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Development of a new work-rest scheduling model based on inventory control theory

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Development of a new work-rest scheduling model based on inventory control theory

by

Xiaopeng Ning

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

Major: Industrial Engineering

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Ames, Iowa

2011

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ABSTRACT

Work-rest scheduling is one tool available to ergonomists to reduce the risk of injury to workers performing physically demanding work tasks. Accurate assessment of the changes in these physical stresses during the work task and during the recovery period is necessary to establish sound work rest schedules. Existing work-rest scheduling models are either based entirely on empirical data without the utilization of a theoretical model of the underlying human physiology or they have relied on abstract optimization modeling techniques that have but been shown to lack robustness to realistic work scenarios. In the current study a new work-rest scheduling model has been developed. This new model makes use of an established modeling technique in the inventory management literature and adapts this technique to the modeling of the development of work stress during work and recovery from work stress during resting periods. This study required the development of time-dependent work stress profiles through the collection of data from human subjects performing simulated work activities. These work stress profile data then formed the database that was utilized by the theoretical model. This new work-rest model is shown to be able to generate optimal work-rest schedules under a variety of work conditions.

Two experiments with four participants each were conducted. Experiment I was dedicated to generate a series of regression equations for tracking the changes in physiological variables during the performance and recovery of two typical low back fatiguing exertions. These two tasks included an isometric trunk flexion task and a repetitive lifting task. As participants performed these tasks, heart rate (to establish cardiovascular stress), median frequency of the erector spinae muscles (to establish muscle fatigue stress), and sway speed (to establish

changes in level of whole body stability) were collected and tracked over time. From these empirical data, regression equations were developed that predicted these three variables as a function of time. Experiment II was conducted to test the validity of these equations by using different participants and performing three different categories of task protocols and then assessing the quality of the predictions of the regression equations developed in Experiment I. Results from Experiment II demonstrated good performances in predicting the changes in heart rate, median frequency and sway speed (with mean absolute percentage error of 5.5%, 11.7% and 15.0% respectively). These results indicate that the more objective measures (heart rate and median frequency) were relatively more stable and were subsequently included in the inventory control theory modeling phase of this study.

The next phase of the study was to use these data in an established inventory management optimization modeling technique. The adaptation of this modeling technique for this application required a translation of inventory variables into physiology variables: production rate, demand rate, set-up cost, holding cost were translated into rate of fatigue development, rate of fatigue recovery, cost of pausing from work, and cost due to increased risk of injury caused by keeping certain level of physiological stresses, respectively. The optimal work-rest schedule was generated by minimizing the total cost, as in the traditional use of the model. These results generated the appropriate duration of a physically demanding work task as well as the appropriate duration of the subsequent rest breaks. Finally, a sensitivity analysis on the values of the inputs to the model was conducted. Results of sensitivity analysis showed that all three cost factors (wage cost, setup cost and holding cost) have clear and reasonable influences on the selection of optimal work-rest schedule. As the

wage costs and setup costs increased the number and duration of scheduled breaks decreased. As the holding cost (cost of injury) increased, the number of breaks increased and the duration of the work time increased. This analysis also revealed that the suggested work duration was fairly robust relative to the hourly wage of the worker, but was sensitive to the setup costs and the predicted cost of injury. The suggested recovery duration was most influenced by the hourly wage of the worker.

The resulting work-rest scheduling model can be adapted to meet the needs of a particular work scenario. The requirements are to develop the development and recovery profiles for the given work scenario. Future work may entail the development of a system to predict the form of these equations without the need to do a full data collection using human subjects. For a given work scenario, the work-rest scheduling tool developed through this research can provide the minimum cost schedule.

CHAPTER 1. INTRODUCTION

Low back pain (LBP) has long been recognized as one of the most prevalent and costly occupational injuries. For a long time researchers have developed risk assessment models to evaluate the risk level of a given lifting task by assessing different risk factors. The existing risk assessment models assess the influence of many occupationally related physical stressors such as awkward body posture, high lifting forces and long working hours on the prevalence of low back injury. These stressors could work either individually or in concert to cause LBP. Although much effort has been devoted by previous scholars, the development of risk assessment models is still far from complete. Low back muscle fatigue has been identified as one potential cause of LBP. Over the short term, low back muscle fatigue can cause acute trauma by reducing overall spinal stability in the presence of fatigue; in the longer term it increases spinal loading, possibly causing micro damage to the spinal structure (e.g. intervertebral discs) and over time could lead to LBP. Most of the existing models have focused exclusively on identifying the hazard characteristics of lifting tasks that may cause acute trauma, but have not put sufficient attention on modeling the long term effect of low back muscle fatigue on the risk of low back injuries. The development of low back muscle fatigue and associated physiological changes during performance of one or multiple lifting tasks has never been precisely tracked and modeled. In addition, while most of the previous risk assessment models have the ability to identify high risk lifting tasks, they are not able to either precisely predict the risk level or to manage risks. Cumulative work stress factors have also been studied and identified as one of the potential risk factors for occupational injuries. Previous researchers have investigated long term (over months, years) effects of cumulative

work stresses but the accumulation of work stress within a shorter interval of minutes or hours has never before been studied.

In general, existing risk assessment models lack the capability of precisely evaluating the effect of low back muscle fatigue on physiology changes within the human body. Job rotation models and work rest systems are able to distribute risk exposure throughout a group of workers but only in a gross fashion. Up until now, none of the existing models has the capability for precise assessment of instantaneous physiological changes in the human body within a short interval (minutes) after task performance or to manage overall risk exposures over longer periods of time. Also, a methodology for precise management of cumulative risk factors has never been developed within previous models.

Here we propose a new low back risk assessment and management model. This model will have capability for quantitatively evaluating physiology changes within an individual during different task performances and will be able to create or select a long term optimal task performance schedule whose objective is to minimize physical risk exposure. Three physiological variables (muscular EMG median frequency, trunk sway speed, and heart rate) have been selected for monitoring because of their sensitivity to low back muscle fatigue. An inventory control model taken from the field of production management will be utilized to frame this new model because of the similarity of managing the inventory of products to managing the inventory of fatigue development (in terms of median frequency, trunk sway speed, and heart rate). This inventory control model will give our new model the theoretical and mathematical power for managing and controlling the changes in all three physiology

parameters (related to low back muscle fatigue) by setting up the sequence of task performance and scheduling the rest duration.

CHAPTER 2. BACKGROUND

2.1 Low back disorders

2.1.1 Epidemiology

Back pain is well recognized as a highly prevalent disorder that annually affects 10-15% of the adult population (Andersson 1999) and 70-85% of the total population at least once per lifetime (Andersson 1997). In the USA almost 2 percent of the entire working population annually suffers from LBP (Murphy & Volinn 1999), and the total cost of LBP was estimated to be between 50 to 100 billion dollars in the year 1990 alone (Frymoyer & Cats-Baril 1991). Analysis of data from the 1988 National Health Interview Survey estimated about 149 million lost workdays because of back pain (Guo et al., 1995), and about 101.8 million of these lost workdays were caused by work related back pain (Guo et al., 1999). Studies have shown that on average 37% of low back pain can be attributed to occupation, and this percentage was even higher among workers in labor intensive industries (e.g. manual materials handling) (Punnett et al., 2005).

Several epidemiology studies have been conducted to further investigate how occurrence of LBP is distributed among different types of jobs. Leigh and Sheetz in 1989 summarized a national survey that contains 1417 samples. In this survey respondents described both their job and their physical wellness (Leigh & Sheetz 1989). By categorizing jobs into different groups the results of the survey generated a set of comparisons related to the risk of LBP among different job groups. By setting the lowest risk job group (“Managers and professionals”) as a reference and comparing all other job groups with it, the authors were able to calculate the “relative risk” index for all groups of jobs. Punnett presented summaries

of these data in his later study (Punnett et al., 2005, as shown in Table 1). Results from this study clearly demonstrated the increase of risk of LBP from both “white collar” and “blue collar” populations. Other studies reported similar results, although some described a lower comparative risk level for the “farmers” group (e.g. Leino-Arjas et al., reported 2.13 for the farmers group (Leino-Arjas et al., 1998)). These results indicate not only that those with jobs involving excessive physical requirements (e.g. farmers or farm workers) can develop LBP, but also those with jobs with moderate physical requirements such as machine operation, cleaning, or delivery can also experience LBP. In the high risk group workers may be constantly exposed to the risk of acute trauma because of the high physical demands of their daily tasks. However, even though moderately risky jobs have much less risk of acute injury, with most of them not requiring high physical exertion or extreme odd postures, these jobs do often require continuous and repetitive low level physical exertions such as maintaining one posture for long time (e.g. cleaning job might require prolonged trunk flexion) or performing low force weight lifting or carrying for a period of time (e.g. unloading a truck). Low back muscle fatigue can easily be created during the performance of these moderate tasks. In an epidemiology study researchers reported association between fatigue of low back extensor muscles and consequent risk of low back disorder (Biering-Sorensen 1984). In that study a total of 928 human subjects participated in a health survey that included a thorough physical examination of the lower back and a questionnaire one year after the examination. Their results indicated that good endurance of back muscles may prevent the first-time occurrence of low back disorder and that participants with weak trunk muscles are more likely to experience recurrence or persistence of low back disorders within that one year period.

Occupational category	Relative risk (95% CI)^a	Exposure category used in CRA
Managers and professionals	1.00 (NA)	Background
Clerical or sales worker	1.38 (0.85–2.25)	Low
Operators	2.39 (1.09–5.25)	Moderate
Service workers	2.67 (1.26–5.69)	
Farmers	5.17 (1.57–17.0)	High

Table 1: Job categories and their relative risk of LBP (Punnett et al., 2005) CI: Confidence Interval; CRA: Comparative Risk Assessment

2.1.2 Low back muscle fatigue and LBP

Low back muscle fatigue has been more and more recognized as an important risk factor for the development of low back disorder. In general, low back muscle fatigue decreases the force generation capacity (Bigland-Ritchie et al., 1995), reduces muscle stiffness (Golhoffer et al., 1987), weakens the muscular support to the spinal structure (Gardner-Morse et al., 1995), and causes impairment of motor co-ordination and control (Parnianpour et al., 1988; Magnusson et al., 1996; Wilder et al., 1996). These changes may result in increased mechanical stress to the spinal functional components (De Beeck & Hermans 2000). Based on the spinal stability model presented by Granata et al. 2004, the reduction of low back stiffness caused by low back muscle fatigue increased antagonist muscle activity. These results have been supported by other researches (Sparto & Parnianpour, 1998; Sparto et al., 1997). It has been hypothesized that the increase in antagonist muscle activity has been seen as a compensation for the reduced spinal stability (Cholewicki et al., 1997; Gardner-Morse & Stokes 1998; Granata & Orishimo 2001; Granata et al., 2004) which results in a spinal loading increase. Another study demonstrated that low back muscle fatigue changes the trunk movement pattern and alternates the muscle recruitment patterns; these changes in turn may

generate negative impact on spinal loading (Marras & Granata 1997). A previous study has concluded that the magnitude of spinal loading is significantly associated with the occurrence of LBP (Neumann et al., 1999) because high spinal loading may over time degenerate the intervertebral disc, resulting in annulus fibrosus bulges and/or ruptures that may press on spinal nerve roots and result in LBP (Chaffin & Park 1973).

From a stability standpoint, the reduction in muscle stiffness impacts the overall stability of lumbar spine which may decrease one's ability to resist external perturbation (Granata et al., 2004). In addition, low back muscle fatigue can induce significant impairment to one's proprioceptive sensitivities (Taimela et al., 1999; Davidson et al., 2004). This impact decreases one's ability to sense changes in body position that may in turn increase the risk of falling or, in the long term, may cause low back dysfunction. Previous studies have shown that low back extensor muscle fatigue increases the magnitude of trunk sway, indicating an impact of low back muscle fatigue on whole body stability (Davidson et al., 2004, Pline et al., 2006, Madigan et al., 2006; Vuillerme et al., 2007). Furthermore, spinal muscle fatigue may exaggerate the effect of whole body vibration (often caused by off-road vehicle driving or long time truck driving) on the development of low back disorders (Johanning 2000).

On the other hand, the difference in responses of muscle fatigue between healthy participants and low back pain patients were investigated in both athletic and non-athletic populations (Roy et al., 1989, Roy et al., 1990). Results showed that differences between healthy participants and low back pain patients can be clearly observed by looking at the descending slope of electromyography median frequency during the development of muscle fatigue

and/or the ascending pattern during the recovery phase. These results demonstrated that chronic low back pain alters the physiology patterns of back muscles in both the development and recovery of muscular fatigue.

2.2 Fatigue

2.2.1 Muscle fatigue physiology

Before discussing muscle fatigue I will first briefly introduce the mechanism of cellular level muscle contraction in step-by-step fashion (from (i) to (ix)) as shown in Figure 1: Physiology and molecular pathway of muscle fiber contraction (Westerblad et al., 1991). The muscle contraction procedure starts from (i) where a command sent from the central nervous system will lead to the conduction of action potentials (ii) down to the neuromuscular junction (iii). Then at the junction point the action potential will propagate (iv) along the sarcolemma (membrane of muscle cell), and when it reaches the transverse tubular system (v) it spreads further down the T tubule to the sarcoplasmic reticulum (SR) membrane and causes a fast release of Ca^{2+} stored in the SR into the myoplasm (vi). The released Ca^{2+} binds to troponin C and causes tropomyosin to be removed from actin (vii) which enables cyclic cross-bridge binding between myosin and actin (muscle cell contracts) (viii). Within the duration of muscle contraction Ca^{2+} continues to be released into the myoplasm and at the same time an adenosine triphosphate (ATP)-dependent pump keeps transporting Ca^{2+} back into the SR (ix). When muscle contraction stops, the release of Ca^{2+} stops and all Ca^{2+} will be transported back to the SR (Westerblad et al., 1991; Stephenson et al., 1998).

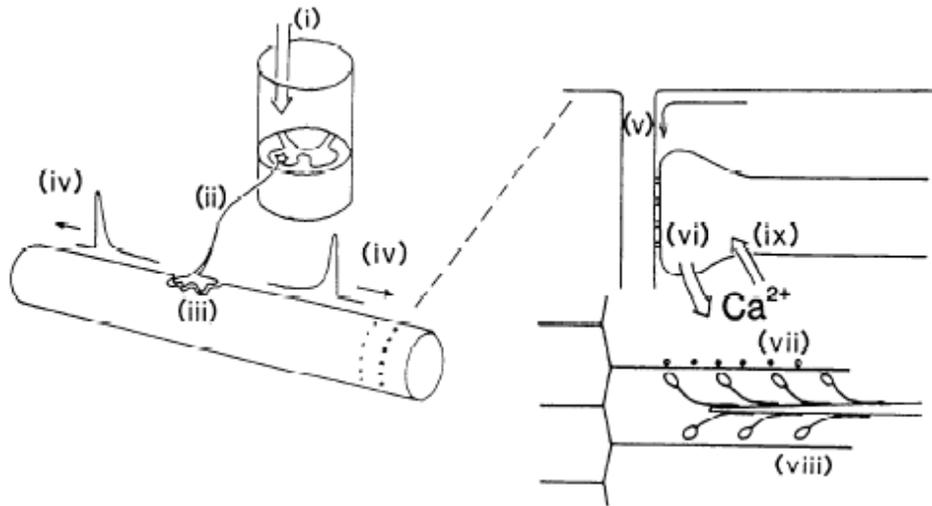


Figure 1: Physiology and molecular pathway of muscle fiber contraction (Westerblad et al., 1991)

Muscle fatigue can be described as a decrease of force exerting capability in response to voluntary effort (Edwards 1981; Bigland-Ritchie et al., 1995). This phenomenon has been viewed as an adaptation of the neuromuscular system that helps prevent serious damage to muscles (Chaffin et al., 2006). It is well known that human muscles consist mainly of two groups of muscle fibers: fast-twitch fiber (Type II (including Type IIa and Type IIb)) and slow-twitch fiber (Type I). Fast-twitch fiber is characterized by high SR and myofibrillar adenosine triphosphatase (ATPase) activities. It has short isometric twitch durations and high maximal shortening velocities. Slow-twitch fiber, in contrast, has low SR and myofibrillar ATPase activities, and slow twitch fibers also have long twitch duration and low shortening velocity compared with fast twitch fibers (Westerblad et al., 1991). In general, slow-twitch fibers have higher resistance to fatigue than fast-twitch fibers (Stephenson et al., 1998).

At the cellular level, muscle fatigue alters multiple metabolic factors (Allen et al., 2008). First of all, during the initial stage of muscle fatigue the production of ATP generates inorganic phosphate (Pi). According to previous studies the increase in Pi is considered to be a major cause of fatigue because of its ability to remarkably reduce myofibrillar force production, and decrease Ca^{2+} sensitivity and SR Ca^{2+} release (step (vi) in Figure 1) (Westerblad et al., 2002). With continuous force exertion the consumption of ATP exceeds its rate of reproduction. In fast-twitch fibers ATP concentration may decrease to less than 20% of its initial value (little or no decrease in slow-twitch fibers) causing reduction in Ca^{2+} release and force output or, in other words, muscle fatigue (Allen et al., 2008). Finally, the development of muscle fatigue may cause depletion of glycogen-a major energy source muscle activity (Bergstrom et al., 1967; Hermansen et al., 1967). This reduction of glycogen may increase muscle fatigue by reducing the SR Ca^{2+} release (Allen et al., 2008).

With this description of the physiological highlight of muscle fatigue one should notice that muscle fatigue is a complex procedure that can be affected by multiple factors. It has been reported that physical exertion tasks performed by individuals represent one of the most important factors that alters the characteristics of muscle fatigue. For low back muscles one study reported that there is a significant difference in the development of muscle fatigue between two different tasks targeted to fatigue the same muscle. (Elfving & Dederling 2007). Another study showed that a small difference between two body postures that both aim to generate the same amount of muscle fatigue on back and hip extensor muscles resulted in significantly different muscle fatigue patterns (Champagne et al., 2008). The rate of muscle fatigue is determined by the degree of blood flow restriction and the response of the central

nervous system that is influenced by many processes and factors that depend on the tasks people perform (Bigland-Ritchie et al., 1995). Studies have shown that the restriction of blood flow is more severe in the isometric contraction situation than in the dynamic case (Bigland-Ritchie et al., 1995) but, however, dynamic exercises introduce much larger metabolic changes (PCr, Pi, pH, lactate, etc.) compared with isometric contractions. In other words, for the same intensity of dynamic exertion dynamic exercise consumes more energy than isometric contractions (9.3 mM ATP/s vs. 4.7 mM ATP/s) (Jones 1993). These facts indicate there are fundamental differences between these two types of muscular exertions.

2.2.2 Physiology marks of muscle fatigue

2.2.2.1 EMG median frequency

The effects of muscle fatigue always generate multiple physiology changes. In many muscle related research studies muscular electromyography (EMG) is often used as the most direct measurement indicating the physiological status of muscles. EMG are the electrical signals that emanate during the contraction of muscle fibers. The discovery of this phenomenon can be traced back to as early as the early 17th century when a special muscle was discovered as the source of the Ray fish's electrical energy (Redi 1617). But not until 1849 were the electrical signals from human muscles discovered (Du Bois-Reymond 1849). Nowadays use of surface EMG has become a convenient tool in the research of muscle physiologies. In the early 1900's researchers discovered a compression of the EMG frequency spectrum toward lower frequencies during a prolonged sustained muscle exertion (Piper 1912). This phenomenon indicated the potential impact of muscle fatigue on the properties of muscular EMG. The median or mean of the frequency spectra from the EMG signal of a muscle has

long been recognized as a reliable physiological indicator of muscle fatigue. As shown in Figure 2, during the performance of a prolonged muscle contraction protocol, the frequency spectra of the EMG signal will gradually compress toward lower frequencies (from “beginning” to the “end” as showing in the Figure 2) with the impact of muscle fatigue, reducing the median or mean frequency. Using the median of EMG frequency spectra as an index of muscle fatigue has several advantages: First, since the EMG signal can be obtained from all desirable muscles simultaneously, individual muscle performance as well as the overall muscle group recruitment strategy can be determined. Second, since we know that the development of muscle fatigue is a continuous procedure, by collecting EMG signals throughout the entire muscle exertion period, one can obtain the full profile of muscle fatigue development. Furthermore, in comparison with other characteristics of the frequency spectrum, the median frequency is more sensitive to muscle physiology changes during fatiguing contraction and is also more robust with respect to noise signals (Deluca 1997).

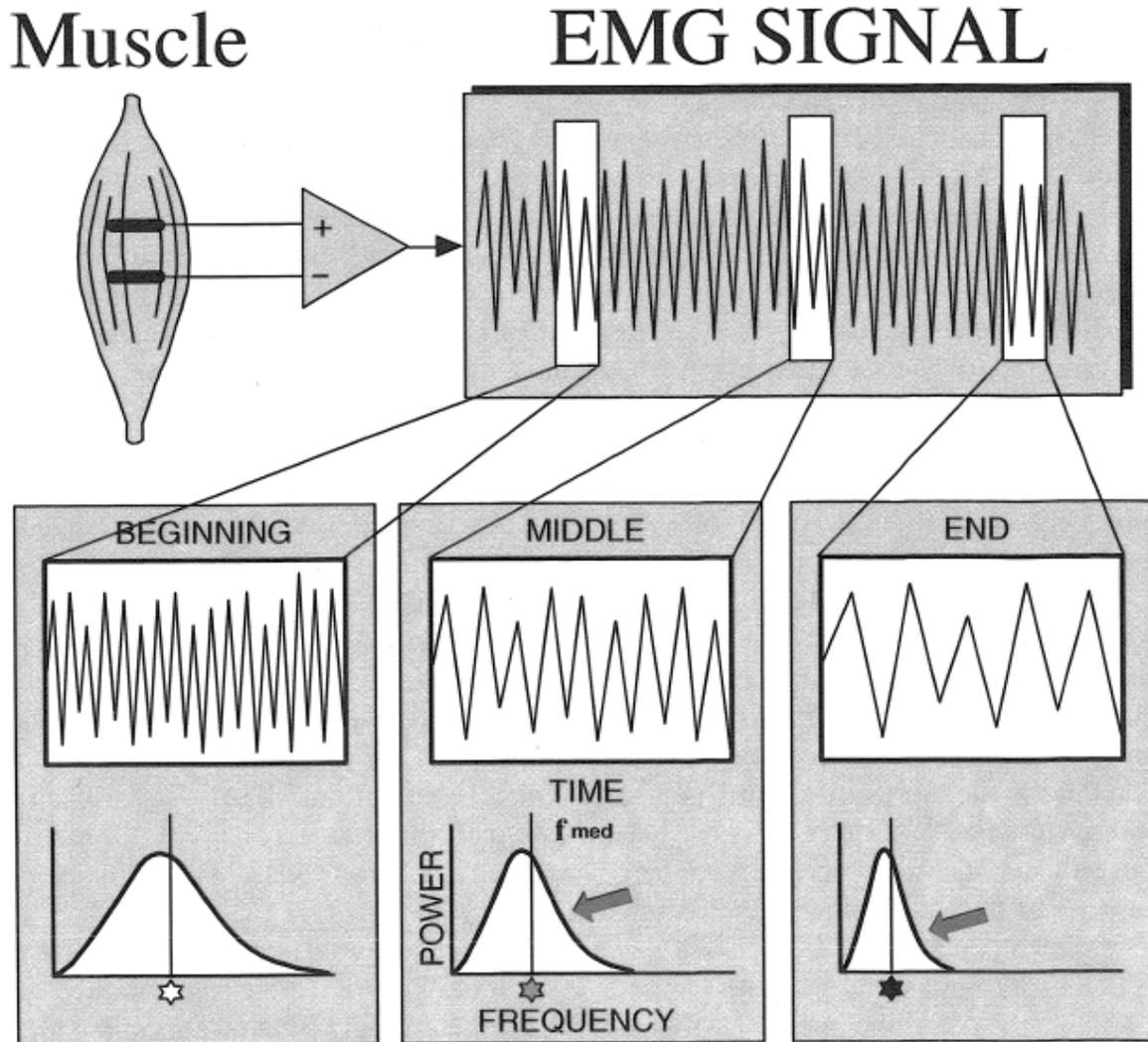


Figure 2: An example of an EMG signal and its corresponding frequencies (Deluca 1997)

2.2.2.2 Trunk sway speed

From a lumbar stability perspective low back muscle fatigue reduces the overall stiffness of the lumbar structure and creates instability in the lumbar region, and it therefore may increase the risk of low back injury (Granata et al., 2004). Panjabi introduced the idea of spinal stability from a physical spinal component point of view. His theory considered the spine as three subsystems: passive, active, and neural. The neural system monitors the

requirements for spinal stability and directs the reaction of the active system (muscles) to provide sufficient stability. Spinal instability may result from the dysfunction of one or more of these subsystems (Panjabi 1992). From the subsystem perspective low back muscle fatigue would affect both the active and neural subsystems, causing a reduction in both force generation capacity and neurological control of the muscles.

Another group of researchers looked at spinal stability issue from the perspective of system potential energy. As described by Bergmark in 1989, lumbar spine stability is determined by its instantaneous stiffness created by both active tissues (muscles) and passive components (vertebrae, discs, capsules, and ligaments) of the lumbar spine. He modeled the combination of both active and passive components as a single spring that connects to one end of a T-shaped structure (as shown in Figure 3) and stated that the lumbar spinal system will have higher stiffness (thicker spring) with higher muscle force and/or further elongation of passive tissues. Higher stiffness would create a more stable system simply because, for the same amount of external perturbation energy, a stiffer system can absorb with less displacement compared to a system with less stiffness (thinner spring). Also a stiffer system can withstand a larger amount of perturbation before failure occurs.

