A Comparison of Muscle Fatigue Responses between Static and Quasi-Static Exertions

By

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Thesis

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ABSTRACT

Background: This study examined localized muscle fatigue responses from sub-maximal quasi-static work protocols and additionally how it compares to purely static work. The goal was to produce research that enhances the understanding of the demands on muscles during manual work to aid in preventing injuries stemming from localized muscle fatigue. Injury rates remain a problem in manual labour sectors, particularly for the lower back and shoulder regions for the manufacturing, service and construction sectors, and for knee and elbow flexors in the sports sector. Few studies have looked at quasi-static work and what the resulting fatigue characteristics are, especially when compared to purely static or purely dynamic work. This comparison is particularly important due to the fact that risk assessment tools that are currently utilized to assess risk in the working environment are based on fatigue studies that focus on purely static or purely dynamic work. This requires attention as many working situations are neither static nor dynamic, but rather quasi-static in nature, with aspects of both dynamic and static muscle components. The scope of this study only encompasses the comparison between purely static and quasi-static work.

Objectives: This study had two objectives, firstly, to determine what the fatigue characteristics of quasi-static work are and how it compares to fully static work. Secondly, to determine whether an underlying static component within an otherwise dynamic muscle force affects localized muscle fatigue compared to quasi-static work that has equal amounts of effort but with no underlying static component.

Methods: Four experimental conditions were tested, each on four muscles, namely the medial deltoid, bicep brachii, bicep femoris and erector spinae muscles. To test the two objectives of this study, 16 volunteers performed a five minute fatigue protocol, that either entailed a fully static condition which involved: 1) producing a steady force at 25 percent of maximum voluntary force, 2) a quasi-static condition with fully dynamic muscle force that alternates the required force level between zero and 50 percent of maximum force, 3) a quasi-static condition with an underlying static component of five percent of maximum force, or 4) a quasi-static condition with a large underlying static component of 15 percent of maximum force. All the experimental conditions in this

study had the same average workload of 25 percent of maximum voluntary force over time and thus total workload. The dependant variables of interest were ratings of perceived exertion, changes in muscle fibre recruitment (% of maximum EMG activity), maximum force and center frequency from a spectral analysis of the surface electromyography. These were measured throughout the protocols at one minute intervals to determine how muscle fatigue progressed, and how the fatigue responses differed between conditions.

Results: The data from comparing fully static and quasi-static work showed that of the variables measured, the rating of perceived exertion (RPE) and maximum force data indicated that for bicep brachii and bicep femoris muscles, fully static work is more fatiguing than work that alternates between zero and 50 percent of maximum force. The results for the medial deltoid and erector spinae muscles were inconclusive. The findings regarding the comparison between quasi-static conditions with and without an underlying static component revealed that an underlying static component results in greater fatigue when compared to a quasi-static condition with no static component. The results may also suggest that a larger static component coupled with a smaller peak force results in less fatigue than a condition with a small underlying static component coupled with a higher peak force in some scenarios, provided total work is kept constant. All conditions had to have the same workload in order to be validly compared and thus the condition with a larger underlying static component had a lower peak force compared to the condition with no underlying static component or the condition with a small underlying static component.

Conclusions: This study presented evidence that quasi-static work does not induce fatigue when measured by RPE and drop in maximum force in the same way as static work. Additionally, the results indicate that a larger underlying static component does not necessarily fatigue a muscle faster if the overall workload is kept constant. However, the results do suggest that any underlying static component will increase the demand on a muscle when compared to a muscle exertion with no static component. When considering the available literature on how muscles fatigue during low level static contractions, the current understanding is that the larger the force during a static contraction, the faster the onset of fatigue and decrements in performance occur. The results of this study suggest that this same relationship cannot

be applied to quasi-static work where an underlying static component is part of an otherwise dynamic muscle force. Thus total workload or peak force may play a larger role than the static muscle exertion in some scenarios.

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DECLARATION

This page declares that the work produced is my own and was conducted whilst completing the degree of Masters of Science in Ergonomics whilst at Rhodes University, Grahamstown, South Africa. This thesis has not been submitted to other Universities, Technikons or Colleges for degree purposes.

Conrad Du Toit Nel

Signed: 

Date: 2015/12/11

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND TO THE STUDY

The injury rate in South Africa for individuals working in manual jobs remains a problem (Health and Safety Executive, 2015). Many of the injuries obtained by manual workers incur from overuse, possibly originating from muscle fatigue levels that exceed recovery rates which could theoretically result in injury (Dugan and Frontera, 2000). Musculoskeletal problems can occur in a diverse range of physical occupations, for example manufacturing activities (Maeda, 1977; Jonsson *et al*., 1988; Veiersted, 1994), the service industry (Sommerich *et al*., 1993; Vasseljen *et al*., 2001) and the construction sector (Malmqvist *et al.*, 1981).

Muscle fatigue has been receiving increasing attention as a research variable to prevent musculoskeletal disorders in the workplace, as well as maintaining optimal levels of productivity, which is critical in the manual labour sector, with muscle fatigue during sustained static work being thoroughly investigated (Sj∅gaard *et al.,* 1986; Jonsson, 1988; Masuda *et al.,* 1999).

Research into muscle fatigue has been conducted extensively on prolonged static work (Bigland-Ritchie *et al*., 1986; Gandevia and McKenzie, 1988; Sahlin *et al*., 1992) and there is also literature on muscle fatigue rates during dynamic contractions at set repetition rates (Potvin and Bent, 1997; Sherman, 2003). Within the literature on muscle fatigue from dynamic and static force exertions, the muscle pump effect has also been studied, and these studies have shown that dynamic and static muscle exertions have different levels of blood flow to the muscles under investigation (Sj∅gaard *et al.,* 1986; Jonsson, 1988), hence resulting in different fatigue responses such as a decrease in maximum force output, increased muscle fibre recruitment, depletion of glycogen levels, metabolite build-up within the muscle and subjective feelings of discomfort (Komi and Tesch, 1979; Nussbaum, 2001). What has been suggested from current research regarding blood flow levels during static and dynamic exertions, is that static work negatively effects blood flow levels compared to dynamic work, and furthermore, the greater the relative muscle workload of the static exertion

the worse this negative impact of blood flow becomes (Savard *et al.,* 1986; Jonsson, 1988; Rådegran, 1997; Laaksonen *et al.,* 2002). There are gaps in the literature on intermittent and quasi-static muscle exertions and their impact on muscle fatigue (Sherman, 2003). Fatiguing effects during intermittent and quasi-static work are less well studied and thus poorly understood. However, these are the most common types of work in actual manual jobs (Iridiastadi and Nussbaum, 2006). The studies that have been conducted on the work-rest cycles with regards to muscle fatigue are often difficult to compare due to the fact that the situations in the studies are very specific and structured around one specific scenario and thus this research cannot be used to understand muscle fatigue responses during quasi-static and intermittent work as a whole (Iridiastadi and Nussbaum, 2007). Further research into muscle fatigue accumulation is therefore needed to allow for more reliable injury risk assessments, and effective intervention strategies (Norman *et al*., 2007; Iridiastadi and Nussbaum, 2007).

As a result, risk assessment tools cannot fully identify and quantify the risk presented during an intermittent work task as there is little evidence to substantiate any evaluation they make Pascual and Naqvi, 2008). The risk assessment tools that are commonly available, such as the Snook/Mital tables (Snook and Ciriello, 1991), the National Institute of Occupational Safety and Health (NIOSH) lifting equation (Waters *et al*., 1993), rapid upper limb assessment (RULA) (McAtamney and Corlett, 2005) and the rapid entire body assessment (REBA) (Hignett and McAtamney, 2000) manage risk in a mostly one-dimensional fashion, in that they assume that a participant will either be performing a task with a static posture for the duration of the task and does not take into account dynamic motions and the impact of these dynamic motions occurring (Ma *et al*., 2008).

Alternatively, the risk assessment tools assume workers perform a task at a consistent speed, with a set repetition rate for the duration of the work shift, which is very rarely the case (Sherman, 2003). Thus, these tools are not sufficiently substantiated for assessing the risk of workers who are performing work with more complex work-rest schemes. For example, a manual materials handling task often requires workers to lift objects and carry them to another location. This results in the muscles in the arms working statically for approximately 5-6 seconds followed by a break of four seconds

before fetching the next object, thus allowing the muscle to relax (Triano, 2006). This type of work, which is common in industry, can thus not be assessed precisely via either a static or a dynamic based risk assessment tool, since this kind of quasi-static work and its effects on muscle fatigue remains understudied. Thus most of the work done in manual labour jobs is neither completely static nor dynamic, and therefore quasi-static work remains an important aspect to study (Pascual and Naqvi, 2008).

Intermittent work can be defined as a type of task that requires moderate to highly demanding physical effort which is interrupted by short periods of rest or light work lasting a few seconds to a few minutes (Sherman, 2003). The research that has been conducted on intermittent work and its effects on muscle fatigue is often only applicable to those very specific situations under investigation (Sherman, 2003; Iridiastadi and Nussbaum, 2007). The term “quasi-static” is similar to “intermittent” in that it refers to a task that is neither purely static nor purely dynamic in nature. However, quasi-static encompasses more than just the work to rest ratio; it also includes the dynamic and static components of the specific muscle action (Tsianos and Loeb, 2013). A quasi-static protocol could thus incorporate a static muscle force, or static muscle length, while keeping the other component unchanged compared to a fully dynamic protocol. This then allows for the specific components of a dynamic muscle exertion to be isolated and studied, thereby possibly shedding light on which aspects are responsible for the muscle pump effect (Tsianos and Loeb, 2013). Defining and researching this void in the literature could assist in reducing the accumulation of muscle fatigue and related injuries that occur in manual jobs (Sherman, 2003).

The two characteristics that define all muscles actions are muscle force and muscle length (Potvin and Bent, 1997; Tsianos and Loeb, 2013). For example, a purely dynamic task is characterized by having changes in both muscle force and muscle length over time (Tsianos and Loeb, 2013); whereas a purely static exertion has no change in force or muscle length and thus both have very different fatigue characteristics stemming primarily from blood flow differences. It is, however, not known which aspect, namely muscle length or muscle force, plays what role in changing the fatigue response. By having protocols that change either muscle length or muscle force compared to a purely static or purely dynamic exertion, one can then

determine what role the altered aspect had in changing a fatigue characteristic (Potvin and Bent, 1997; Tsianos and Loeb, 2013). Quasi-static work protocols allow for this differentiation between muscle length and muscle force and the subsequent fatigue responses to be attributed to a specific muscle action.

1.2 STATEMENT OF THE PROBLEM

The research that has been conducted on muscle fatigue and muscle fatigue rates during dynamic and static work has not prevented the increased prevalence of musculoskeletal disorders, poor productivity and performance levels as well as muscle recovery rates that negatively affect the manual labour sector (Health and Safety Executive, 2015). This is partially due to the fact that many aspects of muscle fatigue have remained unstudied and thus risk assessment tools cannot be fully accurate. The literature does not yet fully cover quasi-static work and the associated muscle fatigue that occurs when it is done (Sherman, 2003). As partly outlined previously, the research that has been done on quasi-static work is currently not sufficient to provide a general risk profile of this type of work. This may be due to the current studies investigating quasi-static work being limited to only the analysis of specific work tasks. These studies cannot be applied to situations outside that of the tasks and work regimes that were studied specifically in those studies. Thus quasi-static work needs to be systematically analysed and the different factors studied in order to understand how it differs from fully static and dynamic work. The current risk assessment tools may then employ this kind of information to assess the risk of any working situation. In order to give more accurate and valid risk assessments, their tools may need to be updated. This can only occur when quasi-static work is better understood, especially how a muscle responds to it compared to static and dynamic work.

Both muscle length and muscle force need to be studied as factors in order to determine which affects the muscle fatigue response in a particular way. The focus of this study will only be on investigating the effects of muscle force on local muscle fatigue responses. The effects of muscle length will not be investigated in this study. The equipment utilised are designed to test very specific work tasks and as the pilot tests revealed, the equipment could not accurately test the muscle fatigue responses of both dynamic muscle length and muscle force work protocols. The effects of muscle

force may aid in providing data on how variations in muscle force during otherwise static muscle exertions affect blood flow levels and fatigue.

1.3 AIMS OF THE STUDY

This research study had two aims: (1) to investigate whether, and to what extent, a work protocol that employs static muscle length and dynamic muscle force fatigues a muscle with the same fatigue characteristics as purely static work. It is expected that the purely static condition will place a greater demand on the muscles tested and induce more muscle fatigue than the condition with fully dynamic muscle force due to the potential differences in blood flow mentioned previously.

(2) To investigate how a constant underlying static exertion affects muscle fatigue responses during an otherwise dynamic muscle force work regime when performed with a static muscle length. It is expected that a low underlying static force exertion will cause a quasi-static condition with dynamic muscle force to fatigue with similar fatigue characteristics as a static work regime since the current literature suggests that the greater the static contraction, the greater the blood flow impingement.

1.3.1 Statistical Hypotheses

Hypothesis 1: This hypothesis tested whether variations in muscle force alone would have a significant impact on the muscle fatigue response when compared to purely static work. The null hypothesis states that the fatigue response is not dependant on muscle force. The alternate hypothesis stated that the fatigue response is dependent on muscle force.

H_o: $\mu SFSL = \mu DFSL0\text{-}50$

Where: SFSL is a condition that has static force and static length over time and is tested at 25 percent of maximum force. The μ refers specifically to the average rate of fatigue over time.

DFSL0-50 is a condition that has a fully dynamic force and static length over time and is tested at varying forces of 0 and 50 percent of maximum force

with a set timing that enforces a 25 percent muscle force average over the course of a minute.

H_a: μSFSL ≠ μDFSL0-50

The alternate hypothesis proposed that the average fatigue rates between condition SFSL and DFSL0-50 would be different.

Hypothesis 2: This hypothesis proposed that underlying static muscle forces of 5%MVC and 15%MVC have a significant impact on the muscle fatigue response compared to a force exertion with no underlying static exertion. The null hypothesis stated that minimal underlying static muscle forces of 5%MVC and 15%MVC would not have a significant impact on the muscle fatigue response.

H_o: μDFSL0-50 = μDFSL5-45 = μDFSL15-35

Where: DF-SL0-50 refers to the condition of dynamic force and static length as in the hypothesis above, where there is no underlying force and a contraction at 50%MVC (i.e. 0% maximum force). As with hypothesis 1, μ refers the average fatigue rate over time.

μDF-SL5-45 is a condition that has dynamic force and static length, with a constant underlying static force of 5% of maximum force, which then increases to 45%.

μDF-SL15-35 is a condition that has dynamic force and static length, with a constant underlying force of 15% of maximum force, which then increases to 35%. Thus all three condition average at 25 percent of maximum force as an average over the work protocol.

H_a: μDFSL0-50 ≠ μDFSL5-45 ≠ μDFSL15-35

The alternative hypothesis proposed that the average fatigue rate of conditions DFSL0-50, DFSL5-45 and DFSL15-35 would be different.

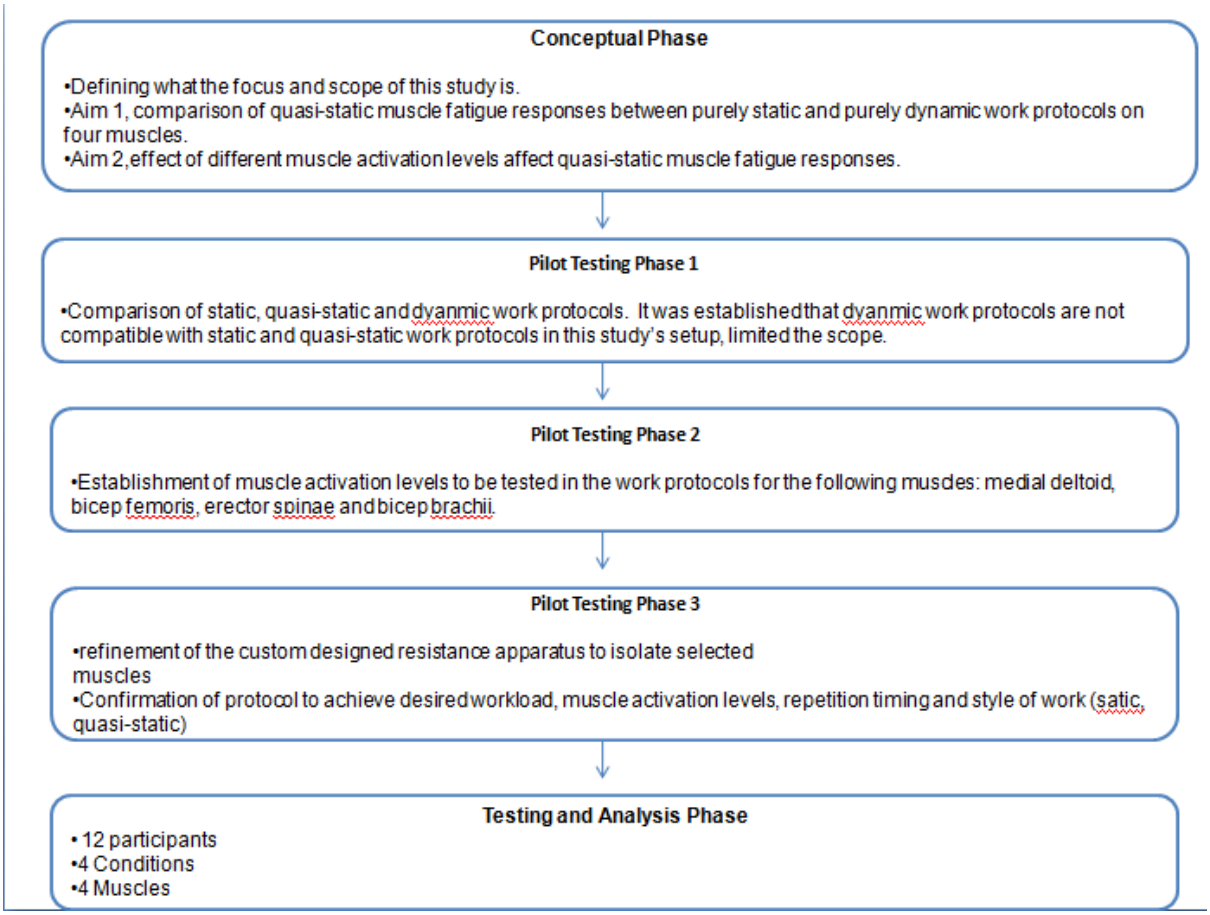
All conditions needed to have the same overall work load in order to be compared. This average was set at 25 percent of maximum force production being maintained over the course of the protocol. SFSL is kept at a constant 25 percent of maximum

force production, and the quasi-static conditions averaging at 25 percent maximum force production, e.g. 0-50%, 5-45% and 15-35%. All the quasi-static conditions had a set timing that enforced a 25 percent average of maximum force production over the course of a minute to ensure that the workloads during these conditions remained the same as the purely static condition.

1.4 DELIMITATIONS

The research was delimited to 8 female and 8 male participants aged between 18 and 25 years. All testing procedures were conducted in a laboratory setting and thus extreme environmental fluctuations were minimized. The conditions in this study were not specific to any one manual work schedule, or limited to tasks used in one industry or work setting. The conditions that were created to test the variables in this study had been designed with the purpose of testing the underlying principles of muscle fatigue, and different fatigue mechanisms that affect different work regimes. Thus the testing conditions can be relevant to a wide range of real world tasks.

Since this study investigated muscle fatigue which is a multifaceted topic, certain parameters had to be set. The research investigated the fatigue responses of four muscles, namely the medial deltoid, bicep brachii, bicep femoris and lower erector spinae muscles. These muscles were selected due to their high injury frequency rates in both manual work and sports as well as covering a diverse number of joints, muscle fiber architectures and sizes. A more detailed justification can be found in section 3.3. The chosen muscle activation levels were 5%, 15%, 25%, 45% and 50% for all muscles, however only the purely static condition had a constant muscle force of 25 percent of maximum muscle force for the duration of the protocol. The testing conditions in this study are unique and thus required a number of pilot tests and custom designed equipment. The procedure followed to reach the final data collection and analysis is sequenced in the summary boxes below.



1.5 LIMITATIONS

Due to the numerous conditions in this research employed to study a wide variety of work regimes, which would be tested on four muscles, it was necessary to test participants over 2 sessions, each lasting 90 minutes. This means that there would be intra and inter-individual variations in the participants' fatigue rates and strength due to factors like sleep, nutrition, fatigue from other activities and stress. To minimize the effects of these as much as possible, participants were given instructions on what to do or avoid prior to testing session. Additionally, the maximum voluntary strength protocol would be retested at the start of both testing sessions, meaning that the results from the fatigue measures would always be proportional to the maximum strength during that particular session. The motivation levels during the maximum strength tests may be dependent on how the individual is feeling that day and thus influence responses. The benefits of testing all conditions in one session, meaning only one maximum voluntary contraction test, did not outweigh the risks of accumulated fatigue, and thus two sessions were favoured. Verbal encouragement to

perform their current maximum exertion was the only method used for the participant to give their best effort. All participants were required to be of stature below 1.98m in order to be able to use the custom-designed equipment used in this study. All participants had the muscles on their right side tested, requiring all of them to be right side dominant.

Since the participants were taken mainly from a student population, and volunteers from the Grahamstown community, the applicability of the results may be limited to that group.

Two of the four fatigue measures were recorded with an electromyogram which can be affected by crosstalk when surface electrodes are used. Effort was made to ensure that interferences were kept to a minimum. The muscles tested were not in close proximity to each other. Only superficial muscles could be accessed by the EMG equipment. All the muscle fatiguing resistance apparatus that were used in this study to isolate a muscle and induce fatigue were custom-designed specifically for this study. As a result, the participants were unfamiliar with them; however during the introductory session, all participants were thoroughly habituated to prepare them for the different work regimes, and how they would be tested in conjunction with the custom designed resistance apparatus.

Finally, the rating of perceived exertion scale used in this study was clearly explained to all participants; however, it was not possible to ensure that they truly understood what the scale represented. What rating should be given to describe a certain degree of effort may have been unclear and thus there may be validity issues with this fatigue measure. This measure is a widely used measure however and has been demonstrated to be accurate and valid.

CHAPTER 2: REVIEW OF LITERATURE

This review of literature will be focusing on two topics, muscle contraction mechanics and muscle fatigue. Muscle contraction mechanics will include the general process of a muscle contraction and the different contraction properties of skeletal muscle. Additionally, the different types of contractions will be defined and discussed with further investigation into how the mechanics of a muscle contraction differ between them. The way in which the current researchers identify fatigue is also covered.

2.1 MUSCLE CONTRACTIONS

2.1.1 Sliding Filament Theory

The interaction between actin and myosin in Mg^{++} ion and adenosine triphosphate solution formed the sliding filament theory from the structure of the muscle fibres as well as measurements of the mechanics and energetics of fibre contraction (Cooke, 1986). The sliding filament theory explains how skeletal muscle contracts when two types of filaments consisting of the proteins actin and myosin slide past each other, with neither of the filaments length changing (Andersen, 2004; Cooke, 2004). Actin and myosin proteins make up a sarcomere, and thousands of these filaments lie in a recurring pattern within each muscle fibre. As the sarcomeres contract, so does the muscle fibre. The cross-bridge structure of the myosin protein utilizes the energy released from the conversion of ATP to ADP, creating the power stroke necessary to slide the filaments across each other by binding, rotating and finally detaching from actin (Szent-Gyorgyi, 2004).

The contraction process has six steps to it. Firstly, the neural stimulation of a muscle fibre causes Ca^{2+} to be released from the vesicles on the sarcoplasmic reticulum and from there the Ca^{2+} binds to troponin (Cooke, 1986; Rayment *et al.,* 1993). Troponin is a protein that is located on the actin filament and along with tropomyosin, inhibits the actin-myosin binding (Cooke, 1986; Rayment *et al.,* 1993). The binding of Ca^{2+} to troponin causes the myosin binding site on actin to become active. The myosin cross-bridges, which are fuelled by ATP hydrolysis, bind to the actin and then rotate. This causes the power stroke that slides the two filaments past each other. The myosin

head then detaches from the actin and recombines with the ATP molecule (Cooke, 1986; Rayment *et al.,* 1993). This process, during a muscle contraction, occurs hundreds of times per second within a muscle as many muscle fibres are working simultaneously, causing the length of the sarcomere to decrease as thousands of sarcomeres are contained in a single muscle fibre (Cooke, 1986; Rayment *et al.,* 1993).

Skeletal muscle consists of three different types of muscle fibers, namely type I, type IIa and type IIb (Brook and Kaiser, 1970). Slow twitch fibers (type I) have a slow contraction speed but are capable of contracting repeatedly over long periods of time (Brook and Kaiser, 1970). Fast twitch fibers (type IIa) have a faster contraction speed and depend less on aerobic energy sources compared to slow twitch; however, they have a faster fatigue time than slow twitch fibers. Type IIb fast twitch fibers have the fastest contraction speed and have the greatest force producing capability, however they also fatigue very quickly and only rely on anaerobic energy sources (Brook and Kaiser, 1970). The intermittent continuation of the contraction process of a motor neuron will continue until the neural stimulation ceases, and the Ca^{2+} is pumped back across the sarcoplasmic reticulum. The myosin-actin binding is thus inhibited (Cooke, 1986; Rayment *et al.,* 1993; Brook and Kaiser, 1970).

2.1.2 Factors Constituting a Muscle Contraction

There are two factors that characterize any muscle exertions that occur; muscle length and muscle force (Faulkner, 2003). These two factors can be used to distinguish and define the different types of muscle actions, and thus allow for further study of aspects like different types of muscle fatigue and their characteristics.

There is a lack in the commonly used terminology describing muscle actions in the literature. An example is; a muscle action having no change in length will be described as isometric, regardless of whether there is a change in force over time. Similarly, eccentric and concentric descriptions will be used for any muscle action either lengthening or shortening respectively, regardless of what is occurring in terms of the force production. Table 1 illustrates how muscle exertion terminology is currently not adequate when only the terms *concentric*, *eccentric* and *isometric* are used. A muscle action with no change in muscle length, but a change in muscle force can be described as an overcoming isometric muscle exertion. Another example is a muscle exertion

that involves an increasing muscle length but no change in muscle force over time, a label such as an “isotonic eccentric” muscle exertion fully describes this scenario, where “eccentric” would not. In order to isolate and investigate specific aspects of a muscle exertion, a more comprehensive description is needed that can differentiate the differences between the muscle force and muscle length actions in a muscle exertion which extends further than simply describing a muscle action as either shortening, lengthening or maintaining constant length, which is the limitation in current terminology (Faulkner, 2003).

Table 1: Terminology for muscle length and muscle force states during a muscle exertion

		Muscle Length	
		Constant (Isometric)	**Varying**
Muscle Force / Tension	**Constant (isotonic)**	Yielding isometric	Isotonic (concentric or eccentric)
	Varying	Overcoming isometric	Auxotonic (concentric or eccentric)

The kinds of descriptions in Table 1 that incorporate both the muscle’s force and length changes over time can be applied to more situations than the more commonly used terms. Currently the established parameters for different types of muscle contractions are not comprehensive to the degree necessary in order to describe all possible conditions for muscle exertions. Creating these descriptions and parameters is imperative to the standardization of terminology which is necessary for the comparison of different studies.

Different contraction properties are involved in different types of muscle exertions, and thus different types of muscle exertions will have different fatigue responses resulting in different levels of risk of injury (Barry and Enoka, 2007). Skeletal muscle can produce body movements and stabilize body positions by contracting either in a sustained manner, or by an alternating contraction (Tortora and Derrickson, 2006). When the term contraction is used, it is implied that the muscle is shortening while

producing a force; however, a more accurate description would be that the muscle is generating or exerting tension (Enoka, 1996). This is more evident during an eccentric exertion, where despite the muscle generating tension, the muscle is still lengthening. In concentric exertions however, the tension produced generally causes the muscle to shorten since the tension produced is greater than the external forces. During a concentric exertion the work is supported by the muscle to overcome external forces (including gravity), and thus the limb moves in the direction of the muscle force. However, during an eccentric exertion, the work is done on the muscle by external forces that often results from inertia acting on the joints that muscles attach to (Enoka, 1996) and therefore results in lengthening of the muscle.

2.1.2.1 Concentric Exertions

In order for a concentric exertion to occur, the external load needs to be less than the maximum tetanic tension that the specific muscle can generate, and thus only if the external load is less than the muscle force produced, will the muscle be actively able to begin to shorten (Jonsson, 1988). The maximum force that can be generated during a concentric muscle contraction is mostly less than the muscles' maximum force production: an eccentric exertion can produce approximately 40 percent more internal muscle force compared to a concentric exertion (Jonsson, 1988). During a concentric exertion, the muscle fibres slide past each other, bringing the Z-lines closer together which causes the muscle to shorten; however, during an eccentric exertion, the muscle fibres slide past each other in the opposite direction.

2.1.2.2 Eccentric Exertion

An eccentric muscle exertion is characterized by a muscle which is lengthening, or is forcibly lengthened while still producing an internal force. If the external force increases to a point where it exceeds the current force that the muscle is generating the muscle will lengthen despite it contracting to its maximum capability (Jonsson, 1988; NSNRC, 2006). The absolute tension achieved during a maximum eccentric contraction is far higher than that of maximum titanic tension that is achieved during a maximum concentric exertion (NSNRC, 2006).This means that one can lower a significantly heavier load than one can lift. Thus the maximum muscle force is dependent on the type of muscle exertion that is occurring; for example, the maximum force of a specific muscle will be different for a concentric exertion compared to an

eccentric exertion. A study conducted by Doss and Karpovich (1964) observed the maximum force differences in muscles during the three types of muscle exertions. Eccentric force was found to be 13.5% greater than isometric force, and 39.7% greater than concentric force. This suggests that the skeletal muscle is resistant to it lengthening (NSNRC, 2006).

While the maximum external load that can be lowered is higher than the maximum load than can be lifted, the electrical activity is significantly lower during an eccentric contraction (Hamilton, 2008). This suggests that during muscle lengthening, fewer muscle fibres can produce a greater force, which confirms the hypothesis of skeletal muscle being resistant to lengthening (Hamilton, 2008). Additionally, since less muscle fibres are able to produce a greater force, eccentric contractions result in a lower metabolic demand than other exertions (Lindstedt *et al*., 2001). An explanation for this may be that when a muscle is stretched by an external force, the implanted mechanical energy could be stored temporarily in the series elastic components of active muscles. This energy can then be utilized to increase mechanical energy output (Moritani *et al,* 1988).The actual movement of the myosin heads during an eccentric contraction is not fully understood however.

2.1.2.3 Isometric Exertions

An isometric exertion is characterized by a muscle that is activated, but the length of the muscle remains constant (Jonsson, 1988; NSNRC, 2006). The maximal force that can be generated during an isometric exertion is partly dependent on the specific length that the muscle is at when the action is occurring (NSNRC, 2006). The optimum muscle length is considered to be where the greatest isometric tension is produced or where the sarcomeres are on the peak of the length tension curve (NSNRC, 2006). This length tension curve is explained in detail in the “muscle force vs. muscle length” section.

There is a positive correlation between EMG activity and muscle force in all types of muscle exertions. During an isometric exertion however, the correlation between muscle force and EMG is stronger (Hagberg and Jonsson, 1975; Milner-Brown and Stein, 1975; Komi and Viitasalo, 1976). This means that the force production of the muscle can be estimated by the EMG/Force regression (Hagberg,1981). “It is possible to obtain a profile of the muscular load during a period of work by analysing the

amplitude probability distribution of the myoelectric signal" (Jonsson, 1988, p. 229). Thus essentially, one can measure and estimate the variation of a load on individual muscles or parts of muscles by observing the wave function of the EMG.

2.1.3 Muscle Force and Muscle Length

It has been established (Cooke and Fay, 1972, Lieber and Ward, 2011) that muscle length affects maximum muscle force at a specific length. Thus, if it is required that a muscle be worked at a set percentage of maximum force production, then either the external load needs to be changed during the range of motion of the respective joint or the muscle length must not be changed. The effects of different rates of muscle length change impact the following types of muscle exertions; eccentric, concentric, isotonic and auxotonic. The current length, as well as the rate of muscle length change, affect the force production capabilities of a certain muscle (Cooke and Fay, 1972, Lieber and Ward, 2011).

2.1.4 The Length-Tension Relationship

The length-tension relationship refers to the relationship between the length of a muscle fibre, and the force that it can produce at that particular length (Cooke and Fay, 1972). This relationship is an important aspect as it affects maximum muscle tension at a given joint angle, and this will directly affect fatigue rates (Cooke and Fay, 1972). The magnitude of the tension produced by a muscle is directly proportional to the amount of overlap between aligned actin and myosin containing filaments (Cooke and Fay, 1972), in other words, the isometric tension produced by a muscle depends on the length at which the muscle is being activated or stimulated (Hill, 1938).The length-tension relationship states that isometric tension generation in skeletal muscle is a function of the magnitude of overlap between actin and myosin (Gordon *et al*., 1966), thus the force of a single muscle fibre is minimal when it is stretched to the point where there is minimal overlap. This is also true for a muscle fibre that is stimulated when it is at maximum overlap of actin and myosin. The maximum tension is produced when the overlap of actin and myosin is at its optimal level (mid-range), as seen in Figure 1. Thus, the length-tension relationship has a parabolic shape when represented on a graph (Abbott and Wilkie, 1953). High tension levels cannot be created when the muscle length is short since there is a lot of overlap between actin

and myosin and the myosin cannot pull the z discs any closer (Abbott and Wilkie, 1953).

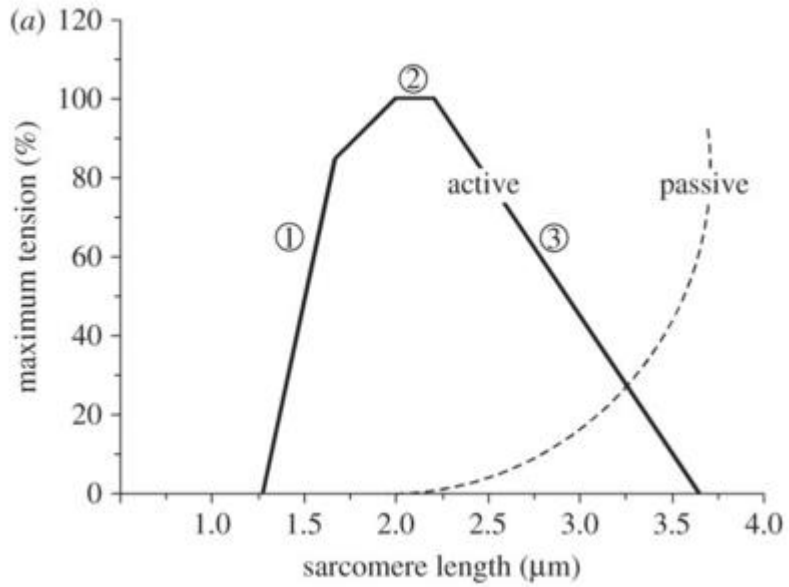


Figure 1: The relationship between muscle length and muscle tension. Source: Lieber and Ward (2011).

Muscle force and muscle length are therefore related; for dynamic contractions, small changes in joint angle of less than 20 degrees in the mid-range of movement yield only small differences in the internal muscle force to produce the same external force (Abbott and Wilkie, 1953).

2.1.5 Force- Velocity Relationship

The force-velocity relationship describes a muscle's maximum force production at a given contraction speed (Fenn and Marsh, 1935; Hill, 1935). The speed at which that limb moves through a range of motion will affect the force that the respective muscle can produce. Thus, if the muscle contracts faster, the maximum force will be lower; this relationship can be seen in Figure 2 (Fenn and Marsh, 1935; Hill,1935). There is, however, a maximum contraction velocity as the external force approaches zero. The optimal shortening velocity for maximum force generation is estimated at one-third of the maximum shortening velocity (Vandewalla *et al.,* 1987*;* MacIntosh and Holash, 2000). The force-velocity relationship is a non-linear curve and the force generated by a muscle is a function of its velocity (Fenn and Marsh, 1935; Hill, 1938). Thus, lighter loads can be lifted faster than heavier loads. As the weight increases, the contraction

speed decreases (Wilkie, 1949). The same relationship is found for eccentric exertions, whereby slower lengthening of the muscle allows for greater force generation. This relationship is due partly to inertia, and partly due to the contractile properties of the muscle, and is still found when an isolated muscle fibre is stimulated (Wilkie, 1949). The muscle can produce higher forces at lower speeds due to the fact that the slower the contraction is, the more it allows actin and myosin binding to occur along with more passive elongation (Schappacher-Tilp *et al.,* 2015).

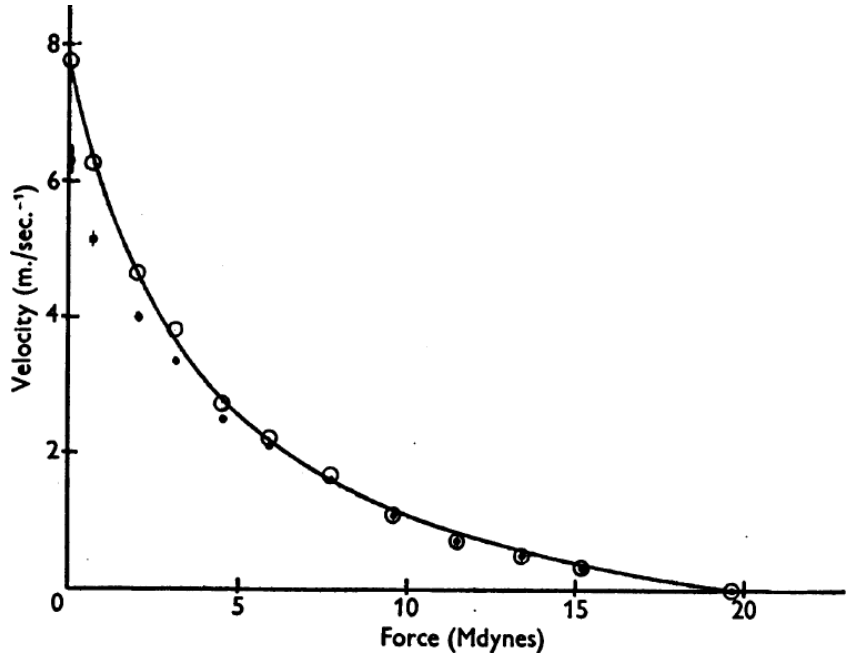


Figure 2: Force-velocity curve of a muscle. Source: Wilkie (1949).

2.1.6 Force-Frequency Relationship

The force-frequency relation is a sigmoid relationship between muscle activation frequency and isometric force output (Yan *et al*., 1993). The method for deriving this relationship is to plot the peak force responses to externally induced electrical pulses across a wide range of frequencies (Yan *et al*., 1993). Force generated in skeletal muscle via motor commands from the central nervous system occur through two inter-related processes, firstly through muscle fibre recruitment, which involves varying the number of motor units that are active during a muscle exertion (Botterman *et al*., 1986; Kernell,1992; Fuglevand *et al.,* 1999). The second process is rate coding which involves modulating the rate that action potentials drive the active motor units (Botterman *et al*., 1986; Kernell, 1992; Fuglevand *et al.,* 1999). Rate coding has been shown to play the more significant role in the overall capacity to grade muscle force

and thus the conversion of discharge rate into force by the motor units is an important feature by which the nervous system controls the skeletal muscle (Botterman *et al*., 1986; Kernell, 1992; Fuglevand *et al.,* 1999). As stated earlier, the relationship between activation rate and isometric force has a sigmoid form and this specific shape depends on the contractile speed of a motor unit. The slow twitch muscle units summate individual force impulses more readily than the fast twitch units and thus the activation rate needed for approximately half-maximal or maximum force is usually slower than for fast twitch units (Bigland-Ritchie *et al*., 1983a). The force-frequency relation can be used to determine the magnitude of fatigue, and whether the muscle fatigue has occurred to the fast or slow twitch muscle fibers (Fuglevand *et al.,* 1999).

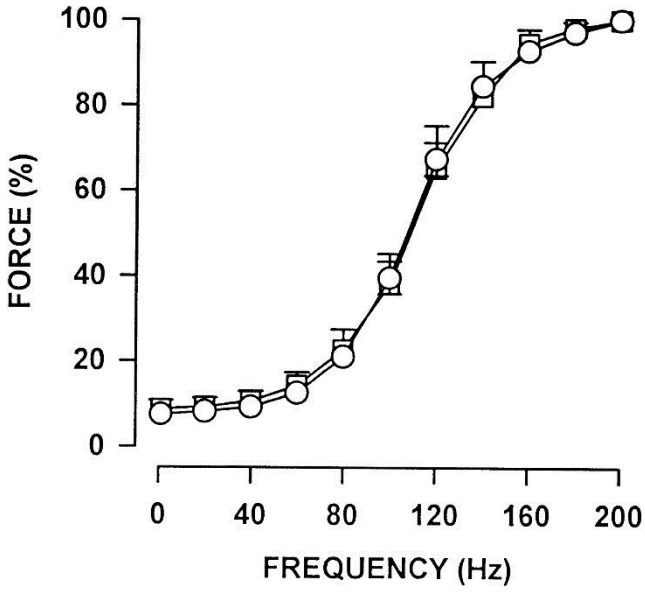


Figure 3: Force-frequency relationship of skeletal muscle under external stimulation. Source: Matar *et al*. (2000).

