Use of inventory control theory and multi-objective optimization to model work-rest scheduling

by

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A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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Fall, 2022

DEDICATION

I want to dedicate my work to my parents, husband, brother, and daughter. I want to tell them they were with me while I was working on completing this work. My parents, thank you for sending me 8000 miles away to obtain this prestigious North American degree so that I can contribute to science. I will never forget the continuous support from my life partner, Kapot Kallol Tarafder, who sacrificed his work so that I could avail time to work on this long-term project. Lastly, I also want to thank my friends (Samira and Johra) in Ames, Iowa, without support from whom I could not complete the data collection.

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ACKNOWLEDGMENTS

I would like to thank my co-major professors Dr. Mirka, and Dr Hallbeck, my committee members Dr. Min, Dr. Gillette, and Dr. De Brabanter, for their guidance and support throughout the course of this research.

In addition, I would also like to thank my friends, colleagues, the department faculty, and staff for making my time at Iowa State University a wonderful experience. I want to also offer my appreciation to those who were willing to participate in my surveys and observations, without whom, this thesis would not have been possible.

ABSTRACT

The research aims to study the effect of varied work-rest scheduling strategies on muscle fatigue development and worker performance. An inventory control theory modeling approach was used to model the level of muscle fatigue under different break schedule strategies and a multi-criteria optimization formulation was employed to simultaneously consider the competing interests of reducing muscle fatigue and increasing worker productivity to determine an optimum number of breaks. Several published preliminary studies prepared the foundation for this modeling approach. The first study (Chapter 2) was conducted to study the effect of breaks on the slope of median frequency of EMG signal (a standard measure of muscle fatigue development). Downward shifts in the median frequency (MDF) of the power spectrum of an electromyographic signal is often used to assess muscular fatigue. How the change in the MDF is affected by repetitive bouts of exertions–with intervening rest breaks- is not well understood. It was hypothesized that repetitive bouts of a fatiguing, isometric exertion, separated by periods of rest, would have cumulative effect (across bouts) on the slope of the decline of the median frequency, with an expectation of an increasing rate of decline in subsequent bouts. To test this hypothesis, 24 participants performed four bouts of an isometric (15% MVC) elbow flexion exertion. Each exertion lasted for four minutes and then a 15-minute break was provided between bouts. Surface electromyography was used to capture the activity of the biceps brachii at twenty-second intervals during the exertions. The median frequency of each of these five-second collection periods was calculated, as was the slope across the four-minute bout. The results showed that there were no statistically significant differences in the rate of decline in the median frequency across bouts. The study helped to interpret median frequency as a measure of muscular fatigue in an ergonomic intervention. The results showed no effect of break on median

frequency slope, indicating that break helped them in developing no long-term fatigue/break helped them to recover and imposed the importance of finding the right ratio of work to break. Based on these results the next study (Chapter 3) was conducted. This study focused on neck muscle fatigue replicating the real-life work-environment where prolonged static neck posture was adopted to perform a task. In real-life, sustained non-neutral postures of the head/neck are related to transient neck discomfort and longer-term disorders of the neck. From the previous study (Chapter 2), we obtained the knowledge that periodic breaks did not increase the slope of median frequency decrease, that is, the fatigue was not carried over to second bout and subjects were recovering. However, the ideal frequency and duration of breaks was yet to be determined. Therefore, the next study (Chapter 3) aimed to quantify the effects of three work-rest strategies on fatigue development. Participants maintained a 45-degree neck flexion posture for a total of 60 minutes and were provided three minutes of rest distributed in different ways throughout the experiment [LONG (one, three-minute break), MEDIUM (two, 1.5-minute breaks), or SHORT (five, 36-second breaks)]. Surface electromyography data were collected bilaterally from the neck extensors and trapezius. Subjective discomfort/fatigue ratings were also gathered. Results of the analysis of the EMG data revealed that the SHORT condition did not show increased EMG activity, while LONG [21%] and MEDIUM [10%] did ($p<0.05$), providing objective data supporting the guidance of short, frequent breaks to alleviate muscular fatigue. The study helped us to find the similarity between trend of muscle fatigue-recovery with production and delivery trend in inventory control theory. The study also shed light on the fact that frequent work-rest bouts reduced muscle fatigue, but it also raised concerns regarding the impact on productivity of the workers. The optimum number of breaks based on both muscle fatigue and performance are yet to be determined. The subjects in this previous study (Chapter 3) performed a task a game-based task and performance was not quantified. The fourth chapter was designed to determine the optimum number of breaks that can minimize fatigue and maximize performance simultaneously. An optimum number of breaks would reduce the negative impact of muscle fatigue without impacting performance. To develop this model, an analogy between inventory control model and fatigue development model was created. Finding optimum production quantity in an inventory control model helped to create the idea of finding optimum number of breaks in this work-rest scheduling model. The work with a laparoscopic simulator was chosen as a work task. To develop this model, 17 subjects were asked to come to practice with the laparoscopic simulator and learn how to operate laparoscopic instruments. When they were proficient, they participated in five experimental sessions (each consisting of 23 minutes of work with a laparoscopic simulator) for five different conditions. Five sessions have five different work-rest schedules as conditions. These conditions aimed to observe the effect of a work-rest schedule on muscle fatigue development and performance. An equation of fatigue vs the number of breaks and the equation of performance vs the number of breaks were quantified. The resulting equations showed conflicting relations with the number of breaks. If the number of breaks was increased, muscle fatigue decreased. On the other hand, performance increased with increasing number of breaks and then started decreasing. These two conflicting equations developed based on inventory control theory model, formed a multi-objective problem that returned the optimum number of breaks. Multi-objective optimization problem can be solved in different ways. Weighted average method was applied to solve this problem. Each optimum number of breaks for different weights (between 0 to 1) is a pareto optimal solution. In this study, Entropy Weight Method (EWM) was applied to determine the value of weight without the influence of personal opinion. The method found a weight of 0.57 which was applied to the objective function for muscle fatigue and a weight of 0.43 was applied to the performance. For a weight of 0.57, the model output suggested 11.1 breaks during 23 minutes of high intensity work. The model also expanded to explore the effects of inter-individual variability on these predictions by finding the number of breaks for different percentile value of muscle fatigue and performance. The result suggested that with a very low fatigue profile and performance score, no break is needed. When high performance is expected from a high fatigue profile person, then number of breaks should be around 14 breaks. After 14 breaks, performance started to decrease significantly, and number of breaks should not exceed 14, if both performance and fatigue are expected to be optimized during a 23-minute period.

CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Neck and shoulder-related Musculoskeletal Disorders (MSDs) are prevalent among blue- and white-collar workers. Many task-related factors can lead to neck and shoulder-related pain and musculoskeletal disorders. Jobs that require repetitive exertion of force or prolonged static posture can result in MSDs in industrial workers as well as surgeons (Baker et al., 2018; Flint et al., 2017; Mclean et al., 2000; Tremblay et al., 2010). Through the application of electromyography on the right and left trapezius, deltoid, and erector spinae muscles, Luttmann et al. (1996) showed that long-term surgeries can create muscle fatigue and it has been hypothesized that muscle fatigue can lead to musculoskeletal disorders (Kumar, 2001). Musculoskeletal disorders can account for the cause of occupational injuries in 29-35% of cases in the United States. MSDs are also responsible for incurring costs both in the form of direct and indirect costs in addition to causing injuries. Costs are incurred not only in the form of days lost but also in the form of loss of productivity. Moreover, MSDs can lead to permanent disabilities, which require hiring and training new employees. New hiring and training require financial investments, which can be termed as expenses for industries.

Industries facing neck and shoulder-related MSDs include manufacturing industries, health care industries, textile industries, etc. Occupations like nursing aides, orderlies, manual laborers, material handling workers, drivers encounter MSDs at a point in their lives, affecting their productivity and sometimes ending their career (Limb and Rockall, 2020). There is already a worldwide shortage of health care workers such as midwives, nurses, and physicians in the health care industry (Long et al., 2012). Data shows that the average age of healthcare workers above middle age (between 45-65 years old) is 56% in Australia (Australian Institute of Health and Welfare. 2009), 21-24% in Canada (Canadian Institute for Health Information, 2007b), 65% in the United Kingdom (Nursing Midwifery Council, 2008). The aging of the workforce is an indication that people are less willing to enter health industries nowadays. Facing MSDs is one of the reasons for which people are not very keen to join the health care sector (Fochsen et al., 2006). The scenario is also true for surgeons who are performing minimally invasive surgery (MIS) (Aitchison et al., 2016; Park et al., 2010; Cavanagh et al., 2012). Over 48% of general surgeons reported musculoskeletal pain of 3 or higher on a scale of 10. About 16% of the surgeons who completed the survey preferred to leave practicing surgeries, and 26% of them reported short-term disability due to MSDs (Wells et al., 2019). The work of surgeons can lead to musculoskeletal discomfort after they perform in relatively static postures. Awkward static postures often increase the force demand exerted by muscle which leads to increased muscle fatigue (Park et al., 2010; Choi, 2012). Muscle fatigue can also affect the cognitive performance of laparoscopic surgeons. Stephenson et al., (2019) recruited 26 participants and asked them to perform shoulder fatiguing task (shoulder flexion at an angle of 70˚-90˚with wrist pronated and elbow extended until volitional failure). This task has some similarities with the task performed by the surgeons in laparoscopic surgery. The muscles that they considered were deltoid and descending trapezius. They also performed dual task cognitive performance check on the participants. The study found that performing laparoscopic surgery can induce shoulder muscle fatigue which resulted in induced tracking error. Moreover, tracking velocity and response time were also affected significantly, indicating a reduction in performance. Therefore, the implications of ergonomics are essential to reduce the effect of the workplace factors that can lead to MSDs.

The application of breaks during work as an ergonomic intervention has been suggested by researchers (Hallbeck et al., 2017; Sarker et al., 2020; Vijendren et al., 2018). However, surgeons are often reluctant to take microbreaks as they consider these types of administrative interventions as distracting and disruptive (Scarlet and Dreesen, 2020). They often sacrifice their comfort to ensure successful surgeries and the welfare of the patient. There is a contradiction in the benefits of microbreaks during surgical tasks. Too frequent breaks can reduce the performance of the surgeons in the workplace setting, while too infrequent breaks can lead to muscular fatigue. Therefore, this dissertation proposal aims to obtain the optimum number of breaks from a multi-objective optimization model that will consider both muscle fatigue and work performance for a particular work setting. The multi-objective optimization model will have two contradictory objective functions. We will also employ the analogy of inventory control theory modeling from logistic management to model the muscle fatigue development and recovery profile. As we performed the experiment to study the effect of work-rest schedule on muscle fatigue development, we learned that muscle fatigue development-recovery followed the same trend as in the inventory control theory model. For the sake of illustration, the main study (Chapter 4) considers the task of a laparoscopic simulator. It takes shoulder muscles (anterior, medial, and posterior deltoid muscles) as an affected muscle group due to prolonged static work during laparoscopic surgeries. We begin with an overview of shoulder muscle anatomy, muscle physiology, muscle fatigue, and a summary of inventory control theory modeling.

1.2 Background

1.2.1 Shoulder Muscle Anatomy, Physiology, and Fatigue

1.2.1.1 Anatomy of Shoulder Muscles

Occupational injuries are a concern among surgeons who perform minimally invasive surgery (MIS) regularly (Park et al., 2010). Laparoscopic surgery is seen as limiting the degrees of freedom of the surgeons, often resulting in static and awkward postures maintained for a prolonged time (Aitchison et al., 2016), leading to muscle fatigue of the involved muscle. The ideal position for laparoscopic surgeons is a slightly abducted arm (Berguer et al., 1997), rotated inwards at the shoulder (Szeto et al., 2012). Such static prolonged posture can cause fatigue in shoulder muscles (Aitchison et al., 2016; Berguer et al. 1997; Park et al., 2010; Szeto et al., 2012). In this proposal, manual laparoscopic surgery was simulated in a laboratory setting. Therefore, a brief description of shoulder muscle anatomy is an integral part of this proposal.

The shoulder has three major bones namely scapula, humerus, clavicle, and multiple muscles that span the joint. Among these muscles, eight muscles are attached to these three bones and create the main shoulder joint titled as glenohumeral joint. The muscles of the shoulder not only help to stabilize the joint but also take active part in arm movement, shoulder flexion, and abduction. The deltoid muscle is a major shoulder muscle that works in these movements. It is a thick, curved triangular shoulder muscle. Its shape looks like the Greek letter delta, and it covers the glenohumeral joint, providing shoulder a round shape. Deltoid muscle can be identified when the arm is abducted against a resistance. The three prominent borders of the deltoid muscle are anterior, medial, and posterior. Origins of anterior, medial, and posterior parts of the deltoid muscle are respectively the lateral third of the clavicle, superior surface of the acromion, and the lower edge of the crest of the scapular spine. The shoulder's normal rounded contour is produced by the deltoid covering the lateral aspect of the greater tubercle of the humerus. Deltoid consequently descends vertically to its humeral attachment. The two nerves C5 and C6 innervate this muscle (Gray, 2016).

Electromyography (EMG) data is a measure of muscle activity and shows that the deltoid muscle is responsible for arm and shoulder movement. The electrical signals from EMG data show that anterior fibers assist the pectoralis major muscle in drawing the arm forwards and rotating it medially. Drawing the arm forward and rotating it medially can be termed as an internal rotation of arms. It is an action seen in laparoscopic surgery. On the other hand, the posterior deltoid acts as an external rotator and work with latissimus dorsi and teres major in pulling the arm backward. External rotation contributes minimally to laparoscopic surgeries. Though the contribution of deltoid muscle may be negligible to the arm's backward motion in laparoscopic surgeries, it takes part in most of the shoulder movements. Therefore, we consider collecting data from anterior, medial, and posterior deltoid.

1.2.1.2 Muscular Fatigue

Muscle fatigue occurs when the metabolic needs of the muscle tissue are not met and the result is that the force generated by the muscle declines from its maximal force-generating capacity (Enoka and Duchateau, 2008). The process of muscle contraction at the cellular level can help to understand the physiology of muscle fatigue. The physiology of muscle contraction is described as below. When a muscle exertion is initiated a command from the central nervous system reaches the neuromuscular junction. The action potential will reach the sarcolemma (membrane of the muscle cell) from the junction point. After its arrival to the transverse tubular system, the action potential spreads further down the T tubule to the sarcoplasmic reticulum (SR) membrane. The last action causes sarcoplasmic Ca^{2+} into the myoplasm. The release of Ca^{2+} to myoplasm helps to bind troponin C and remove tropomyosin from actin. This act allows repetitively binds myosin and actin. The simultaneous release of Ca^{2+} into the myoplasm remains and retrieval of adenosine triphosphate (ATP)-dependent pump sends back Ca^{2+} into the SR simultaneously during the muscle contraction. The release of Ca^{2+} continues as long as the muscles contract. At the end of the contraction, all Ca^{2+} will be transported back to the SR.

When there is a decrease in this force-exerting capability in response to the given contraction by the central nervous system, it can be called muscle fatigue (Edwards, 1981; Bigland-Ritchie et al., 1986). At the cellular level, a change in the metabolic factors is an indicator of muscle fatigue (Allen et al., 2008). Chaffin et al., (2006, p 45) summarized the metabolic factors that work to reduce the force-generating capacity are as follows- "(a) formation of lactic acid and, a decrease in the Ph due to the buildup H^+, (b) an increase in inorganic phosphate (Pi) and di-protonated phosphate (H_2PO_4), (c) a decrease in phosphocreatine (Pcr), (d) an increase in the concentration of calcium (Ca^{++}), and (e) a decrease in the rate of ATP hydrolysis." All these processes work together to decrease the force-generating capacity by hindering the cycle. In the end, the presence of muscle fatigue may generate a decrease of glycogen-a significant energy source muscle activity (Bergstorm et al., 1967). The reduction of glycogen may increase muscle fatigue by reducing the SR Ca^{2+} release (Allen et al., 2008). In laboratory settings, it is hard to assess muscle fatigue using the change in metabolic factors, but it can be estimated by surface electromyography (SEMG). The two parameters of SEMG are median frequency of the signal and signal amplitude. A decrease in the median frequency and an increase in the SEMG amplitude are indicators of muscle fatigue (Cifrek et al., 2009). It is a noninvasive way to determine muscle fatigue. The phenomenon can be well understood if we give a brief description of muscle fiber types. There are two types of muscle fibers in human muscles: i) fast-twitch fiber (Type II (including Type IIa and Type IIb)) and ii) slow-twitch fiber (Type I). The presence of high SR and myofibrillar adenosine triphosphatase (ATPasc) is the main characteristic of fast-twitch muscle fibers. It is faster in isometric twitch and has the maximum shortening velocities. On the other hand, slow-twitch fiber has a long twitch duration, a low level of shortening velocities than fast-twitch muscle fibers, low level of SR and myofibrillar ATPasc activities (Westerblad et al., 1991). In general, slow-twitch fibers exhibit higher resistance to fatigue than fast-twitch fibers (Stephenson et al., 1998).

In the presence of muscle fatigue, and to overcome it, the central nervous system works to recruit more motor units to generate force. The central nervous system works to drive already recruited motor units to fire more rapidly and recruit new motor units. With the progress of fatigue, the firing of motor units becomes low, as the number of active motor units and the conduction velocity of muscle fiber decrease. These effects cause synchronization of the motor units, shifting from fast-twitch muscle fibers' engagement to slow-twitch fibers. The shift from fast-twitch to slow-twitch muscle fibers, reduces the median frequency, and more motor units' recruitment increases EMG amplitude. Both indicate muscle fatigue. Our current research will mainly focus on shoulder muscle fatigue. The shoulder muscle fibers' composition can help us understand the predictive changes in SEMG parameters under muscle fatigue.

1.2.1.3 Physiology of Shoulder Muscle Fatigue

Shoulder muscle fatigue can affect the performance of the workers. Muscle fatigue reduces work performance by altering shoulder movement and proprioception (Carpenter et al., 1998). They showed that the motor performance of upper extremity is greatly affected by muscle fatigue, because it affects contraction force and response time of the performers. This led to reduced shoulder movement of external and internal rotation of shoulder joint thereby affecting work performance. Reduction in work performance can be measured by counting the increment number of errors, measuring working velocity and time to complete the task (Stephenson et al., 2019). Hence, it is important to discuss the physiology of shoulder muscle fatigue and how it affects shoulder movement. Prolonged static awkward posture (Punnett and Wegman, 2004; Abdelrahman et al., 2016) and repetitive movement of arms (Ebaugh et al., 2005; Voight et al., 1996; Lee et al., 2008) mainly cause shoulder muscle fatigue which can alter shoulder kinematics. The shoulder follows some specific movements when a person involves arms and hands to perform a task. In the presence of shoulder muscle fatigue, these movements can be altered (McQuade et al., 1998; Voight et al., 1996). For example, scapulothoracic motion increases while glenohumeral motion decreases with the presence of shoulder muscle fatigue (Ebaugh et al., 2005). Discussion of shoulder anatomy informs that the glenohumeral joint is an important joint for shoulder movement (Cheng et al., 2021). Therefore, decrement in the glenohumeral joint motion affects performance of the workers. Carpenter et al. (1998) also showed that proprioception of shoulder is worsened in the presence of shoulder muscle fatigue. As shoulder muscle fatigue affects shoulder movement, which results in reduction of performance, it is necessary to discuss the rate of muscle fatigue development of the shoulder muscles.

As noted previously, the shoulder consists of numerous muscles. Under repetitive, static, forceful work, these shoulder muscles get fatigued, but the rate of fatigue development is not the same for all the muscles (Ebaugh et al., 2005; Kim et al., 2021). Ebaugh et al. (2005) collected EMG data in the frequency domain from infraspinatus, upper and lower trapezius, serratus anterior, anterior, and posterior deltoid muscles during shoulder fatiguing activity. To fatigue the shoulder gridle muscles and find out the effect of fatigue on shoulder muscle movement, subjects were asked to perform three tasks, such as: i) manipulating two small objects at 45˚ arm elevation; ii) raising and lowering arm against a resistance; iii) raising and lowering arm against a resistance in a diagonal pattern. Deltoid and infraspinatus muscles showed the highest rate of fatigue. Another study by Minning et al. (2007) collected data on shoulder muscles, namely upper, lower trapezius, serratus anterior, and trapezius muscle during an isometric shoulder elevation. The subjects performed 60% of their maximum voluntary isometric contraction

(MVIC). The result revealed that the middle deltoid fatigued at a higher rate than other shoulder muscles considered in the study because it is more phasic type muscle and has more Type II fibers than other shoulder muscles (Minning et al., 2007). Whereas other shoulder muscles work to stabilize shoulder movement, deltoid muscle works to elevate the humerus during arm movement. This phasic nature of the muscle leads the muscle to fatigue faster than other shoulder muscles. It should also be noted that the rate of fatigue development also depends on the conditions of the experiments.

Most of the previous literature indicates deltoid as a faster fatiguing muscle than other shoulder muscles considered in those studies (Ebaugh et al., 2005; Minning et al., 2007). However, it cannot be concluded that only deltoid has a higher fatiguing rate than other shoulder muscles because all the muscle interactions have not been studied. In addition, most of the studies considered only surface electromyography (SEMG) to collect data. It increases the chance of crosstalk and interference from other muscles. Apart from the type of muscle, the external factors like angle, duration, and level of exertion (% of maximum voluntary exertion) also determine the rate of fatigue development of the shoulder muscles (Kim et al., 2021). Kim et al. (2021) collected data on upper trapezius, middle deltoid, pectoralis major, latissimus dorsi and serratus anterior under different external conditions. They changed the duration, angle, and type of the exertion of those experiments. The result showed middle deltoid fatigued in the shortest duration and its fatigue development rate depends on the duration of the task. Upper trapezius gets extremely fatigued during extreme flexion, latissimus dorsi and pectoralis major get fatigued during adduction. Movement involved in laparoscopic surgery involved abduction, internal rotation but no extreme flexion. Only duration of the static work performed was the main external factor to create fatigue. Therefore, deltoid muscle creates the main interest for creating fatigue during laparoscopic surgery.

Now, as we have presented the reason behind choosing deltoid muscle as our muscle interest, we will discuss how breaks have been considered by the researchers as an ergonomic intervention in the next section.

1.2.2 Breaks as an Ergonomic Intervention

There are three types of ergonomics interventions, i.e., engineering, administrative and work practice ergonomic interventions (Tompa and Dolinschi, 2010). Engineering ergonomic interventions involve a physical change of the work environment through engineering manipulations (Gangopadhyay and Dev, 2014). Administrative interventions include alternating duties and jobs, such as job rotation, the inclusion of breaks, rest, enlargement, application of work cells and policies, behavioral interventions, or personal interventions implemented through the change in individual worker's behaviors capacity (Gangopadhyay and Dev, 2014). The last type of intervention tries to increase fitness, reduction of stress, improving work methods. For our study, the main discussion lies with administrative interventions and their application with microbreaks. Microbreaks are short, but frequent, pauses in the work task. Application of microbreaks during work are a comparatively financially feasible option to reduce the effect of MSDs from the prolonged static posture. However, sometimes workers/ employees are reluctant to adopt this type of intervention. For example, surgeons in the operating room often assume prolonged static posture to complete surgeries, and it can lead to discomfort in the neck and lower back part of the body. However, surgeons are reluctant to take microbreaks as they consider these breaks distracting and disruptive (Scarlet and Dreesen, 2020). They often sacrifice their comfort to ensure successful surgeries and the welfare of the patients. Therefore, there is a contradiction in the benefits of breaks during surgical tasks.

Some studies claim that microbreaks are highly beneficial for surgeons during surgery (Dorion and Darveau, 2013; Engelmann et al., 2011; Hallbeck et al., 2017; Nakphet et al., 2015; Waongenngarm et al., 2018). They can reduce an exponential increase in fatigue (Rohmert, 1973). An introduction of short breaks can enhance the rapid recovery rate, reducing muscle fatigue by increasing oxygenation in the muscle. Comparing oxygenation in muscle activity and reduction in discomfort in the neck and upper extremity can demonstrate the positive impact of microbreaks (Nakphet et al., 2015). Though some studies found the positive effects of microbreaks on reducing physical fatigue, other studies found no positive effect of microbreaks on reducing muscle fatigue (Kromberg et al., 2020). Breaks can also be a reason of possible cause of the reduced performance of the workers. Breaks disrupt the workflow, which can reduce the performance of the workers. Therefore, there is an important question about the frequency and duration of breaks in physically demanding work so that muscle fatigue and loss in work performance are simultaneously minimized.

The risk of pain, discomfort, and musculoskeletal disorders associated with the work of the surgeons in the operating room are the results of prolonged static and awkward posture, repetitive force, working without taking any breaks (Punnett and Wegman 2004; Abdelrahman et al., 2016). Introducing microbreaks during work can bring a positive effect in reducing musculoskeletal disorders among workers. The following section will consist of the studies that have found positive results of microbreaks during work.

In a study of 56 attending surgeons, Hallbeck et al. (2017) showed that surgeons did not lose their mental focus and physical performance when microbreaks were applied in the days of surgeries. Moreover, introducing 20-40 seconds of microbreaks every 40 minutes did not increase the duration of surgery significantly. While discomfort was reduced considerably, disruption in the flow was minimized. In fact, 87% of the surgeons agreed to incorporate microbreaks in the surgery. Another study by Nakphet et al. (2015) provided a break of 3 minutes every 20 minutes on video display unit (VDU) workers to find any effect of breaks on muscle discomfort reduction and productivity. Subjects were asked to type during the working period. The study result showed no difference in productivity, but muscle discomfort was significantly reduced. Unfortunately, only subjective data was collected to quantify muscle discomfort (Borg-CR10), which is not the best way to measure muscle fatigue. Galinsky et al. (2007) performed a study on 51 workers (21 of them were in stretch group and 30 of them were in no stretch group) with supplementary break and conventional break. Supplementary break included two 15 minutes break per day with extra four 5-minute break and conventional breaks included only two 15-minute break. Supplementary breaks improved discomfort without performance impairment of data entry operators. Discomfort was measured based on a feeling state questionnaire. However, no objective measurement of fatigue vs performance was compared in this study.