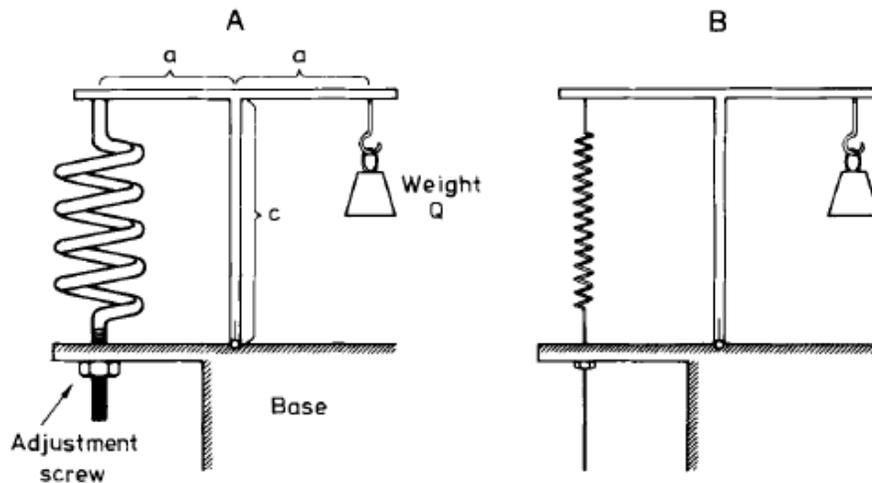


Figure 3: Demonstration of the idea of spinal stiffness represented by different spring size in a structure (Bergmark 1989).

Following Bergmark's spinal stiffness concept, Cholewicki and McGill (1996) developed a method for calculating a single number known as the "stability index" representing the spinal stability level for any instantaneous trunk motion. This index represents the geometry of the local potential energy curvature profile for each fraction of trunk movement. This local potential energy may be calculated by incorporating muscle elastic energy, ligamentous elastic and rotational energy, and work done by external forces. Granata and colleagues further developed an optimization process which incorporates the idea of local potential energy curvature and adapted the calculation procedure created by Cholewicki and McGill. This optimization process minimizes the sum of muscle stresses with constraints of force equilibrium, muscle force feasibility, and guarantee of a local potential energy trough point (Granata & Wilson 2001).

In addition to theoretical models developed to describe the effect of low back muscle fatigue on spinal stability, one study (Davidson et al., 2004) also investigated the effect of lumbar extensor fatigue and rate of fatigue on postural sway, which may directly reflect the effect in a much clearer way. In contrast to those of all other species, the human body constantly maintains erect posture with two feet on the ground, a physically unstable status. To maintain this erect posture, muscles on lower extremities and trunk have to constantly reflexively or voluntarily contract to a certain degree in order to reach equilibrium and prevent falling. The magnitude of body sway for different postures directly represents the ability for maintaining stability. Results of previous studies show that a given level of low back muscle fatigue created by different fatiguing rates (fast and slow) significantly increased body sway to the same level, and there was no difference in the reduction of postural sway during recovery time between the two rates of fatigue. The authors stated that the underlying mechanism of increasing postural sway after low back muscle fatigue is the impairment of trunk and hip proprioceptive feedback (Davidson et al., 2004). Other studies have also shown that low back extensor muscle fatigue will increase the magnitude of whole body sway (Pline et al., 2006, Madigan et al., 2006; Vuillerme et al., 2007).

2.3 Cardiovascular stress

2.3.1 Cardiovascular stress during physical exertion

When investigating occupational related injuries, LBP is not the only risk that should be considered. For example, cardiovascular risks related to all kinds of physical exertions should also be included in the discussion. When a human starts a physical exertion his/her body will respond in multiple ways. From a cardiovascular perspective, to meet the additional energy

requirement, the heart rate will rise along with stroke volume (the volume of blood pumped from one ventricle of the heart with each beat) and cardiac output (the volume of blood pumped by one ventricle during one minute; cardiac output equals stroke volume multiplied by heart rate) (Astrand et al., 1964). When performing maximum physical exertion, the heart rate and cardiac output will linearly increase to their maximum values, while stroke volume will quickly increase to its maximum value and stay at that value while the heart rate continues to grow (Astrand et al., 1964). Moderate physical exercise is shown to have cardiovascular benefits (Thompson 2003). However, research has also shown that excessive physical output may generate unfavorable cardiovascular alternations (Earnest et al., 2004). Previous researchers have demonstrated the risks of experiencing cardiac events or sudden cardiac death during vigorous physical exertions (Siscovick et al., 1984; Thompson et al., 2007). A depression in cardiac function during prolonged intensive physical exertion has also been reported (George et al., 2005; Dawson et al., 2008). These studies suggest that, when designing a job, proper limitation of physical exertion and sufficient resting should be provided in order to avoid excessive cardiovascular stress.

2.3.2 Marks of cardiac stress

In order to control the level of cardiovascular stress that a task will expose to a task performer, a proper physiological variable must be selected to represent the stress level. As described earlier, heart rate has a positive linear correlation with the cardiac output and the level of physical exertion (Davenport et al., 2008). Also, previous epidemiology studies have demonstrated the strong association between heart rate and cardiovascular mortality (Kannel et al., 1987; Gillum et al., 1991). In a prospective study researchers examined the relationship

between resting heart rate and the risk of cardiac disease. In that study 7735 men aged 40-59 years were monitored for 8 years. A total of 488 heart disease events were observed, and the data collected reflected a strong positive relationship between resting heart rate and the risk of having cardiac disease. Men with resting heart rates over 90 beats per min were identified as a particular high risk group (Shaper et al., 1993). Another study further suggested a significant association between heart rate and overall mortality (death from all causes) (Reunanen et al., 2000). In the sports exercise area heart rate has been used to optimize physical exercise (Kindermann et al., 2002) and to monitor the development and recovery of fatigue by coaches and athletes (Hooper et al., 1995). In the ergonomic work design area, heart rate inclination threshold values of 30 to 40 beats per min have been suggested by previous researchers (Luttmann et al., 1992). During physical exertion when these threshold values are exceeded a recovery interval will be considered necessary.

The maximum heart rate (HR_{max}) has been investigated by previous researchers. The most well known equation is $HR_{max} = 220 - \text{age}$ (Tanaka et al., 2001). Studies have demonstrated that the predictive equation of maximum heart rate is influenced by the subjects' ages (Tanaka et al., 2001) and gender (Gulati et al., 2010). These studies have also reported slightly different equations for calculating HR_{max} . For the purpose of this study the traditional equation ($HR_{max} = 220 - \text{age}$) will be used to calculate maximum heart rate.

2.4 Musculoskeletal risk assessment models

2.4.1 OWAS model

To identify risk factors that could cause LBP and to control the risk of injury in a working environment, researchers have developed several different models over the years. The Ovako Working Posture Analysing System (OWAS) was first introduced by a steel company (Ovako Oy from Finland in 1973 (Karhu et al., 1977)), and used and further developed in the ensuing years (Karhu et al., 1981; Kant et al., 1990; Kivi 1991). The OWAS model evaluates the risk of tasks by looking at working postures of different body segments (back, arms and legs) and the load of handling. In one study researchers used this model to investigate the musculoskeletal injury risk level among automobile mechanics (Kant et al., 1990). Forty-two garages were selected and a total number of 84 mechanics were involved in the evaluation. Work sampling methods were employed to record workers' working activities; during task observation workers' instantaneous working postures were recorded by taking samples or "snapshots" with constant or variable time intervals. These snapshots were first classified into different work activities (e.g. "Working underneath the car; using a grease pit", "Working inside the car" or "Administration, work planning"), then the postures of each worker's "Back", "Arms/shoulders", "Legs" and "Head" were further classified into one of four "Action Categories" that generally describe the harmfulness of that posture on a four-level scale ranging from "not harmful" to "extremely harmful". The percentage of time spent in each work activity and the percentage of each of the "Action Categories" within a work activity were calculated and compared. Results from that study identified four working activities ("working at the front, rear or the side of the car", "working underneath the car", "working under the bonnet" and "working in the car") to be more harmful than other

activities. When researchers introduced alternative work methods for three of these four activities, the result were that the new methods significantly reduced the percentage of time workers spent in poor working postures.

The OWAS model does a good job of identifying prolonged awkward posture within a relatively long interval of time (one working day); however, this model only gives provides a rough estimation of risky tasks. When using work-sampling methods conducted by human observers, variability among different observers cannot be avoided. Also in this model only the percentage of time for each work activity or posture was considered, and the sequence of tasks and the resting time between tasks were not considered in necessary detail.

2.4.2 PATH model

Based on an idea similar to the OWAS model, Buchholz et. al. developed a new risk assessment model called PATH (Posture, Activity, Tools, and Handling). This model not only evaluates the working postures, as OWAS does, but also includes descriptions of worker activity, tool usage, load handling, and type of grasp into the evaluation. This model has been used in the work risk assessment of highway construction workers (Buchholz et. al., 1996). In that study a taxonomy was first developed to break each construction project into a series of stages, with each stage further broken down into one or several operations. During data collection an observer will choose a group of workers performing a given operation and randomly select one of them to sample. On the data collection sheet workers “Posture” (adopted from OWAS model), the categories “Activities”, “Tool”, and “Handling” (weight of hand load) were all coded and recorded. Finally, in the data analysis phase, the proportion of

time workers spent in each task and the frequency of exposure for different postures and activities in each task can be calculated. The results of this study identified non-neutral trunk posture as a major hazard that road construction laborers face during their daily operation because of the large proportion of exposure time.

The PATH model is capable of evaluating non-cyclical work and could reasonably reflect the situation of observed tasks. However, like other observational models, this model only gives a general idea of the risk level of certain tasks. It has much less capability of evaluating the risk exposures for body segments that either cannot be observed or are hard to observe (e.g. spinal distal level, hand and wrist).

2.4.3 Job severity index model

Another effort reported by Liles and colleagues (Liles et al., 1984) tested the effectiveness of the Job Severity Index (JSI) in controlling injuries caused by manual material handling (MMH) jobs. The JSI is “a measure of the physical stress level associated with lifting jobs” first developed by Ayoub et al., in 1978. Equation 1 shows the components involved in the calculation of JSI:

$$\text{Equation 1: } \mathbf{JSI} = \sum_{i=1}^n \left[\frac{\mathbf{hours}_i}{\mathbf{hour}_t} \times \frac{\mathbf{days}_i}{\mathbf{day}_t} \right] \sum_{j=1}^{m_i} \left[\frac{\mathbf{F}_j}{\mathbf{F}_i} \times \frac{\mathbf{WT}_i}{\mathbf{CAP}_j} \right]$$

Where:

- n = number of task groups
- $hours_i$ = exposure hours/day for Group i
- $days_i$ = exposure days/week for Group i
- $hours_t$ = total hours/day for job
- $days_t$ = total days/week for job

$$\begin{aligned}
 m_i &= \text{number of tasks in Group } i \\
 WT_j &= \text{maximum required weight of lift for Task } j \\
 CAP_j &= \text{the adjusted capacity of the person working at Task } j \\
 F_j &= \text{lifting frequency for Task } j \\
 F_i &= \text{total lifting frequency for Group } i \\
 &= \sum_{j=1}^{m_i} F_j
 \end{aligned}$$

(Liles et al., 1984)

To use the JSI method, a job must be composed of a series lifting task groups; each task group is a set of lifting tasks involved in the performance of an action. For example, an action like unloading packages from a shelf may require multiple lifting tasks to be performed in different ranges. Among all the variables involved in the equation, the adjusted capacity (CAP) of the person working at a certain task is a subjective measurement defined as the maximum weight of load that an individual would be willing to lift in one lifting task. CAP is a self reported value and all the other variables are gathered by objective measurement.

Lilies' study recorded and calculated the JSI from 453 individuals working in 101 different jobs for a total of 1,057,881 exposure hours, and compared the JSI values with participants' injury records within the duration of data collection. The results indicated that, after a critical JSI value of 1.5, the risk and severity of injury dramatically increased. The authors concluded that the JSI has a strong association with the risk of injury and could be used in preventing injuries during the performance of manual material handing jobs.

This study demonstrated the association between the JSI and risk of injury; however, the direct causation of injuries and the type of injuries were not clarified. This model might work

to provide a broad perspective in predicting the risk of injury among large group of workers over a long period of time, but at a more refined level the JSI does not provide a clear link between the physiological changes during the performance of manual material handling tasks and the risk of injury. Also, since the JSI does not have a clear physiological meaning and is partially a subjective measurement, this value could vary significantly among a group of individuals.

2.4.4 LMM model

In a later study, Marras and colleagues developed another work risk assessment model associating the characters of trunk motion with the prevalence of low back injury among repetitive MMH jobs (Marras et al., 1993). The authors first identified a group of repetitive MMH tasks and divided them into two risk of injury groups (high or low) by comparing the medical and health records of workers performing these tasks. Then, to record workers' trunk motion during work, researchers developed a device called a Lumbar Motion Monitor (LMM) capable of recording a worker's three-dimensional thoracolumbar spine motion during different MMH tasks. By relating the trunk motion characteristics of different tasks to their corresponding injury records, the authors were able to generate a regression function that discriminates between low risk jobs and high risk jobs. The factors involved in this regression function include two workplace factors (load moment and lifting frequency) and three trunk motion factors (lateral trunk velocity, twisting trunk velocity, and sagittal flexion angle). Their model showed that, as the magnitude of each of these five variables increases, the risk of injury increases.

The development of this model clearly demonstrated that higher magnitude of trunk motion is associated with higher risk of injury. Compared with the JSI model, the LMM model is able to provide insight into the linkage between real trunk kinetics variables and the risk of injury for a MMH task. This model will be helpful in designing better workplaces by attempting to reduce the magnitude of the above mentioned five factors. However, the underlining mechanism causing low back injury is still not clearly understood from this model, since it doesn't answer several questions. Is the increase of these five factors causing more muscle fatigue? Are they putting too much burden on passive tissue? Is there a cumulative effect building on the low back area? Are most injuries acute trauma injuries? Results produced by this model provide unclear answers to such questions.

2.4.5 NIOSH lifting equation model

The National Institute for Occupational Safety and Health (NIOSH) first developed and published an equation in 1981 whose purpose was to evaluate the demands of lifting jobs and assisting task designing (NIOSH 1981). This equation is as the well known "NIOSH lifting equation". In 1991 a revised NIOSH lifting equation was published (Waters et al., 1993) with a number of modifications to the original equation. This revised NIOSH lifting equation has been widely used in many MMH related industries all the way up to today. As presented in Equation 2 the NIOSH lifting equation is comprised of seven different components: Load Constant (LC), Horizontal Multiplier (HM), Vertical Multiplier (VM), Distance Multiplier (DM), Asymmetric Multiplier (AM), Frequency Multiplier (FM), and Coupling Multiplier (CM). These components are involved in each MMH task and they can be used to generate

the recommended weight limit (RWL). By comparing the actual weight of handling to this RWL one could in general determine the risk level of a task (Waters et al., 1993).

$$\text{Equation 2: } \mathbf{RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM}$$

The NIOSH lifting equation has become a convenient and effective way to evaluate MMH tasks and thereby control the risk of low back injuries ever since its being published; however, it still has limitations. It describes each task as a static risk factor without consideration of dynamic human body changes (e.g. fatigue development), occurring during task performance. This equation is also incapable of evaluating static exertion tasks (e.g. weight holding, static awkward posture holding).

2.4.6 CABS model

A hybrid risk assessment model called CABS (Continuous Assessment of Back Stress) was finally created by adapting multiple previously well established risk assessment models (the NIOSH Lifting Equation, the Three-Dimensional Static Strength Prediction Program, and the Lumbar Motion Monitor Model) and comparing the results from these models. In one study researchers used the CABS model to investigate the low back injury risk level among workers in the home building industry (Mirka et al., 2000) involving a variety of MMH tasks that create high degree of variability in workers' physical demands. In that study workers' activities were video recorded, reviewed, and coded. For output, CABS model generated a time weight distribution of risk factors of interest (e.g. spinal compression force, NIOSH lifting index) by utilizing different existing risk assessment models to demonstrate the level

of stress involved in different tasks. At the conclusion outputs from all three risk assessment models for the same work activity were compared. Results of this comparison showed inconsistency in identifying high-risk work activities among different risk assessment models. This indicates that different models focus on different perspectives of low back risk of injury. The greatest benefit of the CABS model is that it utilizes multiple risk assessment models to examine the same task from different perspectives and provides a much more comprehensive view for the risk level of a task than any other single model. However, since it is a hybrid model, the CABS model also adapts the common limitations of the models it uses: The time effect of work activities, for example, were not clearly defined and demonstrated. The effect of work rest scheduling was not considered. These perspectives are important because simple MMH tasks could generate physiological changes (e.g. generate muscle fatigue) during the duration of task performance and cause injuries over a long period of time. A proper work-rest schedule may minimize the risk of work activities without reducing the intensity of work activities or the duration of working time.

2.4.7 Cumulative trauma models

Cumulative risk factors have also been considered in some studies. Previous studies have shown that the occupational cumulative spinal loading or “biomechanic load and exposure time integral over the entire work experience” has a significant impact on the occurrence of low back pain within different industries (Kumar 1990, Norman et al., 1998). Other studies suggest that cumulative spinal loading is positively associated with documented spinal injuries (Seidler et al., 2001, 2003). These studies point out that, in a relatively long period of working time, it might not be an acute, excessive single loading that would cause an injury,

but rather an overtime cumulative effect that might take years to develop, just like the total mileage of a car, that eventually could cause the failure of a system or in this case an injury or dysfunction of the spine.

In a case control study (Norman et al., 1998) researchers investigated the relationship between an LBP report and biomechanical variables from over 10,000 automotive assembly workers. A comparison between 104 LBP workers and 130 randomly selected healthy workers revealed that the magnitude of cumulative spinal loading (within a complete work shift (two to eight hours)) is positively correlated with the incidence of LBP. This study demonstrated that for a worker performing physical demanding tasks, not only can the excessive peak spinal loading cause an acute LBP, but also the cumulative spinal loading over long period of time (over years) may generate LBP.

In another study, researchers assessed the effect of ergonomics interventions on the reduction of low back risk of injury among healthcare workers (Daynard et al., 2001). Two types of intervention were tested. The first strategy was to use improved patient handling techniques with existing equipment, while the second strategy involved using new assistive equipment to avoid manual patient handling. A total of five patient handling tasks (“Bed-to-wheelchair transfer”, “Bed-to-stretcher transfer”, “Bed boost”, “Chair boost” and “Bed turn”) were tested. Healthcare workers’ task performances were video recorded and later used to calculate peak spinal loading and cumulative spinal loading by using a combination of subjective estimations from a professional occupational biomechanist and objective calculations from a biomechanical model. Results of this study demonstrate a reduction in

peak spinal loading when complying with interventions. However, in many cases an increase in cumulative spinal loading due to the prolonged task performance duration and increased actions that required by the use of interventions was also observed. In the end, the authors suggested that even though the reduction in peak spinal loading may decrease the risk of acute back injury, the increase in cumulative spinal loading may cause trauma over long time (months or years), especially when a task is performed frequently.

2.4.8 Limitations

Despite having been identified as a risk factor, the cumulative effect of work stress within the duration of multiple task performance (in minutes) has not been well incorporated during the development of previous risk assessment models. In order to avoid long-term cumulative work stress, restricting the amount of physical stress of every physical exertion below an acceptable level is critical. However, none of the previous risk assessment models provides such delicate measurement. One must admit that most risk assessment models (e.g. OWAS, PATH, NIOSH lifting equation and CABS); have somewhat included task duration as one element of their evaluation. However the underlining physiological downside of long task duration has not been carefully monitored and modeled. All the above mentioned risk assessment models were developed while attempting to evaluate the risk level in a gross fashion (e.g. within hours, a day, or even months and years). None of them is able to clearly monitor the physiological changes within minutes. Additionally, most of the previous models were developed using arbitrarily defined variables (e.g. JSI and NIOSH lifting equations) or codes that represent the level of risk (OWAS, PATH). Some models used direct measurements or predicted values to reflect the magnitude of risk of injury such as spinal

compression force (cumulative risk studies) or lumbar angular acceleration (LMM model)... All these variables have been described as indicators of the risk of injury. However, since the term “risk of injury” cannot be well defined, any variable that tries to directly associate with it is debatable.

2.5 Cardiac risk assessment studies

2.5.1 Acute cardiovascular risk

In general, moderate physical activities are proved to be beneficial to cardio-respiratory fitness (Thompson 2003) and may reduce the risk of death from coronary heart disease (Paffenbarger et al., 1993). However, acute vigorous exercise has been shown to cause a transient increase in the risk of primary cardiac arrest and major vascular thrombotic events (Albert et al., 2000; Siscovick et al., 1984). This effect is even greater among coronary artery disease patients whose risk of cardiac arrest during vigorous exercise may increase 100-fold compared at resting condition (Cobb & Weaver 1986).

In a prospective study, researchers followed the physical activity and health information of 21,481 male physicians for 12 years (Albert et al., 2000). In 1982, subjects were aged between 40 and 84 years in and free from cardiovascular and other life threatening diseases. During the 12 years, subject' deaths were recorded and the specific activity that the subject was engaged in at the time of death and for one hour before death was obtained. The degree of physical exertion was quantified on a scale of 1 to 8 metabolic equivalents (MET). Table 2 shows the classifications for physical activity intensity and the corresponding quantity of different measurements (Wang 2006; American College of Sports Medicine 2006). Activity

level at 6 MET (which corresponding to about 80% of maximum heart rate) or more was considered as vigorous exertion, below 6 MET was considered as non-vigorous exertion. A total of 122 sudden deaths were confirmed, among them 23 sudden deaths were related with vigorous exertion (either happened during the vigorous exertion or within 30 minutes after the exertion) accounting for 19% of total sudden deaths. These results suggested that the rate of sudden death during vigorous exertion was on average 20% higher when compared to deaths occurring during light or no exertion conditions. This risk is even higher among less physically active populations.

Intensity	%VO _{2max}	%HR _{max}	MET
Very light	< 30	< 35	< 3
Light	30–49	35–59	3–4
Moderate	50–74	60–79	5–6
Strenuous	75–84	80–89	7–8
Very strenuous	> 85	> 90	> 8

Table 2: Classification of physical activity intensity (Wang 2006) VO_{2max} = maximal oxygen consumption; HR_{max} = maximal heart rate; MET = metabolic equivalents.

The physical changes during acute vigorous physical exertions have also been investigated. A comprehensive review of the effect of physical exertion intensity on thrombotic modification (Wang 2006) summarized that acute, strenuous exercise ($\geq 75\%$ VO_{2max} (equivalent to over 80% HR_{max} or ≥ 6 MET as shown in Table 2) enhances platelet reactivity and activates blood coagulation and fibrinolytic activity simultaneously. A previous clinical study identified platelets as a critical factor for the pathogenesis and progression of cardiovascular disease (Fitzgerald et al., 1986). Elevated platelet activation is

one of the mechanisms causing coronary thrombosis in narrowed coronary arteries. (Holme et al., 1997), furthermore, this response is accentuated in sedentary individuals compared to those who are physically active (Kestin et al., 1993). Dawson et al., (2008) investigated the impact of an acute prolonged strenuous exercise on vascular and cardiac functions. A total of 15 non-elite runners participated in the study the day before and within an hour of finishing the London marathon. Physiological analysis revealed a weakened left ventricular diastolic function and signs cardiomyocyte damage after the marathon.

Collectively, the previous studies suggest that the risk of sudden death may increase following acute intensive exercise in response to increased platelet activity and transient depression. This evidence suggests that in a working environment, it is *critical* to regulate the maximum physical exertion level and duration of tasks. Arguably, workers are exposed to long periods (e.g. 8 hours a day, 5 days a week) of highly physically demanding tasks, therefore it is imperative to monitor and control cardiovascular stress workers experience on a daily basis in order to reduce or avoid acute damage caused by strenuous physical exertion.

2.5.2 Cumulative cardiovascular risk

Other than acute cardiovascular risks caused by vigorous physical exertion, cumulative damages may also occur with long-term prolonged exercise. Previous studies suggest that long term (over years) endurance exercise may cause scar tissue formation in the myocardium (Lindsay & Dunn 2007; La Gerche et al., 2008). These minor but irreversible cardiomyocyte damages may accumulate over time and cause further injury (Whyte 2008).

Animal studies have demonstrated localized myocyte damage after prolonged (3.5 to 5 hours)

vigorous physical exertion (Chen et al., 2000). Additionally, biochemical evidence for cardiac fibrosis in veteran endurance athletes has been reported (Lindsay & Dunn 2007). An autopsy record from a world-record marathon runner revealed small, patchy scar in the left ventricular posterior wall and focal fibrosis of left papillary muscles which may have resulted from long term prolonged strenuous exercise (Rowe 1991). Another case study report of an athlete who died suddenly during a marathon race observed widespread replacement of fibrosis in the ventricular walls and interstitial fibrosis in the myocardium (Whyte et al., 2008). Substantial evidence indicates a relationship between long term repetitive strenuous physical exertions and the development of cardiovascular dysfunctions.

In order to reduce the cumulative damage caused by long term physical exertion a regulation on the physical exertion level needs to be established. The American Heart Association recommends a target exercise heart rate between 60% and 85% of the maximum heart rate in order to induce beneficial outcomes (American Heart Association 2005). For pregnant women, a target exercise zone of 60% to 80% of maximal aerobic capacity (VO_{2max}) was suggested (Wolfe & Mottola 2002) which corresponds to around 70% to 85% of HR_{max} as indicated in Table 2. Pacemaker patients were recommended upper limit heart rates of 75% HR_{max} or 86% HR_{max} during exercise (Kindermann et al., 2002).

While multiple guidelines and scientific reports have been made to suggest target heart rate zones during exercise, there is still a deficiency in controlling/guiding the level of physical exertions during working. From an occupational perspective, Luttmann et al., 1992 suggested heart rate inclination threshold values of 30 to 40 beats per min during working. Consider the

long duration (e.g. 8 hours a day) and high frequency (e.g. 5 days a week) of task performance in an occupation. Undoubtedly, further refined regulations on average and peak heart rate during work task performance must be provided in order to reduce the risk of cardiovascular injury.