2.2 MUSCLE FATIGUE

When a muscle is activated at a high level for a period of a time, a progressive decline in its force producing performance can be observed, and conversely, an increase in performance if the muscle is allowed to recover (Allen *et al.*, 2008). Manifestations of fatigue (reductions in the ability to produce a given force) are seen soon after the initiation of high levels of muscle work (Greene, 1997). This decline in the muscle's force production following an intensive exertion can be attributed to muscle fatigue (Allen *et al.*, 2008). Numerous studies (Fitts, 1994; Greene, 1997; Sahlin *et al.,* 2002;

Kumar *et al*., 2002; Allen *et al.*, 2008; Ørtenblad *et al.,* 2011) have shown that the metabolic changes that occur within the muscle correlate with a decrease in performance following an exercise bout, and thus can be employed as measures to estimate the fatigue level. As a muscle is fatigued, the trend of muscle force production decrease is clear and well established in the literature. Thus, this makes for a simple and objective measure of muscle fatigue. This is particularly true for a muscle's maximal isometric force compared to maximal eccentric or concentric force as a fatigue measure (Allen *et al.*, 2008). There are, however, further important determinants of muscle fatigue. The shortening velocity of a fatigued muscle is reduced, and the rate at which it can release the generated force also slows down. Mechanical power is the result of force multiplied by shortening velocity. However, a decrease in force production has the larger impact on decrease in power output when investigating changes in maximal force production over time as a result of a fatiguing task and thus force production is used as a primary measure for muscle fatigue (Allen *et al.*, 2008).

Muscle fatigue can thus be defined as a failure to maintain the required or expected power output. The rate of muscle fatigue is affected by many factors such as fibre type, intensity of muscle work, type of muscle work and duration of muscle work (Fitts, 1994). Fatigue is also characterized by an increased effort in maintaining a certain force (Fitts, 1994). The current literature describes one objective method of measuring muscle fatigue via the duration that a certain force being produced by a muscle fibre can be maintained, or via the decay in force produced over time. When a muscle, or group of muscles, loses the ability to maintain a certain level of force over a designated time, it is an indication of "force fatigue" (Kumar *et al*., 2002). Additionally, once the muscle activity has ceased its activity or exercise, a sustained weakness persists for days after as a result of disruption in the internal structures within the muscle fibers (Greene, 1997; Allen *et al*., 2008; Ørtenblad *et al.,* 2011).

When observing fatigue from a cellular level, the current theories centre around ATP production. ATP utilization of myosin during high intensity muscle exertions is greatly increased in order to meet the energy requirements. ATP is needed for excitation and contraction of the myosin protein, namely the exchange of Na^+/K^+ in the sarcolemma, the sarcoplasmic reticulum, Ca^+ appropriation and actomyosin cycling (Ørtenblad *et*

al., 2011). In response to this high demand of ATP, high levels of phosphate transfer, glycolysis and oxidative phosphorylation results (Greene, 1997; Allen *et al*., 2008; Ørtenblad*et al.,* 2011). When the ATP production rates cannot keep up with the high demands brought on by the intense work level, there is a reduction in ATP levels (Greene, 1997), which in turn causes the accumulation of metabolic by-products such as hydrogen ions (Allen *et al*., 2008; Ørtenblad*et al.,* 2011). Some of these by-products are believed to disrupt the Na^+/K^+ balance as well as the Ca^{2+} and actomyosin interaction, with the result being muscle fatigue. When this occurs, it is considered to be "metabolic fatigue", which refers to the depletion of intercellular substrates, such as glycogen, and the accumulation of metabolites in the muscle (Greene, 1997; Allen *et al*., 2008). This "metabolic fatigue" can occur with repeated bouts of high intensity work (Greene, 1997; Ørtenblad*et al.,* 2011). Glycogen is the basis for glycolysis and oxidative phosphorylation, and thus decreases in glycogen stores results in fewer motor neurons being recruited, resulting in the subsequent reduction in maximum force (Greene, 1997; Ørtenblad*et al.,* 2011).

Multiple factors are involved when explaining what aspect of muscle physiology is causing the fatigue, with each factor being dependant on the fibre type composition of the fatiguing muscle, type of muscle contraction and contraction intensity (Fitts, 1994; Westerblad *et al.,* 1991; Westerblad and Allen, 2003). The force-frequency relationship allows one to determine the type and the severity of muscle fatigue that has been induced. Muscle fatigue can be divided into two types, namely high and low frequency fatigue (Yan *et al*., 1993;). In high frequency fatigue, there is a discriminating loss of force at high stimulation frequencies and the recovery rate from this kind of fatigue is rapid, for example less than an hour (Yan *et al*., 1993;). Low frequency fatigue occurs at low stimulation frequencies and the recovery from this type of fatigue is far more prolonged when compared to high frequency fatigue (Yan *et al*., 1993;). Both high and low frequency fatigue can be detected by calculating the ratio of force development at low stimulation frequency compared to that at high stimulation frequency (See Figure 4) (Yan *et al*., 1993;). The ratio between these two increases with high frequency fatigue and it decreases with low frequency fatigue (Yan *et al*., 1993).

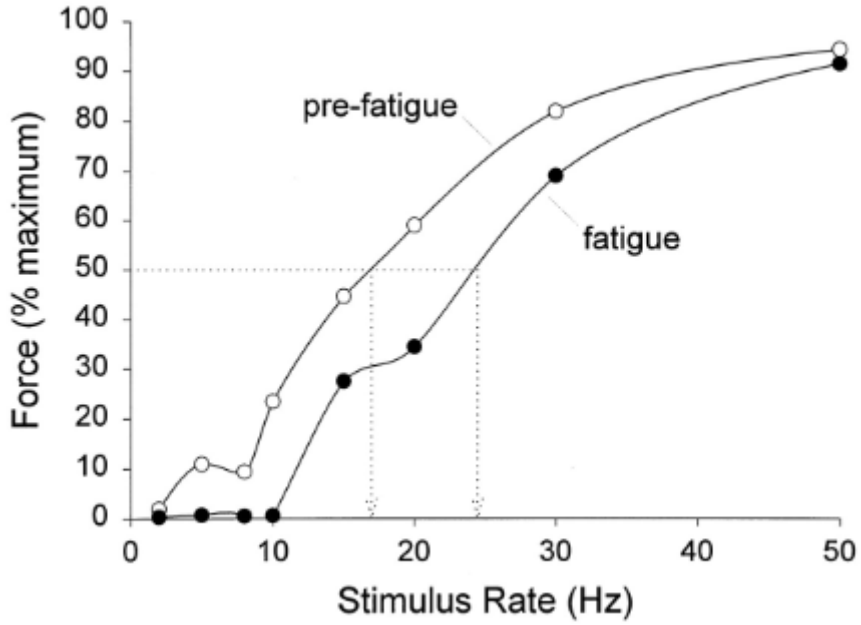


Figure 4: relation between relative force and stimulus frequency. Source: Fuglevand et al. (1999).

According to Fitts (1994) the primary sites where fatigue occurs are within the muscle cells, and not at the level of the central nervous system or the neuromuscular junction. This however doesn't mean that down-regulation of muscle fibres doesn't occur from the central nervous system when muscle fatigue occurs in order to preserve homeostasis (Weir *et al.,* 2006). EMG has been shown to reflect motor unit recruitment as well as motor unit firing rate (Weir *et al.,* 2006). This means that one can measure the level of peripheral fatigue if the force and number of motor units that are active can be measured simultaneously (Weir *et al.,* 2006). Skeletal muscles are composed of at least four different fibre types (Fitts, 1994). The slow type 1 fibres and the fast type 2a fibres have the highest amount of mitochondria which increase their fatigue resistance (Fitts, 1994). The changes that occur with fatigue can be seen in an entire muscle, motor units or single muscle fibres (Fitts, 1994). Signs of fatigue that can be observed and measured at all these levels include a decrease in power output, an increase in contraction and relaxation times; and a decrease in the peak rate of tension development (Fitts, 1994; Westerblad *et al.,* 2002; Westerblad and Allen, 2003). If muscle fatigue has occurred with no muscle fibre damage, the extended relaxation time that coincides with fatigue causes the force-frequency curve to shift to the left (refer to Figure 3), so that peak tensions occurs at lower frequencies of stimulation, meaning that slow twitch muscle fibres are being predominantly recruited to produce

the force (Fitts, 1994; Westerblad *et al.,* 2002; Westerblad and Allen, 2003). It is hypothesized that the nervous system detects this change and thus reduces the alpha-motor neuron activation frequency as the fatigue levels increase (Fitts, 1994).

2.2.1 Muscle Fatigue during Static Exertions

There are well established relationships between fatigue rate and static loading on a muscle. It has been demonstrated that the amount of time that a muscle can sustain activity is inversely proportional to the muscle stress (Load as a percentage of maximum force) raised to the third power (Crowninshield and Brand, 1981) and this relationship can be seen in Figure 5.

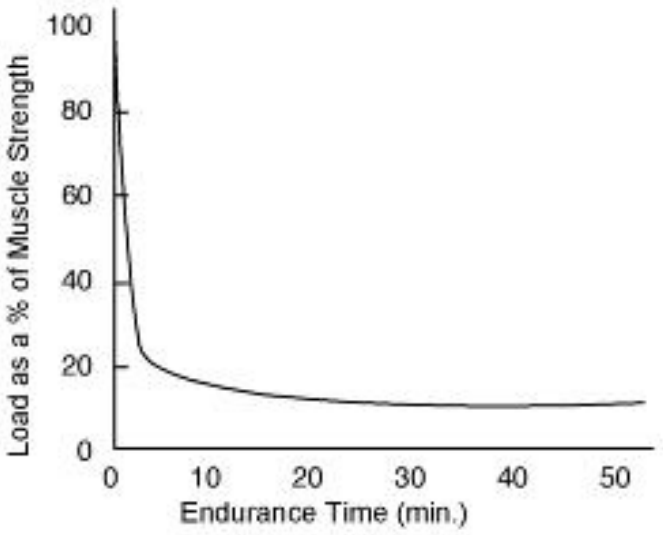


Figure 5:Composite of muscle endurance-load relationship for different muscles and experimental conditions. Source: Chaffin, Anderson and Martin (1999).

The most impacting factor surrounding muscle fatigue during static muscle exertions is regarding blood flow levels. The basic understanding is that dynamic contractions induce a greater blood flow to the respective muscle due to the contraction and relaxation of the muscle during a dynamic exertion, thereby allowing more blood to enter and leave the muscle, as well as helping to pump the blood through the body by the constriction and relaxation of the muscle (Savard *et al.,* 1986). The importance and role of blood flow during an exertion is demonstrated in the literature since the increase in energy turnover during a muscle exertion demands an increase in the

supply of substrates (Savard *et al.,* 1986). Additionally, metabolites need to be removed and the increases in temperature occurring during muscle exertions need to be managed. All of these aspects are critical to maintaining muscle homeostasis, and thus the higher the muscle exertion, the higher the blood supply that is needed (Savard *et al.,* 1986). However, during high exertion static contractions, the demand for blood flow is high, but the blood supply needed cannot be matched, resulting in early fatigue. The constant intramuscular pressure that occurs, when a muscle is being activated statically, prevents blood flow to that muscle and as a result, its recovery is hindered. Thus, the metabolic by-products accumulate in the muscle (Masuda *et al.,* 1999) and hinder performance since the metabolic by-products reduce force and slow relaxation in the muscle by adversely affecting the release of Ca^{2+} from the sarcoplasmic reticulum, contractile myofilaments and Ca^{2+} uptake into the sarcoplasmic reticulum (Hargreaves, 2013).

While constant static exertions may impede a muscle's blood flow levels, lower muscle activation levels during static exertions have been shown not to hinder the blood supply of a muscle, and thus the onset of fatigue may be delayed. Sj∅gaard *et al.* (1986) suggest static muscle activation for an hour at 5% MVC still allowed for the muscle to receive sufficient blood flow and not fatigue prematurely when compared to dynamic contractions at the same activation level. Another study by Sj∅gaard *et al.* (1998) showed that muscle exertions below 10% MVC still allowed sufficient blood flow to the muscle during a static contraction; however the muscle fatigued at a faster rate when compared to dynamic contractions at the same activation levels. This increased muscle fatigue from a static exertion was thus not entirely from blood flow levels, but perhaps due to static exertions having a greater effect on intracellular potassium homeostasis disturbance when compared to dynamic exertions. A third study indicated that the maximum static muscle activation level that supports blood flow is 8% MVC (Jonsson, 1988). Therefore, the research suggests that at lower levels, up to 10% MVC (Sj∅gaard *et al.,* 1988), blood flow may not be the only factor in fatiguing the muscle during a static contraction compared to a dynamic contraction. The critical level at which the blood flow begins to be significantly impeded may be dependent on muscle anatomy and composition and thus, while the literature agrees that 10 percent is the general level; different muscles may show different threshold levels. Anything higher than 10% MVC (Jonsson, 1988), however, has been

demonstrated to significantly reduce blood flow to that muscle, and consequently causes the muscle to fatigue more rapidly when compared to dynamic contractions at similar work levels (Jonsson, 1988).

The joint being utilized during static work has also been demonstrated to affect the level of localized muscle fatigue induced. A meta-analysis done by Frey-Law and Avin (2010) illustrated that static task intensity-endurance time responds differently from joint to joint. The ankle joint had the highest level of endurance and the shoulder joint had the least endurance (Frey-Law and Avin, 2010). This may mean that when investigating static muscle fatigue, it is important to test multiple joints and muscles to determine if and how the joint affects the fatigue response since a risk assessment for one joint and its specific muscles may not be valid for another.

When comparing the motor unit recruitment differences between static and dynamic exertions, some studies indicate that there is no significant difference with regard to the recruitment of motor units. Sj∅gaard (2004) showed that motor units recruited during different types of contractions, namely dynamic, anisotonic (varying in tension) and isotonic, showed very similar properties, and the same author suggested that all types of contractions used similar motor neurons. From the data collected by Sj∅gaard (2004), it was believed that static and dynamic exertions may even recruit similar numbers of motor units, and even the same motor units being recruited for different types of muscle exertions. Similar results were found by Forsman *et al.* (1999) indicating that stereotypic recruitment patterns existed in both static and dynamic exertions.

While the motor unit recruitment patterns between static and dynamic exertions have been demonstrated to be similar, there is a difference between eccentric and concentric exertions. Jensen *et al.* (1996) found that the mean firing rate of motor units was significantly increased when the muscle exertion switched from concentric to eccentric. Thus, recruiting fast twitch motor units may be responsible for higher force productions during concentric and isometric exertions, whereas for eccentric exertions, increasing the firing rate of the active units is how increased force levels are achieved. What was emphasized in the above study was that firing rate was the significant aspect to consider when comparing eccentric to concentric exertions, and not recruitment patterns.

2.2.2 Muscle Fatigue during a Sub-Maximal Underlying Exertion

When considering static muscle fatigue, even low levels of static muscle contraction can cause muscle fatigue over time despite sufficient blood flow being present (Savard *et al.,* 1986; Jonsson, 1988). Signs of muscle fatigue during low level muscle activations are present even if there is change in muscle force, meaning it would be considered to be a more dynamic exertion (Savard *et al.,* 1986; Jonsson, 1988). A constant underlying force less than 10 percent of MVC could result in insufficient muscle relaxation to allow recovery, despite the muscle force changing over time (every 5 seconds) (Savard *et al.,* 1986; Jonsson, 1988). Jonsson (1988) showed that load levels over an extended period of manual work rarely decreased to the point of full muscle relaxation and thus any additional fatigue induced by underlying low level exertions may be present in many manual work situations. Thus, it has been demonstrated that most manual work does not include consistent periods of full relaxation and it is plausible that underlying low level muscle exertions are adding to the fatigue incurred by the manual task. Muscle activation levels above this minimum level are then considered to be the dynamic component if there are changes in muscle force and muscle length.

2.2.3 Muscle Fatigue during Dynamic Exertions

Blood flow plays a role in delaying the onset of fatigue and therefore also causes decrements in muscle performance. Iridiastadi (2003), Sherman (2003) and Allen (2008) conducted research on blood flow levels during intermittent exertions that have phases of contraction and relaxation. The evidence provided in the above studies demonstrated that there is a linear increase in blood flow to the muscle as the work load of that muscle is increased (Rådegran, 1997). Thus, in dynamic contractions, as the need for metabolite removal, heat removal and substrate availability increases, so the blood flow increases to match the need, and the onset of fatigue is delayed when compared to purely static muscle exertions (Rådegran, 1997). The difference in blood flow levels between static and dynamic muscle exertions can be up to 61 percent higher for dynamic exertions, compared to static exertions when the exercise intensity is kept constant (Laaksonen *et al.,* 2002), therefore allowing the former a better fatigue resistance. Additionally, with blood flow levels being higher in dynamic muscle exertions, Laaksonen *et al*. (2002) also demonstrated that the EMG activity for

dynamic exertions is higher compared to isometric exertions despite the force not being significantly higher.

The increase in blood flow during dynamic contractions occurs after the first exertion/relaxation cycle (Rådegran and Saltin, 1997). Some evidence presented in the study conducted by Rådegran and Saltin (1997) on the muscle pump effect indicated an increase in blood flow to the muscle even after steady state heart rate had been reached. Thus, with the heart rate not increasing, it is believed that the muscle pump causes the increase in blood flow. The muscle pump effect theory states that muscle exertions aid in muscle perfusion by emptying the venous circulation; this then lowers the venous pressure during the relaxation phase and increases the pressure gradient across the muscle (Hamann *et al.,* 2003). The muscle pump effect was also shown when blood flow was peaking as the relaxation coincided with peak systolic arterial blood pressure (Rådegran and Saltin, 1997). One can conclude that when a muscle is contracting dynamically, it will receive a greater level of blood flow compared to a muscle that is being exerted statically. This allows for the substrates to be depleted more slowly as well as the build-up of metabolites within the muscle to occur at a decreased rate and thereby delaying fatigue.

When considering the motor unit recruitment during dynamic exertions, research has shown that there is no significant difference in the recruitment order of motor neurons for isometric and dynamic exertions (Stotz and Bawa, 2001). All contractions recruit motor units from smallest to largest (Stotz and Bawa, 2001).

2.2.4 Indices of Muscle Fatigue

When considering measuring and quantifying muscle fatigue, there are direct and indirect methods. There are a number of direct measures of muscle fatigue such as maximum voluntary force generation, power output, titanic force and low frequency fatigue. Indirect methods include twitch interpolation, endurance time and electromyography.

2.2.4.1 Maximum Force Production

Maximum force production, specifically maximum isometric force, is how many authors identify and define muscle fatigue. As a muscle fatigue measure, it is considered to be the most direct method (Vøllestad, 1997; Gandevia and McKenzie, 1988; Windhorst

and Boorman, 1995). This measure relies on force generated voluntarily and thus is limited by motivation levels (Vøllestad, 1995; Gandevia and McKenzie, 1988). Strong encouragement can however compensate for the motivation levels (Vøllestad, 1997). The maximum voluntary contractions (MVC) are recorded while an individual is instructed to generate the highest possible force (Vøllestad, 1997). The most reliable and reproducible measures of maximum force production occur when the movement only allows for one direction of force, such as for knee extensions (Vøllestad, 1997).

2.2.4.2 Power Output

Power output as a muscle fatigue measure is often very energetically demanding and requires faster rates of ATP reproduction when compared to other fatigue measures (Woledge *et al*., 1985). Thus maximal power output provides more information on the energy release and utilization since these aspects are detected more accurately during shortening of the muscle compared to isometric contractions as used in obtaining a MVC (Vøllestad, 1997). Changes in power output are commonly examined from the temporal change in power of each contraction through a brief maximal effort. During a maximum power measure, the highest torque is reached after a few seconds and this is followed by a gradual fall in power (Beelen and Sargeant, 1991). One of the advantages of employing maximum power output as a muscle fatigue measure is that the output is an integrated result of the total chain of events, and thus it includes the various inputs at all levels of the activation process (Vøllestad, 1997). The decline in any output can be due to central or peripheral fatigue, meaning that maximum power output serves as an initial assessment of muscle fatigue, which can then be followed by additional investigations to examine possible sites and mechanisms of fatigue (Vøllestad, 1997).

2.2.4.3 Tetanic Force

Tetanic force can be measured by inducing a maximum force contraction via electrical stimulation of either a single motor neuron or the entire muscle. Using this method eliminates the motivational limitations of a MVC (Vøllestad, 1997). This method requires access to the appropriate nerve in order to stimulate it and this may be problematic for smaller muscles (Bigland-Ritchie *et al*., 1986). Additionally, excessive stimulation leads to a block of the neuromuscular transmission over time which will

yield an overestimated fatigue result (Jones, 1996). There are some physiological response differences between electrically stimulated (ES) and voluntary MVCs (Crameri *et al*., 2007). The level of muscle tenderness from the delayed onset of muscle soreness is similar between voluntary and electrically induced MVCs (Crameri *et al*., 2007). However, there is a significant disruption of cytoskeletal proteins (desmin) that occurs for muscles that are stimulated externally (Crameri *et al*., 2007). Additionally, the intracellular disruption and the destroyed Z-lines are significantly more pronounced in ES muscle MVCs when compared to voluntary MVCs (Crameri *et al*., 2007). These aspects may have some influence on ethical considerations.

2.2.4.4 Low Frequency Fatigue

The measure of low frequency fatigue utilises twitch force to estimate the loss of force generating capacity of a muscle (Vøllestad, 1997). Twitch force requires hours to recover however, which is far longer than titanic force (Vøllestad, 1997). The disproportionate decrease in twitch force is named low-frequency fatigue and is experienced by a muscle during high intensity exercise as well as sub-maximal repetitive muscle exertions (Edwards *et al*., 1977). Edwards *et al*. (1977) and Westerblad *et al*. (1991) suggest that the drop in twitch force is due to a reduced release of Ca^{2+} from the sarcoplasmic reticulum.

2.2.4.5 Twitch Interpolation

Twitch interpolation is similar to the low frequency fatigue measure and entails assessing twitch contraction elicited by either a single or double electrical stimulus (Gandevia and McKenzie, 1988). The force increment in response to the electrical stimulus is a reflection of the force reserve within the muscle (Vøllestad, 1997).

2.2.4.6 Endurance Time

Endurance time as a measure of muscle fatigue is based on the assumption that a relationship exists between the decline in maximal force generation capacity of a muscle and the time until exhaustion (Vøllestad, 1997). It has been demonstrated that these two parameters vary substantially and that there are different mechanisms behind muscle fatigue and exhaustion (Vøllestad, 1997). Thus, decreases in force due

to fatigue and endurance time provide information on different processes (Vøllestad, 1997).

2.2.4.7 Electromyography

Using electromyography to measure fatigue relies on the physiological responses accompanying muscle fatigue (Vøllestad, 1997). Surface electrodes are used to record the electrical activity of superficial muscles and the amplitude and power spectrum can be determined from this signal (Vøllestad, 1997). The amplitude is the reflection of the number and the size of the action potentials in the muscle and thus the number of active muscle fibres or change in firing rates of muscle fibres can be recorded (Basmajian and De Luca, 1985). It is not possible to determine whether a change in muscle fibre recruitment or firing rate is responsible for a change in electrical signal amplitude (Vøllestad, 1997). The gradual increase in amplitude during repetitive or sustained sub-maximal contractions makes this measure a reliable method for assessing fatigue levels (Basmajian and De Luca, 1985). The increase in amplitude is believed to be due to an increase in recruitment of muscle fibres (Basmajian and De Luca, 1985).

EMG power spectrum analysis is another method used in electromyography and is obtained by calculating the median frequency from the raw signal (Basmajian and De Luca, 1985). It has been demonstrated that the spectrum shifts to lower values when a muscle fatigues. The spectrum shift may be explained by a lowered conduction velocity in the muscle fibres when fatigue occurs (Lindström *et al*., 1970). It is predicted that the higher the velocity of propagation of the action potential, the higher the power at high frequencies of the detected surface signal, and thus the power spectral density of the EMG signal can give signs of different motor unit recruitment patterns (Maton, 1981; Farina *et al*., 2002). The results of using this measure are not conclusive however.

EMG power spectrum has been used in many studies to measure muscle fatigue levels, and the shifts herein are quantified by the center frequency of the EMG power spectral density function (Naeije and Zorn, 1982). When fatigue occurs in a muscle, the EMG power spectrum shifts to lower frequencies, and this is used to show, and measure fatigue (Biederman *et al.,* 1990; Biederman, 1991; Gerdle and Fugl-Meyer,

1992; Dolan *et al.,* 1995). As mentioned earlier, it has been demonstrated that the EMG power spectrum shifts to low frequencies due to the lowered conduction velocity in the muscle fibres that occurs when fatigue progresses over time (Lindström *et al*., 1970) and this drop in frequency can be observed in Figure 6.

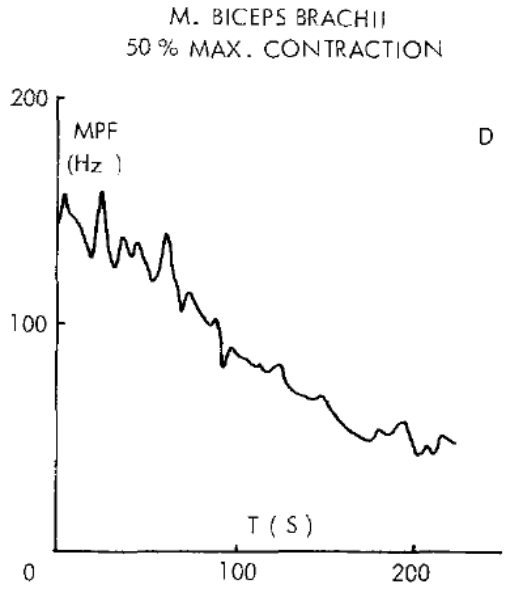


Figure 6: EMG spectral frequency and bicep brachii muscle fatigue. Source: Naeije and Zorn (1982).

The reliability between muscle fatigue measures has been investigated to some degree. In a study conducted by Kumar *et al.* (2003), maximum force production, EMG amplitude, EMG median frequency, muscle bed blood volume, muscle oxygenation, oxygen uptake, ventilation volume, heart rate, rating of perceived exertion, visual analogue score and body discomfort rating were used to determine which factors mirrored localized muscle fatigue most closely. These researchers found that the closest indicator of localized muscle fatigue at 40% MVC fatiguing contractions was EMG median frequency ($r=0.91$; $p<0.01$) (Kumar *et al.,* 2003). However, the median frequency was not the closest indicator when considering lower muscle activation levels specifically (<40% MVC sustained static contraction), but was rather the visual analogue score (Kumar *et al.,* 2003). No single objective or subjective measure could closely represent local muscle fatigue at different levels of muscle contraction, and thus a combination of multiple objective and subjective measures is needed to increase the predictability of force decline in a muscle (Kumar *et al.,* 2002).The

reliability of the EMG spectral frequency alongside maximal torque production has also been tested by multiple studies (Bilodeau *et al*., 1994; Elfving *et al.,* 1999; Ng and Richardson, 1996; Buxbaum *et al.,* 1996) allowing its reliability and accuracy to be reinforced.

Another important aspect to consider when a muscle fatigues is the recruitment of muscle fibres. Muscle fatigue can be tested and measured by exposing a certain muscle to an isometric exertion with a constant force over time, and then measuring the increase in EMG activity over time (Maton, 1981; Arendt-Nielsen and Mills, 1985). What can be observed in the motor unit recruitment during such a muscle exertion is that fatigue occurs right from the beginning of the exertion, with the increase in EMG activity for a constant force increasing as the exertion begins provided the contraction level is above 10% MVC (Jonsson, 1988). However, the increase in motor unit firing frequency depends on the level of force production. Motor units are recruited by the central nervous system, and the smallest motor units are recruited first with the lowest conduction velocity. The onset of fatigue is believed to reduce the maximum force that a motor unit can exert, and thus, in order to maintain a constant isometric exertion, additional muscle fibres need to be recruited to produce the same net force. The firing rates have a hierarchical structure where the firing rate of a motor unit is inversely related to its recruitment threshold, meaning that the earlier recruited muscle fibres have faster firing rates at any force level (Maton, 1981; Arendt-Nielsen and Mills, 1985; Andreassen and Arendt-Nielsen, 1987; Farina and Cescon, 2001; Farina *et al.,* 2002; De Luca *et al.,* 2011).

Subjective and objective measures have been demonstrated to be closely related, and thus the subjective measures can be considered as equally valid as the objective ones (Sundelin and Hagberg, 1992; Dedering *et al.,* 1999). Additionally, one very important aspect of subjective measures is that they can ignore training status as a variable, as the subjective measure is dependent on work intensity, and not maximum work capacity of the individual (Halson, 2014). Dedering *et al.* (1998) investigated the correlation between the objective measures of muscle fatigue in the lower back and the participant's own subjective measure of the fatigue. The electromyography signal and the endurance time were compared to the Borg Scale (Dedering *et al.,* 1998). The target muscle was the lumbar extensor muscles during a modified Sørensen test

(Biering-Sørensen, 1983), which involved an isometric contraction until muscle exhaustion. During the test the participants gave their subjective ratings at set time intervals. It was found that endurance time and EMG median and center frequency were correlated to Borg scale ratings. At a Borg scale rating of 3, the median- and center frequency were reduced by 30% and they were at approximately 30 percent of their maximum endurance time. At a Borg rating of 5, median- and center frequency were reduced by 50% and the participants were at 50% of their maximum endurance time. The same correlation of objective measures was found at a Borg rating of 7. Thus this study demonstrates that subjective measures closely mirror the objective measure of fatigue. Evidence such as this allows subjective measures to be used as an accurate measure of fatigue, and allows for further analysis during different types of muscle contractions leading to fatigue. Similar findings were produced by Dedering *et al.* (1999), where ratings of perceived exertion increased, as muscle fatigue increased, which correlated closely to EMG spectral changes.

CHAPTER 3: METHODOLOGY

Musculoskeletal disorders that affect manual workers is a problem that has received much attention, however it continues to be problem (Graf *et al.,* 1995). The research and literature that substantiates the current risk assessment tools employed to manage the risk in manual jobs does not fully cover all the forms of muscle fatigue that may cause injuries associated with muscle fatigue (Graf *et al.,* 1995). The current literature offers insufficient knowledge of static and dynamic work to give accurate risk assessment of these types of work. However, since it is rare that a manual job is ever completely static or dynamic, there is a need for research investigating fatigue mechanisms and responses to quasi-static in order to substantiate the risk assessment tools regarding this type of work.

This study has two aims, namely: to investigate whether, and to what extent, a quasi-static work regime fatigues a muscle with the same fatigue characteristics as exclusively static work. Secondly, to investigate what effects a constant underlying static component has on fatigue during an otherwise dynamic muscle force work regime.

3.1 RESEARCH CONCEPT

This research study was concerned with how muscles respond to different activity stimuli that simulate static and quasi-static work. There are no standard guidelines that define work as quasi-static, and as such, an original protocol had to be created that could be defined as fitting quasi-static work. Since quasi-static work can essentially be defined as any work that is neither purely dynamic or purely static, a middle ground that fell between both purely dynamic and purely static exertions had to be found, with each quasi-static protocol having both static and dynamic components in equal amount. These quasi-static protocols could then be compared to purely static or purely dynamic protocols.

The two factors that govern muscle exertions are muscle length and muscle force. These two factors were used to define any muscle exertion in this study, and thus were used to create the different quasi-static protocols to have both static and dynamic

components. Each quasi-static protocol has a static or dynamic muscle force and a static length. This then means that a middle ground between purely dynamic and purely static was achieved to some degree. Thus, the protocols used in this study isolated and changed one component of a muscle exertion compared to a purely static or purely dynamic exertion. The difference, if any, in muscle fatigue responses would then be evaluated in order to determine what role muscle force plays specifically in the development of muscle fatigue. The hypotheses in this study will be tested by having participants perform fatiguing protocols under different conditions (i.e. types of contractions) and the subsequent muscle fatigue response measured to determine whether a difference exists between different contraction types.

3.2 EXPERIMENTAL DESIGN

The methodology of this research study only tests isometric conditions. The different fatigue characteristics stemming from changes in muscle force will be investigated while muscle length remains constant in all conditions.

3.2.1 Independent Variables

In order to investigate the two aims in this study, four conditions are employed. Firstly, a purely static condition, and a quasi-static condition with static muscle length and a fully dynamic muscle force. These two conditions can then be compared to investigate the first objective of this study. Secondly, two more conditions with differing levels of small underlying static muscle forces to determine if, and to what degree, a low static forces affect the fatigue responses of an otherwise dynamic muscle force condition. These two conditions will be compared to the quasi-static condition with no underlying static force component.

Thus the four conditions in this study are as follows:

1) A purely static condition that has a fully static muscle force.
2) A quasi-static condition that has a fully dynamic muscle force.
3) A quasi-static condition that has a dynamic muscle force, but with a constant underlying low static force (tested at 5 percent of maximum force).
4) A quasi-static condition that has a dynamic muscle force, but with a constant underlying high static force (tested at 15 percent of maximum force).

All of these conditions were used to induce fatigue into the muscle with the intention of observing how the fatigue characteristic of each condition differ from each other in order to determine what factors of a muscle exertion correlates to what characteristics of fatigue. Conditions one and two were compared in order to determine whether a quasi-static condition with fully dynamic force fatigues in a way that is different to a protocol that is completely static. The muscle fatigue results of conditions three and four were compared to that of condition two to determine if, and to what degree an underlying static component affects the muscle fatigue of an otherwise dynamic muscle force muscle exertion.

Quasi-static work can entail either static muscle length with dynamic muscle force or vice versa and both of these types of quasi-static work should be investigated in order to gain a more in depth understanding of fatigue responses during quasi-static work. This study originally had 6 protocols, with two conditions having dynamic length components; however, these conditions had to removed when pilot tests yielded negative results. These pilot tests will be covered more in detail after the protocol has been discussed.

3.2.2Experimental Conditions

The four different ways of conducting the fatiguing protocol are distinguished by varying the type of muscle contractions performed by the changing muscle force during exertion. By doing this, it was anticipated that the muscle would fatigue in different ways, which can then be determined from the fatigue measures.

Condition 1: SFSL (Static Force, Static Length). This condition was selected to induce muscle fatigue during a purely static exertion. It combined an isotonic (constant tension) and isometric (constant length) exertion, i.e. the muscle contracts with a constant force, while maintaining a static length as seen in Figure 7. Since static fatigue is unique in that it is related to blood flow levels and the fatigue rates for static tasks are shorter than for dynamic tasks (Savard *et al*., 1986; Masuda *et al*., 1999), it was essential to test this condition to get a clear static fatigue response for all the muscles tested in this study. Once a purely static fatigue response was established, the data could be used to compare to the other conditions and determine whether or not they respond similarly to a purely static condition, and thus could be said to have a static fatigue response.

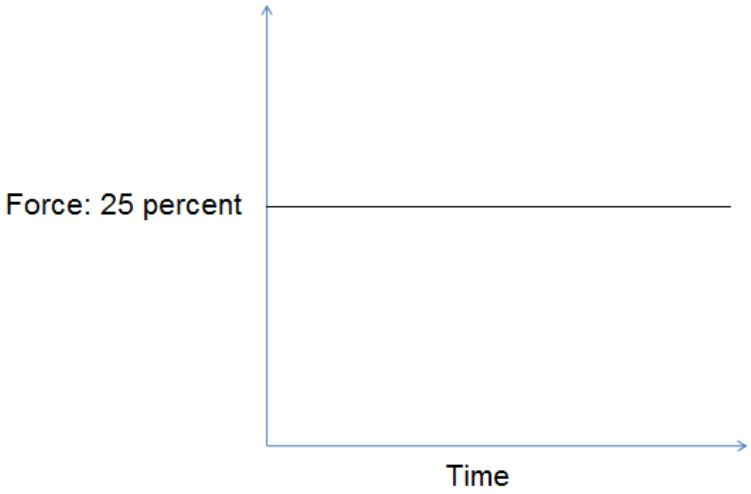


Figure 7: The static force levels (Isometric).

For this condition the muscle activation level in this protocol would be an average of 25 percent of maximum voluntary EMG activation level. The same average activation level was maintained for all conditions over the same period of time and thus the same total work load was kept constant, therefore allowing for comparisons to be made between all the condition's muscle fatigue responses. The 25%MVC activation level was chosen for two reasons; it had been shown to be a safe muscle activation level to study muscle fatigue (Vøllestad, 1997) and based on pre-pilot test results where a number of activation levels were tested to gauge how participants responded, 25 %MVC was deemed to be low enough as to induce a slow enough rate of fatigue for enough data to be collected before the participants was exhausted prematurely. Six measurements of fatigue spaced throughout the fatiguing protocol at one minute intervals were deemed to be sufficient to see a fatigue trend. During the fatiguing protocol of this condition, a set weight that is 25 percent of MVC was held by the participant isometrically in the middle of the range of motion for the relevant joint. The joint angle remained at the middle angle, with the set weight for the 60 second period. The specific muscle testing aspects of the methodology, such as joint angles, are fully covered in section 3.4 and 3.5.

Condition 2: DFSL0-50 (Dynamic Force, Static Length). This condition was designed to test fatigue development in the muscle while its length remains constant (isometric exertion) but the force varies. This would allow for the muscle pump effect (Radegran, 1997) to be tested when no muscle lengthening or shortening occurs, yet

force exertion varies, see Figure 8. This determines whether the muscle activation/relaxation cycle was sufficient to cause the muscle pump effect and whether this prevented an early onset of muscle fatigue. This condition will have an average muscle activation of 25 percent of MVC, with muscle activation levels ranging between 0% MVC and 50% MVC. The joint angle will be fixed at the same values mentioned in condition SFSL.

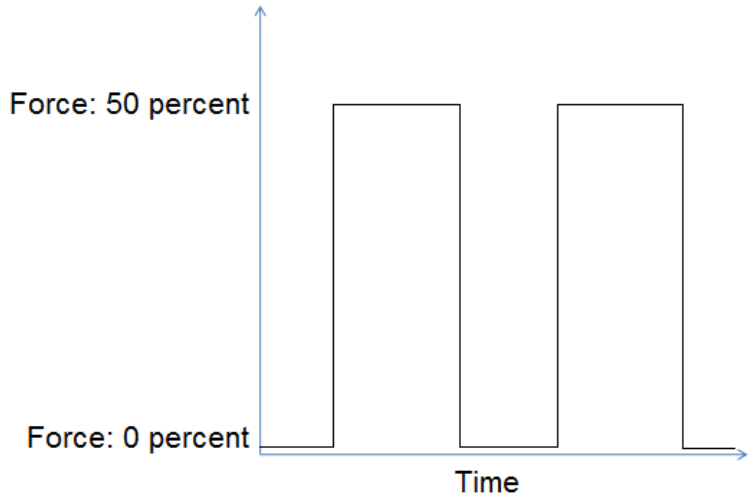


Figure 8: The dynamic force levels (Isometric).

Condition 3: DFSL5-45 (Dynamic Force, Static Length). This condition repeated condition DFSL0-50 but with altered force levels. This was done to test whether the average muscle activation percentage was the determining factor of the muscle fatigue response, or whether the minimum muscle activation level was an impacting factor. This condition tested whether a constant underlying static force of 5 percent MVC changed the static fatigue characteristics, or whether the dynamic component compensated for the constant static component and the muscle can resist fatigue. Many studies suggest that low level muscle activation (<10%MVC) levels can have a fatiguing effect, and thus it is important to study this effect during dynamic contractions to gain a better understanding of actual work situations (Sejersted *et al*., 1984; Sjøgaard *et al*., 1986; Wesche, 1986).

In this condition the muscle activation percentages varied between 5 and 45 percent MVC. The average muscle activation percentage for both conditions DFSL and DFSL5-45 was 25 percent; it was only the baseline muscle activation level that has been increased, and the maximum activation level decreased to allow for an average

activation level of 25% MVC, as is shown in Figure 9. The literature also provides evidence that 5 percent muscle activation is the lowest level of activation that produces fatigue characteristics; thus any lower activation would not induce fatigue to a measurable degree (Sj∅gaard *et al* 1986). The 45% MVC muscle activation level was chosen as the maximum level so that the average activation level of this condition would still be 25 percent to match the other conditions.