Studies demonstrated that microbreaks can reduce muscle fatigue, stress, and increase the performance of the workers by enhancing mental focus (Dorion and Darveau, 2010; Engelmann et al., 2011). In a word, microbreaks can improve the overall well-being of the workers. For example, Hallbeck et al. (2017) showed that microbreaks could help surgeons in the operating room by improving physical performance (by 100%) and mental workload (by 80%). They also showed that microbreaks did not increase the total surgical duration indicating it did not affect productivity. They found that microbreaks reduced the pain of the surgeon during surgical work.

Equally importantly, the primary outcome of intervention impacted the mental focus of the surgeons. They showed a 34% self-reported improvement, and only 12% of them reported a decrement. Moreover, surgeons reported a 57% physical performance improvement, with no surgeon reporting a decrement in physical performance. The report of no decrement can be termed as a positive effect of microbreaks considering the difficulty of surgical procedures. Another study of surgeons by Engelmann et al. (2011) also showed that microbreaks can cause positive effects on the surgeons. They introduced a break of 5 minutes every 30 minutes in randomized 51 surgeries. The result showed that microbreaks in complex laparoscopic surgeries could reduce psychological stress and did not hamper performance considering the duration of the operation. Dorion and Darveau, (2010) designed a cross-over experiment on 16 surgeons. The surgeons were tested three times respectively under control situation, with and without formal micropause. They found a significant difference between the control group and without the micropause group. The presence of micropause reduces muscular fatigue and surgical error. On the other hand, Komorowski et al., (2015) experimented on surgeons and found no significant differences in the precision. Though the study had a significant drawback as it was conducted on only two surgeons, and the measure of accuracy was a mobile application with no real-life clinical implication.

Studies have been performed not only on surgeons but also on office workers. A study on computer terminal workers showed that micropauses helped them to reduce discomfort. Participants of this experiment were members of a computerized work-station environment. They were assigned to three groups randomly, and the three groups were under conditions of no break, with a break every 20 minutes and with breaks every 40 minutes. The frequency-domain result analysis showed no significant differences between the conditions. However, the subject analysis showed conditions with micro-breaks reduced discomfort. The effect of microbreaks on productivity was not significant. Productivity was measured based on typed words, but it was not a real-life measure of productivity as keywords may differ from subject to subject, experience, and work type.

Another study by Nakphet et al. (2015) was performed on right-handed VDU operators. The VDU operators performed prolonged computer terminal work for at least four hours per day. Electromyographic data and muscle discomfort were collected in 60 minutes, where 3 minutes of breaks were provided every 20 minutes of work. They found no significant difference in muscle discomfort and productivity. It could be the result of breaks that reduced the expected level of muscle discomfort. Productivity was measured through the count of correctly spelled and typed words. There was no significant difference between productivity after rest break activity. However, they did not compare the productivity of typing for tasks with or without microbreaks. They quantified the effect of breaks on productivity before and after the rest-break.

Dababneh et al., (2001) applied breaks in meat processing plant to observe its effect on productivity and well-being of the workers. They applied two types of breaks such as: 1) 3-minutes of 12 breaks and 2) 9 minutes of 4 breaks. The total duration of the break was 36 minutes. Apart from this break, the workers also had a regular 30-minute lunch break and 2 15-minutes regular breaks. Researchers found no negative effect on productivity, and they preferred longer breaks over shorter and frequent breaks. Contrary to the studies mentioned above, there have been other studies that have found a negative effect of breaks. A study by Henning et al., (1989) experimented on high-performance data entry tasks. They allowed the workers to choose their breaks according to their mental and physical fatigue levels. The average value of break duration was 27.4 seconds. Participants were asked to enter data and during typing keystroke and level of correction were recorded. Due to the presence of breaks the value of keystroke declined, and correction rate increased. This result indicated that the performance of the workers was negatively affected by microbreaks. Therefore, the debate on the effect of microbreaks on performance is unresolved though we know the positive effect of breaks on muscle fatigue development. In the next section we are going to provide a brief description of inventory control models so that it is easier to draw the analogy of those models with fatigue development profile.

1.2.3 Inventory Control Theory

1.2.3.1 Inventory Control Theory Models

Inventory control theories are essential in the field of logistics management. These models are used to determine the optimum number of products to order to minimize production costs. Producers often face a dilemma to decide on the required number of products to produce. If they fail to manufacture enough products, they will miss the sale. Moreover, producing products in a repetitive lot will increase their fixed cost.

On the other hand, if they produce more products than the demand, it will increase their holding cost. Inventory control theories help the manufacturer to produce required number of products that minimizes total (holding and production) costs. Inventory control theories constitute a vital part of this proposal, as an analogy can be drawn between inventory control theory and muscle fatigue development.

1.2.3.1.1 Economic Order Quantity (EOQ) Model

The most popular inventory control model is Economic Order Quantity (EOQ). The model was introduced by Ford W. Harris in 1913 to minimize both holding and production costs. The term EOQ means the optimum number of products to be ordered that can optimize total costs. The total cost calculated by the model is as follows:

$$\text{Total Production Cost} = H \times Q/2 + F \times A/Q + PQ \qquad (1)$$

Where: *H*=Holding cost per unit of the product, *P*= Price to produce each item, *F*= Fixed cost of each production cycle, *A*= Annual demand, *Q*= Lot size. Thus, *A/Q*= The number of orders.

The model tries to minimize the total production cost of the above equation through determining the economic order quantity, Q. It has some assumptions to determine the optimum order quantity. The assumptions are the constant demand, holding, and cost to produce/order per unit of product. The deterministic assumptions make the mathematical model simple, but for most companies, they are not true in real life. These assumptions become the limitations of the model. The EOQ model also assumes that all the products are delivered/ produced at the instance of time (t_1=0) which is also not true for most of the manufactures in real life. Instead of these limitations, the model helps companies to reduce the loss that is incurred from holding up the cash (Figure 1.1).

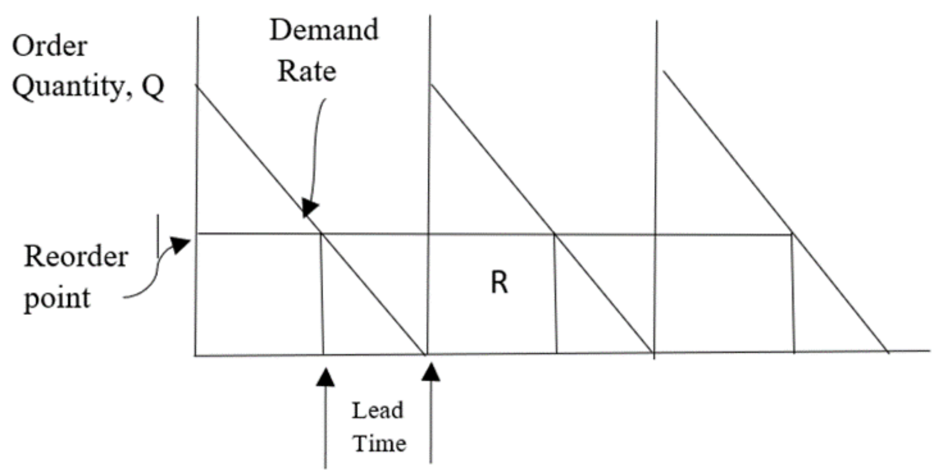

Figure 1.1: Representation of Economic Order Quantity Model

1.2.3.1.2 Economic Production Quantity (EPQ) Model

Economic Production Quantity (EPQ) is an extension of EOQ model. It overcomes one of the limitations of EOQ model. EOQ model assumes that all the products are delivered to the customer when the order is complete, whereas the EPQ model assumes that delivery and production occur simultaneously. Therefore, the product is being delivered incrementally. It updates the assumption of demand of the EOQ model. The model assumes that demand is not only constant but also continuous. All other assumptions are the same as the EOQ model. It assumes to have constant lead time, constant purchase price of the product, and constant production rate. The model also runs to find out the economic quantity of a single product like the EOQ model. Though it has similar assumptions to the EOQ model, the updated demand assumption makes the EPQ model more realistic than the EOQ model (Figure 1.2).

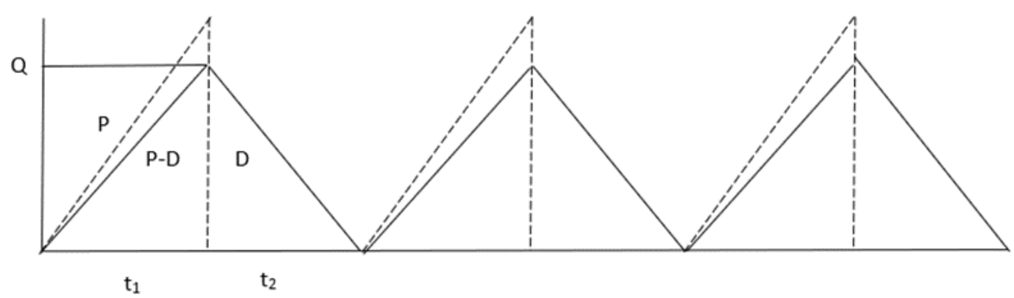

Figure 1.2: Economic Production Quantity (EPQ) Showing Time for both the Production and the Changes in Inventory where, t_1= Time of Production; t_2= Delivery Time; *Q*= Lot Size, *P*=Production Rate, *D*=Demand Rate, *P-D*=Net Production Rate (When production and delivery occur at the same time)

1.2.3.1.3 Other Models

There are some other models available in inventory management to obtain an optimum number of products. The names of the models are Newsvendor Model, Base Stock Model, Dynamic Lot Size Model or Wanger-Whitin Model, Economic Lot Scheduling Model, etc. EOQ model is the basis of these models. Each of these models has updated at least one assumption of the EOQ model. For instance, the Newsvendor problem is well applied when the product is perishable, and demand is random instead of being constant. There is only one-time replenishment in Newsvendor Model. In the Base-Stock Model, there are multiple replenishments, and demand is also random. Dynamic lot size works well when demand varies in a deterministic way. Economic lot scheduling best fits for determining the optimum quantity of multiple products. Apart from these popular models, different features have been added to the base model to fit the real-life scenario better. For example, stochastic demand instead of deterministic demand, variable price instead of constant price, presence of continuous lead time, finite time horizon instead of infinite etc. All these models have been developed over the years to determine optimum product quantity that matches the different scenarios of different companies.

1.2.3.2 Previous Literature on the Models of Work-Rest Cycling

The aim of modeling work rest scheduling is to maximize productivity, performance, ensuring workers' health. There are good number of studies available in literature that have tried to model work rest scheduling to fulfill the purpose. These models include job rotation models and work rest models. Job rotation model is an approach of arranging tasks so that workers do not work on the same task for prolonged periods. These types of models also assist to shift stress of one muscle to another muscle, but the workers do not take actual break from work. They only get chance to change the type of the work which reduces their boredom, muscle fatigue of a specific muscle and enhances productivity. These types of models suit well in large sized facilities. On the other hand, work-rest models allow subjects to work and then take rest for certain period. During work period, subjects get fatigued and during rest period they recover. The cyclic nature of work and rest helps to reduce the development of musculoskeletal disorders. A brief description of the previous job rotation and work-rest model will help to understand the importance and contribution of the current proposal.

Carnahan et al. (2000) developed a job rotation model on lifting task in a material handling industry to ensure safety of the workers. They used the Job Severity Index (Ayoub et al., 1983) to mark the intensity of the risk of the job. In general, scheduling job rotation modeling includes several tasks and integer programming is used to rank them. In this modeling, Carnahan et al. (2000) developed a model of the same task but with different stress levels. Stress level was calculated using Job Severity Index. Job Severity Index depends on physical capacity of the workers and conditions of the work environment. The conditions of the work environment were frequency of the task, mass of the object, lifting height etc. which were varied to develop the model. Both integer programming and genetic algorithm were used to develop 437 acceptable solutions of job rotation that were helpful to move the jobs among workers. Another study by Diego-Mas et al., (2008) developed job rotation model with an aim to reduce stress on a specific muscle in the tasks of an automobile assembly plant. 18 workers at 18 workstations participated in the study. They had adequate training to perform any task from the assembly plant. They studied the implement action of three rotations (each consists of two hours) with one-hour break before start of the last rotation. The study compared the updated rotation with previously practiced rotation which had only one eight-hours rotations with one-hour break at lunch. During assigning task, the capacity of the workers and their preference to choose a task were considered. This model used genetic algorithm to find out the preferable job rotations. Another study by Tharmmaphornphilas and Norman, (2004) applied integer programming to find out suitable job rotation interval. Different job rotation intervals can create different level of stress on the workers. They applied no rotation (8 hours), 2 rotations (4 hours each), 4 rotations (2 hours each), hourly rotations and rotation at worker’s preference. While assigning job interval length, this mathematical modeling considered minimizing stress of lower back pain and minimizing noise exposure. It used Job Severity Index (JSI) as an indicator to rate the stress level of the job and Total Weighted Average (TWA) to rate exposure to noise. The model tried to find out smaller value of JSI and TWA. Considering the practical application, the study found that 2 hours job rotation to be beneficial for the workers. Though these models successfully found job rotation intervals, they have some limitation too. They did not consider the physiological cost and productivity during job rotations. Moreover, these models fit well in facility where a task can be divided into sections and each section can be done by different workers. The model will not work where a task must be completed by one skilled worker-for example, laparoscopic surgery. Several tasks of a laparoscopic surgery are assigned to different workers like surgeon, nurse, anesthetists whose work cannot be rotated among them. Therefore, job rotation model is not applicable in this sector.

Along with job rotation models, there are work-rest models available at literature too. Work-rest models allows workers to take rest between work. There are two types of work rest models: theoretical and empirical. Empirical studies suggest optimum work-rest schedule through collecting data on the real subjects (e.g., Sarker et al., 2021; Hallbeck et al., 2017). Empirical data can be collected in laboratory settings or in real life workstation. Theoretical modeling includes optimization, biomechanical models which can estimate optimum resting period through designing the parameters. Previous literature that suggest duration of microbreaks through empirical studies is described in Section 1.2.2. Following is a brief description of the theoretical models available in literature. Eilon (1964) first developed a mathematical model to design work rest schedule. They adopted the simple assumption that working period reduces productivity and rest period increases productivity. The study also assumed that recovery is linear when rest period is short. Simple assumptions are often violated in most of the real-life scenarios. In addition, functions that can express the relationship of productivity and rest period were not explicitly expressed in this study. Later, several mathematical models were developed after considering complex real-life situations. A study by Bechtold et al., (1984) developed a mathematical model which used mixed integer quadratic programming to decide optimal number, length, and arrangement of breaks. They modeled duration, frequency, and placement of breaks as an integer quadratic programming using linear rate for recovery and decay of the productivity. Their model was well applicable to find out optimum number of breaks with multiple rest breaks in a finite duration of work. The output of the study was applied on airlines company and resulted in 13% increase in productivity. However, this model also had limitations. It only considered maximization of productivity but did not consider the reduction of worker's fatigue level. Some other studies have considered only workers' wellbeing (Hsie et al., 2009; Luttmann et al., 1992). Hseie and his colleagues (2009) designed a work-rest model for construction workers focusing on reduction of energy consumed by workers and minimizing their production time. They used oxygen consumption rate as a measure of energy expenditure and duration to complete the work as a measure of production time. It resulted in a multi-objective optimization problem where they chose a work-rest scheduling that minimizes energy consumed by the workers. A genetic algorithm was applied to find out the optimal solution to this multi-objective optimization and they found that the model is applicable for highly strenuous work, where 33% of VO_{2max} limits the onset of muscle fatigue. However, even low-level long-term static work can also induce fatigue (Sarker et al., 2021). This model would not fit in those types of work. Luttman et al. (1992) suggested duration, frequency and placement of breaks based on a linear relationship between working rate and heart rate. They found that heart rate reduces with a decrease in the work. Using the relationship, they suggested work-rest schedule for workers who collect garbage. Collection and disposal of garbage is a highly strenuous work which not only increases heart rate but also increases muscle fatigue. However, this model only suggested work-rest schedule based on heart rate and did not consider the productivity of the workers. Moreover, these studies (Hsie et al., 2009; Luttmann et al., 1992) considered recovery rate to be linear ignoring the real-life physiological changes which are not true in real life.

Ning (2011) developed a model establishing an analogy of physiological variables with the variables of inventory control theory model. The physiological variables he considered were heart rate, median frequency and sway speed. He suggested an optimum scheduling of work-rest cycle by tracking the changes of these variables and minimizing the total cost. To determine the cost, the study referred to some previous studies that calculated the cost of taking breaks from work. This approach to cost calculation limits the capability of this model to be applied to the type of work where the record of cost associated with taking breaks is not available. It urged the need for the development of the model that will have well established equations expressing recovery rate, fatigue rate and cost of taking breaks. The optimization model of Ning (2011) was not able to identify the problem as multi-objective optimization problem which is important as physiological and performance loss cost are inversely related to each other. Moreover, the model (Ning, 2011) needs real-time data collection to suggest work-rest scheduling. It developed the model based on data collection on four subjects and did not consider the presence of inter-individual variability. Inter-individual variability can alter the result of optimum work-rest schedule. Therefore, the development of a new model for scheduling work-rest model is very important to consider the well-being of the workers, productivity, non-linear nature of the recovery, fatigue rate while considering inter-individual variability. The present proposal aims to develop a multi-objective optimization model to meet the need. It will also be able to suggest an optimum work-rest schedule under the presence of uncertainty arising from inter-individual variability.

The aim of this proposal is to develop an optimization-based work-rest scheduling model. It requires to develop the equations for the objective functions and constraints. To develop the equations an analogy between an inventory control and fatigue development profile will be made. Several inventory control models are available in inventory management. Among them EPQ model will be used because this model considers time for both the production and the changes in inventory (Figure 1.2). It fully represents the cycle of production and consumption which is like the fatigue development and muscle recovery. The profile in Figure 1.2 has the same pattern as in the fatigue profile developed in the work-rest scheduling task (e.g., Figure 1.3 and Figures 3.3 & 3.4 in Chapter 3). Let us refer to the following figure (Figure 1.3) for a muscle fatigue development model. Suppose the total duration to complete the work is, T. To reduce the risk of fatigue, the worker will take breaks while performing the work. They need three bouts (two breaks) to complete the task (for the sake of illustration). Under each bout, when they reach the upper level of fatigue A in time t_1, they will stop working and take a rest. During the rest period, they will recover at a rate of R and take time t_2. After recovery, they start working again and follow the same trend.

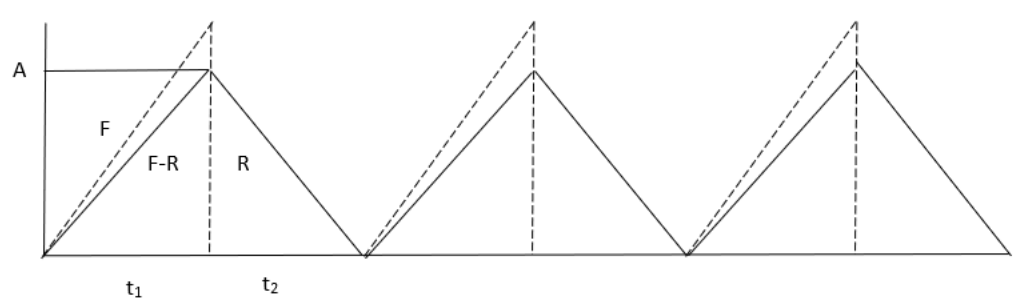

Figure 1.3: Fatigue Development Model Showing Time for both the Fatigue Development Rate and Recovery

Total physiological Cost= $H \times A/2+O \times T/(t_1+ t_2)= H \times A/2+O \times T/(A/P+ A/D)$ (2)

Where, H=Fixed holding cost, A= level of Fatigue (EMG amplitude value), O= Fixed performance loss cost before the start of each bout, t_1= Time of fatigue development to reach level A, t_2= Recovery time, F=Fatigue development rate, R=Recovery rate, A= Upper level of fatigue (EMG amplitude value). Thus, T/ $(t_1+ t_2)$ = The number of bouts, $H \times A/2$=Holding Cost, $F \times T/ t_1+ t_2$)=Fixed Cost.

If the fatigue level is held for a longer time, A will increase in value. It will increase the holding cost but decrease the fixed cost (performance loss cost) of starting each bout and vice versa. Therefore, it ends up as an optimization problem where both costs should be minimized. The total cost is dependent on the fatigue level and performance loss cost of each bout. Again, fatigue level is dependent on the number of bouts. The cost of performance loss in each bout is also dependent on the number of bouts. In the next sections the equations have been developed to obtain the relationship between number of bouts and fatigue level, and number of bouts and performance loss. The variables involved in the previous studies related to the inventory model were considered as deterministic though in recent studies of some these variables were considered as probabilistic. In the similar way, muscle fatigue development parameters e.g., fatigue development rate, recovery rate etc. can be probabilistic too because the rate of fatigue development can be dependent on individual person, physical condition, age, demographic data, type of work, muscle freshness level etc. Therefore, the later part of Chapter 4 will also consider the probabilistic nature of these parameters.

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CHAPTER 2. PRELIMINARY STUDY I: THE EFFECTS OF REPETITIVE BOUTS OF A FATIGUING EXERTION (WITH BREAKS) ON THE SLOPE OF MEDIAN FREQUENCY OF THE EMG POWER SPECTRUM

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Modified from a manuscript published in the *Journal of Electromyography and Kinesiology:*

Abstract

Downward shifts in the median frequency of the power spectrum of an electromyographic signal have been used to assess muscular fatigue. How this reduction is affected by repetitive bouts of exertions - separated by rest breaks - is not well understood. It was hypothesized that repetitive bouts of a fatiguing, isometric exertion, separated by periods of rest, would have cumulative effects (across bouts) on the slope of the decline of the median frequency, with an expectation of an increasing rate of decline in subsequent bouts. To test this hypothesis, 24 participants performed four bouts of an isometric (15% MVC) elbow flexion exertion. Each exertion lasted for four minutes and then a 15-minute break was provided between bouts. Surface electromyography was used to capture the activity of the biceps brachii at twenty-second intervals during the exertions. The median frequency of each of these five-second collection periods was calculated, as was the slope across the four-minute bout. The results showed that there were no statistically significant differences in the rate of decline in the median frequency across bouts. These results have utility in the interpretation of median frequency as a measure of muscular fatigue in ergonomic and other applications.

2.1 Introduction

Physical fatigue of workers is a pressing concern for industry because it has been shown to impact both worker productivity and worker safety. At a high level are the studies that have quantified reduced worker productivity from physical fatigue. Seo et al. (2016) conducted a simulation study of masonry workers and found a 9.7% reduction in productivity as a result of worker fatigue. These authors noted that delays due to the physical fatigue of the laborers resulted in a 12.5% increase in work duration as the masons waited for the laborers to deliver the materials, and they estimated that this delay increased the cost of the job by 10%. Other studies have explored the occupational safety aspects of physical fatigue. A study by Parijat and Lockhart (2008) demonstrated that localized muscle fatigue in the lower limbs could lead to increased risk of slip-induced falls. In their laboratory-based study, 16 participants performed a walking task both with and without quadriceps muscle fatigue. Their results showed that quadriceps fatigue affected several key kinetic and kinematic gait parameters that are linked with risk of slip-induced falls and delays in the responses of the muscles used to recover from a slip and fall incident. While the existing literature on the topic of physical fatigue clearly shows both occupational safety and productivity effects, the impact of muscular fatigue on the development of musculoskeletal disorders, specifically, is less well established.

Though an epidemiologic link between muscular fatigue and musculoskeletal injury has not been clearly established, a paper by Kumar (2001) introduced differential fatigue theory to describe how muscular fatigue may lead these disorders. The main point underlying the author’s model is that as an individual performs a fatiguing exertion, the synergistic muscles working together to perform the fatiguing task are differentially fatigued and this differential fatigue can lead to modified joint loading thereby affecting the stresses and strains in the passive tissues supporting the joint. Supporting this perspective, the impact of muscular fatigue on the distribution of trunk muscle forces during a fatiguing axial loading (i.e., torso twisting) task was explored (Kumar and Narayan, 1998). In this study, researchers analyzed total power and median frequencies of the electromyographic signal. They found that the slope of the decrease in the median frequencies of the sampled muscles varied across the seven trunk muscles. They showed that this disproportional differential loading created a kinematic imbalance and reasoned that this response would heighten the chance of low back injury. It is unfortunate that there is limited epidemiologic evidence of a relationship between muscle fatigue and musculoskeletal disorders, but theoretical constructs do provide some support for this relationship.

Quantifying the degree of muscle fatigue can be accomplished using electromyography (EMG), particularly the spectral parameters of the EMG signal. The surface electromyographic technique has the advantages of being relatively non-invasive and capable of real-time muscle monitoring. As an example of an early assessment of the technique for establishing muscle fatigue, Kadefors et al., (1968), showed a downward shift in median frequency of the frequency spectrum of the biceps brachii muscle. In this study, the authors investigated four different conditions and found that under a constant load and muscle length condition, there was a significant downward shift of the frequency spectrum of EMG signal as the muscle was fatigued. In a subsequent study, Lindström et al., (1977) again collected EMG data on the biceps brachii muscle, but this time they observed the continuous change in the median frequency and quantified the time-dependent, downward slope of the median frequency. These authors performed a regression analysis on the value of the median frequency of the power spectrum data and used the slope of the spectrum as a fatigue index. More recently studies have explored the relationship between this value of median frequency slope and joint angle (Doheny, et al., 2008); shoulder muscle coactivation (Evans et al., 2018); chronic back pain experience (da Silva et al., 2015); rotator cuff tear status (Hawkes et al., 2015); knee joint angles (Pereira et al., 2011) temperature reduction (Merletti et al., 1984). One area that has not yet been explored is the effect of repetitive bouts of a fatiguing exertion (with intermittent breaks) on the slope of the median frequency of the EMG spectrum. This is of potentially great importance as this EMG measure is used in ergonomic assessment of workers performing repetitive bouts of fatiguing work tasks.

The hypothesis of the current study is that with repeated bouts of an isometric exertion, the slope of the decline in median frequency will become steeper. The underlying muscle physiology that motivates this hypothesis focuses on the challenges of replenishing the energy stores necessary for anaerobic metabolism. Previous studies have shown that low-level muscle contractions (10-20% MVC) can create circulatory compromise, negatively affecting blood flow in muscular tissue (e.g., Griffin et al., 2001). As muscle glycogen is consumed during an isometric exertion of this intensity it is not replenished due to compromised blood flow. When the isometric exertion ceases and normal blood flow is restored, replenishment can begin. If the duration of rest is not sufficient, the muscle glycogen would only be partially restored, so one might expect the muscle to be quicker to fatigue after multiple bouts of an isometric fatiguing exertion. Therefore, it is hypothesized that the median frequency of recovered muscle will have the same initial value, but the slope of decline of the median frequency will be steeper in later bouts of the exertion.