2.6 Job rotation, work/rest models

2.6.1 Job rotation model

Job rotation is a management methodology where individuals are moved through a sequence of jobs or tasks in a given amount of time. A job schedule is often designed with a multi-function purpose to reduce work stress, boredom and increase job satisfaction or create a more flexible working environment. A well-designed job rotation schedule is capable of reducing the overall risk of injury in a working environment, by rotating workers through a set of tasks that have different risk levels or expose risk to different parts of the body. Job rotation ensures that the total amount of risk exposure will be averaged over every worker in the rotation plan, minimizing the risk of injury.

2.6.1.1 Job rotation model #1

A theoretical model has been developed with purpose of designing a job rotation schedule for a group of lifting tasks performed by a group of workers in order to minimize the risk of back injury (Carnahan et al., 2000). In that model the authors create a working scenario in which a series of weight lifting tasks need to be performed within a period of time by a group of workers. Different lifting tasks required different levels of physical exertion; the working capacity of workers also varied (e.g. 50th percentile lifting capacity female worker, 25th

percentile lifting capacity male worker). In this case, the same lifting task exposed different levels of physical burden to different performers. To count for the individual differences JSI was used to assess the risk of back injury for different performers. As mentioned before, JSI considers the lifting capacity of task performer as well as the requirement of lifting tasks (weight of the object, rate of lifting, distance of the load from lifter...) and generates a unitless number that describes the risk level of back injury (Liles 1984). Integer programming and genetic algorithm were then used to select the most desirable job rotation schedule with objective function of minimizing the total JSI number that add up from each individual worker. An example of the job rotation schedule is shown in Table 3.

Time period	50th percentile male	90th percentile female	25th percentile male	50th percentile female
08:00 – 09:00	Task C	Task B	Task D	Task A
09:00 – 10:00	Task C	Task A	Task D	Task B
10:00 – 11:00	Task C	Task A	Task D	Task B
11:00 – 12:00	Task C	Task A	Task D	Task B
13:00 – 14:00	Task C	Task A	Task D	Task B
14:00 – 15:00	Task C	Task A	Task B	Task D
15:00 – 16:00	Task B	Task A	Task C	Task D
16:00 – 17:00	Task A	Task B	Task C	Task D
Mean JSI	1.50	1.55	1.50	1.56
SD JSI	0.098	0.038	0.13	0.102

Table 3: An example of job rotation schedule (Carnahan et al., 2000).

This model creates a job rotation model that fits the capacity of individuals; however it also has its limitations. First, the JSI used in this model is a subjectively defined index that intends to describe the risk of back injury for each individual. Similar to any other subjectively defined index the dependability of JSI is debatable. In addition, one important factor used in

the calculation of JSI was the maximum weight lifting capacity of an individual which was obtained in a self report fashion (Liles et al., 1984). This fact obviously puts more variability to the result of JSI. Secondly, by considering individual differences between workers the model has a tendency of resulting in heavier demanding tasks to workers with higher capabilities (Table 3) which may create issues of fairness among workers.

2.6.1.2 Job rotation model #2

Another job rotation strategy was created to avoid using the same group of muscle (cumulate stress on the same part of body) among consecutive tasks (Diego-Mas et al., 2008). The experiment investigated 18 workers working consecutively on 18 workstations each day. This study aimed to develop a four-section job rotation plan, able to rotate (or relocate) 18 workers among the 18 workstations 4 times a day (2 hours for each rotation) in order to reduce the risk of injury. First of all, the physical requirement of each workstation in terms of required body movement (e.g. arm abduction, neck flexion, trunk rotation...) and required working capacities that included “general capacities”, “mental capacities” and “communication capacities” were analyzed and described in detail. For each workstation the required movement was scored by its performing frequency and workers’ ability to perform the movement (Table 4). Workers’ personal preferences of working in those 18 workstations were also considered. A genetic algorithm was used to generate an optimal job rotation schedule with the objectives of minimizing the consecutive time consumed by the same body movement and assign workstations with similar requirement not in consecutive sequence. An example of job rotation schedule is shown in Table 5. In this study authors clearly demonstrated the idea of relocating physical stresses to different parts of body by employing

proper job rotation plans; however, the methods used to create movement scores and capability levels were subjective. The clear physiological impact of task performance was unable to be revealed through this scoring method or any method that does not incorporate physiology measurement. In addition, the two hour job rotation duration was arbitrarily selected, which could be an understandable simplification for the purpose of this study; however it is important to recognize that the duration of task performance or job rotation interval is an important factor that could significantly increase the risk of injuries.

Frequency of movement per minute	Description of movement	Score
>8	Very frequent	3
3-7	Medium frequency	2
1-2	Infrequent	1
0	Never	0

Table 4: The frequencies of movements and their corresponding scores (Diego-Mas et al., 2008).

	Rotation 1	Rotation 2	Rotation 3	Rotation 4
Worker 1	Job 17	Job 16	Job 5	Job 15
Worker 2	Job 13	Job 7	Job 15	Job 10
Worker 3	Job 18	Job 8	Job 7	Job 13
Worker 4	Job 3	Job 17	Job 8	Job 5
Worker 5	Job 14	Job 4	Job 17	Job 16
Worker 6	Job 8	Job 10	Job 2	Job 18
Worker 7	Job 6	Job 13	Job 12	Job 1
Worker 8	Job 12	Job 1	Job 6	Job 14
Worker 9	Job 15	Job 5	Job 18	Job 8
Worker 10	Job 4	Job 14	Job 1	Job 6
Worker 11	Job 7	Job 18	Job 3	Job 9
Worker 12	Job 11	Job 3	Job 11	Job 2
Worker 13	Job 16	Job 12	Job 14	Job 4
Worker 14	Job 2	Job 11	Job 16	Job 3
Worker 15	Job 9	Job 2	Job 9	Job 12
Worker 16	Job 1	Job 6	Job 10	Job 11
Worker 17	Job 5	Job 9	Job 4	Job 17
Worker 18	Job 10	Job 15	Job 13	Job 7

Table 5: An example of final job rotation schedule involving 18 workers and 18 workstations (Diego-Mas et al., 2008).

2.6.1.3 Job rotation interval

The effect of job rotation interval on low back disorder has also been investigated (Tharmmaphornphilas and Norman 2004). In this study a manual lifting environment with a series of dynamic lifting tasks, and a number of non-identical workers that vary in gender, anthropometry, age, strength, etc were all simulated. JSI was used as a measure to represent the stress of a lifting task exposed worker (higher value represents higher risk of low back injury). Job rotation interval was defined as the time of performing each task until the next rotation occurs. The rotation intervals of 8 hours (no rotation during a day), 4 hours (2 rotations in a day), 2 hours, 1 hour or any time as wanted (allowing rotation continuously) were tested. By developing a mathematical optimization model that calculates the maximum JSI value that is created by using different job rotation intervals, the authors were able to demonstrate which interval was preferable. Results suggested that decreasing job rotation interval from 8 hours to “any time as wanted” the JSI value decreased significantly which indicates significant decrease in low back risk of injury. If we associate this JSI value to the number of worker lost days per hundred full-time equivalent worker years then it is equivalent of reducing from 63.0 in 8-hour rotation interval condition to 53.8 in the “any time as wanted” interval condition. Finally consider only a slight, non-statistically significant decrease for rotation interval shorter than 2 hours (from 55.0 to 53.8) and the practicality of the operation the job rotation interval of 2 hours was recommended by authors.

2.6.2 Work-rest scheduling model

Work-rest scheduling model has also been explored over the years. In general two types of work-rest scheduling research have been investigated: empirical study and theoretical model study. As the name indicates most of the time an empirical study is conducted among a real set of participants and to test different work-rest schedules with the purpose of selecting the optimal solution. A theoretical model study most of the time is built by utilizing mathematical methodologies (e.g. optimization, linear programming) and making necessary assumptions with the purpose of building a predictive model.

2.6.2.1 Empirical work-rest study

A large number of empirical studies have focused on investigating video display terminal (VDT) associated jobs which are highly related with mental stress and/or muscle strain created by prolonged awkward posture. For physically intensive jobs one study investigated the effect of active micro breaks on the reduction of discomfort level of meatpacking workers (Genaidy et al., 1995). Results indicated that active micro breaks significantly reduced the level of discomfort perceived by these workers during the testing period. Another empirical study, conducted on industrial workers (Bhatia & Murrell, 1969). In this study researchers aimed to investigate and compare the effectiveness of two fixed resting schedules on the improvement of fatigue and job satisfaction. Schedule A had 10 minutes of rest after every 50 minutes of work and schedule B had 15 minutes of resting for about every 65 minutes of work. This study suggested that organized rest pauses can reduce fatigue, increase productivity and mitigate monotony. In addition, shorter break (schedule A) was much preferred than longer break schedule (schedule B) by the participants. Finally a nice

summary and guidelines of work-rest scheduling have been published by Konz in 1998 (Konz 1998a, b).

2.6.2.2 Theoretical work-rest model

On the other hand, operations research approaches have been used in the development of theoretical work-rest scheduling models. In 1964, Eilon first introduced an optimization mathematical model to calculate the optimal resting schedule during a work shift with the object of maximizing productivity (Eilon 1964). Since then several mathematical models have been developed (Gentzler et al., 1977; Bechtold et al., 1984; Bechtold and Summers 1988; Bechtold 1991). One of the models developed by Bechtold and colleagues in 1984 (Bechtold et al., 1984) used an optimization approach with the objective of maximizing labor productivity. This model utilizes a mixed-integer quadratic programming formulation to decide the optimal scheduling (including the number, duration and placement) of rest breaks. In this model the type of work was not specified; the overall work stress included physical stress and mental stress and/or any other stress factors that would reduce the productivity. The impact of work exposure on productivity uniformly considered as “work decay”. A resting time was considered to provide recovery to the work decay and also the productivity. In this model, productivity (not the actual work stress) was modeled in a circular fashion (decrease during work and recover during rest) the rates of decreasing work productivity and its recovery are assumed to be linearly related with exposure time (either work or rest) as shown in Figure 4. This model was tested in a group of airline corporation employees. Results showed that the model-generated work-rest schedules increased the average productivity by 13%. Although supported by real (empirical) data this modeling

methodology is still questionable. First of all, the assumed linearity of decreasing and recovering rate of productivity may not be realistic and could have an impact on the final result. In a recently published comprehensive review on work-rest modeling (Lodree et al., 2009) authors concluded that the existing operation research oriented work-rest modeling literature lacks a sense of realism. The review stated that “nonlinear and time varying decay and recovery rates” and “the introduction of more realistic representations of work rate decay and recovery...is likely to result in further performance improvements in practice.” In addition, being a model focused exclusively on the changing of productivity the meaning of work stress was not specifically defined, the risk of physical injury and the cost associated with these injuries was not considered in this model.

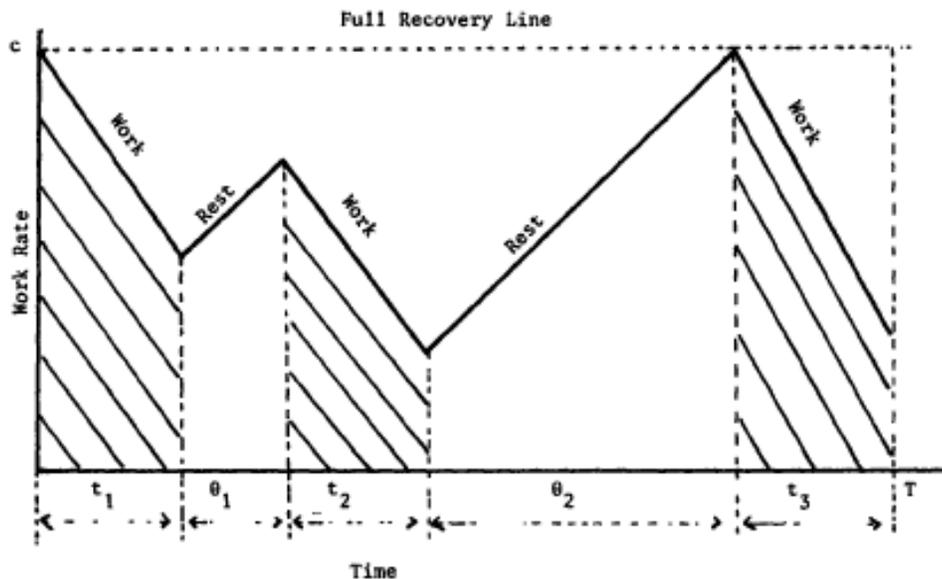


Figure 4: The theoretical productivity profile during work and rest (Bechtold et al., 1984).

In 2009, Hsieh et al., developed a theoretical model that emphasized attention on workers' health or risk of injury perspective. This model was developed to create work-rest schedules

for construction workers with the purpose of providing laborers sufficient resting time without delaying the working schedule. To achieve this, equations have been developed to calculate the maximum acceptable work duration and the rest time required after a certain time of work by using a measurement of subject's oxygen consumption rate. An optimization process was then created with objectives of minimizing the time for completing jobs and minimizing extra energy expenditure of laborers due to inappropriate work assignments that force them to work beyond the maximum acceptable work duration. This research showed that the model developed for this specific construction project successfully created a work-rest schedule that fulfilled the purpose. However, this model still does not have the ability predict physiological changes of workers while performing physical tasks, plus the selection of resting placement and duration is still in lack of theoretical support.

One group of researchers have used the profile of heart rate during working and resting time to produce a work rest schedule in order to protect refuse collection workers from injury (Luttmann et al., 1992). Work rate (number of containers emptied per unit time) and heart rate were recorded simultaneously and a linear relationship was found between these two variables, namely higher work rate resulted in higher heart rate. Researchers concluded that short breaks should be provided after every hour of working in order to recover muscles from fatigue and heart rate to the normal level.

Building upon all the great works that have been done by previous researchers, now is the time to develop a new risk assessment and management model that could precisely monitor the physiological changes of workers during the performance of one task or a group of tasks.

This model should also be able to setup the time and duration resting, and/or select optimal task performance sequence according to these physiology changes in order to reduce the risk of injury while maintain productivity. In addition, the variables used to reflect “risk of injury” must have a direct relationship with injuries (e.g. median frequency, trunk sway speed and heart rate).

2.7 Introduction of inventory control theory

Modern operations management research is a highly mathematical involved science. The goal of operations management research is to precisely control and manage different aspects of product such as manufacturing, transportation, sale and etc. Over the years production scheduling models have been developed with the purpose to optimally synchronize production, inventory and demand in order to reach to maximum profit. One of the earliest mathematical production scheduling models the “Economic Order Quantity” (EOQ) model was developed by Ford W Harris in the early 20th century (Harris 1913) and it has been widely studied later on.

We can have a better understanding about EOQ by using an example. Product X has an constant annual demand of 100 pieces, to meet the demand a store can have many different ordering plans, for example, plan A: order 100 pieces at the beginning of the year, plan B: 50 pieces at both the beginning and the middle of a year. As long as its inventory can meet the demand any plan would work. However there is a setup cost involved in each ordering event which means the more times the store orders the more setup cost it has to pay, the consideration of this setup cost will make plan A preferable since it has only one setup cost

per year. On the other hand, products that have been ordered become inventory before sale which also creates a holding cost, that's the money a store will lost by tying up money in their inventory products. The more products in the inventory the higher holding cost will be generated. In this case there is a benefit of ordering more products for fewer times but also a penalty for keeping more products in the inventory. EOQ model can be applied in this case to generate an optimal ordering plan that balances this trade off with the purpose of maximizing the overall profit. The inventory vs. time relationship is showing in Figure 5.

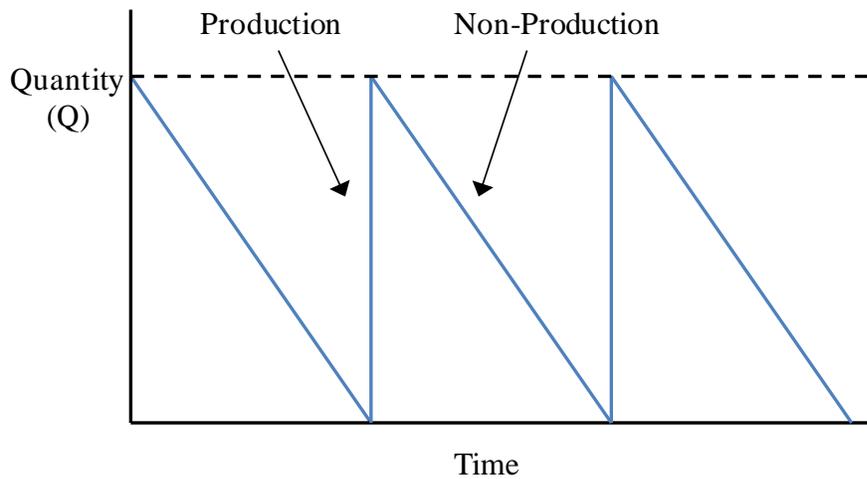


Figure 5: Inventory profile of EOQ model.

The EOQ model considers the production time to be zero which means the inventory can be immediately filled up any time an order is placed. Whereas in reality most productions do not have an infinite production rate, in this case an extended EOQ model which considers the time of production (more realistic) was developed. This model is called the economic production lot (EPL), its inventory vs. time curve is showing in Figure 6. As we have introduced before EOQ model stand for Economic Order Quantity which only considers

ordering point, this model considers purely the inventory perspective, whereas the EPL model considers both the production and also the changes in inventory. The EPL model can fully represent the inventory cycle during the production and non-production time which becomes similar to the idea of work-rest cycle (as shown in Figure 4).

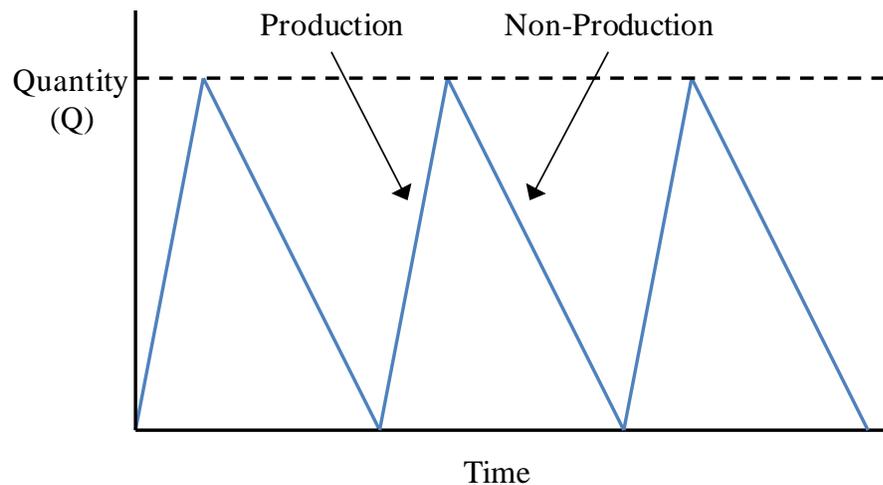


Figure 6: Inventory profile of EPL model.

The idea of this inventory control theory can now be applied to the ergonomics arena to develop a job rotation model and work rest scheduling model. Similar with production and consumption of any product when workers perform tasks muscle fatigue will build up causing increase of metabolic rate and instability, when muscle fatigue reaches a certain level and resting time is provided, a worker's metabolic rate will gradually decrease and the instability will be reduced. This similarity enlightened us to develop a quantitative model that is able to manage the physiological parameters of the human body by using production management model with purposes of minimizing the risk of injury or work burden while still keeping the productivity.

As introduced above the EPL model is more desired to be applied to monitor physiological changes because both the development and recovery of any physiological change would take time. The instantaneous production assumption of the EOQ model does not suit for the current model.

In order to apply EPL model to the modeling of physiology changes introduced by low back muscle fatigue we must first link the variables used in the EPL model to the corresponding variables that are involved in the development and recovery of muscle fatigue. Also as described before, low back muscle fatigue generates multiple physiology changes (e.g. heart rate, median frequency and body sway), these changes can be investigated individually and modeled by EPL model. The variables involved in the EPL and their corresponding variable in the new model is presented in the Table 6.

EPL variables	Original definition	New definition
P	Production rate	Rate of fatigue development
D	Demand rate	Recovery rate of fatigue
c	Unit production cost (not counting setup or inventory costs)	N/A
W	N/A	Wage cost
A	Fixed setup cost	Cost of setup each recovery section
h	Holding cost ($h=ic$, where i is the annual interest rate)	Potential cost of holding high level of fatigue
Q	Lot size (decision variable)	Upper and lower limit of risk level

Table 6: Definition of variables involved in an inventory control model and their corresponding meanings in the new model.

Similar with EOQ model in the EPL model several variables must be defined. As shown in Table 6, setup cost was reconsidered as the cost for having each rest (e.g. turn on/off machine; having other workers perform job rotation...). “Unit production cost” was not modeled (or assumed to be zero) in the new model because there is no corresponding concept existing. A new variable “Wage cost” was introduced to the new model only to track the total salary cost during the task performance. Holding cost was modeled as the cost of keeping high level of trunk sway (caused by muscle fatigue); this cost was considered non-linear function of magnitude of trunk sway.

2.8 Problem statement

In summary, the high prevalence and cost of LBD (low back disorder) encouraged researchers to dedicate huge amount of effort in searching for the cause of the problem and to find ways to avoid LBD from happening. Although numerous of risk assessment models have been developed, most of them focus on identifying the hazard tasks that are more likely to cause acute injuries but do not consider the dynamic physiology changes of human body during physical task performance (cumulative effect of risk exposure). This is important because low risk task performed from excessive durations could be equally or even more hazard than a high risk task. Job rotation models and work-rest schedule systems did consider the cumulative effect of task performance on a gross scale. However, none are able to provide enough theoretical and mathematical power to track and manage the physiological changes in a refined level.

Now a new model needs to be developed with the capability of instantaneously tracking the physiology changes of human body during the performance of tasks that create low back muscle fatigue. An inventory control model will be applied to monitor the effect of low back muscle fatigue on different physiology variables and their recovery. The optimal task sequence and work-rest schedule will be generated with the consideration of minimizing work burden and risk of injury while maintaining the productivity and balance the cost. The flow chart of project procedure is showing in Figure 7.

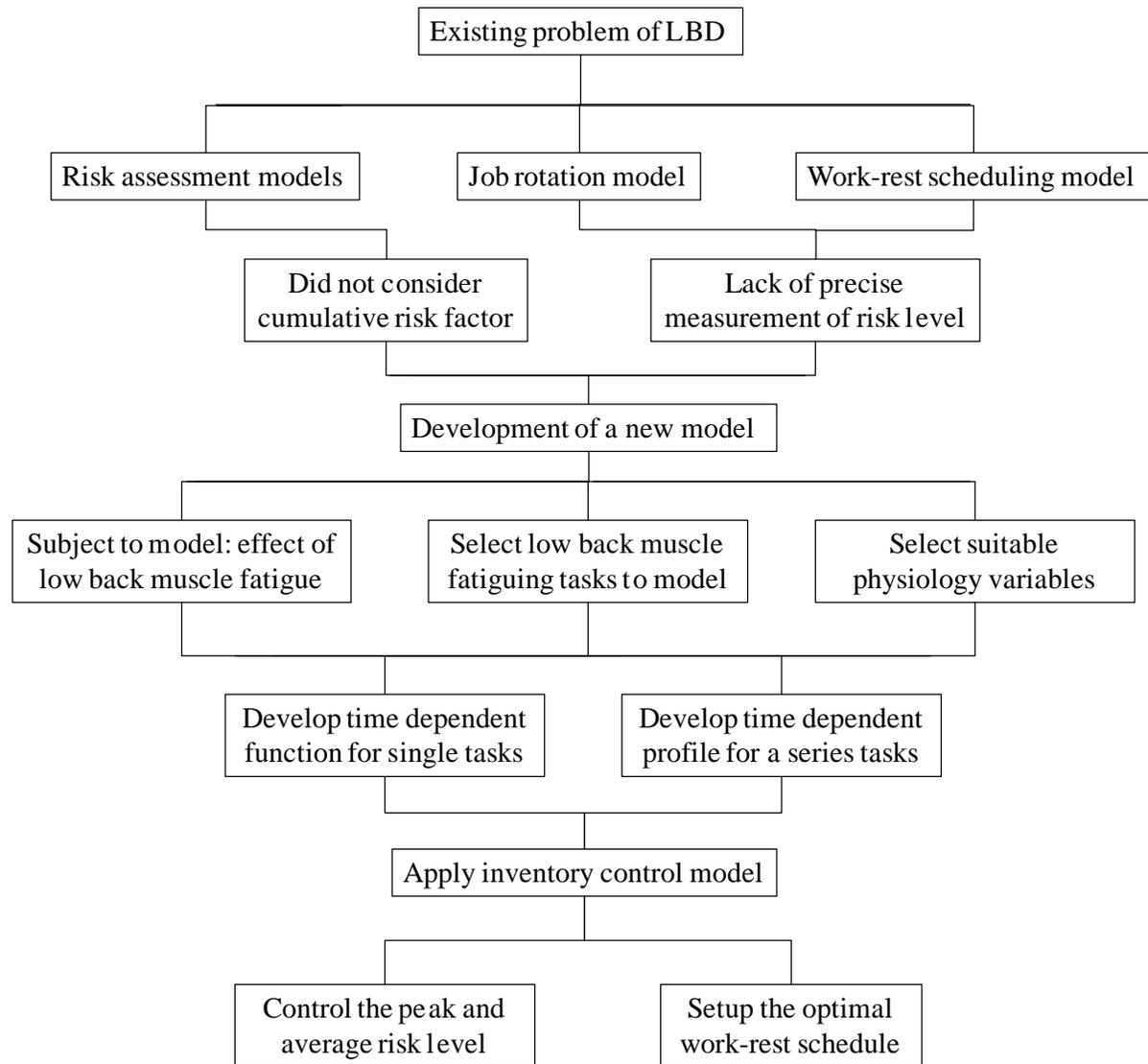


Figure 7: The flow chart of project idea.