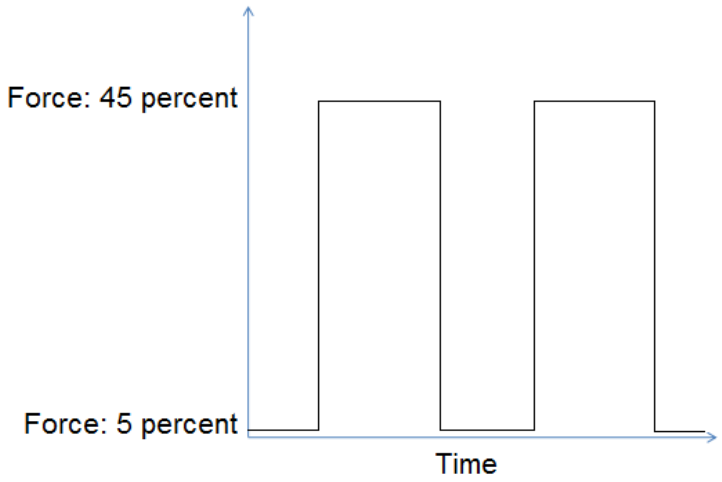


Figure 9: The dynamic force levels (isometric), with a constant static force of 5 percent over time.

Condition 4: DFSL15-35(Dynamic Force, Static Length). This condition, like condition DFSL5-45, repeated condition DFSL0-50, but the muscle activation percentages were altered to range between 15%MVC and 35%MVC, but with constant muscle length, as is shown in Figure 10. The average muscle activation level remained at 25 percent MVC. Therefore, with conditions DFSL5-45 and DFSL15-35, the effect of a higher minimum constant underlying static component on muscle fatigue was measured.

The percentage levels for condition DFSL15-35 were chosen for not only 15 percent being a substantial underlying static force which has also been shown to restrict blood flow levels to the specific muscle(Sejersted *et al*., 1984; Sjøgaard *et al*., 1986; Wesche, 1986), and thus the effect of a bigger static underlying force can be measured, but also since activation levels 0-50%MVC, 5-45%MVC, and a constant 25 percent muscle activation was used in other conditions, 15-35 percent muscle

activation level allows for an intermediary activation range (between 5-45%MVC and a constant 25%MVC) averaging at 25 percent to be tested.

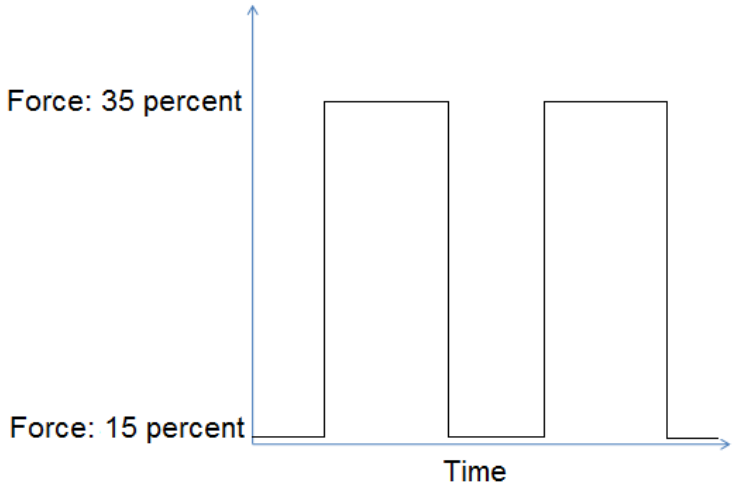


Figure 10:The dynamic force levels (isometric), with the constant underlying force of 15 percent MVC.

3.2.3 Dynamic Length Conditions

In this study: no static component, a small 5 percent constant static component, a larger 15 percent constant static component, and the constant 25 percent muscle activation condition have all been tested for the dynamic force, static length conditions.

During the pilot testing phase, however, it was revealed that the variation between subjects was too great to control when the muscle length was not constant. Regardless of all efforts, all participants would contract at different speeds and reach the desired force level at different times and thus the average work done during the protocol would vary to a large degree for every participant and every dynamic length protocol. This then meant that the fatigue responses could not be compared between conditions or participants. Controlling for variations in dynamic muscle force with a static length was possible however, and thus the scope of this study was reduced to only focus on what role dynamic muscle force plays on muscle fatigue responses.

3.2.3.1 Repetition Rates during Work Protocols

All the conditions in this study, with the exception of the fully static condition, had a set repetition rate for force frequency and in order to achieve the same workload over all conditions, these repetitions needed to be of similar length between participants and

conditions. The variability between the speed of force generation and relaxation between participants, as well as the fact that different conditions have different percentages of maximum force requirements, meant that the time under the correct tension would vary to a significant degree between not only participants, but also conditions and thus this variability needed to be managed as it would affect total work done and result in invalid muscle fatigue measures that could not be accurately compared. The progression of the repetitions can be seen in Figure 8. There were six repetitions per minute for all conditions with a dynamic force. This frequency was selected because it had two yields; firstly, it helped control the variability between force productions between participants. The variation between participants comes into the different rates in which the desired force levels were generated and released by a participant, thus the longer the time that the desired force is held, the smaller impact the force generation and force release phases are since they make up relatively less of the total contraction time. Thus six repetitions per minute resulted in significantly smaller variations in total work done between participants during the pilot testing phase. Six repetitions per minute also enables the protocols to still have a dynamic frequency (Salter, 1955) allowing for optimal blood flow while also having a long enough contraction time to minimizing the effects of variability between participants.

Another strategy put in place to manage the variability between participants and conditions was to create custom timing profiles for every participant for every condition, which meant that while every participant performed six repetitions per minute, the exact length of time that each repetition was held for was slightly different for every participant and every condition to match their individual tension generating and release rates. This meant that the total work was strictly controlled between conditions and participants and it also meant that during the habituation session, every participant needed to be tested with regards to their individual contraction and relaxation rates. A custom timing profile would then be created for that participant to ensure that all conditions had the same overall contraction time and average work load. The custom timing profile caused the dynamic length conditions to be removed from the methodology due to the variations in total work between participants and between dynamic and static length conditions being too significant and could not be controlled with the methods and equipment employed in this study. The length of the

habituation session was also extended considerably since the custom timing needed to be found.

3.3 MUSCLES TESTED IN THIS STUDY

The considerations for the muscle selections in this study were based on acquiring data from both muscles in the upper and lower body, muscles of different size classes, muscle fibre architecture as well as muscles that were relevant to injury prevention and that had high injury rates. The different muscle fibers types that predominantly make up a muscle would be a relevant factor with which to select a muscle, however the studies looking at the muscle fiber types predominantly making up a muscle are few and what these studies reveal is that the inter-individual variability of muscle fiber make-up for a specific muscle is large and whether a muscle has relatively more or less fast twitch muscle fibers is based on genetics, and not on the specific muscle (Simoneau and Bouchard 1995, Vikne *et al.,* 2012). This essentially means that muscle fiber types making up a muscle cannot be used as selection criteria unless there is a pre-test to ensure all participants have similar muscle fiber make-ups (Simoneau and Bouchard 1995, Vikne *et al.,* 2012).

3.3.1 Medial Deltoid

The medial deltoid is a small muscle that has a pennate configuration to its muscle fibres and is responsible for shoulder abduction (Azizi, 2014). Injuries occurring at the shoulder joint are very common in manual and industrial work, even more so when the work is done at shoulder height, or at a higher level (Keyserling, 2000; Sherman, 2003). There is evidence that the injury rate for shoulder muscles are increasing over time; this could be indirectly related to the lack of literature of fatigue levels of shoulder muscles in combination with different work-rest ratios, and thus no accurate risk assessments can be performed on shoulder intensive tasks (Allander, 1974; Maeda, 1977; Kourinka and Koskinen, 1979; Sommerich *et al.,* 1993). Additionally, injuries occurring at the shoulder joint make up 18% of all injuries that occur in industry (Pietracola, 2008), thus making the shoulder joint an important area of the body to study for its specific fatigue mechanisms.

3.3.2 Bicep Femoris

The bicep femoris is a large muscle that has a parallel muscle fibre configuration and is responsible primarily for knee flexion (McLester and Pierre, 2008). Injuries to knee flexors, and most notably bicep femoris, are the most prevalent muscle injury in sports (Heiderscheit *et al*., 2005; Hoskins and Pollard, 2005). The rapid acceleration and maximum speed of running are big contributors to these injuries. Injuries typically occur during a high force eccentric exertion after the muscle has been fatigued (Heiderscheit *et al*., 2005; Hoskins and Pollard, 2005). The lack of research into knee flexor injury aetiology is a contributor to not only injuries occurring but also the re-injuring of these muscles, thus making fatigue research into knee flexors like bicep femoris necessary.

3.3.3 Erector Spinae

The erector spinae is a large muscle that has a parallel muscle fiber configuration and is responsible for back extension (Netter, 2013). There is a very high prevalence of lower back pain and musculoskeletal disorders in the manual labour sector, with cases of workers either being injured or decreasing in overall performance in work tasks that require lifting and carrying, still increasing (Daniel *et al*., 1980; Masset and Malchaire, 1994; Habibi *et al*., 2008; Aghilinejad *et al*., 2012). Thus, while extensive, there is not sufficient investigation into the risks that cause these injuries in lower back muscles such as the erector spinae and as such this lack of adequate risk assessment of the lower back remains an obstacle in reducing injuries, musculoskeletal disorders and decreases in performance of manual workers (Ning *et al*., 2014).

3.3.4 Bicep Brachii

The bicep brachii is a small muscle that has a parallel muscle fibre configuration and is responsible for elbow flexion (Masuda and Sadoyama, 1991). While the bicep brachii muscle is a small muscle and is rarely used in isolation, it acts as a secondary muscle in many movements of the upper limbs and as such, investigating the fatigue characteristics of this muscle may be useful in order to better understanding decreases in performance when tasks require extensive long term use of the upper limbs (Gerdle *et* al., 1989; Lovecchio *et al*., 2013; Vilaca-Alves *et al*., 2014). While injuries to the bicep brachii muscle from overuse were traditionally thought to mainly originate from sport related activities, the prevalence of injuries occurring to the bicep brachii muscle

from occupational work is increasing (Chumbley *et al*., 2000). Thus if manual work is now beginning to affect smaller secondary muscles such as bicep brachii, then it becomes essential to investigate how this muscle fatigues, and if it fatigues differently to other muscles.

3.4 REFERENCE TASKS

Reference tasks refer to standardised tests for all work protocols that determine the muscle fatigue levels. These reference tasks were chosen to measure any muscle fatigue that is induced during the fatiguing protocols to ensure that the data from different protocols can be compared, since the reference tasks were the same for all conditions for a specific muscle. Thus the reference tasks that were used in this study allow the fatigue results gathered over all four conditions to be comparable without influence from the measurement method. The conditions vary in some aspect of activation level or muscle force, and thus if fatigue measures were collected during the protocol itself, it cannot be concluded whether the results from one condition differ to that of another due to the protocol or the method used of collecting the data.

All reference tasks are implemented directly into the fatiguing protocol and are employed to measure all the different fatigue measures. There were two main considerations when selecting fatigue measures in this study, namely: reliability in detecting fatigue, and measures that would work in combination with the protocols utilized in this study. The following fatigue measures were selected:

- Drop in maximum force
- Rating of perceived exertion
- Increase in EMG activity for a set load
- Changes in EMG center frequency

Center frequency is calculated as follows:

$$MNF = \sum_{j=1}^{M} f_j P_j \Big/ \sum_{j=1}^{M} P_j ,$$

Where fj is the frequency value of EMG power spectrum at the frequency bin j, Pj is the EMG power spectrum at the frequency bin j, and M is the length of frequency bin.

In the analysis of EMG signal, M is usually defined as the next power of 2 from the length of EMG data in time-domain (Phinyomark *et al., 2012).*

The above measures all have strong evidence that supports that they can reliable measures of fatigue and are sensitive enough to detect the presence and the degree of muscle fatigue (Naeije and Zorn, 1982; Kumar *et al*., 2002; Luca, 2003) and additionally can measure the induced fatigue from the protocols in a short space of time. This essentially means that muscle fatigue can be measured accurately and without significant interference to the fatigue responses, such as the muscle recovering during an extended measurement time. Maximum endurance time was initially suggested as an additional measure of fatigue; however, it was not compatible with the general layout of this study's methods, as there are four muscles being tested, as well as four conditions that are tested on each. Thus, in order for the demand on a participant to be viable, one needs to test more than one condition on a particular muscle in one session. The time demands on the participants would have been too excessive if a protocol was performed until complete failure for every condition; it would induce a high level of fatigue and would make any further testing on that muscle impossible.

Additionally, in order to make all the fatigue results across all conditions and muscle comparable, the fatiguing protocol needed to be limited to a set length of time. This also made more sense as the testing sessions in this study were lengthy and the motivation levels of participants enduring a challenging fatiguing protocol for more than 90 minutes was impractical and would lead to decreases in performance levels, and thus skewed muscle performance measures.

There were three reference tasks that were used to measure the fatigue responses that occur during intervals in the fatiguing protocols, namely: the Static EMG Reference Task EMG center frequency recording will occur during this measure as well), the MVC Force Reference Task and the RPE measure.

These reference tasks allowed not only for the progression of fatigue to be observed over time, but also for the differences in fatigue responses during different fatiguing protocols. The reference tasks better represented the differences in the fatigue response due to the protocol and not due to different tasks or methods used to

measure the fatigue. Since all conditions were performed for a set length of time, all three of the reference tasks were measured six times per condition for any given muscle.

3.4.1. Reference Task (1): Static Electromyography Reference Task

This reference task comprised a sustained sub-maximal exertion for a weight that initially evokes a set percentage of MVC for all participants. This external load varied between participants, however the internal muscle effort and thus workload was constant across individuals, during which the changes in EMG activity that have occurred over the time of a fatiguing protocol were measured. The increase in EMG activity over time for a set external load had been chosen as an indicator for fatigue as it demonstrates that if a muscle is producing a constant force, the muscle fibres are fatiguing and thus more muscle fibres needed to be recruited in order to maintain the same force level (Falentin *et al*., 1993; Moritani *et al*., 1986). The reference tasks had to be as similar to the tasks in the protocol as possible to ensure that the same muscle fibres that were fatigued in the protocol are tested for fatigue in the measurements taken during the reference task. This particular measurement will be referred to as the "Static EMG reference task" in this study. The specific positions used to measure the static EMG reference task while using the custom-made equipment for each muscle are:

- Bicep Brachii: 90 degrees of elbow flexion
- Medial deltoid: 45 degrees shoulder abduction
- Bicep Femoris: 90 degrees of knee flexion
- Erector Spinae: 135 degrees of back extension

The Illustrations and full explanation of the custom-made equipment is in the following section. Thus the fatigue response was measured at regular intervals allowing the rate of fatigue increase to be measured and compared across the different protocols. The static EMG reference task consisted of a static contraction that lasted for seven seconds at 25 percent of each participant's maximum force production. This was the same for all muscle groups and protocols. Seven seconds allowed for enough EMG data to be collected to obtain five seconds of stable EMG readings when the weight is held steady, without the initial spike reading (refer to Figure 11 – interval A) and change in EMG activity when lowering the weight at the end (Figure 11 – interval B),

as the researcher only wanted to evaluate the stable EMG readings between points A and B, seen at interval RD (RD – recorded data) during which the weight is held steady.

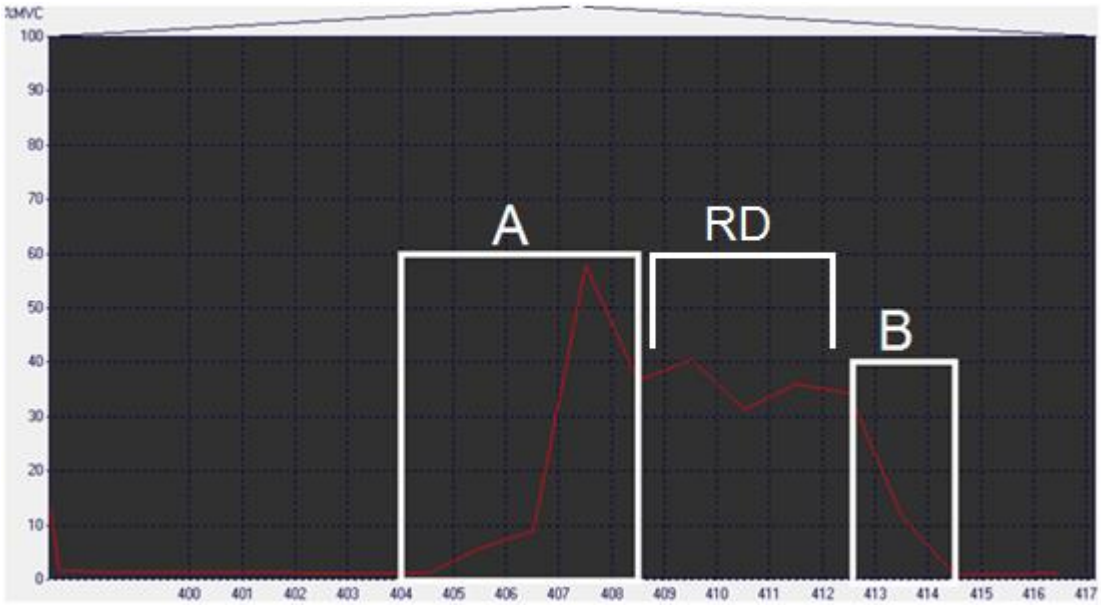


Figure 11: EMG readings during a static EMG reference task, illustrating the initial spike in force (A), recorded data phase (RD) and the force release (B) phases.

In the above figure, areas “A” (initial spike), and “B” (the releasing of the weight) will be excluded from the data analysis. Only the EMG data in the “RD” section will be analysed. The total contraction time for this reference task is defined and set at seven seconds, however the analysis of the results and the elimination of areas “A” and “B” was done by the discretion of the researcher.

3.4.2 Reference Task (2): Maximum Voluntary Contraction Force Reference Task

This reference task was similar in movement to the static EMG reference task in that the readings will also be taken when the respective limb is in the same position as the static EMG reference task. However, the participant will exert their maximum voluntary force against a dynamometer. This force, and the drop in maximum force over successive measurements of this reference task, was recorded on a digital force gauge. Within the reference task battery, the static EMG reference task will be measured first, followed by the MVC reference task. This is in order for the MVC

reference task not to interfere with the EMG readings for the static EMG reference task. The static EMG reference task requires a low force exertion, and was similar to the fatiguing protocol, and will therefore not have much effect on a MVC. This measurement will be referred to as the "MVC force reference task" in this study.

3.4.3. Reference Task (3): Rating of Perceived Exertion

This study employed the Rating of Perceived Exertion (RPE) scale as one of its fatigue measures as it has been used extensively (Hagberg, 1981; Sundelin, 1993; Marcora *et al*., 2008) to measure the progression of fatigue, particularly during exercise activities. The RPE scale has a range of 6 to 20. This range was chosen when the scale was created due to the fact that heart rate and perceived exertion are closely correlated, and thus the RPE scale starts at six, representing the average resting heart rate for the lowest level of exertion, and 20 representing the average maximum heart rate of 200 for an individual's maximum exertion level. The evidence that subjective measures such as the RPE scale may ignore training status and are closely correlated to objective measures such as EMG muscle activation levels and endurance time (Sundelin, 1992; Dedering *et al.,* 1998; Crosby, 2011) make this measure a suitable addition to the fatigue measures and allows for a more diverse participant pool with different training statuses.

The RPE measurement within the work protocol occurs at the end of the protocol segment in order for the exertion level to be clearly felt by the participant to give an accurate description of the exertion level during the fatiguing protocol land thus should give a valid estimate of the participant's workload since it correlates with heart rate, lactate levels, $\%VO_2$ max and breathing rate for that interval (Borg, 1982). The 50 second mark was chosen instead of the 60 second mark (end of fatiguing protocol segment) so that the RPE measure could be complete before the fatiguing segment ended in order for the static EMG reference task to be taken immediately after the fatiguing protocol segment.

3.5 EQUIPMENT AND METHODS

Four muscle testing resistance apparatus which weren't significantly affected by external forces, such as gravity, were designed specifically for this research project,

and all of them were created to isolate the specific muscles included in this study. Additionally, all the custom machines needed to be able to reliably produce the muscle activation patterns necessary for all conditions, not just the set activation levels such as for condition SFSL. All the apparatus had an analogue force scale that was clearly visible to the participant and this allowed them to produce the desired force level(s) that represented the relevant percentages of maximum force for a specific condition (e.g. 5%, 15% and 45%).

3.5.1 Medial Deltoid Upright Row Machine

This machine is a modification of the standard rowing ergometer and utilizes the "upright row" movement to isolate the medial deltoid. However, the user of this machine is lying supine underneath a horizontal bar while pulling on handles attached to a weight, thereby performing shoulder flexion. This has two benefits; firstly, the user cannot use trunk movements to help lift the weight with momentum, and secondly this design eliminates the effects of gravity on the user's body segments when doing the exercise. Figure 12 illustrates this machine, and the direction of force.

Figure 12: Illustration of the medial deltoid upright row machine with the directions of contraction and relaxation.

3.5.2 Bicep Femoris Single Leg Hamstring Curl Machine

This machine allows the user to perform a knee flexion. The participant is seated on a bicycle with the right foot strapped onto a box. The lower leg is positioned

perpendicular to the floor, with the movement occurring at the 90-degree flexion point, in a horizontal direction. Thus while the effects of gravity on the lower leg is not eliminated and may pull on the leg, the force application is horizontal and not against gravity, thus its effects on muscle fatigue were insignificant (Kurtus, 2011). The seat is adjustable, allowing for different users with different statures to get the appropriate knee angle. This machine and the direction of force are illustrated in figure 13.

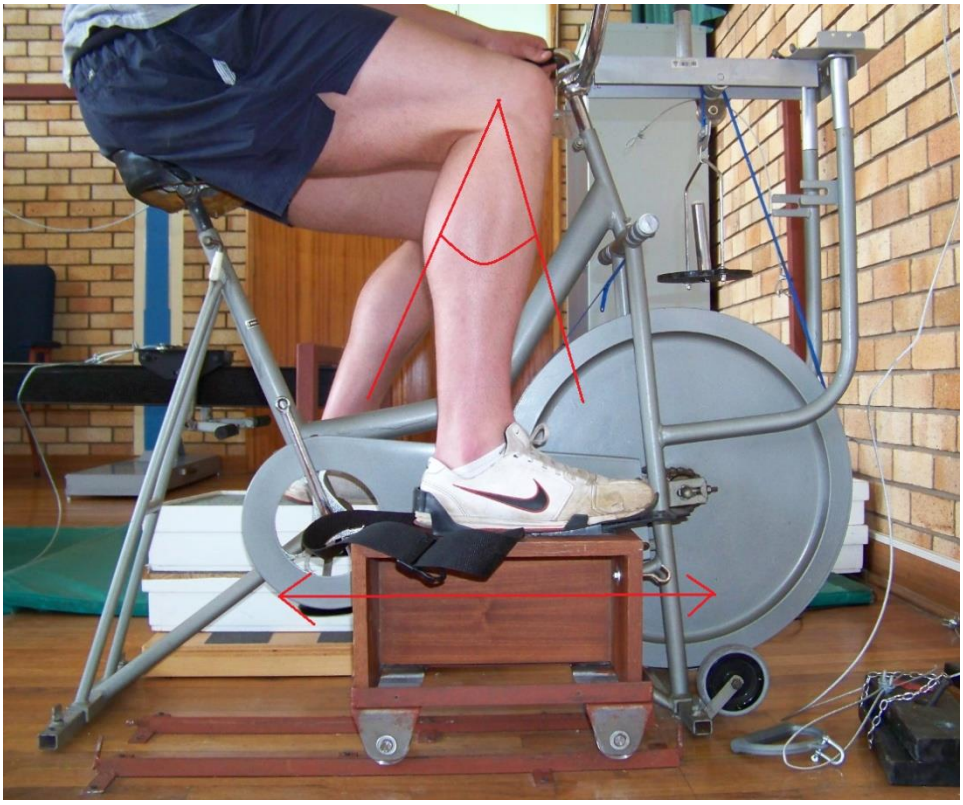


Figure 13: illustration of the hamstring curl machine with the directions of contraction and relaxation

3.5.3 Erector Spinae Back Extension Machine

This machine uses the back extension movement to recruit the erector spinae. Participants lie prone on a padded bench with their legs stabilized and their arms wrapped around a platform that holds their torso. Due to the nature of this movement, gravity needs to be compensated for, and its effects on the moving segment being minimized. The platform that the user's torso is on is connected via cables and pulleys to a counter weight. This allows for the bodyweight of the user to be taken into consideration as any weight attached to the pulley would "lighten" the load, while any weight attached to a hook on the platform that the participant is holding would increase

the load and thus the appropriate muscle activation level being achieved, regardless of the user's upper body weight, or muscle strength level. Figure 14 illustrates the machine, as well as the direction of force.

Figure 14: Illustration of back extension machine with the directions of contraction and relaxation.

3.5.4 Bicep Brachii Isolated Arm Curl Machine

This machine uses the simple, single arm bicep flexion movement to isolate the bicep brachii. Again the upper arm is perpendicular to the ground, and the exertion occurs at the 90-degree flexion in order to minimize the effects of gravity on the lower arm to an insignificant level. The upper arm is always rested flat on the provided surface to ensure that no momentum from other muscles other than the bicep brachii is used to move the weight. This machine, as well as the direction of force is illustrated in Figure 15.

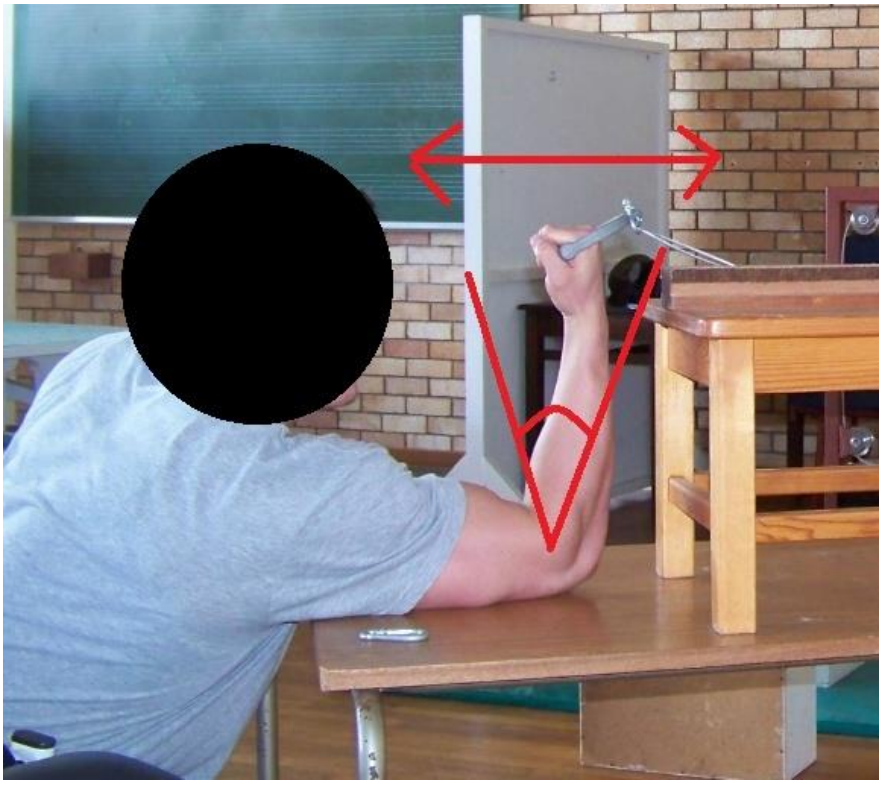


Figure 15: Illustration of bicep brachii intense arm curl machine with directions of contraction and relaxation.

3.5.5 Equipment Pilot Tests

When considering the aspect of repetition timing with regard to the individual muscles, each muscle had its own unique movement, with large variations in the ratio between the rest phase and work phase occurring if the same timing is used for all of them.

Thus separate timing schemes needed to be created for every muscle as well as for all the conditions for every participant. In Figure 8, it can be observed what was needed to be achieved with regard to timing. Theoretically, to achieve an average of 25%MVC the muscle under investigation would have to contract and relax in a 1:1 ratio. However apart from the fact that the minimum activation level can never be completely 0%MVC (Huff,2014), it should also be mentioned that during activation, there is a certain “ramp-up” phase until the muscle has achieved the required level of activation (e.g. 50%MVC). This phase varied not only from muscle to muscle but also between participants and thus required fine tuning to achieve the mean 25% MVC.

Since the apparatus were not standard pieces of equipment used by other studies, pilot tests needed to be conducted on each machine for every testing condition to

ensure that it functioned in the way that it was intended. The initial testing that was performed on every piece of equipment was to determine that muscle activation levels were as they were intended to be. For example, if the protocol states that the muscles activation needs to be zero percent MVC muscle activation (or as close to zero as possible) for two seconds, followed by 50% MVC muscle activation for two seconds, with a total average of 25% of MVC muscle activation, then the machines needed to allow the muscles to produce this. The ideal muscle activation pattern and percent of MVC muscle activation can be seen in figure 8.

In condition DFSL0-50, the muscle force needs to vary from 0% MVC to 50% MVC. It can be observed from Figure 16 that in this case the baseline muscle activation was between 4-6%MVC and thus a full relaxation did not occur, meaning that condition DFSL was not fully dynamic in muscle force as there was an underlying static contraction.

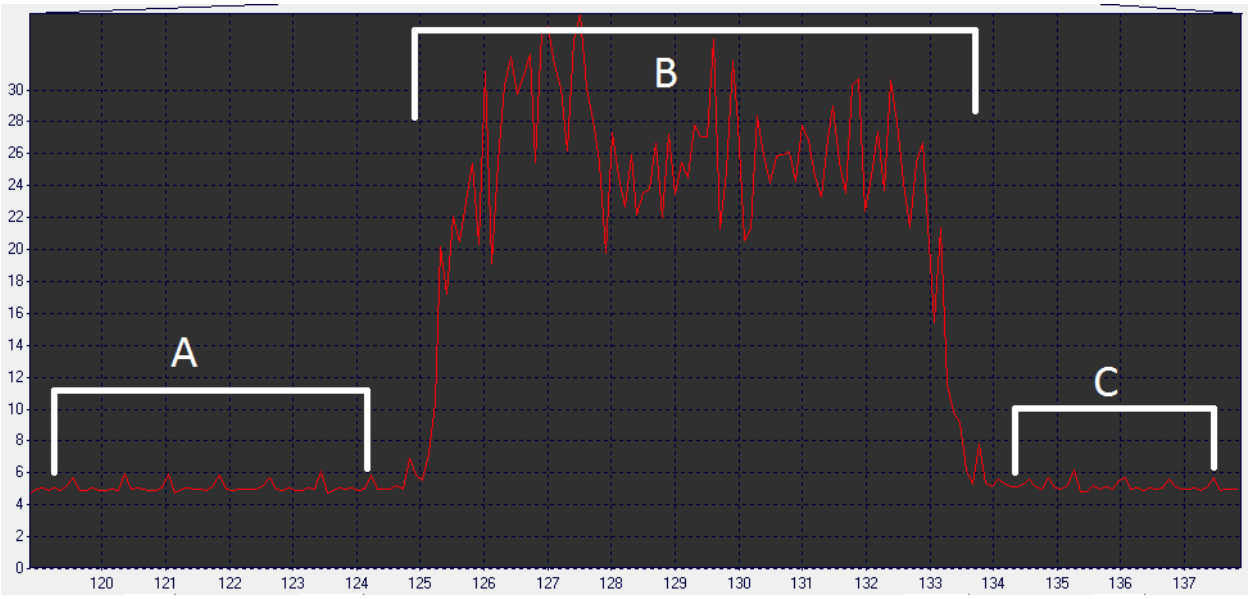


Figure 16: EMG activity of the erector spinae over time.

The minimum muscle activation that could be achieved in the initial design of the machines is seen figure 16 as represented by areas “A” and “C”. With the approximate average of five percent of MVC muscle activation and higher being the lowest value that could be achieved, it meant that the muscle never truly relaxed, and this made the 5%-45% of MVC muscle activation condition too similar to the 0%-50% of MVC muscle activation too similar.

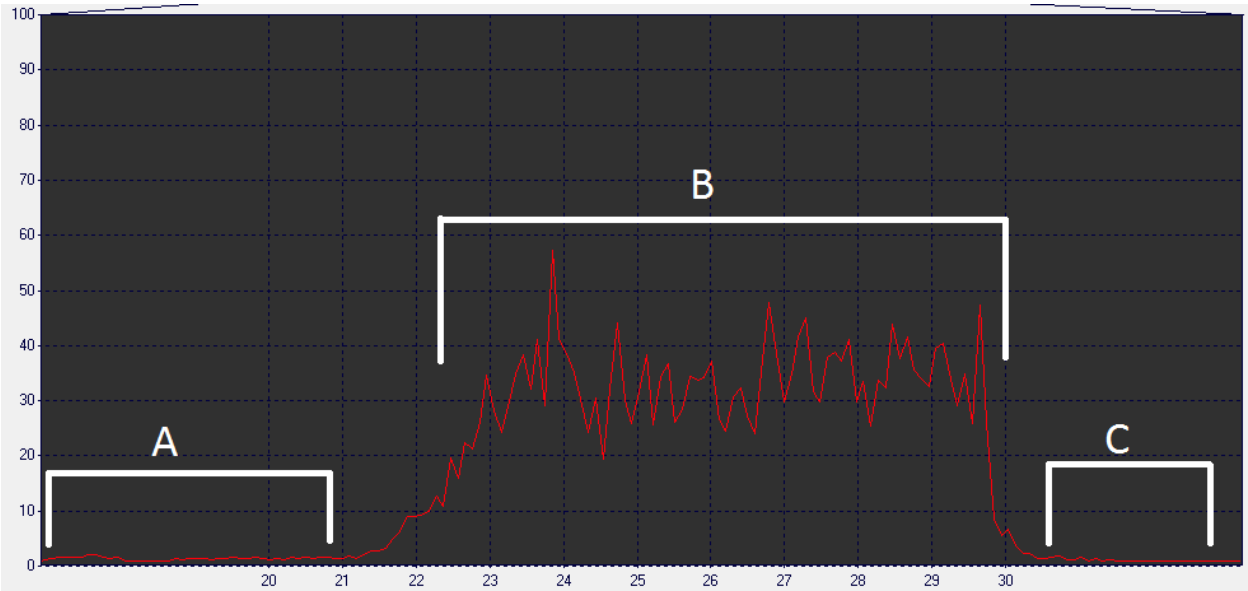


Figure 17: EMG activity over time

Figure 17 shows an example of an EMG for this protocol over time. The minimum percent of MVC muscle activation is now reduced to less than one percent. The values recorded while the participants were in a supine, fully relaxed, position were the same values achieved when fully relaxed and using the custom machines, thus the values during operating the machine is not zero, but is the same as for a fully relaxed individual in a supine position. With adjustments to the machines, the relaxation phase of the DFSL condition yielded the same EMG results as when the muscle was fully relaxed and not operating the machine, which is between 0-2% MVC. These EMG values for muscles at rest when not operating the machine were measured during pilot testing and were obtained in the same testing sessions for the same participant as the baseline EMG measures while at rest and operating the machine.

3.5.6 Practical Issues Encountered During Pilot Studies

Since the machines for isolating the muscles in this study were custom made, some aspects like comfort and the recruitment of muscles other than the one being tested were considered. The custom machines were designed to serve the purpose of fatiguing a certain muscle in the ways that were needed in all experimental conditions as well as allow the user to operate the machine comfortably for the required time. Padding in certain areas solved all the aspects of comfort, however the issue of incorporating a secondary muscle in the movement needed to considered as it would negatively affect the fatigue results. If the secondary muscle is allowed to be recruited

to a large degree the fatigue responses collected from the primary muscle may not reflect what the participant was meant to be exposed to as the secondary muscle may be recruited more and more as the primary muscle fatigues. A situation such as this would affect fatigue measures such as maximum force production since the changes in force over time would not reflect the fatigue that is occurring in the primary muscle and thus the machines needed to be designed to accommodate this.

The two instances of secondary muscles being recruited were with the medial deltoid machine and the erector spinae machine. The upright row movement performed on the medial deltoid machine recruited the brachialis and bicep brachii muscles if performed incorrectly. The recruitment of these muscles was detected by participants during pilot testing of the machine. The incorporation of the secondary muscles caused not only significant discomfort in those areas but EMG readings confirmed that the recruitment of bicep brachii and brachialis were being recruited to a similar level as medial deltoid, indicating that the total load was being shared between these muscles. The solution to this was to create handles for the machine that allowed stricter form during the upright row movement as well as additional habituation of what form to employ during the protocol. The pilot tests on the erector spinae machine indicated that the hip extensors were being recruited significantly again detected by discomfort levels of the participant and EMG readings. This issue was sufficiently addressed when the range of motion that the participant went through during the erector spinae exercise was changed so that the erector spinae was the only muscle being recruited and fatigued.

3.6PARTICIPANTS

3.6.1 Inclusion Criteria

There were 16 participants in order for randomization for 4 conditions and limited to 16 for testing time constraints, which were split evenly between male and female. The age of the participants was between 18-25 years. This age range was chosen for two reasons; it includes most of the student population at Rhodes University which is where the researcher primarily drew participants from. The students of Rhodes University were targeted since their education level would aid in their understanding of the testing procedures in this study such as the RPE scale and that would yield

more valid results. Additionally, due to the effects of sarcopenia, sedentary individuals past the age of 25 may be subject to reduced muscle function and thus beyond 25 years, the decrements in strength increases the risk of injury (Kwan, 2013). Also the risk of a participant having intervertebral disc degeneration also increases with age and thus no participants older than 25 years were selected (Kwan, 2013).

Participants needed to be physically able to operate the custom designed machines, which meant a minimum strength level is required to operate the machines used in this study. While the minimum level was very low, individuals with very little resistance strength were shown to be unable to use the machines during explorative studies. The machines utilized in this study use levels of resistance, e.g. one plate being equal to 0.9kg (two pounds), and thus when a participant is performing a condition that requires 25% of their maximum force and this equates to less than one level of resistance of the machines, they will be unable to perform the protocol at their respective sub-maximal strength. Therefore, in order for all participants to be tested accurately, the permissible maximum strength of all participants needed to be equal to, or higher than98N for all muscles tested.

All participants needed to be healthy at the time of testing, with no recent history (6 months) of acute injuries, or any history of musculoskeletal disorders affecting the strength and endurance of any of the shoulder abductor, knee flexor, back extensor or elbow flexor muscles.

All participants needed to have a stature of less than 1.98m due to limitations of the equipment used in this study. The machinery used has limited adjustment settings for individual anthropometric characteristics, and thus if an individual is taller than 1.98m, then he/she would not be able to achieve a full range of motion during the required task. There was no minimum stature requirement for any machine.

All participants were required to have a minimum level of physical activity in order to participate. The current minimum recommended physical activity for healthy bone, muscle strength and flexibility is 60 minutes of moderate-intensity physical activity twice a week (Miles, 2007). Since the equipment were designed to isolate and fatigue specific muscles, completely sedentary individuals may get injured even if there were

safety parameters in the protocol design and thus the recommended physical activity of Miles (2007) was a requirement.

All participants in this study needed to be right-handed due to the fact that the custom designed machinery used in this study measures only the muscles on the right-hand side of the body, and thus left-handed individuals may have less muscular control and the muscles mostly used in daily activity or in sporting scenarios will not be tested in left-handed participants.

3.7 EXPERIMENTAL PROCEDURES

This study employs a repeated measure design and thus the testing time for every participant, including the testing time needed during the habituation session, amounts to 210 minutes, with the testing sessions being 90 minutes each and the habituation session being 30 minutes. The physical testing time that a participant underwent the fatiguing protocols was 132 minutes. In order to keep motivational levels and overall fatigue in check, the testing sessions needed to be split up. Participants were required to attend three sessions in the Human Kinetics and Ergonomics Department at Rhodes University. The initial session was dedicated to introductory and habituation purposes, while the other two sessions were experimental testing sessions where the muscle fatigue data from all muscles and conditions will be collected.

3.7.1 Introductory and Habituation Session

During this session the participants were verbally informed of all the conditions and protocols they would need to perform if they agreed to be part of the study, as well as the risk and benefits of participation. It also served as an opportunity to be exposed to all the equipment, to familiarize themselves with the apparatus and to practice the experimental conditions that they would perform during the testing sessions. As all equipment was either custom-made or had been modified from existing equipment, it was important that participants felt comfortable with their use and can accurately perform the required movements with the required timing. The habituation session also served to create the custom timing scheme for every participant and every condition necessary to create valid results as explained in “Repetition Rates during Work Protocols” and “Equipment Pilot Tests” sections. Once the familiarization was

completed, all participants were required to sign a consent form, indicating that they fully understood all the requirements expected of them if they agreed to take part the study, as well as the risks and benefits associated with participation, as well as issues such as privacy, anonymity and confidentiality.