2.2 Methods

2.2.1 Participants

There were twenty-four participants (twelve men and twelve women) in this study, and they had the following characteristics (mean ± SD): age (27.6 ± 6.6years), stature (168.8 ± 11.6cm), whole body mass (75.2 ± 20.3kg), standing elbow height (105 ± 20.8cm). Before participation, each participant provided written informed consent. Exclusion criteria were a history of chronic upper extremity pain/injury or current pain in the upper extremity, and less than 18 or greater than 65 years of age.

2.2.2 Apparatus

Surface electromyography of the dominant arm biceps brachii was captured using a DELSYS® Bagnoli-16 EMG system, (Massachusetts, USA). Before attaching the electrode (location defined by SENIAM standards), the skin was cleaned with alcohol. Data were collected using a sampling frequency of 4096Hz and collection period of five seconds, and these data collections occurred every twenty seconds during the fatiguing exertions.

A Kin-Com Isokinetic Dynamometer (125E, Chattanooga TN, USA), was employed to measure the maximum voluntary isometric contraction (MVIC) of the elbow flexors as well as provide the static resistance and video feedback that allowed the participants to control their elbow flexion moment at 15% of their MVIC during the submaximal trials (Figure 2.1).

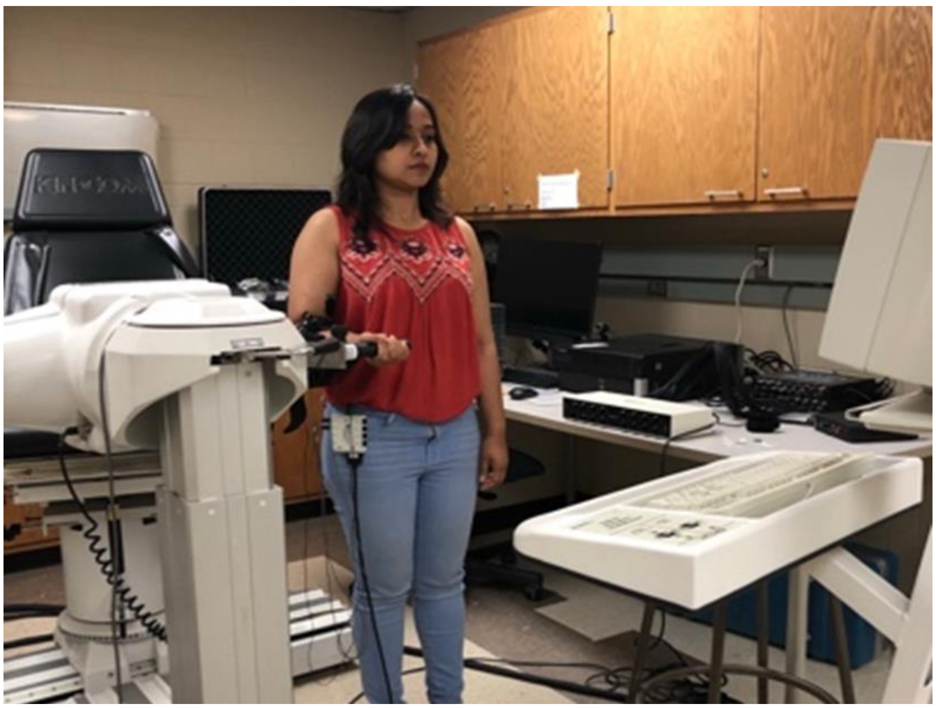

Figure 2.1: Experimental Apparatus Demonstrating the Elbow Flexion Dynamometer and the Video Feedback System

2.2.3 Experimental Tasks

Upon arrival, the experiment was described to the participant and the participant was asked to provide written informed consent. Basic anthropometric characteristics (stature, whole body weight, standing elbow height, upper elbow length, etc.) were then measured. Hand dominance was noted. The participant was then guided to the dynamometer where the axis of rotation of the dynamometer was aligned to the axis of rotation of the participant's dominant hand elbow joint with the elbow in a 90-degree elbow flexion posture. Once aligned vertically, the handle of the dynamometer was positioned anteriorly/posteriorly so it fit comfortably in the palm of the participant and the forearm was strapped to secure in that position. To capture the participant-specific maximum elbow flexion moment, the participant was asked to exert maximum elbow flexion two times (exertions separated by one-minute rest), and if the maximum moments generated were within 10% of each other, the larger of the two was used as the maximum flexion moment. If they were not within 10% of each other, the participant was asked to perform a third maximum elbow flexion exertion and the largest of the three was used as the maximum flexion moment. The participant was then provided a five-minute rest. The participant then re-entered the apparatus and used the video feedback of the dynamometer to maintain an elbow flexion moment equal to 15% MVIC for four minutes. Upon completion of the four-minute exertion the participant was then provided a fifteen-minute rest, seated on a stool outside of the apparatus. The four-minute exertion then fifteen-minute rest sequence was repeated four times. Total experimental time was 57 minutes (4+15+4+15+4+15+4 minutes). Each of the four-minute segments of 15% MVIC exertion were considered a “BOUT” of the exertion.

2.2.4 Data Collection and Processing

Data were collected for four seconds every twenty seconds during the four-minute bouts. Data were processed in a MATLAB (MathWorks Inc., MA) code that utilized the Fast Fourier

Transform function convert to the frequency domain and then the code filtered (high-pass 10 Hz, low-pass 400, notch filter 60 Hz and harmonics) and then computed the median frequency of the power spectrum. The computed median frequencies for each four-minute bout were then used in a least-squares regression that created a linear fit to these median frequencies as a function of time in each bout. The slope of that line was determined to be the dependent variable and was found for each bout for each participant.

2.2.5 Experimental Design

2.2.5.1 Independent variables

The independent variable in this experiment was BOUT with values of 1, 2, 3, and 4.

2.2.5.2 Dependent Variables

The dependent variable of this experiment was the slope of the median frequency of the captured electromyographic signal of the dominant-hand, biceps brachii muscle.

2.2.5.3 Statistical analysis

Statistical software JMP was used to perform an ANOVA to assess the hypothesis that these slope values change (become steeper) as the value of BOUT increases. This was a randomized block design, with participant acting as the blocking variable. A significance level of 0.05 was used as the criteria value for statistical significance.

2.3 Results

Figures 2.2-2.5 show the median frequency in each of the four bouts. The median frequency of the biceps muscle demonstrated, on average, a negative slope in all four bouts. The values of MDF slopes were -0.006 Hz/sec, -0.014 Hz/sec, -0.015 Hz/sec, and -0.011 Hz/sec for BOUT 1, BOUT 2, BOUT 3, and BOUT 4, respectively. The statistical analysis revealed that there were no significant differences ($p=0.77$) in the slopes across bouts, a result that does not support the original hypothesis.

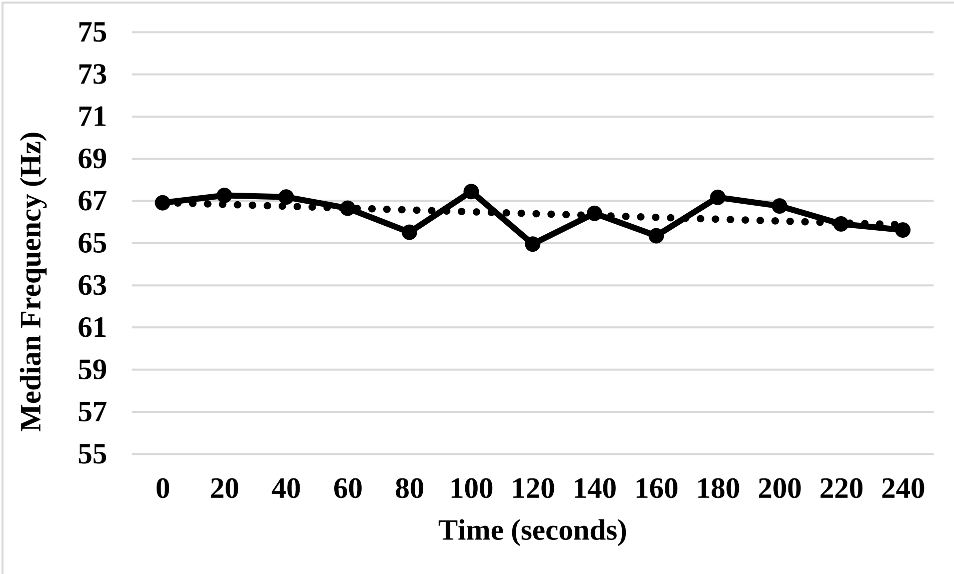

Figure 2.2: The Plot of the Mean Median Frequency of all the Subjects During BOUT 1

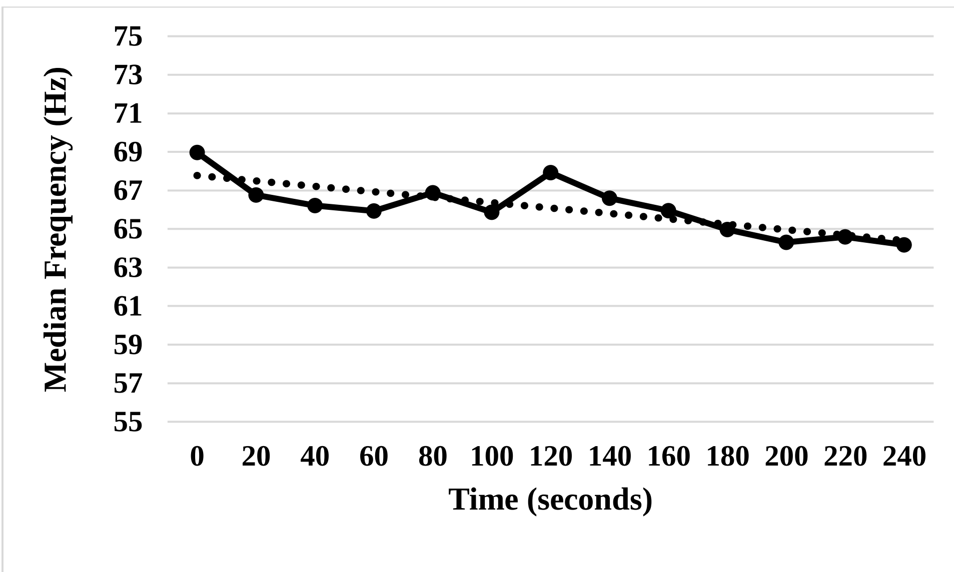

Figure 2.3: The Plot of the Mean Median Frequency of all the Subjects During BOUT 2

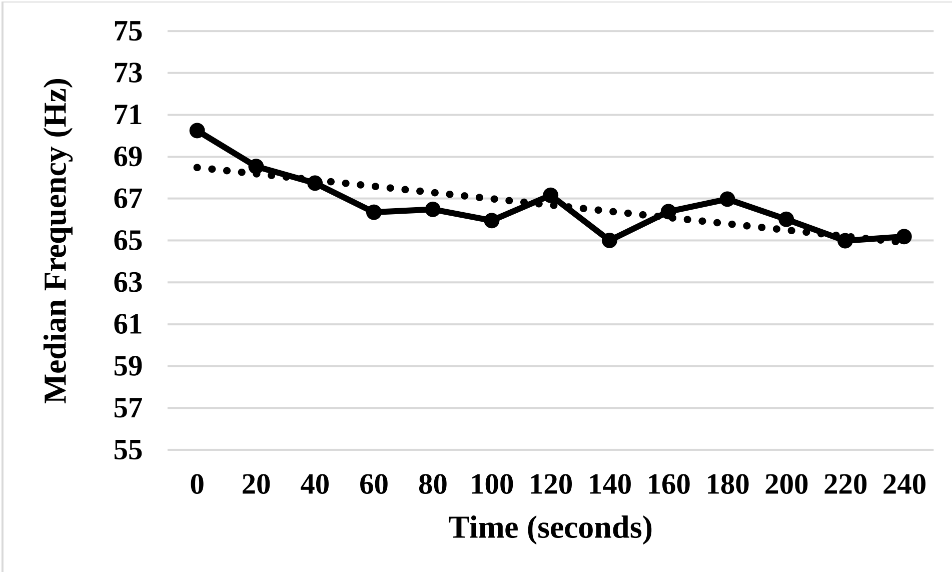

Figure 2.4: The Plot of the Mean Median Frequency of all the Subjects During BOUT 3

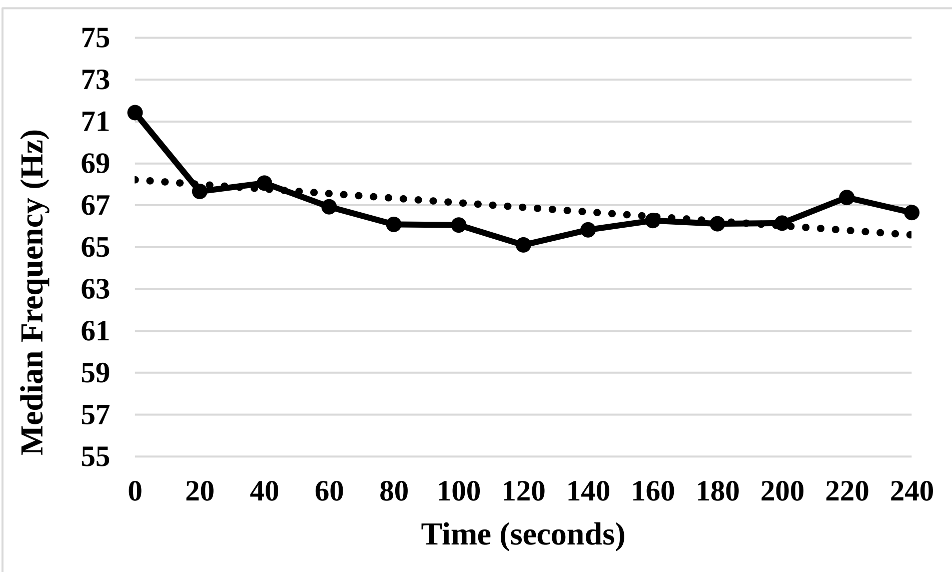

Figure 2.5: The Plot of the Mean Median Frequency of all the Subjects During BOUT 4

2.4 Discussion

Previous studies have established that a decrease in the median frequency is an indicator of peripheral muscle fatigue (e.g. Kadefors et al., 1968; Lindstrom et al., 1977), and subsequent studies have explored the slope of this decrease as a measure of the rate of fatigue of the muscle. The current research sought to document the changes in this slope in repeated bouts of a fatiguing exertion with rest breaks in between the bouts of the fatiguing exertion and it was hypothesized that this rate of fatigue may increase in subsequent bouts. The study hypothesis was not supported by the data in that these slope values did not change as a function of bout number. The results of the current study demonstrate that, for this work-rest protocol, if a break is large enough to bring the median frequency back to its initial value, the rate of decline of the median frequency does not increase (i.e., decrease) by bout.

There have been a number of studies that have explored the topic of slope of median frequency decline as a measure of rate of fatigue, and the comparison of the slope of the current study with those of previous research may be informative. These previous studies have typically focused on single bout exertions (i.e., without intervening rest breaks). A good example is a study by Hollman et al., (2013) who studied the slope of the median frequency of the gluteus maximus and semitendinosus as participants performed an isometric modified Biering–Sørensen test. Their participants held the trunk extension posture for five seconds and they used surface electrodes to sample these muscles. These authors found that the slopes of the median frequencies were -0.075 Hz/s for the gluteus maximus and -0.0166 Hz/s for the semitendinosus. These values are significantly larger than those seen in the current study, but this can result from the relative intensity of the exertions performed as well as differences in relative proportion of Type I and Type II muscle fiber combinations. A study that evaluated the same muscle considered in the current study (bicep brachii) was performed by Kuthe et al., (2018). In their study they asked their participants (14 that participated in a daily structured training program and 14 untrained) to exert 50%, 75%, and 100% elbow flexion MVC for the 60s or until failure occurred. They then evaluated the slope of the median frequency through surface electromyography. They found that training did not have a consistent effect on the slope of the median frequency but did find that the slope became more negative as a function of increasing exertion level. Averaged across all participants, the slope of the 50%MVC exertion was -0.140Hz/sec, at 75%MVC the value of the slope was -0.255Hz/sec, and at 100%MVC the value of the slope was -0.294Hz/sec. The slopes seen in the current study are significantly lower, a result that is consistent with the exertion-level trends seen in this previous study.

The principal contribution of the current study was the introduction of rest breaks into a fatigue protocol and evaluating the effects of these breaks on the median frequency slope values. Rest breaks are a particularly important and interesting aspect of the fatigue response particularly for ergonomic (i.e., occupational settings). As median frequency analysis is used to evaluate the development of fatigue in occupational scenarios, understanding the relationship between median frequency shift during a fatiguing exertion and the associated impacts of rest breaks is critical. By design, the recovery period considered in this study was sufficient to return the median frequency to its initial value (established in pilot studies). This was very important because Rashedi and Nussbaum (2017) demonstrated that the rate of fatigue reduction and recovery of a muscle depend on the initial condition. Since it was our objective to evaluate the changes in slope after periods of rest, initial conditions (i.e., initial median frequency) were critically important. As is evidenced in figures 2.2-2.5, this objective was achieved. There have been a number of studies that have explored this topic of necessary (and sufficient) time for recovery and this was shown to vary both by muscle and exertion intensity level (e.g. Iguchi et al., 2008; Kroon et al., 1991), therefore we relied on the results of our pilot work to set the rest break duration. With an understanding of the basic muscle physiology involved, it is recognized that the choice of a higher percent MVC and/or a shorter rest break might have generated results that were supportive of our hypothesis. This may form the foundation for future research on this important topic.

This exploratory study was done on subjects of young group of people and may not be extrapolated for people of elderly community. The group of people have no experience of performing intermittent contractions in their day-to-day life. The result of manifestation of fatigue can highly affected by work experience of people. The result of this study may be common for most muscles, however the consideration of a very simple muscle joint like biceps brachii should be a major factor leading towards the result of this current research. Muscle joints with different combinations of slow and fast twitch muscle fibers can exhibit a different outcome than the current study. Future studies can be done on another muscle joint to observe any change in the slope of median frequency of repetitive bouts. Moreover, current research mainly focused on low level exertions so that long endurance time can be analyzed. The rate in the decline of muscle fatigue being dependent on level of exertion, can also vary for repetitive exertion with high level of exertion. Future research can consider the effect of short time repetitive bouts with higher exertion level to observe any significant change in the slope of median frequency.

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Statement of Authorship

AUTHOR CONTRIBUTIONS

Conception and design: PS, GM

Analysis and interpretation: PS

Data collection: PS

Writing the article: PS, GM

Critical revision of the article: GM

Final approval of the article: PS, GM

Statistical analysis: PS

Overall responsibility: PS

Appendix A. IRB Approval Memo

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- **Retain signed informed consent documents for 3 years after the close of the study,** when documented consent is required**.**
- **Obtain IRB approval prior to implementing any changes** to the study.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.
- **Submit an application for Continuing Review** at least three to four weeks prior to the **date for continuing review** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

IRB 03/2018

- Please be aware that IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**
- Please be advised that your research study may be subject to **post-approval monitoring by Iowa State University's Office for Responsible Research**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.
- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

Appendix B. Informed Consent Form

ISU IRB: 18-281-00
Approved Date: 07/13/2018
Expiration Date: 07/12/2020

Consent Form for: The Effect of Fatigue on the Slope of the Median Frequency of the Electromyographic Signal of the Biceps Brachii

Invitation to be Part of a Research Study

You are invited to participate in a research study. This form has information to help you decide whether or not you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary and you can stop at any time.

Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

Who is conducting this study?

This study is being conducted by Dr. Gary A. Mirka and Ms. Pramiti Sarker

Why am I invited to participate in this study?

You are being invited to participate in this study because you are in the appropriate age range. You should not participate if you are less than 18 years of age or are over 65 years of age; have a history of high blood pressure; have a history of chronic upper extremity problems (wrist, elbow, shoulder, arm, forearm); or are currently experiencing pain in these areas.

What is the purpose of this study?

The purpose of this study is to evaluate the effect of fatigue on the response of the biceps brachii muscles (muscle of the arm). These data will be helpful as we study industrial workers and design work tasks to minimize the risk of injury due to fatigue.

What will I be asked to do?

Figure 1

If you agree to participate, you will perform an experiment in the environment shown in Figure 1. Your experiment will start with a five-minute warm up session. We will then gather a few measures of your body (height, weight, age, hand dominance). You will then have a sensor attached on the skin over the elbow flexor muscle of your dominant arm. You will then be asked to exert a maximum elbow flexion force (for three seconds, 90-degree elbow flexion) against the static resistance of the machine in the figure (see Figure 1) with your dominant hand. You will then be asked to perform a series of sustained (4 minutes) elbow flexion exertions. In these exertions, you will be asked to maintain a force level equal to 15% of your capability (as measured during the maximum elbow flexion exertions) while maintaining a 90-degree flexion of your elbow. You will use a computer monitor to hold the force constant. You will do this procedure four times with a 15-minute break between each segment. Your participation will last for 75 minutes.

ISU IRB: 18-281-00
Approved Date: 07/13/2018
Expiration Date: 07/12/2020

What are the possible risks or discomforts I may experience during the study?

While participating in this study you may experience the following risks or discomforts:

- Likely: discomfort in the elbow flexor muscles during the fatiguing exertions
- Minimal risk: strained elbow flexor muscle during the maximum elbow flexion exertions

Individuals that do not meet the eligibility criteria are at increased risk of muscle strain and injury. There may be risks or discomforts that are currently unforeseeable at this time. We will tell you about any significant new information we learn that may relate to your willingness to continue participating in this study.

What are the benefits of participation in the study?

It is hoped that the information gained in this study will benefit society by better understanding how muscles fatigue. This can help us prevent fatigue-related injuries in the working population. You are not expected to directly benefit from participation in the study.

What measures will be taken to ensure the confidentiality of the data or to protect my privacy?

Research records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available without your permission. However, it is possible that other people and offices responsible for making sure research is done safely and responsibly will see your information. This includes federal government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy study records for quality assurance and data analysis. These records may contain private information.

To protect confidentiality of the study records and data, the following measures will be taken: paper copies of any data and informed consent forms will be stored in a locked cabinet and electronic copies of data will be stored on a password-protected desktop computer and these data

Will I incur any costs from participating or will I be compensated?

You will not have any costs from participating in this study. You will be compensated for participating in this study by receiving an ErgoLab t-shirt.

Will the information I provide be used for anything other than the current study?

Data collected in this study will not be used in any study other than the current one and our data will not have any personal identifiers linking you to your data.

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What are my rights as a research participant?

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences.

If you withdraw from the study early the electrodes will be removed and you will be free to go and all data collected up to that point will destroyed.

We may end your participation in the study if we believe you are at risk of injury and all data collected up to that point will destroyed.

If you have any questions *about the rights of research subjects or research-related injury*, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

What if I am injured as a result of participating in this study?

Please tell the researchers if you believe you have any injuries caused by your participation in the study. The researchers may be able to assist you with locating emergency treatment, if appropriate, but you or your insurance company will be responsible for the cost. Eligible Iowa State University students may obtain treatment from the Thielen Student Health Center. By agreeing to participate in the study, you do not give up your right to seek payment if you are harmed as a result of being in this study. However, claims for payment sought from the University will only be paid to the extent permitted by Iowa law, including the Iowa Tort Claims Act (Iowa Code Chapter 669).

Whom can I call if I have questions about the study?

You are encouraged to ask questions at any time during this study. For further information ***about the study,*** contact Dr. Gary Mirka (mirka@iastate.edu, (515) 294-8661).

Your Consent

By signing this document, you are agreeing to participate in this study. Make sure you understand what the study involves before you sign. If you have any questions about the study after you agree to participate, you can contact the research team using the information provided above.

I have been given a copy of this informed consent form.

Participant's Name (printed) ____

______________________________________ ______________________

Participant's Signature Date

CHAPTER 3. PRELIMINARY STUDY II: EFFECTS OF BREAK SCHEDULING STRATEGIES ON SUBJECTIVE AND OBJECTIVE MEASURES OF NECK AND SHOULDER MUSCLE FATIGUE IN ASYMPTOMATIC ADULTS PERFORMING A STANDING TASK REQUIRING STATIC NECK FLEXION

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Modified from a manuscript published in the Journal of *Applied Ergonomics:*

Abstract

Sustained non-neutral postures of the head/neck are related to transient neck discomfort and longer-term disorders of the neck. Periodic breaks can help but the ideal length and frequency of breaks are yet to be determined. The current study aimed to quantify the effects of three work-rest strategies on fatigue development. Participants maintained a 45-degree neck flexion posture for a total of 60 minutes and were provided three minutes of rest distributed in different ways throughout the experiment [LONG (one, three-minute break), MEDIUM (two, 1.5-minute breaks), or SHORT (five, 36-second breaks)]. Surface electromyography data were collected from the bilateral neck extensors and trapezius. Subjective discomfort/fatigue ratings were also gathered. Results of the analysis of the EMG data revealed that the SHORT condition

did not show increased EMG activity, while LONG [21%] and MEDIUM [10%] did ($p<0.05$), providing objective data supporting the guidance of short, frequent breaks to alleviate fatigue.

Keywords: Work-rest cycle; Neck Pain; Cervical Spine; Electromyography; Musculoskeletal disorder

3.1 Introduction

Neck pain is prevalent in both the general and working populations (Bovim et al., 1994; Côté et al., 1998). In a cross-sectional study by Côté et al., (1998), the lifetime prevalence of neck pain was found to be 66.7% in adults between the ages of 20 and 69 years. The annual incidence rate of neck pain in a similar study by the same author was found to be 14.6% (Côté et al. 2004). In another cross-sectional study by Genebra et al., (2017), among adults aged 20 and over, 20.3% of the interviewed participants had experienced neck pain once or more in the last 12 months. It has been estimated that health care spending on low back and neck pain in the United States was $87.6 billion in 2013, making it the third most costly condition for personal health care spending in 2013 (Dieleman et al., 2016). Neck pain can be transient, such as that from muscular fatigue during extended bouts of work with non-neutral neck postures; or chronic, indicating the potential for an underlying musculoskeletal disorder. Work that requires sustained non-neutral postures of the head and neck have been shown to be related to transient neck discomfort as well as longer-term disorders of the tissues of the neck (Vijendren et al., 2018; Davila et al., 2019).

