.46	1.68
	5	16.25	95.50	104.75	385.98	-114.71	20.00	109.28	8.80
	6	15.57	108.75	90.75	392.33	-148.34	9.87	156.86	1.70
	7	17.39	103.75	120.75	693.12	-202.89	22.40	99.44	-0.39
	MEAN	15.24	106.75	102.71	403.22	-139.16	18.08	82.47	5.06
	SD	2.96	12.42	17.11	134.82	31.59	4.97	44.91	3.97
5PF	1	13.25	119.50	80.75	238.39	-147.59	21.70	58.46	1.70
	2	15.17	117.50	94.25	294.44	-131.90	24.60	64.11	3.98
	3	12.96	116.25	110.50	279.49	-108.73	18.20	29.04	5.27
	4	6.56	76.50	89.50	271.27	-87.43	17.20	90.88	0.45
	5	13.63	96.50	102.75	272.77	-103.50	20.20	106.19	0.83
	6	13.04	108.50	87.25	303.03	-134.14	11.30	125.11	0.08
	7	15.16	115.00	103.75	371.41	-125.55	25.20	96.91	-0.11
	MEAN	12.82	107.11	95.54	290.11	-119.83	19.77	81.53	1.74
	SD	2.92	15.59	10.56	41.31	20.79	4.79	32.72	2.09
10PF	1	10.24	120.50	75.75	161.04	-120.69	22.30	42.29	1.73
	2	12.60	115.75	87.00	249.23	-113.22	25.50	25.36	10.25
	3	10.94	116.75	104.00	222.32	-96.78	18.70	18.74	4.13
	4	5.76	85.50	78.00	191.31	-69.87	17.70	57.24	-0.74
	5	10.27	97.00	100.00	191.31	-84.45	20.10	52.53	0.98
	6	11.33	111.50	79.25	187.95	-127.04	12.90	76.96	3.79
	7	13.27	109.25	100.50	315.74	-121.06	26.50	63.21	0.25
	MEAN	10.63	108.04	89.21	216.99	-104.73	20.53	48.05	2.91
	SD	2.43	12.48	12.07	51.82	21.53	4.71	20.73	3.69
15PF	1	7.14	117.25	75.00	110.60	-82.20	22.60	32.94	1.21
	2	9.31	114.50	83.50	157.68	-84.45	25.90	31.63	3.19
	3	8.27	105.50	110.00	144.23	-70.25	19.10	14.53	5.28
	4	4.41	84.00	95.50	141.61	-49.32	17.50	50.50	0.07
	5	6.59	93.00	90.75	134.89	-58.29	19.60	57.19	2.88
	6	8.35	106.50	80.50	149.09	-95.65	14.10	76.24	0.40
	7	10.94	109.25	96.25	217.09	-94.16	27.70	40.52	-0.08
	MEAN	7.86	104.29	90.21	150.74	-76.33	20.93	43.36	1.85
	SD	2.08	11.85	11.74	32.77	17.72	4.78	20.04	2.00
20PF	1	2.22	109.50	72.00	36.62	-31.39	22.90	21.36	0.82
	2	5.14	117.25	78.75	87.81	-53.81	26.10	46.98	0.22
	3	6.78	112.50	94.00	130.40	-64.27	19.10	13.94	1.70
	4	1.99	88.25	79.75	85.94	-46.33	17.60	37.07	1.89
	5	3.86	97.25	98.25	102.38	-60.91	19.70	58.95	0.61
	6	4.17	112.25	71.50	74.36	-48.20	15.90	60.46	1.82
	7	6.43	108.25	88.25	113.59	-59.41	29.40	53.89	-0.15
	MEAN	4.37	106.46	83.21	90.16	-52.05	21.53	41.81	0.99
	SD	1.88	10.13	10.51	30.16	11.25	4.85	18.40	0.82

SCI - PF

	Participant	PT	TPT	1/2RT	mxRTD	mxRTR	M-wave	tetT	mxRTD	mxRTR
20DF	1	8.08	64.75	107.50	260.44	-56.42	2.45	13.38	279.49	-98.27
	2	2.94	40.75	30.25	131.90	-113.59	0.40	14.24	209.62	-237.64
	3	7.15	30.50	146.00	386.36	-151.33	4.07	20.06	404.29	-181.97
	4	1.70	49.25	89.00	57.54	-21.30		6.30	97.15	-66.88
	5	10.82	39.75	85.75	492.85	-116.58	8.80	38.24	861.64	-717.41
	6	9.53	63.75	90.00	244.37	-105.74	2.14	24.96	305.65	-220.08
	7	10.24	86.75	46.00	323.21	-160.67	1.41	20.84	352.73	-185.33
	MEAN	7.21	53.64	84.93	270.95	-103.66	3.21	19.72	358.65	-243.94
	SD	3.58	19.30	38.27	147.75	49.68	2.99	10.18	243.17	217.80
15DF	1	7.72	73.75	152.00	204.39	-48.95	2.26	14.21	257.07	-103.88
	2	0.70	140.00	139.00	24.66	-21.30	0.34	9.84	143.11	-63.52
	3	4.92	126.75	84.50	204.01	-93.41	4.95	19.13	297.80	-165.53
	4	1.90	57.50	100.75	70.25	-22.42		6.50	94.16	-29.14
	5	9.15	54.25	95.75	326.95	-72.86	9.97	44.19	1610.07	-1632.48
	6	8.86	69.00	96.75	175.62	-83.32	4.69	29.00	313.12	-181.59
	7	10.39	81.50	48.25	317.60	-150.96	1.35	24.09	354.97	-167.77
	MEAN	6.23	86.11	102.43	189.07	-70.46	3.93	20.99	438.61	-334.84
	SD	3.79	33.80	34.48	113.52	45.40	3.48	12.88	525.01	575.09
10DF	1	8.30	68.75	122.25	255.20	-57.92	2.43	15.64	284.72	-106.49
	2	2.61	62.50	102.25	67.63	-22.42	0.39	15.86	221.95	-107.24
	3	6.30	33.25	26.00	313.49	-184.58	4.61	16.90	321.34	-261.18
	4	1.74	52.75	99.50	58.29	-22.05		6.14	85.94	-52.31
	5	9.48	44.00	87.25	359.45	-115.83	10.10	43.02	498.08	-440.91
	6	9.72	60.00	86.00	219.71	-115.08	4.62	26.50	325.82	-185.33
	7	10.14	86.25	49.25	364.31	-142.36	1.36	19.72	365.43	-156.56
	MEAN	6.90	58.21	81.79	234.01	-94.32	3.92	20.54	300.47	-187.15
	SD	3.48	17.19	33.14	127.96	62.00	3.48	11.61	127.01	130.31
5DF	1	8.34	75.75	118.50	249.97	-61.65	2.64	14.38	279.49	-96.40
	2	3.10	64.50	118.75	81.46	-25.78	0.43	16.19	225.69	-120.32
	3	6.71	31.25	33.75	335.17	-147.59	3.99	14.31	347.12	-174.50
	4	1.53	74.75	98.25	49.70	-22.42		5.91	76.22	-35.12
	5	9.77	47.00	82.00	373.28	-122.93	8.87	35.14	544.04	-380.00
	6	9.39	57.75	80.50	215.97	-112.47	5.17	23.53	297.80	-145.35
	7	8.96	85.75	49.00	300.04	-134.14	1.64	15.87	304.15	-123.31
	MEAN	6.83	62.39	82.96	229.37	-89.57	3.79	17.90	296.36	-153.57
	SD	3.27	18.75	32.56	123.60	52.20	3.00	9.17	140.07	108.85