If an individual agreed to partake in the study, their stature would be checked, as well as perform a minimum strength test to ensure that they are compatible with the equipment. This session lasted approximately 30 minutes.

3.7.2 Experimental Sessions

Each experimental session lasted approximately 90 minutes with 8 protocols tested on a participant in one session. Randomization was employed to assign each participant a condition testing order. However, the order in which muscles are tested remained constant due to the fact that each muscle needs time to recover and there is an overlap of the secondary muscles that could be fatigued.

3.7.3 Muscle Testing

The muscles that are tested overlap to some degree when they are fatigued, for example, as covered earlier the bicep brachii muscle during the medial deltoid testing, while the recruitment of a secondary muscle was minimized as much as possible in the modification of the custom designed equipment to isolate each muscle, the testing order of the muscles was not be randomized, but rather will follow a set sequence to ensure that two muscles are never fatigued in a row. The muscles which may overlap are the bicep brachii (during the medial deltoid isolation exercise), the bicep femoris (during the erector spinae isolation exercise) and the erector spinae (during the bicep femoris isolation exercise). The sequence (number) of muscle testing was therefore:

1. Medial deltoid
2. Erector Spinae
3. Bicep Brachii
4. Bicep Femoris

While the sequence of muscles always followed the above order, every combination within these parameters is tested, and this can be seen in Table 2 where the muscle tested first was alternated but the testing order still followed the specified muscle testing sequence.

Table 2: Condition Testing Order.

	Session 1		Session 2	
	Muscle Order	**Condition Order**	**Muscle Order**	**Condition Order**
Participant 1	MD, BF, BB, ES	SFSL, DFSL0-50	MD, BF, BB, ES	DFSL5-45, DFSL15-35
Participant 2	MD, BF, BB, ES	DFSL0-50, DFSL5-45	MD, BF, BB, ES	DFSL15-35, SFSL
Participant 3	MD, BF, BB, ES	DFSL5-45, DFSL15-35	MD, BF, BB, ES	SFSL, DFSL0-50
Participant 4	MD, BF, BB, ES	DFSL15-35, SFSL	MD, BF, BB, ES	DFSL0-50, DFSL5-45
Participant 5	BF, BB, ES, MD	SFSL, DFSL0-50	BF, BB, ES, MD	DFSL5-45, DFSL15-35
Participant 6	BF, BB, ES, MD	DFSL0-50, DFSL5-45	BF, BB, ES, MD	DFSL15-35, SFSL
Participant 7	BF, BB, ES, MD	DFSL5-45, DFSL15-35	BF, BB, ES, MD	SFSL, DFSL0-50
Participant 8	BF, BB, ES, MD	DFSL15-35, SFSL	BF, BB, ES, MD	DFSL0-50, DFSL5-45
Participant 9	BB, ES, MD, BF	SFSL, DFSL0-50	BB, ES, MD, BF	DFSL5-45, DFSL15-35
Participant 10	BB, ES, MD, BF	DFSL0-50, DFSL5-45	BB, ES, MD, BF	DFSL15-35, SFSL
Participant 11	BB, ES, MD, BF	DFSL5-45, DFSL15-35	BB, ES, MD, BF	SFSL, DFSL0-50
Participant 12	BB, ES, MD, BF	DFSL15-35, SFSL	BB, ES, MD, BF	DFSL0-50, DFSL5-45
Participant 13	ES, MD, BF, BB	SFSL, DFSL0-50	ES, MD, BF, BB	DFSL5-45, DFSL15-35
Participant 14	ES, MD, BF, BB	DFSL0-50, DFSL5-45	ES, MD, BF, BB	DFSL15-35, SFSL
Participant 15	ES, MD, BF, BB	DFSL5-45, DFSL15-35	ES, MD, BF, BB	SFSL, DFSL0-50
Participant 16	ES, MD, BF, BB	DFSL15-35, SFSL	ES, MD, BF, BB	DFSL0-50, DFSL5-45

Note:

MD- Medial Deltoid

BF- Bicep Femoris

BB-Bicep Brachii

ES-Erector Spinae

The muscle testing order that is set allows not only for the overlapping muscle issue to be addressed, but it also means that every muscle has a minimum of 21 minutes of rest between being tested allowing for sufficient recovery time to perform maximally once again (Matuszak *et al*., 2003). Every muscle is tested twice in every session.

An example of the progression of one full testing session is illustrated in figure 18. The 21 minutes of rest between each testing of an individual muscle can be observed, as well as the total time for a participant performing fatiguing protocols.

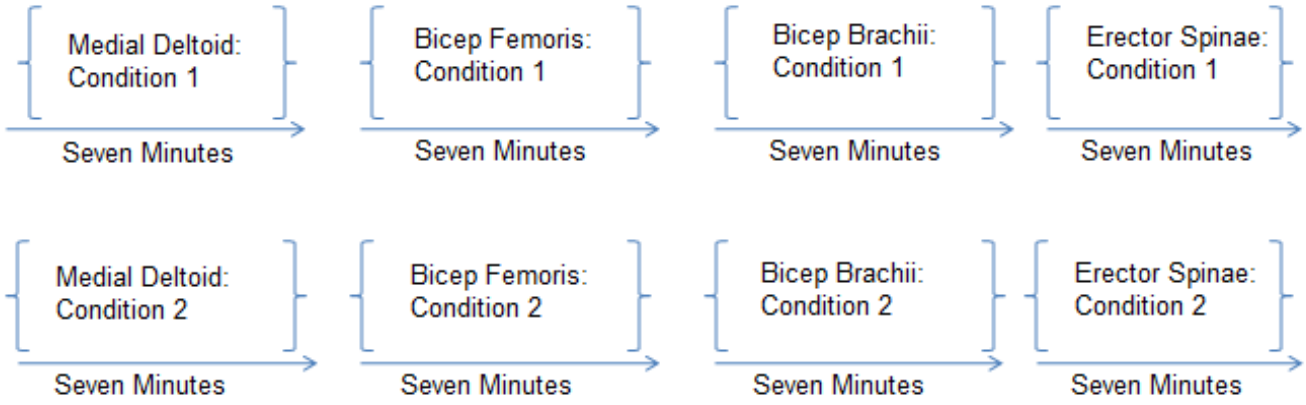


Figure 18: Progression of an experimental session (Authors own representation).

3.7.4 Equipment and Measurement Procedures

The list of the equipment used for the testing was as follows:

- A Stadiometer.
- A Back Machine, which was custom-made to test the erector spinae during back extension.
- A Shoulder Machine, also custom-made to test the medial deltoid muscle during shoulder abduction.
- A Hamstring Machine, custom-made as well, to test the biceps femoris muscle during knee flexion.
- A Bicep Machine also custom-made to test the biceps brachii muscle during elbow flexion.
- An EMG measurement system (Biometrics Datalogger).
    - Activity measurement in order of processing:
        - Differential amplification x1000
        - Analog Filter 5 Hz Highpass
        - 16 bit Digital Sampling 1000 Hz
        - Digital Lowpass Filter 400 Hz (FFT)
        - Rectification
        - Averaging over 0.2s
        - Normalisation to MVC measured over 3s
    - EMG Amplifier SX230FW electrodes (sampling frequency 20KHz)
- A force gauge.

- A Rating of Perceived Exertion (RPE) scale.

The fatigue measurements were recorded in the same way for all conditions. The EMG was normalized for each participant by recording maximal voluntary contraction on each machine, i.e. for each muscle. These MVCs were measured during all three testing sessions. The MVC protocol used to normalize the EMG to the participant was the method used in other studies investigating muscle fatigue (Doorenbosch *et al.,* 2005). This method involves two 5 second maximum voluntary contractions at a 60degree joint angle and has been shown to be safe, but also produce a high mean integrated EMG value (Hunter *et al*., 2002). The participants were verbally encouraged to perform maximum exertions during the initial maximum voluntary contraction.

Over the two experimental testing sessions, a participant was tested 16 times (four conditions for all four muscles). To measure the indices of fatigue mentioned above, participants underwent a seven-minute fatiguing protocol, interspersed with reference tasks during which the fatigue measures are recorded. The purpose of the reference task was to measure the progression of fatigue throughout the fatiguing protocol. Each experimental condition started off with the reference tasks, namely static EMG reference task and the MVC force reference Task. This was followed by 60 seconds of the fatiguing protocol, with the RPE reference task being measured at the 50 second mark during the fatiguing protocol. This was then followed by the reference tasks again. This pattern of testing will be repeated five times and is concluded with the participant performing the reference tasks for a final measurement. The full testing time needed for one condition including all measures of the reference tasks is eight minutes. Once participants have completed one condition for a certain muscle, they perform the same general protocol on a different machine, using a different muscle to prevent cumulative fatigue. The time of rest allowed before any muscle is re-tested is 21 minutes due to there being four muscles in rotation.

3.8 OVERVIEW OF THE TESTING PROCESS

When considering the data collection aspect of the methodology, there is a certain progression that is required for all the measures to be collected accurately. Figure 19 shows that testing began with an initial maximum voluntary contraction during which

the maximum force a specific muscle could produce was recorded. From this maximum force exertion, the force level needed for the static EMG reference task and the fatiguing protocol were calculated. The static EMG reference task required a force production of 25 percent of the maximum force obtained during the initial MVC. The relevant force levels needed for the specific protocols were also calculated from the initial maximum exertion. Although the maximum force was measured after the EMG reference task for the following five intervals, the initial maximum force was measured before the initial static EMG reference task. The initial measure had to start with the maximum force measure due to the fact that the relevant load for the static EMG reference task needed to be calculated from the maximum force measure. Thus, even though it would have been beneficial to measure the static EMG reference task first for the initial measure, as explained previously, it was necessary to measure the maximum force first. Once the initial maximum force measure and static EMG reference task had been recorded, the first fatiguing protocol interval was started. This process was then repeated until a total of six measures (one measure prior to the fatiguing protocol and five measures during) were recorded for all reference tasks.

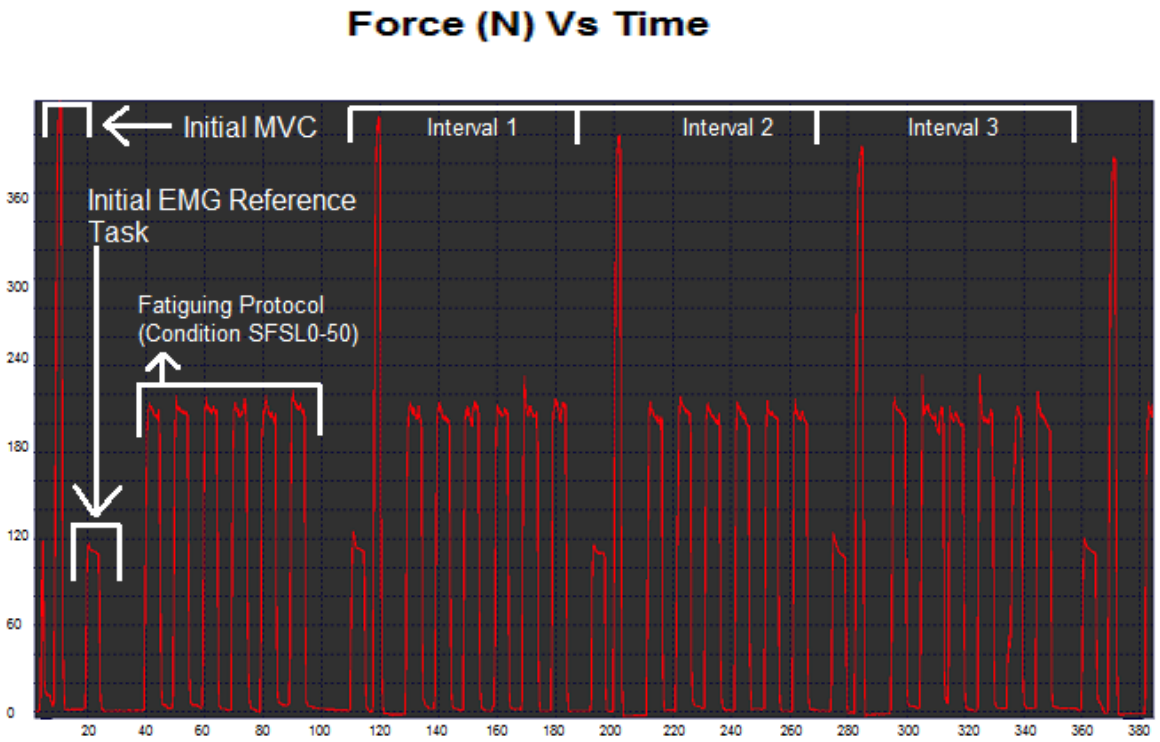


Figure 19: Diagram depicting the progression of the testing process (Note: the figure is a sample print out of the EMG readings during the DFSL0-50 condition).

3.8.1 Control for Contraction Levels over all Conditions

To compare the fatigue responses of all conditions, it first had to be verified that all the participants adhered to the same fatiguing protocols for all conditions. In other words, the muscle contractions during the fatiguing protocol had to average as close as possible to 25 percent of maximum muscle activation over the entire minute. This meant that the average muscle activation over the five one-minute intervals of the fatiguing protocol was the same for all conditions, and thus the same workload was placed on the muscle with the differences in fatigue being attributable to the differences in the contraction type and not due to one condition requiring more overall work or higher average muscle activation than another.

Table 3 summarizes the mean muscle activation (%MVC) of all four muscles under investigation and under all four testing conditions. This data was recorded over the entire first minute (testing interval) of the fatiguing protocol for every muscle, condition and participant as an average percentage of maximum force over time. Only the first minute was included due the effects that muscle fatigue may have had on EMG results on the following intervals. This control measure was only intended to ensure that strategies such as the individual timing schemes for every participant created during the habituation sessions that were implemented to control the total work done for every participant, condition and muscle was successful. Thus, only data unaffected by muscle fatigue was used to establish whether the conditions were similar. The p-values indicate no significant differences in the average muscle activation over time as a percentage of initial maximum force during the fatiguing protocol (illustrated in Figure 19).Therefore all conditions could be compared and differences in responses attributed to the “type” of contraction, rather than differences in workloads. The variability between all muscles had similar ranges of contractions (as seen in the coefficient of variation). Thus, each muscle contracted in a similar manner for each of the conditions.

Table 3: Mean, Standard deviation and Coefficient of variation (in brackets) of the percentage of maximum force for the fatiguing protocols for the tested muscles.

	SFSL	DFSL0-50	DFSL5-45	DFSL15-35	P-value
Medial Deltoid	24.3 ±1.9%MVC (8%)	24.4 ±4.1%MVC (16.6%)	24.4 ±2.6% MVC (10.8%)	24.3 ±2.2%MVC (8.9%)	0.99
Bicep Femoris	23.9 ±3%MVC (12.7%)	25.2 ±4.3%MVC (17.1%)	26 ±5.6%MVC (21.5%)	24.8 ±4.9%MVC (19.8%)	0.38
Bicep Brachii	24 ±4.9%MVC (20.5%)	23.5 ±5.8%MVC (24.7%)	24.6 ±4.4%MVC (17.7%)	23.3 ±4.98%MVC (21.3%)	0.81
Erector Spinae	27.5 ±4.3%MVC (15.6%)	26.1 ±6.4%MVC (24.6%)	27.5 ±5.89%MVC (21.3%)	26.35 ±4.7%MVC (18.1%)	0.75

3.9 STATISTICAL ANALYSIS

The study's two hypotheses are:

1) To investigate whether, and to what extent, a quasi-static work regime fatigues a muscle with the same fatigue characteristics as exclusively static work.
2) To investigate what effects a constant underlying static component has on fatigue during an otherwise dynamic muscle force work regime.

The general linear model Analysis of Variance (ANOVA) was employed by Statistica 12 to determine whether there was any significant differences($p<0.05$) in muscle fatigue responses between condition SFSL and DFSL0-50 in order to test Hypothesis 1, which compared dynamic and static muscle forces over set time intervals. The general linear model is also employed to determine if any significant differences exist between conditions DFSL0-50, DFSL5-45 and DFSL15-35 to test Hypothesis 2, which was comparing the effects of underlying static components on muscle fatigue over set time intervals. The tukey post-hoc test was employed when significance was found. Other personal (e.g. sex, age, race and baseline strength) and procedural factors (e.g. testing order) were not considered as additional factors in the data analysis since this was deemed to be beyond the scope of this project, although it is acknowledged that these may influence the statistical power.

CHAPTER 4: RESULTS

The primary focus of this study was to examine different muscle fatigue responses to protocols that differ in muscle force levels (with same overall average work), with either dynamic or static muscle force states. In order to study these two hypotheses, there are two aims:

1. To investigate whether, and to what extent, a quasi-static work regime fatigues a muscle with the same fatigue characteristics as exclusively static work
2. To investigate what effects a constant underlying static component has on fatigue during an otherwise dynamic muscle force work regime

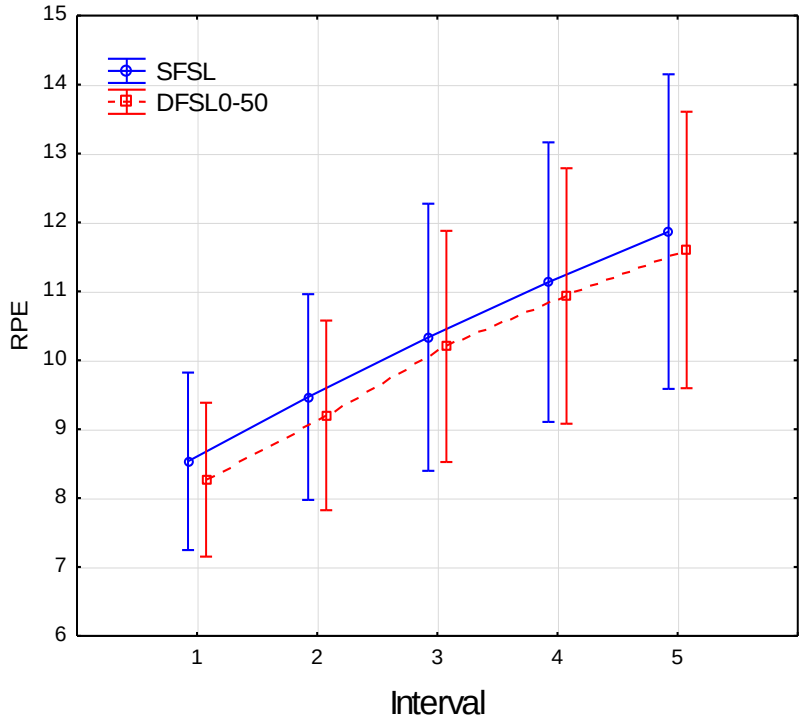
Four conditions were employed which varied in muscle force levels, with equal total work, and were tested on the medial deltoid, bicep femoris, bicep brachii and erector spinae muscles on 16 participants in a repeated design study. The results were statistically processed by employing a two factorial ANOVA for SFSL and DFSL0-50 to test hypothesis 1, and for DFSL0-50, DFSL5-45 and DFSL15-35 to test hypothesis 2.Statisticalanalysisoccurredindependently for each hypothesis.

4.1 HYPOTHESIS 1: COMPARISON OF QUASI-STATIC AND PURELY STATIC WORK ON MUSCLE FATIGUE RESPONSES

4.1.1Ratings of Perceived Exertion

The starting RPE for any muscle and condition is always six, signifying a rested state, the initial interval (pre fatiguing protocol) has not been displayed for the RPE results.

4.1.1.1Medial Deltoid



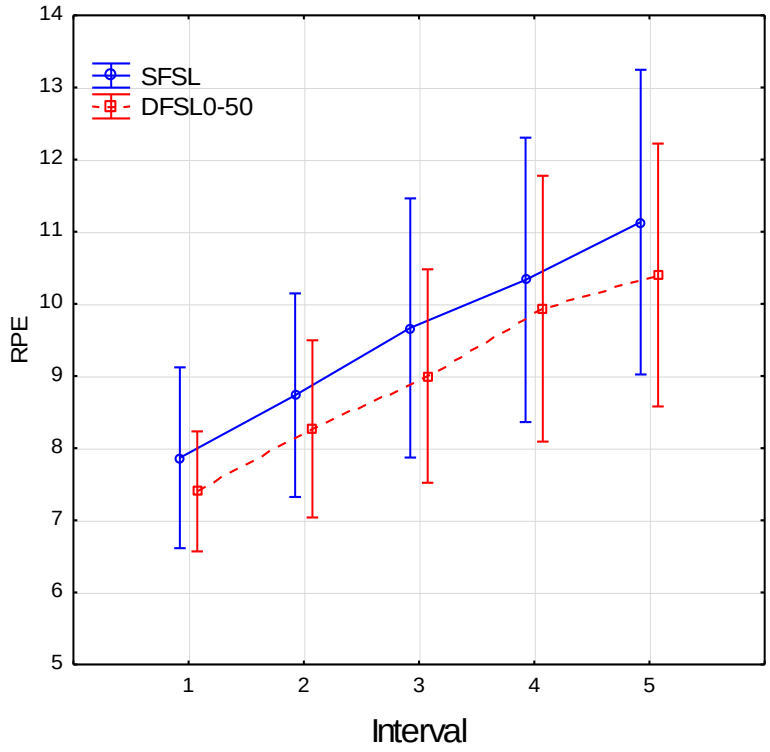
Error probability for effects:

- Condition: p=0.76
- Time: p<0.01
- Condition x Time:0.99

Figure 20: RPE values of the medial deltoid muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There was a significant increase in RPE over time with an error probability of less than 1%. Post-hoc tests revealed that both conditions SFSL and DFSL0-50 had a significant increase in RPE at interval one from the pre-protocol measure (p<0.01). The RPE measurements increased from 8.8 (±2.25) to 12.2 (±4.26) for the SFSL, while for the DFSL0-50 condition, they rose from 8.3 (±1.99) to 11.6(±3.62).

4.1.1.2 Bicep Femoris



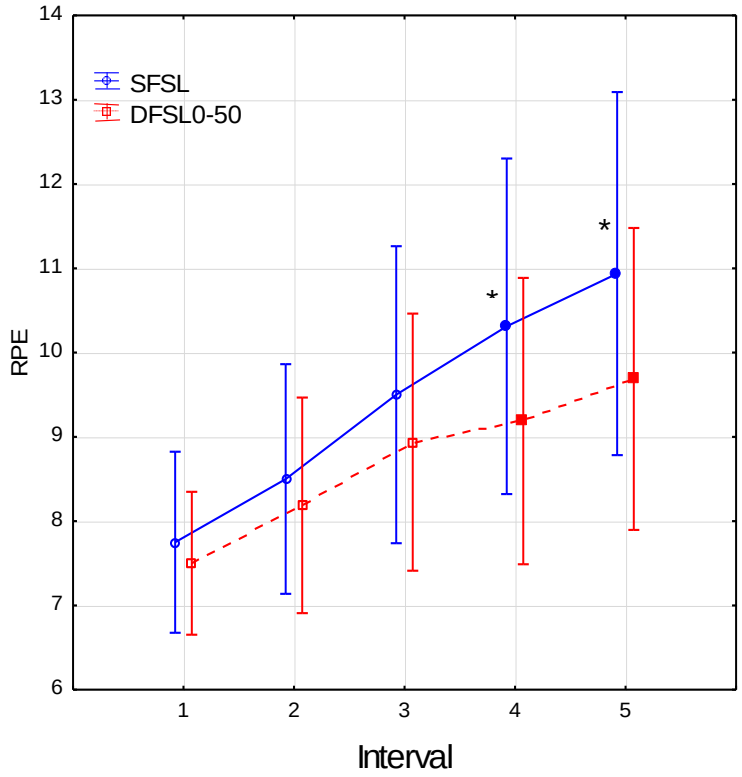
Error probability for effects:

- Condition: p=0.14
- Time: p<0.01
- Condition x Time: p=0.84

Figure 21: RPE values of the bicep femoris muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There was a significant increase in RPE over time with an error probability of less than 1%. Post-hoc tests revealed that both conditions SFSL and DFSL0-50 had a significant increase in RPE at interval one from the pre-protocol measure ($p<0.01$). RPE measurements increased from 8(±2.25) to 11.1(±3.81) for the SFSL condition, while for the DFSL0-50 condition they rose from 7.5(±1.5) to 10.5(±3.2).

4.1.1.3 Bicep Brachii



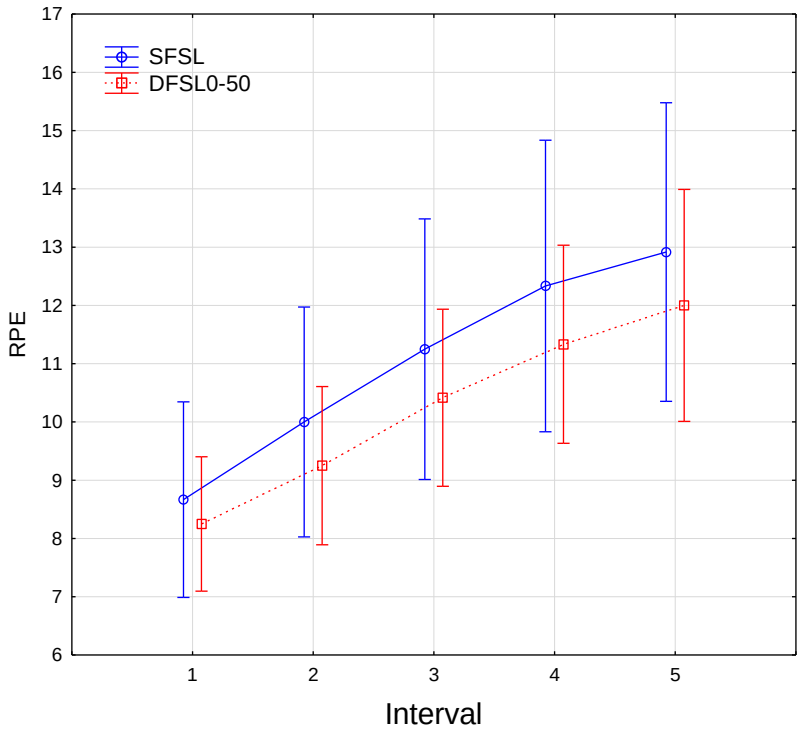
Error probability for effects:

- Condition: p=0.22
- Time: p<0.01
- Condition x Time: p<0.01

Figure 22: RPE values of the bicep brachii muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals, * indicates a significant difference between conditions at p<0.05.

There was a significant increase in RPE over time with an error probability of less than 1%. Post-hoc tests revealed that both conditions SFSL and DFSL0-50 had a significant increase in RPE at interval one from the pre-protocol measure (p<0.01). A significant interaction effect was demonstrated in this result (p<0.01). Post-hoc tests revealed that there was a significant difference between conditions at intervals four and five with error probabilities of less than 1%, indicating that the fatigue levels were significantly different at these points. RPE measurements increased from 7.7 (±2) to 10.9 (±4.04) for the SFSL condition, while for the DFSL0-50 condition they went up from 7.5 (±1.5) to 9.68 (±3.3).

4.1.1.4 Erector Spinae



Error probability for effects:

- Condition: p=0.2
- Time: p<0.01
- Condition x Time: p=0.76

Figure 23: RPE values of the erector spinae muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There was a significant increase in RPE over time with an error probability of less than 1%. Post-hoc tests revealed that both conditions SFSL and DFSL0-50 had a significant increase in RPE at interval one from the pre-protocol measure ($p<0.01$). RPE measurements increased from 9.2(±2.5) to 13.2(±4) for the SFSL condition, while for the DFSL0-50 condition they rose from 8.4(±1.9) to 12(±3.1).

When considering the results for the first hypothesis, the RPE results showed some consistencies that were shared between all muscles. While it was not always statically significant, condition SFSL always had a higher RPE value for all intervals and muscles compared to DFSL0-50. The variability between participants increased with the progression of intervals for all muscles, and additionally for all muscles, condition SFSL experienced the larger increase in variability when compared to DFSL0-50.

4.1.2 Maximum Force Production

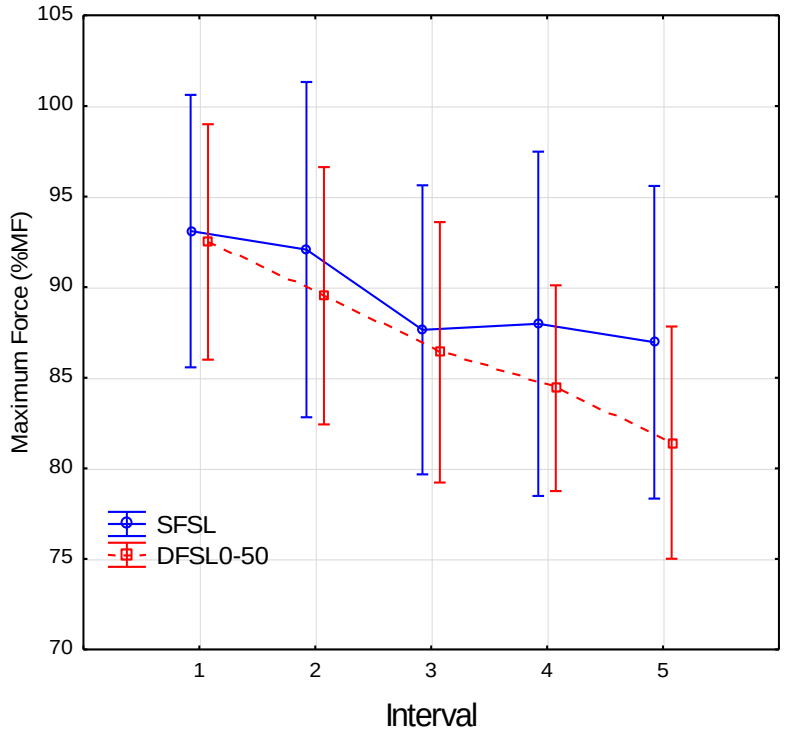
Since the maximum force had to be recorded before every single condition and for every single muscle tested, it was important to first verify whether there was a significant difference in the average of all participants' starting maximum force between any condition or muscle. Only if there was no significant difference, could the results be compared in absolute values (Newton).

Table 4: Mean, standard deviation and coefficient of variation (in brackets) for the initial maximum force measure for all muscle and conditions, measured in Newton.

	SFSL	**DFSL0-50**	**DFSL5-45**	**DFSL15-35**	**P-value**
Medial Deltoid	290 ±91.4 (32%)	316.5 ±100.4 (32%)	316 ±106.8 (34%)	323.1 ±116.7 (36%)	0.02
Bicep Femoris	206.4 ±64.1 (31%)	199.8 ±73.3 (37%)	207.2 ±80.7 (39%)	211.6 ±81.2 (38%)	0.53
Bicep Brachii	175.6 ±57.8 (33%)	177.5 ±59.7 (34%)	181.1 ±63.6 (35%)	172.7 ±61.8 (36%)	0.54
Erector Spinae	172.1 ±73 (42%)	182 ±76.6 (42%)	164.6 ±71.7 (44%)	175.3 ±83.6 (48%)	0.34

Due to the fact that there was a significant difference in starting maximum force (MF) for one condition (medial deltoid, condition SFSL), all of the maximum force production results have been relativized to the initial reading as a percentage. The initial measure will always be referenced to 100 percent, thus only the measures after the pre-protocol measure will be displayed. Fatigue within conditions was inferred from the decrease in force production that is significantly lower to the starting value of 100%.

4.1.2.1Medial Deltoid



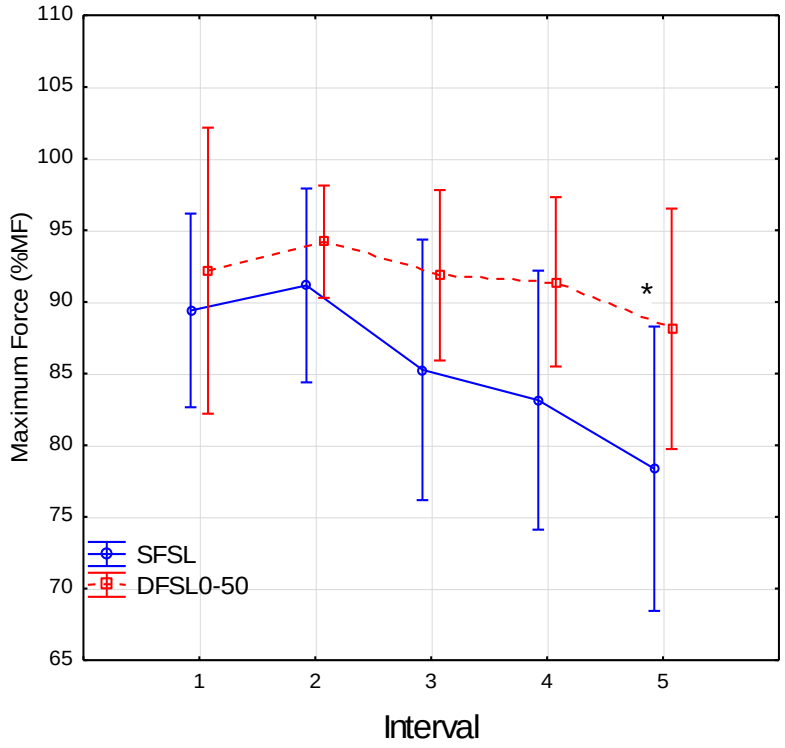
Error probability for effects:

- Condition: p=0.41
- Time: p<0.01
- Condition x Time: p=0.31

Figure 24: Percentage of maximum force for the medial deltoid muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There was a significant decrease in maximum force over time with an error probability of less than 1%. Post-hoc tests demonstrated that condition SFSL decreased in maximum force significantly at interval five (p=0.03), while condition DFSL0-50 had the first significant decrease in maximum force at interval three (p=0.03). The two conditions began to diverge at interval three and while not statistically significant, the difference in means between condition SFSL and DFSL0-50 at interval three, four and five are 1.2%Maximum force (MF), 3.5%MF and 5.5%MF, respectively.

4.1.2.2 Bicep Femoris



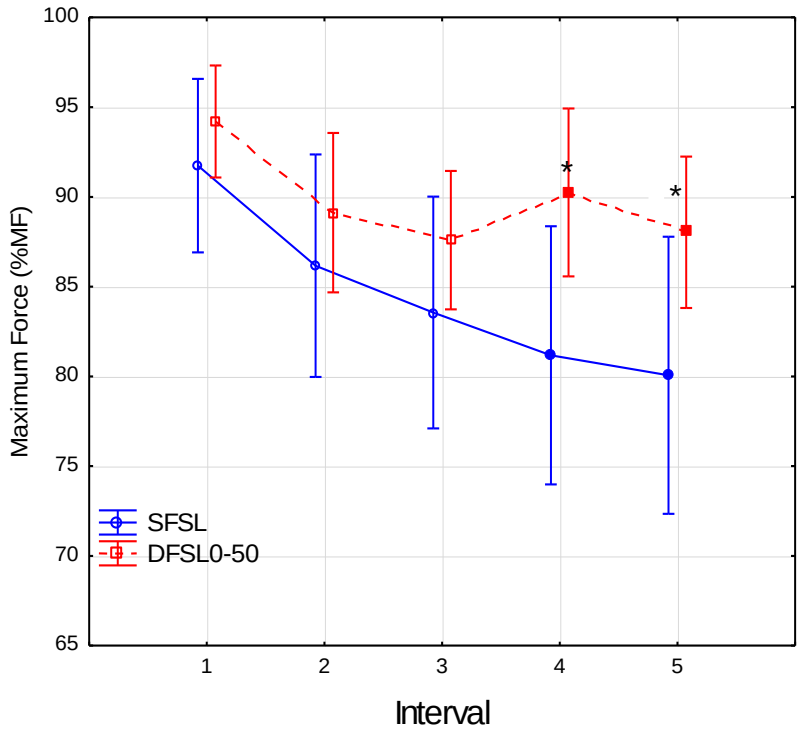
Error probability for effects:

- Condition: p=0.09
- Time: p<0.01
- Condition x Time: p=0.23

Figure 25: Percentage of maximum force for the bicep femoris muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals, * indicates a significant difference between conditions at p<0.05.

There was a significant decrease in maximum force over time with an error probability of less than 1%. Post-hoc tests demonstrated that there was no significant fatigue in condition DFSL0-50, with mean values ranging between 89% (±15%) and 94.7% (±7.2%) of initial maximum force. However, condition SFSL showed significant fatigue from interval five when compared to the initial maximum force (p=0.03). Condition SFSL began to diverge from condition DFSL0-50 at interval two with the differences between their means at interval two, three four and five being 3%MF, 6.5%MF, 8.2%MF and 9.8%MF respectively. Additionally, post-hoc tests indicated that there is a significant difference between condition SFSL and condition DFSL0-50 at interval five (p= 0.014), indicating that the two conditions differed significantly at this point.

4.1.2.3 Bicep Brachii



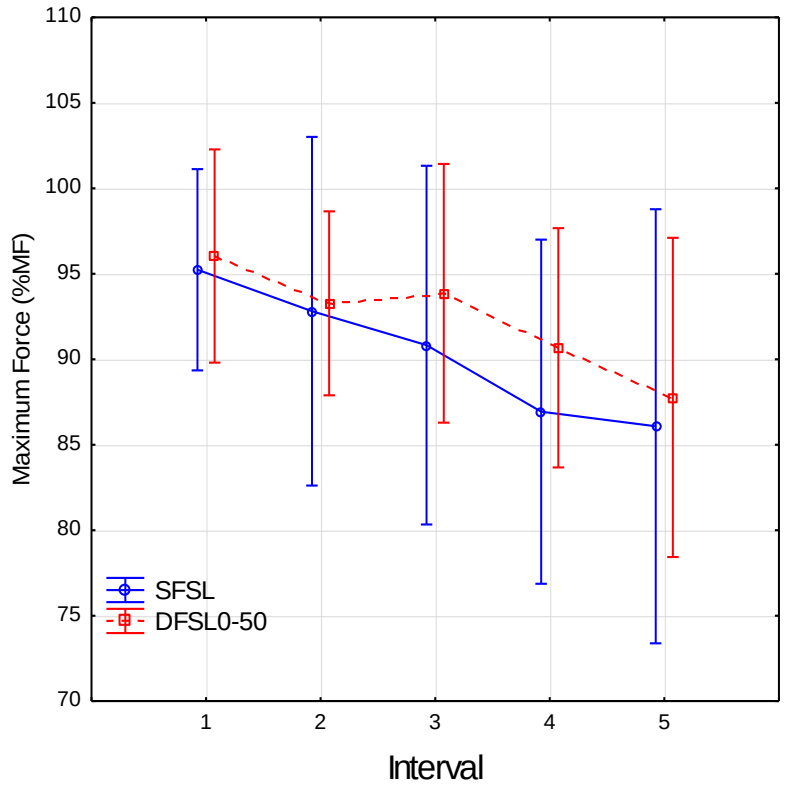
Error probability for effects:

- Condition: p=0.08
- Time: p<0.01
- Condition x Time: p=0.02

Figure 26: Percentage of maximum force for the bicep brachii muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals, * indicates a significant difference between conditions at p<0.05.

There were significant decreases in maximum force over time with an error probability of less than 1%. For condition SFSL, post-hoc tests demonstrated that there was significant fatigue from interval two when compared to the initial MVC reading (p<0.01), however condition DFSL0-50 significantly fatigued at interval three (p<0.01). A significant interaction effect was found (p=0.02), with post-hoc tests indicating that there were significant differences between the two conditions for intervals four and five (P<0.01). The difference between the two conditions' means for interval four and five are: 9%MF and 8%MF, respectively.

4.1.2.4ErectorSpinae



Error probability for effects:

- Condition: p=0.41
- Time: p<0.01
- Condition x Time: p=0.88

Figure 27: Percentage of maximum force for the erector spinae muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

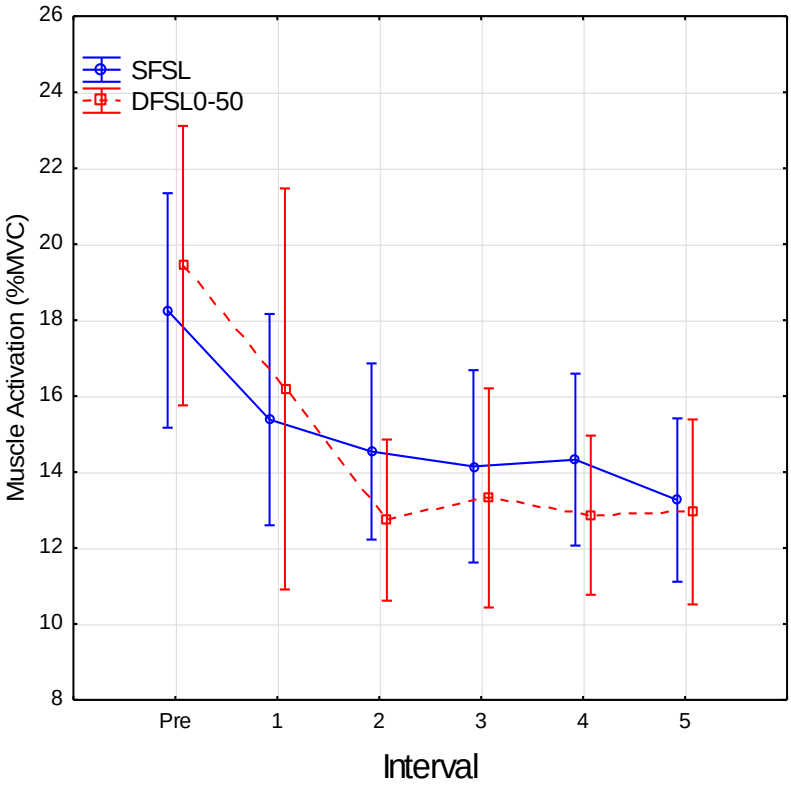
There were significant decreases in maximum force over time with an error probability of less than 1%, however the only significant finding in post-hoc tests in the above result were that condition SFSL showed significant fatigue at the fifth interval when compared to the initial MVC reading (p=0.04). Condition DFSL0-50 showed no significant fatigue. The reason for this finding may be due to the larger inter-individual variation for this muscle compared to other muscles.