Neck pain/discomfort is seen across a wide variety of working populations. It can be a burdensome problem causing disabling conditions and work absenteeism (Côté et al., 2008; Côté et al., 2009; Palmer et al., 2001). A high prevalence of neck discomfort has been reported in scissor makers, shop assistants, factory workers and surgeons (Kuorinka and Koskinen, 1979;

Luopajarvi et al., 1979; Howarth et al., 2019; Coleman et al., 2019; Davila et al., 2019; Wells et al., 2019). Similarly, recent surveys of surgeons have shown that they experience high levels of work-related pain in the neck (Howarth et al., 2019; Coleman et al., 2019; Davila et al., 2019; Wells et al., 2019; Szeto et al., 2005) and these surgeons are concerned that this pain will influence their ability to perform surgical procedures in the future (Park et al., 2017; Howarth et al., 2019; Coleman et al., 2019; Davila et al., 2019; Wells et al., 2019). Extended time on computers (desktops, laptops or tablets) for work or home use is also associated with neck fatigue and discomfort symptoms (Jensen et al., 2002; Brandt et al., 2004). One study reported that over 61% of visual display terminal users experienced neck/shoulder discomfort determined through questionnaires and a physiotherapist's examination (Bergqvist et al., 1995).

Prolonged static posture due to high work demand can generate negative muscular responses such as ischemia/hypoxia (Merletti et al., 1984) and lead to neck muscle fatigue. In the presence of ischemia, oxygen supply to blood is hindered (Griffin et al., 2001) and in the absence of adequate oxygen supply, anaerobic muscle metabolism occurs with the inevitable accumulation of lactate in the muscle (di Prampero and Ferretti, 1999) resulting in transient discomfort in the muscle tissue. Lactate accumulation results in reduced production of ATP, thereby accelerating fatigue (Westerblad et al., 2010). These physiological responses result in changes in the electrical activity of the muscles measured through electromyography. As the muscle fatigues, there is a loss in the force-generating capacity of individual motor units and to maintain the posture, the central nervous system (CNS) gradually recruits new motor units, thereby increasing the measured magnitude (integrated EMG) of the signal (Bosch et al., 2007; Vijendren et al., 2018). In some muscles, shifting from the engagement of fast-twitch muscle fibers to slow-twitch fibers can lead to a decrease in median frequency, but that has not been seen consistently in the muscles of the neck (Szeto et al., 2005).

Previous studies have demonstrated the positive effects of periodic breaks on fatigue development (Mclean et al., 2001; Sjøgaard et al., 1988; Griffin et al., 2001). Studies exploring the effect of breaks during surgical tasks (Engelmann et al., 2012; Hallbeck et al., 2017; Vijendren et al., 2018) and computer terminal work (Galinsky et al., 2000; Galinsky et al., 2007; Mclean et al., 2000) have shown that incorporating breaks between bouts of static posture can reduce participants' subjective discomfort and fatigue. Several previous studies have considered varied break durations and frequencies, but there is no consensus on the frequency or duration of the breaks (Galinsky et al., 2000; Galinsky et al., 2007; Mclean et al., 2000; von Thiele Schwarz et al., 2008). To successfully incorporate work breaks into practice, further quantitative research using objective measures of fatigue (EMG) may be needed to identify the optimal frequency and duration of breaks to reduce muscle fatigue.

The current study aims to explore the impact of varied work-rest intervals and how they can affect the development of neck and shoulder muscular fatigue during a simple standing task that requires static neck flexion. We hypothesize that the fatigue response of the neck and shoulder muscle will vary across the three different work-rest scheduling models.

3.2 Methods

3.2.1 Participants

Fourteen participants (seven men, seven women) from the Iowa State University student community completed data collection for all conditions in this study. Sixteen participants consented, but two participants were unable to complete the study. Participants were all adults between 18 and 65 years of age with no history of chronic problems in the neck, shoulders, back, legs, or neck, and all were right-handed. Mean (standard deviation) of anthropometric variables were as follows: age was 24 (4.2) years; whole body mass was 70.1(12.0) kg; stature was 172.2 (8.4) cm; standing elbow height was 112.3 (5.3) cm. Participants were all college students, so their experience in performing tasks similar to those in this study were comparable. Participants provided written informed consent prior to each day of participation.

3.2.2 Apparatus

Surface electromyography was used to collect muscle activity of the cervical extensor musculature and trapezius muscles using DELSYS® Bagnoli-16 EMG system and DE-2.1 sensors (Delsys Inc., MA). Eight surface electrodes were used to record the activity of the right and left pairs of the neck extensors at the C2/C3 level (SC2/3), the neck extensors at the C3/C4 level (SC3/4), and the right and left pairs of the trapezius at two locations of the upper trapezius (UT1 and UT2). The SC2/3 electrodes were placed bilaterally at the C2-C3 levels 1.5 cm from the midline of the spine (shaving as necessary). The SC3/4 electrodes were placed bilaterally at the C3-C4 level at a distance of 2.5 cm from the midline of the spine. These horizontal locations varied slightly from participant to participant, depending on the anthropometry of the neck so that the electrodes were placed over the belly of the most superficial muscle. Prior to electrode placement the skin was cleaned thoroughly with rubbing alcohol. While it is recognized that there are other neck extensor muscles within the pickup area of the surface electrodes for the neck extensors (SC2/3 and SC3/4), we will refer to these dependent variables as the SC2/3 and SC3/4 emphasizing the significant contributions of the semispinalis capitis and splenius capitis muscles to the captured signal. The location of the UT1 electrodes were on the superior surface of the trapezius over the belly of the muscle at that location, while the UT2 electrodes were 4cm inferior to that position. Surface EMG data collection was initiated every 30 seconds throughout the experiment and data were collected for four seconds at a frequency of 1024 Hz.

To capture the participants' subjective level of discomfort and fatigue, a simple visual analog scale (VAS) was used. Participants were asked to evaluate on a scale of 0 ("no discomfort") to 10 ("significant discomfort") their level of discomfort in the neck, shoulder, upper back, lower back, wrists/hands, knees, and ankles, as well as their overall fatigue (on a scale of 0 ("no fatigue") to 10 ("extremely fatigued")) (Hallbeck et al., 2017). Participants provided these data immediately before and immediately after the 63-minute experimental task.

3.2.3 Experimental Procedures

Participants came to the lab on three separate days, once for each work-rest condition. Participation sessions were separated by at least 48 hours to allow for recovery and reduce potential carry-over effects. Each day participants provided written informed consent. On the first day, basic anthropometric data including age, stature, body weight, standing elbow height, standing knee height, and hand dominance were collected.

Upon arrival each day, participants provided written informed consent to participate, and then they were led through a series of non-strenuous warm-up/stretch exercises that focused on the neck and shoulder region (flexion/extension, rolling and lateral motions of the neck). Surface electrodes were then affixed to the skin over the muscles to be sampled. The participants then provided baseline discomfort and fatigue level using the VAS to provide these baseline discomfort and fatigue scores. Participants were then asked to stand next to a table and perform a simple distractor task on a tablet computer for a total of 60 minutes with a total of 3 minutes of rest. While performing the distractor task (a simple computer game called "2048"), participants were required to flex their neck at a 45-degree angle. In pilot studies, this flexion angle was shown to generate muscular fatigue without engaging the flexion- relaxation phenomenon. At specified times, participants were given a short rest break - variable frequency and duration depending on the condition (Figure 3.1). The rest break schedule varied between conditions, but the total work time was 60 minutes and total rest time was three minutes for all conditions. The order in which the work-rest (W-R) conditions were presented was randomized across the three days. The experiment consisted of three work-rest conditions shown graphically in Figure 3.1.

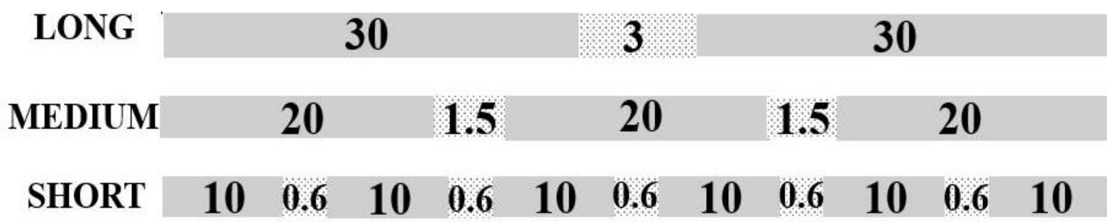


Figure 3.1: Graphical Presentation of the Three Work-Rest Conditions - All Times in Minutes. Darker Regions Represent Time When Neck is Flexed at a 45-Degree Angle (Work) And Lighter Regions Represent Time when the Head is in an Upright Neutral Posture (Rest)

The work surface was set at the height of 5 cm below the participant's standing elbow height, and the participant selected a comfortable (but not staggered) stance. This foot position was marked with tape so that the participant could return to this same foot position for every experimental condition across days. The 45-degree flexed neck position was then identified. Participants wore a baseball cap (secure fit) with a lightweight laser light attached to the bill. The participants were asked to flex their head-neck until a 45-degree angle was reached and tape was placed on the table marking the laser pointer location when the head was flexed to 45 degrees (Figure 3.2). During the neck flexion phases of the experiment, participants were required to keep the laser beam on the tape to ensure they maintained a continuous 45-degree head flexion posture. Once the participant was in position, the tablet computer was placed on the tabletop surface in front of them. The tablet was set at an angle of around 30 degrees, so the screen was slightly tilted towards the participant. The participants placed the tablet in a position that was within their comfortable line of vision and within a comfortable hand/arm reach. The distance from the tablet to the table edge was recorded and the tablet was placed in the same location for every experimental condition.

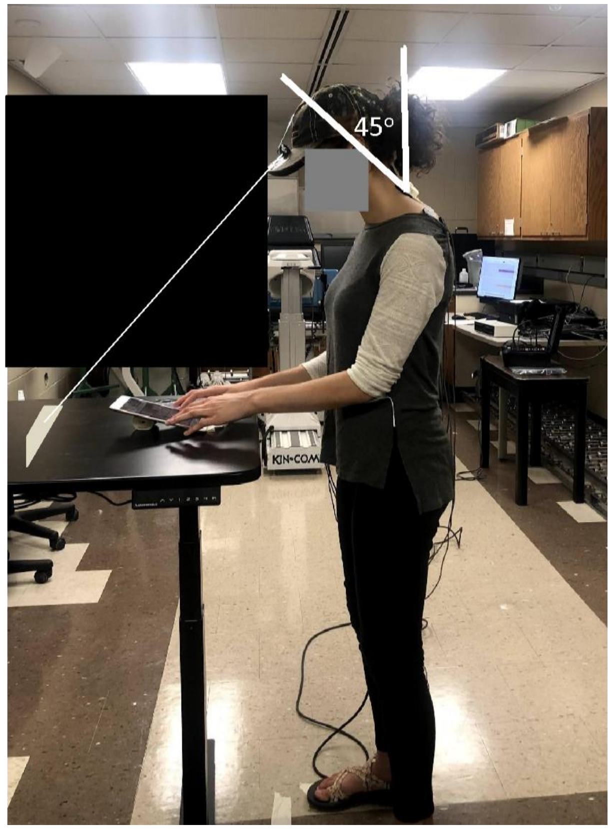


Figure 3.2: Experimental Apparatus Showing how the Laser Pointer Secured to the Bill of the Ballcap and the Masking Tape on the Table were used to Control 45-Degree Head-Neck Flexion During the Experimental Procedure. Also Shown in the Upper Extremity Posture while Interacting with the Tablet

During the work task, participants played a simple game on the tablet computer. They were required to keep both hands just above the tablet, even if only one hand was being used in playing the game. At thirty-second intervals, the participants were asked to pause in their game playing for a static (no motion to control for motion artefacts) EMG data collection. During this "pause", participants maintained the 45-degree head-neck flexion angle but placed the tips of their index fingers lightly against marked positions on the sides of the tablet (Figure 3.2). Once the participant achieved the required position, data were collected for four seconds and then the participants were instructed to resume the game-playing task. During the experimental task, an experimenter watched closely as the participant performed the task to ensure that the trunk remained in an upright posture.

At the designated time and for the designated duration as determined by the W-R condition assigned for that day and participant took a break. At the designated time, the experimenter said "rest" and the participants raised their head-neck to an upright neutral posture. They were allowed to move around, but they were asked to keep their head in the upright posture. At the completion of the break period, the experimenter said "return" and that was the signal for the participant to flex the head-neck so that the laser was focused on the tape target, and they were to resume the game on the tablet. This continued until the 63-minute total experiment duration was completed. At that time, the participant again completed the VAS form for body part discomfort and overall fatigue.

3.2.4 Data Processing

The first step in the processing of the EMG data was to apply a simple band-pass filter eliminating signal frequencies less than 10 Hz and greater than 400 Hz as well as 60 Hz and its aliases. These filtered data were then processed in two different ways – one in the time domain and one in the frequency domain. In the time domain, these data were demeaned, rectified, and then averaged over the full four-second data collection period creating the average value of the rectified amplitude (AVRA). Since the task was symmetric in the sagittal plane, the average of the right and left of each muscle was calculated. In the frequency domain, a Fast Fourier Transform (FFT) was applied to these data to calculate the median frequency (MDF) for each trial, and then the average of the right and left of each muscle was calculated. For each participant, there were 120 data points (two data collections/minute for 60 minutes (no data collected during the rest intervals)) of AVRA and MDF per condition. To control day-to-day and person-to-person variability, the AVRA data were normalized with respect to the muscle-specific average of these 120 data points. It is noteworthy that as the participants "settled in" to the experiment each day, there was often transient noise observed in the EMG signals early in the trial, so the first two minutes of data collection (four data points) were not considered in this analysis nominally rendering a total of 116 data points per participant per condition. For the AVRA and MDF variables, the difference between the average of the values in the first five minutes and the average of the values in the last five minutes of the 63-minute period (omitting the first two minutes from the analysis) were calculated. This difference in the values from the beginning to the end are simply noted by the variable names SC2/3, SC3/4, UT1 and UT2 and are considered in both the time and frequency domain. The processing of the subjective responses of the participants (discomfort and fatigue from the VAS) was simply to calculate the difference in these integer (0-10) values (the post-experiment value minus the pre-experiment value).

3.2.5 Experimental Design

The independent variable in this study was the work-rest cycle strategy (W-R), which had three levels of LONG, MEDIUM, and SHORT, and these profiles are shown in Figure 3.1.

The dependent variables considered in this study included both objective and subjective measures. The objective measures of fatigue were the changes in the AVRA (variable names: SC2/3, SC3/4, UT1 and UT2), and MDF (mfSC2/3, mfSC3/4, mfUT1 and mfUT2) from the beginning of the experiment to the end of the experiment of the right-left average of the sampled muscles (calculations and normalization described above in Section 2.4). The subjective measures were the change (end - beginning) in the discomfort of the neck, shoulders, upper back, lower back, wrists/hands, knees, and ankles/feet, as well as overall fatigue.

3.2.6 Statistical Analyses

A randomized block design was employed, with participants acting as a random-effects blocking variable, and W-R cycle strategy was considered as the treatment. Statistical software JMP Pro 15 was used to perform all the statistical analyses. Prior to conducting the statistical analysis, the assumptions of the ANOVA procedure were assessed. The normality of residuals and the equality of variances were tested for all dependent variables using Shapiro-Wilk test and O'Brien test, respectively. For those dependent variables that passed these tests, the one-way ANOVA was conducted. For those dependent variables that violated these assumptions, the non-parametric Kruskal-Wallis test was employed, as were the non-parametric Wilcoxon Signed-Rank tests for the post-hoc pairwise comparisons. A significance level of 0.05 was used as the criteria value for statistical significance in all tests. In order to maintain an overall significance level of 0.05, the Bonferroni correction was applied for the pairwise comparisons (0.05/3=0.0167). A Kruskal-Wallis test was used to evaluate the effects of different conditions on the change in the subjective discomfort and fatigue scores. A criterion significance level of 0.05 was again used.

3.3 Results

An analysis of the subjective measures of body part discomfort and overall fatigue showed statistically significant increases in all measures over the 63-minute task, with a particularly strong response of the neck and shoulder discomfort as well as the overall fatigue. This was true for all three W-R strategies (Table 3-1). The statistical analysis of the independent variable W-R, however, did not reveal any statistically significant differences in the increase in the discomfort or overall fatigue scores among the three different work-rest conditions tested (all p-values >0.05) indicating that while the participants were subjectively fatigued, there were no statistically significant differences as a function of work-rest schedule strategy.

With respect to the more objective EMG data, a comparison of the AVRA values collected at the beginning and the ending of the 63-minute task did show evidence of muscle fatigue development. Figures 3.3 and 3.4 show the responses of the AVRA for SC3/4, SC2/3, respectively. For both the SC2/3 and the SC3/4 sampling locations, there was a statistically significant increase in the average rectified value of the amplitude for medium and long condition – an indicator of muscle fatigue development. This response was not seen in the upper trapezius sampling locations and, consistent with the results of Szeto et al. (2005), none of the muscle sampled showed a statistically significant decrease in median frequency of the EMG signal.

In terms of testing the effects of work-rest scheduling strategies, the response of the SC3/4 at different levels of W-R was statistically significant (Kruskal-Wallis Test: p=0.0009), while the response of the SC2/3 - while demonstrating a similar trend - was not statistically significant. The pairwise comparison using the Wilcoxon Signed-Rank Test for the response of the SC3/4 showed that there is a significant difference between LONG and SHORT conditions (p=0.0004) and MEDIUM and SHORT conditions (p=0.0063) while LONG and MEDIUM conditions were not significantly different. The statistical analysis of the AVRA of the two levels of the trapezius did not show a statistically significant difference across levels of W-R. The analysis of the median frequency of all sampled muscles revealed small, inconsistent and non-significant differences.

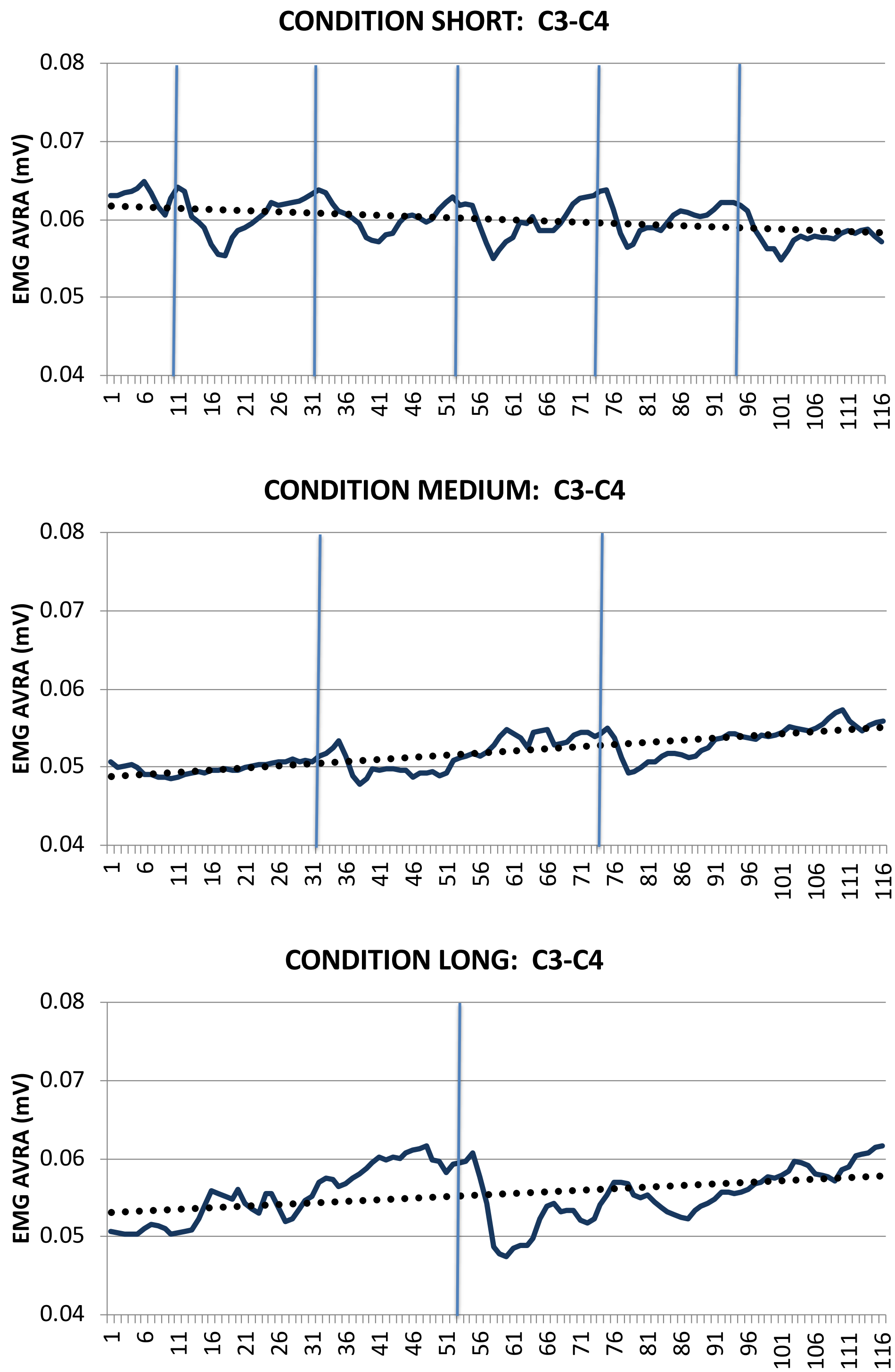
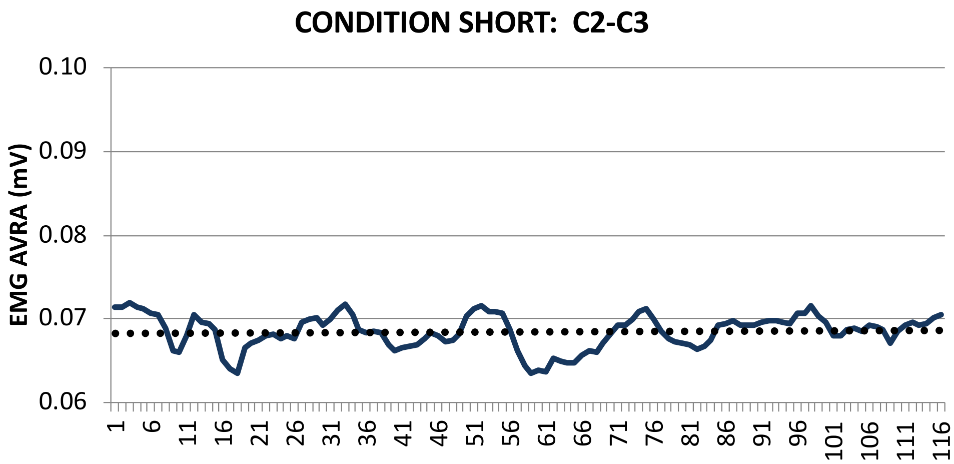
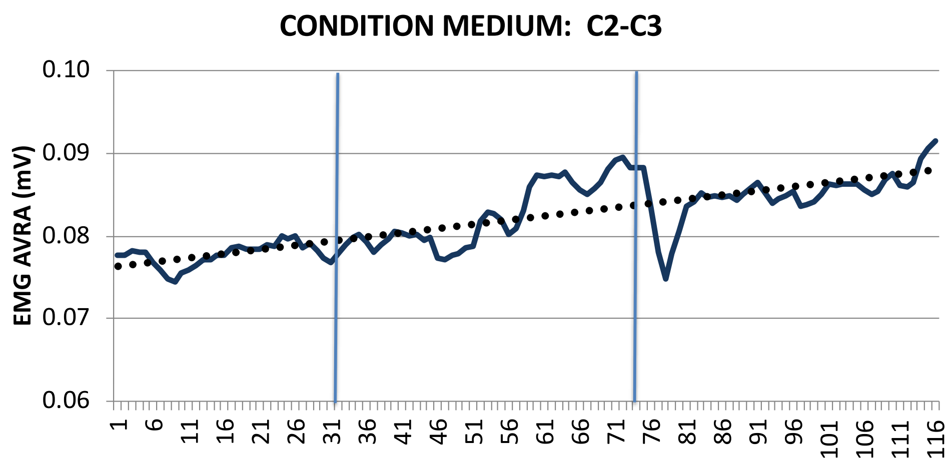


Figure 3.3: Average AVRA Values for SC3/4 (Averaged for Left and Right Muscles in mv) of all the Subjects over The Duration of the 116 Data Collections (One Collection Every 30 Seconds). The Post-Hoc Analyses Showed that the Response in the SHORT Condition was Significantly Different than that of the MEDIUM and LONG Conditions.





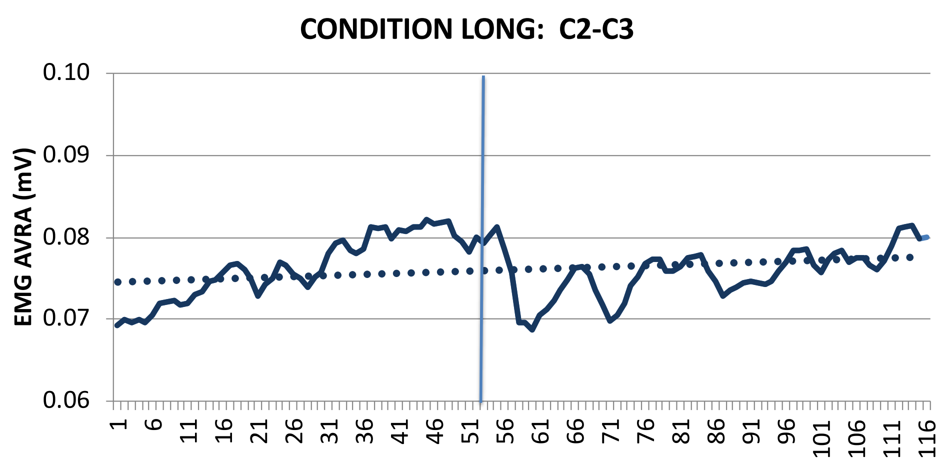


Figure 3.4: Average AVRA Values for SC2/3 (Averaged for Left and Right Muscles in mV) of all the Subjects over the Duration of the 116 Data Collections (One Collection Every 30 Seconds). While there were Trends that were Consistent with the Response ofSC3/4, these Responses were not Statistically Significant as They were for SC3/4.