	Participant	PT	TPT	1/2RT	mxRTD	mxRTR	M-wave	tetT	mxRTD	mxRTR
0	1	6.14	82.00	81.75	206.63	-60.53	2.56	10.00	201.40	-74.36
	2	4.35	63.75	80.25	130.78	-36.62	0.36	21.09	205.88	-152.08
	3	6.55	32.50	32.50	379.63	-147.97	3.95	13.01	391.59	-175.24
	4	1.11	55.50	93.25	48.57	-20.55		5.52	76.97	-41.10
	5	8.85	45.75	84.00	356.09	-117.33	10.30	30.75	428.20	-374.03
	6	8.19	65.25	70.00	210.37	-97.15	4.81	19.18	290.33	-173.37
	7	8.23	83.50	52.25	314.61	-121.06	1.24	12.97	313.49	-107.61
	MEAN	6.20	61.18	70.57	235.24	-85.89	3.87	16.07	272.55	-156.83
	SD	2.73	18.47	21.21	121.76	47.52	3.56	8.34	121.21	108.34
5PF	1	6.63	79.25	83.50	171.13	-57.54	2.58	11.56	217.84	-73.24
	2	1.42	80.25	123.25	35.87	-17.94	0.57	18.23	151.33	-62.40
	3	5.66	42.25	228.25	223.07	-66.14	4.08	12.40	275.75	-92.67
	4	0.86	72.75	62.75	36.99	-15.69		4.06	68.75	-14.95
	5	8.26	67.50	76.00	219.71	-102.75	10.10	32.14	402.80	-346.00
	6	4.74	69.00	65.25	133.02	-57.54	5.31	17.00	238.39	-118.07
	7	5.36	80.75	49.75	124.05	-80.71	1.79	9.33	193.93	-63.52
	MEAN	4.70	70.25	98.39	134.83	-56.90	4.07	14.96	221.26	-110.12
	SD	2.69	13.48	61.83	77.24	31.55	3.39	8.93	104.19	108.68
10PF	1	3.31	74.75	51.25	102.75	-49.32	2.50	7.04	152.08	-50.82
	2	2.17	63.00	134.00	62.77	-21.30	0.48	16.84	209.24	-126.29
	3	6.80	42.50	181.00	299.67	-58.66	2.00	10.78	316.86	-87.81
	4	0.41	60.75	46.25	17.94	-18.68		4.07	49.70	-35.50
	5	6.19	53.50	68.00	244.74	-73.61	10.90	22.00	401.68	-264.92
	6	5.15	76.75	57.00	168.52	-73.98	5.69	14.63	243.99	-115.83
	7	2.86	76.75	38.25	81.83	-62.03	2.25	5.53	108.73	-50.07
	MEAN	3.84	64.00	82.25	139.75	-51.08	3.97	11.56	211.75	-104.46
	SD	2.30	13.07	53.95	102.40	22.91	3.80	6.58	121.52	78.76
15PF	1	2.21	73.00	38.75	84.45	-42.60	2.40	6.41	112.10	-47.08
	2	0.56	49.25	53.75	28.40	-15.32	0.49	13.56	165.90	-122.18
	3	5.35	54.00	158.50	181.22	-68.00	1.37	7.58	231.66	-68.38
	4	0.25	45.25	52.25	14.95	-12.70		3.50	36.99	-34.00
	5	5.52	60.00	59.75	185.70	-69.87	8.54	23.08	295.18	-264.55
	6	3.23	63.50	45.75	109.85	-54.93	5.49	12.46	202.52	-99.02
	7	2.32	77.50	38.25	69.87	-50.82	2.37	4.25	98.27	-36.99
	MEAN	2.78	60.36	63.86	96.35	-44.89	3.44	10.12	163.23	-96.03
	SD	2.09	11.94	42.48	67.64	23.13	3.02	6.88	87.95	81.23
20PF	1	0.17					2.34	4.20	66.51	-32.51
	2	0.18	50.75	42.50	12.33	-13.45	0.48	10.99	109.48	-91.17
	3	4.13	90.25	89.25	124.80	-43.72	0.96	5.89	129.28	-60.53
	4	0.11	43.25	77.50	13.08	-14.95		2.41	25.03	-16.07
	5	3.12	59.50	51.50	113.59	-45.59	7.81	20.69	233.91	-254.08
	6	0.61	94.00	32.50	24.66	-18.68	5.64	10.02	140.12	-81.83
	7	0.28	13.50	17.00	49.70	-68.00	2.38	1.69	75.10	-69.13
	MEAN	1.23	58.54	51.71	56.36	-34.07	3.27	7.98	111.35	-86.47
	SD	1.67	30.29	27.32	50.64	21.93	2.86	6.63	67.02	78.50

Chapter III: Muscle Fatigue Characteristics of the Paralyzed Tibialis Anterior After Spinal Cord Injury

AB Group

Twitch 1-20 = fatigue protocol (2 minutes)
Twitch 21-37 = recovery period (15 minutes)

PT (Nm)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_AB	3.73	5.07	6.24	6.80	6.83	6.73	6.65	6.52	5.68	6.11	6.24	6.77	5.28
02_AB	3.73	6.04	5.88	6.12	5.97	5.61	5.57	5.21	5.10	5.15	4.96	4.63	4.30
03_AB	3.41	6.11	7.23	6.33	7.46	6.88	6.44	6.81	6.18	5.78	5.61	5.37	5.35
04_AB	3.83	5.39	6.36	7.23	7.84	7.88	7.79	8.94	7.33	2.87	7.14	6.16	6.00
06_AB	4.64	13.40	8.38	13.20	12.80	11.94	10.45	9.87	8.51	7.84	6.59	6.02	5.92
09_AB	2.83	2.91	3.73	2.55	3.41	3.51	6.39	3.35	3.47	3.63	3.36	3.62	2.50
MEAN	3.70	6.49	6.30	7.04	7.38	7.09	7.21	6.78	6.04	5.23	5.65	5.43	4.89
SD	0.59	3.58	1.55	3.45	3.09	2.80	1.74	2.39	1.75	1.79	1.36	1.15	1.32

TWITCH											
13	14	15	16	17	18	19	20	21	22	23	24
5.33	5.17	5.48	5.54	4.77	5.87	5.62	5.49	5.40	5.75	5.84	5.98
4.24	4.28	4.41	4.46	4.53	4.32	4.29	4.03	5.31	5.19	4.89	4.62
5.11	5.10	4.80	4.57	4.55	4.49	4.14	3.94	5.17	5.32	5.46	5.40
5.49	5.37	4.97	6.58	4.55	4.52	3.89	3.89	4.79	5.12	4.98	4.97
5.35	5.40	4.46	3.95	3.84	4.00	3.78	3.70	3.05	2.93	2.94	2.87
3.52	3.51	3.39	3.51	2.76	3.39	3.47	3.60	3.71	3.84	4.07	3.95
4.84	4.81	4.59	4.77	4.17	4.43	4.20	4.11	4.57	4.69	4.69	4.63
0.79	0.76	0.70	1.12	0.76	0.82	0.75	0.69	0.97	1.07	1.05	1.10

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
5.94	6.04	6.14	6.17	6.25	6.02	5.91	5.85	5.70	5.65	5.41	4.95	4.49
4.72	4.68	4.52	4.67	4.27	4.60	4.64	4.58	4.73	4.82	4.63	4.23	4.21
5.59	5.73	5.84	5.83	5.73	5.32	4.99	4.98	4.45	4.51	4.30	3.84	3.38
4.95	4.76	4.53	4.30	4.25	4.26	4.18	4.17	4.11	4.11	4.03	3.92	3.55
2.79	2.97	3.16	3.43	3.55	3.61	3.93	3.58	3.46	3.52	3.48	4.02	3.60
3.99	4.10	3.94	3.90	4.00	3.93	3.90	3.87	3.88	3.85	3.74	3.45	3.17
4.67	4.71	4.69	4.71	4.68	4.62	4.59	4.50	4.39	4.41	4.26	4.07	3.74
1.14	1.12	1.13	1.08	1.07	0.90	0.77	0.82	0.78	0.76	0.69	0.50	0.51

TPT (ms)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_AB	95.00	76.75	83.5	90.75	93	100	95.5	108.25		133.25			128.75
02_AB	91.75		66	71.5	71.75	71.5	71.25	74	70.75	71.75	72	70.5	72.5
03_AB	90.5	65	73.25	68	76.75	75.25	75.5	88.75	80	79.75	83	82.75	79.5
04_AB	87.75			78.25	79	80.5	80.5	62.75	80			78	84.25
06_AB	75		82		91.5	96.75	98.5	95	100.5	105	100	106.5	
09_AB	128	110.75		94.25				106.25	109.25	105.75	104.50	103.00	85.75
MEAN	94.67	84.17	76.19	80.55	82.40	84.80	84.25	89.17	88.10	99.10	89.88	88.15	90.15
SD	17.73	23.76	8.16	11.58	9.38	12.85	12.14	17.99	16.07	24.33	15.09	15.82	22.19

	TWITCH											
	13	14	15	16	17	18	19	20	21	22	23	24
	114		85.5						101.5	107	110.75	123.5
	72.25	72.75	72.75	71.5	71.5	68.5	69.25	69.25	72.5	74.75	86.75	88
	84.25	84	84.5	86.75	80.5	89.5	85.75	80.5	84.75	87.5	95.5	113
	79.25	79.25	77.25	82	78.5	45	79.75	75.25	82.5	83	78.5	78.25
	111.75			106	113.75	113.25	169.25	107.25	99.75	104.5	100	106.5
	104.00	100.75	103.00	102.50		97.00	99.25	107.50	107.75	114.50	115.25	123.50
	94.25	84.19	84.60	89.75	86.06	82.65	100.65	87.95	91.46	95.21	97.79	105.46
	17.89	11.97	11.55	14.39	18.86	26.49	39.85	18.17	13.56	15.65	13.98	18.73