When considering all the results for maximum force, similar to the RPE results, the variability was always higher in the SFSL condition compared to condition DFSL0-50; however, the same trend on variability increasing with the progression of intervals was not present with the maximum force results. Additionally, neither condition is consistently higher or lower such as in the RPE results.

4.1.3Electromyography Activity

The EMG activity levels were processed during the seven second static contraction at 25 percent of maximum force.

4.1.3.1 Medial Deltoid



Error probability for effects:

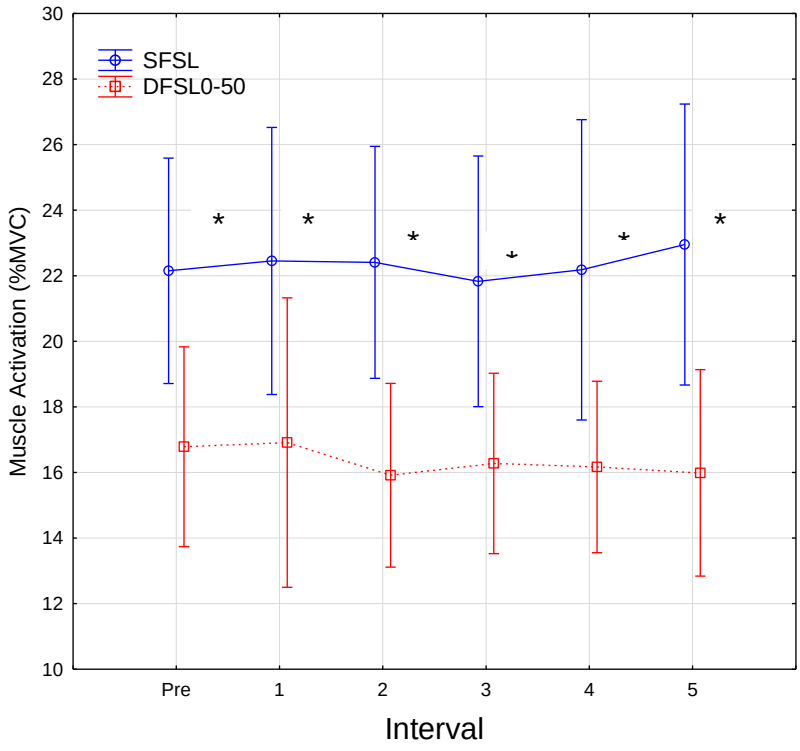
- Condition: p=0.73
- Time: p<0.01
- Condition x Time: p=0.34

Figure 28: EMG Muscle activity during 25% MVC reference task for the medial deltoid muscle for the purely static (SFSL) and quasi-static (DFSL0-50) contraction conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There were significant changes in EMG activity level over time with an error probability of less than 1%. What should be noted in the above result is that that there is a distinct down regulation of activated muscle fibres over time. This is the contrary to what was expected as when a muscle is fatiguing and required to produce a constant force, the EMG activity is expected to increase over time. It is worth mentioning here that the muscle was always required to produce 25% of its initial maximum force for seven seconds when this data was recorded. Post-hoc tests demonstrated that condition SFSL showed a significant difference in EMG activation at interval three (p=0.02) when

compared to the pre-protocol measure, while condition DFSL0-50 showed a significant difference at interval two (p<0.01).

4.1.3.2 Bicep Femoris



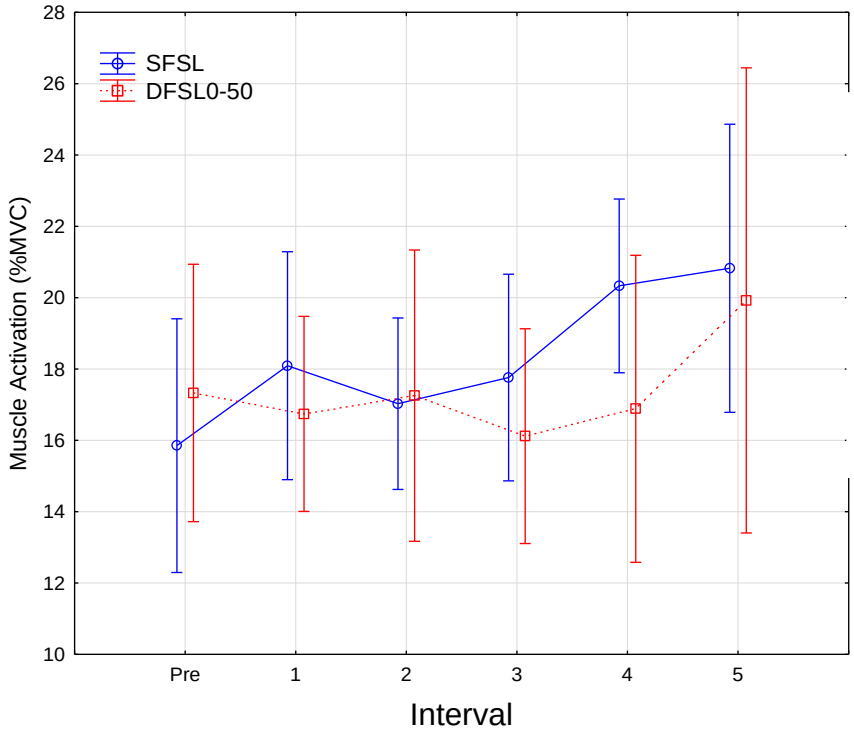
Error probability for effects:

- Condition: p<0.01
- Time: p=0.97
- Condition x Time: p=0.93

Figure 29: EMG Muscle activity during 25% MVC reference task for the bicep femoris muscle for the purely static (SFSL) and quasi-static (DFSL0-50) contraction conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

No significant fatigue occurred in either condition along with no interaction effect (P=0.93). There is however a significant condition effect with an error probability of less than 1%. Post-hoc tests demonstrated that every interval, including the pre-protocol measure are significantly different between the two conditions (p<0.01). There is a clear difference between the values for all intervals for these two conditions.

4.1.3.3 Bicep Brachii



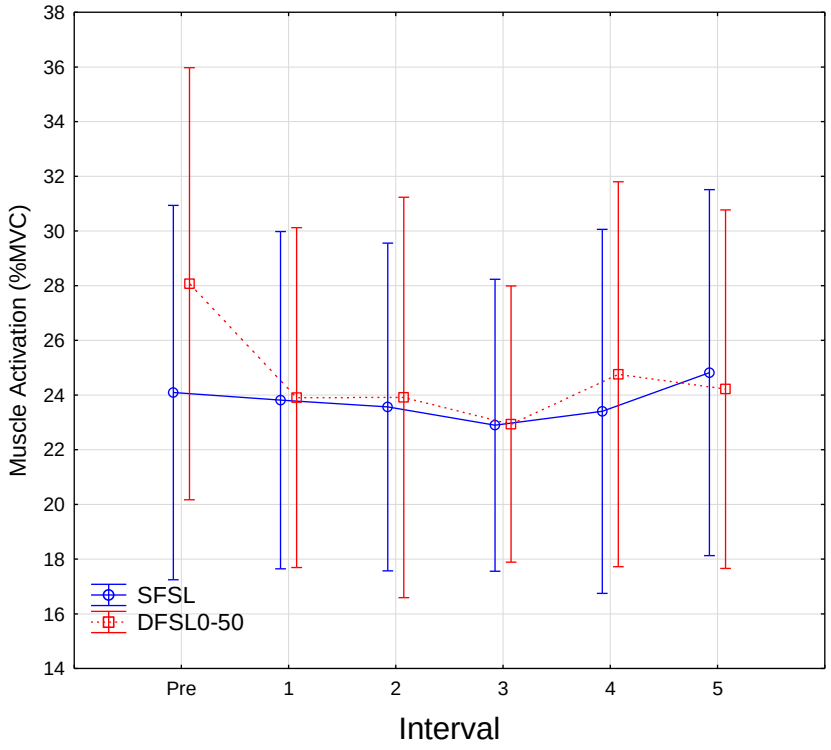
Error probability for effects:

- Condition: p=0.58
- Time: p=0.03
- Condition x Time: p=0.23

Figure 30: EMG Muscle activity during 25% MVC reference task for the bicep brachii muscle for the purely static (SFSL) and quasi-static (DFSL0-50) contraction conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There were significant differences found in EMG activity over time (p=0.03) however post-hoc tests revealed that the only significant finding was found for condition SFSL at interval five when compared to the pre protocol measure (p=0.03). The means for condition DFSL0-50 ranged between 16.1%MVC (±5.7) and 19.9%MVC (±12.2). What can be observed in the above result is that both conditions are following the expected trend to indicate fatigue, with muscle activation levels increasing over time. Interval five of condition DFSL0-50 has very high variability which could be affecting the diverging affect between the two conditions.

4.1.3.4ErectorSpinae



Error probability for effects:

- Condition: p=0.74
- Time: p=0.05
- Condition x Time: p=0.15

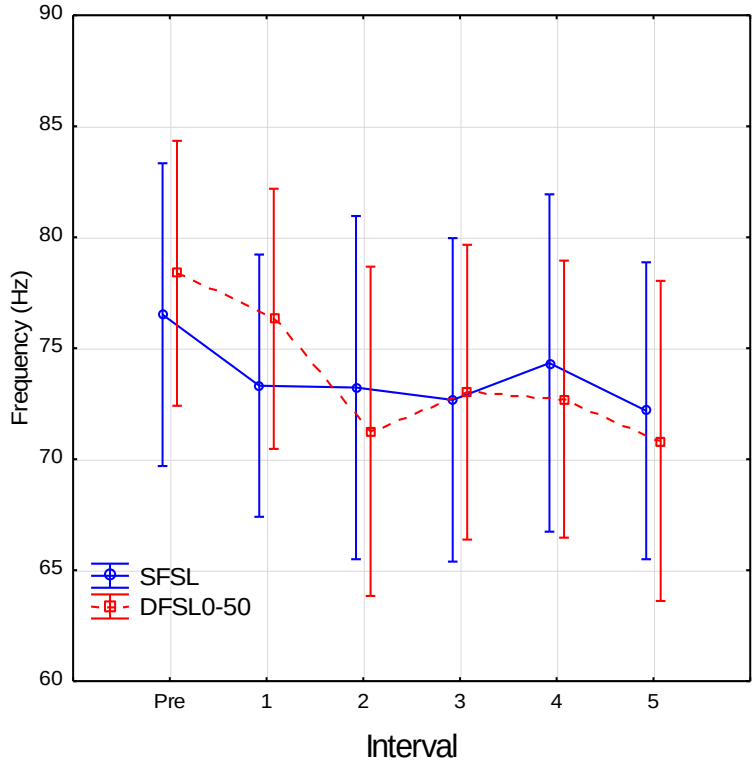
Figure 31: EMG Muscle activity during 25% MVC reference task for the erector spinae muscle for the purely static (SFSL) and quasi-static (DFSL0-50) contraction conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

No significance was found between conditions or intervals. Both conditions are very similar and have similar variability.

4.1.4Electromyography Center Frequency

The electromyography center frequency parameters were processed during the seven second static contraction at 25 percent of maximum force.

4.1.4.1 Medial Deltoid



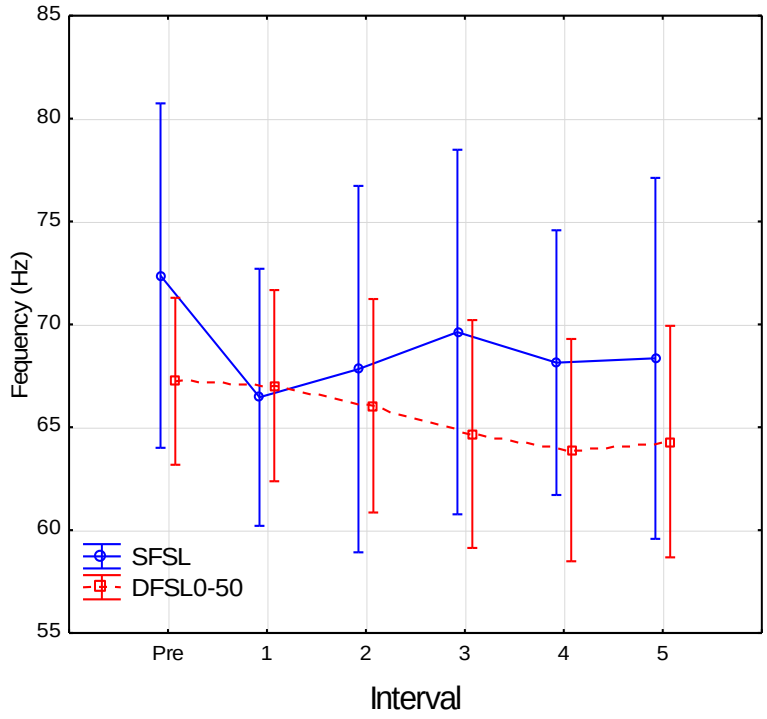
Error probability for effects:

- Condition: p=0.97
- Time: p<0.01
- Condition x Time: p=0.24

Figure 32: EMG center frequency, measured during the static EMG reference task, for the medial deltoid muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

No significant changes in EMG center frequency occurred for condition SFSL, with mean values ranging between 72.4Hz (±11.7) and 77.2Hz (±12.2); however post-hoc testes demonstrated that condition DFSL0-50 showed significant fatigue at interval two when compared to the pre protocol measure ($p<0.01$). The above results follow the expected trend of the EMG center frequency decreasing over time as fatigue is induced with more slow twitch muscle fibres recruited.

4.1.4.2 Bicep Femoris



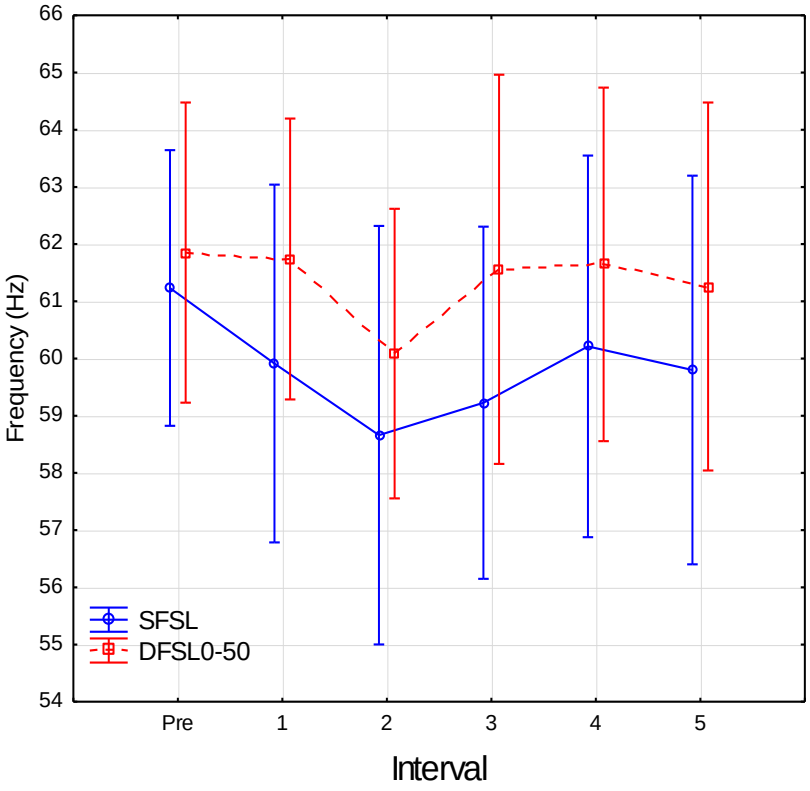
Error probability for effects:

- Condition: p=0.32
- Time: p=0.15
- Condition x Time: p=0.28

Figure 33: EMG center frequency, measured during the static EMG reference task, for the bicep femoris muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There was no significant difference between any intervals for either condition. The means for condition SFSL range between 71.7Hz (±13.6) and 66.3Hz (±10.1) and for DFSL0-50 range between 64.4Hz (±8.9) and 67Hz (±6.9). There was no significant difference between the two conditions (p=0.32). However, both muscles show some small trend to a decreased center frequency (p=0.15), similar to the medial deltoid muscle.

4.1.4.3 Bicep Brachii



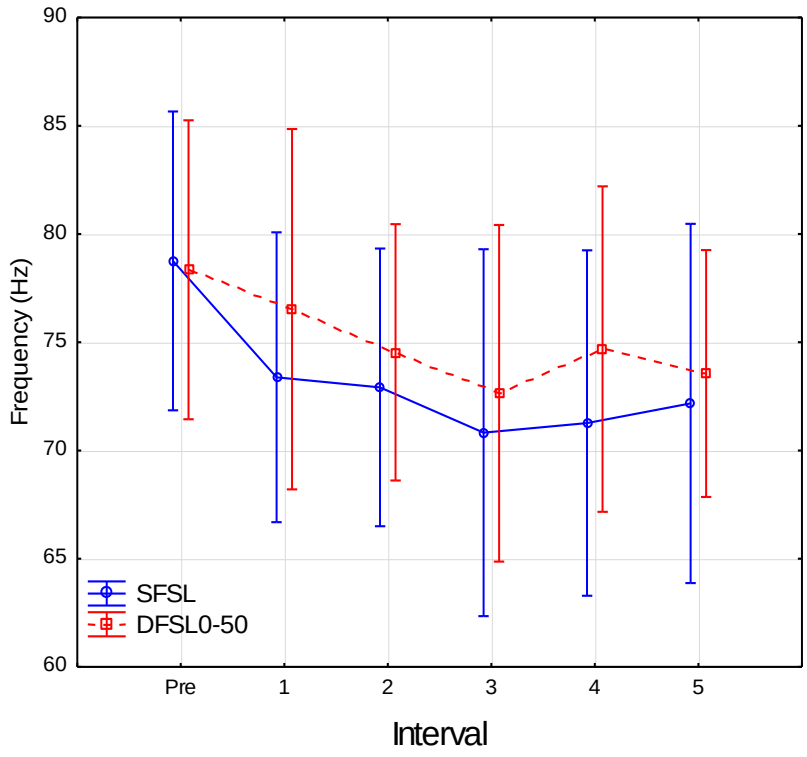
Error probability for effects:

- Condition: p=0.23
- Time: p=0.88
- Condition x Time: p=0.92

Figure 34: EMG center frequency, measured during the static EMG reference task, for the bicep brachii muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

No significance was found between intervals or conditions in the above results. The means of condition SFSL range between 58.6Hz (±6.4) and 61Hz (±4.3) and of condition DFSL0-50 range from 60.3Hz (±4.5) to 62Hz (±4.6). What can be observed is the distinct dip for both conditions at interval two.

4.1.4.4 ErectorSpinae



Error probability for effects:

- Condition: p=0.41
- Time: p<0.01
- Condition x Time: p=0.6

Figure 35: EMG center frequency, measured during the static EMG reference task, for the erector spine muscle for the purely static (SFSL) and quasi-static (DFSL0-50) conditions over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

Significant changes in center frequency had occurred over time with an error probability of less than 1%. Post-hoc tests revealed that fatigue had occurred in both conditions when compared to their respective pre-protocol measures; at interval two for condition SFSL (p=0.03) and at interval three for condition DFSL0-50 (p=0.04). This indicates that condition SFSL had fatigued one minute earlier compared to DFSL0-50.

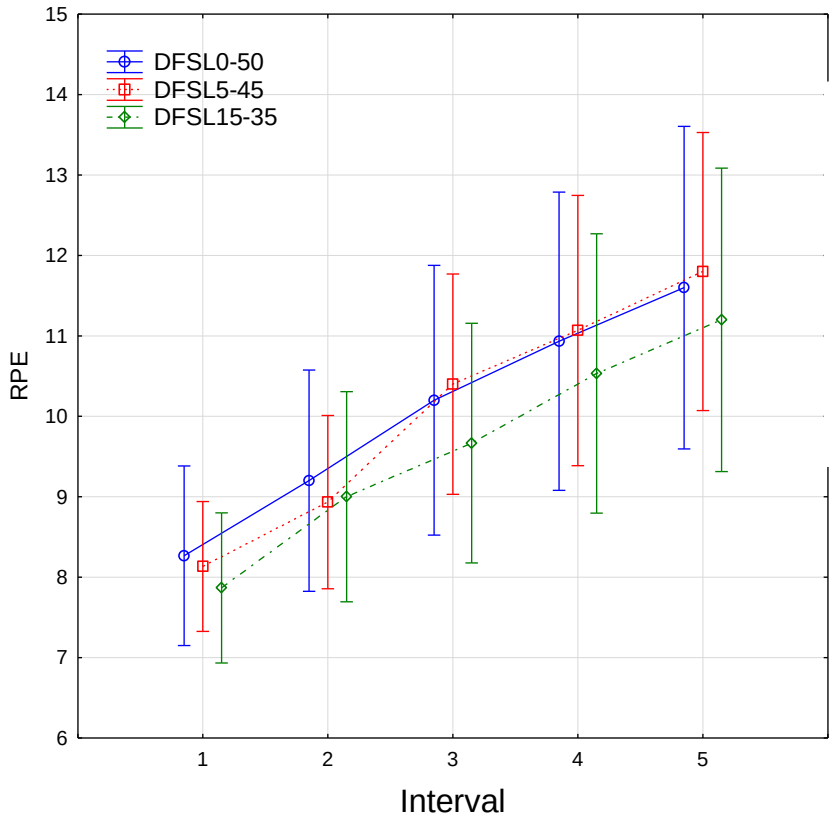
4.2 HYPOTHESIS 2: INFLUENCE OF AN UNDERLYING STATIC COMPONENT ON MUSCLE FATIGUE RESPONSES

In this section of the results, condition DFSL0-50 are compared to conditions DFSL5-45 and DFSL15-35 in order to determine what effects the underlying static components have on the muscle fatigue response.

4.2.1 Rating of Perceived Exertion

As with the RPE results in the previous section, the pre-protocol measure will not be displayed as it had a constant reading of six.

4.2.1.1 Medial Deltoid



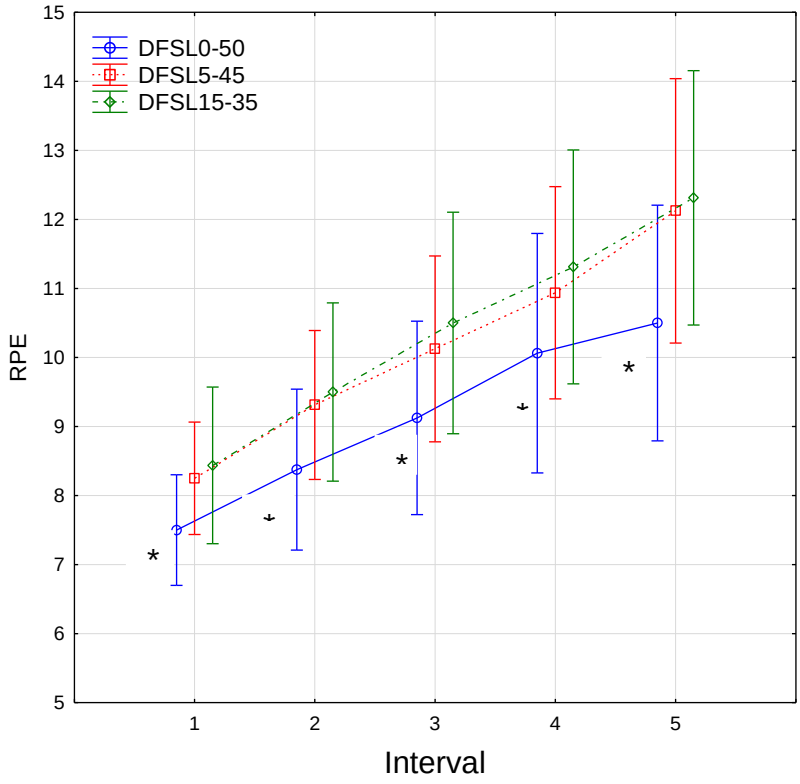
Error probability for effects:

- Condition: p=0.52
- Time: p<0.01
- Condition x Time: p=0.51

Figure 36: RPE values of the medial deltoid muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

There were significant increases in RPE over time ($p<0.01$) and post-hoc tests show that for all the above conditions, it was significant from the pre-protocol measure to interval one ($p<0.01$); indicating that fatiguing had started to occur for all the conditions after the first minute of the fatiguing protocol. There was no significant condition effect ($p=0.52$). RPE measurements increased from 8.4 (±2) to 11.6 (±3.6) for condition DFSL0-50 between interval one to five; 8.3 (±1.5) to 11.8 (±3.1) for condition DFSL5-45; and 7.8 (±1.6) to 11.6 (±3.6) for condition DFSL15-35.

4.2.1.2 Bicep Femoris



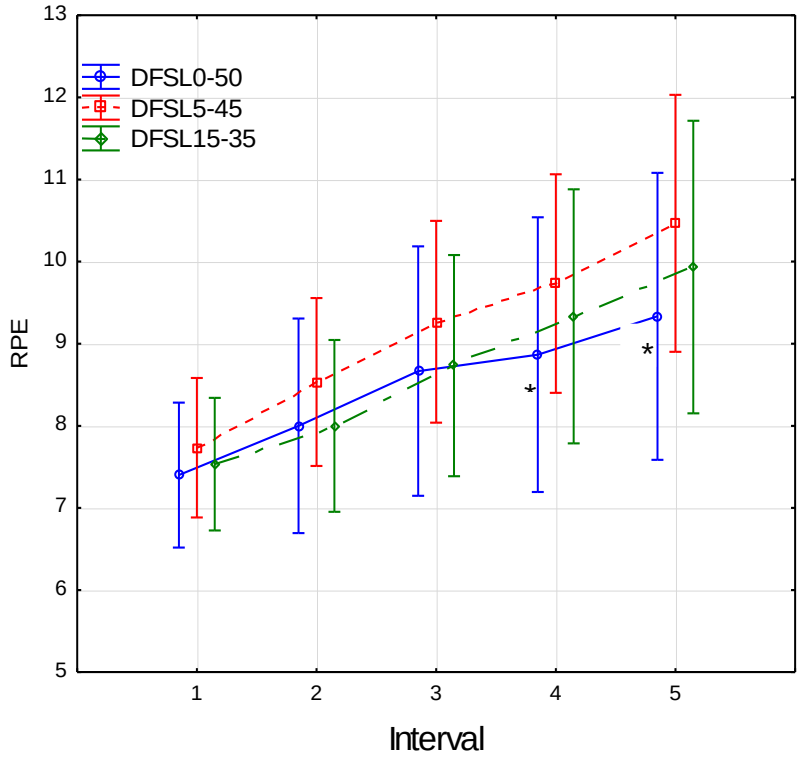
Error probability for effects:

- Condition: p<0.01
- Time: p<0.01
- Condition x Time: p=0.17

Figure 37: RPE values of the bicep femoris muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals, * indicates a significant difference between conditions at p<0.05.

There were significant changes in RPE over time with an error probability of less than 1%. Post-hoc tests demonstrated that all three conditions had significant increases in RPE from the pre-protocol measure to interval one (p<0.01); indicating that fatiguing was occurring from the first minute of fatiguing protocol for all three conditions. There was a significant condition effect (p<0.01) and post-hoc tests demonstrated that condition DFSL0-50 was significantly lower in RPE for all intervals compared to DFSL15-35 (p<0.01) and was significantly lower for intervals two to five when compared to DFSL5-45 (p<0.01). Condition DFSL5-45 and DFSL15-35 are very similar, but condition DFSL0-50 shows a constant lower reading for RPE over all intervals with a further diverging effect at interval five.

4.2.1.3 Bicep Brachii



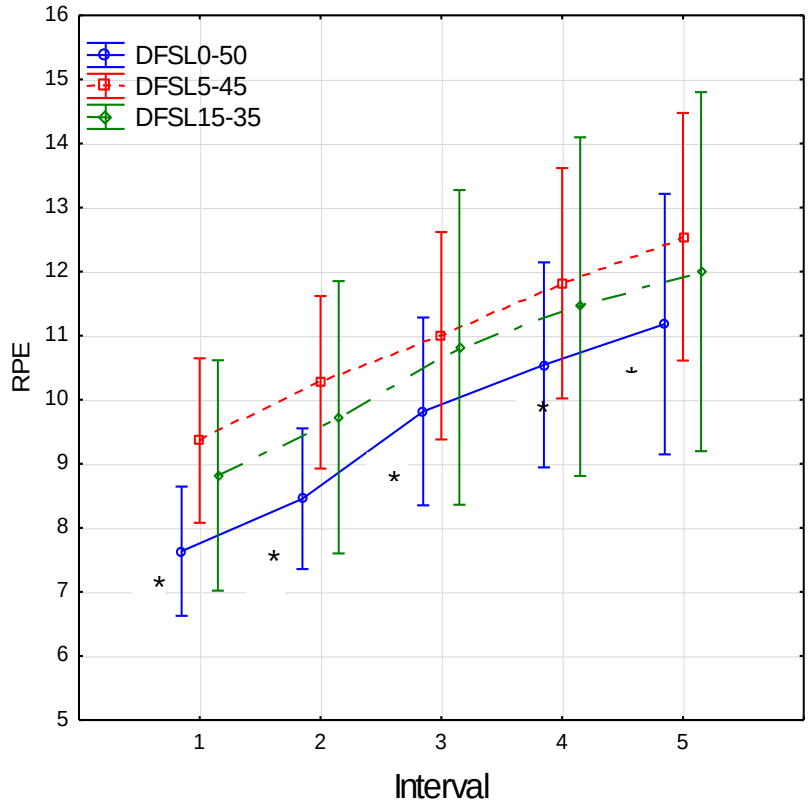
Error probability for effects:

- Condition: p=0.18
- Time: p<0.01
- Condition x Time: p=0.28

Figure 38: RPE values of the bicep brachii muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

There were significant changes in RPE over time with an error probability of less than 1%. Post-hoc tests demonstrate that condition DFSL0-50, DFSL5-45 and DFSL15-35 all had significant increases in RPE from the pre-protocol measure to interval one indicating that they all started fatiguing from the first minute of the fatigue protocol ($p<0.01$). Condition DFSL0-50's interval four and five were significantly different to condition DFSL5-45 with error probabilities of less than 1%.

4.2.1.4 Erector Spinae



Error probability for effects:

- Condition: p=0.06
- Time: p<0.01
- Condition x Time: p=0.67

Figure 39: RPE values of the erector spinae muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

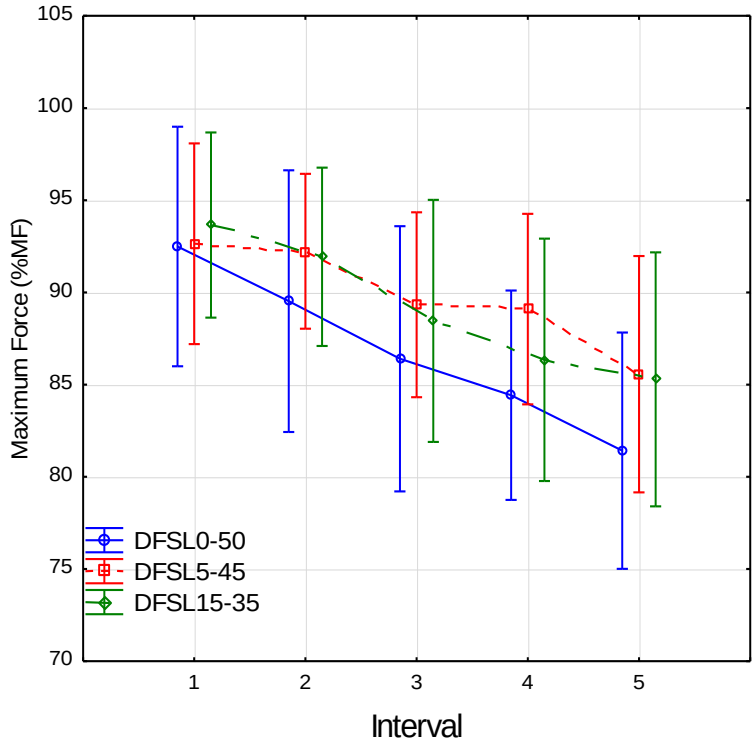
There were significant changes in RPE over time with an error probability of less than 1%. Post-hoc tests demonstrate that there was a significant increase in RPE from the pre-protocol measure to interval one for all the above conditions ($p<0.01$). This indicates that all three conditions began fatiguing significantly after the first minute of the fatiguing protocol. Condition DFSL0-50 has the lowest RPE for all intervals, similar to bicep femoris; however in this result all the intervals of condition DFSL0-50 were all significantly lower than condition DFSL5-45 with all error probabilities less than 1%. Condition DFSL0-50 was also significantly lower than DFSL15-35 at intervals one, two, three and four with p-values of <0.01, <0.01, 0.01 and 0.04 respectively. Thus there was a significantly lower fatigue level in DFSL0-50 when compared to the other conditions and the condition effect does reflect this to some degree (p=0.06). What is

worth noting is that condition DFSL15-35 had a lower RPE across all intervals when compared to DFSL5-45.

4.2.2 Maximum Force Production

As with the previous hypothesis, due to the fact that the maximum force results have been relativized to the pre-protocol reading, only intervals one to five are displayed, with the pre-protocol measure always constant at 100%MVC.

4.4.2.1 Medial Deltoid



Error probability for effects:

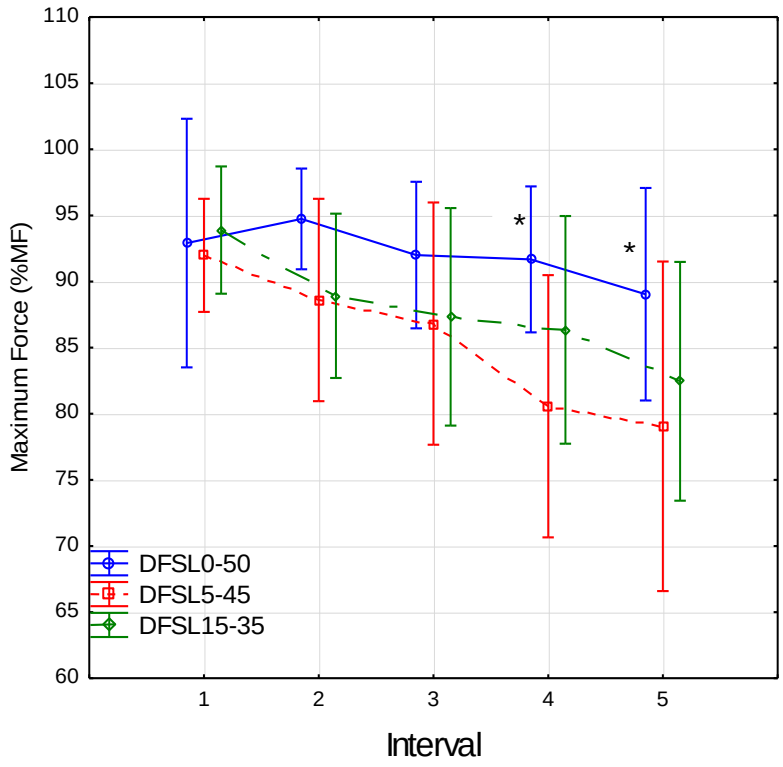
- Condition: p=0.49
- Time: p<0.01
- Condition x Time: p=0.78

Figure 40: Percentage of maximum force for the medial deltoid muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

The above results show a clear decrease in maximum force over time, as what was expected to occur when a muscle fatigues. The decreases in maximum force were significant ($p<0.01$) with post-hoc tests showing that conditions DFSL0-50 and DFSL15-35 decreasing significantly compared to the initial reading (100%) at interval four with error probabilities less than 1%. Condition DFSL5-45 only showed a significant decrease in maximum force at interval five

(P=0.014); indicating that this condition fatigued more slowly when compared to conditions DFSL0-50 and DFSL15-35.

4.2.2.2 Bicep Femoris



Error probability for effects:

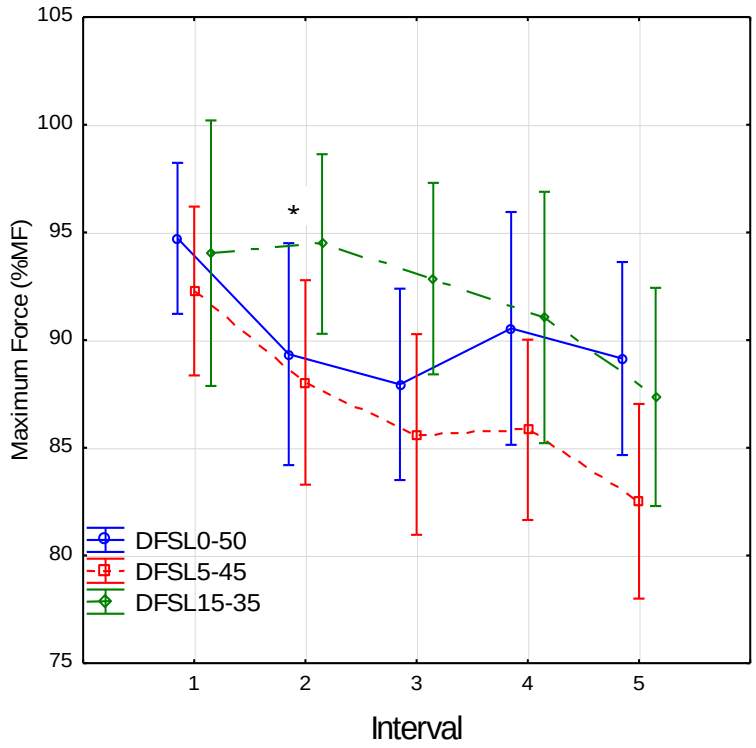
- Condition: p=0.11
- Time: p<0.01
- Condition x Time: p=0.25

Figure 41: Percentage of maximum force for the bicep femoris muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals, * indicates a significant difference between conditions at p<0.05.

There were significant changes in maximum force across intervals with an error probability of less than 1%. Post-hoc tests demonstrated that there was no significant decrease in maximum force for condition DFSL0-50. The mean values of condition DFSL0-50 ranged between 94.7%MF (±15) and 89%MF (±15). Condition DFSL5-45 showed a significant decrease in maximum force at interval four when compared to the initial reading (p<0.01), while condition DFSL15-35 showed a significant decrease at interval five (p<0.01). Post-hoc tests also demonstrated that condition DFSL0-50 was significantly different to condition DFSL5-45 at interval four (p=0.01) and five

(p=0.04). The difference in means for between in interval four and five for these conditions are 11.2%MF and 10%MF respectively.