Table 3-1 The Mean (Standard Deviation) of the Increase in Discomfort Scores and Overall Fatigue for Three Different Conditions (LONG, MEDIUM, And SHORT). * Indicates that the Increase over the 63-Minute Task was Statistically Significant (*** P<0.0001; ** P<0.001; * P<0.05). There were No Statistically Significant Differences in these Values as a Function of the W-R Condition.

	LONG	MEDIUM	SHORT
Neck	5.14 (2.63) ***	4.64 (2.71) ***	5.36 (2.56) ***
Shoulder	4.14 (2.54) **	3.68 (3.12) ***	3.79 (2.42) ***
Upper back	2.93 (2.16) **	2.93 (2.87) **	3.07 (2.70) **
Lower back	2.71 (2.67) **	2.14 (2.28) **	2.29 (2.55) *
Wrist/ hand	2.43 (2.56) *	1.93 (2.37) *	1.29 (1.90) **
Knee	3.14 (2.71) *	2.43 (2.68) **	2.79 (3.29) **
Ankle/ feet	5.00 (2.69) ***	4.43 (2.10) ***	4.57 (2.31) ***
Overall fatigue	5.07 (2.34) ***	4.71 (2.43) ***	4.43 (2.06) ***

3.4 Discussion

Physical fatigue is a highly subjective and challenging-to-measure human response to work. There are established objective physical responses of skeletal muscle that have been used extensively in ergonomics and work physiology literature and most of these have involved the capture and interpretation of the electrical activity of the muscles through surface electromyography. In the current study, both time-domain and frequency-domain electromyography measures of neck muscle fatigue were considered and, interestingly, the time-domain measures were responsive while the frequency domain measures were not. This result is consistent with the results of previous studies (Szeto et al., 2005; Vijendren et al., 2018) and may be the result of complex neural strategies that involve the increased recruitment of Type II muscle fibers that may be somewhat unique in the cervical muscles.

It is well established that the introduction of breaks during prolonged static neck flexion can delay the onset of neck and shoulder fatigue/pain (e.g. Genaidy et al., 1995; Vijendren et al., 2018). The aim of the current study was to explore the effects of different work-rest cycles on neck muscle fatigue development, while keeping the total work time and total rest time constant. The results support our hypothesis that different work-rest strategies will impact the development of muscular fatigue. The LONG and MEDIUM conditions showed significantly higher muscle fatigue (as demonstrated by an increase in the AVRA value for the C3-C4 cervical erector spinae) than the SHORT condition. However, following that trend, our hypothesis might have predicted that the LONG condition would have created even more muscular fatigue than the MEDIUM condition which was not the case. It appears that there may be thresholds/discontinuities in this response that may be important in the development of work-rest cycles for the attenuation of fatigue in the cervical musculature. Our results would indicate that the threshold is somewhere in between what we have called the MEDIUM and SHORT conditions. Future research may seek to elucidate more precisely this threshold value.

While these results demonstrated a significant effect of W-R on the SC3/4, there were no significant effects of W-R on the trapezius muscles or the SC2/3. To explore the non-response of the trapezius, it is important to remember that the upper extremities were not supported in the task. Some participants may have chosen to utilize a posture wherein the shoulders would be elevated, while others could choose to abduct the shoulders during the task, resulting in differing levels of trapezius muscle utilization. This variability in strategy would have a direct impact on the fatigue development in the trapezius muscles – creating variability that would make it difficult to find statistically significant trends. The case for SC2/3 is a bit more challenging to interpret but may again focus on different strategies for accomplishing the experimental task.

The SC2/3 muscles may be a bit more focused on maintaining head tilt angle and therefore may be performing a slightly different role during the experimental task. Tracking the sagittal plane angle at multiple levels in the cervical spine in future research might provide some insights to this slightly differential response.

The result of the current study showed that more frequent and shorter breaks reduce muscle fatigue – a result consistent with several field studies that have focused the subjective assessment of muscular fatigue and the effects of break duration and break activity. For example, Balci and Aghazadeh (2010) studied video display terminal workers. In this study the total work time was 120 minutes, and the total rest period was 30 minutes, but the distribution and duration of the resting bouts varied. The results of the body part discomfort analysis showed that the more frequent/short duration breaks resulted in lowered levels of body part discomfort. A study by Mclean et al. (2000) on computer terminal workers also suggested that microbreak can reduce discomfort significantly when applied every 20 minutes. Participants were assigned with no breaks, microbreaks at their wish, breaks at every 20 minutes and breaks every 40 minutes. The results obtained from this study based on a discomfort survey, showed that taking a break every 20 minutes reduced muscle discomfort significantly. The EMG-based results in the current study do support the results of these studies that have focused on the subjective assessments. Interestingly, our participants' subjective ratings did not show a clear advantage of one work-rest strategy over another. Finally, a study by Hallbeck and colleagues (2017) with surgeons as the occupational group, explored the effects of breaks, but this time by adding simple exercise. In this multi-site cohort study, the authors did a pre- post- survey of 56 attending surgeons – one day without microbreaks and one day with microbreaks. At intervals of 20-40 minutes, the surgeons were provided breaks lasting 1.5-2 minutes. The results showed that shoulder discomfort was significantly reduced and almost 60% of the surgeons reported improved physical performance (none noted decreased physical performance). Eighty-seven percent of the surgeon studies said that they would like to incorporate the microbreaks with exercises into their regular operating room routine. The break frequency and duration are similar to the MEDIUM and LONG conditions in the current study, indicating that the use of exercise during a break may further enhance the effectiveness of the breaks.

There are some limitations to the generalizability of these results that should be noted. First, the duration of our study is quite a bit shorter than the duration of tasks requiring static work postures experienced by workers in many occupations. In this controlled laboratory study, the allocated time proved to be enough to objectively develop muscle fatigue without creating any strain from prolonged neck flexion (Kromberg et al., 2020), but to achieve this muscular fatigue artificial constraints on participant mobility during this standing task was required to avoid small periods of recovery. More realistic scenarios (longer task duration, allowing participants to self-select break periods, neck stretching/motions during breaks) may prove to be a valuable next step in this line of research. Second, the sample of fourteen participants were relatively inexperienced in performing work requiring this posture. If our sample was larger and included workers experienced in work requiring these postures, different work strategies of this type of standing task might emerge. Finally, the participants were all healthy, pain-free individuals with no history of chronic neck problems. Future studies can examine the effect of breaks on the responses of those with chronic neck pain.

3.5 Conclusion

Overall, it appears that of the work-rest strategies tested, the best W-R period strategy for preventing neck muscle fatigue for flexion of 45 degrees is the shortest one tested with a 10-minute static work posture and 36 second relaxation period. This is shorter than most of the recommendations in the literature, which may balance the physiologic data with the acceptability of task interruption. Determining the best work-rest cycle strategy for performing work requiring neck flexion is important as more and more office work is performed on laptops and tablets. Other types of work may also require long periods of neck flexion to complete tasks. Future work can be done considering the effects of different strategies on the other aspects of an occupation including physical and cognitive performance (such as productivity and accuracy). It could help to determine the appropriate strategy for each specific occupation.

Statement of Authorship

AUTHOR CONTRIBUTIONS

Conception and design: PS, GM, HN, MSH

Analysis and interpretation: PS, HN, JK, GM, MSH

Data collection: PS, JK, HN

Writing the article: PS, HN, JK, GM, MSH

Critical revision of the article: GM, MSH

Final approval of the article: PS, HN, JK, GM, MSH

Statistical analysis: HN, PS

Overall responsibility: PS

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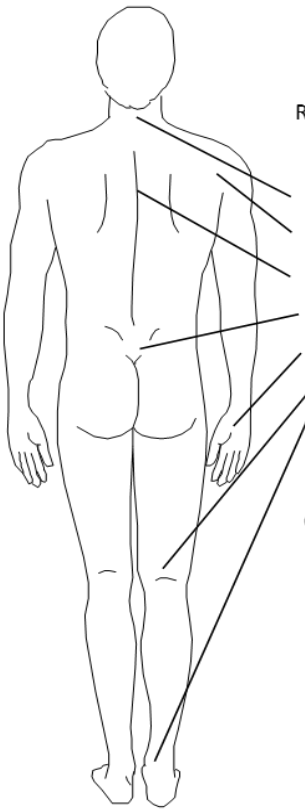
Appendix A. Discomfort and Fatigue Survey

Discomfort and Fatigue Survey

DATE:_______________CONDITION:_________
Participant ID #___________________________



Rate your level of **<u>discomfort</u>** in the table below.

BODY PART	PRIOR to Task	DURING Task	AFTER Task
SCALE	0 = no discomfort	→	10 = significant discomfort
Neck			
Shoulder			
Upper Back			
Lower Back			
Wrists/Hands			
Knees			
Ankles/Feet			

Circle your level of <u>overall fatigue</u>. (0 = no fatigue, 10 = extremely fatigued).

a. PRIOR to Task

0 1 2 3 4 5 6 7 8 9 10

b. DURING Task

0 1 2 3 4 5 6 7 8 9 10

c. AFTER Task

0 1 2 3 4 5 6 7 8 9 10

Appendix B. IRB Approval memo

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date:	09/24/2019
To:	Gary Mirka
From:	Office for Responsible Research
Title:	**Effects of Break Schedule on Neck Muscle Fatigue**
IRB ID:	**19-392**

Submission Type: Initial Submission **Review Type**: Expedited

Approval Date: 09/24/2019 **Approval Expiration Date: N/A**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp.**
- **Retain signed informed consent documents for 3 years after the close of the study, when** documented consent is required.

- **Obtain IRB approval prior to implementing any** changes to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of (1) all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of

those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to **post-approval monitoring** by **Iowa State University's Office for Responsible Research**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.

- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.

- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

Appendix C. Informed Consent Form

ISU IRB: 19-392-00
Approved Date: 09/24/2019
Expiration Date: N/A

INFORMED CONSENT FORM

Title of Study: **Effects of Break Schedule on Neck Muscle Fatigue**

Investigators: **Ms. Pramiti Sarker, Mr. Hamid Norasi, and Dr. Gary A. Mirka**

Invitation to be Part of a Research Study

You are invited to participate in a research study. This form describes a research project. It has information to help you decide whether you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary, and you can stop at any time. Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

Introduction and Purpose of the Study

The aim of this study is to evaluate how different work-rest schedules affect the neck muscle fatigue.

Eligibility to Participate

You are eligible to participate in this study if you are between age of 18-65 years and have no history of chronic pain in neck, shoulder, legs or back, area and are not currently experiencing neck pain.

You should not participate if you are less than 18 years of age or are over 65 years of age. You should also not participate if have a history of chronic pain in neck, shoulder, legs or back area or are currently experiencing neck pain. You should have capability to stand for 63 minutes.

Description of Study Procedures

If you agree to participate in this study, you will be asked to perform the following activities on three different days (three experimental sessions). On your first session, some simple body dimensions (age, stature, body weight, standing elbow and knee height) will be obtained with a tape measure and bathroom scale. Surface electrodes will be placed over muscles of your neck and shoulder region (Figure 2). Your skin will be cleaned with rubbing alcohol before attaching those electrodes with double sided tape. Researchers will help you to attach the electrodes. You will then be asked to stand next to a table and look at a tablet computer for 60 minutes (playing a simple game: Name 2048). At intermittent times, you will be given a short rest break. During rest breaks you continue to stand, but will be able to raise your hand to the vertical position. The rest break schedule and duration will be different for each of the three sessions, but the total time we will ask you hold your head in a 45-degree posture (Figure 1) will be 60 minutes each day and there will be a total of 3 minutes of breaks throughout each session. To help maintain the

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Expiration Date: N/A

required 45-degree head flexed posture, you will wear a basketball cap with laser light on the bill (Figure 3). A target on the table will be placed such that the laser will need to stay near the target to maintain the 45-degree head flexed posture. While you are performing this task, some muscles of the neck and shoulders will be monitored using sensors called surface electromyography. During data collection you will hear the word "pause" and we will ask you to touch the top of the tablet with your fingertips. A short time later you will hear "resume" and at that time you can go back to your tablet activity. Periodically, you will be given a rest break and told to look up from the tablet and hold your head in a vertical orientation for a specific time duration. You will be asked to fill out a form to record your level of fatigue.


Figure 1. 45-Degree Head Flexion Posture


Figure 2. Surface Electrodes.


Figure 3. Cap with Laser

Expected Time or Duration of Participation:

You will be asked to visit our lab on three different days with a gap of minimum 2 days between consecutive participation. On each day your participation will last for about 90 minutes. The rest break schedule and duration will be different for each of the three sessions, but the total time we will ask you hold your head in a 45-degree posture will be 60 minutes each day and there will be a total of 3 minutes of breaks throughout each session. The remaining time will be used to describe the experiment and fill out inform consent form and complete the survey.

Risks or Discomforts

While participating in this study you will likely experience some fatigue-related discomfort as your task will require to perform static contraction of neck at a flexion angle of 45 degrees. The duration of each neck flexion exertion will last for at least 10 minutes and at most 30 minutes uninterruptedly. Holding the head at this posture can create some fatigue in the neck and shoulder region. Prolonged standing can also create discomfort in your legs and back region. You should not participate in this study if you have a history chronic pain in neck, shoulder, leg and back areas or are currently experiencing pain in your neck. Please initial here if these do not apply to you______. If you begin to experience significant pain during the experiment, let the researchers know about it and the researchers will stop the experiment and your participation in the study will be concluded. You will be compensated for the time you have spent in the experiment. Also, if you experience an injury in the period between data collections (not associated with the study) you will not be allowed to continue participation. Because participants will not be able to go outside (for washroom, take a walk, etc.) during data collection, we will encourage you to use the restroom before electrodes are attached.

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Expiration Date: N/A

There may be risks or discomforts that are currently unforeseeable at this time. We will tell you about any significant new information we learn that may relate to your willingness to continue participating in this study.

Benefits to You and to Others

If you decide to participate in this study, there is no direct benefit to you as a participant. You may derive some indirect benefits including an understanding of ergonomics research methods. The result of the analysis will be used to inform our understanding of the relationship between work-rest cycles and the development of muscular fatigue.

Costs and Compensation

You will not have any costs from participation in this study. For participating in this research study, you will be paid $15 per hour of participation (prorated for partial hours completed). You will receive this compensation regardless of whether you were able to complete all three sessions. You will need to complete a simple form to receive a cash payment. This form will not be kept by the research team as a research record but will be maintained by an ISU financial secretary for audit purposes.

Please know that payments may be subject to tax withholding requirements, which vary depending upon whether you are a legal resident of the U.S. or another country. If required, taxes will be withheld from the payment you receive.

Your Rights as a Research Participant

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. On the survey, you can skip any questions that you do not wish to answer.

If you withdraw from the study early, the electrodes will be removed, and you will be free to go. We may end your participation in the study if we believe you are at risk of injury. If your participation ends before data collection is complete, information obtained from you will be destroyed and will not be used for further analysis.

If you have any questions *about the rights of research subjects or research-related injury*, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

Research Injury

Please tell the researchers if you believe you have any injuries caused by your participation in the study. The researchers may be able to assist you with locating emergency treatment, if appropriate, but you or your insurance company will be responsible for the cost. Eligible Iowa State University students may obtain treatment from the Thielen Student Health Center. By agreeing to participate in the study, you do not give up your right to seek payment if you are harmed as a result of being in this study. However, claims for payment sought from the

University will only be paid to the extent permitted by Iowa law, including the Iowa Tort Claims Act (Iowa Code Chapter 669).

Confidentiality

Research records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available without your permission. However, it is possible that other people and offices responsible for making sure research is done safely and responsibly will see your information. This includes auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy study records for quality assurance and data analysis. These records may contain private information.

To protect confidentiality of the study records, the following measures will be taken: subjects will be assigned a unique code (study key) and letter and will be used on forms instead of their name, all data will be stored in a locked cabinet in the office of the principal investigator and all data will be saved in a password protected computer in the lab which will only be accessed by the researchers from this study. At the end of data collection, the study key will be destroyed.

To protect your confidentiality when results are reported, all results will be reported in aggregate. We will not report information that may identify any individuals.

Future Use of Your Information

Information about you, including your data, will *only* be used by the research team for the project described in this document.

CHAPTER 4. USE OF INVENTORY CONTROL THEORY AND MULTI-OBJECTIVE OPTIMIZATION TO MODEL WORK-REST SCHEDULING

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Modified from a manuscript to be submitted to *Theoretical Issues in Ergonomics Science*

Abstract

The effectiveness of introducing breaks during work tasks is a controversial topic. Some researchers considered it a positive ergonomic intervention in the work environment as it enhanced performance by reducing fatigue. Others claimed it was a source of distractions creating a negative effect on performance. The current study was designed to develop a multi-objective optimization model that could determine the optimum number of breaks considering both muscle fatigue and performance. Inventory control theory was applied to develop the model and find optimum number of breaks. An optimum number of breaks would reduce the negative impact of muscle fatigue and minimize the impact on performance. Work with a laparoscopic simulator was chosen as a work task. To develop this model, 17 subjects were asked to practice with the laparoscopic simulator and learn how to operate laparoscopic instruments. When they were proficient, they participated in five experimental sessions (each consisting of 23 minutes of work with a laparoscopic simulator) for five different conditions. The five sessions had five

different work-rest schedules. These conditions aimed to observe the effect of a work-rest schedule on muscle fatigue development and performance. An equation describing the relationship between fatigue vs the number of breaks and an equation describing the relationship between performance vs the number of breaks were derived. The equations showed conflicting relations with the number of breaks. Hence, they formed a multi-objective problem, the solution to which returned the optimum number of breaks. The model was also expanded to explore the effects of inter-individual variability on these predictions by finding the number of breaks for different percentiles of performance and fatigue.

4.1 Introduction

Work-breaks can reduce muscle fatigue and may improve performance/ productivity (Dorion and Darveau, 2013; Hallbeck et al., 2017). There are many studies that have explored the effects of introducing breaks on muscle fatigue reduction (e.g., Vijendren et al., 2018; Hallbeck et al., 2017; Sarker et al., 2021); however, there are only a few studies that have quantitively analyzed the impact of breaks on worker performance (e.g., Hallbeck et al., 2017; Nakphet et al., 2015; Dorion and Darveau, 2010). The literature on the effects of rest breaks on work performance is unclear in its findings. Some studies showed the negative impact of breaks on worker performance (e.g., Henning et al., 1989), whereas some found a positive impact of introducing breaks during work (e.g., Hallbeck et al., 2017), and some studies did not find any effect of breaks on performance (e.g., Komorowski et al., 2015).

Though it is well established that short, frequent breaks can moderate increase in muscle fatigue (Rohmert, 1973), there is still uncertainty as to the optimal frequency and duration of work breaks. Frequent and short breaks can affect the workers' performance and some white-collar workers, such as surgeons, are not willing to accept breaks during their work performance. For example, surgeons may consider the implementation of the break as “unsurgical”, “unwelcoming”, and “disturbing” (Engelmann et al. 2012). Further, it has been noted that disruption during surgery can be a source of surgical error (Wiegmann et al., 2007). These authors note that frequent breaks can impede good communication among surgical teams, and lack of communication results in distraction and surgical error. After reviewing the previous literature on the relationship between work breaks and task performance, the effect of work breaks on human performance remains unclear and may rely heavily on the nature of the work being performed. In Chapter 3, we found a similarity between the effect of break on fatigue development (neck muscle) with inventory control model. The effect of breaks on performance was not studied. Therefore, in this study, we designed an experiment to gather empirical data to directly explore the effect of work breaks on performance/productivity and muscle fatigue and explored the utility of inventory control theory models in the modeling of the muscle fatigue and recovery process. In the next section, we are going to provide a brief description of inventory control models so that it is easier to draw the analogy of those models with fatigue development profile.

4.1.1 Inventory Control Theory

4.1.1.1 Inventory Control Theory Models

Inventory control theories are essential in the field of logistics management. These models are used to determine the optimum number of products in order to minimize production costs. Producers often face a dilemma to decide on the required number of products to produce. If they fail to manufacture enough products, they will miss the sale. Moreover, producing products in a repetitive lot will increase their fixed cost.

On the other hand, if they produce more products than the demand, it will increase their holding cost. Inventory control theories help the manufacturer to produce the required number of products that minimizes total (holding and production) costs. Inventory control theories constitute a vital part of this proposal, as an analogy can be drawn between inventory control theory and muscle fatigue development.

4.1.1.1.1 Economic Order Quantity (EOQ) Model

The most popular inventory control model is Economic Order Quantity (EOQ). The term EOQ means the optimum number of products to be ordered that can optimize total costs. The total cost calculated by the model is as follows:

$$\text{Total Production Cost} = H \times Q/2 + F \times A/Q + PQ \qquad (3)$$

Where: H=Holding cost per unit of the product, P= Price to produce each item, F= Fixed cost of each production cycle, A= Annual demand, Q= Lot size. Thus, A/Q= The number of orders.

The model tries to minimize the total production cost of the above equation through determining the economic order quantity, Q. It has some assumptions to determine the optimum order quantity. The assumptions are the constant demand, holding, and cost to produce/order per unit of product. The deterministic assumptions make the mathematical model simple, but for most companies, they are not true in real life. These assumptions become the limitations of the model. The EOQ model also assumes that all the products are delivered/ produced at the instance of time (t_1=0) which is also not true for most of the manufactures in real life. Instead of these limitations, the model helps companies to reduce the loss that is incurred from holding up the cash (Figure 4.1).

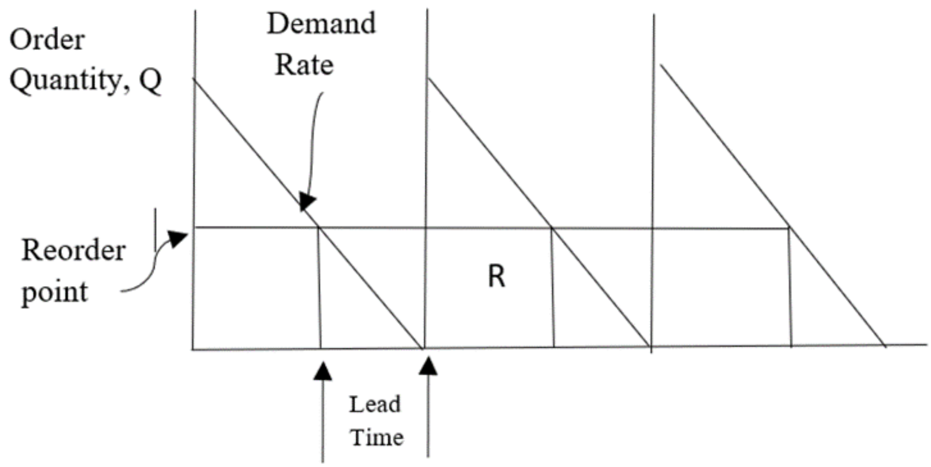


Figure 4.1: Representation of Economic Order Quantity Model

4.1.1.1.2 Economic Production Quantity (EPQ) Model

Economic Production Quantity (EPQ) is an extension of EOQ model. It overcomes one of the limitations of EOQ model. EOQ model assumes that all the products are delivered to the customer when the order is complete, whereas the EPQ model assumes that delivery and production occur simultaneously. Therefore, the product is being delivered incrementally. It updates the assumption of demand of the EOQ model. The model assumes that demand is not only constant but also continuous. All other assumptions are the same as the EOQ model. It assumes to have constant lead time, constant purchase price of the product, and constant production rate. The model also runs to find out the economic quantity of a single product like the EOQ model. Though it has similar assumptions to the EOQ model, the updated demand assumption makes the EPQ model more realistic than the EOQ model (Figure 4.4).

4.1.1.1.3 Other Models

There are some other models available in inventory management to obtain an optimum number of products. The names of the models are Newsvendor Model, Base Stock Model, Dynamic Lot Size Model or Wanger-Whitin Model, Economic Lot Scheduling Model, etc. EOQ model is the basis of these models. Each of these models has updated at least one assumption of the EOQ model. For instance, the Newsvendor problem is well applied when the product is perishable, and demand is random instead of being constant. There is only one-time replenishment in Newsvendor Model. In the Base-Stock Model, there are multiple replenishments, and demand is also random. Dynamic lot size works well when demand varies in a deterministic way. Economic lot scheduling best fits for determining the optimum quantity of multiple products. Apart from these popular models, different features have been added to the base model to fit the real-life scenario better. For example, stochastic demand instead of deterministic demand, variable price instead of constant price, presence of continuous lead time, finite time horizon instead of infinite etc. All these models have been developed over the years to determine optimum product quantity that matches the different scenarios of different companies

4.2 Research Questions and Hypotheses

Musculoskeletal disorders (MSDs) are prevalent in many occupational settings. Some studies suggest that breaks can reduce the prevalence of MSDs among workers by reducing muscle fatigue. Still, their suggestions on the type of breaks vary in duration and frequency. Most of the empirical studies, which are performed on breaks, either replicate a work task in a laboratory, or explore subjective assessments of real-life work. Mere subjective assessment of a task does not always reflect the muscle stress, strain, and fatigue experienced by the workers. Some studies (Mital et al., 1991, Konz, 1998) provided thought of optimizing fatigue and performance, but they emphasized on reviewing previous articles to show the importance of optimizing fatigue and performance. They did not apply any objective measure of fatigue. Mital et al., (1991) urged the need for objective measure of fatigue and thought a performance vs time curve could provide a better insight to model optimization model. As no study was found in the literature that had developed a model considering the relationship of both performance and muscle fatigue with breaks simultaneously, there is a need to develop an analytical model that can predict the optimal frequency of breaks considering both muscle fatigue and worker performance.