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
128.25	137.5	142.25	151.25	145.5	144	140.75	138	138.5	134.5	135.75	102.5	94.5
124.5	127.5	124	131.25	126.25	125	130.5	123.5	124	124.5	109.75	108	105.5
123.25	127.75	138.75	144.5	144.5	145.5	139	139.25	138.5	136	130.5	103.25	94.75
80	79.75	79	80.25	78.5	83	86.25	85.5	88.5	94.75	96.75	101.5	92.75
110.75	117.75	126.5	125.25	124.25	118.5	123	120.25	82.25	85.5	78.5	70	80
120.50	128.25	139.25	145.75	149.50	151.00	149.25	144.50	145.50	144.25	140.00	137.75	134.00
114.54	119.75	124.96	129.71	128.08	127.83	128.13	125.17	119.54	119.92	115.21	103.83	100.25
17.92	20.57	23.70	26.11	26.49	25.36	22.40	21.62	27.45	24.09	24.45	21.54	18.42

1/2 RT (ms)

	Baseline	TWITCH 1	2	3	4	5	6	7	8	9	10	11	12
01_AB	88.00	68.5	78.5	84	87.5	96.75	106.5	104.25	104.25	92.5	104.5	111.25	94.75
02_AB	72	79.75	51.75	55	62.25	63.25	66.75	66	71.5	73	71.75	72.75	76.75
03_AB	78	53.25	62.5	61.5	76.75	82	86.5		98	99.75	101.25	100.5	110.25
04_AB	85	74	69	76.5	77.25	87.75	91.75		108.5	173.25	120	106.75	122.25
06_AB	89		67.5	80.25	88.25	92.5	95.5	108.25	99.25	101.75	100	96.25	104.5
09_AB	110	102.00		80.75	114.25	106.00		120.50	165.50	161.50	114.25	131.25	129.25
MEAN	87.00	75.50	65.85	73.00	84.38	88.04	89.40	99.75	107.83	116.96	101.96	103.13	106.29
SD	12.99	17.79	9.78	11.85	17.41	14.62	14.63	23.54	31.08	40.52	16.73	19.22	19.01

	TWITCH 13	14	15	16	17	18	19	20	21	22	23	24
		96.75		92.75	84		81.25	76.75	113.75	98.25	93.75	96.25
	77	74	76.75	73	74.5	77.25	78.25	79.75	71.75	83.25	100	134.75
	104.5	109.25	106.25	105.75	112.5	110.5	109.5	109.75	97.5	86.75	85.5	86.25
	122.5	127.25	119.25		118.5		118.25	129.75	125.25	115	107.75	101
	89.75	107	84.75	90	82	95.25	82.75	81.75	81.75	70.5	79.25	77.25
	156.50	218.25	140.00	142.00		147.00	152.50	183.25	142.50	115.75	120.75	113.75
	110.05	122.08	105.40	100.70	94.30	107.50	103.75	110.17	105.42	94.92	97.83	101.54
	31.02	50.24	25.68	25.87	19.79	29.63	29.04	41.41	26.81	18.15	15.12	20.51

TWITCH 25	26	27	28	29	30	31	32	33	34	35	36	37
109.25	115.25	137.75	126	143.75	132	122.75	114.25	100.75	96	87.75	80	79.5
116.25	117	117	119	102.25	111.75	103.25	97.25	84	81.75	77.5	72	69.5
98.5	103.5	110.75	111.5	113.25	108	106.25	106.5	92	86.5	81.25	90	83.25
101	102	120.25	135.5	147	153.5	158.25	155.75	149	138	137.5	104.75	94.25
86.25	92.75	109	112.5	109	117.75	106.5	103.75	127	121.75	119.5	100.5	83.25
126.25	129.75	135.75	137.25	136.00	128.00	128.00	128.50	123.00	120.00	121.50	125.25	122.25
106.25	110.04	121.75	123.63	125.21	125.17	120.83	117.67	112.63	107.33	104.17	95.42	88.67
14.12	13.19	12.33	11.18	19.33	16.66	20.89	21.52	24.59	22.48	25.11	19.07	18.27

RTD (Nm/s)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_AB	91.17	136.38	190.56	214.10	223.82	223.82	229.42	204.01	183.84	199.90	182.34	177.11	176.74
02_AB	98.72	422.6	365.81	408.4	417	376.27	369.92	344.51	344.51	383.74	355.72	347.12	301.91
03_AB	91.17	208.87	207.75	440.54	277.25	422.97	220.45	192.43	176.74	170.01	175.99	161.04	162.91
04_AB	189.44	237.64	307.89	299.3	378.88	339.65	389.35	357.59	340.77	36.992	359.45	370.29	321.34
06_AB	280.24	156.56	789.53	806.34	770.1	658.75	609.05	557.86	486.12	483.88	431.94	249.6	258.94
09_AB	60.53	51.94	71.74	68.38	74.73	77.72	108.36	76.97	87.06	90.05	81.46	91.17	67.63
MEAN	135.21	202.33	322.21	372.84	356.96	349.86	321.09	288.90	269.84	227.43	264.48	232.72	214.91
SD	83.38	125.59	250.46	251.82	236.01	195.71	175.36	168.27	146.19	172.85	136.72	110.06	96.63

TWITCH											
13	14	15	16	17	18	19	20	21	22	23	24
171.51	175.99	149.09	146.85	155.81	137.50	142.74	118.45	172.63	154.69	158.80	140.12
302.28	316.48	305.27	349.36	354.97	312.37	323.21	305.65	473.04	479.77	377.76	387.48
154.69	164.03	155.81	149.46	144.23	146.1	147.22	132.27	146.85	139.37	127.42	116.95
317.98	303.41	302.66	320.59	285.1	294.81	263.05	252.59	274.63	264.92	225.69	248.85
267.16	277.25	228.3	146.1	154.69	187.95	212.23	161.42	240.26	199.53	298.92	264.92
82.95	90.42	87.06	91.55	96.03	96.03	92.29	99.02	83.32	90.05	82.95	96.03
216.10	221.26	204.70	200.65	198.47	195.79	196.79	178.23	231.79	221.39	211.92	209.06
93.70	90.99	88.98	106.67	99.16	88.63	85.92	82.47	136.29	139.68	111.23	111.85

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
144.23	146.10	165.15	153.57	194.30	158.43	147.59	147.97	146.10	139.00	124.05	153.20	120.69
355.72	328.07	309.76	278.37	254.08	294.81	314.24	279.12	282.85	279.49	309.01	217.84	216.72
116.21	120.69	116.58	108.73	112.1	101.26	107.99	209.99	93.787	105.74	107.99	72.862	60.158
240.26	217.09	210.74	199.53	191.31	189.82	189.82	187.95	177.11	173.37	170.39	152.08	140.87
202.89	208.87	210.37	177.49	215.97	195.79	204.39	195.05	209.99	209.25	216.72	226.43	187.2
100.89	93.41	78.84	78.84	81.46	65.02	71.37	69.13	70.99	64.27	59.04	60.16	47.83
193.36	185.70	181.91	166.09	174.87	167.52	172.56	181.53	163.47	161.85	164.53	147.09	128.91
95.46	84.97	81.43	70.59	65.24	80.60	85.34	69.74	77.86	76.70	88.99	69.90	67.26

RTR (Nm/s)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_AB	-41.85	-63.89	-73.98	-78.47	-75.48	-68.38	-63.89	-64.64	-64.27	-60.91	-63.15	-51.56	-45.21
02_AB	-124.05	-95.281	-150.96	-129.66	-118.07	-134.14	-134.89	-150.21	-116.21	-119.2	-111.72	-116.95	-118.07
03_AB	-40.35	-93.413	-88.929	-89.303	-78.841	-72.115	-69.873	-66.136	-58.29	-57.169	-52.311	-54.553	-50.443
04_AB	-54.55	-94.908	-84.445	-105.74	-75.478	-117.33	-69.873	-72.115	-64.642	-209.62	-110.6	-133.77	-116.58
06_AB	-65.76	-74.88	-160.67	-160.67	-143.86	-125.92	-159.18	-141.99	-140.12	-131.53	-176.36	-121.44	-127.42
09_AB	-26.53	-26.90	-21.67	-31.39	-30.27	-32.51	-28.02	-49.32	-31.39	-25.78	-27.28	-28.40	-21.67
MEAN	-58.85	-74.88	-96.78	-99.20	-87.00	-91.73	-87.62	-90.74	-79.15	-100.70	-90.24	-84.45	-79.90
SD	34.62	26.77	51.75	44.44	39.37	40.15	49.19	43.62	40.59	66.70	53.72	44.66	45.87