4.2.2.3 Bicep Brachii



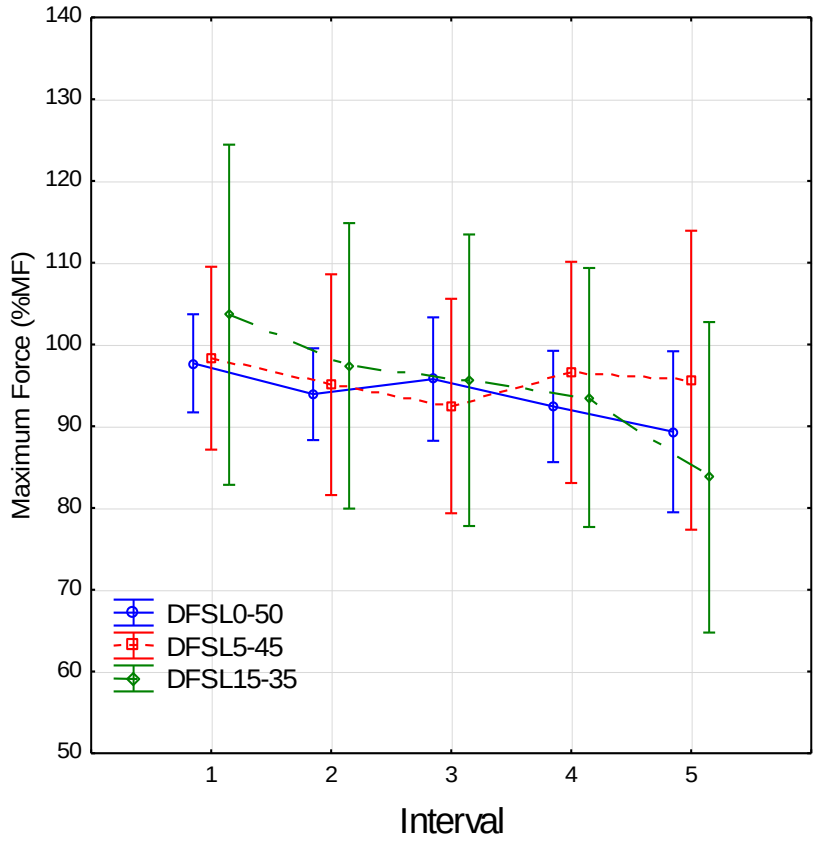
Error probability for effects:

- Condition: p=0.12
- Time: p<0.01
- Condition x Time: p=0.11

Figure 42: Percentage of maximum force for the bicep brachii muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals, * indicates a significant difference between conditions at p<0.05.

There were significant differences in maximum force measures over time with the error probability less than 1%. Post-hoc tests reveal that when compared to the initial measure (100%), significant fatigue occurred at interval three for condition DFSL0-50 (p=0.04) and at interval five for condition DFSL5-45 (p<0.01). There was no significant decrease in maximum force for condition DFSL15-35 with mean values ranging between 93.6%MF (±9.9) and 88.1%MF (±9.1). Condition DFSL5-45 is consistently lower than the other two conditions at every interval. Post-hoc tests demonstrated that Condition DFSL15-35 had a significantly lower drop in maximum force at interval two when compared to DFSL5-45 (p=0.02). The difference between the means of interval two between these two conditions is 5.3%MF.

4.2.2.4 Erector Spinae



Error probability for effects:

- Condition: p=0.95
- Time: p<0.01
- Condition x Time: p=0.11

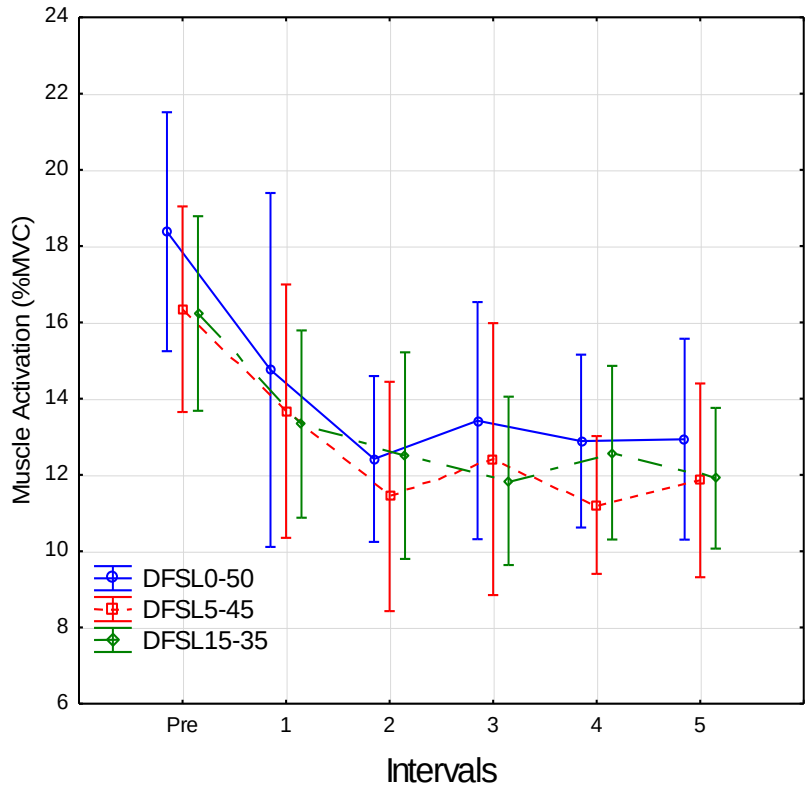
Figure 43: Percentage of maximum force for the erector spinae muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

There was no significant drop in maximum force for any condition in this result as well as no significant difference between conditions. The mean values for conditions DFSL0-50, DFSL5-45 and DFSL15-35 range between 86.4%MF (±13) to 92.5%MF (±10.1), 88.4%MF (±19.1) to 95.8%MF (±15.1) and 81.6%MF (±25.8) to 99.4%MF (±26.6) respectively.

4.2.3 Electromyography Activity

As with the results for the first hypothesis, both the EMG activity and the EMG center frequency results were obtained and processed from the seven-second static contraction at 25 percent of maximum force.

4.2.3.1 Medial Deltoid



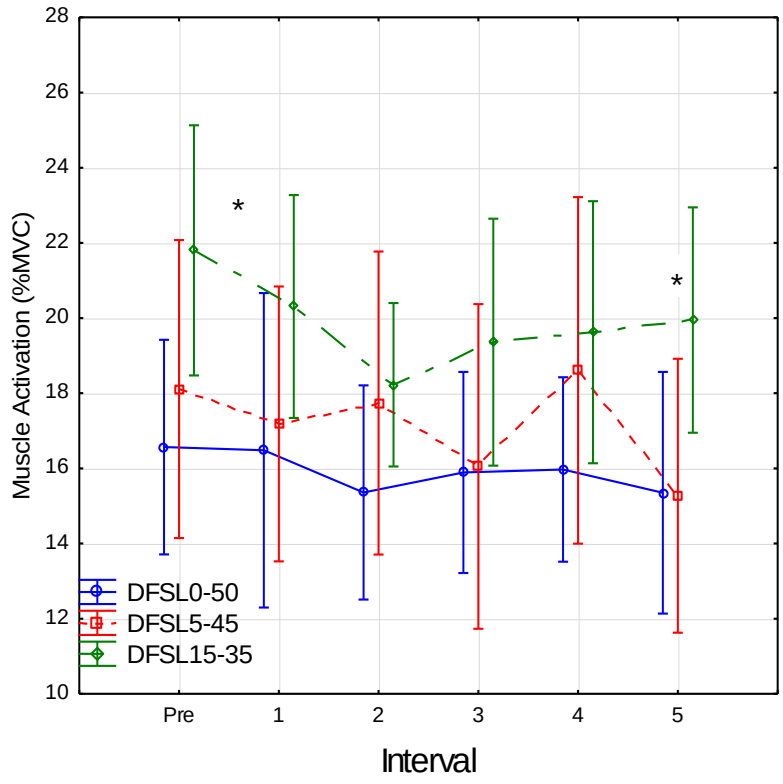
Error probability for effects:

- Condition: p=0.33
- Time: p<0.01
- Condition x Time: p=0.92

Figure 44: EMG Muscle activity during 25% MVC reference task for the medial deltoid muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

As with the results for EMG reference task for the first hypothesis, the medial deltoid again shows a sudden down regulation of muscle fibres. There were significant changes in EMG activity levels over time with an error probability of less than 1%. Post-hoc tests demonstrated that conditions DFSL0-50 and DFSL5-45 both had significant changes in muscle activity when compared to the pre protocol measure from interval two ($p<0.01$). Condition DFSL15-35 showed a significant difference in muscle activity at interval three ($p<0.01$). The muscle activation levels remain relatively constant after the initial decrease with no significant differences between intervals for all conditions after interval two.

4.2.3.2 Bicep Femoris



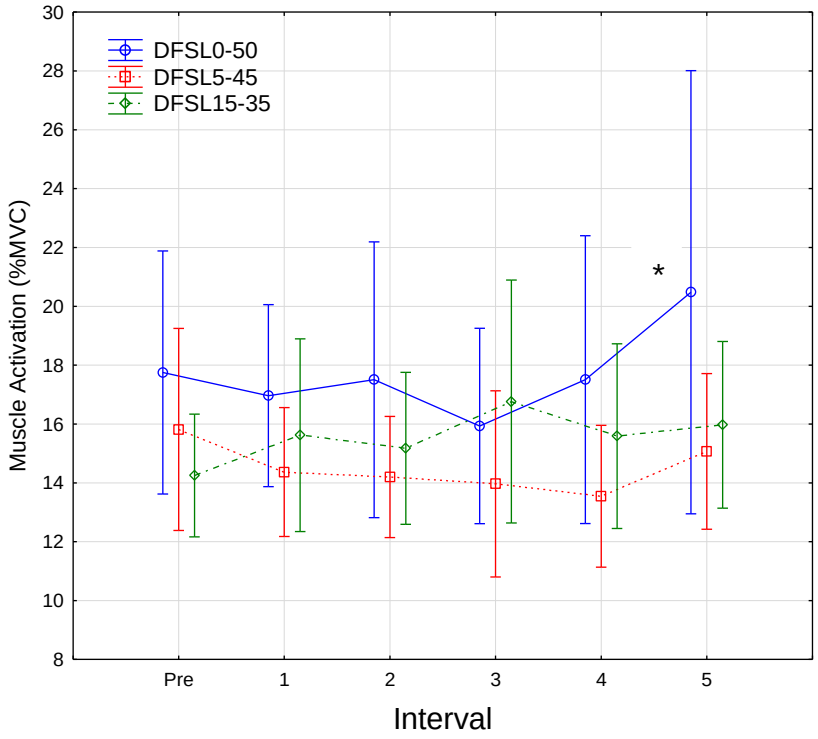
Error probability for effects:

- Condition: p=0.09
- Time: p=0.044
- Condition x Time: p=0.44

Figure 45: EMG Muscle activity during 25% MVC reference task for the bicep femoris muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

For the above results, there were no significant differences between intervals for any condition. The mean values for conditions DFSL0-50, DFSL5-45 and DFSL15-35 ranged between 15.1%MVC (±5.1) to 16.5%MVC (±5), 15%MVC (±6.5) to 18.2%MVC (±8.1) and 18.9%MVC (±4.8) to 22.1%MVC (±5.9) respectively. What is worth noting, however, is the fact that condition DFSL15-35 had a consistently higher muscle activation percentage for all intervals and the condition effect reflects this to some degree. Post-hoc tests demonstrated that the pre-interval and interval five being statistically higher than DFSL0-50, with error probabilities being<1% and 2% respectively. Condition DFSL15-35 was also significant higher than DFSL5-45 at interval five (p=0.018).

4.2.3.3 Bicep Brachii



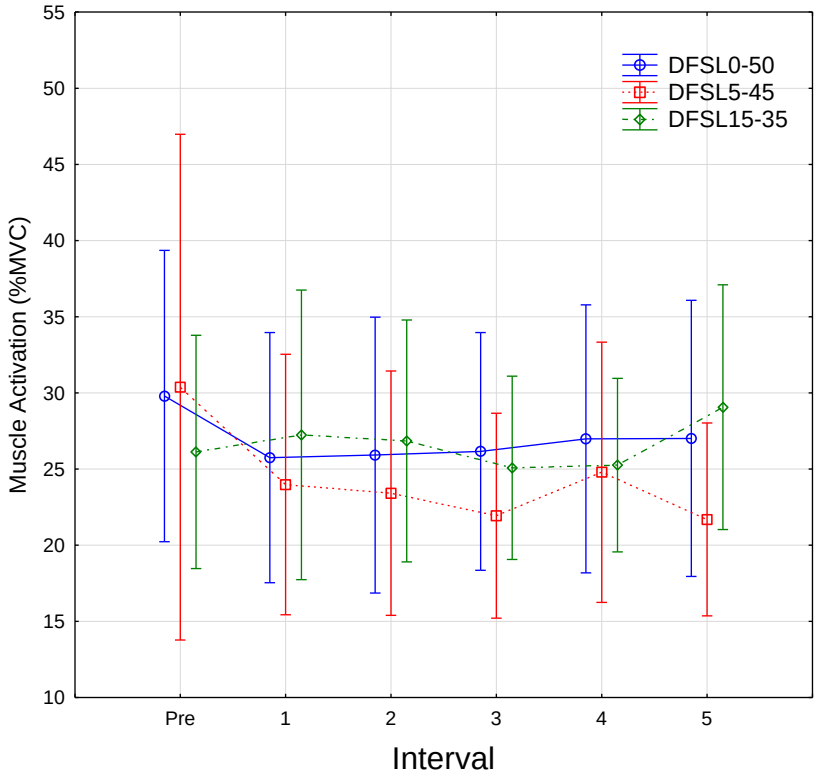
Error probability for effects:

- Condition: p=0.27
- Time: p=0.41
- Condition x Time: p=0.27

Figure 46: EMG Muscle activity during 25% MVC reference task for the bicep brachii muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There were no significant changes in EMG activity over time. Post-hoc test did however show that DFSL0-50 and DFSL5-45 are significantly different at interval five (p=0.014). The mean values of conditions DFSL0-50, DFSL5-45 and DFSL15-35 ranged between 15.1%MVC (±5.1) to 16.5%MVC (±4.9), 14.9%MVC (±6.5) to 18.3%MVC (±8.1) and 18.9%MVC (±4.8) to 22.1%MVC (±5.9) respectively.

4.2.3.4 Erector Spinae



Error probability for effects:

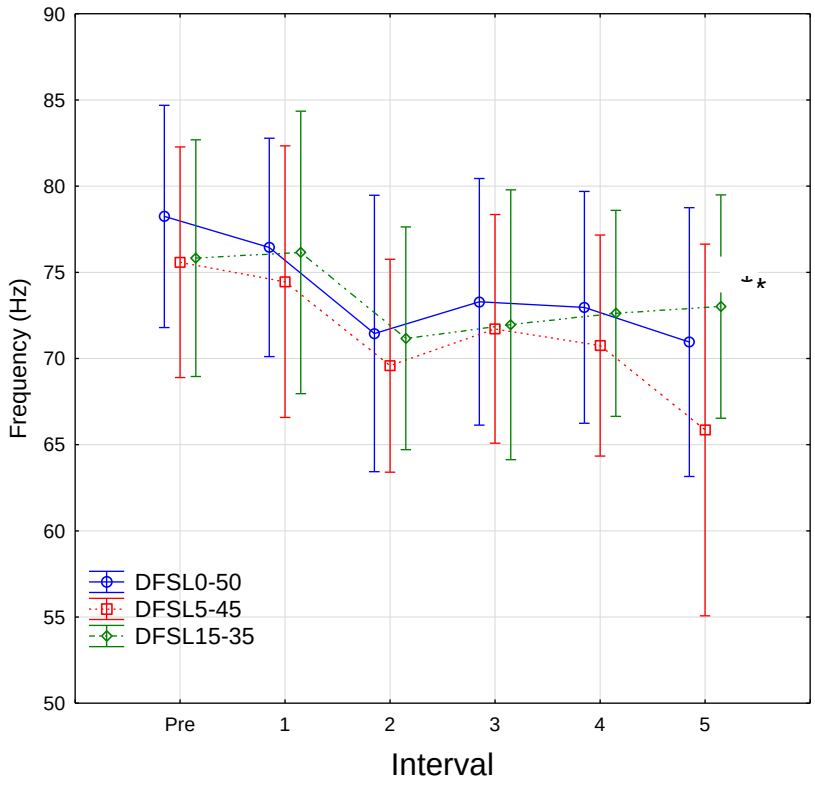
- Condition: p=0.59
- Time: p=0.02
- Condition x Time: p=0.27

Figure 47: EMG muscle activity during 25% MVC reference task for the erector spinae muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) over time (represented by intervals taken every minute).Vertical bars denote 95% confidence intervals.

There were no significant changes in EMG activity or significant differences between conditions. The mean values of conditions DFSL0-50, DFSL5-45 and DFSL15-35 range between 16.1%MVC (±5.7) to 19.9%MVC (±12.2), 13.8%MVC (±3.9) to 15.8%MVC (±5.5) and 14%MVC (±3.5) to 16.3%MVC (±6.8) respectively. There's no diverging effect to speak of in the above result.

4.2.4 Electromyography Center Frequency

4.2.4.1 Medial Deltoid



Error probability for effects:

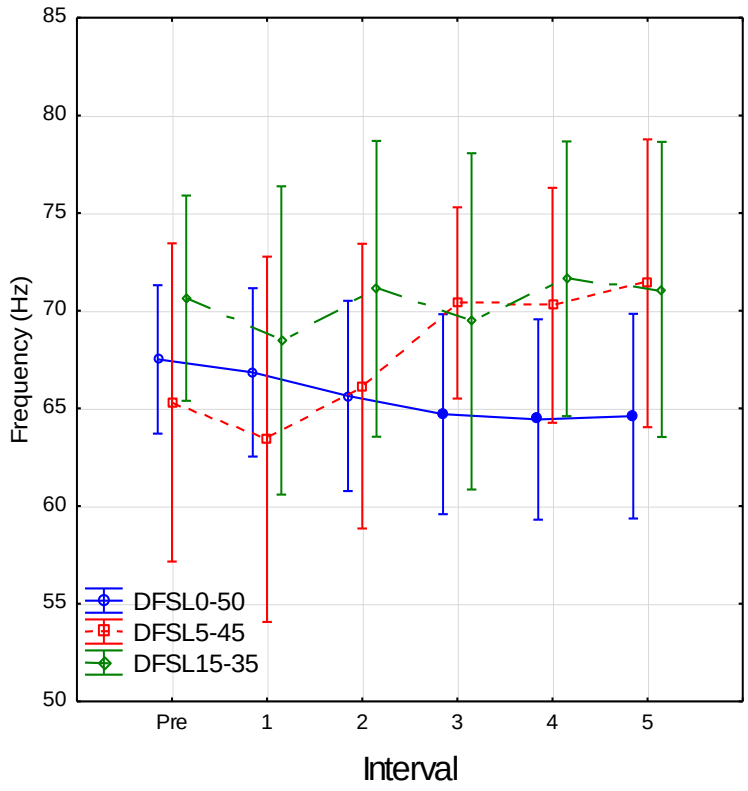
- Condition: p=0.11
- Time: p<0.01
- Condition x Time: p=0.5

Figure 48: EMG center frequency, measured during the static EMG reference task, for the medial deltoid muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals; * indicates a significant difference between conditions at p<0.05.

There were significant changes in centre frequency over time with an error probability of less than 1%. Post-hoc tests demonstrated that condition DFSL0-50 showed a significant decrease in EMG center frequency compared to the pre-protocol measure at interval two (p=0.04). Condition DSFL5-45 portrayed a significant decrease in EMG center frequency at interval five (p<0.01). Condition DFSL15-35, however, did not show any significant changes in EMG center frequency over time, with mean values ranging from 72.3Hz (±10.1) to 76.9Hz (±11.6). This result suggests that DFSL15-35 put the smallest demand on medial deltoid muscle. There is a general increase in slow

twitch muscle fibre recruitment over time for all conditions with a decrease in mean frequency for conditions DFSL0-50, DFSL5-45 and DFSL15-35 from the pre-protocol measure to interval five being 7.2Hz, 10.3Hz and 2.8Hz respectively. There is a clear dip in center frequency at interval two. Post-hoc tests also revealed that at interval six, there is a significant difference between condition DFSL15-35 and DFSL5-45 (p= 0.02).

4.2.4.2 Bicep Femoris



Error probability for effects:

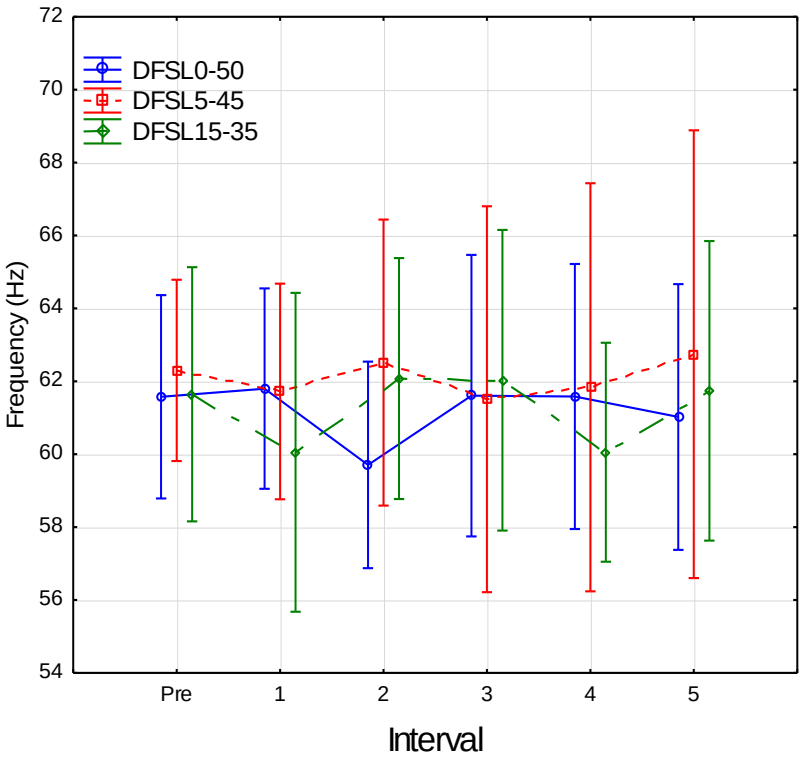
- Condition: p=0.23
- Time: p=0.53
- Condition x Time: p=0.046

Figure 49: EMG center frequency, measured during the static EMG reference task, for the bicep femoris muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

There were no significant changes in center frequency over time, nor was there a condition effect. The mean values for conditions DFSL0-50, DFSL5-45 and DFSL15-35 range between 64.4Hz (±8.9) to 67Hz (±6.9), 63.3Hz (±16.3) to 71.4Hz (±12.8) and 68.2Hz (±13.8) to 71.7Hz (±12.3) respectively. There was an interaction effect between the conditions in the above result with an error probability of 4.6%. There is

a diverging effect at interval three. The variability of condition DFSL0-50 is substantially lower compared to DFSL5-45 and DFSL15-35.

4.2.4.3 Bicep Brachii



Error probability for effects:

- Condition: p=0.84
- Time: p=0.93
- Condition x Time: p=0.73

Figure 50: EMG center frequency, measured during the static EMG reference task, for the bicep brachii muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

The above result yielded no significant results between intervals for any condition suggesting that there was no significant increase in slow twitch recruitment. The mean values of conditions DFSL0-50, DFSL5-45 and DFSL15-35 ranged between 64.4Hz (±8.9) to 67Hz (±6.9), 63.3Hz (±16.3) to 71.4Hz (±12.9) and 68.8Hz (±13.8) to 71.7Hz (±12.2) respectively. There was no interaction effect between conditions (P=0.73). There is no diverging effect to speak of in the above result. What is worth noting, is that the variability of condition DFSL5-45. It increases substantially with the progression of intervals.

4.2.4.4 Erector Spinae

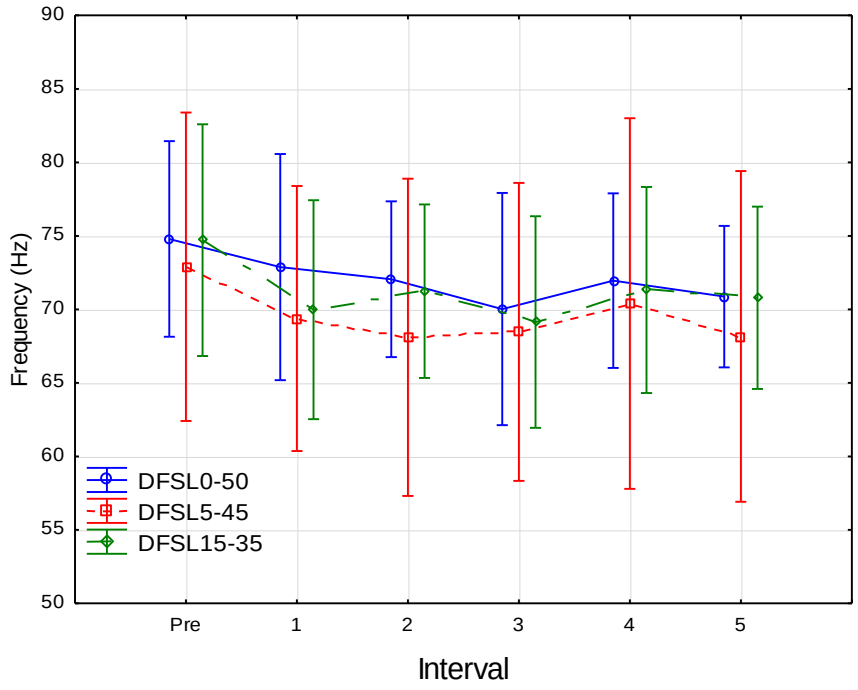


Figure 51: EMG center frequency, measured during the static EMG reference task, for the erector spinae muscle for the quasi-static (DFSL0-50), small underlying static component (DFSL5-45) and large underlying static component (DFSL15-35) conditions over time (represented by intervals taken every minute). Vertical bars denote 95% confidence intervals.

The above result yielded no significant differences between intervals for any condition. While not significant, there is a general trend for all conditions showing a decrease in EMG center frequency with the progression of intervals, indicating that more slow twitch muscle fibres were being recruited over time. The decrease in frequency from the pre measure to interval five for conditions DFSL0-50, DFSL5-45 and DFSL15-35 are 4.1Hz, 4.7Hz and 3.9Hz respectively.

4.3OVERVIEW OF FATIGUE

The following table summarizes where significant fatigue occurred for all conditions, muscles and fatigue measures.

Table 5: Summary data of significant fatigue, post-hoc tests for significant changes occurring over time for each condition where “S” indicates statistical significance and “N.S.” indicates that no statistical significance was found between the conditions’ intervals from which the level of fatigue is measured. “RPE” refers to the rating of perceived exertion, “Max. Force” refers to the maximum force results relativized to a percentage of maximum force. “EMG Ref. Task” refers to the electromyography activity recorded for the EMG reference task and “Spec. An.” refers to the center frequency results also processed during the EMG reference task.

	RPE	Max. Force	EMG Ref. Task	Spec. An.
Medial Deltoid				
SFSL	**S**	N.S.	**S**	N.S.
DFSL0-50	**S**	**S**	**S**	**S**
DFSL5-45	**S**	**S**	**S**	**S**
DFSL15-35	**S**	**S**	**S**	N.S.
Bicep Femoris				
SFSL	**S**	**S**	N.S.	N.S.
DFSL0-50	**S**	N.S.	N.S.	N.S.
DFSL5-45	**S**	**S**	N.S.	N.S.
DFSL15-35	**S**	**S**	N.S.	N.S.
Bicep Brachii				
SFSL	**S**	**S**	**S**	N.S.
DFSL0-50	**S**	**S**	N.S.	N.S.
DFSL5-45	**S**	**S**	N.S.	N.S.
DFSL15-35	**S**	**S**	N.S.	N.S.
Erector Spinae				
SFSL	**S**	N.S.	N.S.	**S**
DFSL0-50	**S**	N.S.	N.S.	N.S.
DFSL5-45	**S**	N.S.	N.S.	N.S.
DFSL15-35	**S**	**S**	N.S.	N.S.

What can be observed from Table 5 are the consistent effects for the different parameters and muscles. The RPE results are the most consistent across muscles and conditions and demonstrate significance for all. The maximum force results are

relatively consistent for the medial deltoid, bicep femoris and bicep brachii muscles. The EMG activity and center frequency results however, are the least consistent and do not demonstrate a high number of statistically significant results.

CHAPTER 5: DISCUSSION

The results of isometric contractions of four muscles have been compared to identify muscle fatigue for static compared to quasi-static muscle exertions. Hypothesis one of this study investigated whether a quasi-static work regime with dynamic force and static length would differ in its fatigue responses compared to an exclusively static work regime. Hypothesis two tested whether a quasi-static work regime with a constant underlying static component (one of 5%MVC and one of 15%MVC) would have a significant effect on fatigue when compared to a quasi-static work regime with a purely dynamic force.

5.1GENERAL FATIGUE CHARACTERISTICS

Table 5 summarizes fatigue occurrences over time for all conditions, muscles and the different fatigue measures. The RPE results demonstrate that all conditions showed fatigue development over the five-minute protocol, which suggests that RPE may indicate fatigue sooner than other measures, or that the perceived workload was higher than the actual workload. Similar findings were found in a study by Sundelin and Hagberg (1992), where a five-minute fatiguing protocol of the shoulder muscles produced an average RPE of 11 for all participants. Similar to Sundelin and Hagberg (1992), the protocol in this research was also five minutes of work and the average RPE for all conditions was close to 11 as well. Sundelin and Hagberg's (1992) suggest that the reason for the steady increase in RPE over time can be due to the monotony of the task, the level of the workload and a lack of mental stimulation. This research also had a highly monotonous work rate, a relatively high work load and no mental stimulation. This could explain the steady increase in RPE across conditions and muscles (Figures 20, 21, 22 and 23) that is not observed in other fatigue measures. When comparing the RPE measures to all the other muscle fatigue measures, it is suggested that these mental aspects of the protocol caused the perceived workload to be higher than the actual workload. Therefore, while the increase in RPE from interval to interval within one condition may have been affected by the previously mentioned factors, the significant differences between the conditions can still be compared as the factors affecting RPE were constant for all of them.

When considering the EMG activity for the reference task and the EMG center frequency for both hypotheses, the values are acceptable and in line with what one would expect to see in such data. The mean power frequencies of the EMG center frequency results are within similar ranges found in other literature (Komi *et al.*, 1979; Moritani *et al*., 1986; Richardson *et al*., 1996; Dedering *et al*., 1999).

The results for all fatigue measures and muscles were not homogenous; however, there are a number of results that demonstrate trends across muscle and fatigue measures that were not found to be statistically significant with the sample and conditions in this study. The differences between the conditions were subtle in that the workloads in all them were carefully maintained at 25 percent of maximum force and the differences in forces were small when considering that they were maintained for five minutes in all protocols. While the workload during the fatiguing protocol itself was maintained at 25 percent of maximum force, the pre-protocol measure for the EMG results show that the static EMG reference task did not start at 25 percent of maximum muscle recruitment (Figures 28, 29, 30, 31, 44, 45, 46 and 47). The load used for this task was calculated according to maximum weight lifted in the initial MVC test and not calibrated according to EMG readings. Thus the 25 percent of maximum weight did not always equate to 25 percent of maximum EMG activation.

5.2 HYPOTHESIS ONE: STATIC MUSCLE FORCE vs. DYNAMIC MUSCLE FORCE

In this hypothesis, the differences in fatigue characteristics of condition Static Force Static Length were compared to condition Dynamic Force Static Length0-50, for which the results are demonstrated in Figures 20 to 35. Based on the current literature, it was expected that there would be a difference between these two conditions due to the muscle pump effect which allows more blood to reach a dynamically contracting muscle compared a static one (Savard *et al.,* 1986; Jonsson, 1988; Radegran, 1997;Laaksonen*et al.,* 2002). Since the SFSL condition had a completely static force and length, it should receive the least amount of blood compared to condition DFSL0-50 (Savard *et al.,* 1986) and therefore should result in a greater fatigue response, whereas condition DFSL0-50 had a period of complete relaxation between every exertion, allowing blood to enter the muscle freely. This was followed by a 50 percent of maximum force exertion, pumping blood through the muscle and essentially

allowing for an optimal muscle blood flow scenario (Marko *et al.,* 2002). With the exception of the maximum force results for medial deltoid (Figure 24) and the center frequency results for bicep femoris (Figure 33), the results suggest that this may be true. When analysing the results, there are several findings such as the RPE and maximum force measures on the erector spinae muscle in Figures 23 and 27 respectively that, while not statically significant, show a diverging effect and suggests that there is a difference in the muscle fatigue response between these two conditions.

The results for RPE as a whole for hypothesis one showed that condition DFSL0-50 had a consistently lower RPE than SFSL (Figure 20, 21, 22 and 23). This difference between conditions was only statistically significant for the bicep brachii muscle (Figure 22). The trends for all the RPE results for all muscles suggest that the SFSL condition is slightly more demanding compared to DFSL0-50, since even after the first minute of fatiguing protocol the RPE was higher for all muscles and all intervals when compared to DFSL0-50. This gives an indication that the blood flow during a quasi-static condition may be increased even when no change in muscle length is present. Other factors that may have played a role in the consistently higher RPE for the SFSL condition is an anticipation of earlier fatigue for static work or increased activations levels during the SFSL condition. Baden *et al.* (2005) found evidence that would indicate that there is a significant anticipatory aspect to RPE responses. Thus, If participants anticipated the experience of earlier fatigue for the purely static condition it may explain why, from interval one onwards, there was a clear and consistently higher RPE for all muscles for the fully static condition.

When examining the EMG results, there is a trend for the medial deltoid (Figure 28), bicep femoris (Figure 29) and bicep brachii (Figure 30) muscles to have higher muscle activation levels for the SFSL condition compared to DFSL0-50. While not significantly higher, the trends would suggest that the perceived workload may be from the increased muscle activation that the purely static condition induced for the same overall workload.

When considering the maximum force results (Figures 24, 25, 26 and 27), the data shows similar traits to the RPE results where, while not always statistically significant, DFSL0-50 always had a smaller drop in the percentage of maximum force decrements compared to SFSL. This means that the fatigue level of SFSL is suggested to be higher

and as with RPE, this demand would accumulate more fatigue over time compared to DFSL0-50. Since the results of maximum force are similar to the results of RPE in that condition SFSL appears to have a consistently higher demand, it also suggests that the SFSL condition's RPE being consistently higher than DFSL0-50may not be due to a mental or anticipatory effects towards static work, but rather be purely from the fact that from the onset, static work has a higher physical demand and muscle activation levels. The results for maximum force do differ to those of RPE in that the medial deltoid muscle for SFSL has a smaller drop in maximum force compared to DFSL0-50 at all intervals as seen in Figure 24. The variability for condition SFSL for the medial deltoid muscle is far higher than DFSL0-50 and could have affected the results for this muscle. The gross maximum force measures shown in Table 4 indicate that participants had the greatest strength variability for the medial deltoid muscle. This greater variability in strength may have affected the average fatigue measures over time for this muscle.

The EMG activity and EMG center frequency results demonstrate trends that confirm the results of RPE and maximum force and suggest that the demand of SFSL is higher than DFSL0-50. EMG activation levels for the medial deltoid, bicep femoris and bicep brachii (Figures 28, 29 and 30) are higher for condition SFSL compared to DFSL0-50, and while not always statistically significant, do present a trend. Center frequency is less homogenous than the other measures, however with the exception of medial deltoid (Figure 32) and bicep femoris (Figure 33), the overall trends also suggest that the that SFSL has a larger fatigue response compared to DFSL0-50.

While the EMG results for the medial deltoid muscle indicate that the muscle activation levels of SFSL was higher when compared to DFSL0-50 as seen in Figure 28, a decrease in muscle activation levels are seen over time for both conditions. The principle of the static EMG reference task measure was that an increase in muscle activation for the same weight would indicate a muscle fatigue response (Maton, 1981; Arendt-Nielsen and Mills, 1985; Andreassen and Arendt-Nielsen, 1987; Farina and Cescon, 2001). From the pre-protocol measure to interval two, there was a lower activation levels when considering the static EMG reference task results (Figure 28). When looking at RPE (Figure 20) and maximum force (Figure 24) for medial deltoid however, it can be confirmed that fatigue and decreasing activation levels over time

were occurring concurrently. Since other fatigue measures were demonstrating an increase in muscle fatigue over time, it appears to contradict what the EMG data is showing. An explanation is suggested when considering the actual movement that a participant was performing for the medial deltoid muscle during the fatiguing protocol. It was the “upright row” movement and the positioning of the moving limbs that were not dictated by the machine that was being used during the medial deltoid muscle fatiguing protocol as with the other muscles. The participant was in partial control of the horizontal hand positioning during the movement. This means that the degree of abduction was controlled by the participant, and thus the extent to which the bicep brachii muscle is being recruited. During the habituation session, all participants were explicitly shown how to perform the movement in order to isolate the medial deltoid muscle. As the protocol progressed, it may have been possible that participants started narrowing their grip, meaning that it would alleviate the strain on the isolated medial deltoid muscle and allow the bicep brachii muscle to take on more of the burden.

A specific study done by McAllister *et al.* (2013) showed that the wider the grip during the upright row movement, the more it resulted in the medial deltoid muscle recruitment, and vice versa. The narrower the grip, the more it resulted in the bicep brachii muscle being predominantly recruited. This may explain why there was significant fatigue from other measures during the fatiguing protocol of the medial deltoid muscle; the increase in perceived effort and drop in maximum force do not isolate their readings to the medial deltoid muscle. Thus, the down-regulation seen in the medial deltoid muscle (Figure 28) may have been due to the participant recruiting it to a lesser degree, while recruiting the bicep brachii muscle to a larger extent, and the subsequent RPE increase (Figure 20) and decrease in maximum force (Figure 24) is suggested to be due to the fatigue occurring in the bicep brachii muscle, and not medial deltoid.

The aspect of variability within the SFSL condition is a factor that may have affected the results significance. The results for RPE (Figures 20, 21, 22 and 23) and maximum force (Figures 24, 25, 26 and 27) for all muscles and intervals show that the variability is always higher for SFSL compared to condition DFSL0-50. This might suggest that there are participants who have higher levels of resistance to fatigue during purely

static work, compared to other participants, while this does not seem to be the case for the DSFL0-50 condition. Both well-trained and more sedentary participants constituted the participant pool, and while all of them had to have at least one hour of moderate or intense physical activity twice per week, this disparity may have played a part in the static work fatigue resistance results. It has been shown by researchers such as Hickner *et al.* (1997), Piehl *et al*. (2008), and Hermansen *et al*. (2008) that trained muscles store more glycogen than untrained ones. This could aid trained individuals to endure static work for longer as the muscle has more reserves to rely on without the aid of blood flow before the glycogen stores begin to deplete, which then signals the onset of fatigue.

This would explain the rather large variability in the purely static condition, and why it only occurred to a lesser extent in the DFSL0-50 condition, since blood flowed freely in that condition. Another possible explanation for this is the finding that maximum isometric strength levels of a participant determine the percentage of maximum force that intramuscular blood occlusion begins during static work (Barnes, 1980). Maximum isometric strength has a significantly negative correlation with intramuscular blood occlusion, and as such, stronger individuals have lower thresholds for the effects of static work to negatively affect their blood flow levels (Barnes, 1980). This means that individuals with higher force productions would have an increased fatigue response during the SFSL condition compared to more untrained individuals with lower maximum force productions, which may explain the very large variability found in this condition (Barnes, 1980).

When evaluating all the results concerning the first hypothesis (Figures 20 to 35) and focusing on the general trends and evidence that they provide on whether they support the first hypothesis, the majority of them do, despite that this sample and the conditions could not draw out statistically significant results for all measures. The results that were found to statically significant support the overall trends of the results in that SFSL was found to be more demanding that DFSL0-50. Of the statistically significant results, RPE revealed that the bicep brachii muscle for condition SFSL was significantly different toDFSL0-50 and shows that SFSL was more demanding as seen in Figure 22. The statistically significant maximum force results (Figures 25 and 26) indicate two muscles with a significant diverging affect between conditions DFSL0-50 and SFSL.

Both of these muscle demonstrated that SFSL was significantly more demanding than DFSL0-50. This provides evidence that, over time, a purely static condition would begin to fatigue these muscles to a greater degree when compared to a condition that has a fully dynamic muscle force. This difference would become even greater over a long period of time since there is a diverging effect within two minutes of fatiguing protocol. This may suggest that this could occur for all muscles eventually, however only the bicep brachii muscle and the bicep femoris muscle had a short enough endurance time for condition SFSL for the differences to appear in the five-minute window of the testing protocol.

While the majority of the EMG and center frequency results (Figures 28, 29, 30, 34 and 35) show trends that support that SFSL is more demanding than DFSL0-50,the fact that there were no statistically significant changes in EMG or center frequency over time in the bicep brachii or bicep femoris muscles, or that there was no significant differences between SFSL and DFSL0-50,(with the exception of the bicep femoris muscle static EMG reference task result, seen in Figure 30, which is explained later in this section) indicates that the muscle did not up regulate the recruitment of muscle fibres and that it did not have to resort to low frequency motor units to a statistically significant degree. The protocol ran for five minutes, meaning that glycogen stores would not be depleted in that time. When considering the literature on glycogen depletion rates (Saltin and Karlsson 1971; Hultman *et al*., 1971; Baldwin *et al*., 1971; Gollnik *et al*., 1974), it was found that the glycogen stores within a muscle deplete very slowly when sub maximal work is performed, particularly when the work is at 30 percent or less of maximum force. The testing in this study had an average work rate of 25 percent of maximum force. Additionally, significant amounts of glycogen are only lost when the work is performed for 20 minutes or more (Saltin and Karlsson 1971; Hultman *et al*., 1971; Baldwin *et al*., 1971; Gollnik *et al*., 1974). Thus, when considering that this protocol ran for five minutes at the average work rate of 25 percent of maximum voluntary contraction, glycogen stores would most likely not have been significantly depleted and thus no metabolic fatigue would have occurred. Thus, the significant changes over time are not observed, however muscle fatigue is not the issue in question, when considering what evidence the results present for the first hypothesis, Figures 28, 29, 30, 34 and 35 do show that SFSL was more demanding, just not to a significant degree in the sample tested.