The present study aims to design an optimization-based mathematical model overcoming the limitations of the previous studies, that will determine the optimum number and duration of breaks for an individual performing a physically fatiguing task on a laparoscopic surgery simulator. During the optimization modeling, the model will seek to balance muscle fatigue development (physiological cost) and task performance simultaneously. The model will try to answer two research questions through the development of mathematical equations:

i) Can an inventory control model be used as an analytical tool to model fatigue development and then use the inventory control results to develop a multi-criterion optimization model to find the optimum number and duration of breaks that balance muscle fatigue development and performance?

ii) How are the optimal frequency and duration of breaks affected by inter-individual variability?

To find the optimum work-rest schedule which considers both physiological and performance loss costs, we hypothesize that more frequent breaks will reduce the physiological cost of the workers but increase the performance loss cost. Conversely, less frequent, and longer breaks will increase physiological costs but decrease performance loss costs. Therefore, this conflict creates a multi-objective optimization problem having two contradictory objectives: minimizing the physiological cost and maximizing performance/productivity.

4.3 Methods

4.3.1 Participants

Participants (ten males and ten females) were selected from the Iowa State University community. Participants were between the age of 18-65 years old. Participants did not have any current or chronic history of pain or injury in their low back, neck, shoulder, and upper extremities. Two subjects dropped out of data collection after completing half of the trials and one subject's data was excessively noisy, due to poor experimental conditions. Hence, the final data set consisted of data from 17 subjects (seven males and ten females).

4.3.2 Apparatus

4.3.2.1 Data Collection Apparatus

Surface electromyography was used to collect data on shoulder muscles using DELSYS® Bagnoli-16 EMG system and DE-2.1 sensors (Delsys Inc., MA). Six bipolar silver/silver chloride surface electrodes were used to record the right and left pairs of the shoulder muscles' activity at the anterior, medial, and posterior deltoid muscles. The electrodes were placed maintaining SENIAM standard (Hermens et al., 2000) (Figure 4.2). These locations varied slightly from participant to participant, depending on the size of the shoulder muscles. Surface EMG data were collected on a predetermined schedule for twenty seconds at a frequency of 1024 Hz.

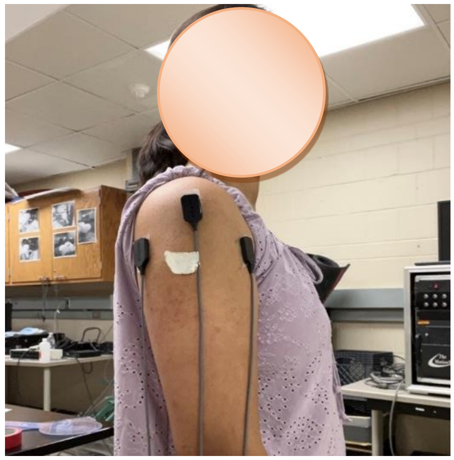


Figure 4.2: Placement of the Electrodes on Deltoid Muscles

4.3.2.2 Laparoscopic Simulator Apparatus

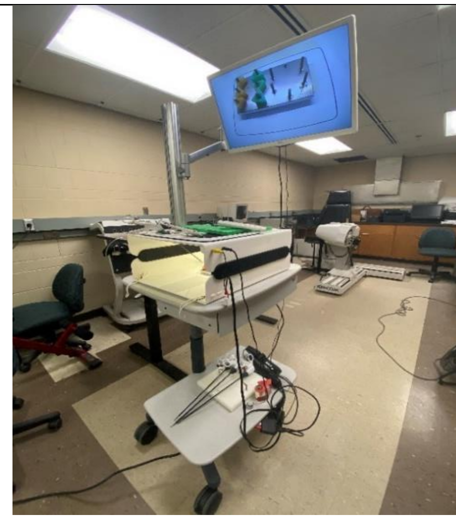
The fundamentals of laparoscopic simulator trainer (FLS, by Limbs &Things, Savannah, GA) (Figure 4.3a, b) was used in this experiment. The simulator had a test device with 24 pegs and 3 triangular blocks (Figure 4.3d) and disposable laparoscopic grasper- (Figure 4.3c). The artificial “skin” frame through which the instruments were inserted (seen in Figure 4.3a) was constructed from durable Neoprene and there were two pre-incised holes for the laparoscopic instruments. It also employed a USB camera which projected the working view to a monitor (Figure 4.3a). It has ambient light which can be turned on/ off as required.

4.3.3 Experimental Procedures

4.3.3.1 Training Days

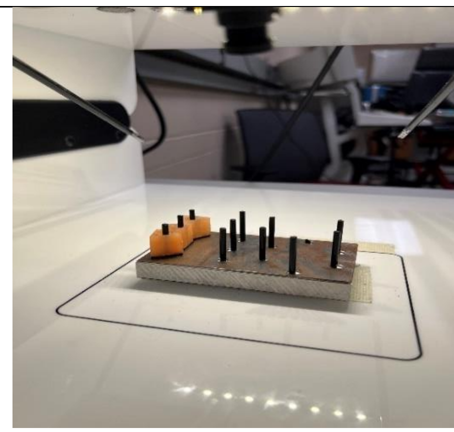
Participants were asked to come to the lab over two to four days (depending on how quickly they learned to work with the simulator. Definition of learning is explained later part of this section) to train themselves with the laparoscopic simulator and then five additional days to participate in the data collection portion of the experiment. Training with the simulator was crucial before participating in the actual experiments to overcome any learning effect on the

a) Subject Performing on Laparoscopic Simulator



b) Laparoscopic Simulator

c) Laparoscopic graspers



d) Test base with pegs and three triangular blocks from the Laparoscopic Simulator

Figure 4.3: Laparoscopic Simulator and its Different Parts

performance. As part of this study, the impact of rest breaks on performance was quantified. As performance should be only dependent on number of breaks, the subjects must be proficient on those data collection days. If they continued to learn to improve their performance, then their performance score will not be only dependent on number of breaks. Therefore, assurance of no significant learning on experimental days was essential. There were at least 24 hours between successive trials.

On each data collection day, upon arrival, participants were asked to read and sign the informed consent form. Then they were asked to do a warm-up focusing on the shoulder muscles. The warm-up session included arm circles (5 times each direction), crossing arm in front stretch (3 times each arm), touching toes (2 times), one hand touching shoulder, pull elbow straight back (each arm 3 times). On the first day, anthropometric data, (i.e., age, body mass, standing knee, elbow height) were collected. The participant was then asked to work on the laparoscopic simulator. Before starting the experiment, the laparoscopic simulator table was adjusted to a height 10 cm below the standing elbow height of the participant (Figure 4.3a). The height was set to accelerate fatigue development at a rate greater than that which would be seen in regular laparoscopic procedures. The monitor used to observe the handling of the blocks was set at a fixed distance (19 inch) from top of the simulation that had skin like texture and angle (25˚) for all participants throughout all experiments. As the simulator table was set according to the elbow height of the subject, the screen height was also adjustable based on the height of the subject. The simulator had two laparoscopic instruments to manipulate three plastic blocks. The participants were asked to lift the blocks one by one using the laparoscopic instruments in non-dominant hand (Figure 4.3c), transfer the block to the other laparoscopic instrument in dominant hand mid-air and place them on the table within the visible limit (Figure 4.3d) (in front of the base and within the visible limit of the monitor) as quickly as possible with the dominant hand. Just after placing the third block, they returned the blocks back in the original position. They were instructed to use their non-dominant hand to pick up the blocks from the table and then transfer the blocks to the instrument held in the dominant hand in mid-air and then return the block on the desired post with their dominant hand. Standardization of the work was essential as it would create the same workload for all. Transferring the three blocks to one side and returning them back into the original position was considered one complete task. The participants were allowed to participate in the actual experiments only when they stabilized the learning effect. We followed a step-by-step process for each subject to ensure they had stabilized the learning effect: 1) The subject was bound to practice one entire session (1 hour on the first day); 2) From the second day, the minimum time was recorded, and the subject continued repeating the task; 3) If they could complete the task within 20% of the least recorded time at least five consecutive times, then they were declared proficient; 4) If they achieved another minimum value, then they were observed to follow the same rule (Step #3 above) using the new recorded minimum time.

4.3.3.2 Experimental Trials

When the subjects were declared proficient, they were asked to come for five experimental sessions. Each day, upon arrival they went through a short warm-up session as in the training trials. Then the skin over the muscles of interest was cleaned using rubbing alcohol. After drying, the electrodes were placed on the skin over the muscles of interest. A reference electrode was placed on the elbow. Each participant worked for a total of 23 minutes (21 minutes of work and 2 minutes of break) with the laparoscopic simulator. Only the experimental condition (distribution of worktime and break time) varied from day to day. The five experimental conditions were i) Condition 1: two 10.5-minute work periods and one 2-minute break period; ii) Condition 2: three 7-minute work periods and two 1-minute break periods; iii) Condition 3: seven 3-minute work periods and six 20-second break periods; iv) Condition 4: nine 140-second work periods and eight 15-second break periods; v) Condition 5: twenty-one 1-minute work periods and twenty 6-second break periods. During each session, the performance score of cycles of three transfer completed was recorded. If a participant completed partial work, a fraction was calculated accordingly.

While participants were working on the laparoscopic simulator, electromyographic data were collected at 1024 Hz (duration was as long as the bout) were collected from their left and right anterior, medial, and posterior deltoid muscles. The data collection continued throughout each bout of 23 minutes. No data were collected during the rest periods between bouts.

4.3.4 Independent and Dependent Variables

The independent variable for this study was the work-rest schedule with five levels (as determined by the number of breaks (1, 2, 6, 8, 20)) and dependent variables considered both objective and subjective measures. The objective measures were 1) average (across bouts) decrease in MDF from the beginning of each bout of work to the end of each bout of work and 2) the performance/productivity of transferred blocks. If a participant completed partial work, a fraction was calculated accordingly. For example, after six complete tasks, if a participant picked up all the blocks and put two of them back to the correct place, then his/her score was (6+5/6) =6.83. EMG data were collected on the right and left anterior, medial, and posterior deltoid. While we collected data from six muscles, we only considered the activity of two deltoid muscles to develop the optimization model. This was because we found that left side deltoid muscles were not as active as the dominant side (right). In addition, we found that the posterior deltoids also did not participate actively in laparoscopic simulator work. As all the subjects were right-handed, the right anterior and medial deltoid muscles were the principal contributors, we considered the average MDF of the EMG data from these two muscles as our dependent variable. The subjective measures were the change (beginning-end) in the discomfort of the neck, shoulders, upper back, lower back, wrists/hands, knees, and ankles/feet, as well as overall fatigue using 0-10 Likert scale. (Appendix A).

4.3.5 Data Processing

4.3.5.1 EMG data processing

The EMG data were processed using in-house MATLAB code to obtain median frequency data. In MATLAB code, only the first 20 seconds of data (removing the first 10 seconds to overcome the effect of motion) and last 20 seconds of each work bout data were analyzed. Data were analyzed in the time and frequency domain, and later, only frequency domain data were presented in the results. In the frequency domain, data were demeaned, and then filtered to remove noise artifacts. To filter, data were passed through a bandpass filter of (10 Hz-400 Hz) at an order of 4. The filtered data were analyzed only in the frequency domain, and the median frequency (MDF) was calculated. The change (decrease) in MDF during each work time (bout) was considered the change in fatigue development. The difference in the median frequency of the EMG signal for each break and performance for each trial was recorded.

4.3.5.2 Performance Data Processing

Performance data were collected while the subject was working with the laparoscopic simulator. If the subject completes transfer of three blocks (pickup and returning) then it was counted as one complete task and the person achieved a score of 1. During each session, total performance score of cycles of three transfer completed was recorded. If a participant completes partial work before rest period starts, a fraction was recorded, and the subject would start working from the position where they left. A sheet helped to keep records of their task completion. If at the end of the task session (23 minutes), the subject completes partial task, then their score was recorded accordingly. For example, after six complete tasks, if a participant picked up all the blocks and put two of them back to the correct place, then his/her score was (6+5/6) =6.83. All performance scores of individual subjects of each individual day were collected. Then mean and standard deviation was calculated using EXCEL across the five work/rest conditions.

4.3.5.3 Subjective Data Processing

Subjective fatigue score before and after the 23 minutes of work were collected using the sheet in Appendix A. The beginning score of fatigue/ discomfort was subtracted from the ending fatigue/discomfort score and the average change in fatigue/discomfort change was calculated for each part of the body (as in the discomfort/fatigue collection sheet). Simple ANOVA procedures were used to test the hypothesis that these change values were statistically significantly different that zero.

4.4 Results

4.4.1 Subjective Result Analysis

A subjective result analysis on body part discomfort and overall fatigue showed a significant increase in fatigue after 23 minutes of laparoscopic work. The low back and upper back areas were not significantly fatigued in all the conditions but neck and shoulder area experienced considerable muscle fatigue. These data indicated that the subjects experienced muscle fatigue even after work of only 23 minutes and the laparoscopic table height was able to create muscle fatigue needed for this short data collection. However, there was no significant difference between the five conditions (after one-way ANOVA analysis on JMP). Subjective data were not applied to develop the model, as the data is not as specific and true representative of muscle fatigue as objective data (EMG).

Table 4-1 The Mean (Standard Deviation) of the Increase in Discomfort Scores and Overall Fatigue across 17 subjects for Five Different Conditions. * Indicates that the Increase over the 23-Minute Task was Statistically Significant.

	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Neck	1.67 (1.72)*	1.2(2.5)*	1.4(2.4)*	1.33(2.3)*	1.3(2.7)*
Shoulder	2(1.65)*	1.6(1.7)*	1.2(1.61)*	1.267(1.4)*	1.47(1.6)*
Upper Back	1.1(1.3)*	1.13(2.6)*	1(2.13)	1(2.4)	0.67(1.12)*
Lower Back	1.4(2.1)*	0.73(2.1)	1.2(2.6)	0.87(1.8)	0.867(1.9)*
Wrists	3.67(3.2)*	2.3(1.91)*	2.8(2.5)*	2.4(2.1)*	1.867(1.7)*
Knees	1.7(2.3)*	1(1.3)*	1.067(1.3)*	1.2(1.5)*	1.33(2.02)*
Ankles/feet	3.33(2.5)*	2.2(2.1)*	2.267(2.2)*	2.267(2.7)*	2.067(2.6)*

4.4.2 Inventory Control Theory Modeling: Modeling the Mean (Average Across Participants)

To formulate the optimization model, an analogy was created between an inventory model (Economic Production Quantity (EPQ)) and the fatigue development and recovery process model. As the EPQ model considers time for both the production and the changes in inventory, it can fully represent the cycle of production and consumption, which is similar to fatigue development and muscle recovery (Figure 4.6-Figure 4.10). The saw-tooth appearance of muscle fatigue development in (Figure 4.6-Figure 4.10) looks like the inventory replenishment model in Figure 4.4. Figures 4.4 and 4.5 can help to understand the analogy between the EPQ model and fatigue development model. Figure 4.4 shows that three cycles (for illustration) of production are needed to meet the demand of customer. On each cycle of production, a manufacturer needs t_1 time to produce Q number of products. It takes t_2 time to deliver them. When stock comes to zero, the second cycle starts to meet up with the demand of the customers. This process continues to repeat until the quantity of the total order was met.

Total Holding Cost= $H\times Q/2$ (4)

Where, H=Holding cost per unit of the product; t_1= Time of production; t_2= Delivery time; and Q=Lot size, P=Production rate, D=Demand rate, P-D=Net Production Rate (when production and delivery occur at the same time)

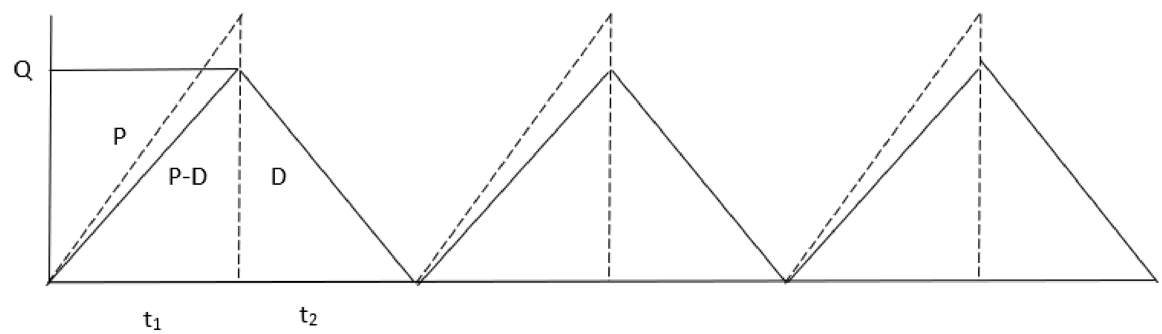


Figure 4.4: Economic Production Quantity (EPQ) Showing Time for both the Production and the Changes in Inventory

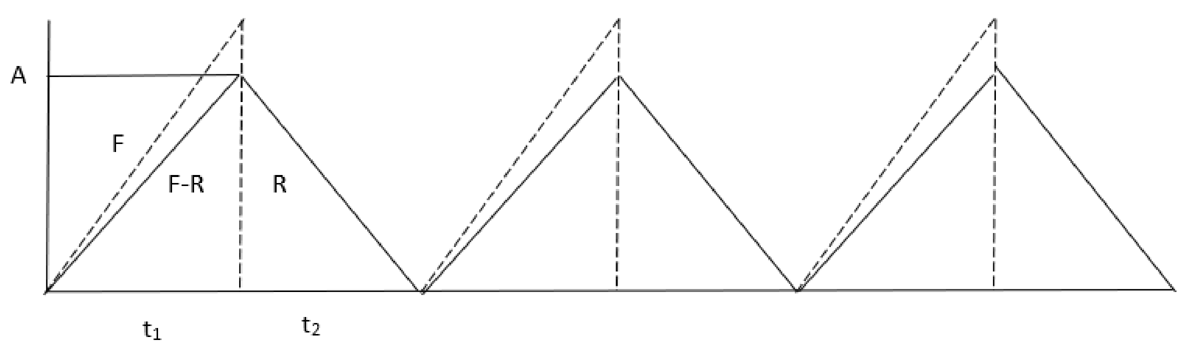


Figure 4.5 : Fatigue Development Model Showing Time for both the Fatigue Development Rate and Recovery

Similarly, physiological holding Cost= $H\times A/2$ (5)

where H=Holding cost per unit increase in fatigue development; F=Fatigue development rate; R=Recovery rate; A= Muscle fatigue level (change in MDF value per bout) F-R=Net fatigue development rate (when fatigue and recovery occur at the same time). For ease of illustration, holding costs are considered constant. Therefore, only a change in A, an increase in the fatigue development per bout, will decide the physiological cost. This variable is a function of the number of breaks as from the outcome of our experiment.

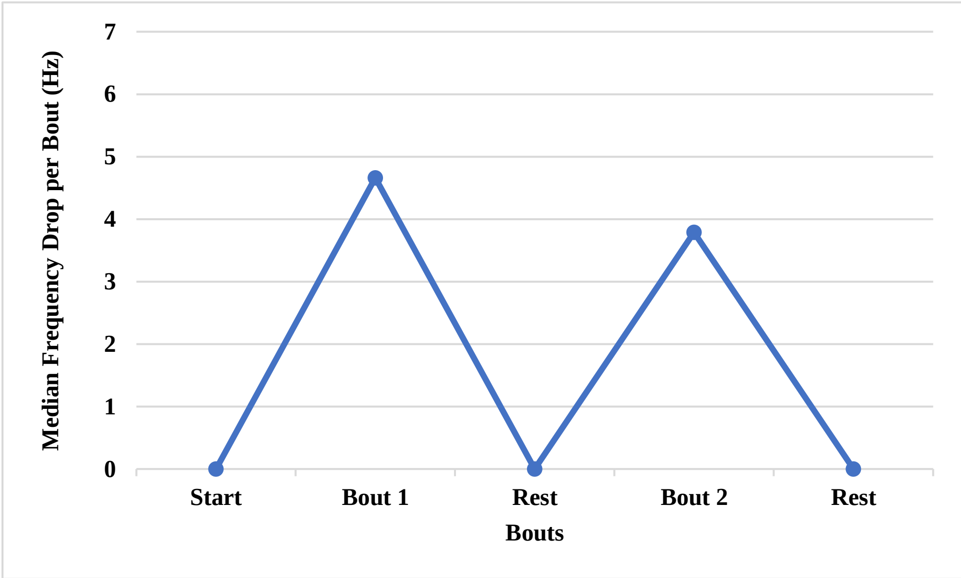


Figure 4.6: Fatigue Development Model Showing Time for both the Fatigue Development Rate and Recovery for Condition 1

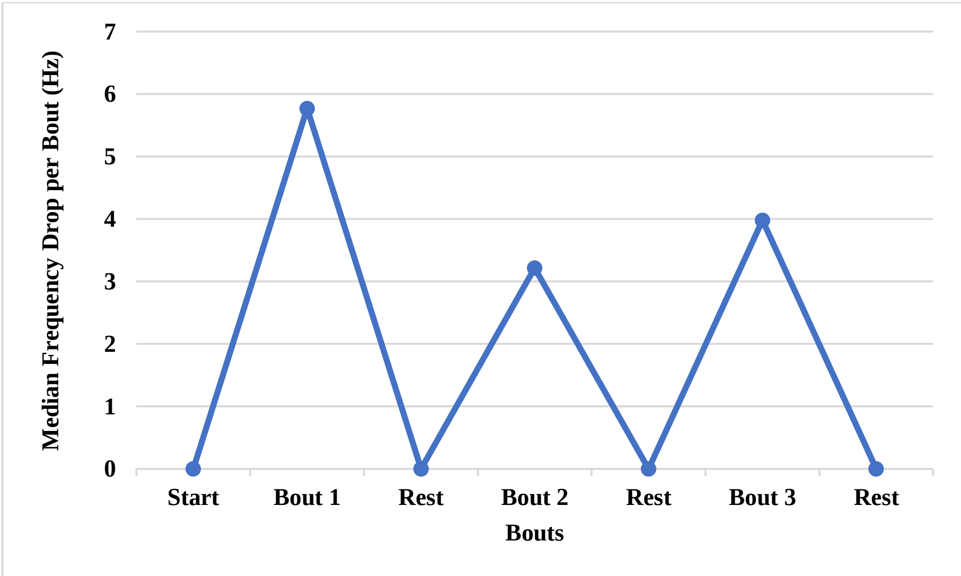


Figure 4.7: Fatigue Development Model Showing Time for both the Fatigue Development Rate and Recovery for Condition 2

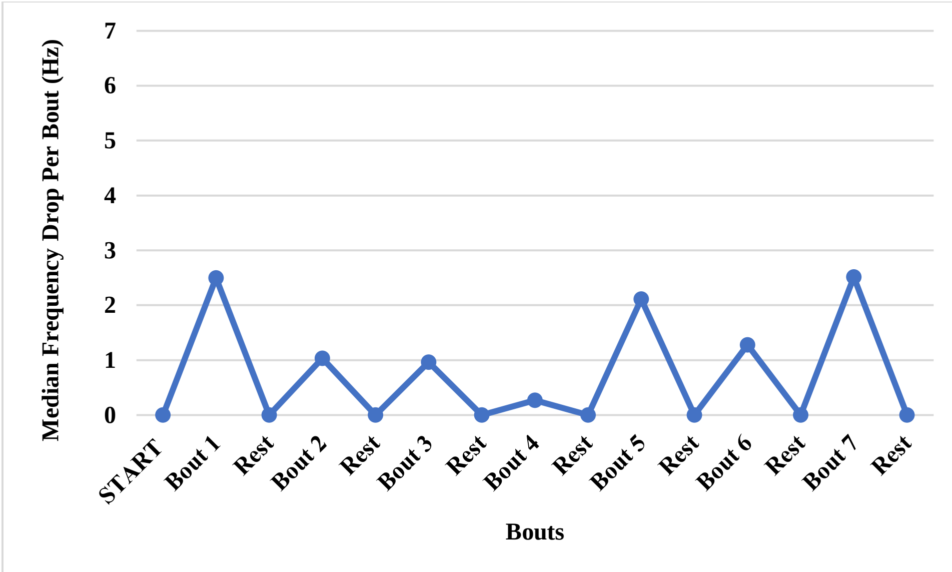


Figure 4.8: Fatigue Development Model Showing Time for both the Fatigue Development Rate and Recovery for Condition 3

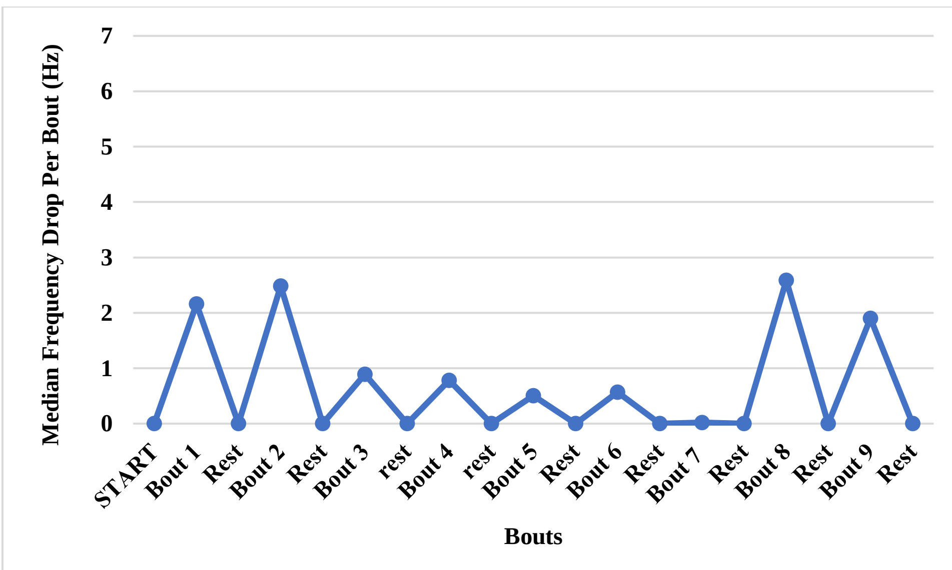


Figure 4.9: Fatigue Development Model Showing Time for both the Fatigue Development Rate and Recovery for Condition 4

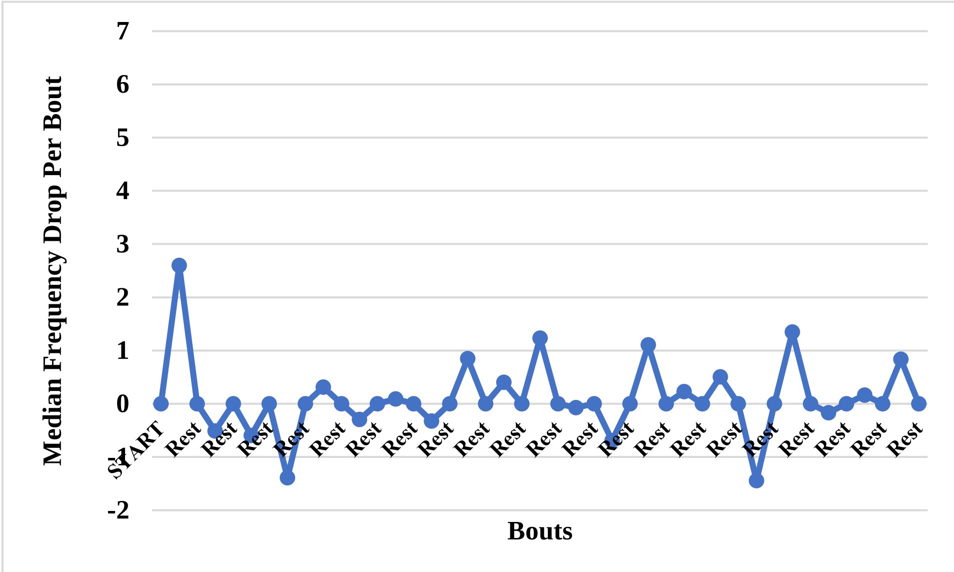


Figure 4.10: Fatigue Development Model Showing Time for both the Fatigue Development Rate and Recovery for Condition 5

4.4.2.1 Fatigue Profile

Previous literature shows that fatigue development decreases with the increase of the number of short and frequent breaks. However, the equation to express the relationship between the number of breaks and fatigue development is unknown. To develop the optimization model, we need to derive the equation for fatigue by number of breaks. This relationship can be expressed as an equation based on the average data collected from 17 participants.