TWITCH											
13	14	15	16	17	18	19	20	21	22	23	24
-55.67	-60.16	-57.92	-56.80	-56.42	-51.56	-56.80	-64.27	-48.95	-50.82	-51.56	-47.83
-119.2	-117.33	-118.82	-121.44	-117.7	-113.59	-108.73	-117.33	-156.19	-192.8	-121.44	-127.04
-48.575	-46.706	-48.201	-47.827	-44.465	-42.223	-39.607	-41.102	-51.19	-56.048	-56.795	-50.069
-88.555	-83.324	-91.918	-129.66	-85.193	-113.96	-99.018	-117.7	-94.534	-85.193	-54.553	-88.182
-109.11	-123.31	-118.07	-132.27	-138.63	-115.46	-112.84	-65.389	-125.92	-59.784	-149.46	-100.14
-22.79	-26.90	-25.78	-28.40	-17.56	-25.04	-30.27	-24.29	-30.27	-32.13	-31.39	-31.76
-73.98	-76.29	-76.79	-86.06	-76.66	-76.97	-74.54	-71.68	-84.51	-79.46	-77.53	-74.17
37.66	38.78	38.67	46.76	45.90	41.81	36.69	38.67	49.54	58.10	46.61	36.71

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
-47.45	-44.09	-38.11	-41.48	-39.23	-39.23	-42.97	-44.84	-50.82	-48.58	-48.95	-60.91	-59.78
-122.56	-113.22	-95.281	-69.126	-71.741	-108.73	-122.93	-92.292	-127.04	-88.182	-147.59	-87.434	-96.776
-46.333	-46.706	-45.959	-47.08	-46.333	-42.223	-44.838	-64.268	-41.102	-48.201	-46.333	-43.344	-35.871
-44.838	-46.706	-45.212	-47.08	-35.871	-37.739	-49.322	-35.497	-31.76	-35.871	-39.233	-35.497	-50.817
-38.112	-47.08	-64.642	-88.182	-74.357	-79.961	-84.819	-131.53	-94.534	-83.698	-133.39	-159.18	-131.9
-33.63	-31.76	-30.64	-29.15	-29.52	-29.89	-29.89	-28.77	-31.76	-30.64	-28.77	-29.89	-27.65
-55.49	-54.93	-53.31	-53.68	-49.51	-56.30	-62.46	-66.20	-62.84	-55.86	-74.05	-69.37	-67.13
33.29	29.15	23.47	21.29	19.04	31.11	34.87	39.37	39.18	24.36	52.14	48.68	39.82

M-wave Amplitude (mV)

	Baseline	TWITCH 1	2	3	4	5	6	7	8	9	10	11	12
01_AB	7.90	8.27	8.78	8.83	8.83	8.66	8.49	8.70	9.99	8.61	8.49	8.41	8.00
02_AB	4.29	4.56	4.24	3.67	3.49	3.14	3.26	3.43	3.53	3.21	3.15	3.37	4.03
03_AB	3.30	3.78	3.92	3.86	4.16	4.17	4.15	4.15	4.27	4.34	4.08	4.37	4.46
04_AB	10.90	11.40	11.90	12.10	12.50	12.50	12.80	12.70	13.00	16.00	12.80	13.00	13.10
06_AB	5.52	5.16	6.11	5.67	5.24	5.01	4.71	4.59	4.89	4.72	4.54	4.62	4.87
09_AB	2.42	3.32	3.44	3.37	3.14	2.90	3.10	2.76	2.82	2.47	2.63	2.40	2.03
MEAN	5.72	6.08	6.40	6.25	6.23	6.06	6.09	6.06	6.42	6.56	5.95	6.03	6.08
SD	3.18	3.14	3.33	3.52	3.70	3.78	3.83	3.86	4.11	5.09	3.94	3.98	3.94

TWITCH 13	14	15	16	17	18	19	20	21	22	23	24
8.45	8.55	8.04	8.99	8.55	8.21	8.67	8.10	7.90	8.01	8.50	8.76
4.15	3.90	3.87	3.53	3.57	4.25	4.10	4.18	3.44	3.67	3.83	4.02
4.15	4.39	4.19	4.23	4.29	4.19	4.34	4.05	3.59	3.24	3.35	3.25
13.00	12.80	12.70	12.70	12.60	12.80	13.10	12.80	11.70	11.50	11.20	11.30
4.80	4.77	4.60	4.99	4.75	4.72	4.57	4.53	3.68	3.59	3.59	3.67
2.43	2.09	2.17	2.19	1.99	1.94	1.99	1.89	2.14	2.21	2.18	2.22
6.16	6.08	5.93	6.11	5.96	6.02	6.13	5.93	5.41	5.37	5.44	5.54
3.90	3.91	3.83	3.96	3.91	3.89	4.05	3.92	3.65	3.61	3.57	3.62

TWITCH 25	26	27	28	29	30	31	32	33	34	35	36	37
8.94	9.15	9.26	9.25	9.16	8.80	8.71	8.67	8.64	8.71	8.48	8.28	8.04
3.93	3.98	4.08	3.86	3.94	4.20	3.86	3.93	3.96	3.84	3.87	3.61	3.88
3.27	3.33	3.27	3.21	3.16	3.37	3.34	3.11	3.07	3.34	3.24	3.48	3.43
11.30	11.40	11.50	11.50	11.60	11.70	11.60	11.70	11.60	11.60	11.60	11.70	11.70
3.66	3.86	3.97	4.19	4.30	4.38	4.38	4.44	4.47	4.46	4.52	4.90	5.76
2.16	2.32	2.24	2.30	2.29	2.35	2.28	2.29	2.35	2.46	2.32	2.59	2.73
5.54	5.67	5.72	5.72	5.74	5.80	5.70	5.69	5.68	5.74	5.67	5.76	5.92
3.67	3.68	3.74	3.73	3.74	3.64	3.64	3.68	3.64	3.60	3.60	3.53	3.42

M-wave Area (mV*ms)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_AB	44.80	40.46	44.46	45.05	45.67	46.48	46.17	47.08	50.44	46.81	45.74	48.01	43.60
02_AB	15.62	10.78	10.74	7.91	11.38	11.56	12.98	15.32	15.31	13.82	14.64	15.12	18.63
03_AB	21.56	29.91	23.35	23.85	24.64	24.08	23.48	24.08	23.98	25.33	25.32	24.61	21.97
04_AB	92.57	80.01	75.9	75.2	75.79	77.6	77.96	79.29	80.85	73.2	83.65	84.1	83.9
06_AB	21.56	25.79	22.37	25.28	26.02	29.07	28.82	30.59	32.23	31.48	28	29.89	29.57
09-AB	12.4	14.9	14.70	13.70	13.2	13.1	13.5	12.3	12.6	11	13.1	12.2	11.2
MEAN	34.75	33.64	31.92	31.83	32.78	33.65	33.82	34.78	35.90	33.61	35.08	35.66	34.81
SD	30.52	25.08	24.50	24.75	24.37	24.98	24.82	25.09	25.90	23.31	26.53	26.93	26.45

	TWITCH											
	13	14	15	16	17	18	19	20	21	22	23	24
01_AB	46.46	48.33	44.00	51.42	49.72	47.59	50.31	48.83	47.28	48.43	52.40	54.99
02_AB	19.04	17.62	17.95	17.57	17.28	19.34	19.22	19.74	15.29	16.74	15.82	16.43
03_AB	24.17	23.1	24.44	23.18	25.11	24.38	25.49	24.27	21.36	22.4	19.7	18.94
04_AB	81.95	81.2	82.8	85	83	82.31	82.8	82.49	90.22	90.63	92.45	91.69
06_AB	31.26	31.41	29.15	28	29.98	29.07	28.28	28.21	29.3	27.39	26.82	26.73
09-AB	13.2	11.1	12.3	12.1	11.7	11.8	12.3	11.6	15.6	18.4	16.7	17.4
MEAN	36.01	35.46	35.11	36.21	36.13	35.75	36.40	35.86	36.51	37.33	37.32	37.70
SD	25.26	25.84	25.76	27.49	26.43	25.79	26.11	26.01	28.88	28.52	30.25	30.17

	TWITCH												
	25	26	27	28	29	30	31	32	33	34	35	36	37
01_AB	53.54	57.72	61.92	62.90	62.05	59.77	56.91	56.84	55.83	53.20	53.60	47.31	46.13
02_AB	15.73	16.25	17.12	15.66	15.98	16.61	15.67	15.65	15.45	15.05	14.92	14.78	14.18
03_AB	18.83	21.08	17.78	17.11	15.89	16.71	17.14	15.8	14.89	16.22	15.82	15.11	15.18
04_AB	94.35	92.4	96.36	96.84	97.13	96.8	95.04	93.1	93.72	91.4	88.33	83.13	84.25
06_AB	24.78	23.43	23.19	22.87	22.6	22.85	22.51	22.08	21.66	20.69	20.16	18.59	20.4
09-AB	15.1	16.1	14.9	16.5	17.2	16.2	15	13.9	13.8	14	13.6	14.9	14.6
MEAN	37.06	37.83	38.55	38.65	38.48	38.16	37.05	36.23	35.89	35.09	34.41	32.30	32.46
SD	31.54	30.98	33.39	33.78	33.81	33.31	32.58	32.25	32.53	31.33	30.45	27.94	28.16