CHAPTER 3. PILOT WORK

3.1 Design of the experiment

The purpose of this pilot experiment was to investigate the effect of low back muscle fatigue on physiological changes of the human body and to develop a series of time dependent functions able to describe and predict these changes. To do that a muscle fatigue protocol must be selected. As discussed in the previous muscle fatigue physiology section the development and recovery of muscle fatigue varies significantly depending on the fatiguing tasks that are performed. In this pilot study we explored low back muscle fatigue induced by two types of exertions: sustained static exertion and dynamic intermittent exertion. Three physical responses: trunk sway speed, muscle EMG median frequency and heart rate were selected to represent the physiological changes created by low back muscle fatigue.

3.2 Participants

One participant was recruited from the student population of Iowa State University. This subject was free from any chronic lower extremity injury or current discomfort and did not have any history of chronic low back pain.

3.3 Apparatus

A force platform was used to capture the three-dimensional ground reaction forces and moments (Bertec, Columbus, OH). A custom made pelvis restriction apparatus was set on the top of force platform (Figure 8) in order to restrict movement below subjects' pelvis level and also to enable the force platform to capture all the changes in forces from the system (human body plus pelvis restriction). In this case impact from outside the system was

eliminated. Muscular electromyography data collection system with 1 pair of bi-polar surface electrodes (Model: Bagnoli, Delsys Inc, Boston, MA, USA) (Figure 9 left) was used to capture musculature activities. Electrodes were placed bilaterally on the L4 level of lumbar spine 3 cm apart from the midline of spinal column. A heart rate monitor (Model: T31, Polar Electro Inc, Lake Success, NY, USA) (Figure 9 right) was also used to measure subject's heart rate.

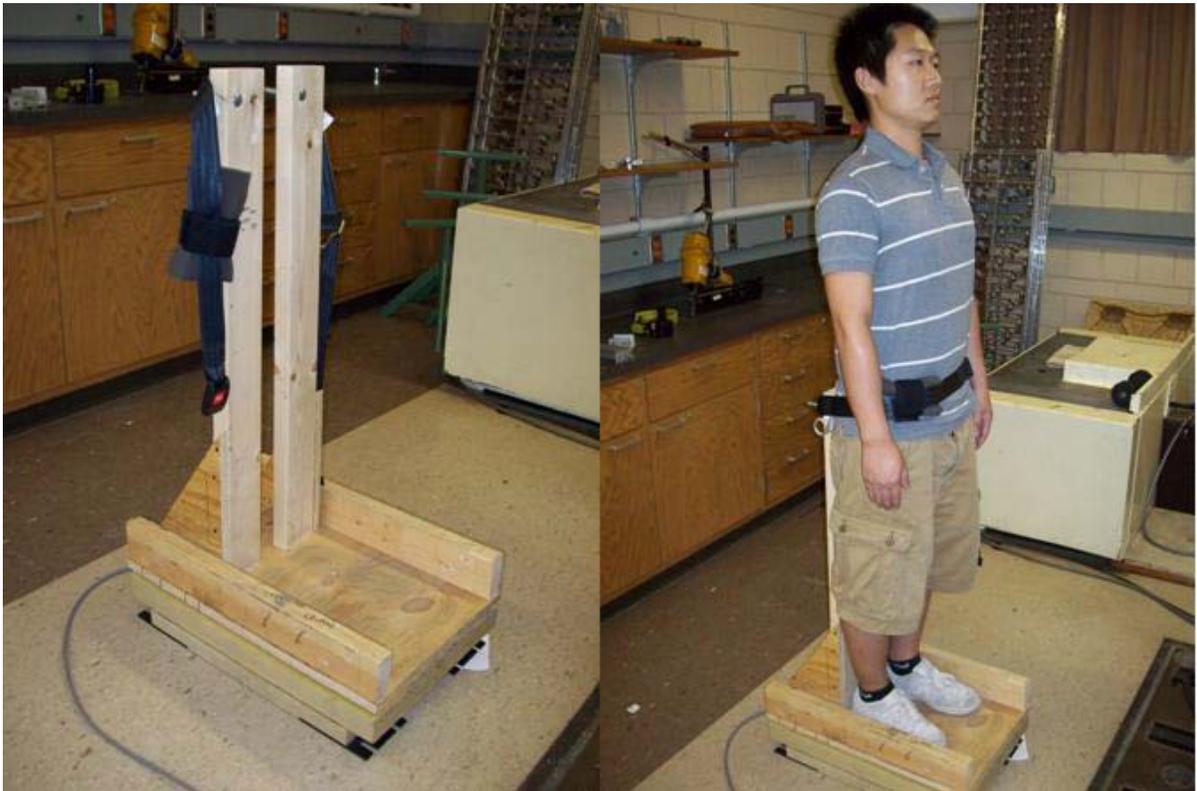


Figure 8: Customized pelvis restriction apparatus.



Figure 9: Experimental apparatus (Bipolar EMG electrodes (left) and Heart rate monitor (right)).

3.4 Experimental tasks

3.4.1 Fatigue development tasks

The rationale for considering two types of fatiguing exertions are based on evidence suggesting different types of muscle exertions (especially between static and dynamic exertions) fatigue the muscles differently. In the current study both static and dynamic muscle exertions were tested. First a sustained static low back muscle exertion task was selected and defined as: holding a 45 deg forward trunk flexion posture for 4 minutes. During this protocol subject was asked to drop his arms without any movement and maintain their lumbar as straight as possible (keep lumbar lordosis) in order to fatigue low back muscles as quick as possible in a consistent rate while avoiding creating tension in the passive ligaments (Figure 10 left). For the dynamic intermittent muscle exertion, subjects lifted a 35lbs crate from ground level to approximately knuckle height and lowered the crate to the ground once

every 8 seconds for 3 minutes (Figure 10 right). For this subject was asked to always straighten his arms during both lifting and lowering in order to avoid any fatigue on upper extremity muscles, the subject was required to perform a smooth and constant pace motion during that 8 seconds in order to conduct a nearly continuous lifting and lowering movement in the whole 3 minutes without significant resting time between lifts. In both of these fatiguing tasks the subject was standing still with the pelvis secured, eliminating lower extremity movements as much as possible. Pilot studies have shown in order to reduce or avoid acute damage caused by strenuous physical exertion that both tasks were able to generate sufficient fatigue on low back muscles.

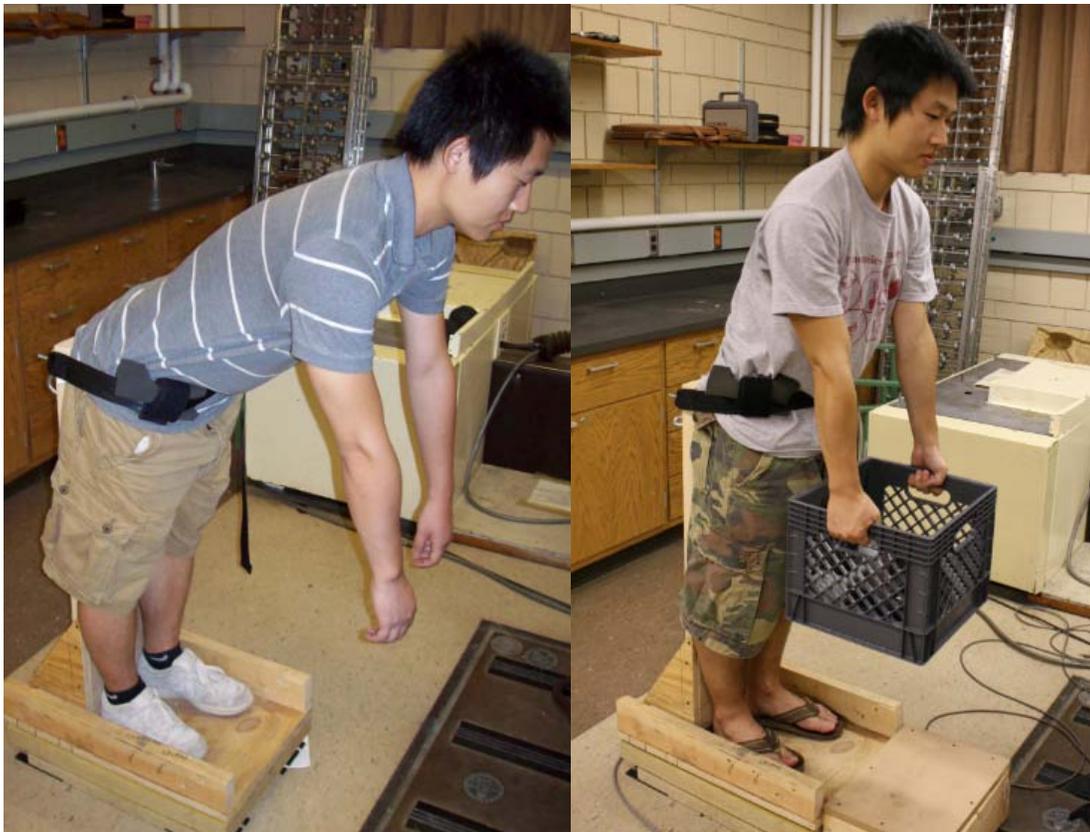


Figure 10: Sustained static weight holding (left) task and dynamic intermittent weight lifting (right) task.

3.4.2 Measurement tasks

Other than the muscle fatiguing tasks, measurements were also taken to track the physiological changes of the body. Three tasks were contained in the measurement protocol, firstly, the subject performed the same task as for the sustained static exertion task with additional requirements to close their eyes and try to hold their body as steady as possible for 10 seconds (Figure 11 left). For the second task, the subject performed exactly the same protocol as the first task but with an additional 20 lbs of weight on the shoulder (Figure 11 middle). Finally, for the third task the subject stood stand upright with their eyes closed, again trying to hold their body as still as possible for 10 seconds (Figure 11right).



Task 1: Sway Speed

Task 2: Median Frequency

Task 3

Figure 11: Measurement tasks used in the pilot testing.

In order to develop time functions that describe the relationship between the dose of muscle fatigue and physiological related variables without affecting the quality of the data collected

during the measurement protocols, one complete experiment was divided into multiple sections that were conducted on different days. For example, to track the changes of a four minute low back muscle fatiguing trial and its following recovery section, multiple data points could be selected. To obtain the profile (SS, MF and HR) during muscle fatigue it was possible to select several measurement points such as: 1. before fatiguing protocol (no fatigue); 2. after 1 minute of static exertion, 3. after 2 minutes of static exertion... For the recovery profile, preliminary tests indicated that muscle fatigue created by sustained static exertion task recovered very quickly, within one or two minutes trunk sway speed and low back muscle median frequency were almost fully recovered, whereas fatigue created by dynamic intermittent lifting recovered in a much slower fashion, taking over 10 minutes to recover. In this case, to obtain the recovery profile of sustained static exertion we needed multiple points within the first minute of the recovery (e.g. 15s, 30s, 45s and 60s of recovery) which makes it impossible to conduct. Hence, for the sustained static exertion task it was critical to conduct each recovery measurement on different days in order to avoid the influence of previous measurement trials when having two trials too close to each other. In this case, only one data point was obtained and over multiple trials to aid in obtaining sufficient data points to develop time dependent functions. Preliminary tests showed that for the same subject identical experiment protocol performed on different days generated very stable results, this conclusion supported the validity of generating relationships between time exposure of muscle fatigue and physiological measurements base on the information collected at different times. The recovery profile of the dynamic intermittent lifting task was very straight forward to obtain, since the recovery time takes more than 10 minutes, multiple data points can be take at 5 min, 10 min and 15 min... Because each point is 5 minutes apart

from the other, the impact of measurement protocol is negligible and all recovery points can be collected in recovery phase of the same fatiguing trial.

3.5 Independent variables

To develop a mathematical equation that monitors the physiological effect of low back muscle fatigue and recovery for each task, TIME (either time in fatiguing protocol or time in recovery section) becomes the only independent variable.

3.6 Dependent variables

To represent the effect of muscle fatigue three dependent variables (Sway Speed, Median Frequency, and Heart Rate) were selected and recorded. First, during each of the three measurement tasks the instantaneous location of the center of pressure (COP) on a force platform was calculated during the entire data collection period (10 seconds), and based on this the traveling distance and traveling speed of the COP can be calculated. The traveling speed of the COP was interpreted as the subject's whole body stability level and called the "Sway Speed" (SS). Second, the Median Frequency (MF) of the low back muscle, based on muscular EMG, was calculated to represent the level of fatigue created in the muscle. Third, the subject's Heart Rate (HR) was self reported to the experimenter by the participant just before each measurement protocol. HR provides a global measure that represents the subject's whole body metabolic level.

3.7 Experimental procedure

Upon arrival at the work site, the experimental procedures were described to the participant and a five minute lower extremity/torso warm up routine was followed. Surface electrodes and a heart rate monitor were then secured in the appropriate locations. When the experiment starts, the subject first stood on the pelvis restriction apparatus with the pelvis secured by a nylon belt. The first step was to collect information when the subject was not experiencing low back muscle fatigue and to use these measurements as the “baseline” to compare with the same measurements under other future conditions. One measurement protocol with 2 minutes rest between tasks was performed for this baseline measurement. As described earlier, each measurement protocol involves three tasks: 45 degree trunk flexion, 45 degree trunk flexion with 20 lbs on shoulder, and standing upright. Before each measurement protocol the subject’s heart rate is also recorded. After finishing the baseline measurement, two minutes rest was taken and then the muscle fatigue protocol was conducted. As described in the experimental design section, the complete data collection activity took multiple days and for each day the fatiguing protocol was randomly assigned from a pool of protocols (Table 7). All trials contained only one measurement protocol except for the recovery section of the dynamic intermittent weight lifting task containing 4 measurement protocols (Table 7).

Stages of muscle fatigue	Muscle fatiguing trials	Measurement protocols
Static fatigue development	1 minute static weight holding	Right after protocol
	2 minutes static weight holding	Right after protocol
	3 minutes static weight holding	Right after protocol
	4 minutes static weight holding	Right after protocol
Static fatigue recovery	4 minutes static weight holding	15 seconds after protocol
	4 minutes static weight holding	30 seconds after protocol
	4 minutes static weight holding	45 seconds after protocol
	4 minutes static weight holding	60 seconds after protocol
Dynamic fatigue development	1 minute dynamic weight lifting	Right after protocol
	2 minutes dynamic weight lifting	Right after protocol
	3 minutes dynamic weight lifting	Right after protocol
Dynamic fatigue recovery	3 minutes dynamic weight lifting	5 minutes after protocol
		10 minutes after protocol
		15 minutes after protocol
		20 minutes after protocol

Table 7: Pool of experimental protocols and point measurements.

3.8 Data processing

The EMG data from the four muscles were filtered using a 500 Hz low pass filter, a 10 Hz high pass filter, and a 60 Hz (and all aliases) notch filter. . Then a time domain EMG signal from the back muscles was transformed into the frequency domain using a Fast Fourier Transform (FFT). The median of the EMG signal frequency spectrum was calculated as the dependent variable “Median Frequency” (DeLuca 1997).

Data from the force platform were used to calculate the X-Y coordinates of the COP on the force platform using Equation 3 and 4 where h has a constant value of 0.005 meter, this value

representing the thickness of the force platform covering material. F_x , F_y and F_z are the force vectors on X, Y, and Z axes respectively, and M_x and M_y are the corresponding moments with respect to X and Y axes respectively (Figure 12).

$$\text{Equation 3: } x_p = \frac{-h \times F_x - M_y}{F_z}$$

$$\text{Equation 4: } y_p = \frac{-h \times F_y - M_x}{F_z}$$

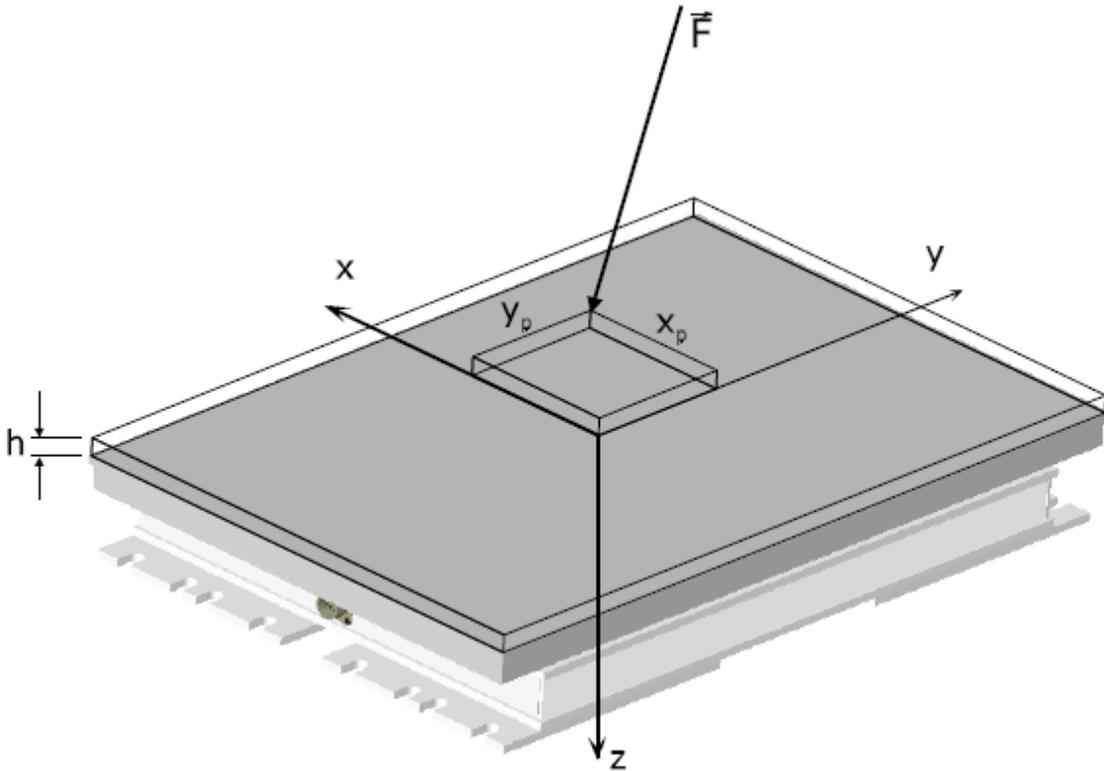


Figure 12: Force plate and its force coordination.

3.9 Data analysis

From the “45° trunk flexion” measurement trials the COP total travel distance was calculated, then the SS was calculated by dividing the travel distance by the time of travel. Low back muscle MFs were obtained from the “45° trunk flexion with 20 lbs weight on shoulder” trials and HR values were recorded before each measurement protocol. In the next step, data from all three physiological variables (SS, MF and HR) were separated into a fatigue section and a recovery section, representing the muscle fatigue development phase and the fatigue recovery phase, respectively. Next the baseline of each variable was subtracted from all the measured values, so that they represent only the variable changes introduced by muscle fatigue or recovery. The benefit of this approach is to limit the influence of daily differences within each subject and the variance between different subjects. Finally, variables in each section (development or recovery) were individually plotted in time sequence. Best-fit equations were then generated for each plot (Figure 13 through Figure 24).

3.10 Results

3.10.1 Sustained static weight holding

During the four minute sustained static low back muscle fatiguing protocol results from the subject demonstrated a clear increase in SS (a 2.3cm/s increase from 2.5cm/s (baseline)), in HR (a 45beats/min increase from 83 beats/min (baseline)), and a decrease in MF (a 26Hz drop from 70Hz (baseline)). The profile of increase/decrease and the functions are shown in Figure 13 through Figure 15. To simplify the calculation and to be consistent with the other two variables here we presented the changes of MF in its absolute value.

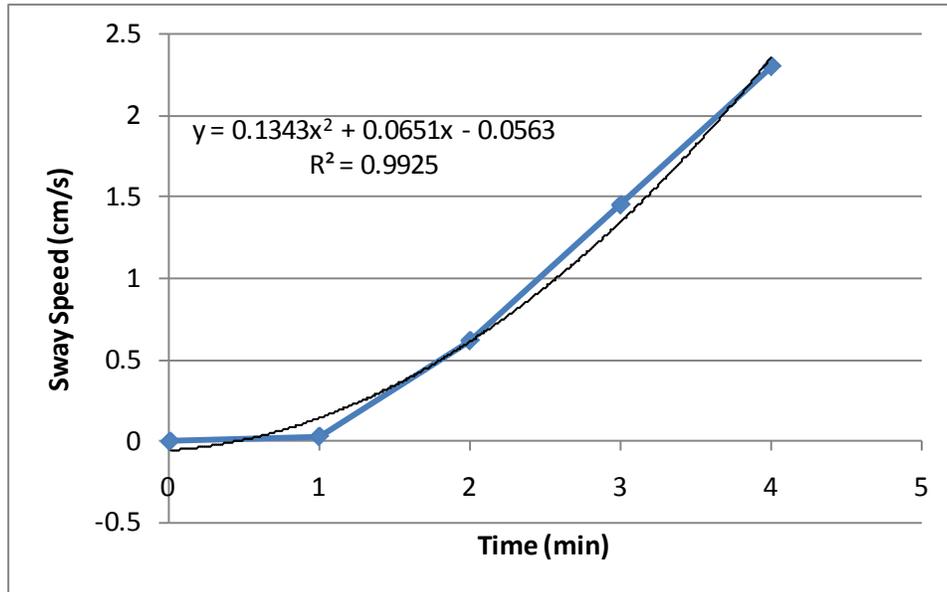


Figure 13: Sway speed profile during 4 minutes of sustained static weight holding task.

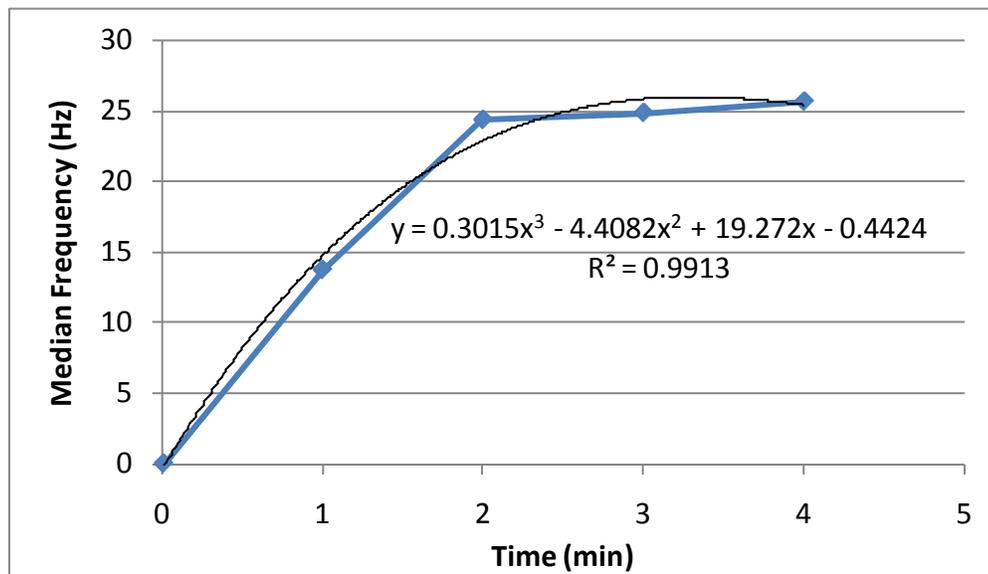


Figure 14: Median frequency profile during 4 minutes of sustained static weight holding task.

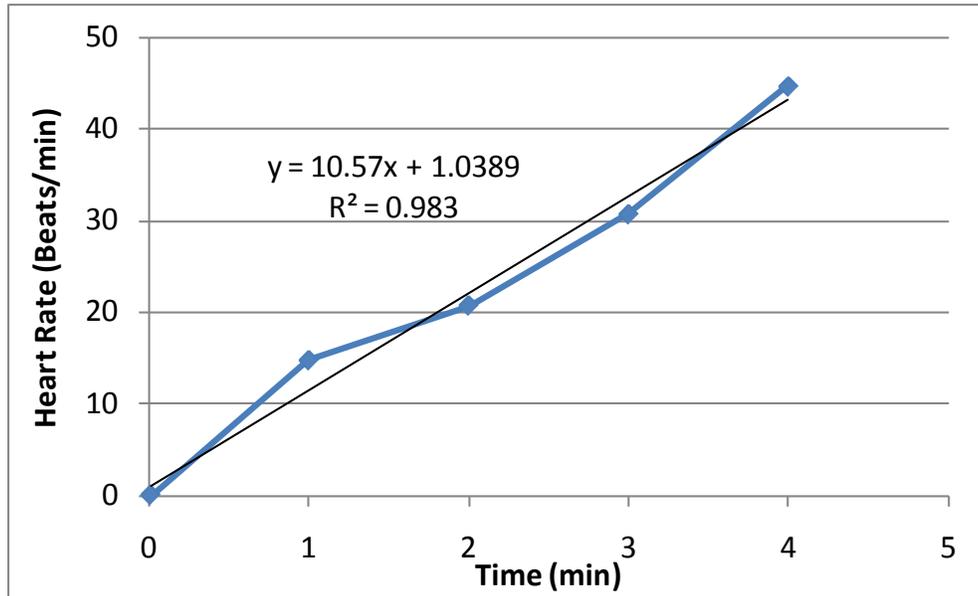


Figure 15: Heart rate profile during 4 minutes of sustained static weight holding task.

During the recovery phase different variables recovered at different rates and in different fashions. The SS recovered fairly quickly, e.g., after 30 seconds of recovery the SS reduced to the original baseline value (Figure 16). Similar to the SS, the MF recovered very quickly in the first 30 seconds; however in the following recovery interval the MF stayed at about 10Hz below baseline for a long time, indicating a significant long interval of muscle fatigue effect, i.e. the MF takes a much longer time to recover (Figure 17). The full HR recovery took about 3 minutes and demonstrated a gradually decreasing pattern (Figure 18).