The average change in the decrease of the fatigue development over the 17 participants was plotted against the number of breaks to obtain the equation (Figure 4.11). The newly developed equation represented a decrease in MDF per bout (fatigue development), *A*, as a function of the number of breaks, *x*, averaged across participants. The fatigue equation:

$$A = -79.45 * x \wedge 0.02081 + 84.5; \; (R^2 = 0.9729) \tag{6}$$

Where, *x*= number of breaks. The equation indicates that frequent breaks help to develop less muscle fatigue.

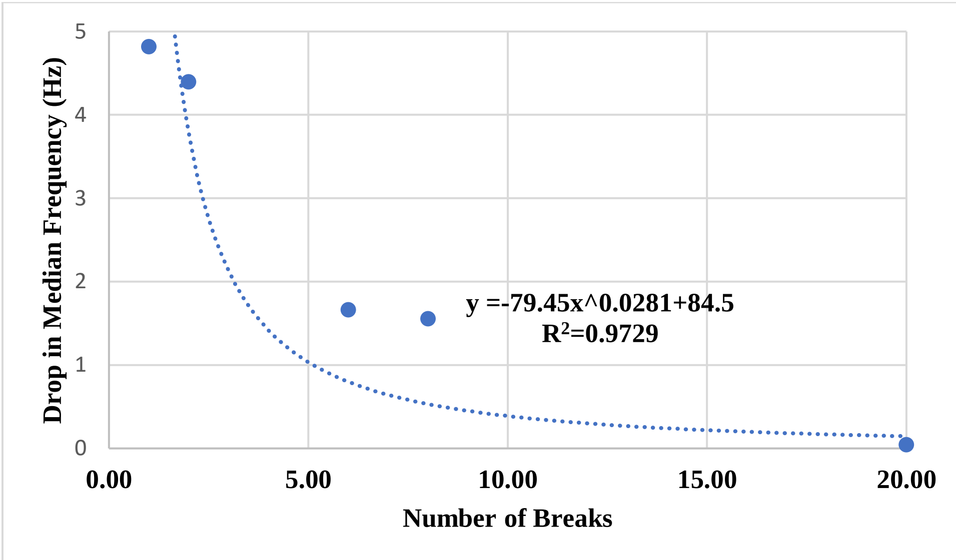


Figure 4.11: The Average Curve Shows the Relationship between a Decrease in MDF (right medial deltoid) with the Number of Breaks

4.4.2.2 Performance Profile

Similarly, performance data were collected simultaneously from 17 participants, and performance was plotted against the number of breaks to develop the equation which expresses the relationship and number of breaks. The curve that depicted the relationship between the number of breaks and performance, followed Equation (7) and looked like Figure 4.12.

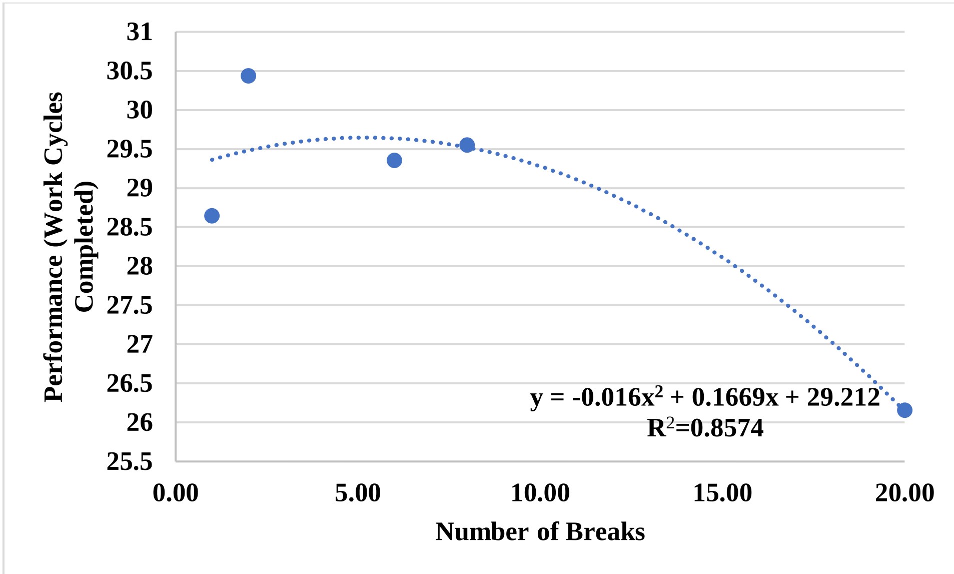


Figure 4.12: The Average Curve Shows the Relationship between a Decrease in Performance with Change in the Number of Breaks

The equation shows that performance decreases with an increase in the number of breaks to develop this model. The obtained equation represented performance as a function of the number of breaks, *x*, averaged across participants. The performance equation:

$$P = -0.016x^2 + 0.1669x + 29.212; (R^2 = 0.8574) \qquad (7)$$

Where *x*=number of breaks.

Figures 4.11 and 4.12 showed that fatigue development and performance decreased with an increase in the number of breaks. It implied that increasing the number of breaks indefinitely would result in decrease in fatigue(desired) and decrement in performance (not desired) or vice versa. Our objective was to determine the optimum number of breaks which can help minimize muscle fatigue and maximize performance simultaneously. Therefore, it is a multi-objective optimization problem consisting of two contradictory objective functions. The deterministic solution to that optimization model would minimize fatigue development and performance loss simultaneously.

4.4.2.3 Optimization Modeling

Equations 6 and 7 represent two curves. Both curves are decreasing with an increase in the number of breaks. The aim is to minimize fatigue development and maximize performance, but both cannot be minimized and maximized simultaneously, as minimizing fatigue development will minimize performance. Therefore, a multi-objective optimization problem was formulated that includes two conflicting objective functions. The multi-objective optimization problem is a mathematical problem that contains two or more conflicting objective functions—for example, minimizing the cost of the car while maximizing comfort. Mathematically,

$$\begin{aligned} &\textit{minimize} && f_m(x),\ m=1,2,\ldots.M \\ &\textit{subject to,} && g_j(x) \geq 0,\ j=1,2,\ldots.J \\ & && h_k(x)=0, \quad k=1,2,\ldots.K \\ & && x_i^{(L)} \leq x \leq x_j^{(U)} \quad i,j=1,2,\ldots..n \end{aligned}$$

where: f_m= objective functions; $g_j(x)$= inequality constraint; $h_k(x)$=equality constraint; x=design variable, $x_i^{(L)}$ =lower limit of x; $x_j^{(U)}$=upper limit of x.

The multi-objective optimization problem cannot provide a single solution; instead, it offers a set of Pareto optimal solutions. Pareto optimal solutions are also called non-dominated solutions. These solutions are a set of solutions that no member of the solution set can dominate over the other alternatives. Several popular methods can be used to obtain Pareto optimal solutions, i.e., i) Weighted Sum Method; ii) ε-Constraint Method; iii) Weighted Metric Method; iv) Genetic Algorithm. All these methods can solve the problem when it is deterministic. Each method has its advantages and disadvantages. The weighted sum method is simple, but it is hard to determine the weight of the objective functions. Moreover, Pareto optimal solution cannot be found when the problem is non-convex. Under the ε-constraint method, one objective function is converted to the main objective functions, and the other is converted to constraints and ε is employed as the upper bound of that constraint. The solution to the problem depends on the correct assumption of the value of the ε. The ε-constraint method is suitable for solving non-convex problems but can lead to misleading results if the value of ε is not assumed correctly. The weighted metric method can also find all Pareto optimal solutions, but the knowledge of the maximum and minimum value of the objective functions is required. The genetic algorithm provides all the Pareto optimal solutions but can generate different solutions to the same problem in each run.

For the data collected in the empirical phase of this pilot work, the optimization problem takes the following form:

$$\begin{aligned} &\text{minimize, } A = -79.45 * x^{\wedge}0.02081 + 84.5 \\ &\text{maximize, } P = -0.016x^2 + 0.1669x + 29.212 \\ &\text{subject to, } Ft_1 - Rt_2 = 0 \\ &x = T/(t_1 + t_2) \\ &x \geq 0;\ t_1 \geq 0;\ t_2 \geq 0;\ F \geq 0;\ R \geq 0; \end{aligned} \tag{8}$$

where A=Increase in AVRA, P=Magnitude of performance; t_1=Work time, t_2=Rest time, F=Fatigue development rate, R=Recovery rate, T=Total work time.

To solve this optimization problem, we applied the weighted sum method to obtain the optimum solutions. The pareto front obtained from our data using the weights ranging from 0 to 1 is presented in Figure 4.13. In the figure, we can see the graph of optimum number of breaks vs weights that minimize both fatigue and performance loss. When weight is 0, it implies that only performance is maximized and that happened at approximately 5 breaks (Figure 4.12). Therefore, pareto front chose the minimum number of breaks which is 5. When the weight is 1, the function minimized only fatigue, hence the multi-objective function returned 20 as optimum number of breaks, because increasing number of breaks will minimize fatigue. However, the aim of this model is to minimize muscle fatigue and maximize performance. Different values of the weight will provide different optimum number of breaks which will create pareto front. Each point of the pareto front minimizes fatigue and maximizes performance. However, determining the preferred value of the weight of the objective functions is a challenge. That is why a well-established method helped to decide the value of weight from the objective data and performance score collected assessment.

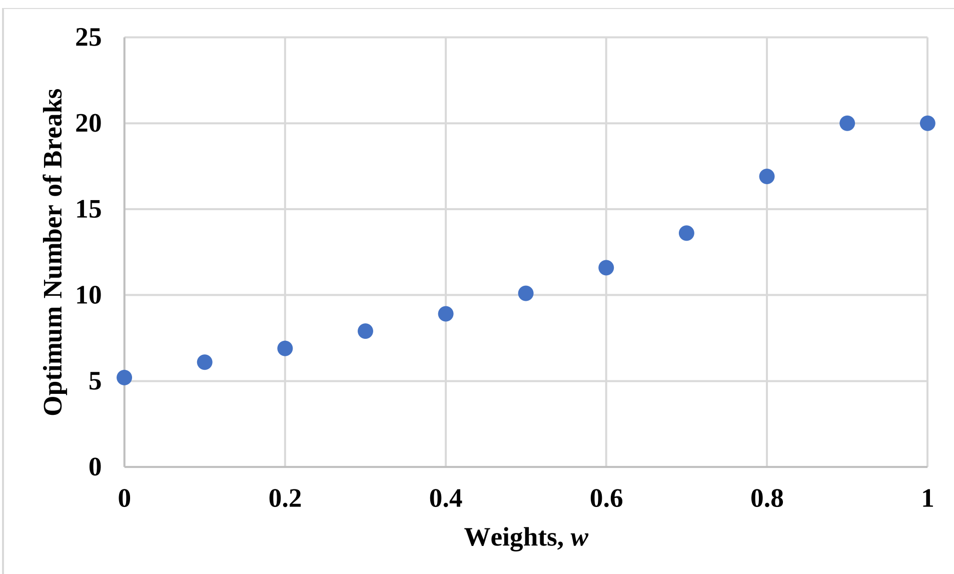


Figure 4.13: Pareto Front of the Multi-Objective Optimization for Different Values of Weight Ranging from 0 to 1

4.4.2.3.1 Determining Weight of Objective Functions

The multi-objective optimization provides multiple optimal solutions which are called pareto optimal solutions. In an actual case scenario, there should be one solution for one real life situation for any deterministic problem. The Weighted Average Method can provide one solution to the deterministic multi-objective optimization problem for each value of weight. However, the main challenge is to determine the value of the weight for each objective function. The weight of multi-objective optimization can be determined in several ways, through objective, subjective or both subjective/objective ways. Often experts use their experience to determine weight value. Subjective techniques generally reflect the opinion of the experts and quite often suggest equal distribution of weights to the competing objective functions. Popular subjective methods are the direct weighing method, pairwise comparison, AHP (Analytical Hierarchy Process), least square method, Delphi method, etc. Popular objective methods include methods like EWM (Entropy Weighting Method), horizontal and vertical method, multiple correlation coefficient etc. Among these methods EWM (Entropy Weighting Method) was chosen for the current study to determine weight of the multi-objective optimization because it considers relative importance of response variable without considering any opinion from the experimenter or expert (Kumar et al., 2020). This method determines weight based on the importance of output response. EWM method consists of following steps: i) determining objective function ii) development of decision matrix containing the response of the objective function's variable iii) normalization of decision matrix iv) probability and entropy v) divergence and vi) entropy weight. The steps are well established methods to determine weight and are found in several publications related to the field of manufacturing and engineering. The value of weight ranges from 0 to 1. To calculate the weight, we first need to derive the decision matrix of the response variable of the objective functions. The response variables in this model are fatigue and performance. Average value of Median Frequency Drop across 17 subjects, $F= [4.82, 4.84,1.11,1.31,0.25]$ and average performance change over 17 subjects from maximum performance, $P= [1.79, 0, 1.08,0.89,4.3]$. The calculations involved in this method (EWM) using the empirical data collected during the current study are described below:

Table 4-2 Calculation to Derive Weight Using Relative Entropy Weight Method

Objective Functions	Minimize Fatigue	Maximize Performance
Decision Matrix	*F= [4.82, 4.84,1.11,1.31,0.25]*	*P= [1.79, 0, 1.08,0.89,4.3]*
Normalize Decision Matrix	$F_{NDM} = \frac{F_{min}}{F} =$ *[0.053,0.053,0.23,0.19,1]*	$P_{NDM} = \frac{P}{P_{max}} =$ *[0.42, 0, 0.25, 0.21, 1]*
Probability	$P_{ij} = \frac{F_{NDM}}{\sum_i^j F_{NDM}}$ *= [0.034, 0.034,0.15,0.13,0.65]*	$P_{ij} = \frac{P_{NDM}}{\sum_i^j P_{NDM}}$ *= [0.22,0,0.13,0.11,0.53]*
Entropy	$E_n = \sum -(1/ln(5)) * P_{ij} * ln(P_{ij})$ = *0.656112793*	$E_n = \sum -(1/ln(5)) * P_{ij} * ln(P_{ij})$ = 0.734417
Divergence	*D=1-0.656112793=0.343887*	*D=1-0.734417=0.265583*
Weight	*w=0.34/0.60947027=0.57*	*w=0.43*

Table 4-2 shows the calculation of relative weight of fatigue and performance using Entropy Weight Method (EWM). One important point to note in this calculation is the calculation of the weight of performance. As entropy weight method assigns weight based on the variation of response. More weight is provided to the parameter which has higher variation than the variation of other variable. The value of performance was varying between 26.15-30.42 (Total score over 23 minutes of work). EWM identifies this variation as too low compared to the absolute value of performance. However, precision tasks like in laparoscopic surgery such variation means a higher difference in work (Milerad and Ericson, 1994). Therefore, to compute the value of weight of performance, the difference of performance with highest obtained value was considered, so that EWM can identify the significant variability. The calculation provided a value of w=0.57 for fatigue development function and w=0.43 for performance function. Therefore, weight, w=0.57 was chosen for fatigue as the best value of w. It implies that, more importance was provided to the fatigue than performance function.

4.4.2.3.2 Optimal Value Number of Breaks

Using the computed values for weighting the objective function values (0.57 for fatigue and 0.43 for performance) the multicriteria optimization formulation was derived:

$$\text{minimize, } A = (-79.45 * x^{\wedge}0.02081 + 84.5) \text{ weighting at } (0.57)$$

$$\text{maximize, } P = (-0.016x^2 + 0.1669x + 29.212) \text{ weighting at } (0.43)$$

$$\text{subject to, } Ft_1 - Rt_2 = 0$$

$$x = T/(t_1 + t_2)$$

$$x \geq 0;\ t_1 \geq 0;\ t_2 \geq 0;\ F \geq 0;\ R \geq 0;$$

where A=Increase in AVRA, P=Magnitude of performance; t_1=Work time, t_2=Rest time, F=Fatigue development rate, R=Recovery rate, T=Total work time. Solving this optimization function resulted in an optimal number of breaks of 11.1 over the total 23-minute work period.

4.4.3 Inventory Control Theory Modeling: Modeling Inter-Personal Variability

4.4.3.1 Effects of Inter-Participant Variability on Model

The previous section describes the multi-objective problem as a deterministic problem. The deterministic problem can provide a solution (the optimum number of breaks) without considering the inter-individual variability. However, in real life, the optimum number of breaks depends on the fatigue development rate and recovery rate. The fatigue development and recovery rate can vary significantly from person to person. Therefore, the optimum number of breaks could be a range of values rather than one single value. Running the model for different percentile values of fatigue and performance can be a way to determine optimum number of breaks for different individuals.

Different percentile combinations of fatigue and performance can predict the range of break values by implementing different values for a variable instead of using one single value. Monte Carlo simulation was used in our preliminary studies because it was not possible to predict the different values of the outcome easily due to the uncertainty of the input variables. At that time, Monte Carlo simulation helped to generate different values based on the probability distribution of the random variables and their parameters. Therefore, the values of the constants of the equations shown in Figures 4.12 & 4.13 will vary from person to person. In the current analysis, we have data from 17 subjects, and we can apply the data of the input variables to predict the output variables at different percentiles. Therefore, we used the data from all the subjects to predict distribution of the output variables and determine percentile values of fatigue and performance. The curve for different percentile values of fatigue and performance are presented in the following figures (Figure 4.14 and Figure 4.15).

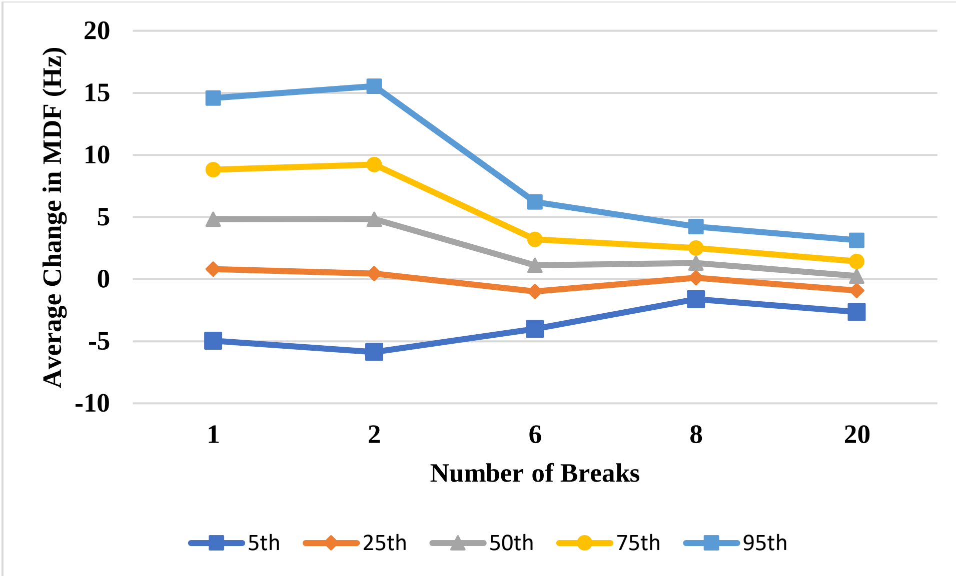


Figure 4.14: Predicted Fatigue Profile for Different Percentile Values (5^{th}, 25^{th}, 50^{th}, 75^{th}, 95^{th})

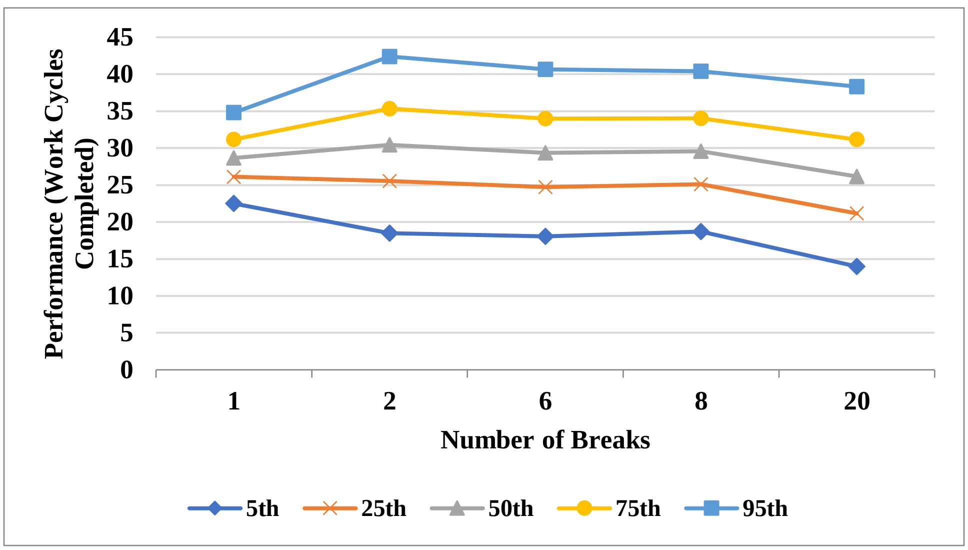


Figure 4.15: Predicted Performance Profile for Different Percentile Values (5^{th}, 25^{th}, 50^{th}, 75^{th}, 95^{th})

4.4.3.2 Effect of Inter-Individual Variability on the Optimum Result

Data from 17 subjects were applied to predict the distribution of the output variables (performance and fatigue). All the distributions were approximately normal distributions. The mean and variance of fatigue and performance (from the 17 subjects) at each level of breaks were applied to determine the various percentile values (5th, 25th, 50th, 75th and 95th) of fatigue development and performance. Later the values at each percentile were used to develop equations of fatigue and performance at 5th, 25th, 50th, 75th and 95th percentile. The different combinations of percentile values were run through the optimization model to obtain the optimum number of breaks. A weight of w=0.57 for fatigue and a weight of =0.43 for performance were applied to the model every time it was run for each percentile combination. The results have been tabulated in the Table. 4-3, which shows for an average number of performance (50th percentile) and average number of fatigue (50th percentile), the optimum number of breaks is 11.1, consistent with the prediction shown in Section 4.4.2.3. The result also shows that keeping a fixed fatigue level, with the increment of performance percentile increases the number of optimum number of breaks. For example, at 50th percentile level of fatigue, if we expect better performance, we should increase the number of breaks up to 14.4 breaks in 23 minutes of work. It raises the question of such frequent and breaks for a work of only 23 minutes. However, it is very unlikely to occur higher level of fatigue and performance at the same time. According to our hypothesis, and based on the data obtained, we can observe that at the higher level of fatigue, the performance score was at the lower percentile. This probabilistic model can provide results for these types of situations. Moreover, the model can also provide the optimum number of breaks for such uncommon situations. At a fixed performance level, the optimum number of breaks did not vary significantly as more weight was provided on performance maximization. This implies that when a fixed performance level is expected, then lower and higher levels of fatigue require almost equal number of breaks as most of the weight is assigned to performance. To provide a broader understanding of this process, we considered two approaches: fatigue as established with the average of the right side medial and anterior deltoid (as with the initial analysis) (Table 4-3) and then also with only the most responsive muscle (right medial deltoid) (Table 4-4). Not surprisingly, our subjective assessment of these two tables indicates that the two-muscle approach is a bit more stable than the one muscle model.

Table 4-3 Optimum Number of Breaks for Different Combinations of Performance and Fatigue Percentile Considering Right Medial and Anterior Deltoid Muscles using weight of 0.57 for Fatigue and 0.43 for Performance

		Performance Percentile				
		5	25	50	75	95
Fatigue Percentile	5	0	0	0	0	0
	25	0	12.7	12.8	13.3	16.4
	50	12.6	9.9	11.1	12	14.4
	75	12.6	9.9	11.1	12	14.1
	95	12.6	10	11.1	12	14.1

Table 4-4 Optimum Number of Breaks for Different Combinations of Performance and Fatigue Percentile Considering Only Right Medial Deltoid Muscle using weight of 0.57 for Fatigue and 0.43 for Performance

		Performance Percentile				
		5	25	50	75	95
Fatigue Percentile	5	0	0	0	0	0
	25	0	0	0	0	0
	50	15.4	12.4	12.5	12.9	14.7
	75	12.4	10.4	11.4	12.2	14.5
	95	12.2	9.7	11	11.9	14.1

4.5 Discussion

Laparoscopic surgery is often considered more physically demanding than open surgery (Berguer et al., 2001) because it requires concentration and good depth perception and these often lead to restrictions in freedom of movement which imposes prolonged static postures. Prolonged static postures create muscle fatigue. Introducing administrative ergonomic interventions like rest breaks can reduce the risk of developing musculoskeletal pain and disorders due to muscle fatigue. However, breaks are often not welcomed by medical professionals because they consider it a distraction and obstacle to complete their surgery in the desired time frame. Surgeons who are proficient in completing surgical tasks in short time frames are more negative about implementing breaks than surgeons who are slow performers or novices (Koshy et al., 2020). Surgeons often consider breaks as an obstacle to completing surgery in the shortest time -something in which they take pride. Interestingly there have been studies that have found no negative effect of breaks on performance/ productivity of the surgeons (Dorion and Darveau, 2013; Hallbeck et al., 2017). Despite the fact, surgeons do not accept breaks simply due to lack of mind set to accept it (Koshy et al., 2020). The aim of the current research was to develop an analytical model that can seek to determine the optimum number of breaks without considering any personal bias towards the implication of breaks during work. This calculated optimum number of breaks seeks to balance muscle fatigue development and performance/ productivity.