M-wave Duration (ms)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_AB	28.00	23.25	26.00	26.50	26.25	27.50	27.00	26.75	26.00	26.75	26.75	28.75	27.25
02_AB	17.75	11.5	14.25	11	18.25	19.5	20	21.25	22	21	22.25	24	21
03_AB	28.75	25.75	28.75	28.5	28.75	28	26	27	27	28.75	29.75	27.75	21.75
04_AB	40.25	31.5	28.25	26.75	26.5	26.75	26.25	27.25	27.5	22.25	29.25	29	29.25
06_AB	24.5	28.5	23.75	28	30.5	31.5	32.75	35	35.5	35	32	34	32.25
09-AB	27.5	28.00	26.75	26.50	27.00	28.75	28.00	26.75	25.75	24.25	26.75	26.50	24.50
MEAN	27.79	24.75	24.63	24.54	26.21	27.00	26.67	27.33	27.29	26.33	27.79	28.33	26.00
SD	7.32	7.06	5.38	6.69	4.22	4.02	4.10	4.40	4.46	5.11	3.36	3.32	4.39

	TWITCH											
	13	14	15	16	17	18	19	20	21	22	23	24
01_AB	26.25	27.00	27.50	28.25	28.25	28.50	29.25	31.50	30.50	32.50	34.25	35.25
02_AB	20.25	20.75	22	26.5	26.5	21.25	24	23.75	27.75	27	22	22.75
03_AB	27	23.5	27	24.25	27	25.5	26.75	26.5	24.5	28.5	24.75	23.5
04_AB	27.5	27.25	28.75	31.25	29.75	29.5	28.75	29.25	37.75	39.75	43	40.75
06_AB	33.25	32.25	32	28	30.25	30.5	31.25	32.5	45.5	41.5	39.5	40.25
09-AB	29.50	26.50	29.00	30.75	29.50	28.00	28.50	30.00	34.75	46.50	42.00	44.00
MEAN	27.29	26.21	27.71	28.17	28.54	27.21	28.08	28.92	33.46	35.96	34.25	34.42
SD	4.27	3.88	3.30	2.62	1.54	3.37	2.47	3.27	7.57	7.80	8.99	9.19

	TWITCH												
	25	26	27	28	29	30	31	32	33	34	35	36	37
01_AB	32.25	37.00	43.00	42.50	42.50	43.00	39.25	39.75	40.75	33.25	40.00	31.75	30.75
02_AB	23	19.75	20.75	19.5	20.25	18.75	17.75	17.25	17	16.5	16.5	16	17.25
03_AB	23.75	26.75	22.5	22.25	20.75	20.5	21.5	21.5	19.25	20	20.25	19.5	20
04_AB	41.75	42	44	45.25	46.25	44	44	41.75	44	41.75	37.75	33.25	35.25
06_AB	35.25	29	28.25	27	26.75	25.5	25.75	25.5	24.75	24.25	23.5	21.25	21
09-AB	37.25	35.75	36.00	45.50	47.25	43.75	38.75	34.25	36.75	32.25	33.75	31.75	29.00
MEAN	32.21	31.71	32.42	33.67	33.96	32.58	31.17	30.00	30.42	28.00	28.63	25.58	25.54
SD	7.51	8.06	10.11	12.06	12.77	12.26	10.87	10.06	11.56	9.43	9.82	7.52	7.12

MVC (Nm)

	1	2	3	4	5	6	7	8	9	10	11
01_AB	34.68	32.61	32.54	32.99	32.36	30.97	29.35	29.34	31.63	30.84	31.16
02_AB	48.85	41.92	43.43	41.77	39.23	37.35	37.45	37.01	39.37	37.19	36.97
03_AB	48.17	41.60	41.05	38.53	38.13	38.73	37.47	25.26	36.17	34.55	37.41
04_AB	31.54	38.42	38.78	39.17	38.53	37.74	35.70	24.70	33.69	29.48	33.09
06_AB	55.54	44.95	48.48	47.28	45.73	44.33	44.41	42.32	43.06	40.14	39.09
09_AB	15.94	14.47	17.33	15.29	13.04	18.83	9.97	20.24	21.11	16.13	19.88
MEAN	39.12	35.66	36.93	35.84	34.50	34.66	32.39	29.81	34.17	31.39	32.93
SD	14.56	11.20	10.95	11.09	11.34	8.84	11.99	8.33	7.58	8.45	7.04

	12	13	14	15	16	17	18	19	20
	31.08	29.37	15.77	29.72	18.28	30.62	31.45	9.27	32.71
	35.44	36.10	34.63	34.66	35.39	33.83	34.70	36.02	33.23
	35.49	35.99	35.80	33.90	34.17	34.28	32.98	33.01	31.51
	32.64	28.26	29.05	29.37	30.02	21.14	28.87	22.91	26.69
	37.37	36.88	36.36	35.71	32.70	34.16	33.23	35.49	34.75
	19.06	18.03	20.67	19.22	22.10	19.83	2.66	18.18	14.50
	31.85	30.77	28.71	30.43	28.78	28.98	27.31	25.81	28.90
	6.66	7.26	8.67	6.08	6.99	6.73	12.24	10.86	7.57

Fatigue Index - PT	
01_AB	-47.18
02_AB	-8.04
03_AB	-15.54
04_AB	-1.57
06_AB	20.26
09_AB	-27.21
MEAN	-13.21
SD	22.97

Fatigue Index - MVC	
01_AB	5.68
02_AB	31.98
03_AB	34.59
04_AB	15.38
06_AB	37.43
09_AB	9.03
MEAN	22.35
SD	13.96

SCI Group
Twitch 1-20 = fatigue protocol
Twitch 1-37 = recovery period

PT (Nm)	Baseline	TWITCH 1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	6.50	6.73	3.62	4.67	3.82	2.91	2.59	2.30	1.98	1.60	1.38	1.12	0.96
02_SCI	3.70	8.02	8.50	8.94	8.63	8.19	7.66	7.17	6.71	6.16	5.53	4.95	4.32
03_SCI	1.88	2.03	2.13	2.08	2.18	2.14	2.21	2.15	2.11	2.07	2.02	2.00	1.98
04_SCI	2.06	2.23	3.10	2.86	3.32	3.54	3.53	3.39	3.24	3.26	3.14	3.02	2.89
06_SCI	5.19	7.41	4.94	5.08	5.04	4.94	4.92	4.74	4.66	4.53	4.37	4.16	4.01
09_SCI	3.34	2.87	2.67	2.89	2.87	2.82	2.79	2.73	2.76	2.62	2.62	2.57	2.41
MEAN	3.78	4.88	4.16	4.42	4.31	4.09	3.95	3.75	3.58	3.37	3.18	2.97	2.76
SD	1.80	2.78	2.33	2.50	2.33	2.22	2.05	1.92	1.82	1.71	1.54	1.40	1.26

TWITCH 13	14	15	16	17	18	19	20	21	22	23	24
0.86	0.65	0.62	0.62	0.65	0.50	0.52	0.23	0.69	2.17	2.24	2.24
3.64	2.97	1.11	1.68	1.51	1.19	1.04	0.94	1.52	1.52	1.47	1.44
1.95	1.91	1.68	1.98	1.93	1.95	1.80	1.82	2.21	2.22	2.35	2.44
2.85	2.76	2.70	2.63	2.61	2.54	2.43	2.35	2.39	2.29	2.24	2.23
3.87	3.69	3.45	3.30	3.22	2.95	2.78	2.71	2.71	2.85	2.93	2.92
2.31	2.26	2.18	2.05	1.95	1.97	1.91	1.80	1.73	1.73	1.78	1.86
2.58	2.37	1.96	2.04	1.98	1.85	1.75	1.64	1.88	2.13	2.17	2.19
1.12	1.04	1.04	0.90	0.89	0.89	0.85	0.91	0.73	0.47	0.50	0.50

TWITCH 25	26	27	28	29	30	31	32	33	34	35	36	37
1.89	2.47	2.08	1.71	1.47	1.61	1.59	2.90	2.56	3.41	2.21	2.15	1.85
1.46	1.47	1.50	1.50	1.60	1.72	1.74	1.80	1.89	1.75	1.91	2.31	2.57
2.56	2.71	2.88	2.91	2.93	2.96	3.09	2.81	2.73	2.69	2.83	2.40	2.24
2.16	2.22	2.26	2.24	2.22	2.20	2.24	2.27	2.22	2.25	2.24	2.25	1.76
3.11	3.11	2.84	3.14	3.22	3.45	3.67	3.68	3.73	3.87	3.93	4.16	3.99
2.01	2.01	2.32	2.59	2.64	2.92	3.03	2.99	3.17	3.26	3.32	3.35	3.21
2.20	2.33	2.31	2.35	2.35	2.48	2.56	2.74	2.72	2.87	2.74	2.77	2.60
0.57	0.57	0.51	0.65	0.71	0.75	0.83	0.64	0.66	0.79	0.77	0.81	0.86