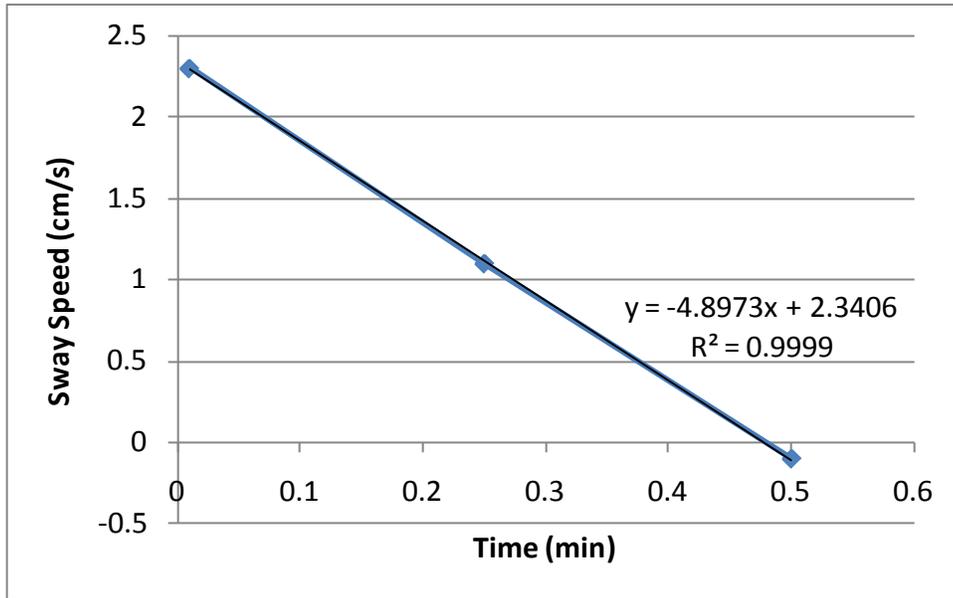


Figure 16: The recovery of sway speed after 4 minutes of sustained static weight holding task.

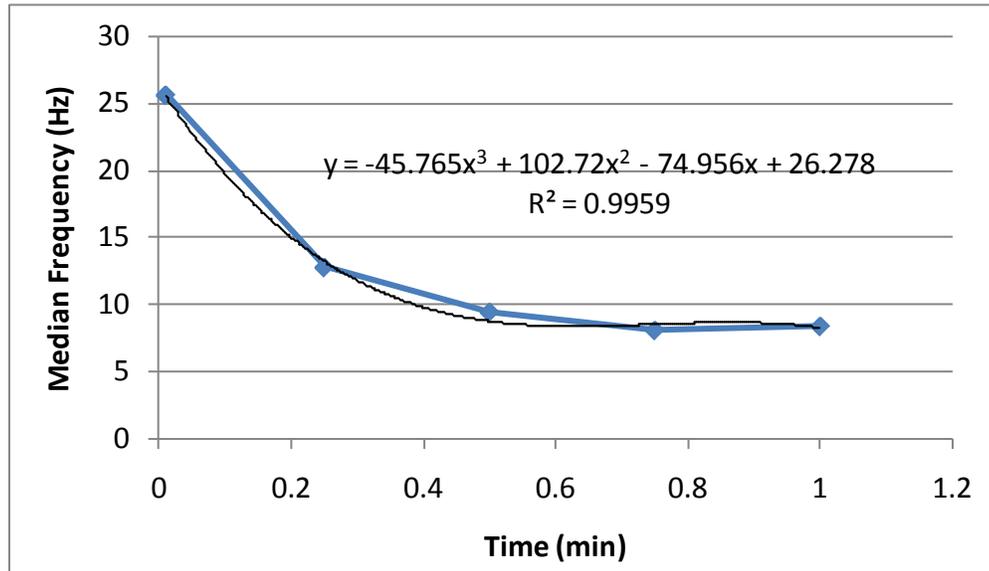


Figure 17: The recovery of median frequency after 4 minutes of sustained static weight holding task.

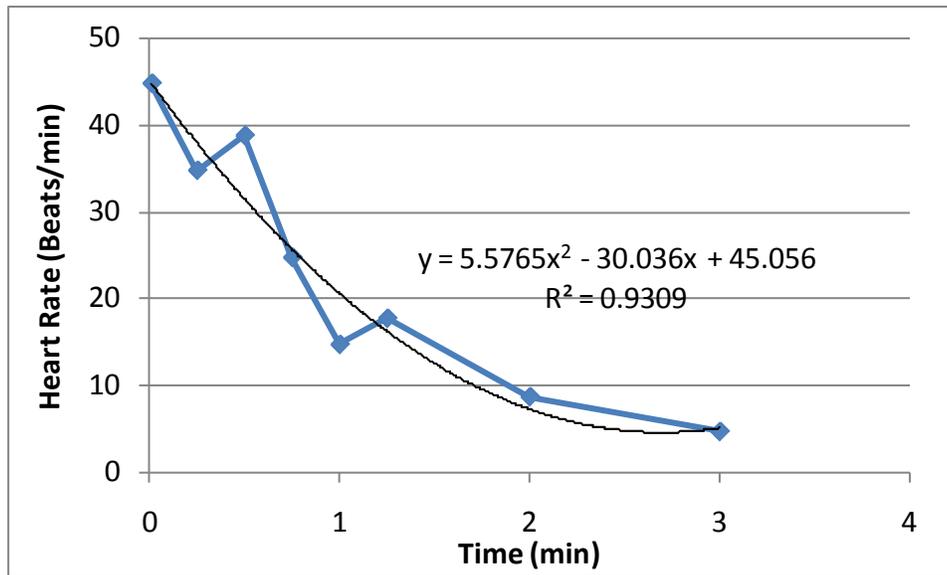


Figure 18: The recovery of heart rate after 4 minutes of sustained static weight holding task.

3.10.2 Dynamic intermittent weight lifting

The physiological variable changes during the development of low back muscle fatigue created by dynamic intermittent weight lifting protocol are shown in Figure 19 through Figure 21. Three minutes of 35-lb weight lifting and lowering generated a 2.2 cm/s increase in trunk SS, the median frequency MF decreased 18.5 Hz in a linear fashion, the heart rate HR increased 48.3beats/min from the baseline value at the end of the 3 minute duration of the lifting task.

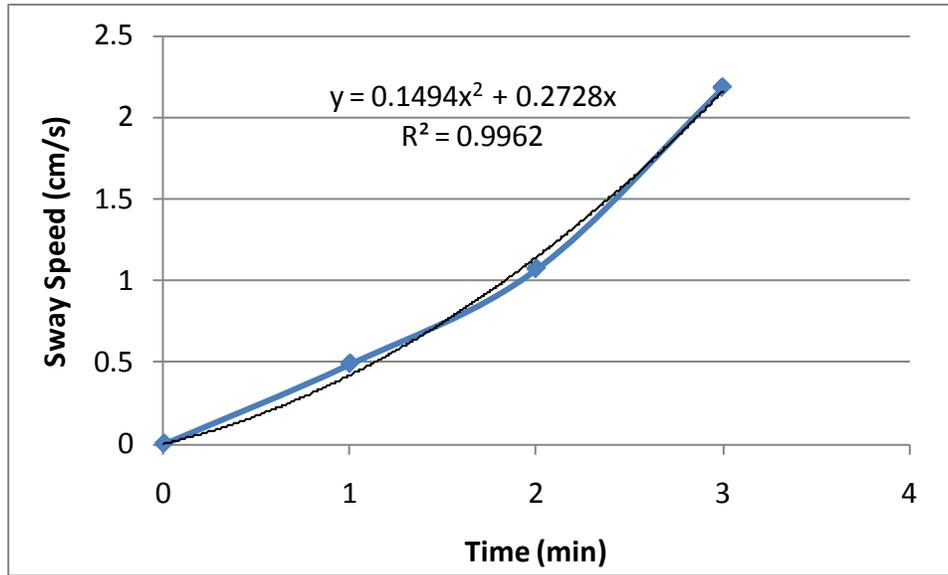


Figure 19: Sway speed profile during 3 minutes of dynamic intermittent weight lifting task.

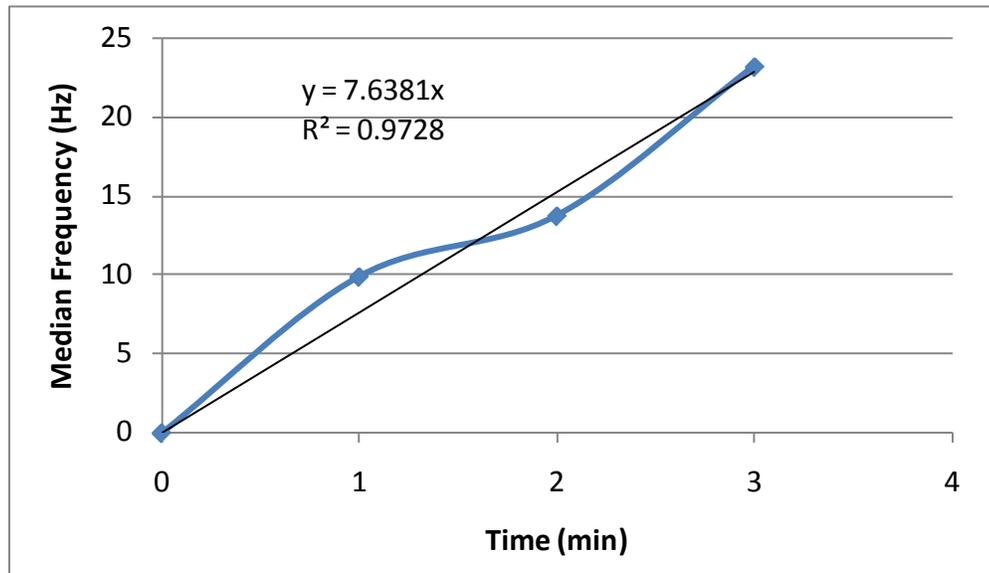


Figure 20: Median frequency profile during 3 minutes of dynamic intermittent weight lifting task.

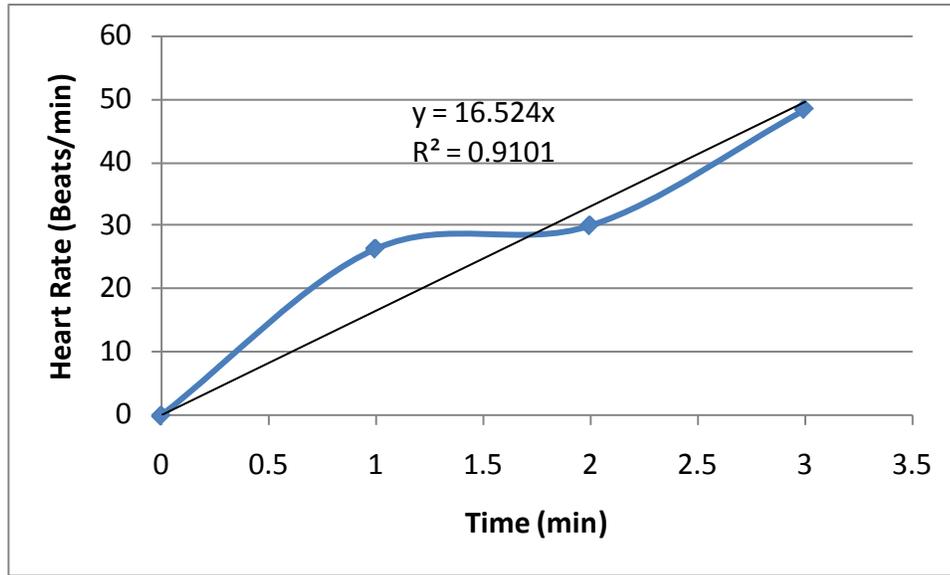


Figure 21: Heart rate profile during 3 minutes of dynamic intermittent weight lifting task.

As mentioned earlier, the task dependency of muscle fatigue indicates potential physiological response differences among different fatiguing tasks. By comparing the figures and equations for the recovery section of both the static fatiguing protocol and the dynamic fatiguing protocol, one can observe that the recovery of SS and MF corresponding to the dynamic intermittent weight lifting task (Figure 22 and Figure 23) takes a much longer time than those corresponding to the sustained static weight holding task (Figure 16 and Figure 17). However, the HR recovery profiles (Figure 18 and Figure 24) show a similar pattern between the two tasks. A summary of all 12 equations are presented in Table 8.

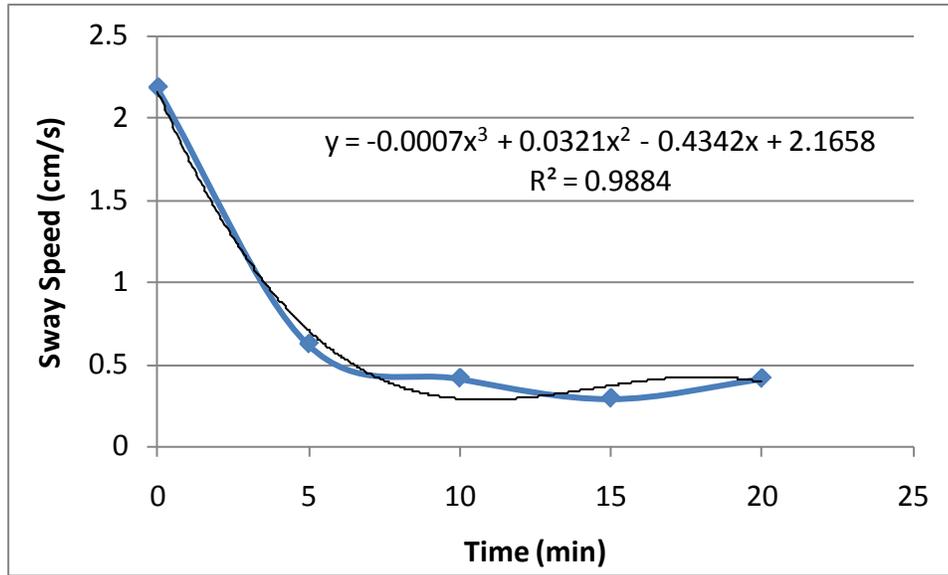


Figure 22: The recovery of sway speed after 3 minutes of dynamic intermittent weight lifting task.

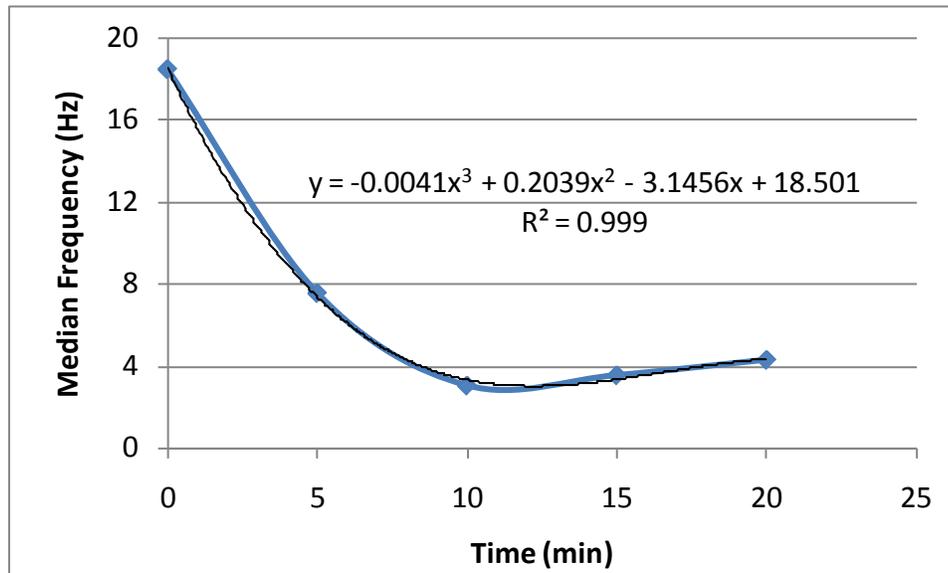


Figure 23: The recovery of median frequency after 3 minutes of dynamic intermittent weight lifting task.

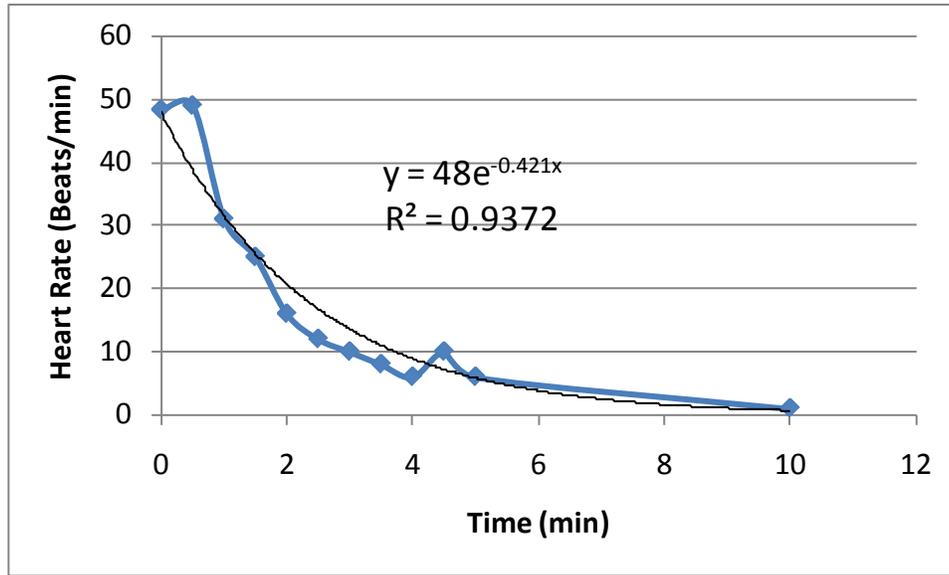


Figure 24: The recovery of heart rate after 3 minutes of dynamic intermittent weight lifting task.

Stages of muscle fatigue	Physiology variables	Time dependent function
Static fatigue development	Sway Speed	$SS = 0.13t^2 + 0.07t - 0.06$
	Median Frequency	$MF = 0.3t^3 - 4.41t^2 + 19.27t - 0.44$
	Heart Rate	$HR = 10.57t + 1.04$
Static fatigue recovery	Sway Speed	$SS = -4.9t + 2.34$
	Median Frequency	$MF = -45.77t^3 + 102.72t^2 - 74.96t + 26.28$
	Heart Rate	$HR = 5.58t^2 - 30.04t + 45.06$
Dynamic fatigue development	Sway Speed	$SS = 0.15t^2 + 0.27t$
	Median Frequency	$MF = 7.64t$
	Heart Rate	$HR = 16.52t$
Dynamic fatigue recovery	Sway Speed	$SS = -0.0007t^3 + 0.03t^2 - 0.43t + 2.17$
	Median Frequency	$MF = -0.004t^3 + 0.2t^2 - 3.15t + 18.5$
	Heart Rate	$HR = 48e^{-0.42t}$

Table 8: Summary of time dependent regression functions.

3.11 Summary

From the results of our pilot study we have learned several things. First of all, the two low back muscle fatiguing tasks (sustained static weight holding and dynamic weight lifting) we selected were able to successfully generate sufficient back muscle fatigue in a short period of time. Secondly the measurement tasks we used in the pilot study were able to generate very stable and reliable data for SS, HR and MF this is demonstrated by the fact that measurement points from different trials could be plotted together and generate reasonably smooth development and recovery curves. Pilot results also demonstrated that most of the regression equations followed non-linear curves especially during the recovery phase. This finding is also in-line with our current understanding of the recovery performance of these physiological variables (especially HR and MF).

One of the major limitations in the pilot experimental design is that only one data point can be generated from each trial which means to complete one fatigue development and recovery profile each subject has to perform the same fatiguing and recovery protocol for multiple times and each in a different day. This design could avoid the concern of the impact of measurement trials on the following data; however this design is extremely inefficient and also introduces unpredictable errors to the dataset. In the following data collection a new design must be incorporated to satisfy the requirements both for the reliability of the data and the efficiency of the data collection.

CHAPTER 4. RESEARCH OBJECTIVES

The purpose of this dissertation work was to create an optimal work-rest decision model with the implication of inventory control theory. This model will be able to balance between productivity and the risk of injury by selecting an optimal work-rest schedule.

To create such a model the first step was to demonstrate the linkage between an inventory control model that manages the production and inventory of a certain product aiming to reach an optimal economical benefit, and the management of workers' physical burden during the performance of physical exertion tasks. As introduced in the background section, inventory control model such as EPL (Economic Production Lot) model is able to continuously monitor the size of inventory with the consideration of both production (increase in inventory) and non-production (decrease in inventory) as shown in Figure 6. From a work hazard assessment perspective the accumulation and relief of physical burden of the human body that created by work stresses (such as muscle fatigue) can be modeled in a similar fashion (as shown in the pilot work section).

This new work-rest decision model will be able to instantaneously predict the physiological changes induced by different physical exertion tasks and also the recovery of these changes during recovery. Then, by redefining the variables involved in the EPL model (e.g. Table 6) this new model should be able to generate an optimal work-rest cycle such that the minimum total cost can be reached while still keeping the productivity.

In order to use inventory control theory to model physiological changes created by work stress, the first step is to choose proper variables and track the changes of these variables within the intervals of task performance and recovery. In the pilot study section three variables (SS, MF and HR) have been selected to represent the changes. Results from the pilot test demonstrated that we are able to track the changes of all three physiological variables in both the development and recovery phase of low back muscle fatigue introduced by two types of exertion tasks (sustained static weight holding and dynamic intermittent weight lifting). The next step in the model development is to regenerate all the regression equations from a larger group of subjects and test the validity of those equations during the performance of multiple episodes of low back muscle fatigue development and recovery.

CHAPTER 5. METHODS

5.1. Overview of study

In order to generate regression equations for both the development and recovery of low back muscle fatigue (in terms of SS, MF and HR) two experiment sections were conducted. The first section was designed for collecting all data points that were necessary for the formation of regression equations; this section was referred as the “model development section”. The second section was conducted to test the validity of the regression equations that generated from the model development section by using new subjects and different task protocols; this section was referred as the “model validation section”.

5.2. Experiment I: Model development section

5.2.1 Objective

The objective of the model development section was to generate regression equations for both the development and recovery of low back muscle fatigue during the performance of single fatiguing exertion task and its recovery. These regression equations would be used later as the founding blocks to predict the changes of physiological variables (SS, MF and HR) when performing multiple-task protocols.

5.2.2 Participants

In this section a total of 4 participants were recruited from the student population of Iowa State University. All participants were free from any chronic or current lower back, hip or upper/lower extremity injuries. A written informed consent was collected from each

participant prior to participation (approved by the Institutional Review Board of Iowa State University).

5.2.3 Experimental tasks

5.2.3.1 Fatigue and recovery tasks

Both the sustained static weight holding protocol (task A) and the dynamic intermittent weight lifting protocol (task B) were adopted from our pilot study. When performing “task A”, participants stood on the force platform while having their pelvis restricted. As shown in Figure 10 (left) subjects were asked to hold a 45 deg forward trunk flexion posture and drop their arms without any movement and maintain their lumbar spine as straight as possible (keep lumbar lordosis) in order to avoid creating tension on the passive ligaments and to fatigue low back muscles as quickly as possible in a consistent rate. When performing “task B”, participants performed lifting a 35-lb crate from ground level to about knuckle height and lowering it down to the ground at a once per 8 seconds rate (Figure 10 right). In this task subjects were asked to always straighten their arms during both lifting and lowering in order to avoid any fatigue development on upper extremity muscles, and they were also required to perform a smooth and constant rate motion during that 8 seconds in order to conduct a nearly continuous lifting and lowering movement during the entire interval of task performance without significant resting time between lifts. During the recovery time (task C), pelvis restriction were released but participants were still required to stand at the same location.

5.2.3.2 Measurement tasks

To perform the measurement of three physiological variables, measurement protocols similar to those used in the pilot testing were used. First of all, heart rate was still reported from each subject at the very beginning of each measurement point or any other time point of the task protocol. Secondly, to measure the trunk sway speed participants performed the same task as for the sustained static exertion task but with their eyes closed and under instructions that encourage them to hold their body as steady as possible for 6 seconds (instead of 10 seconds as in the pilot study) (as shown in Figure 25 left). Following the SS measurement task, subjects performed another task that measures the median frequency of the low back muscle electromyography signal. This MF measurement task required subjects to hold a 35 lbs crate (as shown in Figure 25 right). The reason for putting more weight in hands is to increase the magnitude of low back muscle exertion and obtain a more reliable median frequency measurement. The measurement duration was 6 seconds (instead of 10 seconds as in the pilot study). The 6 second duration was chosen for both tasks because additional analysis of our pilot data indicated that reliable and stable measurements can be obtained for both SS and MF with a minimum of 6 seconds of measurement task duration. Finally, the “standing upright” task from our pilot test was eliminated since it does not have any role to play in our current analysis. In this case our measurement protocol included two tasks, each lasts for 6 seconds. This reduction in the number and duration of measurement trials enabled us to embed all measurement trials in one single recovery section without much impact on the recovery performance.