To develop the model, the effect of the number of breaks on performance and fatigue curve was studied. Based on previous literature on neck muscle fatigue (Sarker et al., 2021), we hypothesized that fatigue development decreases with increment of breaks. The fatigue vs number of breaks curve showed a similar trend that matched with our hypothesis. With increment of breaks, fatigue development decreased. When there was only 1 break in 23 minutes, the data showed highest muscle fatigue per bout and when there were 20 breaks in 23 minutes, the data showed lowest fatigue development per bout. We hypothesized that performance would decrease with the increase of the number of breaks, but performance curve (based on the data of 17 subjects) showed a bit of a different trend than what was hypothesized. Performance increased with the increasing number of breaks up to a certain level and then decreased (Figure 4.11). The probable reason behind this is the effect of fatigue on performance. Fatigue affects performance through decreased accuracy and increased errors in a non-surgical task during a surgical procedure (Dorion and Darveau, 2013). With the introduction of breaks, fatigue is reduced, and performance is enhanced up to a certain number of breaks. Then again when we increase the number of breaks, performance decreases, because too frequent breaks can increase distraction in work.

The current multi-objective optimization model developed from these two functions with a weight of 0.57 for fatigue and a weight of 0.43 for performance. The output determined 11.1 number of breaks in total work time of 23 minutes and the total duration of these breaks is 2 minutes. At first glance, this number of breaks seems large compared to the total duration of work. The number of breaks is also high if we compare with available studies in the literature that have suggested the number and the duration of breaks for surgical procedures. A study by (Dorion & Darveau, 2013) suggested 20 seconds of break every 20 minutes whereas Hallbeck et al., (2017) suggested 1.5-2 minutes of break per 20-40 minutes. Another study suggested one 5 minutes long break in 25 minutes of work (Engelmann et al., 2011). Dorion & Darveau suggested a 20 second break based on an experiment which included only two conditions: 1) with presence of formal micro-pause (MP) that includes 20 seconds break every 20 minutes 2) without formal MP. Considering these results, it would be suggested that there be a 20-second break every 20 minutes as a suggested intervention. Hallbeck et al., (2017) performed a questionnaire-based study on 56 attending surgeons after regular surgeries on two days. On the first day, surgeons performed their work without breaks and on the second day they performed their work with breaks. The intervention of breaks included a 1.5-2-minute pause with exercise every 20-40 minutes. 87% of the surgeons provided consent that would prefer to incorporate breaks during surgery. Hence, Hallbeck et al., (2017) suggested 1.5-2 minutes breaks every 20-40 minutes with exercise to reduce the negative impact of prolonged static posture; however, she faced resistance with the 2-minute interval as being too frequent. Again, they did not explore the options of different combinations of work-rest cycles. None of these previous studies captured muscle activity and observed the effect of breaks and performance to determine the optimum number of breaks among several other options that could exist.

The optimum number of breaks in the current study is much greater than the other studies available in literature. There are several experimental design factors that led to this higher number of breaks. For example, the laparoscopic table height was raised considerably higher than the typical laparoscopic table height. As laparoscopic instruments are longer than open surgery, the table height should be set at a lower height than open surgery according to a study by Berguer et al., (2001). They suggested that a table height for laparoscopic surgery such that the working instruments are at elbow height or 10 cm below elbow height of the surgeons (Berguer et al., 2001). Our higher setting was intentional. We set the table height higher specifically to accelerate the development of shoulder muscle fatigue to create a feasible experimental protocol.

In the current study, the table was set at 10 cm below elbow height which set the laparoscopic instruments approximately 10 cm above elbow height to work with the blocks. This produced the intended effect of accelerating shoulder muscle fatigue development. In real life, laparoscopic table height is typically lower, but surgery duration is considerably longer than the experimental set up in the current study. Developing the same level of fatigue in laboratory set up would require recruiting participants for long hours. It would decrease the probability of finding participants. Hence, the participants were recruited for experimental sessions of only 23 minutes duration on five different days thanks to the raised laparoscopic table height. That is why the optimum number of breaks is 11.1 from deterministic optimization model is not too unrealistic for 23 minutes of laparoscopic work. It is noteworthy that raising this table height had no impact on performance of the surgeons (Berguer et al., 2001). Hence, it did not affect the performance curve but accelerated the fatigue development. The term ‘break’ in the current study means to stop working with laparoscopic simulator instruments, keeping the hand straight by the side of the body and looking up with head in neutral position. The breaks did not include any exercise. Active breaks have been shown to reduce development of muscle fatigue more quickly than passive breaks (Dyke et al., 2014; Hallbeck et al., 2017). Introducing breaks without exercise or hand movement may lead to a higher number of breaks for 23 minutes of laparoscopic work.

The experiment was designed keeping in mind all possible real-life scenarios, but it could not overcome some limitations. One of the limitations of this study is that the optimization model was developed based on shoulder muscle fatigue only. It did not consider neck muscle fatigue. The experimental set up of the laparoscopic simulator imposed prolonged static neck extension position for the participants. Neck muscle showed less muscle activity in neck extension position than neck flexion and neutral position (Cheon et al, 2017). Therefore, the participants reported significant neck discomfort in neck area but due to low level muscle activity in SEMG, neck muscle fatigue development was not considered in the developing the optimization model. Experience of the participants was also a limitation of the study compared to real life study. The participants were neither attending surgeons nor resident surgeons. They were novice students at Iowa State University. Experience plays a vital role in muscle activity of laparoscopic surgeons. Study by Uhrich et al., (2001) showed that attending surgeons experience less muscle exertions than resident surgeons. Therefore, optimum number of breaks based on the fatigue data of novice participants of laparoscopic simulation may overestimate the number of breaks. Another limitation of the current model is that it considered only one parameter of and EMG signal (median frequency) and did not include amplitude (time domain) of the electromyographic data which may have provided another interesting perspective on this fatigue response. Noise in EMG makes interpretation of the time domain response challenging. To overcome this effect in our previous study (Chapter 3), we asked the subject to stand motionless periodically during data collection. This controlled for the motion artifact challenges. However, it was not possible in this experiment as we were also quantifying their performance and pausing work would impact their performance. Applying wireless EMG sensors can overcome this effect on EMG data and applying both parameters would potentially make the model more robust. Another limitation of the current study was the data collection for condition 5, where each bout was only 1-minute long. As we were collecting data for 20 seconds in beginning (discarding first 10 seconds data) and 20 seconds in the end, it provided us only 10 seconds gap between beginning and end. It led to some negative or very little change in fatigue development in condition 5. However, the effect of this limitation on result analysis is very low, because the trend shows that the fatigue development was decreasing with increment of breaks.

Despite the limitations of the study, this paper is a contribution to the field as it develops a new way of thinking to establish a model using inventory control theory that can explore other work rest schedule options. Inventory control theory can provide optimum number of products considering production and delivery as continuous variable. In a similar way, the current model considers the relationship of performance and fatigue continuous with respect to break. It enables to predict the effect of work-rest schedule option can be predicted before implementing a particular work-rest schedule in workplace. Moreover, at present more studies are considering production and delivery rate as probabilistic. The inventory control model also provided us with the idea that fatigue and performance could be probabilistic too. Considering that, it led our research to include inter-individual variability on the optimum result. The analytical model developed in the current study is free from these subjective influences. The present model may also be capable of developing similar optimization model in other sectors i.e., manufacturing. However, the model is based on intensity of exertion which created shoulder muscle fatigue in shorter duration of work. It means the 23 minutes of work in laparoscopic simulator represents longer duration of laparoscopic surgery work in real life situation. Future work can be done to develop this model overcoming this limitation. Future models can work on determining the total duration of laparoscopic work that is presented by short term fatiguing task in laboratory set up. The model will be more robust if the participants are real life workers instead of novice students from university who have no previous experience working in that situation. Using motion capturing IMUs, wireless EMG and including neck muscle fatigue can determine the optimum number of breaks more precisely.

Statement of Authorship

AUTHOR CONTRIBUTIONS

Conception and design: PS, GM. MSH

Analysis and interpretation: PS

Data collection: PS

Writing the article: PS, GM

Critical revision of the article: GM. MSH

Final approval of the article: PS, GM, MSH

Statistical analysis: PS

Overall responsibility: PS

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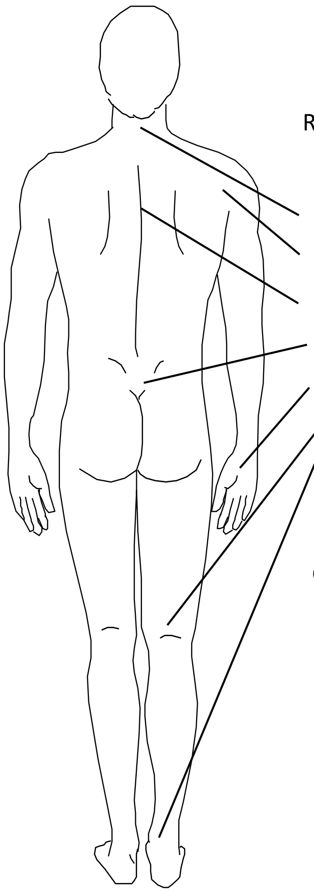
Appendix A. Discomfort and Fatigue Survey Sheet

Discomfort and Fatigue Survey

DATE:______________CONDITION:________
Participant ID #_________________________



Rate your level of **<u>discomfort</u>** in the table below.

BODY PART	**PRIOR to Task**	**DURING Task**	**AFTER Task**
SCALE	**0 = no discomfort**	**→**	**10 = significant discomfort**
Neck			
Shoulder			
Upper Back			
Lower Back			
Wrists/Hands			
Knees			
Ankles/Feet			

Circle your level of <u>overall fatigue</u>. (0 = no fatigue, 10 = extremely fatigued).

a. PRIOR to Task

0 1 2 3 4 5 6 7 8 9 10

b. DURING Task

0 1 2 3 4 5 6 7 8 9 10

c. AFTER Task

0 1 2 3 4 5 6 7 8 9 10

Appendix B. IRB Approval Memo

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office of Research Ethics
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 10/14/2021

To: Pramiti Sarker Gary Mirka

From: Office of Research Ethics

Title: Muscle Fatigue while Using a Laparoscopic Surgery Simulator

IRB ID: 21-364

Submission Type: Initial Submission **Review Type**: Expedited

Approval Date: 10/14/2021 **Approval Expiration Date:** N/A

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.

- **Retain signed informed consent documents for 3 years after the close of the study,** when documented consent is required**.**
- **Obtain IRB approval prior to implementing any changes** to the study or study materials.
- **Promptly inform the IRB of any addition of or change in federal funding for this study.** Approval of the protocol referenced above applies only to funding sources that are specifically identified in the corresponding IRB application.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected adverse experiences** involving risks to subjects or others; and (2) **any other unanticipated problems involving risks** to subjects or others.
- IRB approval means that you have met the requirements of federal regulations and ISU policies governing human subjects research. **Approval from other entities may also be needed.** For example, access to data from private records (e.g., student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of

those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **IRB approval in no way implies or guarantees that permission from these other entities will be granted.**

- Your research study may be subject to **post-approval monitoring by Iowa State University's Office of Research Ethics**. In some cases, it may also be subject to formal audit or inspection by federal agencies and study sponsors.

- Upon completion of the project, transfer of IRB oversight to another IRB, or departure of the PI and/or Supervising Investigator, please initiate a Project Closure to officially close the project. For information on instances when a study may be closed, please refer to the IRB Study Closure Policy.

If your study requires continuing review, indicated by a specific Approval Expiration Date above, you should:

- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.

- **Submit an application for Continuing Review** at least three to four weeks prior to the **Approval Expiration Date** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

Please don't hesitate to contact us if you have questions or concerns at 515-294-4566 or IRB@iastate.edu.

Appendix C. Informed Consent Form

ISU IRB: 21-364-00
Approved Date: 10/14/2021
Expiration Date: N/A

INFORMED CONSENT FORM

Title of Study: **Muscle Fatigue while Using a Laparoscopic Surgery Simulator**

Investigators: **Pramiti Sarker, Dr. Gary A. Mirka**

Invitation to be Part of a Research Study

This form describes a research project. It has information to help you decide whether you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary, and you can stop at any time. Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

Introduction and Purpose of the Study

The aim of this study is to evaluate shoulder muscle fatigue and work performance on a laparoscopic surgery simulator.

Eligibility to Participate

You are eligible to participate in this study if you are between age of 18-65 years and have no history of chronic pain in neck, shoulder, legs or back, area and are not currently experiencing neck or shoulder pain. You will need to stand for 60 minutes continuously without any support/assistance.

You should not participate if you are less than 18 years of age or are over 65 years of age. You should also not participate if have a history of chronic pain in your neck, shoulders, legs, or back area or are currently experiencing neck or shoulder pain. You should be comfortable with wearing short sleeve shirts during data collection and willing to allow us to shave your hair on shoulders if needed.

Description of Study Procedures

If you agree to participate in this study, you will be asked to perform the following activities on multiple days (two to three practice sessions and exactly five experimental sessions). On your first practice session, some simple body dimensions (age, stature, body weight, standing elbow and knee height) will be obtained with a tape measure and bathroom scale and you will be asked to perform a simple dexterity task using the Purdue Pegboard test which will ask you to place rods and washers in the holes on a board (Figure 1). You will then be asked to stand next to a laparoscopic surgery simulator (Figure 2) and practice with the hand tools (Figure 4) to move these blocks around the workspace (Figure 3) to simulate a simple surgical procedure. The aim of this practice is to become proficient at this task of manipulating these blocks.

Once you are proficient at this task you will be asked to come to the lab on five additional days to complete the study. On each day you will be led through some simple stretching exercises designed to warm up your shoulders and neck. Surface electromyography (EMG) electrodes will then be placed over some of your shoulder muscles (anterior, medial, and posterior deltoid muscles), a refence electrode on your elbow and will be asked to perform something called a maximum voluntary contraction where you will use your shoulder muscles to lift against manual resistance provided by the experimenter (see Figure 5) and the muscle activity will be recorded.

Upon completion of these preliminary activities, you will be asked to perform the block manipulation task on the laparoscopic surgery simulator for 23 minutes, with breaks set at various times throughout the experiment. The total time we will ask you to work with laparoscopic simulator will be 21 minutes each session and there will be a total of 2 minutes of breaks throughout each session. While you are performing this task, muscles of the shoulders will be monitored using the EMG sensors. At the beginning of a scheduled rest break, you will hear the word "pause" and a short time later you will hear "resume". When you will hear the word "pause", you will set the hand tools down on a nearby table and relax your hands to the side of your body and hold your head upright during this relaxation period. When you will hear the word "resume", you will pick up the hand tools and go back to your activity in the laparoscopic surgery simulator. At the beginning and end of each day, you will be asked to fill out a survey form that will record your level of fatigue.

Figure 1. Purdue Pegboard Task

Figure 2. Subject Performing on Laparoscopic Surgery Simulator

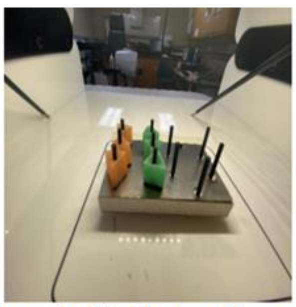


Figure 3. Six Blocks of Laparoscopic Simulator

Figure 4. Laparoscopic Surgery Simulator Hand tools

Figure 5: Shoulder maximum voluntary contraction (left), placement of EMG electrodes (right)

Expected Time or Duration of Participation:

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You will be asked to visit our lab on several days to practice until you become proficient (time varies but not more than 60 minutes per day) and five different days with a gap of minimum 24 hours between consecutive participation. On each day your participation will last for about 60 minutes. The total time we will ask you to work with the simulator will be 21 minutes each day and there will be a total of 2 minutes of breaks throughout each session. The remaining time will be used to describe the experiment and fill out inform consent form and complete the survey.

Risks or Discomforts

While participating in this study you may experience some fatigue-related discomfort as your task will require to hold shoulder postures that may be a bit awkward to you. The duration of the task will be 23 minutes with a total break of 2 minutes. Working with shoulder muscles at this posture can create some fatigue in the neck and shoulder region. Prolonged standing can also create discomfort in your legs and back region. There is a slight risk of muscle injury during the maximum voluntary contraction activity shown in Figure 5. You will go through short warm up session at the beginning of study to minimize this risk.

You should not participate in this study if you have a history chronic pain in neck, shoulder, leg and back areas or are currently experiencing pain in your neck/shoulder. Please initial here if these do not apply to you______. If you begin to experience significant pain during the experiment, the researchers will stop the experiment and your participation in the study will be concluded. You will be compensated for the time you have spent in the experiment. Also, if you experience an injury in the period between data collections (not associated with the study) you will not be allowed to continue participation. Data collected up to the time when participation ends will be maintained and used in the analysis.

There may be risks or discomforts that are currently unforeseeable at this time. We will tell you about any significant new information we learn that may relate to your willingness to continue participating in this study.

Benefits to You and to Others

If you decide to participate in this study, there is no direct benefit to you as a participant. You may derive some indirect benefits including an understanding of ergonomics research methods. The result of the analysis will be used to inform our understanding of the relationship between work-rest cycles and the development of muscular fatigue and performance.

Costs and Compensation

You will not have any costs from participation in this study. For participating in this research study, you will be paid $10 per hour of participation (prorated for partial hours completed). You will receive this compensation regardless of whether you were able to complete all sessions. You will need to complete a simple form to receive a cash payment. This form will not be kept by the research team as a research record but will be maintained by an ISU financial secretary for audit purposes.

Please know that payments may be subject to tax withholding requirements, which vary depending upon whether you are a legal resident of the U.S. or another country. If required, taxes will be withheld from the payment you receive.

Your Rights as a Research Participant

Your participation in this study is completely voluntary and you may refuse to participate or leave the study at any time. If you decide not to participate in the study or leave the study early, it will not result in any penalty or loss of benefits to which you are otherwise entitled. Information about you will never be shared with other researchers or used in other research studies. For studies involving surveys you can skip any questions that you do not wish to answer.

If you have any questions *about the rights of research subjects or research-related injury*, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115 or Office of Research Ethics, Iowa State University, Ames, Iowa 50011.

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Research Injury

Please tell the researchers if you believe you have any injuries caused by your participation in the study. The researchers may be able to assist you with locating emergency treatment, if appropriate, but you or your insurance company will be responsible for the cost. Eligible Iowa State University students may obtain treatment from the Thielen Student Health Center. By agreeing to participate in the study, you do not give up your right to seek payment if you are harmed as a result of being in this study. However, claims for payment sought from the University will only be paid to the extent permitted by Iowa law, including the Iowa Tort Claims Act (Iowa Code Chapter 669).

Confidentiality

Research records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available without your permission. However, it is possible that other people and offices responsible for making sure research is done safely and responsibly will see your information. This includes auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy study records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: subjects will be assigned a unique code and letter and will be used on forms instead of their name, all data will be stored in a locked cabinet in the office of the principal investigator and all data will be saved in a password protected computer. If the results are published, your identity will remain confidential.

In order to protect your confidentiality when results are reported, all results will be reported in aggregate. We will not report information that may identify any individuals, but plan to report the mean, standard deviation, and range of important anthropometric data.
Signed informed consent documents will be stored for three years after the study is closed to IRB oversight (per human subject research protection regulations and university policy).

Future Use of Your Information

Information about you collected for this study may used by the research team for other research studies but will never be shared with other researchers. These studies may be similar to this study or completely different. We will make sure that your identity cannot be linked to the information we use for other research, and we will not ask you for additional permission to use your information for other projects.

Questions

You are encouraged to ask questions at any time during this study. For further information about the experiment please contact supervising contact Dr. Gary Mirka (515) 294-8661 and study contact Pramiti Sarker (316-993-8015).

Your Consent

By signing this document, you are agreeing to participate in this study. Make sure you understand what the study involves before you sign. If you have any questions about the study after you agree to participate, you can contact the research team using the information provided above. You will receive a copy of the written informed consent prior to your participation in the study.

I am 18 years of age or over and agree to take part in this study.

Participant's Name (printed) ____

______________________________________ ______________________

Participant's Signature Date

CHAPTER 5. GENERAL CONCLUSION

The current dissertation is a collection of consecutive studies to answer important questions related to an ergonomic intervention: breaks to reduce the negative impact of muscle fatigue. Two preliminary studies provided the methodological, practical, and theoretical design of the final dissertation study. The general conclusion part includes the discussion on what we learnt from the first two preliminary studies and how we implemented the obtained knowledge to design the main study. The final study uses inventory control methods to propose ways to optimize the tradeoff between muscular fatigue and performance of a short task. It also includes the information for future researchers on how to improve the present study for robust results.

The first study was a basic research study to observe the effects of breaks on muscle fatigue development. This study showed that allowing breaks between work does not have any impact on cumulative muscle fatigue development. The slope of the decrement of median frequency did not change from bout to bout which indicated positive effect of break on fatigue development. Breaks did not allow them to develop/ increase fatigue cumulatively. Though this first study had a more basic-science focus, it provided important methodological insights and a theoretical foundation for the next study. This first study chose biceps brachii muscle of dominant hand of the subjects but most of the static posture available in literature and real-life work is in the neck/shoulder area of the body. Therefore, the follow-up study was conducted on neck extensors and trapezius muscle. Moreover, the first preliminary study had a break (15 minutes) longer than work (4 minutes). Such work-rest scheduling is unrealistic. The work-rest schedule in neck muscle study was designed keeping in mind the realistic nature of work. Instead of having some unrealistic methodological parameters, the first study provided the understanding that median frequency can be a usable EMG parameter to quantify effect of break on muscle fatigue.

The second study (Chapter 3) was conducted to observe the effect of different work-rest schedules on neck muscle fatigue. It also provided us with information that helped to improve methodology and dependent parameters to analyze as an indicator of muscle fatigue. In this0P/ study, EMG amplitude along with MDF was considered. As neck muscles have higher percentage of slow twitch muscle fibers, MDF did not show any trend due to effect of different work-rest schedule. Hence, it provided the idea of including both time and frequency domain data. Subjective fatigue analysis was also included in this study. The study concluded that shorter and frequent breaks resulted in less muscle fatigue than longer and less frequent breaks. Moreover, this study (Chapter 3) also helped to find the similarity between fatigue and recovery trend with inventory control theory. In the inventory control theory model, production, and delivery curve looked same as fatigue development and recovery curve in neck muscle. The larger the production cycle, the more product is produced in inventory control model. In a similar way, the more is the length of bout, the more is the fatigue development. The inventory control model sought to find optimum number of production quantity through minimizing fixed and production cost. These two costs (production and fixed costs) are similar to fatigue (physiological) and performance cost. However, Chapter 3 did not observe the impact on the performance/ productivity of the workers. Hence, the main study was developed to consider this perspective. It helped to create the idea of finding optimum number of breaks optimizing physiological and performance cost. It also helped to determine the optimum number of breaks alike optimum quantity of products in the inventory control theory model.

The final study was more realistic than the previous two studies. It was based on laparoscopic simulator work and studied the effect of breaks on both muscle fatigue and performance. The subjects came on several days to train themselves with laparoscopic simulator so that they can act as a proficient worker and carry no learning effect from day to day. It was done to ensure that their productivity score is a true predictor of their performance. The study used both time and frequency domain EMG and subjective fatigue/discomfort score data. The study was able to show two important outcomes. First, it is not always wise to choose the most frequent and short duration as suggested work-rest schedule based on only muscle fatigue. It showed that performance/productivity should be considered along with muscle fatigue. Second outcome of this study is that it developed a model that can suggest work-rest schedule independent of opinion and in uncertain conditions. It is also based on the inventory control theory. Like the parameters of inventory control theory, the parameter of fatigue development can also be probabilistic in nature due to inter-individual variability. Uncertain conditions include scenarios such subject is a new learner or highly proficient and quickly fatiguing or less sensitive to fatigue. To develop the uncertain model different percentile values of fatigue (5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th}) and performance (5^{th}, 25^{th}, 50^{th}, 75^{th} and 95^{th}) values were computed. Later combination of these percentile values provided insight for different number of breaks in predicted uncertain situation. Although the main research aimed to replicate the real-life scenario, develop result for those scenarios and worked to predict the uncertain scenarios, there are still some sectors where future work can be done on this work in the following directions:

1. Including experienced practicing workers/ surgeons
2. Including the method of extrapolating the total duration of work represented by short work hour in experimental set up

3. Including neck muscles and neck flexion activities in prolonged static work of laparoscopic simulator
4. Choosing different work-rest cycle depending on the duration of surgery and then running the model
5. Developing biomechanical model to understand the load on shoulder/ neck muscle during a laparoscopic work
6. Developing similar model for other manufacturing work that requires prolonged static work
7. Considering updated version of Inventory Control Theory and applying similar methods in developing more robust work-rest schedule. For example, alike the lead time in inventory control theory, the duration of exertion may vary from bout to bout. Future work can also consider it in the model
8. The present model did not include the concept of back-orders of inventory control model theory. Back orders happen when demand exceeds supply. Similar situations can be observed when workers work beyond their fatigue level. However, tolerance of fatigue level of subjects was not studied which can be included in future studies to find similarity between back-order modeling and fatigue development model.

In conclusion, the dissertation paved a way to predict different combinations of work-rest schedules for different uncertain situations. It developed a methodology which can be helpful to predict such uncertain situations in other sectors too if data is collected in proper way. This model will work better if data is collected in real life workplace setting with full time data collection.