TPT (ms)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	92.25		110.75	143.75	158	174	219.5	203.5	206.25	212	237.25	237.5	225.5
02_SCI	64.50	79.25	83.75	87.25	89.50	99.50	100.25	110.75	114.50	119.75	120.50	131.25	125.00
03_SCI	137.50	138.00	157.75	174.75	171.50	182.75	208.75	218.50	230.00	237.00	222.25	235.25	154.25
04_SCI	94.50	61.25	69.25	60.50	73.75	82.50	85.00	86.50	92.75	93.25	89.25	97.25	101.25
06_SCI	92.25	169.50	81.75	93.00	99.00	102.75	111.50	109.75	124.00	119.00	122.50	124.25	118.50
09_SCI		118.75	117.00	110.75	116.50	117.25	121.75	130.00	348.25	122.00	133.00		128.50
MEAN	96.20	113.35	103.38	111.67	118.04	126.46	141.13	143.17	185.96	150.50	154.13	165.10	142.17
SD	26.19	43.78	32.29	41.41	38.98	41.80	57.95	54.53	96.25	58.81	60.56	66.30	44.29

TWITCH											
13	14	15	16	17	18	19	20	21	22	23	24
220.75	226.5	217	207	185	229.5	205.5	260.5	182.25	103	97.75	102.25
131.00	124.00	204.75	105.00	107.75	89.50	84.50	66.25	72.75	72.00	67.75	71.00
157.75	154.50	261.00	146.50	150.00	140.75	147.25	152.00	142.50	151.50	230.75	227.50
103.50	102.00	100.75	96.00	110.00	98.75	100.50	98.75	95.00	96.25	98.75	82.75
124.00	136.25	139.00	134.25	128.50	131.25	130.00	115.75	72.75	92.25	87.50	86.50
144.75	144.00	152.00	132.00	142.75	150.25	141.00	150.75	127.50	139.25	132.25	134.75
146.96	147.88	179.08	136.79	137.33	140.00	134.79	140.67	115.46	109.04	119.13	117.46
40.59	42.55	58.79	39.31	28.85	49.89	42.24	67.09	43.37	30.23	58.56	58.24

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
102.25	102.5	106.75	118.25	125	123.5	127.25	101.5	101.25	99.25	105.5	103.25	91.75
71.25	72.25	63.75	64.75	67.75	60.00	64.75	63.50	60.25	60.00	61.75	52.50	50.50
230.50	234.50	264.75	268.50	268.75	274.00	287.25	270.00	270.00	278.50	261.00	218.00	207.00
91.00	92.25	94.50	104.25	95.50	96.00	94.50	103.00	102.50	110.00	95.00	89.50	76.50
84.75	86.75	104.75	82.75	100.25	87.75	87.00	88.25	89.75	86.25	84.75	76.75	77.50
141.50	131.50	130.25	142.50	132.50	147.75	148.50	135.00	147.75	143.50	148.00	173.25	139.00
120.21	119.96	127.46	130.17	131.63	131.50	134.88	126.88	128.58	129.58	126.00	118.88	107.04
59.07	59.51	70.63	72.98	71.02	76.05	80.38	73.86	74.79	77.97	72.00	63.36	57.01

1/2 RT (ms)

	Baseline	TWITCH 1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	96	71.25	60.25	91.25	97.25	99.5	119.5	125.75	136.25	156.5	158.25	181.25	196.75
02_SCI	64.00	66.75	75.00	95.00	111.25	120.75	140.25	153.00	173.25	192.75	216.75	233.50	265.00
03_SCI		162.25	144.75	163.25	174.50	182.75	168.00	176.00	182.50	191.75	215.75	217.75	
04_SCI	130.00	85.75	95.00	89.25	101.00	105.50	117.25	134.75	138.00	147.75	156.50	157.50	161.00
06_SCI	130.00		115.00	120.25	125.25	134.25	143.50	164.50	163.75	188.25	195.50	203.50	217.50
09_SCI	120.00	79.50	85.00	98.50	101.50	106.75	110.75	115.75	137.75	143.50	140.50	156.50	161.75
MEAN	108.00	93.10	95.83	109.58	118.46	124.92	133.21	144.96	155.25	170.08	180.54	191.67	200.40
SD	28.25	39.35	30.26	28.56	29.26	30.99	21.51	23.39	20.51	23.25	33.02	31.88	43.37

	TWITCH 13	14	15	16	17	18	19	20	21	22	23	24
01_SCI	202.25	0	201.75	208.25	205.75	188.75	198.5	195.5	214	165.5	158.5	154.5
02_SCI	276.25	285.25	59.50	272.00	239.25	207.50	179.50	168.50	191.00	172.25	158.25	150.75
03_SCI					299.25	317.00				310.75		
04_SCI	160.50	161.25	166.25	170.50	158.75	162.00	158.50	155.25	151.25	142.75	132.25	146.75
06_SCI	225.25	211.75	212.00	215.50	229.75	216.25	213.25	218.50	216.25	207.50	199.25	193.25
09_SCI	151.50	159.00	151.50	175.25	162.00	157.00	161.50	153.00	166.00	144.00	141.00	130.25
MEAN	203.15	163.45	158.20	208.30	215.79	208.08	182.25	178.15	187.70	190.46	157.85	155.10
SD	50.79	104.77	60.50	40.71	52.84	58.37	23.60	28.19	28.80	63.48	25.76	23.25

	TWITCH 25	26	27	28	29	30	31	32	33	34	35	36	37
01_SCI	155.5	142.5	150.75	143.5	150.5	163.5	152.5	151.75	149.5	145.75	140.75	140.75	132.25
02_SCI	143.00	136.00	134.00	122.25	118.00	124.00	118.25	117.50	120.25	106.75	106.75	90.75	72.50
03_SCI													234.75
04_SCI	135.25	131.75	139.75	137.25	150.00	149.50	157.00	142.50	148.00	140.25	162.00	132.50	122.25
06_SCI	196.75	193.50	179.25	227.75	209.25	232.50	222.50	217.25	206.25	202.50	200.50	162.50	132.50
09_SCI	126.00	124.50	127.25	124.25	134.00	139.75	134.00	148.75	127.00	139.00	139.25	152.25	168.00
MEAN	151.30	145.65	146.20	151.00	152.35	161.85	156.85	155.55	150.20	146.85	149.85	135.75	143.71
SD	27.61	27.54	20.39	43.81	34.51	42.03	39.82	37.03	33.85	34.68	34.52	27.61	54.16

RTD (Nm/s)

	Baseline	TWITCH 1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	130.78	85.566	93.039	88.182	78.841	60.532	46.333	46.333	37.739	32.134	29.892	24.661	23.166
02_SCI	149.83	276.13	313.12	288.09	292.57	236.15	206.26	183.84	165.53	147.97	131.90	120.32	102.38
03_SCI	42.60	54.18	48.95	50.82	50.44	56.80	52.31	52.31	51.56	47.83	47.45	45.59	45.96
04_SCI	134.14	206.26	247.73	310.13	303.03	276.50	279.12	251.09	232.41	229.80	235.77	210.74	202.89
06_SCI	133.02	169.26	130.40	127.79	127.79	127.42	122.93	115.83	110.60	106.12	96.40	93.04	91.92
09_SCI	109.11	94.16	78.47	80.34	77.72	75.10	81.08	70.25	60.91	73.61	58.66	51.94	61.65
MEAN	116.58	147.59	151.95	157.56	155.07	138.75	131.34	119.94	109.79	106.24	100.01	91.05	88.00
SD	38.51	84.69	104.97	112.58	113.39	95.37	93.29	82.17	76.31	73.45	75.96	68.10	63.38

TWITCH 13	14	15	16	17	18	19	20	21	22	23	24
24.661	20.924	19.056	22.045	21.672	18.683	16.814	13.825	20.177	50.069	53.059	51.938
93.04	90.80	59.41	162.91	63.52	65.02	60.16	61.65	73.98	99.02	95.66	108.73
41.48	42.60	43.34	46.71	44.84	44.47	38.49	43.34	63.89	62.03	66.88	63.15
194.30	189.07	183.84	179.35	183.84	184.21	176.74	174.50	168.89	172.63	189.07	183.46
81.83	78.09	75.48	72.12	65.39	71.37	62.03	62.40	98.64	72.12	70.62	73.98
58.66	53.06	57.17	54.18	46.71	50.07	52.69	48.58	48.20	46.33	47.08	56.80
82.33	79.09	73.05	89.55	70.99	72.30	67.82	67.38	78.97	83.70	87.06	89.68
60.34	59.37	57.47	65.41	57.49	57.83	55.94	55.37	51.24	47.48	52.75	50.23