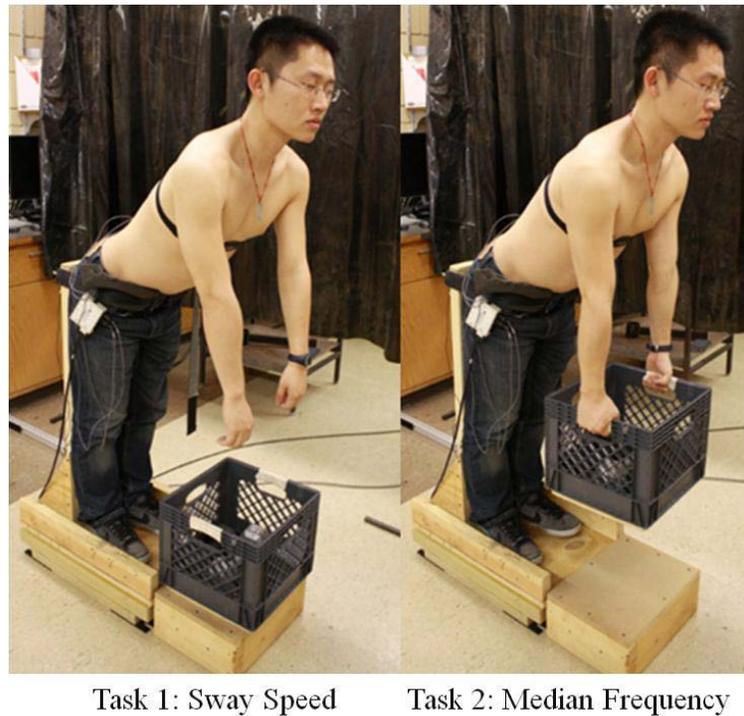


Figure 25: New measurement tasks used in the data collection

5.2.4 Experimental design

This section was further divided into two phases. In phase I each participants performed four different single work-cycle protocols (Table 9) results from these protocols were used to summarize regression equations for SS, MF and HR during low back fatigue development and recovery. In the pilot work section the time dependent functions for fatigue development and recovery were all summarized based on either 4 minutes of a static weight holding task (task A) or 3 minutes of a dynamic intermittent weight lifting task (task B). In the ideal situation infinitely many different durations of task performance should be tested and one recovery function for different durations of fatiguing exertion task should be summarized; however that is not practical. In current study, the recovery profiles of all three physiological variables after 2 minutes (half point) of the sustained static weight holding task or 1.5

minutes (half point) of the dynamic intermittent weight lifting task were summarized representing the recovery profiles of moderate low back fatiguing exertions. The regression equations for long task duration (4 minutes of task A, 3 minutes of task B) were also regenerated from this section. In each trial the designated data collection points were embedded in different time points of the recovery section (use Figure 26 as an example). Regression equations during fatigue recovery were generated by finding the best fit equations for the data collected from all subjects. To develop the regression equations during fatigue development the “zero” time point in the recovery section (right after fatiguing exertion) from both moderate and long exertions (e.g. 2 and 4 minutes of task A) were used (as shown in Figure 27).

Trials	Muscle exertion tasks	Recovery task
1	2 min Weight Holding (Task A)	10 min Recovery (Task C)
2	4 min Weight Holding (Task A)	15 min Recovery (Task C)
3	1.5 min Weight Lifting (Task B)	10 min Recovery (Task C)
4	3 min Weight Lifting (Task B)	15 min Recovery (Task C)

Table 9: Task descriptions for the model development section.

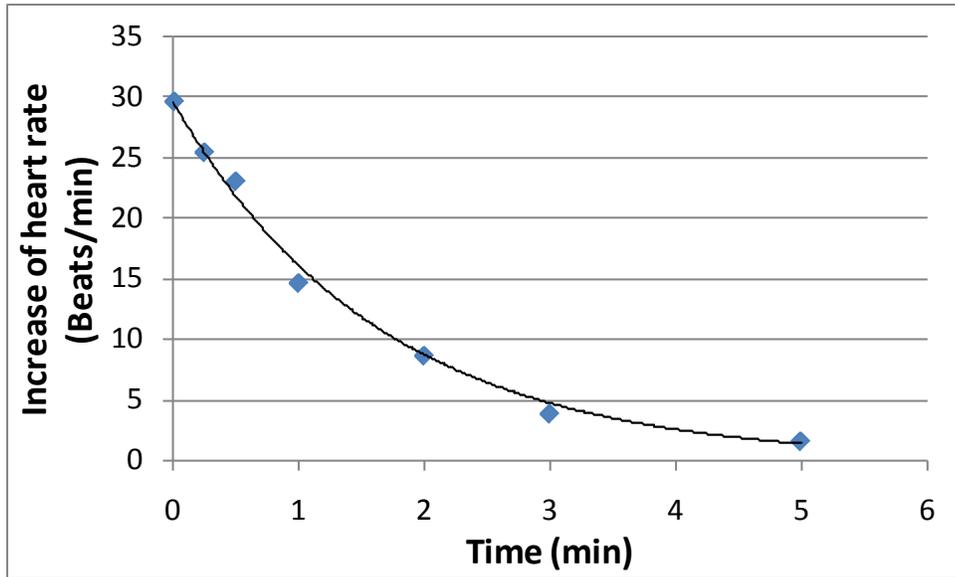


Figure 26: An example of the increase of heart rate profile during the recovery section after 4 minutes of Task A.

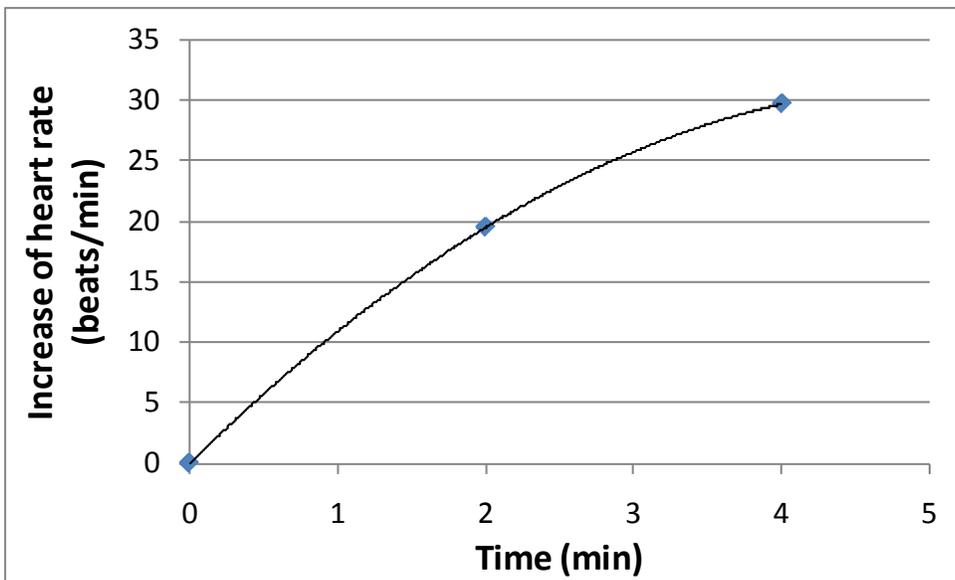


Figure 27: An example of heart rate profile during the performance of 4 minutes of Task A.

In the second phase of model development section the goodness of all summarized time dependent functions (both development and recovery of low back muscle fatigue) for all three physiological variables (HR, MF, SS) were tested using data from the performance of two consecutive work-rest cycle protocols. The experimental tasks were selected from a series of basic tasks and combined to create a task performance sequence. The descriptions of our basic tasks are shown in Table 10; each two-work-rest-cycle protocol involved 4 tasks (two fatiguing exertion tasks and two recovery tasks). The presentation of these four tasks followed the setting of: Fatiguing exertion task + Recovery task + Fatiguing exertion task + Recovery task. This limited combination created a total of 256 (4^4) different sequences. Each subject performed two trials which were both randomly selected from these 256 combinations. All three physiological variables (SS, MF, HR) were collected from designated time points and their corresponding predicted values were calculated by using previously summarized regression equations. Mean absolute percentage error (MAPE) was calculated for each trial to evaluate the goodness of our prediction (described in detail in the prediction evaluation section). If any of the three physiological changes occurring during the task performance clearly do not follow the prediction of our time dependent functions then further testing was employed to summarize the proper functions.

	Fatiguing exertion tasks	Recovery tasks
	4 minutes of Task A	10 minutes of Task C
Task	2 minutes of Task A	3 minutes of Task C
Descriptions	3 minutes of Task B	5 minutes of Task C
	1.5 minute of Task B	1.5 minutes of Task C

Table 10: Basic task components for two work-rest cycle protocol.

5.2.5 Experimental procedure

Upon arrival at the testing site, the participant was given a description of the experimental procedures and a five minute, lower extremity/torso warm up routine was performed. Two EMG surface electrodes were placed bilaterally at the L4 level of lumbar spine and spaced 2cm apart from the midline of the spinal column. A heart rate monitor was then secured over the chest of the subject. When the experiment starts the subject first stood on the pelvis restriction apparatus with his pelvis secured by a nylon belt. The first step was to collect information when the subject did not exhibit effects of low back muscle fatigue; this set of measurements constituted the “baseline” data to be compared with data collected during low back muscle fatigue and recovery. Three replications of measurement protocol with 2 minutes rest in between were performed for the baseline measurement; each measurement protocol involved two tasks: the SS measurement task and MF measurement task (both have been described in detail before). Before each measurement protocol the subject’s heart rate was also recorded. After finishing the baseline measurement, another two minutes of rest was taken and then the designated task protocol was conducted. During the performance of fatiguing exertions no measurement tasks were performed, during the recovery section, measurement tasks were performed at designated time points (normally located at 0, 0.5, 1, 2, 4, 8 minutes of recovery, depending on the length of the recovery section).

5.2.6 Data processing

The EMG data from the two muscles were filtered using a 500 Hz low pass filter, a 10 Hz high pass filter and the signal was notch filtered at 60 Hz and its aliases. Then the time domain EMG signal from the back muscles were transformed into frequency domain using a

Fast Fourier Transform (FFT). The median point of the EMG signal frequency spectrum was calculated as the dependent variable “Median Frequency” (DeLuca 1997).

Data from the force platform were used to calculate the X-Y coordinates of COP on the force platform by using Equation 3 and 4 where h is a constant value of 0.005 meter, this value representing the thickness of the covering material of force platform. F_x , F_y and F_z are the force vectors along X, Y and Z axes respectively, and M_x and M_y are the corresponding moments with respect to X and Y axes, respectively (Figure 12).

5.2.7 Prediction evaluation

After obtaining all three physiological variables from each measurement point a comparison was made between the predicted values and the actual measurement values to evaluate the goodness of the predictions. Mean absolute percentage error (MAPE) was used to represent the degree of agreement between our predicted value and the actual values and to see if there is a difference when performing sequential multiple tasks. The equation of calculating the MAPE is shown in Equation 5 where “ P_i ” is the predicted value, “ A_i ” is the actual measurement and “ n ” is the total number of measurement points.

$$\text{Equation 5: } M = \frac{1}{n} \sum_{i=1}^n \left| \frac{P_i - A_i}{A_i} \right| \times 100\%$$

5.3 Experiment II: Model validation section

5.3.1 Objective

The objective of the model validation section was to evaluate the goodness of our regression equations.

5.3.2 Participants

A new group of 4 participants were recruited from the student population of Iowa State University. All participants were free from any chronic or current lower back, hip or upper/lower extremity injuries. A written informed consent was collected from each participant prior to participation (approved by the Institutional Review Board of Iowa State University).

5.3.3 Experimental tasks

5.3.3.1 Fatigue and recovery tasks

Both the sustained static weight holding protocol (task A) and the dynamic intermittent weight lifting protocol (task B) were adopted from our pilot study. When performing “task A”, participants stood on the force platform while having their pelvis restricted. As shown in Figure 10 (left) subjects were asked to hold a 45 deg forward trunk flexion posture and drop their arms without any movement and maintain their lumbar spine as straight as possible (keep lumbar lordosis) in order to avoid creating tension on the passive ligaments and to fatigue low back muscles as quickly as possible in a consistent rate. When performing “task B”, participants performed lifting a 35-lb crate from ground level to about knuckle height and lowering it down to the ground at a once per 8 seconds rate (Figure 10 right). In this task subjects were asked to always straighten their arms during both lifting and lowering in order

to avoid any fatigue development on upper extremity muscles, and they were also required to perform a smooth and constant rate motion during that 8 seconds in order to conduct a nearly continuous lifting and lowering movement during the entire interval of task performance without significant resting time between lifts. During the recovery time (task C), pelvis restriction were released but participants were still required to stand at the same location.

5.3.3.2 Measurement tasks

To perform the measurement of three physiological variables, measurement protocols similar to those used in the pilot testing were used. First of all, heart rate was still reported from each subject at the very beginning of each measurement point or any other time point of the task protocol. Secondly, to measure the trunk sway speed participants performed the same task as for the sustained static exertion task but with their eyes closed and under instructions that encourage them to hold their body as steady as possible for 6 seconds (instead of 10 seconds as in the pilot study) (as shown in Figure 25 left). Following the SS measurement task, subjects performed another task that measures the median frequency of the low back muscle electromyography signal. This MF measurement task required subjects to hold a 35 lbs crate (as shown in Figure 25 right). The reason for putting more weight in hands is to increase the magnitude of low back muscle exertion and obtain a more reliable median frequency measurement. The measurement duration was 6 seconds (instead of 10 seconds as in the pilot study). The 6 second duration was chosen for both tasks because additional analysis of our pilot data indicated that reliable and stable measurements can be obtained for both SS and MF with a minimum of 6 seconds of measurement task duration. Finally, the “standing upright” task from our pilot test was eliminated since it does not have any role to play in our

current analysis. In this case our measurement protocol included two tasks, each lasts for 6 seconds. This reduction in the number and duration of measurement trials enabled us to embed all measurement trials in one single recovery section without much impact on the recovery performance.

5.3.4 Experimental design

In this section, to further test the validity of previously summarized regression equations. Each participant was required to perform three different task protocols each from a different category. The first category of protocols was designed to include two consecutive work-rest cycles in which the fatiguing tasks in both cycles were moderate duration tasks (less than 4 minutes of task A and less than 3 minutes of task B). The second category of protocols was also designed to include two consecutive work-rest cycles but only involved long duration fatiguing tasks (i.e. 4 minutes of task A and 3 minutes of tasks B). Finally, the third category of protocols included four consecutive work-rest cycles and all fatiguing tasks were moderate duration tasks. The detailed protocol descriptions of all three categories are showing in Table 11 where “WH” is the weight holding task (Task A); “WL” represents the weight lifting task (Task B) and “R” is the recovery task (Task C), the number before each task indicates the task duration (in minutes). MAPE was also calculated for each trial and an average MAPE was calculated for each category.

Categories	Participant	Task descriptions
Moderate two-work-rest cycle	1	1.5WL+2.5R+3WH+2R
	2	2.5WH+2R+1.5WH+5R
	3	2WL+4R+3WH+5R
	4	2WL+4R+2WH+6R
Hard two-work-rest cycle	1	3WL+5R+4WH+7R
	2	4WH+8R+3WL+8R
	3	3WL+6R+4WH+4R
	4	4WH+4.5R+3WL+4R
Moderate four-work-rest cycle	1	2WH+5R+1.5WL+6R+2WL+8R+2WH+5R
	2	1.5WL+6R+2.5WH+8.5R+1.5WL+7R+1.5WH+6R
	3	3WH+8R+1.5WL+7R+2WH+9R+2WL+7.5R
	4	1.5WH+5R+3WH+9.5R+1.5WL+7R+2WL+5R

Table 11: Description of experimental protocols in the model validation section

5.3.5 Experimental procedure

Upon arrival at the testing site, the participant was given a description of the experimental procedures and a five minute, lower extremity/torso warm up routine was performed. Two EMG surface electrodes were placed bilaterally at the L4 level of lumbar spine and spaced 2cm apart from the midline of the spinal column. A heart rate monitor was then secured over the chest of the subject. When the experiment starts the subject first stood on the pelvis restriction apparatus with his pelvis secured by a nylon belt. The first step was to collect information when the subject did not exhibit effects of low back muscle fatigue; this set of measurements constituted the “baseline” data to be compared with data collected during low back muscle fatigue and recovery. Three replications of measurement protocol with 2 minutes rest in between were performed for the baseline measurement; each measurement protocol involved two tasks: the SS measurement task and MF measurement task (both have been described in detail before). Before each measurement protocol the subject’s heart rate was also recorded. After finishing the baseline measurement, another two minutes of rest was

taken and then the designated task protocol was conducted. During the performance of fatiguing exertions no measurement tasks were performed, during the recovery section, measurement tasks were performed at designated time points (normally located at 0, 0.5, 1, 2, 4, 8 minutes of recovery, depending on the length of the recovery section).

5.3.6 Data processing

The EMG data from the two muscles were filtered using a 500 Hz low pass filter, a 10 Hz high pass filter and the signal was notch filtered at 60 Hz and its aliases. Then the time domain EMG signal from the back muscles were transformed into frequency domain using a Fast Fourier Transform (FFT). The median point of the EMG signal frequency spectrum was calculated as the dependent variable “Median Frequency” (DeLuca 1997).

Data from the force platform were used to calculate the X-Y coordinates of COP on the force platform by using Equation 3 and 4 where h is a constant value of 0.005 meter, this value representing the thickness of the covering material of force platform. F_x , F_y and F_z are the force vectors along X, Y and Z axes respectively, and M_x and M_y are the corresponding moments with respect to X and Y axes, respectively (Figure 12).

5.3.7 Prediction evaluation

After obtaining all three physiological variables from each measurement point a comparison was made between the predicted values and the actual measurement values to evaluate the goodness of the predictions. Mean absolute percentage error (MAPE) was used to represent the degree of agreement between our predicted value and the actual values and to see if there

is a difference when performing sequential multiple tasks. The equation of calculating the MAPE is shown in Equation 5 where “ P_i ” is the predicted value, “ A_i ” is the actual measurement and “ n ” is the total number of measurement points.

CHAPTER 6. RESULTS

6.1 Results from Experiment I

A series of regression equations were created by using the data from “model development section” phase I (showing in Table 12). One set of equations were created for each fatiguing task to track the changes of physiological variables with the increase of low back muscle fatigue, however during the recovery two different sets of equations were created one for moderate fatigue exertion (≤ 1.5 minutes of weight lifting and ≤ 2 minutes of weight holding) and the other set for more intensive fatigue exertions (> 1.5 minutes of weight lifting and > 2 minutes of weight holding).

Development		Recovery	
Weight lifting	$SS=0.66 \times t^{0.85}$	Weight lifting (≤ 1.5 min)	$SS=0.97 \times e^{(-0.947t)}$
	$MF=10.8 \times t^{0.7}$		$MF=14.73 \times e^{(-0.443t)}$
	$HR=21.6 \times t^{0.4}$		$HR=25.92 \times e^{(-0.404t)}$
Weight holding	$SS=0.54 \times t$	Weight holding (≤ 2 min)	$SS=1.60 \times e^{(-0.344t)}$
	$MF=7.45 \times t^{0.9}$		$MF=24.90 \times e^{(-0.297t)}$
	$HR=12.9 \times t^{0.6}$		$HR=29.40 \times e^{(-0.395t)}$
Weight lifting	$SS=0.54 \times t$	Weight lifting (> 1.5 min)	$SS=0.97 \times e^{(-2.764t)}$
	$MF=7.45 \times t^{0.9}$		$MF=10.92 \times e^{(-1.127t)}$
	$HR=12.9 \times t^{0.6}$		$HR=19.39 \times e^{(-0.493t)}$
Weight holding	$SS=0.54 \times t$	Weight holding (> 2 min)	$SS=2.23 \times e^{(-1.157t)}$
	$MF=7.45 \times t^{0.9}$		$MF=26.17 \times e^{(-0.335t)}$
	$HR=12.9 \times t^{0.6}$		$HR=25.90 \times e^{(-0.577t)}$

Table 12: Summary of regression equations.

The goodness of fit for these regression equations was first tested by using the same group of participants performing two-work-rest cycle protocols. The detailed task descriptions and summarized MAPE values are showing in Table 13. We can see that our summarized regression equations performed best in predicting the changes of HR and MF (with average

MAPE value of 8.3% and 9% respectively), less accurate in predicting SS (with average MAPE value of 14.9%).

Trials	Task Description	Mean Absolute Percentage Error		
		SS	MF	HR
1	1.5WL+1.5R+1.5WL+10R	21.4%	20.2%	9.1%
2	4WH+10R+2WH+5R	15.8%	6.7%	12.0%
3	1.5WL+3R+4WH+5R	15.6%	8.4%	8.1%
4	3WL+10R+4WH+3R	19.0%	13.6%	3.0%
5	4WH+5R+1.5WL+10R	12.5%	9.0%	8.3%
6	4WH+3R+2WH+10R	15.4%	3.6%	7.4%
7	4WH+1.5R+3WL+5R	9.4%	7.7%	12.5%
8	2WH+10R+1.5WL+3R	9.8%	3.0%	5.6%
Average		14.9%	9.0%	8.3%

Table 13: Task descriptions and a summary of MAPE values from the phase II of the “Model development section”.

6.2 Results from Experiment II

In the “Model validation section” the validity of the previously summarized regression equations were tested in a new group of participants with three different categories of task protocols. The predicted and actual measurement values of all three physiological variables during the performance of two of the “Moderate four-work-rest-cycle” trials are demonstrated in Figure 28 to 33. The physiological variables profiles of the first trial are demonstrated in Figure 28, 29 and 30. This is a relatively “good” trial where the actual measurement of all three physiological variables followed very well with their corresponding predicted values. In this trial participant performed 3 minutes of weight holding followed by 8 minutes of resting then 1.5 minutes of weight lifting followed by 7 minutes of resting, then

2 minutes of weight holding followed by 9 minutes of resting, finally 2 minutes of weight lifting followed by 7.5 minutes of resting. The physiological variables profiles of the second trial are demonstrated in Figure 31, 32 and 33. This is a relatively “bad” trial where the actual measurement of all three physiological variables did not match very well with their corresponding predicted values. In this trial participant performed 1.5 minutes of weight lifting followed by 6 minutes of resting then 2.5 minutes of weight holding followed by 8.5 minutes of resting, then 1.5 minutes of weight lifting followed by 7 minutes of resting, finally 1.5 minutes of weight holding followed by 6 minutes of resting. The averaged MAPE values for all trial and from all three categories were calculated and summarized in Table 14. In this section HR still had the lowest mean MAPE value among all three physiological variables, MF had a higher MAPE value than HR and SS had the highest MAPE value among all three variables. Compare with the validation trials in the phase II of the “Model development section” we can see that the goodness of fit for HR predictions actually improved in the “Model validation section” whereas the predictions for MF and SS became not as good. Comparing the MAPE values between different categories of tasks we can see that the “Moderate two-work-rest-cycle” trials and the “Moderate four-work-rest-cycle” trials have very close average MAPE values, whereas in the “Hard two-work-rest-cycle” trials these values were slightly higher.

Because our summarized regression equations performed reasonably well in predicting physiological changes in all three categories of tasks, they were used in the model formulation without further change.

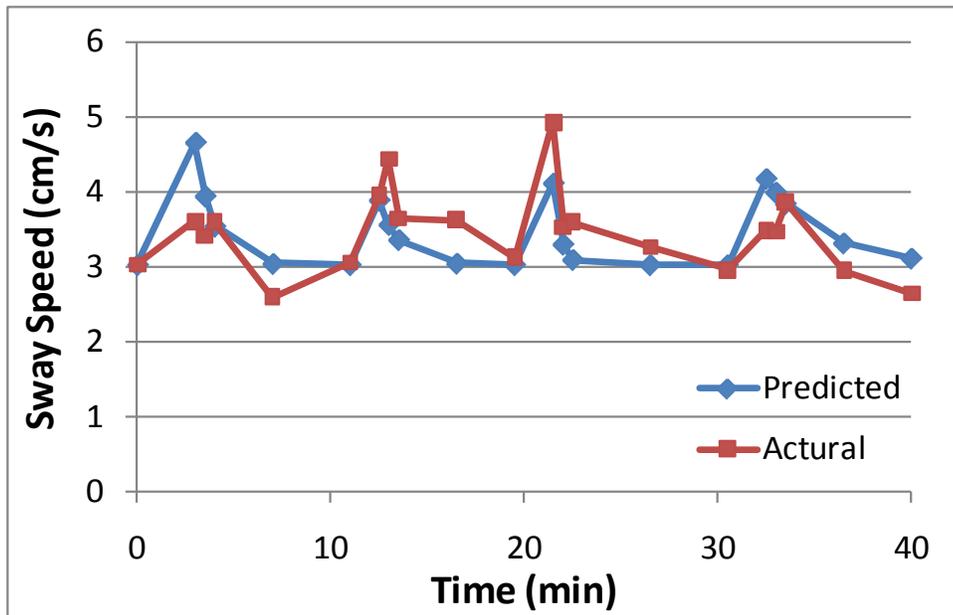


Figure 28: The predicted and actual measurement of trunk sway speed during a four-work-rest cycle protocol (From a “good” trial).

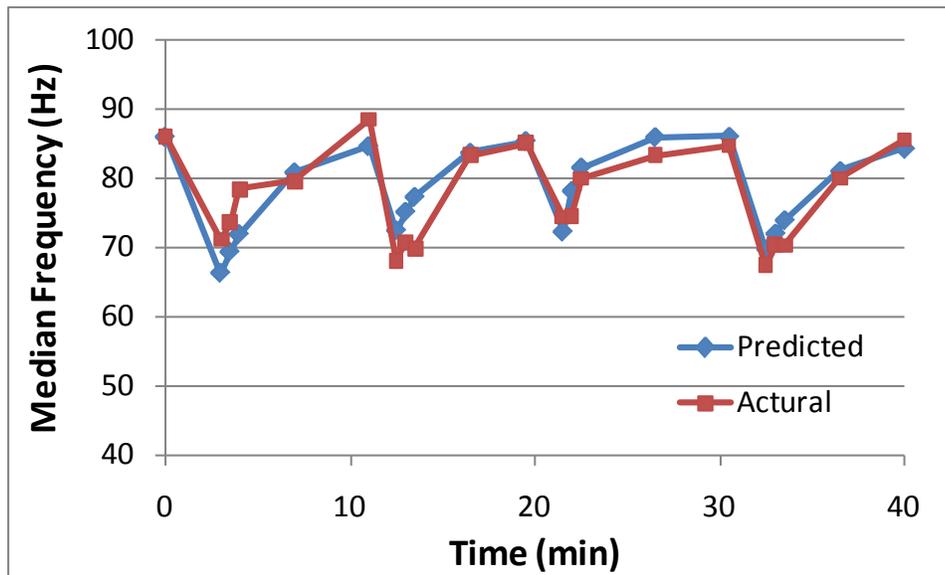


Figure 29: The predicted and actual measurement of L4 paraspinal muscle EMG median frequency during a four-work-rest cycle protocol (From a “good” trial).