The maximum force over the time intervals for the SFSL (Figures 24, 25, 26 and 27) decreased by no more than 15 percent, and thus, while it was significant enough to indicate that fatigue was occurring, this is not a substantial decrease in maximum force (Allen, 2008). One of the characteristics of low-frequency fatigue is small reductions in maximum force production and only excessive levels of maximum force drop are associated with high-frequency fatigue (Jones, 1996). When evaluating both the maximum force and center frequency results (Figures 31, 32, 33 and 34), it appears that low frequency fatigue was being induced and this would lead to a moderate decrease in maximum force production and no decrease in EMG center frequency and this was confirmed in the results for both these measures. The consequence of low frequency fatigue is a slow recovery over the course of hours or even days (Jones, 1996).

The bicep femoris muscle (Figure 29) demonstrated a significant difference between condition SFSL and DFSL0-50 at all intervals, including the pre-protocol measure. Since the initial measure of the EMG reference task was done according the initial MVC reading, and before any fatigue had occurred, it is suggested that there is an anticipatory response to static work. Literature supports the notion that mental factors can affect EMG responses. These factors include motivation levels (Waersted *et al*., 1994), psychological stress (Lundberg *et al*., 1994), incentives and perceived difficulty of the task that is being performed (Surwillo, 1956). The mean of all participants for all intervals for the bicep femoris muscle revealed that the SFSL condition yielded a statistically significantly higher muscle activation level, and particularly because the pre-protocol measure is significantly different, it is suggested that the perceptual factor played a role.

Another point worth mentioning with regard to the bicep femoris results is why only the bicep femoris muscle showed this significant difference between conditions, especially the pre-protocol measure while none of the other muscles displayed it. This could be due to the bicep femoris muscle, like a fully static condition, is perceived to be a muscle that requires a substantial amount of effort to fatigue compared to other muscles, and thus this immediate increase in EMG would only be displayed for this muscle and for the purely static condition.

When the previously discussed factors that may have had significant effects on the results have been excluded, and the overall trends of the majority of the results are evaluated, it is plausible that the SFSL condition has a higher demand and greater muscle fatigue response when compared to DFSL0-50. The amount of blood flow could be responsible for these differences in fatigue and would suggest that a dynamic muscle force is all that is necessary for a muscle to fatigue in a similar manner to one that is performing fully dynamic work with changes in muscle force and length. If this finding is true, it suggests that a muscle exertion with a dynamic muscle force cannot be considered to be static when evaluating its fatigue rates. This could mean that even if there was no change in muscle length, but only a change in muscle force with a period of full relaxation between contractions, fatigue would be delayed since the blood flow aspect is able to make a significant difference. This does not seem to be in line with risk assessment tools based on the perception that only an exertion with a change in joint angle is considered to be dynamic, while a muscle exertion that has no change in joint angle is considered static (Pascual and Naqvi, 2008). The implications of this are that contractions that are dynamic in force, but not in length may put a muscle at less of a risk compared to a contraction with a static length and force. A muscle exertion such as this should be evaluated according to the risk factors associated with dynamic muscle exertion fatigue.

5.3 HYPOTHESIS TWO: EFFECTS OF A CONSTANT UNDERLYING STATIC COMPONENT

This hypothesis compares conditions DFSL0-50, DFSL5-45 and DFSL15-35 to investigate whether there were any significant differences in fatigue characteristics with the addition of a static underlying contraction, while force variations occurred over and above this (Figures 36 to 51). It was surmised, based on the current literature (Sj∅gaard *et al.* 1986; Jonsson, 1988; Sj∅gaard *et al.,* 1998) that condition DFSL0-50 would fatigue the least, with conditions DFSL5-45 and DFSL15-35 fatiguing to a larger degree due to a compromised blood supply due to the static component.

Similarly to the EMG results for the medial deltoid muscle (Figure 28) of hypothesis one, lower activation levels are also observed overt time for DFSL0-50, DFSL5-45 and DFSL15-35 in Figure 44. Seemingly this is due to the same mechanism discussed

under hypothesis one. What is worth noting, however, is that the decreased activation levels occurred until interval two and then begin to level off. When looking at the EMG center frequency results for the medial deltoid muscle (Figure 48), a dip in the power frequency was seen from interval two. Thus this relationship in the EMG activity can also be observed in EMG center frequency results. There was a decrease in power frequency indicating fatigue was occurring in the form of low frequency muscle fibres being recruited. After interval two it also levelled off similarly to the EMG results for the medial deltoid muscle. The medial deltoid muscle was therefore fatiguing until the bicep brachii and other elbow flexors such as brachialis muscles started being predominantly recruited, at which point the fatigue within the medial deltoid ceased. The RPE (Figure 36) and maximum force (Figure 40) results for the medial deltoid muscle cannot determine in which muscle the fatigue is occurring, it is assumed that it is occurring in whichever muscle is being tested. The EMG and EMG center frequency results however measure the responses on a specific muscle. The EMG center frequency results suggests that the fatigue to the medial deltoid muscle ceased after interval two and the increases in RPE and decreases in maximum force are a result of bicep brachii and brachialis fatigue.

When evaluating the results for the second hypothesis, there appears to be a greater difference in fatigue between condition DFSL0-50 and DFSL5-45 than between DFSL0-50 and DFSL15-35, and furthermore that condition DFSL15-35 fatigues less than DFSL5-45. It was hypothesized, and deduced based on the literature (Sj∅gaard *et al.* 1986; Jonsson, 1988; Sj∅gaard *et al.,* 1998) that the greatest difference in fatigue would be between DFSL0-50 and DFSL15-35, with DFSL5-45 being somewhere in between, but this does not seem to be borne out of the results in this study. Existing literature on muscle fatigue during the type of work done in this research is very limited, and as such no comparison of results can be made. The deductions made from the literature all relate to fatigue during low level static exertions, with the simple mechanism being that the higher the percentage of maximum force that a purely static exertion is performed, the more blood flow is impeded and thus the muscle fatigues more rapidly. This study incorporates dynamic muscle forces over and above a static components and when comparing the results to that of low level static contractions in isolation, there is evidence from the results that all small underlying static components may impede blood flow levels similarly

during an otherwise dynamic force muscle exertion, and thus as long as total work is kept constant, a larger underlying static component may cause the same increase in muscle fatigue responses as a comparatively smaller one. (Sj∅gaard *et al.,* 1986; Jonsson, 1988; Sj∅gaard *et al.,* 1998).

For all the fatigue measures and muscles, there is one finding in support of the initial expectation with regards to blood flow responses (Savard *et al.,* 1986; Jonsson, 1988; Masuda *et al.,* 1999). The EMG activity results for the bicep femoris muscle (Figure 45) showed that DFSL0-50 fatigued the least, and was statistically significantly less fatigued than DFSL15-35, with DFSL5-45 falling between these two conditions. The idea that all sub-maximal underlying static components may affect fatigue similarly when compared to a fully dynamic force muscle exertion may be more plausible when looking at the trends of the results. Figures 37, 38, 39, 41 and 45all demonstrate trends that suggest that any static component added to an otherwise dynamic muscle force exertion places a higher demand on the muscles tested, however only Figure 45 provides evidence for the originally hypothesised idea that the larger the static component, the greater the muscle fatigue response.

The EMG activity results for the bicep femoris muscle (Figure 45) demonstrates a different trend to other measures and muscles where DFSL0-50 and DFSL5-45 seemed to remain relatively constant, while DFSL15-35 had significantly higher muscle fibre recruitment at interval one and five. It also exhibited consistently higher muscle activation at all intervals. It showed an initial decrease in activation levels followed by a significant increase. The bicep femoris muscle in the first hypothesis displayed results that differed to the other muscles as well (Figure 30). The SFSL condition indicated a consistently and statistically significantly higher EMG activation over all intervals, and this included the pre-protocol measure. As discussed earlier, this may be due to mental perceptions of static work influencing muscle activation level (Waersted *et al*., 1994; Lundberg *et al*., 1994; Surwillo, 1956). The EMG results for the bicep femoris muscle in the second hypothesis showed a similar trait where one condition had a significantly higher EMG muscle activation from the pre-protocol measure and thus again it is plausible that the combination of a large static exertion coupled with the bicep femoris muscle resulted in a higher muscle activation even before any fatiguing has occurred.

While the EMG results for the bicep femoris muscle for the first and second hypothesis both displayed different trends compared to the other muscles tested, they were not similar in that DFSL15-35 did not show statistically significantly higher EMG levels compared to DFSL0-50 and DFSL5-45 for all intervals like SFSL had when compared to DFSL0-50. The static exertion in DFSL15-35 is smaller than SFSL, and thus if the idea that mental perceptions of static work affected the EMG results is adopted, what may have occurred to cause the down regulation is that the required effort during this protocol did not seem to match the initial perception such as in SFSL and thus a lower activation level matching the DFSL0-50 and DFSL5-45 conditions would still allow the appropriate performance, leading to a down regulation (Waersted *et al*., 1994; Lundberg *et al*., 1994; Surwillo, 1956).The up regulation seen from interval two may then represent a physiologically significant fatigue response when compared to both DFSL0-50 and DFSL5-45. The observation that both of these results occur within the same muscle may suggest that for the bicep femoris muscle, the initial idea that the degree of the underlying static component is the main determining factor in the progression of fatigue when considering quasi-static muscle exertions. As mentioned in Chapter 2, this may then have implications in sports performance, as the bicep femoris muscle injuries due to muscle fatigue are most prevalent in that sector (Heiderscheit *et* al., 2005; Hoskins and Pollard, 2005).

Among the data that displays trends that supports the idea than any static component may place a higher demand on a muscle when compared to a fully dynamic muscle force exertion, (Figures 37, 38, 39, 41 and 45), the RPE results for bicep brachii and erector muscle (Figures 38 and 39 respectively), along with the maximum force results for bicep femoris muscle (Figure 41) all demonstrate a general trend that DFSL15-35 may place less demand on a muscle than DFSL5-45 when compared to the purely dynamic force condition DFSL0-50. It is plausible to a degree to suggest that in some cases, a larger underlying static component coupled with a lower peak force fatigues less than a smaller underlying static component coupled with a larger peak force, with the total work load kept constant across conditions. DFSL0-50 remains the condition that fatigues the least however. Thus, a complete relaxation phase with the highest peak force may yield the best fatigue resistance. Regarding the RPE results for the erector spinae muscle (Figure 39), condition DFSL0-50 had a significantly lower RPE when compared to DFSL5-45 and DFSL15-35. Unlike the bicep femoris muscle RPE

results (Figure 37), however, the DFSL15-35 had a consistently lower RPE rating when compared to DFSL5-45, and thus while it had a significantly higher RPE compared to DFSL0-50, it was on average 0.5 RPE lower when compared to DFSL5-45. The absence of a static underlying component combined with a higher peak force therefore resulted in a significantly smaller fatigue response. However, what can only be inferred here is that because there was also a clear and consistent distinction of 0.5 RPE for every interval when comparing DFSL15-35 and DFSL5-45, the lower peak force together with a larger underlying static component may fatigue less than a lower underlying static component with a higher peak force.

The RPE results for the bicep brachii muscle (Figure 38) are less distinctive than the erector spinae muscle; however, a diverging effect does develop over time between DFSL0-50, DFSL5-45 and DFSL15-35, with the difference in RPE between DFSL0-50 and DFSL5-45 being statistically significant. What can be observed with the bicep brachii muscle, as with the erector spinae muscle, is that DFSL15-35 fatigued on average 0.5 RPE less than DFSL5-45 from interval two onwards. This provides some evidence that no underlying static component does yield statistically less significant fatigue, but in this result the idea that DFSL15-35 may fatigue less than DFSL5-45 has more substantiation as there was no statistical significant difference between DFSL0-50 and DFSL15-35, but there was between DFSL0-50 and DFSL5-45. Additionally, a statistically significant finding in the maximum force results for the bicep brachii muscle (Figure 42) indicates that DFSL15-35 fatigued less than DFSL5-45, and there was a distinctly reduced decrease in force when DFSL15-35 is compared to DFSL5-45. Thus, the drop in maximum force production results supports the idea that a smaller peak force is the determining factor when a constant underlying static component is present in a muscle exertion and total work is kept constant.

The maximum force results of the bicep femoris muscle (Figure 41) are similar to the results in RPE and maximum force found in the bicep brachii muscle (Figures 38 and 42 respectively) where DFSL5-45 fatigued more than DFSL0-50 and was found to be statistically significant, and while not statistically significant, DFSL15-35 fatigued more than DFSL0-50, but less than DFSL5-45. This is worth noting as the only result confirming the initial expectation that DFSL15-35 would fatigue a muscle more than DFSL5-45 was found for the EMG results for the bicep femoris muscle. One theoretical

explanation of this inconsistency is that decreases in maximum force relates more closely to high frequency fatigue than to low frequency fatigue since when the former is occurring, the fast twitch muscle fibres are responsible for the large decreases in force and thus the conditions associated with higher peak force would fatigue to a greater degree with this particular muscle fatigue measure (Yan *et al*., 1993; Karthi, 2008). DFSL15-35 had the lowest peak force suggesting that it would be recruiting more low-frequency muscle fibres during the fatiguing protocol and thus would leave the high-frequency muscle fibres less fatigued and result in smaller decreases in maximum force (Yan *et al*., 1993; Karthi, 2008). This may explain why this result differs to the EMG activity task and RPE results of the same muscle (Yan *et al*., 1993; Karthi, 2008).

The EMG activity results for the bicep brachii muscle (Figure 46) displays a trend where DFSL0-50 showed an increase in muscle fibre recruitment from interval three, and demonstrates higher activation levels than DFSL5-45 and DFSL15-35. This difference is statistically significant between DFSL0-50 andDFSL5-45. This result would suggest that condition DFSL0-50 has the largest muscle fatigue response compared to DFSL5-45 and DFSL15-35. This trend is supported by the EMG center frequency results of the bicep femoris muscle (Figure 49).

The EMG center frequency results for the bicep femoris muscle illustrates that DFSL0-50 places a greater demand on the fast-twitch muscle fibres over time when compared to DFSL5-45 and DFSL15-35. Since both conditions DFSL5-45 and DFSL15-35 fatigued less according to this measure, however, it may suggest that while the average work performed for all the conditions was kept constant at 25 percent of maximum over time, the higher force needed for condition DFSL0-50 compared to DFSL5-45 and DFSL15-35 may have been fatiguing the muscle faster for this particular measure. This is despite the fact that there was no constant underlying component. This confirms to some degree the results from the medial deltoid muscle's EMG center frequency (Figure 48) where DFSL5-45 fatigued more significantly compared to DFSL15-35. Again the higher force condition caused more low frequency muscle fibres to be recruited (Jones, 1996). It may be that high frequency fatigue was occurring in the conditions that have a higher force, which would mean that the higher

force conditions would receive the greatest increase in the recruitment of low frequency muscle fibres (Jones, 1996).

5.4 SUMMARY OF HYPOTHESIS CONCLUSIONS

Based on the evidence provided in the above results, there is merit to the notion that an isometric, dynamic muscle exertion will place less of a demand on a muscle compared to a fully static muscle exertion with no change in force or length provided total work is kept constant. This is supported by the results of the of RPE for all muscles tested, the maximum force results for the bicep femoris, bicep brachii and erector spinae muscles, by the EMG activity results for bicep femoris and bicep brachii, and for center frequency results for bicep brachii and erector spinae muscles. As for hypothesis two, when looking at all the trends that are prevalent, it is plausible to say that when a muscle is performing a quasi-static muscle exertion, adding a small underlying static component, while keeping total work constant, will fatigue a muscle to a greater degree than compared to a condition with no underlying static component, despite having the higher peak force. The previously hypothesized idea that: the greater the static underlying component, the greater the fatigue response, does not seem to be supported by the results. There are a number of inconsistencies in the results of hypothesis two however and it suggests that there may be other factors that significantly impact the fatigue responses of muscles during the type of work incorporating underlying static components.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

The primary purpose of this study was to compare muscle fatigue responses of the medial deltoid, bicep brachii, bicep femoris and erector spinae muscles between different isometric work protocols. Within the primary focus were two aims; to test whether an isometric, dynamic exertion fatigued a muscle similarly to that of a fully static exertion. Secondly, to test whether, and to what degree, an underlying static component affects muscle fatigue responses compared to a muscle exertion with no static component when the total work kept constant.

The results presented in this study shed light on what muscle fatigue characteristics occurred during quasi-static work, but also highlights the importance of research into this subject as muscle fatigue during this type of work is not so easily understood as the results showed. The results comparing purely static work to quasi-static work demonstrated trends that suggest that fully static work does place a higher demand on the muscles tested when compared to quasi-static work. Though the results are not significant or conclusive across all results, the idea that blood flow levels are impeded to a lesser degree when a muscle has a change in force is plausible and supported by the results.

When considering the results of what effect the underlying static component had on an otherwise fully dynamic force work protocol, the results were less homogenous when compared to the results of hypothesis one. The two main trends that were drawn from the results were that in general, a sub-maximal underlying static component in an otherwise dynamic muscle force exertion may increase demand on a muscle when total work is kept constant. Additionally, peak force may play a larger role than the magnitude of the underlying static component in determining the degree of muscle fatigue response when an underlying static component is present is muscle work.

6.1 RECOMMENDATIONS

The following recommendations for future research have been made in order to fill some of the gaps found in the results of this study. Further investigations into the RPE, maximum force, muscle fibre recruitment and EMG centre frequency responses to quasi-static work should consider the following recommendations:

1. A protocol with sufficient length that allows enough time for a wide range of muscles to display significant differences between conditions when muscle forces are being manipulated.

2. To either accumulate a participant pool that includes individuals that have very similar training statuses and histories, or to use training status as an independent variable to determine whether this aspect of static work resistance does exist and can affect the muscle fatigue responses significantly during static work.

3. Future research may benefit from incorporating more task specific work protocols when researching quasi-static muscle fatigue responses.

4. Including demographic variables (e.g. sex, age, race and baseline strength) and procedural factors (e.g. testing order) and task performance measures should be considered as additional factors in the data analysis.

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APPENDICES

APPENDIX A:

1) Pre-test letter of information letter.
2) Informed consent form

APPENDIX B:

1) General linear model tables and detailed p-values from paired t-tests (p-values given for conditions with significance).

APPENDIX A

7.1 PRE-TEST INFORMATION LETTER

HUMAN KINETICS AND ERGONOMICS

Cell: 0733373808 Fax: (046) 603 8934 E-mail: g08n4990@campus.ru.ac.za

Dear: _____,

Thank you for offering to participate in this Masters Degree research project titled:

A Comparison of Muscle Fatigue Responses Between Static, Quasi-Static and Dynamic Exertions.

The injury rate in South Africa for individuals working in manual jobs remains a large problem. Many of the injuries obtained by manual workers incur from overuse, originating from muscle fatigue levels that exceed recovery rates. Further research

into muscle fatigue accumulation related injuries is needed to develop more reliable risk assessments, and effective intervention strategies. Thus, the purpose of this study is to measure muscle fatigue while exposing selected muscles to different types of muscle contraction schemes which vary in their static and dynamic characteristics. The conditions range from purely static (no movement, or change in weight lifted), to purely dynamic (change in limb positions, and change in the weight lifted).

PROCEDURES

If you agree to be a participant in this study you will be required to attend 4 sessions, at the Human Kinetics and Ergonomics Department at Rhodes University: one introduction and habituation session, and three testing sessions.

The first session will be a short introductory session during which the project aims, testing procedures and requirements will be explained to you in detail. Data such as age, stature, mass and resting heart rate will then be collected. The habituation session will then follow. The aim of the habituation session is to familiarize you with the testing procedures as well as all equipment used in the study. Some of the equipment that is used in this study has been custom-made, and thus you will not have been exposed to them before. Habituation is thus necessary to put you at ease with their use. You will also be given a chance to familiarize yourself with the electromyography system, which measures muscle activation, and the maximum voluntary contraction (MVC) procedure used to normalise its readings to each individual. This will require the placement of the necessary electromyography (EMG) electrodes on the shoulder, the hamstring, the bicep and the lower back muscles, followed by three all-out maximal muscle exertions during the two following testing sessions. If female participants feel uncomfortable with a male researcher placing electrodes in these areas, the option for a female assistant to place all the electrodes will be made available.

You will then be asked to sign a consent form, stating that you are comfortable with the procedures and giving your permission to participate in the study. Furthermore, it

is important to note that on arrival to the habituation session, you will be given a participant code number which will ensure that all your personal data collected during the study, remains anonymous. This habituation session should be no longer than 30 minutes.

Following the habituation session, there will be the two testing sessions. Each of these testing sessions will be approximately 90 minutes in length, and cannot be performed on the same day, or without at least two days rest in between testing sessions. In each testing session you will be required to perform four different conditions, with each condition lasting approximately 10 minutes. The placement of the EMG electrodes on the four muscles mentioned earlier will occur at the beginning of every testing session, and will remain in place until the session is completed. The placement of electrodes will be followed by a guided warm up and stretch session. In order to obtain the baseline muscle activity measurements, you will then be required you to complete an all-out maximal muscle exertion, called a maximum voluntary contraction (MVC), for all of the four muscles that are tested. Each exertion will be repeated twice. Following this, the four conditions for testing will start. Each condition starts with a maximal exertion, and a reference EMG measure. This is followed a one minute fatigue protocol during which you will be required to perform an exercise task with a load that averages to 25 percent of your maximum, followed by another maximal exertion, a reference EMG reading, and rating of perceived exertion (RPE). The central RPE rating is collected by showing you a chart that ranges from 6(very light) to 20 (very hard), you then state how hard you feel you’re exerting yourself.

Risks associated with the study:

Muscular or joint-related injury: In this study, you are required to perform multiple maximal exertions, as well as prolonged muscle contractions, which are aimed to fatigue the selected muscles. The fatigue induced by the conditions may cause DOMS (Delayed Onset of Muscle Soreness) which is predominately a result of these

excessive and possibly unaccustomed muscle contractions. DOMS is however fully recoverable within a few days (4-7days), with no permanent damage.

Acute muscle strain is an injury that occurs when muscle fibres are severely damaged due to high loads or excessive strain to the muscle.However to reduce the risk injury, sufficient time will be provided for each muscle to recover both within one session, and between sessions. You will be also performing a guided warm up and stretching routine before any testing commences to minimize the risk of injury. If you have any form of muscular pain, testing will be postponed to a time when either the DOMS or the muscle pain is no longer experienced.

Skin discomforts

Skin irritations**:** to ensure optimal conduction during testing, an EMG electrode gel is placed on the EMG electrodes which are then placed on your skin. Sensitive skin may experience minor skin irritations. In such a case, the electrode cream will be removed from the skin. EMG electrode gel is however aqueous based and should therefore not affect the skin. The electrodes will be held in place using Fixomull Stretch adhesive fabric. You may react to this plaster; however this product has been designed to be used on bare skin, and therefore poses minimal risk.

The area where the EMG electrodes are placed will need to be shaved and the skin may be nicked, resulting, in a risk of infection of the affected area. To prevent infection, the razor used to shave the skin will be a new and sterile razor and alcohol will be used to sterilize the skin that is to be shaved, thus further reducing any risk of infection. Anti-septic cream and plasters will also be available in the situation that such a skin injury occurs.

Acute injuries

There are also some other risks apart from muscle strain, e.g. for maximum trunk extension, there is the risk of Intervertebral disc injury due to compression and

shearing forces placed on the lower back during maximal exertions. The risk of this occurring has been minimized due to the fact that you cannot participate in this study if you have any history of injury in any of the areas that are tested, and additionally, the duration of the testing does not pose a big risk to injuring surround connective tissue. All the potentially dangerous exertions that would place you at risk of an acute injury in this study are maximum voluntary contractions while the specific muscle is isolated, and thus the chance of a load exceeding what the safety limits of the individual is, is small. The fatiguing protocol only taxes muscles at 25% MVC, or at 25% percent average (0% MVC to 50%MVC), thus it is a sub-maximal exertion relative to your maximal strength, and low enough to have minimal risk of an acute injury. Additionally you will not be carrying any external load, so you are only moving your own bodyweight. Although head, arms and trunk constitute 75 percent of an individual's bodyweight, the movements they are required to do are standard movements performed during a gym work out and if you are moderately trained, you would be familiar with such movement exertions.

Benefits associated with the study:

Knowledge (education): Participation in this study will allow you to obtain knowledge about your strength and endurance levels of the various muscles, as well as how fatigue can be measured. You will be exposed to the processes, procedures and equipment used during the experimental sessions as well as the results obtained from the trial conditions. The information and practices presented to you while participating in this study will allow you to gain some more understanding of muscle fatigue, and the processes causing it. The results will also contribute to your knowledge of your own personal capabilities. This information can then be used to further your own training, or prevent injury for yourself in the future.

Pre-Data Collection Do's and Don'ts

If you agree to be a participant in this study, there are a few aspects that you should try and adhere to in order for the most accurate data to be collected from your testing sessions, these include:

- You should not perform resistance training before a testing session.
- You should avoid performing resistance training after the testing session as to not incur a greater risk of injury to the affected muscles.
- You should avoid performing a testing session if you haven't eaten sufficiently that day.
- If you are experiencing DOMS, from either the testing sessions included in this study or from another form of physical exertion, you should postpone the testing session until you are fully recovered.

Additional Information:

Please note that the information obtained during the study will be kept confidential and will only be used for statistical analysis. Your identity will remain anonymous through the use of a participant code. I may request to take a photograph of you for illustrative purposes for my thesis, but will do so only with your consent and will also ensure that any identifying features are blacked out to ensure your anonymity. You will receive feedback in writing once the study is complete. If at any time you feel uncomfortable or do not want to continue with the study for whatever reason, you may withdraw without any negative consequences. The data will be archived in the Human Kinetics and Ergonomics Department and may be used for further research purposes, however your anonymity is still ensured.

Thank you for showing interest and participating in this study. If there are any questions that you may have please do not hesitate to contact me or my supervisor in the Human Kinetics and Ergonomics Department.

Yours sincerely,

Conrad Nel (Researcher) **Matthias Goebel (Supervisor)**

Cell: 0733373808 Tel: 046-603 7366

Email: g08n4990@campus.ru.ac.za. Email: m.goebel@ru.ac.za

7.2 INFORMATION TO PARTICIPANTS

INFORMED CONSENT FORM

HUMAN KINETICS AND ERGONOMICS

Cell: 0733373808 Fax: (046) 603 8934 E-mail: g08n4990@campus.ru.ac.za

PARTICIPANT CONSENT FORM

I, _____, agree that I have been informed, both verbally and in writing, of the procedures required in this research project entitled:

Different Fatigue Responses of Static, Quasi-Static and Dynamic Protocols.

I have read the information sheet and fully understand the testing procedures that will take place during this study. I understand that the aim of this study is to fatigue different muscles, and then to measure these fatigue responses across conditions that vary in

static, and dynamic components. The risks and benefits associated with the study have also been brought to my attention. I have further been given the opportunity to ask questions or express my concerns regarding the testing procedures. By voluntarily consenting to participate in this research project I accept responsibility together with the Human Kinetics and Ergonomics Department, whereby should injury occur as a result of the protocol being performed, the Human Kinetics Department will cover fees incurred and provide support to ensure my recovery. If, however, injury it is shown to be self-inflicted, not directly related to the study, or due to non-compliance with the researcher's instructions, the Department will waive any recourse against the researcher, the Department or of Rhodes University. I further understand that all information gained from this study will be treated confidentially and that my anonymity will be protected at all times. I am aware that data obtained from this study may be used and published for statistical and scientific purposes. I realize that, I may withdraw from this study at any time without negative consequences.

Please indicate by ticking the appropriate box whether, or not, you agree to photographs being taken of you performing the experimental protocols.

☐ I AGREE that the researcher may take photographs of me during the experiment to be used for illustrative purposes.

☐ I DO NOT agree to have photographs taken of me

I have read and fully understood that above information, as well as the information in the letter accompanying this form.

I therefore consent to voluntarily participate in this study.

PARTICIPANT (OR LEGAL REPRESENTATIVE):

_____	_____	_____
(Print name)	(Signed)	(Date)

WITNESS:

_____	_____	_____
(Print name)	(Signed)	(Date)

PERSON ADMINISTERING INFORMED CONSENT:

_____	_____	_____
(Print name)	(Signed)	(Date)

WITNESS:

_____	_____	_____
(Print name)	(Signed)	(Date)

APPENDIX B

8.1 HYPOTHESIS ONE: SFSL vs. DFSL0-50.

8.1.1 Rating of Perceived Exertion

8.1.1.1 Medial Deltoid

Effect	Repeated Measures Analysis of Variance (All results for statistica) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 8,440435 SS	Degr. of Freedom	MS	F	p
Intercept	15463,53	1	15463,53	217,0595	0,000000
Error	997,37	14	71,24		
COND	1,93	1	1,93	0,0932	0,764624
Error	289,37	14	20,67		
INTERVAL	210,91	4	52,73	42,9837	0,000000
Error	68,69	56	1,23		
COND*INTERVAL	0,11	4	0,03	0,0480	0,995537
Error	31,09	56	0,56		

8.1.1.2 Bicep Femoris

Effect	Repeated Measures Analysis of Variance (All results for statistica) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 8,438404 SS	Degr. of Freedom	MS	F	p
Intercept	12899,21	1	12899,21	181,1517	0,000000
Error	996,89	14	71,21		
COND	11,21	1	11,21	2,4479	0,140001
Error	64,09	14	4,58		
INTERVAL	187,83	4	46,96	23,5681	0,000000
Error	111,57	56	1,99		
COND*INTERVAL	0,63	4	0,16	0,3431	0,847721
Error	25,57	56	0,46		

8.1.1.3 Bicep Brachii

Effect	SS	Degr. of Freedom	MS	F	p
Repeated Measures Analysis of Variance (All results for statistica) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 8,402380					
Intercept	13104,40	1	13104,40	185,6147	0,000000
Error	1059,00	15	70,60		
COND	19,60	1	19,60	1,6461	0,218956
Error	178,60	15	11,91		
INTERVAL	148,54	4	37,13	26,8239	0,000000
Error	83,06	60	1,38		
COND*INTERVAL	6,84	4	1,71	3,9504	0,006527
Error	25,96	60	0,43		

Tukey HSD test; variable DV_1 (All results for statistica)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = ,43271, df = 60,000

Cell No.	COND	INTERVAL	{1} 7,7500	{2} 8,5000	{3} 9,5000	{4} 10,313	{5} 10,938	{6} 7,5000	{7} 8,1875	{8} 8,9375	{9} 9,1875	{10} 9,6875
1	1	1		0,058594	0,000150	0,000150	0,000150	0,985410	0,681298	0,000283	0,000151	0,000150
2	1	2	0,058594		0,002509	0,000150	0,000150	0,002509	0,938920	0,681298	0,113015	0,000283
3	1	3	0,000150	0,002509		0,028538	0,000151	0,000150	0,000165	0,333778	0,938920	0,998276
4	1	4	0,000150	0,000150	0,028538		0,202469	0,000150	0,000150	0,000155	0,000507	0,202469
5	1	5	0,000150	0,000150	0,000151	0,202469		0,000150	0,000150	0,000150	0,000150	0,000200
6	2	1	0,985410	0,002509	0,000150	0,000150	0,000150		0,113015	0,000151	0,000150	0,000150
7	2	2	0,681298	0,938920	0,000165	0,000150	0,000150	0,113015		0,058594	0,002509	0,000150
8	2	3	0,000283	0,681298	0,333778	0,000155	0,000150	0,000151	0,058594		0,985410	0,058594
9	2	4	0,000151	0,113015	0,938920	0,000507	0,000150	0,000150	0,002509	0,985410		0,501359
10	2	5	0,000150	0,000283	0,998276	0,202469	0,000200	0,000150	0,000150	0,058594	0,501359	

8.1.1.4 Erector Spinae

Effect	SS	Degr. of Freedom	MS	F	p
Repeated Measures Analysis of Variance (All results for statistica) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 8,548746					
Intercept	13589,41	1	13589,41	185,9498	0,000000
Error	803,89	11	73,08		
COND	18,41	1	18,41	1,8393	0,202218
Error	110,09	11	10,01		
INTERVAL	253,38	4	63,35	45,0884	0,000000
Error	61,82	44	1,40		
COND*INTERVAL	1,22	4	0,30	0,4650	0,761042
Error	28,78	44	0,65		

8.1.2 Maximum Force

8.1.2.1 Medial Deltoid

Effect	Repeated Measures Analysis of Variance (MVC FR) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 36,30933 SS	Degr. of Freedom	MS	F	p
Intercept	1166940	1	1166940	885,1399	0,000000
Error	18457	14	1318		
COND	273	1	273	0,7262	0,408459
Error	5260	14	376		
INTERVAL	1479	4	370	11,3145	0,000001
Error	1831	56	33		
COND*INTERVAL	115	4	29	1,2359	0,306202
Error	1302	56	23		

8.1.2.2 Bicep Femoris

Effect	Repeated Measures Analysis of Variance (MVC FR) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 32,40944 SS	Degr. of Freedom	MS	F	p
Intercept	1175185	1	1175185	1118,828	0,000000
Error	14705	14	1050		
COND	1391	1	1391	3,187	0,095882
Error	6109	14	436		
INTERVAL	1554	4	389	5,205	0,001230
Error	4180	56	75		
COND*INTERVAL	290	4	72	1,428	0,236642
Error	2839	56	51		

Cell No.	COND	INTERVAL	{1} 89,407	{2} 91,152	{3} 85,261	{4} 83,150	{5} 78,369	{6} 92,183	{7} 94,208	{8} 91,862	{9} 91,410	{10} 88,128
	Tukey HSD test; variable DV_1 (MVC FR) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 50,697, df = 56,000											
1	1	1		0,999603	0,845189	0,341901	0,003170	0,985948	0,703368	0,994171	0,998782	0,999970
2	1	2	0,999603		0,426754	0,086059	0,000451	0,999995	0,973252	1,000000	1,000000	0,975031
3	1	3	0,845189	0,426754		0,998154	0,219364	0,214510	0,033932	0,271474	0,366069	0,982495
4	1	4	0,341901	0,086059	0,998154		0,708231	0,031004	0,003096	0,043218	0,067513	0,659418
5	1	5	0,003170	0,000451	0,219364	0,708231		0,000224	0,000155	0,000264	0,000361	0,014060
6	2	1	0,985948	0,999995	0,214510	0,031004	0,000224		0,998673	1,000000	1,000000	0,861310
7	2	2	0,703368	0,973252	0,033932	0,003096	0,000155	0,998673		0,995825	0,985163	0,381796
8	2	3	0,994171	1,000000	0,271474	0,043218	0,000264	1,000000	0,995825		1,000000	0,910369
9	2	4	0,998782	1,000000	0,366069	0,067513	0,000361	1,000000	0,985163	1,000000		0,957926
10	2	5	0,999970	0,975031	0,982495	0,659418	0,014060	0,861310	0,381796	0,910369	0,957926	

8.1.2.3 Bicep Brachii

Effect	SS	Degr. of Freedom	MS	F	p
Repeated Measures Analysis of Variance (MVC FR) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 22,97849					
Intercept	1216283	1	1216283	2303,517	0,000000
Error	7920	15	528		
COND	1122	1	1122	3,338	0,087664
Error	5044	15	336		
INTERVAL	1546	4	386	16,370	0,000000
Error	1416	60	24		
COND*INTERVAL	292	4	73	3,139	0,020702
Error	1396	60	23		

Tukey HSD test; variable DV_1 (MVC FR)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 23,263, df = 60,000

Cell No.	COND	INTERVAL	{1} 91,740	{2} 86,165	{3} 83,558	{4} 81,172	{5} 80,063	{6} 94,201	{7} 89,120	{8} 87,589	{9} 90,244	{10} 88,030
1	1	1		0,052202	0,000561	0,000151	0,000150	0,908292	0,871757	0,324901	0,996664	0,484342
2	1	2	0,052202		0,875193	0,120572	0,022466	0,000709	0,772558	0,997720	0,349065	0,983544
3	1	3	0,000561	0,875193		0,922773	0,568799	0,000151	0,053313	0,365593	0,008167	0,230274
4	1	4	0,000151	0,120572	0,922773		0,999697	0,000150	0,000823	0,013119	0,000211	0,005972
5	1	5	0,000150	0,022466	0,568799	0,999697		0,000150	0,000213	0,001757	0,000153	0,000796
6	2	1	0,908292	0,000709	0,000151	0,000150	0,000150		0,106983	0,009308	0,391640	0,020025
7	2	2	0,871757	0,772558	0,053313	0,000823	0,000213	0,106983		0,996030	0,999663	0,999739
8	2	3	0,324901	0,997720	0,365593	0,013119	0,001757	0,009308	0,996030		0,862939	1,000000
9	2	4	0,996664	0,349065	0,008167	0,000211	0,000153	0,391640	0,999663	0,862939		0,950353
10	2	5	0,484342	0,983544	0,230274	0,005972	0,000796	0,020025	0,999739	1,000000	0,950353	

8.1.2.4 Erector Spinae

Effect	SS	Degr. of Freedom	MS	F	p
Repeated Measures Analysis of Variance (MVC FR) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 37,94037					
Intercept	1001406	1	1001406	695,6759	0,000000
Error	15834	11	1439		
R1	113	1	113	0,7366	0,409064
Error	1694	11	154		
R2	1160	4	290	7,6131	0,000094
Error	1676	44	38		
R1*R2	48	4	12	0,2836	0,887060
Error	1854	44	42		

8.1.3 Static EMG Reference Task

8.1.3.1 Medial Deltoid

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 12,55742				
	SS	Degr. of Freedom	MS	F	p
Intercept	39341,47	1	39341,47	249,4879	0,000000
Error	2207,64	14	157,69		
COND	7,34	1	7,34	0,1168	0,737561
Error	879,17	14	62,80		
INTERVAL	723,92	5	144,78	10,4604	0,000000
Error	968,88	70	13,84		
COND*INTERVAL	54,46	5	10,89	1,1537	0,340715
Error	660,90	70	9,44		

8.1.3.2 Bicep Femoris

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 15,37925				
	SS	Degr. of Freedom	MS	F	p
Intercept	62818,06	1	62818,06	265,5913	0,000000
Error	3074,78	13	236,52		
R1	1506,77	1	1506,77	11,2269	0,005214
Error	1744,73	13	134,21		
R2	8,18	5	1,64	0,1777	0,970036
Error	598,26	65	9,20		
R1*R2	13,93	5	2,79	0,2748	0,925299
Error	658,72	65	10,13		

Cell No.	Tukey HSD test; variable DV_1 (Data Sheet 1 (ARFS)) Approximate Probabilities for Post Hoc Tests Error: Within MSE = 10,134, df = 65,000													
	R1	R2	{1} 22,151	{2} 22,456	{3} 22,410	{4} 21,833	{5} 22,185	{6} 22,956	{7} 16,787	{8} 16,914	{9} 15,917	{10} 16,278	{11} 16,168	**{12} 15,989**
1	1	1		1,000000	1,000000	1,000000	1,000000	0,999939	0,001968	0,002763	0,000247	0,000527	0,000414	0,000280
2	1	2	1,000000		1,000000	0,999995	1,000000	1,000000	0,000866	0,001203	0,000164	0,000272	0,000228	0,000176
3	1	3	1,000000	1,000000		0,999998	1,000000	0,999999	0,000974	0,001396	0,000172	0,000296	0,000244	0,000186
4	1	4	1,000000	0,999995	0,999998		1,000000	0,998523	0,004592	0,006408	0,000479	0,001162	0,000874	0,000564
5	1	5	1,000000	1,000000	1,000000	1,000000		0,999960	0,001803	0,002531	0,000235	0,000489	0,000387	0,000264
6	1	6	0,999939	1,000000	0,999999	0,998523	0,999960		0,000277	0,000368	0,000128	0,000147	0,000139	0,000130
7	2	1	0,001968	0,000866	0,000974	0,004592	0,001803	0,000277		1,000000	0,999868	0,999999	0,999996	0,999944
8	2	2	0,002763	0,001203	0,001396	0,006408	0,002531	0,000368	1,000000		0,999516	0,999994	0,999971	0,999763
9	2	3	0,000247	0,000164	0,000172	0,000479	0,000235	0,000128	0,999868	0,999516		1,000000	1,000000	1,000000
10	2	4	0,000527	0,000272	0,000296	0,001162	0,000489	0,000147	0,999999	0,999994	1,000000		1,000000	1,000000
11	2	5	0,000414	0,000228	0,000244	0,000874	0,000387	0,000139	0,999996	0,999971	1,000000	1,000000		1,000000
12	2	6	0,000280	0,000176	0,000186	0,000564	0,000264	0,000130	0,999944	0,999763	1,000000	1,000000	1,000000	