TWITCH 25	26	27	28	29	30	31	32	33	34	35	36	37
41.475	56.421	49.696	37.365	34.75	36.618	36.992	64.642	61.279	73.609	48.948	46.706	48.948
107.99	110.60	112.47	82.95	101.26	100.51	96.40	81.08	77.72	92.29	86.31	94.53	101.26
66.51	57.54	59.78	52.31	65.76	53.06	71.74	57.92	47.45	44.84	47.08	36.99	42.97
187.20	199.53	195.79	193.18	175.99	175.24	173.37	168.14	183.84	166.28	184.96	153.57	106.49
73.98	78.47	65.02	77.35	78.09	85.19	87.81	100.89	99.39	104.25	110.98	109.85	122.56
58.29	66.88	71.74	63.52	77.72	70.62	86.31	96.78	69.13	94.16	82.20	76.60	111.72
89.24	94.91	92.42	84.45	88.93	86.87	92.11	94.91	89.80	95.90	93.41	86.38	88.99
52.79	55.00	55.06	55.79	47.85	48.85	45.00	39.69	49.22	40.35	50.97	42.99	34.12

RTR (Nm/s)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	-53.06	-73.236	-56.048	-43.717	-34.376	-27.65	-21.672	-22.045	-20.177	-13.451	-13.451	-14.199	-13.825
02_SCI	-43.72	-96.78	-98.64	-78.84	-69.13	-62.03	-58.29	-47.45	-42.22	-34.75	-33.63	-27.28	-21.30
03_SCI	-17.56	-25.04	-26.90	-20.55	-21.67	-23.17	-18.68	-16.44	-17.56	-17.19	-16.07	-16.81	-16.81
04_SCI	-69.87	-88.93	-99.77	-127.42	-134.89	-115.83	-133.02	-106.49	-104.25	-98.64	-105.74	-90.80	-90.42
06_SCI	-44.09	-29.15	-41.85	-38.86	-38.49	-37.37	-32.13	-33.63	-28.77	-27.28	-25.04	-25.78	-23.17
09_SCI	-25.03	-42.97	-36.62	-39.23	-32.13	-33.63	-30.27	-30.27	-27.65	-23.91	-23.91	-25.78	-23.91
MEAN	-42.22	-59.35	-59.97	-58.10	-55.11	-49.94	-49.01	-42.72	-40.11	-35.87	-36.31	-33.44	-31.57
SD	18.93	31.07	31.82	38.93	42.22	35.00	43.47	33.00	32.58	31.66	34.76	28.61	29.09

TWITCH											
13	14	15	16	17	18	19	20	21	22	23	24
-13.078	-12.331	-12.331	-12.331	-12.331	-13.078	-10.836	-13.451	-15.32	-16.067	-19.056	-17.188
-20.55	-18.31	-24.29	-88.93	-14.20	-13.08	-14.57	-16.44	-17.19	-14.57	-16.07	-14.95
-40.35	-15.32	-15.32	-15.32	-16.44	-17.94	-16.07	-14.20	-16.07	-17.19	-16.81	-16.81
-93.04	-93.79	-91.55	-84.82	-88.18	-83.32	-86.69	-87.06	-81.46	-91.92	-101.26	-91.55
-21.67	-25.04	-20.18	-20.18	-22.42	-18.68	-18.31	-18.68	-68.38	-19.06	-21.30	-19.06
-26.53	-23.17	-19.43	-42.22	-19.06	-20.55	-18.31	-23.54	-18.31	-18.31	-22.42	-20.18
-35.87	-31.32	-30.52	-43.97	-28.77	-27.77	-27.46	-28.90	-36.12	-29.52	-32.82	-29.95
29.43	30.96	30.18	34.87	29.32	27.38	29.15	28.73	30.35	30.61	33.62	30.23

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
-18.683	-22.045	-20.551	-17.188	-17.935	-13.825	-16.067	-19.43	-18.683	-23.914	-32.508	-17.935	-18.309
-18.31	-16.44	-15.69	-17.19	-16.81	-18.31	-20.18	-19.06	-19.06	-22.42	-22.42	-22.79	-29.15
-18.31	-16.44	-14.95	-17.56	-19.43	-14.20	-15.32	-13.83	-14.57	-14.95	-16.44	-16.07	-19.80
-106.86	-107.99	-93.79	-93.04	-86.69	-81.08	-93.79	-63.89	-86.31	-71.37	-104.62	-47.08	-41.85
-19.43	-20.55	-19.80	-18.68	-19.06	-21.67	-20.92	-20.92	-21.30	-20.92	-28.02	-24.66	-29.15
-20.55	-27.28	-26.53	-23.91	-25.41	-23.17	-89.68	-25.78	-28.77	-28.02	-25.41	-26.53	-112.84
-33.69	-35.12	-31.89	-31.26	-30.89	-28.71	-42.66	-27.15	-31.45	-30.27	-38.24	-25.84	-41.85
35.86	35.92	30.61	30.37	27.50	25.94	38.10	18.40	27.28	20.58	32.97	11.14	35.79

M-wave Amplitude (mV)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	1.97	2.03	1.82	1.77	1.57	1.31	1.23	1.26	1.16	1.07	1.02	0.82	0.94
02_SCI	5.32	6.18	6.35	6.30	6.25	6.33	6.47	6.59	6.66	6.81	6.95	6.99	7.02
03_SCI	0.93	0.75	0.93	0.99	0.91	0.85	0.91	0.89	0.92	0.90	0.86	0.87	0.80
04_SCI	2.52	3.11	3.53	3.84	3.86	3.75	3.74	3.86	3.89	3.93	3.95	4.00	3.96
06_SCI	3.10	3.72	4.02	4.38	4.53	4.66	4.70	4.85	4.87	4.91	4.92	4.93	4.89
09_SCI	1.24	1.60	1.64	1.64	1.60	1.55	1.63	1.70	1.74	1.85	1.91	1.87	1.90
MEAN	2.51	2.90	3.05	3.15	3.12	3.08	3.11	3.19	3.21	3.25	3.27	3.25	3.25
SD	1.59	1.93	2.00	2.04	2.09	2.19	2.23	2.28	2.31	2.37	2.43	2.48	2.47

TWITCH											
13	14	15	16	17	18	19	20	21	22	23	24
0.84	0.99	0.69	0.62	0.71	0.60	0.72	0.32	0.67	1.82	1.77	1.63
7.04	6.97	6.91	6.76	6.76	6.47	6.39	6.29	6.10	6.05	5.94	6.00
0.66	0.69	0.80	0.66	0.68	0.64	0.73	0.69	0.75	0.82	0.83	0.84
3.98	3.96	3.96	3.93	3.93	3.90	3.88	3.83	3.46	3.32	3.29	3.21
4.90	4.86	4.81	4.74	4.72	4.64	4.59	4.54	4.12	3.85	3.76	3.70
1.94	1.96	1.97	1.95	1.94	1.89	1.89	1.84	1.70	1.73	1.66	1.70
3.23	3.24	3.19	3.11	3.12	3.02	3.03	2.92	2.80	2.93	2.88	2.85
2.52	2.46	2.47	2.46	2.43	2.37	2.30	2.35	2.14	1.89	1.86	1.88

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
1.59	1.77	1.65	1.46	1.24	1.24	1.17	1.67	1.59	1.80	1.26	0.99	0.87
5.95	5.98	6.01	6.04	6.09	6.19	6.25	6.34	6.39	6.43	6.44	6.11	5.77
0.82	0.78	0.85	0.81	0.89	0.92	0.88	0.87	0.79	0.84	0.88	0.89	0.93
3.20	3.18	3.18	3.16	3.15	3.14	3.11	3.09	3.04	3.03	3.04	2.84	2.78
3.67	3.70	3.71	3.64	3.68	3.77	3.90	3.93	3.97	3.90	4.00	4.12	3.79
1.66	1.70	1.68	1.63	1.62	1.63	1.54	1.51	1.53	1.51	1.57	1.83	1.76
2.82	2.85	2.85	2.79	2.78	2.82	2.81	2.90	2.89	2.92	2.87	2.80	2.65
1.87	1.87	1.88	1.92	1.96	1.99	2.06	2.02	2.07	2.04	2.11	2.03	1.90