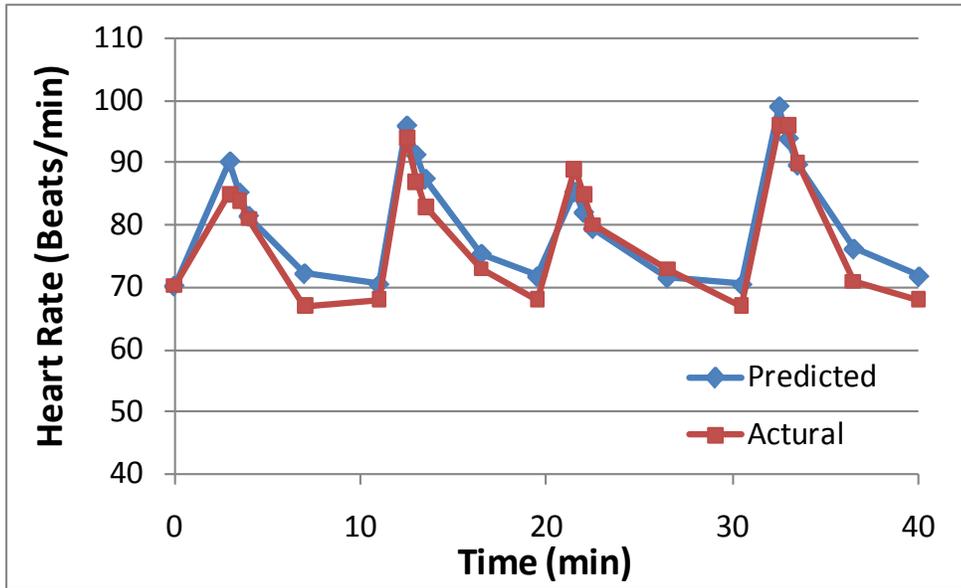


Figure 30: The predicted and actual measurement of heart rate during a four-work-rest cycle protocol (From a “good” trial).

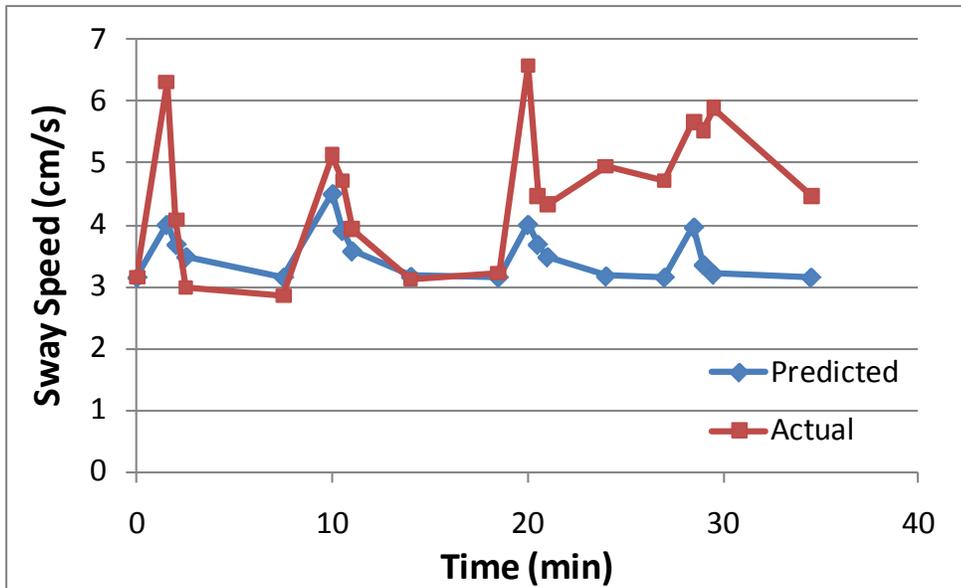


Figure 31: The predicted and actual measurement of trunk sway speed during a four-work-rest cycle protocol (From a “bad” trial).

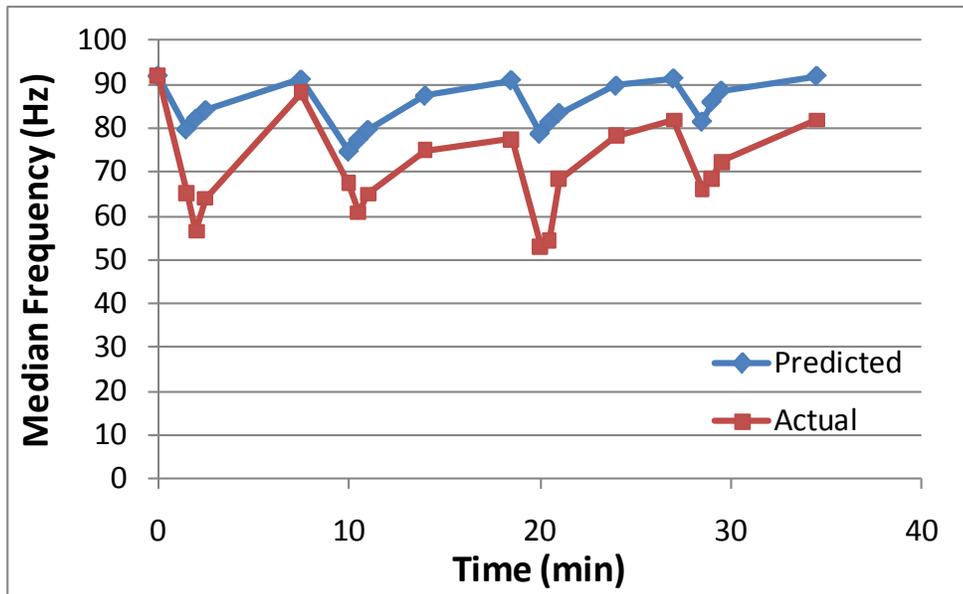


Figure 32: The predicted and actual measurement of L4 paraspinal muscle EMG median frequency during a four-work-rest cycle protocol (From a “bad” trial).

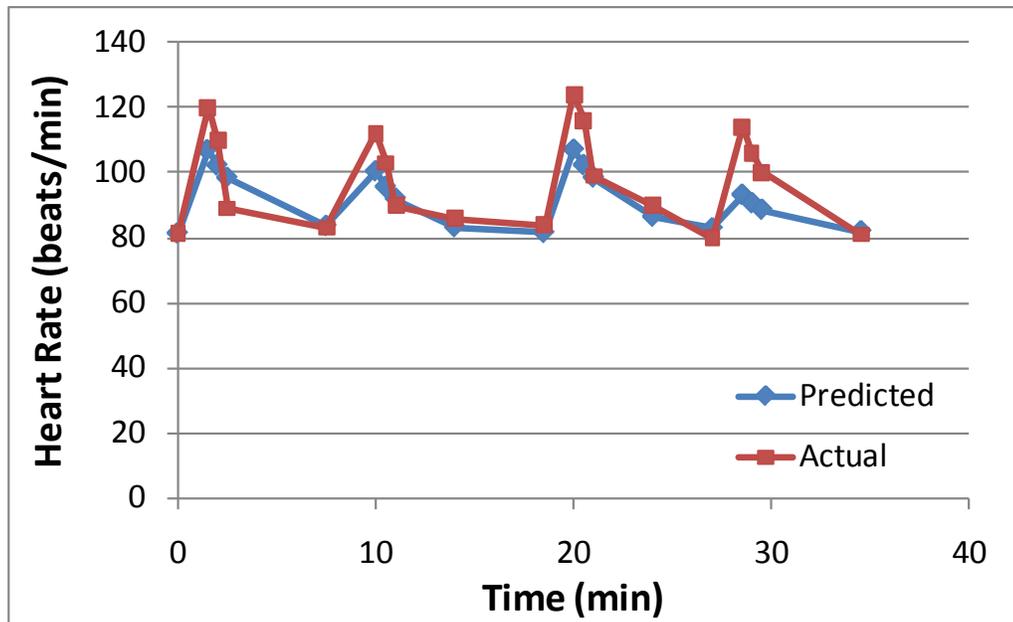


Figure 33: The predicted and actual measurement of heart rate during a four-work-rest cycle protocol (From a “bad” trial).

Trials	Mean Absolute Percentage Error		
	SS	MF	HR
Moderate two-work-rest cycle	12.6%	14.1%	3.3%
	16.6%	10.9%	6.8%
	17.3%	3.3%	6.3%
	19.3%	20.9%	7.2%
Average	16.5%	12.3%	5.9%
Hard two- work-rest cycle	14.2%	14.6%	5.1%
	13.2%	23.1%	4.8%
	25.6%	4.9%	7.8%
	24.5%	12.0%	6.5%
Average	19.4%	13.7%	6.1%
Moderate four- work-rest cycle	11.3%	9.5%	5.2%
	22.5%	23.7%	7.5%
	11.2%	3.9%	3.8%
	15.0%	9.8%	5.7%
Average	15.0%	11.7%	5.5%

Table 14: Summary of MAPE values for all three physiological variables from the

“model validation section”.

CHAPTER 7. MODELING

7.1 Define variables

After achieving empirically the time dependent functions of all three physiological variables during the performance of different low back fatiguing protocols, the next step of model development is to use an inventory control model (EPL model) to generate an optimal work-rest schedule with the purpose of reducing the risk of injury while meeting productivity requirements. As mentioned in the Background section, the first step of adaptation the EPL modeling approach to our novel applications is to redefine the original parameters involved in the EPL model (as shown in Table 6). For a physical task that creates low back muscle fatigue its production rate and demand rate were viewed as the changes in all three physiological variables during the development and recovery of muscle fatigue. Our summarized regression equations showed in Table 12 were used to predict the changes. The “Unit production cost” was not modeled (or assumed to be zero) in the new model because there is no corresponding concept existing. Since the result of model is not affected by the “Unit production cost” (i.e. optimal inventory quantity will not be affected by the unit production cost in the EPL model), lacking this element will not affect our modeling. Our new model has a new variable that was not specifically defined in the EPL model, which is workers’ wage cost. This cost changes only with total work time (includes both work and rest durations). “Fixed setup cost” can be viewed as the cost to initiate each recovery section (e.g. cost of shutting down a machine or conveyor belt, time spent walking to resting area, etc.); “holding cost” would be the estimated cost of maintaining a certain level of injury risk or, more specifically in current study, SS, MF and HR that are elevated by the increase of low back muscle fatigue; finally “Lot size” was translated to the upper and lower limit of muscle

fatigue level (also in terms of SS, MF and/or HR). Each set of “upper and lower limit of muscle fatigue level” would also correspond to a specific task performance time and resting time (a work-rest schedule) which is the decision variable that needs to be calculated based on the other parameters described above.

In the traditional EPL model the total cost includes the total holding cost, total setup cost and total unit production cost. In current model the total holding cost, total setup cost and total wage cost were considered. Because the same methodology can be applied to model all three physiological variables and all different fatiguing tasks, in the following part of modeling section only the change of HR or MF during the performance of weight lifting task (Task B) were modeled in order to demonstrate our modeling technique. The reason for selecting HR and MF is that our regression equations performed best in predicting these two variables, in addition, HR and MF are two objective measures which are not affected by individual’s will, whereas SS is affected not only by low back muscle fatigue but also subjective factors (such as participants’ willingness to cooperate, the degree of focus utilized, etc.).

As shown in Figure 34, HR increases during fatiguing task performance and recovers during the resting time. In each work-rest cycle the holding cost is calculated as the total area under the “Increase of heart rate” profile and multiplies by a cost factor “h”. In the traditional EPL model “h” is a constant value (does not change with the level of inventory) with an unit of dollar per item per year, however in our model, with the understanding of cardiovascular risks we assumed that for HR should have a cost factor that increases with the increment of HR. A quadratic function was selected to represent the relationship between increase of HR

and the cost factor, namely $h=a \times y^2$ where “y” is the amount of HR increase from resting level and “a” is a constant parameter that determines the magnitude of cost factor. The calculation of total holding cost is showing in Equation 6. One way to find the value of “a” is to build a relationship between the risk of injury for keeping certain amount of HR and the direct cost of that injury. Studies have shown that marathon runners have a sudden cardiac death incident rate of 1/50000 (Maron & Roberts 1996). Other studies have reported the average finish time of a marathon running to be 4 hours and average HR to be 40 beats/min above resting HR (Neilan et al 2006). The Food and Drug Administration suggested that a human life was worth \$7.9 million dollars (Sinha et al., 2010). In our modeling \$7.9 million dollars was used as the penalty for losing a human’s life and “a” was calculated. The detailed calculations are showing in Equation 6 and 7.

$$\text{Equation 6: } C_h = \int_0^t h \times y \times \Delta t = \int_0^t a \times y^3 \times \Delta t$$

$$\text{Equation 7: } 7900000/50000 = a \times (40)^3 \times (4 \times 60)$$

$$a = 1 \times 10^{-5} \left(\frac{\$ \times \text{min}^2}{\text{beats}^3} \right)$$

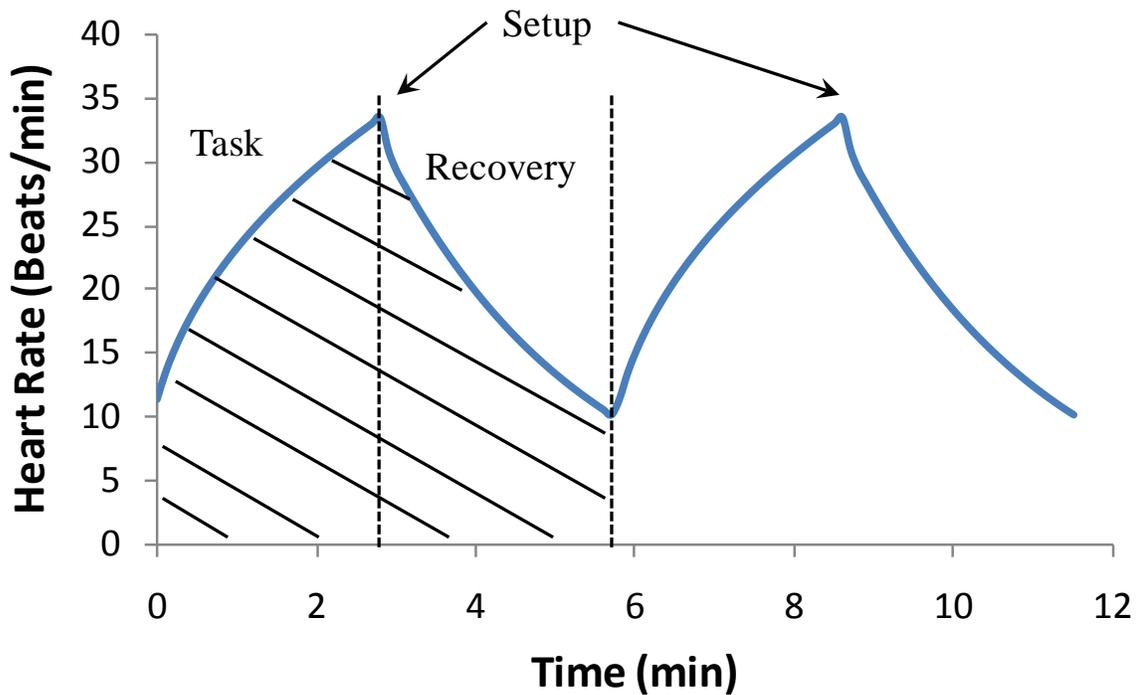


Figure 34: An example of the amount of heart rate increase from resting level during the performance of two work-rest cycles.

A similar holding cost function can be developed for MF. Previous researchers have found a linear correlation between the change in MF and change in Borg scale when performing low back fatiguing tasks (Dedering et al 1999; Kankaanpaa et al 1997). Here we assume that the holding cost rate of MF is linearly related with the change of MF, namely $h=b \times y$ where “y” is the amount of MF decrease (a positive value) from resting level and “b” is a constant parameter that determines the magnitude of the holding cost rate. The calculation of total holding cost is shown in Equation 8. Similar for finding the holding cost for HR, one way to find the value of “b” is to build a relationship between the risk of injury for keeping certain amount of MF and the direct cost of that injury. One study showed that nurses working in geriatric wards experiences 20 Hz of MF drop after 8 hours work shift (Hui et al 2001).

Another study showed that in a group of geriatric nurses 16% of them had taken sick leave because of low back pain within 12 months (Dulon et al 2008). Previous study has indicated that the average compensation claim for low back pain was 8300 dollars (Johanning 2000; Webster and Snook 1994). Similar to what we did for finding the holding cost parameter “a” for HR, Equation 8 and 9 were developed to calculate the holding cost parameter “b” for MF. It is assumed that a geriatric nurse gradually develop low back muscle fatigue during the 8 hours shift (MF gradually drop from 0 to 20 Hz) and it equivalent to having an average of 10 Hz MF drop during entire 8 hours. We assumed a standard 2000 working hours per year (40 hours a week, 50 weeks a year) for each nurse. Result from Equation 8 and 9 showed “b” equals 6.9×10^{-4} .

$$\text{Equation 8: } C_h = \int_0^t h \times y \times \Delta t = \int_0^t b \times y^2 \times \Delta t$$

$$\text{Equation 9: } 8300 \times 16\% = b \times (10)^2 \times 60 \times 2000$$

$$b = 6.9 \times 10^{-4} \left(\frac{\$}{\text{min} \times \text{Hz}^2} \right)$$

Setup cost is one variable that must be determined based on the details of a real work situation. Examples might include the cost of the time it takes the worker to move from their work station to the rest area (time * wage), cost of shutting down and starting up a piece of equipment that must be disabled during the break (energy costs of startup, idle time of worker while waiting to have equipment ramp up, etc.). For the purpose of our model formation, realistic, but arbitrary, values will be assigned in order to observe the influence of

this variable to the model output. Total setup cost is this cost value multiplied by the number of setups (i.e. breaks) taken during the whole work period. The total wage cost is the wage rate multiplied by the total time spent performing the work task (sum of work and rest time).

7.2 Assumptions

Going back to Table 6, all the necessary variables to calculate the “Upper and lower limit of risk level” for HR have been defined. The next step is to formulate the new work-rest schedule model. First, several assumptions have been made: 1. Assume there is a fixed duration of certain task to be performed. 2. Assume this task can be cut into infinite small sections (this task can be stopped at anytime). 3. Assume all work-rest cycles to be identical (in terms of HR and MF profile). 4. Assume that this is a memory-less process implying that the set of regression equations can always be applied no matter how many work-rest cycles have been performed.

7.3 Problem statement

Suppose one worker needs to perform a total of “ T_n ” minutes of certain physical exertion task. Setting up each recovery section generates an initiation cost of “ M ” per worker and total setup cost in each day is “ C_s ” per worker. Wage cost is “ W ” per worker per minute. The work stress target is S_t (when this target (in terms of HR or MF) is reached work will be stopped and a recovery section will be initiated). The recovery target is “ R_t ” (when this target (in terms of HR or MF) is reached a recovery section will be stopped and work will be resumed). The optimal work duration in each work-rest cycle is “ T ”. The locations of “ T ” and “ R_t ” are showing in Figure 35.

7.4. Model formation

This model involves multiple variables among them the most important ones were recovery target “ R_t ”, work duration “ T ” and total cost “ C_{total} ”. The objective of this model was to find out the optimal work-rest schedule that generates minimum cost. In a real work condition, normally the wage cost “ W ”, setup cost “ M ” and the holding cost parameter “ a ” and “ b ” will be known. By minimizing the total cost “ C_{total} ” this model can generate an optimal selection of “ R_t ” and “ T ”, and the corresponding recovery time “ T_r ” and stress target “ S_t ” can be calculated based on “ R_t ” and “ T ”. The detailed calculations were demonstrated below.

First of all, the relative starting time and ending time of work duration were defined as t_1 and t_2 , similarly the starting and ending time for recovery were defined as t_3 and t_4 . These “relative” time points were calculated by finding the corresponding time points in the regression equations based on recovery target “ R_t ” and optimal work duration “ T ”. Their way of calculation were demonstrated from Equation 10 to 13 where $Y_d(t)$ is the development function of low back muscle fatigue (in terms of SS, MF or HR) during the task performance; $Y_r(t)$ is the recovery function of low back muscle fatigue during resting period. As we can see from Equation 10 to 13, all four time points (t_1 , t_2 , t_3 and t_4) can be expressed by $Y_d(t)$, $Y_r(t)$, “ R_t ” and “ T ”. Then the total holding cost is summarized in Equation 14. Total setup cost is shown in Equation 15 where T_n/T calculates the total number of work-rest cycles. Total wage cost is shown in Equation 16. The wage cost in each cycle is only affected by the cycle time which is summation of task performance time T and recovery time (t_4-t_3). Finally the total cost “ C_{Total} ” is the summation of the total holding cost, total setup cost and total

wage cost as shown in Equation 17. A summary of all variables that were involved in the modeling is showing in Table 15.

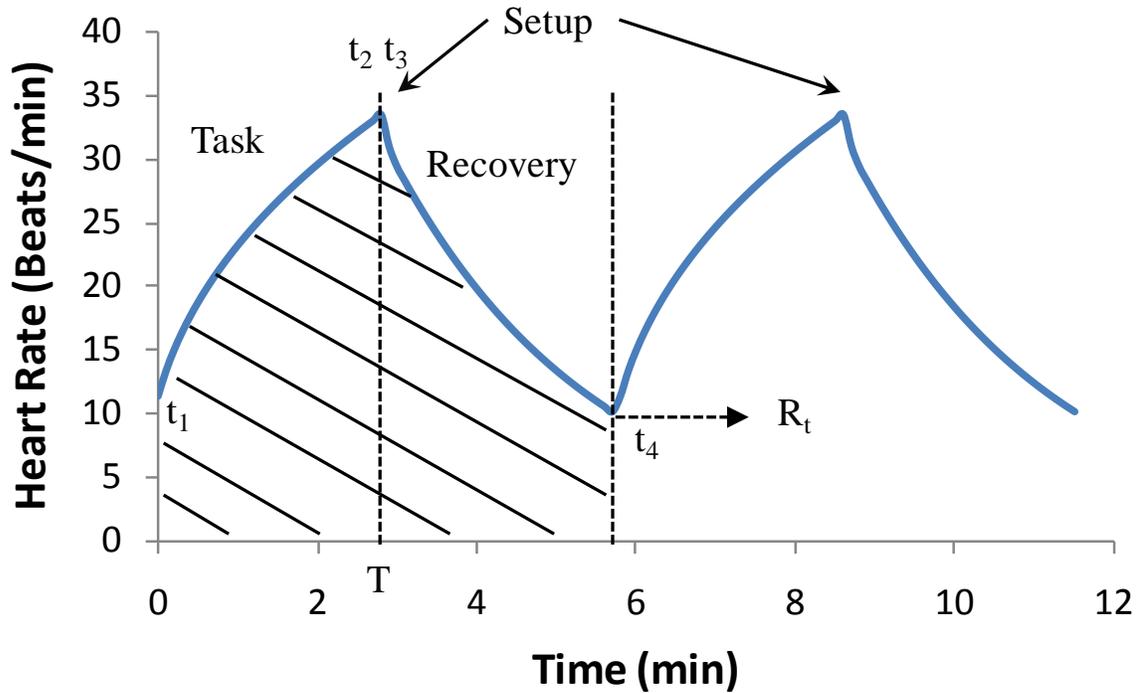


Figure 35: A demonstration of the location of t_1 to t_4 , the work duration “ T ” and recovery target “ R_t ” in an example of heart rate profile during the performance of two work-rest cycles.

$$\text{Equation 10: } R_t = Y_d(t_1) \rightarrow t_1 = Y_d^{-1}(R_t)$$

$$\text{Equation 11: } t_2 = t_1 + T \rightarrow t_2 = Y_d^{-1}(R_t) + T$$

$$\text{Equation 12: } Y_d(t_2) = Y_r(t_3) \rightarrow t_3 = Y_r^{-1}(Y_d(t_2)) \rightarrow t_3 = Y_r^{-1}(Y_d(Y_d^{-1}(R_t) + T))$$

$$\text{Equation 13: } R_t = Y_r(t_4) \rightarrow t_4 = Y_r^{-1}(R_t)$$

$$\text{Equation 14: } C_h(T) = \frac{T_n}{T} \times \left\{ \int_{t_1}^{t_2} h \times Y_d(t) \times dt + \int_{t_3}^{t_4} h \times Y_r(t) \times dt \right\}$$

$$\text{Equation 15: } C_s(T) = \frac{T_n}{T} \times M$$

$$\text{Equation 16: } C_w(T) = W \times (T + t_4 - t_3)$$

$$\text{Equation 17: } C_{Total}(T) = C_s + C_h + C_w$$

Variables	Description	Unit
T_n	Total task performance time	min
M	Setup cost rate	\$/person
W	Wage cost rate	\$/min/person
h	Holding cost rate	\$/beat or \$/Hz/min
a	Holding cost parameter for HR	\$/min ² /beat ³
b	Holding cost parameter for MF	\$/min*Hz ²
$T (T_p)$	Task performance time in each cycle	min
T_r	Recovery time in each cycle	min
t_1	Starting time point of task performance (corresponding to development function)	min
t_2	Ending time point of task performance (corresponding to development function)	min
t_3	Starting time point of recovery (corresponding to recovery function)	min
t_4	Ending time point of recovery (corresponding to recovery function)	min
S_t	Stress target (peak HR or MF at the end of task performance in each cycle)	beats/min or Hz
R_t	Recovery target (minimum HR or MF at the end of recovery in each cycle)	beats/min or Hz
$Y_d(t)$	HR or MF development function	beats/min or Hz
$Y_r(t)$	HR or MF recovery function	beats/min or Hz
C_h	Holding cost	\$
C_s	Setup cost	\$
C_w	Wage cost	\$
C_{total}	Total cost	\$

Table 15: A summary of all the variables involved in the current model

7.5 Single risk factor modeling

7.5.1 Heart rate

7.5.1.1 Model formation

Assume a worker needs to perform a total of “ T_n ” minutes of 35 lbs weight lifting task with a lifting frequency of one lifting every eight seconds (Task B). HR was first selected to be modeled for the calculation of holding cost. The same modeling technique can be used to model other tasks and variables. Equation 18 and 19 were used to predict the increase and recovery of HR during fatiguing exertion and resting time respectively. Time points t_1 - t_4 were regenerated and shown in Equation 20 to 23 by subsidize HR development and recovery equations (Equation 18 and 19) to Equation 10 to 13. The total holding cost is shown in Equation 24. Total setup cost is shown in Equation 25. Total wage cost is shown in Equation 26. Finally the total cost “ C_{Total} ” is shown in Equation 27. From the equations we can see that because the total work time “ T_n ”, initiation cost “ M ”, wage cost “ W ” and parameter “ a ” are all constant values (“ M ” and “ W ” may change depending on the specific work situation) the total cost “ C_{Total} ” is a function of work duration “ T ” and HR recovery target “ R_t ”.

$$\text{Equation 18: } Y_d(t)_{HR} = 21.6 \times t^{0.4}$$

$$\text{Equation 19: } Y_r(t)_{HR} = 29.4 \times e^{(-0.395 \times t)}$$

$$\text{Equation 20: } t_1 = (R_t / 21.6)^{2.5}$$

$$\text{Equation 21: } t_2 = (R_t / 21.6)^{2.5} + T$$

$$\text{Equation 22: } t_3 = -1.01 \times \ln \{0.463 \times [(R_t/21.6)^{2.5} + T]\}$$

$$\text{Equation 23: } t_4 = -2.53 \times \ln (R_t/29.4)$$

Equation 24:

$$C_h(T) = \frac{T_n}{T} \times \left\{ \int_{t_1}^{t_2} a \times (21.6 \times t^{0.4})^3 \times dt + \int_{t_3}^{t_4} a \times (29.4 \times e^{(-0.395 \times t)})^3 \times dt \right\}$$

$$\text{Equation 25: } C_s(T) = \frac{T_n}{T} \times M$$

$$\text{Equation 26: } C_w(T) = W \times (T + t_4 - t_3)$$

$$\text{Equation 27: } C_{Total}(T) = C_s + C_h + C_w$$

After finding the function for total cost (as shown in Equation 24-27), now we can apply one set of numbers for “T_n”, “M”, “W” and “a” and demonstrate the changes of total cost with different task duration “T” and HR recovery target “R_t”. Assume a worker needs to perform a total of 50 minutes (T_n=50 min) of weight lifting task (Task B), each time the worker stops lifting and takes a rest there is a initiation cost of \$0.05/person. Worker’s salary is \$0.2/min/person (\$12/hr/person). The parameter “a” equals 1×10⁻⁵ as we have calculated before. Then we can create a 3-D cost profile as shown in Figure 36 to demonstrate the relationship between total cost and different task performance time “T” and heart rate recovery target “R_t”. Results showed that the optimal work duration “T” is 1.4 minutes, the optimal HR recovery target “R_t” is 18 beats/min and the corresponding recovery time is 1.2 minutes. With this schedule the 50 minutes weight lifting task will be finished in 92.2 minutes (including both task performance and recovery time) with minimum cost of \$32.8 and the corresponding peak HR “S_t” at the end of task performance is 42.2 beats/min (for a

physically fit person this would correspond to an actual heart rate of 100 -110 beats/minutes after adding the baseline heart rate.).