8.1.3.3 Bicep Brachii

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 15,59574 SS	Degr. of Freedom	MS	F	p
Intercept	61145,79	1	61145,79	251,3938	0,000000
Error	3648,41	15	243,23		
COND	42,35	1	42,35	0,3076	0,587313
Error	2065,05	15	137,67		
INTERVAL	321,55	5	64,31	2,5880	0,032518
Error	1863,72	75	24,85		
COND*INTERVAL	113,11	5	22,62	1,3904	0,237572
Error	1220,31	75	16,27		

8.1.3.4 Erector Spinae

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 30,33212 SS	Degr. of Freedom	MS	F	p
Intercept	84343,87	1	84343,87	91,67433	0,000001
Error	10120,42	11	920,04		
COND	27,19	1	27,19	0,11302	0,743063
Error	2646,90	11	240,63		
INTERVAL	135,14	5	27,03	2,38383	0,049918
Error	623,61	55	11,34		
COND*INTERVAL	82,03	5	16,41	1,68277	0,154154
Error	536,21	55	9,75		

8.1.4 EMG center frequency

8.1.4.1 Medial Deltoid

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 37,61400				
	SS	Degr. of Freedom	MS	F	p
Intercept	978485,6	1	978485,6	691,6003	0,000000
Error	19807,4	14	1414,8		
COND	0,1	1	0,1	0,0007	0,979315
Error	1876,6	14	134,0		
INTERVAL	689,1	5	137,8	4,5157	0,001263
Error	2136,4	70	30,5		
COND*INTERVAL	157,4	5	31,5	1,3775	0,243301
Error	1600,2	70	22,9		

8.1.4.2 Bicep Femoris

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 30,33117				
	SS	Degr. of Freedom	MS	F	p
Intercept	757814,6	1	757814,6	823,7292	0,000000
Error	11959,7	13	920,0		
COND	448,5	1	448,5	1,0732	0,319111
Error	5433,0	13	417,9		
INTERVAL	257,9	5	51,6	1,7041	0,146177
Error	1967,6	65	30,3		
COND*INTERVAL	173,5	5	34,7	1,2812	0,282795
Error	1760,7	65	27,1		

8.1.4.3 Bicep Brachii

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 14,75160				
	SS	Degr. of Freedom	MS	F	p
Intercept	661012,7	1	661012,7	3037,605	0,000000
Error	3046,5	14	217,6		
COND	103,5	1	103,5	1,555	0,232867
Error	932,0	14	66,6		
INTERVAL	78,1	5	15,6	2,003	0,088790
Error	545,7	70	7,8		
COND*INTERVAL	11,9	5	2,4	0,285	0,920058
Error	584,9	70	8,4		

8.1.4.4 Erector Spinae

Effect	SS	Degr. of Freedom	MS	F	p
	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 34,26349				
Intercept	791417,8	1	791417,8	674,1282	0,000000
Error	12913,9	11	1174,0		
COND	120,3	1	120,3	0,7411	0,407670
Error	1785,0	11	162,3		
INTERVAL	698,2	5	139,6	4,0997	0,003100
Error	1873,3	55	34,1		
COND*INTERVAL	57,0	5	11,4	0,7297	0,604235
Error	858,7	55	15,6		

8.2 HYPOTHESIS TWO: DFSL0-50 vs. DFSL5-45 vs. DFSL15-35.

8.2.1 Rating of Perceived Exertion

8.2.1.1 Medial Deltoid

Effect	SS	Degr. of Freedom	MS	F	p
	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 9,353481				
Intercept	22141,44	1	22141,44	253,0808	0,000000
Error	1224,83	14	87,49		
COND	8,03	2	4,01	0,6606	0,524404
Error	170,11	28	6,08		
INTERVAL	342,25	4	85,56	39,6588	0,000000
Error	120,82	56	2,16		
COND*INTERVAL	3,22	8	0,40	0,9135	0,508162
Error	49,32	112	0,44		

8.2.1.2 Bicep Femoris

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 9,364175 SS	Degr. of Freedom	MS	F	p
Intercept	23482,82	1	23482,82	267,8003	0,000000
Error	1315,32	15	87,69		
COND	75,61	2	37,80	8,4980	0,001191
Error	133,46	30	4,45		
INTERVAL	378,43	4	94,61	36,3645	0,000000
Error	156,10	60	2,60		
COND*INTERVAL	5,02	8	0,63	1,4683	0,175830
Error	51,25	120	0,43		

Tukey HSD test; variable DV_1 (Data Sheet 1 (ARFS))
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = ,42708, df = 120,00

Cell No.	COND	INTERVAL	{1} 7,5000	{2} 8,3750	{3} 9,1250	{4} 10,063	{5} 10,500	{6} 8,2500	{7} 9,3125	{8} 10,125	{9} 10,938	{10} 12,125	{11} 8,4375	{12} 9,5000	{13} 10,500	{14} 11,312	**{15} 12,313**
1	1	1		0,018483	0,000140	0,000140	0,000140	0,091617	0,000140	0,000140	0,000140	0,000140	0,007470	0,000140	0,000140	0,000140	0,000140
2	1	2	0,018483		0,091617	0,000140	0,000140	1,000000	0,007470	0,000140	0,000140	0,000140	1,000000	0,000442	0,000140	0,000140	0,000140
3	1	3	0,000140	0,091617		0,007470	0,000142	0,018483	0,999964	0,002851	0,000140	0,000140	0,178858	0,950260	0,000142	0,000140	0,000140
4	1	4	0,000140	0,000140	0,007470		0,851733	0,000140	0,091617	1,000000	0,018483	0,000140	0,000140	0,495052	0,851733	0,000165	0,000140
5	1	5	0,000140	0,000140	0,000142	0,851733		0,000140	0,000231	0,950260	0,851733	0,000140	0,000140	0,002851	1,000000	0,042849	0,000140
6	2	1	0,091617	1,000000	0,018483	0,000140	0,000140		0,001075	0,000140	0,000140	0,000140	0,999964	0,000165	0,000140	0,000140	0,000140
7	2	2	0,000140	0,007470	0,999964	0,091617	0,000231	0,001075		0,042849	0,000140	0,000140	0,018483	0,999964	0,000231	0,000140	0,000140
8	2	3	0,000140	0,000140	0,002851	1,000000	0,950260	0,000140	0,042849		0,042849	0,000140	0,000140	0,315003	0,950260	0,000231	0,000140
9	2	4	0,000140	0,000140	0,000140	0,018483	0,851733	0,000140	0,000140	0,042849		0,000231	0,000140	0,000140	0,851733	0,950260	0,000142
10	2	5	0,000140	0,000140	0,000140	0,000140	0,000140	0,000140	0,000140	0,000140	0,000231		0,000140	0,000140	0,000140	0,042849	0,999964
11	3	1	0,007470	1,000000	0,178858	0,000140	0,000140	0,999964	0,018483	0,000140	0,000140	0,000140		0,001075	0,000140	0,000140	0,000140
12	3	2	0,000140	0,000442	0,950260	0,495052	0,002851	0,000165	0,999964	0,315003	0,000140	0,000140	0,001075		0,002851	0,000140	0,000140
13	3	3	0,000140	0,000140	0,000142	0,851733	1,000000	0,000140	0,000231	0,950260	0,851733	0,000140	0,000140	0,002851		0,042849	0,000140
14	3	4	0,000140	0,000140	0,000140	0,000165	0,042849	0,000140	0,000140	0,000231	0,950260	0,042849	0,000140	0,000140	0,042849		0,002851
15	3	5	0,000140	0,000140	0,000140	0,000140	0,000140	0,000140	0,000140	0,000140	0,000142	0,999964	0,000140	0,000140	0,000140	0,002851	

8.2.1.3 Bicep Brachii

Effect	Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 8,417593 SS	Degr. of Freedom	MS	F	p
Intercept	17301,02	1	17301,02	244,1720	0,000000
Error	991,98	14	70,86		
COND	18,46	2	9,23	1,8159	0,181333
Error	142,34	28	5,08		
INTERVAL	154,56	4	38,64	31,7713	0,000000
Error	68,11	56	1,22		
COND*INTERVAL	3,76	8	0,47	1,2307	0,287789
Error	42,77	112	0,38		

Tukey HSD test; variable DV_1 (Data Sheet 1 (ARFS))
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = ,38190, df = 112,00

Cell No.	COND	INTERVAL	{1} 7,4000	{2} 8,0000	{3} 8,6667	{4} 8,8667	{5} 9,3333	{6} 7,7333	{7} 8,5333	{8} 9,2667	{9} 9,7333	{10} 10,467	{11} 7,5333	{12} 8,0000	{13} 8,7333	{14} 9,3333	{15} 9,9333
1	1	1		0,343902	0,000152	0,000141	0,000141	0,977063	0,000308	0,000141	0,000141	0,000141	0,999999	0,343902	0,000144	0,000141	0,000141
2	1	2	0,343902		0,188767	0,015909	0,000144	0,997313	0,546706	0,000152	0,000141	0,000141	0,752584	1,000000	0,091668	0,000144	0,000141
3	1	3	0,000152	0,188767		0,999895	0,188767	0,005887	0,999999	0,343902	0,000727	0,000141	0,000308	0,188767	1,000000	0,188767	0,000152
4	1	4	0,000141	0,015909	0,999895		0,752584	0,000308	0,977063	0,903932	0,015909	0,000141	0,000144	0,015909	0,999999	0,752584	0,000727
5	1	5	0,000141	0,000144	0,188767	0,752584		0,000141	0,040012	1,000000	0,903932	0,000308	0,000141	0,000144	0,343902	1,000000	0,343902
6	2	1	0,977063	0,997313	0,005887	0,000308	0,000141		0,040012	0,000141	0,000141	0,000141	0,999895	0,997313	0,002053	0,000141	0,000141
7	2	2	0,000308	0,546706	0,999999	0,977063	0,040012	0,040012		0,091668	0,000185	0,000141	0,002053	0,546706	0,999895	0,040012	0,000142
8	2	3	0,000141	0,000152	0,343902	0,903932	1,000000	0,000141	0,091668		0,752584	0,000185	0,000141	0,000152	0,546706	1,000000	0,188767
9	2	4	0,000141	0,000141	0,000727	0,015909	0,903932	0,000141	0,000185	0,752584		0,091668	0,000141	0,000141	0,002053	0,903932	0,999895
10	2	5	0,000141	0,000141	0,000141	0,000141	0,000308	0,000141	0,000141	0,000185	0,091668		0,000141	0,000141	0,000141	0,000308	0,546706
11	3	1	0,999999	0,752584	0,000308	0,000144	0,000141	0,999895	0,002053	0,000141	0,000141	0,000141		0,752584	0,000185	0,000141	0,000141
12	3	2	0,343902	1,000000	0,188767	0,015909	0,000144	0,997313	0,546706	0,000152	0,000141	0,000141	0,752584		0,091668	0,000144	0,000141
13	3	3	0,000144	0,091668	1,000000	0,999999	0,343902	0,002053	0,999895	0,546706	0,002053	0,000141	0,000185	0,091668		0,343902	0,000185
14	3	4	0,000141	0,000144	0,188767	0,752584	1,000000	0,000141	0,040012	1,000000	0,903932	0,000308	0,000141	0,000144	0,343902		0,343902
15	3	5	0,000141	0,000141	0,000152	0,000727	0,343902	0,000141	0,000142	0,188767	0,999895	0,546706	0,000141	0,000141	0,000185	0,343902	

8.2.1.4 Erector Spinae

Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS))
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 9,411598

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	17721,82	1	17721,82	200,0698	0,000000
Error	885,78	10	88,58		
COND	62,95	2	31,47	3,2205	0,061310
Error	195,45	20	9,77		
INTERVAL	234,61	4	58,65	40,1306	0,000000
Error	58,46	40	1,46		
COND*INTERVAL	2,08	8	0,26	0,7227	0,670947
Error	28,85	80	0,36		

Tukey HSD test; variable DV_1 (Data Sheet 1 (ARFS))
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = ,36061, df = 80,000

Cell No.	COND	INTERVAL	{1} 7,6364	{2} 8,4545	{3} 9,8182	{4} 10,545	{5} 11,182	{6} 9,3636	{7} 10,273	{8} 11,000	{9} 11,818	{10} 12,545	{11} 8,8182	{12} 9,7273	{13} 10,818	{14} 11,455	{15} 12,000
1	1	1		0,111593	0,000146	0,000146	0,000146	0,000147	0,000146	0,000146	0,000146	0,000146	0,001424	0,000146	0,000146	0,000146	0,000146
2	1	2	0,111593		0,000219	0,000146	0,000146	0,043451	0,000146	0,000146	0,000146	0,000146	0,983044	0,000468	0,000146	0,000146	0,000146
3	1	3	0,000146	0,000219		0,247819	0,000219	0,900916	0,900916	0,001424	0,000146	0,000146	0,014987	1,000000	0,014987	0,000147	0,000146
4	1	4	0,000146	0,000146	0,247819		0,462600	0,001424	0,999061	0,900916	0,000468	0,000146	0,000147	0,111593	0,999061	0,043451	0,000161
5	1	5	0,000146	0,000146	0,000219	0,462600		0,000146	0,043451	0,999992	0,462600	0,000219	0,000146	0,000161	0,983044	0,999061	0,111593
6	2	1	0,000147	0,043451	0,900916	0,001424	0,000146		0,043451	0,000147	0,000146	0,000146	0,711113	0,983044	0,000161	0,000146	0,000146
7	2	2	0,000146	0,000146	0,900916	0,999061	0,043451	0,043451		0,247819	0,000149	0,000146	0,000161	0,711113	0,711113	0,001424	0,000147
8	2	3	0,000146	0,000146	0,001424	0,900916	0,999992	0,000147	0,247819		0,111593	0,000149	0,000146	0,000468	0,999992	0,900916	0,014987
9	2	4	0,000146	0,000146	0,000146	0,000468	0,462600	0,000146	0,000149	0,111593		0,247819	0,000146	0,000146	0,014987	0,983044	0,999992
10	2	5	0,000146	0,000146	0,000146	0,000146	0,000219	0,000146	0,000146	0,000149	0,247819		0,000146	0,000146	0,000147	0,004729	0,711113
11	3	1	0,001424	0,983044	0,014987	0,000147	0,000146	0,711113	0,000161	0,000146	0,000146	0,000146		0,043451	0,000146	0,000146	0,000146
12	3	2	0,000146	0,000468	1,000000	0,111593	0,000161	0,983044	0,711113	0,000468	0,000146	0,000146	0,043451		0,004729	0,000147	0,000146
13	3	3	0,000146	0,000146	0,014987	0,999061	0,983044	0,000161	0,711113	0,999992	0,014987	0,000147	0,000146	0,004729		0,462600	0,001424
14	3	4	0,000146	0,000146	0,000147	0,043451	0,999061	0,000146	0,001424	0,900916	0,983044	0,004729	0,000146	0,000147	0,462600		0,711113
15	3	5	0,000146	0,000146	0,000146	0,000161	0,111593	0,000146	0,000147	0,014987	0,999992	0,711113	0,000146	0,000146	0,001424	0,711113	

8.2.2 Maximum Force

8.2.2.1 Medial Deltoid

Effect	Repeated Measures Analysis of Variance (MVC FR) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 30,19047 SS	Degr. of Freedom	MS	F	p
Intercept	1765702	1	1765702	1937,213	0,000000
Error	12761	14	911		
COND	353	2	177	0,724	0,493496
Error	6826	28	244		
INTERVAL	2259	4	565	13,919	0,000000
Error	2272	56	41		
COND*INTERVAL	118	8	15	0,594	0,781483
Error	2795	112	25		

8.2.2.1 Bicep Femoris

Effect	Repeated Measures Analysis of Variance (MVC FR) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 39,25197 SS	Degr. of Freedom	MS	F	p
Intercept	1876402	1	1876402	1217,875	0,000000
Error	23111	15	1541		
COND	1825	2	913	2,329	0,114770
Error	11758	30	392		
INTERVAL	2632	4	658	6,007	0,000392
Error	6574	60	110		
COND*INTERVAL	657	8	82	1,300	0,249923
Error	7584	120	63		

Tukey HSD test; variable DV_1 (MVC FR)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 63,199, df = 120,00

Cell No.	COND	INTERVAL	{1} 92,908	{2} 94,737	{3} 92,001	{4} 91,671	{5} 89,039	{6} 91,981	{7} 88,606	{8} 86,819	{9} 80,571	{10} 79,061	{11} 93,888	{12} 88,920	{13} 87,329	{14} 86,342	**{15} 82,457**
1	1	1		0,999998	1,000000	1,000000	0,987938	1,000000	0,969125	0,687447	0,002285	0,000371	1,000000	0,984061	0,802955	0,566165	0,023025
2	1	2	0,999998		0,999694	0,998887	0,778248	0,999668	0,677425	0,252506	0,000282	0,000151	1,000000	0,751907	0,357778	0,174269	0,002461
3	1	3	1,000000	0,999694		1,000000	0,999257	1,000000	0,996676	0,875118	0,007242	0,001043	0,999997	0,998826	0,940215	0,786476	0,060830
4	1	4	1,000000	0,998887	1,000000		0,999804	1,000000	0,998888	0,920660	0,010801	0,001595	0,999975	0,999674	0,966636	0,850411	0,084041
5	1	5	0,987938	0,778248	0,999257	0,999804		0,999309	1,000000	0,999974	0,163999	0,038363	0,921121	1,000000	0,999999	0,999740	0,562096
6	2	1	1,000000	0,999668	1,000000	1,000000	0,999309		0,996865	0,878157	0,007415	0,001068	0,999996	0,998903	0,942082	0,790552	0,062023
7	2	2	0,969125	0,677425	0,996676	0,998888	1,000000	0,996865		0,999998	0,231375	0,060134	0,858713	1,000000	1,000000	0,999967	0,672691
8	2	3	0,687447	0,252506	0,875118	0,920660	0,999974	0,878157	0,999998		0,648013	0,281281	0,438107	0,999987	1,000000	1,000000	0,965354
9	2	4	0,002285	0,000282	0,007242	0,010801	0,163999	0,007415	0,231375	0,648013		1,000000	0,000666	0,180903	0,516673	0,762175	0,999997
10	2	5	0,000371	0,000151	0,001043	0,001595	0,038363	0,001068	0,060134	0,281281	1,000000		0,000188	0,043530	0,191611	0,384840	0,996560
11	3	1	1,000000	1,000000	0,999997	0,999975	0,921121	0,999996	0,858713	0,438107	0,000666	0,000188		0,906193	0,568219	0,327116	0,007229
12	3	2	0,984061	0,751907	0,998826	0,999674	1,000000	0,998903	1,000000	0,999987	0,180903	0,043530	0,906193		1,000000	0,999846	0,592957
13	3	3	0,802955	0,357778	0,940215	0,966636	0,999999	0,942082	1,000000	1,000000	0,516673	0,191611	0,568219	1,000000		1,000000	0,918297
14	3	4	0,566165	0,174269	0,786476	0,850411	0,999740	0,790552	0,999967	1,000000	0,762175	0,384840	0,327116	0,999846	1,000000		0,987476
15	3	5	0,023025	0,002461	0,060830	0,084041	0,562096	0,062023	0,672691	0,965354	0,999997	0,996560	0,007229	0,592957	0,918297	0,987476	

8.2.2.3 Bicep Brachii

Repeated Measures Analysis of Variance (MVC FR)
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 17,47736

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	1690461	1	1690461	5534,182	0,000000
Error	3971	13	305		
COND	950	2	475	2,253	0,125177
Error	5482	26	211		
INTERVAL	1221	4	305	14,921	0,000000
Error	1064	52	20		
COND*INTERVAL	361	8	45	1,705	0,105799
Error	2752	104	26		

Tukey HSD test; variable DV_1 (MVC FR)
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 26,460, df = 104,00

Cell No.	COND	INTERVAL	{1} 94,728	{2} 89,350	{3} 87,948	{4} 90,545	{5} 89,150	{6} 92,281	{7} 88,041	{8} 85,624	{9} 85,837	{10} 82,519	{11} 94,041	{12} 94,466	{13} 92,861	{14} 91,056	{15} 87,365
1	1	1		0,281749	0,048253	0,697506	0,228622	0,994825	0,055310	0,000895	0,001317	0,000140	1,000000	1,000000	0,999729	0,853128	0,019399
2	1	2	0,281749		0,999991	0,999999	1,000000	0,972402	0,999996	0,839597	0,890127	0,044755	0,511428	0,362056	0,890278	0,999905	0,999458
3	1	3	0,048253	0,999991		0,990732	0,999999	0,643816	1,000000	0,996933	0,998907	0,267614	0,124631	0,070517	0,431061	0,955420	1,000000
4	1	4	0,697506	0,999999	0,990732		0,999992	0,999883	0,993483	0,428346	0,505125	0,006280	0,893696	0,783951	0,997036	1,000000	0,946501
5	1	5	0,228622	1,000000	0,999999	0,999992		0,952617	1,000000	0,887313	0,927243	0,060003	0,439039	0,299934	0,843241	0,999657	0,999838
6	2	1	0,994825	0,972402	0,643816	0,999883	0,952617		0,677261	0,057797	0,078133	0,000327	0,999863	0,998422	1,000000	0,999998	0,429967
7	2	2	0,055310	0,999996	1,000000	0,993483	1,000000	0,677261		0,995428	0,998267	0,242859	0,140008	0,080245	0,464166	0,965135	1,000000
8	2	3	0,000895	0,839597	0,996933	0,428346	0,887313	0,057797	0,995428		1,000000	0,955659	0,003103	0,001438	0,023805	0,267048	0,999880
9	2	4	0,001317	0,890127	0,998907	0,505125	0,927243	0,078133	0,998267	1,000000		0,926350	0,004599	0,002109	0,033322	0,329446	0,999975
10	2	5	0,000140	0,044755	0,267614	0,006280	0,060003	0,000327	0,242859	0,955659	0,926350		0,000142	0,000140	0,000193	0,002492	0,454969
11	3	1	1,000000	0,511428	0,124631	0,893696	0,439039	0,999863	0,140008	0,003103	0,004599	0,000142		1,000000	0,999999	0,967864	0,056249
12	3	2	1,000000	0,362056	0,070517	0,783951	0,299934	0,998422	0,080245	0,001438	0,002109	0,000140	1,000000		0,999954	0,910370	0,029550
13	3	3	0,999729	0,890278	0,431061	0,997036	0,843241	1,000000	0,464166	0,023805	0,033322	0,000193	0,999999	0,999954		0,999815	0,249521
14	3	4	0,853128	0,999905	0,955420	1,000000	0,999657	0,999998	0,965135	0,267048	0,329446	0,002492	0,967864	0,910370	0,999815		0,848595
15	3	5	0,019399	0,999458	1,000000	0,946501	0,999838	0,429967	1,000000	0,999880	0,999975	0,454969	0,056249	0,029550	0,249521	0,848595	

8.2.2.4 Erector Spinae

Repeated Measures Analysis of Variance (MVC FR)
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 62,46559

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	1481109	1	1481109	379,5816	0,000000
Error	39020	10	3902		
R1	88	2	44	0,0514	0,950034
Error	17211	20	861		
R2	1785	4	446	9,6516	0,000015
Error	1850	40	46		
R1*R2	1170	8	146	1,7052	0,109906
Error	6864	80	86		

8.2.3 EMG REFERENCE TASK

8.2.3.1 Medial Deltoid

Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS))
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 15,0425

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	44860,21	1	44860,21	198,2537	0,000000
Error	2941,60	13	226,28		
COND	81,40	2	40,70	1,1670	0,327064
Error	906,70	26	34,87		
INTERVAL	763,25	5	152,65	16,7293	0,000000
Error	593,11	65	9,12		
COND*INTERVAL	35,29	10	3,53	0,4347	0,927156
Error	1055,24	130	8,12		

8.2.3.2 Bicep Femoris

Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS))
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 15,30426

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	84191,90	1	84191,90	359,4556	0,000000
Error	3279,09	14	234,22		
R1	732,26	2	366,13	2,5327	0,097492
Error	4047,66	28	144,56		
R2	130,44	5	26,09	2,4113	0,044737
Error	757,32	70	10,82		
R1*R2	116,45	10	11,65	1,0113	0,437017
Error	1612,14	140	11,52		

Tukey HSD test; variable DV_1 (Data Sheet 1 (ARFS))
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 11,515, df = 140,00

Cell No.	COND	INTERVAL	{1} 16,567	{2} 16,482	{3} 15,360	{4} 15,891	{5} 15,971	{6} 15,353	{7} 18,110	{8} 17,182	{9} 17,739	{10} 16,051	{11} 18,609	{12} 15,272	{13} 21,802	{14} 20,308	{15} 18,227	{16} 19,359	{17} 19,624	**{18} 19,947**
1	1	1		1,000000	0,999962	1,000000	1,000000	0,999958	0,998974	1,000000	0,999975	1,000000	0,975592	0,999898	0,003179	0,190874	0,997486	0,717274	0,556251	0,361130
2	1	2	1,000000		0,999987	1,000000	1,000000	0,999985	0,997997	1,000000	0,999932	1,000000	0,963775	0,999961	0,002369	0,160404	0,995459	0,666929	0,502539	0,314964
3	1	3	0,999962	0,999987		1,000000	1,000000	1,000000	0,740885	0,992580	0,904588	1,000000	0,436812	1,000000	0,000062	0,008180	0,673534	0,110067	0,058222	0,024316
4	1	4	1,000000	1,000000	1,000000		1,000000	1,000000	0,946757	0,999902	0,991317	1,000000	0,758171	1,000000	0,000287	0,038926	0,917710	0,313028	0,193787	0,096644
5	1	5	1,000000	1,000000	1,000000	1,000000		1,000000	0,961846	0,999960	0,994706	1,000000	0,799416	1,000000	0,000381	0,048162	0,938604	0,355984	0,226101	0,116090
6	1	6	0,999958	0,999985	1,000000	1,000000	1,000000		0,736784	0,992240	0,902221	1,000000	0,432366	1,000000	0,000061	0,007990	0,669094	0,108230	0,057134	0,023807
7	2	1	0,998974	0,997997	0,740885	0,946757	0,961846	0,736784		0,999999	1,000000	0,973425	1,000000	0,690448	0,209787	0,951139	1,000000	0,999938	0,999193	0,991916
8	2	2	1,000000	1,000000	0,992580	0,999902	0,999960	0,992240	0,999999		1,000000	0,999985	0,999625	0,987613	0,022109	0,512783	0,999995	0,955189	0,883624	0,732992
9	2	3	0,999975	0,999932	0,904588	0,991317	0,994706	0,902221	1,000000	1,000000		0,996900	1,000000	0,873890	0,095093	0,832091	1,000000	0,998118	0,989317	0,949255
10	2	4	1,000000	1,000000	1,000000	1,000000	1,000000	1,000000	0,973425	0,999985	0,996900		0,836622	1,000000	0,000508	0,059157	0,955350	0,401349	0,261618	0,138360
11	2	5	0,975592	0,963775	0,436812	0,758171	0,799416	0,432366	1,000000	0,999625	1,000000	0,836622		0,384918	0,470780	0,996672	1,000000	1,000000	0,999997	0,999842
12	2	6	0,999898	0,999961	1,000000	1,000000	1,000000	1,000000	0,690448	0,987613	0,873890	1,000000	0,384918		0,000053	0,006168	0,619696	0,089721	0,046335	0,018834
13	3	1	0,003179	0,002369	0,000062	0,000287	0,000381	0,000061	0,209787	0,022109	0,095093	0,000508	0,470780	0,000053		0,999316	0,260469	0,883046	0,954889	0,990954
14	3	2	0,190874	0,160404	0,008180	0,038926	0,048162	0,007990	0,951139	0,512783	0,832091	0,059157	0,996672	0,006168	0,999316		0,970563	0,999999	1,000000	1,000000
15	3	3	0,997486	0,995459	0,673534	0,917710	0,938604	0,669094	1,000000	0,999995	1,000000	0,955350	1,000000	0,619696	0,260469	0,970563		0,999985	0,999716	0,996158
16	3	4	0,717274	0,666929	0,110067	0,313028	0,355984	0,108230	0,999938	0,955189	0,998118	0,401349	1,000000	0,089721	0,883046	0,999999	0,999985		1,000000	1,000000
17	3	5	0,556251	0,502539	0,058222	0,193787	0,226101	0,057134	0,999193	0,883624	0,989317	0,261618	0,999997	0,046335	0,954889	1,000000	0,999716	1,000000		1,000000
18	3	6	0,361130	0,314964	0,024316	0,096644	0,116090	0,023807	0,991916	0,732992	0,949255	0,138360	0,999842	0,018834	0,990954	1,000000	0,996158	1,000000	1,000000	

8.2.3.3 Bicep Brachii

Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS))
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 13,28818

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	63832,36	1	63832,36	361,5009	0,000000
Error	2295,49	13	176,58		
COND	444,83	2	222,41	1,3751	0,270596
Error	4205,31	26	161,74		
INTERVAL	84,25	5	16,85	1,0226	0,411790
Error	1071,01	65	16,48		
COND*INTERVAL	172,14	10	17,21	1,2379	0,273022
Error	1807,85	130	13,91		

Tukey HSD test; variable DV_1 (Data Sheet 1 (ARFS))
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 13,907, df = 130,00

Cell No.	COND	INTERVAL	{1} 17,751	{2} 16,964	{3} 17,505	{4} 15,934	{5} 17,509	{6} 20,479	{7} 15,815	{8} 14,368	{9} 14,200	{10} 13,965	{11} 13,545	{12} 15,071	{13} 14,250	{14} 15,621	{15} 15,174	{16} 16,764	{17} 15,590	**{18} 15,974**
1	1	1		1,000000	1,000000	0,998415	1,000000	0,898323	0,996602	0,607970	0,515076	0,390234	0,207857	0,911946	0,542922	0,990028	0,936439	1,000000	0,988335	0,998803
2	1	2	1,000000		1,000000	0,999999	1,000000	0,535033	0,999997	0,932144	0,887440	0,800172	0,588041	0,997396	0,902422	0,999972	0,998684	1,000000	0,999961	1,000000
3	1	3	1,000000	1,000000		0,999755	1,000000	0,810957	0,999360	0,736394	0,649616	0,521051	0,306491	0,961720	0,676422	0,997534	0,974675	1,000000	0,996997	0,999828
4	1	4	0,998415	0,999999	0,999755		0,999748	0,110882	1,000000	0,999767	0,999117	0,995875	0,967998	1,000000	0,999395	1,000000	1,000000	1,000000	1,000000	1,000000
5	1	5	1,000000	1,000000	1,000000	0,999748		0,812273	0,999345	0,734855	0,647930	0,519321	0,305078	0,961259	0,674771	0,997484	0,974338	1,000000	0,996939	0,999823
6	1	6	0,898323	0,535033	0,810957	0,110882	0,812273		0,086978	0,001977	0,001170	0,000556	0,000153	0,014877	0,001371	0,057144	0,019464	0,426709	0,053241	0,120169
7	2	1	0,996602	0,999997	0,999360	1,000000	0,999345	0,086978		0,999921	0,999648	0,998032	0,980621	1,000000	0,999769	1,000000	1,000000	1,000000	1,000000	1,000000
8	2	2	0,607970	0,932144	0,736394	0,999767	0,734855	0,001977	0,999921		1,000000	1,000000	1,000000	1,000000	1,000000	0,999990	1,000000	0,966965	0,999993	0,999673
9	2	3	0,515076	0,887440	0,649616	0,999117	0,647930	0,001170	0,999648	1,000000		1,000000	1,000000	1,000000	1,000000	0,999938	1,000000	0,938867	0,999955	0,998817
10	2	4	0,390234	0,800172	0,521051	0,995875	0,519321	0,000556	0,998032	1,000000	1,000000		1,000000	0,999998	1,000000	0,999512	0,999994	0,876436	0,999620	0,994780
11	2	5	0,207857	0,588041	0,306491	0,967998	0,305078	0,000153	0,980621	1,000000	1,000000	1,000000		0,999836	1,000000	0,992477	0,999606	0,695379	0,993652	0,962476
12	2	6	0,911946	0,997396	0,961720	1,000000	0,961259	0,014877	1,000000	1,000000	1,000000	0,999998	0,999836		1,000000	1,000000	1,000000	0,999349	1,000000	1,000000
13	3	1	0,542922	0,902422	0,676422	0,999395	0,674771	0,001371	0,999769	1,000000	1,000000	1,000000	1,000000	1,000000		0,999963	1,000000	0,948635	0,999973	0,999178
14	3	2	0,990028	0,999972	0,997534	1,000000	0,997484	0,057144	1,000000	0,999990	0,999938	0,999512	0,992477	1,000000	0,999963		1,000000	0,999997	1,000000	1,000000
15	3	3	0,936439	0,998684	0,974675	1,000000	0,974338	0,019464	1,000000	1,000000	1,000000	0,999994	0,999606	1,000000	1,000000	1,000000		0,999714	1,000000	1,000000
16	3	4	1,000000	1,000000	1,000000	1,000000	1,000000	0,426709	1,000000	0,966965	0,938867	0,876436	0,695379	0,999349	0,948635	0,999997	0,999714		0,999996	1,000000
17	3	5	0,988335	0,999961	0,996997	1,000000	0,996939	0,053241	1,000000	0,999993	0,999955	0,999620	0,993652	1,000000	0,999973	1,000000	1,000000	0,999996		1,000000
18	3	6	0,998803	1,000000	0,999828	1,000000	0,999823	0,120169	1,000000	0,999673	0,998817	0,994780	0,962476	1,000000	0,999178	1,000000	1,000000	1,000000	1,000000	

8.2.3.4 Erector Spinae

Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS))
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 42,66395

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	121396,3	1	121396,3	66,69349	0,000019
Error	16381,9	9	1820,2		
R1	234,4	2	117,2	0,53844	0,592773
Error	3917,3	18	217,6		
R2	324,5	5	64,9	2,77715	0,028640
Error	1051,7	45	23,4		
R1*R2	400,8	10	40,1	1,24980	0,271122
Error	2886,4	90	32,1		

8.2.4 EMG center frequency

8.2.4.1 Medial Deltoid

Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS))
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 46,83374

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	1338867	1	1338867	610,4072	0,000000
Error	28514	13	2193		
COND	317	2	158	2,3764	0,112763
Error	1732	26	67		
INTERVAL	1490	5	298	6,0590	0,000116
Error	3197	65	49		
COND*INTERVAL	244	10	24	0,9352	0,503395
Error	3398	130	26		

Tukey HSD test; variable DV_1 (Data Sheet 1 (ARFS))
Approximate Probabilities for Post Hoc Tests
Error: Within MSE = 26,137, df = 130,00

Cell No	COND	INTERVAL	{1} 78,243	{2} 76,443	{3} 71,450	{4} 73,286	{5} 72,964	{6} 70,950	{7} 75,586	{8} 74,457	{9} 69,579	{10} 71,721	{11} 70,750	{12} 65,857	{13} 75,821	{14} 76,150	{15} 71,171	{16} 71,957	{17} 72,621	{18} 73,014
1	1	1		0,999980	0,045845	0,479697	0,358024	0,018743	0,996558	0,888480	0,001031	0,071462	0,012767	0,000036	0,998886	0,999835	0,028194	0,102466	0,247123	0,376022
2	1	2	0,999980		0,465599	0,977545	0,944319	0,285959	1,000000	0,999920	0,040589	0,574277	0,227072	0,000041	1,000000	1,000000	0,360570	0,667675	0,880260	0,951020
3	1	3	0,045845	0,465599		0,999973	0,999998	1,000000	0,792548	0,986349	0,999965	1,000000	1,000000	0,255452	0,710882	0,582899	1,000000	1,000000	1,000000	0,999997
4	1	4	0,479697	0,977545	0,999973		1,000000	0,999295	0,999422	1,000000	0,905275	0,999997	0,998031	0,014467	0,998031	0,991912	0,999810	1,000000	1,000000	1,000000
5	1	5	0,358024	0,944319	0,999998	1,000000		0,999902	0,997066	0,999999	0,956279	1,000000	0,999648	0,026434	0,992131	0,975452	0,999981	1,000000	1,000000	1,000000
6	1	6	0,018743	0,285959	1,000000	0,999295	0,999902		0,608667	0,940205	1,000000	1,000000	1,000000	0,426763	0,513886	0,386486	1,000000	1,000000	0,999993	0,999863
7	2	1	0,996558	1,000000	0,792548	0,999422	0,997066	0,608667		1,000000	0,151975	0,869912	0,528232	0,000100	1,000000	1,000000	0,694903	0,920313	0,988271	0,997669
8	2	2	0,888480	0,999920	0,986349	1,000000	0,999999	0,940205	1,000000		0,511018	0,995173	0,905275	0,001195	1,000000	0,999992	0,966910	0,998345	0,999973	0,999999
9	2	3	0,001031	0,040589	0,999965	0,905275	0,956279	1,000000	0,151975	0,511018		0,999772	1,000000	0,902353	0,109119	0,066002	0,999997	0,999111	0,984560	0,950101
10	2	4	0,071462	0,574277	1,000000	0,999997	1,000000	1,000000	0,869912	0,995173	0,999772		1,000000	0,183476	0,803839	0,689514	1,000000	1,000000	1,000000	1,000000
11	2	5	0,012767	0,227072	1,000000	0,998031	0,999648	1,000000	0,528232	0,905275	1,000000	1,000000		0,505297	0,434996	0,316116	1,000000	1,000000	0,999965	0,999528
12	2	6	0,000036	0,000041	0,255452	0,014467	0,026434	0,426763	0,000100	0,001195	0,902353	0,183476	0,505297		0,000069	0,000048	0,345425	0,133783	0,048106	0,024120
13	3	1	0,998886	1,000000	0,710882	0,998031	0,992131	0,513886	1,000000	1,000000	0,109119	0,803839	0,434996	0,000069		1,000000	0,602958	0,869912	0,974349	0,993534
14	3	2	0,999835	1,000000	0,582899	0,991912	0,975452	0,386486	1,000000	0,999992	0,066002	0,689514	0,316116	0,000048	1,000000		0,471226	0,773843	0,936982	0,979022
15	3	3	0,028194	0,360570	1,000000	0,999810	0,999981	1,000000	0,694903	0,966910	0,999997	1,000000	1,000000	0,345425	0,602958	0,471226		1,000000	0,999999	0,999972
16	3	4	0,102466	0,667675	1,000000	1,000000	1,000000	1,000000	0,920313	0,998345	0,999111	1,000000	1,000000	0,133783	0,869912	0,773843	1,000000		1,000000	1,000000
17	3	5	0,247123	0,880260	1,000000	1,000000	1,000000	0,999993	0,988271	0,999973	0,984560	1,000000	0,999965	0,048106	0,974349	0,936982	0,999999	1,000000		1,000000
18	3	6	0,376022	0,951020	0,999997	1,000000	1,000000	0,999863	0,997669	0,999999	0,950101	1,000000	0,999528	0,024120	0,993534	0,979022	0,999972	1,000000	1,000000	

8.2.4.2 Bicep Femoris

Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS))
Sigma-restricted parameterization
Effective hypothesis decomposition; Std. Error of Estimate: 34,49957

Effect	SS	Degr. of Freedom	MS	F	p
Intercept	1246767	1	1246767	1047,509	0,000000
Error	16663	14	1190		
R1	1031	2	516	1,516	0,237132
Error	9526	28	340		
R2	222	5	44	0,836	0,528306
Error	3723	70	53		
R1*R2	821	10	82	1,929	0,046002
Error	5961	140	43		

8.2.4.3 Bicep Brachii

Effect	SS	Degr. of Freedom	MS	F	p
Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 17,59883					
Intercept	885895,4	1	885895,4	2860,320	0,000000
Error	3716,6	12	309,7		
R1	38,9	2	19,4	0,165	0,849255
Error	2835,0	24	118,1		
R2	18,9	5	3,8	0,256	0,935359
Error	889,3	60	14,8		
R1*R2	95,6	10	9,6	0,686	0,735757
Error	1672,8	120	13,9		

8.2.4.4 Erector Spinae

Effect	SS	Degr. of Freedom	MS	F	p
Repeated Measures Analysis of Variance (Data Sheet 1 (ARFS)) Sigma-restricted parameterization Effective hypothesis decomposition; Std. Error of Estimate: 34,4459					
Intercept	906187,6	1	906187,6	763,7356	0,000000
Error	10678,7	9	1186,5		
R1	196,9	2	98,4	0,2146	0,808937
Error	8257,5	18	458,7		
R2	436,1	5	87,2	4,6374	0,001693
Error	846,3	45	18,8		
R1*R2	55,1	10	5,5	0,2446	0,990597
Error	2026,4	90	22,5		