M-wave Area (mV*ms)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	23.98	20.85	19.16	19.18	17.14	14.11	13.07	13.58	12.17	11.31	10.12	7.59	9.02
02_SCI	47.30	71.29	47.45	51.72	55.03	57.34	61.56	64.33	66.94	69.66	71.81	72.63	72.25
03_SCI	5.28	4.51	6.24	6.16	5.87	5.21	5.25	5.33	4.92	4.99	4.97	5.12	4.37
04_SCI	26.65	25.51	30.77	31.96	34.35	38.76	38.85	38.01	38.89	39.20	40.19	40.61	40.66
06_SCI	32.76	36.70	38.70	42.90	46.20	48.50	51.40	54.70	56.80	58.80	59.80	59.90	60.30
09_SCI	13.16	21.60	22.70	23.10	25.10	24.60	26.40	28.00	28.20	30.30	31.20	50.20	30.90
MEAN	24.86	30.08	27.50	29.17	30.62	31.42	32.76	33.99	34.65	35.71	36.35	39.34	36.25
SD	14.77	22.69	14.69	16.56	18.32	20.25	21.90	22.98	24.42	25.56	26.54	27.68	27.13

	TWITCH											
	13	14	15	16	17	18	19	20	21	22	23	24
01_SCI	8.33	9.79	6.69	5.91	6.82	5.88	6.97	3.21	40.67	23.14	19.30	18.17
02_SCI	71.36	69.60	67.60	64.68	62.41	58.14	56.70	54.51	51.03	49.54	49.35	49.02
03_SCI	3.17	3.72	5.22	3.47	3.54	3.19	3.82	3.72	4.47	5.36	5.09	5.32
04_SCI	41.18	40.26	40.35	40.29	39.08	38.76	38.77	37.93	38.14	33.54	34.01	34.35
06_SCI	60.80	60.60	60.30	59.50	58.80	57.80	55.70	55.10	44.40	40.60	40.40	35.20
09_SCI	32.60	32.40	32.40	31.10	31.10	25.70	31.40	30.50	25.90	24.70	22.40	20.60
MEAN	36.24	36.06	35.43	34.16	33.63	31.58	32.23	30.83	34.10	29.48	28.43	27.11
SD	27.37	26.44	26.17	25.92	24.99	24.27	22.97	23.23	16.72	15.41	15.98	15.46

	TWITCH												
	25	26	27	28	29	30	31	32	33	34	35	36	37
01_SCI	17.87	19.26	18.45	15.82	13.55	14.01	13.85	19.78	19.62	22.44	16.24	11.89	10.92
02_SCI	49.35	49.67	50.40	52.14	54.39	54.69	56.93	59.09	58.19	60.12	58.69	66.60	59.57
03_SCI	4.95	4.75	5.11	4.49	5.30	4.75	4.92	4.28	4.27	4.69	4.85	4.91	5.56
04_SCI	34.26	34.13	36.52	37.85	38.64	40.31	40.41	41.65	41.24	41.71	40.94	37.95	34.69
06_SCI	59.60	35.80	40.30	45.30	46.10	46.90	50.10	49.10	47.80	45.80	45.20	43.20	43.00
09_SCI	21.30	20.70	15.70	19.30	20.70	20.40	21.30	20.90	23.30	30.70	26.00	24.10	20.50
MEAN	31.22	27.39	27.75	29.15	29.78	30.18	31.25	32.47	32.40	34.24	31.99	31.44	29.04
SD	20.54	15.72	17.27	18.70	19.47	19.93	20.95	20.78	20.09	19.41	19.94	22.61	20.55

M-wave Duration (ms)

		TWITCH											
	Baseline	1	2	3	4	5	6	7	8	9	10	11	12
01_SCI	45.25	40.25	40.25	42.25	41.50	44.25	41.50	46.50	42.25	43.50	42.50	35.00	39.75
02_SCI	43.00	36.75	32.50	34.25	35.50	34.75	38.00	38.75	38.25	40.50	41.75	41.50	42.25
03_SCI	22.00	24.00	28.00	26.00	22.00	22.75	25.00	25.50	21.75	22.50	24.75	24.50	22.75
04_SCI	32.25	32.25	36.50	35.00	38.00	49.50	49.75	42.00	42.00	40.75	45.00	42.00	43.25
06_SCI	39.00	41.00	36.50	37.25	40.50	39.75	40.50	42.75	47.75	47.75	48.25	47.50	47.50
09_SCI	28.00	54.75	58.75	52.25	57.75	57.50	58.00	54.75	53.00	55.75	57.00	61.50	58.00
MEAN	34.92	38.17	38.75	37.83	39.21	41.42	42.13	41.71	40.83	41.79	43.21	42.00	42.25
SD	9.06	10.25	10.65	8.82	11.51	12.06	11.17	9.65	10.68	11.03	10.60	12.38	11.52

TWITCH											
13	14	15	16	17	18	19	20	21	22	23	24
35.00	37.50	35.00	31.25	32.00	32.50	35.75	32.75	40.75	50.75	48.25	44.75
43.25	43.50	42.25	42.00	39.25	38.25	40.50	39.50	34.25	33.25	35.00	32.25
24.00	28.00	27.75	27.75	25.25	24.50	28.50	26.00	26.00	25.75	24.00	24.50
44.00	41.25	42.25	43.00	40.25	40.00	42.00	41.50	56.00	49.25	52.25	56.50
52.00	50.25	52.00	51.75	53.00	54.50	51.25	51.00	48.25	46.25	49.25	48.50
67.25	62.25	64.75	62.00	60.25	57.75	69.00	77.75	70.75	63.25	51.50	43.00
44.25	43.79	44.00	42.96	41.67	41.25	44.50	44.75	46.00	44.75	43.38	41.58
14.74	11.64	13.01	12.72	13.00	12.77	14.15	18.23	16.02	13.37	11.39	11.50

TWITCH												
25	26	27	28	29	30	31	32	33	34	35	36	37
45.25	45.75	45.00	42.75	44.00	44.75	50.00	51.50	52.75	55.00	56.00	58.00	56.00
35.00	32.25	31.50	33.00	36.75	32.75	34.50	36.25	33.25	36.00	32.25	55.50	52.25
24.25	23.50	23.75	25.25	25.75	24.25	23.00	21.75	24.75	23.00	25.50	21.00	26.00
57.00	54.00	55.00	57.00	56.00	58.50	56.75	59.00	58.00	58.25	56.00	44.75	38.25
52.75	52.75	52.25	73.00	72.00	79.25	80.50	77.25	74.00	70.00	66.50	55.75	56.75
49.50	46.00	41.75	44.00	52.50	53.75	60.00	56.75	73.00	48.45	87.00	68.75	54.75
43.96	42.38	41.54	45.83	47.83	48.88	50.79	50.42	52.63	48.45	53.88	50.63	47.33
12.23	12.05	12.04	17.11	16.11	19.61	20.21	19.27	20.26	16.77	22.53	16.40	12.49

TT (Nm)

	1	2	3	4	5	6	7	8	9	10	11
01_SCI	8.941	8.329	7.445	7.09	6.775	6.288	5.924	5.396	4.908	4.536	3.812
02_SCI	22.90	19.94	20.51	20.79	20.51	20.00	19.67	19.08	17.98	16.85	15.29
03_SCI	6.58	5.64	5.05	4.68	5.24	4.69	4.58	4.30	4.15	3.85	3.67
04_SCI	7.13	7.17	6.69	6.98	6.93	6.82	7.03	7.13	7.08	6.98	6.66
06_SCI	12.65	7.52	11.20	10.92	10.73	10.36	10.21	9.89	9.56	8.92	8.56
09_SCI	4.75	4.44	4.27	4.25	4.26	4.26	4.17	4.24	4.21	4.38	4.34
MEAN	10.49	8.84	9.19	9.12	9.08	8.74	8.60	8.34	7.98	7.59	7.06
SD	6.64	5.61	6.05	6.19	6.02	5.93	5.84	5.67	5.32	4.93	4.46

12	13	14	15	16	17	18	19	20
3.671	3.179	2.804	2.613	2.483	2.336	2.273	2.461	2.253
13.49	11.80	9.80	8.18	6.54	5.41	4.73	3.96	3.51
3.58	3.46	3.30	3.16	6.34	3.23	3.30	3.15	3.11
6.38	6.07	5.95	5.65	5.27	4.66	4.54	4.68	4.22
8.08	7.76	7.19	7.00	6.34	6.14	5.93	5.55	5.34
4.12	4.25	4.18	4.13	3.72	3.60	3.47	3.27	3.22
6.55	6.09	5.54	5.12	5.11	4.23	4.04	3.85	3.61
3.83	3.29	2.66	2.20	1.67	1.43	1.29	1.13	1.06

Fatigue Index - PT	
01_SCI	96.46
02_SCI	74.59
03_SCI	6.00
04_SCI	-14.08
06_SCI	47.78
09_SCI	46.11
MEAN	42.81
SD	41.27

Fatigue Index - TT	
01_SCI	74.83
02_SCI	84.67
03_SCI	52.74
04_SCI	40.81
06_SCI	57.79
09_SCI	32.21
MEAN	57.175
SD	19.89365