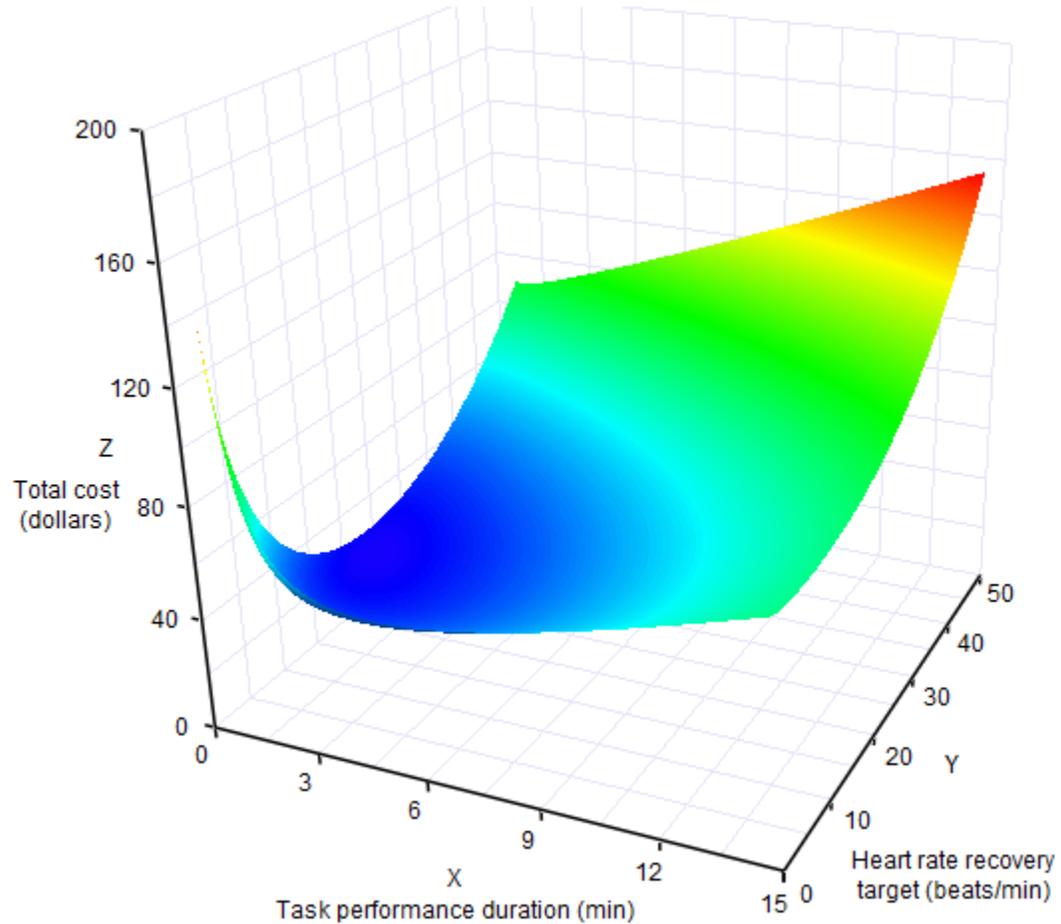


Figure 36: The task duration, heart rate recovery target and total cost relation curve when $T_n=50\text{min}$, $M=\$0.05/\text{person}$, $W=\$0.2/\text{min}/\text{person}$ and $a=1\times 10^{-5}\$ \text{min}^2/\text{beats}^3$.

7.5.1.2 Sensitivity analysis

As we have demonstrated in the previous section, a fixed set of “M”, “W” and “a” values will generate one unique optimal work-rest schedule. Next we want to further explore the effect of changes in “M”, “W” and “a” values to the result of optimal work-rest schedule.

Table 16 demonstrated how changes in setup up cost “M”, wage cost “W” and holding cost parameter “a” affect the selection of optimal task duration “T”, optimal recovery duration “Tr”, HR recovery target “R_t” total job finishing time (in this example that’s the total time to finish 50 minutes of weight lifting) and the minimum total cost “C_{total}”. After analyzing the data in Table 16 we can find that when wage cost and setup cost are constant the optimal work duration and HR recovery target both decrease with the increase of holding cost parameter “a”, which means our model tried to reduce the level of HR in order to reduce the holding cost. For the setup cost “M” we have tested three different levels: M=\$0 means there is no setup cost. From the Table 16 we can see that because there is no penalty for taking multiple breaks the optimal task duration when M=\$0 is the lowest among all conditions. In the second level M=\$0.05/person which means each time a person takes a break there is 5 cent cost associated with it, this 5 cents could represent the cost of time that workers spent in the transition between work area and rest area. In this condition the optimal work duration become longer compared with the M=\$0 condition. In the third condition M=\$0.5/person for each break. This cost represents the scenario that a machine operator turns off a machine or shuts down a conveyor belt, the costs associate with the machine tear-and-wear, could generate a much higher cost. In this M=\$0.5/person condition we can observe the highest optimal work durations which means that our work-rest model tried to increase work duration in each cycle and reduce the number of breaks. Finally we have also tested the effect of different salary level. Table 16 shows that with the increase of worker’s wage the optimal work duration slightly increased, but recovery duration decreased (which generated a higher HR recovery target), these changes generated a decreased total time which has a direct impact on the total wage cost.

Model input			Model output				
W	M	a	T	T _r	R _t	Total Time	C _{total}
0.1	0	5.00E-06	1.1	0.9	19	92.5	15.4
0.1	0	1.00E-05	1.1	1.2	16	105.4	20.9
0.1	0	1.50E-05	1.1	1.5	14	116.7	25.8
0.1	0.05	5.00E-06	1.8	1.5	17	90.9	17.2
0.1	0.05	1.00E-05	1.3	1.5	15	106.3	23.1
0.1	0.05	1.50E-05	1.1	1.5	14	116.7	28.1
0.1	0.5	5.00E-06	4.1	2.8	13	83.9	24.6
0.1	0.5	1.00E-05	3.0	2.7	12	94.6	33.4
0.1	0.5	1.50E-05	2.5	2.7	11	104.2	40.5
0.2	0	5.00E-06	1.1	0.7	23	80.5	23.8
0.2	0	1.00E-05	1.1	0.9	19	92.5	30.7
0.2	0	1.50E-05	1.1	1.1	17	100.7	36.5
0.2	0.05	5.00E-06	1.9	1.1	21	79.6	25.6
0.2	0.05	1.00E-05	1.4	1.2	18	92.2	32.8
0.2	0.05	1.50E-05	1.1	1.1	17	100.7	38.8
0.2	0.5	5.00E-06	4.3	2.2	17	75.6	32.5
0.2	0.5	1.00E-05	3.1	2.2	15	85.4	42.4
0.2	0.5	1.50E-05	2.6	2.2	14	92.1	50.4
0.3	0	5.00E-06	1.1	0.5	26	74.2	31.6
0.3	0	1.00E-05	1.1	0.7	22	83.1	39.5
0.3	0	1.50E-05	1.1	0.9	19	92.5	46.1
0.3	0.05	5.00E-06	2.1	1.0	23	74.8	33.3
0.3	0.05	1.00E-05	1.4	0.9	21	83.2	41.6
0.3	0.05	1.50E-05	1.2	1.0	19	91.2	48.3
0.3	0.5	5.00E-06	4.5	2.0	19	72.2	39.9
0.3	0.5	1.00E-05	3.3	2.0	17	79.9	50.7
0.3	0.5	1.50E-05	2.7	2.1	15	88.3	59.4

Table 16: Changes of optimal work duration “T”, recovery duration “T_r”, heart rate recovery target “R_t”, total job finishing time and total cost “C_{total}” with different setup cost “M”, holding cost parameter “a” and wage cost “W”.

7.5.2 Median frequency

7.5.2.1 Model formation

Similar modeling technique can be applied when modeling MF. Assume a worker needs to perform a total of “ T_n ” minutes of 35 lbs weight lifting task with a lifting frequency of one lifting every eight seconds (Task B). Regression equations (Equation 28 and 29) were used to predict the increase and recovery of MF during fatiguing exertion and resting time respectively. Time points t_1 - t_4 were regenerated and shown in Equation 30 to 33 by substitute MF development and recovery equations (Equation 28 and 29) to Equation 10 to 13. The total holding cost is shown in Equation 34. Total setup cost is shown in Equation 35. Total wage cost is shown in Equation 36. Finally the total cost “ C_{Total} ” is shown in Equation 37. From the equations we can see that the total cost “ C_{Total} ” is a function of work duration “ T ” and MF recovery target “ R_t ”.

$$\text{Equation 28: } Y_d(t)_{MF} = 10.8 \times t^{0.7}$$

$$\text{Equation 29: } Y_r(t)_{MF} = 24.9 \times e^{(-0.297 \times t)}$$

$$\text{Equation 30: } t_1 = (R_t / 10.8)^{1.43}$$

$$\text{Equation 31: } t_2 = (R_t / 10.8)^{1.43} + T$$

$$\text{Equation 32: } t_3 = -2.36 \times \ln \{0.3 \times [(R_t / 10.8)^{1.43} + T]\}$$

$$\text{Equation 33: } t_4 = -3.37 \times \ln (R_t / 24.9)$$

$$\text{Equation 34:}$$

$$C_h(T) = \frac{T_n}{T} \times \left\{ \int_{t_1}^{t_2} b \times (10.8 \times t^{0.7})^2 \times dt + \int_{t_3}^{t_4} b \times (24.9 \times e^{(-0.297 \times t)})^2 \times dt \right\}$$

$$\text{Equation 35: } C_s(T) = \frac{T_n}{T} \times M$$

$$\text{Equation 36: } C_w(T) = W \times (T + t_4 - t_3)$$

$$\text{Equation 37: } C_{Total}(T) = C_s + C_h + C_w$$

After finding the function for total cost (as shown in Equation 34-37), now we can apply one set of numbers for “ T_n ”, “ M ”, “ W ” and “ b ” and demonstrate the changes of total cost with different task duration “ T ” and MF recovery target “ R_t ”. Assume a worker needs to perform a total of 50 minutes ($T_n=50$ min) of weight lifting task (Task B), each time the worker stop lifting and take a rest there is a initiation cost of \$0.05/person. Worker’s salary is \$0.2/min/person (\$12/hr/person). The parameter “ b ” equals 6.9×10^{-4} as we have calculated before. If we define the task performance time “ T ” changes from 0.5 min to 11 min and the MF recovery target “ R_t ” varies between 0 (full recovery) to 60 Hz. Then we can create a 3-D cost profile as shown in Figure 37. This figure demonstrates how total cost changes with “ T ” and “ R_t ”. Results showed that the optimal work duration “ T ” is 1.3 minutes, the optimal MF recovery target “ R_t ” is 11Hz (11Hz below resting MF) and the corresponding recovery time is 1.9 minutes. With this schedule the 50 minutes weight lifting task will be finished in 123.2 minutes (including both task performance and recovery time) with minimum cost of \$46.3 and the corresponding peak MF change “ S_t ” at the end of task performance is 19.5Hz (19.5Hz below resting MF). Figure 37 demonstrates the corresponding total cost with the changes of task performance duration “ T ” and MF recovery target “ R_t ”.

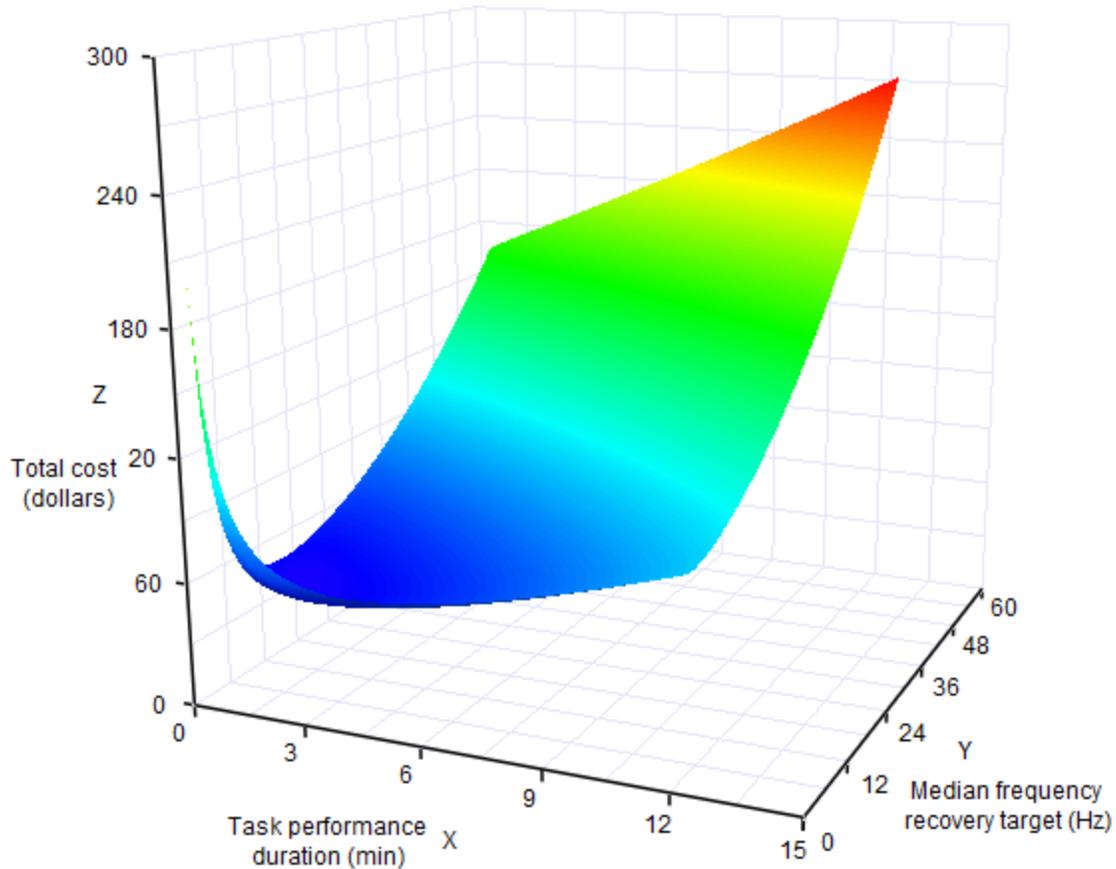


Figure 37: The task duration, median frequency recovery target and total cost relation curve when $T_n=50\text{min}$, $M=\$0.05/\text{person}$, $W=\$0.2/\text{min}/\text{person}$ and $b=6.9\times 10^{-4} \text{ \$/minHz}^2$.

7.5.2.2 Sensitivity analysis

Similar to what included in the HR model, sensitivity analysis was performed on the results of the MF model as well. Again, we want to further explore the effect of changes in “M”, “W” and “b” values to the result of optimal work-rest schedule. Table 17 demonstrated how changes in setup up cost “M”, wage cost “W” and holding cost parameter “b” affect the selection of optimal task duration “T”, optimal recovery duration “ T_r ”, MF recovery target “ R_t ” total job finishing time (in this example that’s the total time to finish 50 minutes of

weight lifting) and the minimum total cost " C_{total} ". After analyzing the data in Table 17 we can find that when wage cost and setup cost are constant the optimal work duration and MF recovery target both decrease with the increase of holding cost parameter "b", which means our model tried to reduce the reduction of MF in order to reduce the holding cost. For the setup cost "M" same as what we did in the sensitive analysis of HR model three different levels were tested: $M=\$0$, $M=\$0.05$ and $M=\$0.5$. When $M=\$0$, model output the lowest optimal work duration among all conditions. In the second level $M=\$0.05$ /person. In this condition the optimal work duration become longer compare with the $M=\$0$ condition. In the third condition $M=\$0.5$ /person for each break our model generated the highest optimal work durations which means that our work-rest model tried to increase work duration in each cycle and reduce the number of breaks. Finally we have also tested the effect of different salary level. Table 17 shows that with the increase of worker's wage the optimal work duration slightly increased, but recovery duration decreased and MF recovery target increased. This resulted in a decrease in total time which has a direct impact on the total wage cost.

Model input			Model output				
W	M	b	T	T _r	R _t	Total Time	C _{total}
0.1	0	3.45E-04	0.3	0.4	14	119.5	21.2
0.1	0	6.90E-04	0.3	0.6	11	146.1	29.2
0.1	0	1.04E-03	0.3	0.7	9	174.3	35.9
0.1	0.05	3.45E-04	1.7	2.5	10	123.0	24.0
0.1	0.05	6.90E-04	1.2	2.4	8	151.5	32.9
0.1	0.05	1.04E-03	1.0	2.4	7	172.3	40.2
0.1	0.5	3.45E-04	3.8	4.9	7	114.4	31.9
0.1	0.5	6.90E-04	2.8	5.3	5	143.9	43.8
0.1	0.5	1.04E-03	2.3	4.8	5	155.4	53.4
0.2	0	3.45E-04	0.3	0.3	18	98.9	31.9
0.2	0	6.90E-04	0.3	0.4	14	119.5	42.3
0.2	0	1.04E-03	0.3	0.5	12	135.6	50.9
0.2	0.05	3.45E-04	1.7	1.8	14	103.1	35.0
0.2	0.05	6.90E-04	1.3	1.9	11	123.2	46.3
0.2	0.05	1.04E-03	1.0	1.7	10	137.0	55.4
0.2	0.5	3.45E-04	4.1	4.0	10	99.1	42.5
0.2	0.5	6.90E-04	3.0	4.0	8	117.3	56.5
0.2	0.5	1.04E-03	2.5	4.1	7	131.1	67.7
0.3	0	3.45E-04	0.3	0.2	21	89.2	41.3
0.3	0	6.90E-04	0.3	0.3	16	107.8	53.5
0.3	0	1.04E-03	0.3	0.4	14	119.5	63.5
0.3	0.05	3.45E-04	1.7	1.5	17	93.4	44.8
0.3	0.05	6.90E-04	1.3	1.6	13	111.7	57.8
0.3	0.05	1.04E-03	1.0	1.4	12	121.8	68.3
0.3	0.5	3.45E-04	4.2	3.6	12	92.6	52.0
0.3	0.5	6.90E-04	3.1	3.5	10	106.4	67.7
0.3	0.5	1.04E-03	2.5	3.4	9	117.6	80.2

Table 17: Changes of optimal work duration “T”, recovery duration “T_r”, heart rate recovery target “R_t”, total job finishing time and total cost “C_{total}” with different setup cost “M”, holding cost parameter “b” and wage cost “W”.

7.6 Multiple risk factors modeling

7.6.1 Heart rate and median frequency

7.6.1.1 Model formation

In the single risk factor modeling sections, we have demonstrated the way to generate optimal work-rest schedule by only considering holding cost that generated from one risk factor (HR or MF) in this section we will demonstrate how to consider multiple risk factors at the same time. In the current model both HR and MF will be considered. One challenge for modeling multiple risk factors is that, it is not practical to setup recovery target (in term of HR or MF) in more than one physiological variable simply because each variable has its unique function of development and recovery. However the common point that all variables share is that all variables will have the same durations for development and recovery. So in the current modeling we will first define the task performance time “ T_p ” and recovery time “ T_r ”. Because the speed of fatigue development (in terms of HR and MF) always slows down and the speed of recovery always increase with higher level of fatigue (reflected in the regression equations showing in Table 12) no matter what work- rest schedule were chosen the change of physiological variables (HR and MF) will always reach to steady state. To calculate total cost we need to first calculate the holding cost of both HR and MF, the way of calculation are showing in Equation 18-27 and Equation 28-37. As mentioned before in this multiple risk factors model the recovery target “ R_t ” for each variable cannot be pre-determined, but it can be calculated using “ T_p ” and “ T_r ”. Equation 38 demonstrates one way of calculating the recovery target “ R_t ” for MF. However this method is quite complicated. An easier way of obtaining “ R_t ” for different variables for a specific work-rest schedule is to develop a computer program that simulates performing this work-rest schedule for enough

cycles until the development and recovery profile reaches to steady state. Then “ R_t ” can be directly obtained from the profile. Then similar methods were developed to calculate the holding cost of HR and MF as shown in Equation 39 and 40 where “ C_{h_HR} ” and “ C_{h_MF} ” represent the total holding cost for HR and MF respectively. In these two equations “ t_1 ” to “ t_4 ” for both HR and MF can be calculated using Equation 20 to 23 and Equation 30 to 33. Equation 41 demonstrates the total setup cost and Equation 42 shows the total wage cost. Finally Equation 43 shows the total cost.

$$\text{Equation 38: } R_t = 10.8 \times \left[\left(\frac{R_t}{10.8} \right)^{1.43} + T_p \right]^{0.7} \times e^{-0.297 \times T_r}$$

$$\text{Equation 39: } C_{h_HR}(T_p) = \frac{T_n}{T_p} \times \left\{ \int_{t_1}^{t_2} a \times (21.6 \times t^{0.4})^3 \times dt + \int_{t_3}^{t_4} a \times (29.4 \times e^{(-0.395 \times t)})^3 \times dt \right\}$$

$$\text{Equation 40: } C_{h_MF}(T_p) = \frac{T_n}{T_p} \times \left\{ \int_{t_1}^{t_2} b \times (10.8 \times t^{0.7})^2 \times dt + \int_{t_3}^{t_4} b \times (24.9 \times e^{(-0.297 \times t)})^2 \times dt \right\}$$

$$\text{Equation 41: } C_s(T_p) = \frac{T_n}{T_p} \times M$$

$$\text{Equation 42: } C_w(T_p, T_r) = W \times (T_p + T_r)$$

$$\text{Equation 43: } C_{Total}(T_p, T_r) = C_s + C_h + C_w$$

Similar to what we did in the single risk factor model now we can apply one set of numbers for “ T_n ”, “ M ”, “ W ” “ a ”, “ b ” and demonstrate the changes of total cost with different task duration “ T_p ” and recovery duration “ T_r ”. Assume a worker needs to perform a total of 50 minutes ($T_n=50$ min) of weight lifting task (Task B), each time the worker stop lifting and take a rest there is a initiation cost of \$0.05/person. Worker’s salary is \$0.2/min/person (\$12/hr/person). The parameter “ a ” equals 1×10^{-5} and parameter “ b ” equals 6.9×10^{-4} as we

have calculated before. If we define the task performance time “ T_p ” changes from 1 min to 16 min and the recovery duration “ T_r ” also varies between 1 min to 16 min. Then we can create a 3-D cost profile as shown in Figure 38. This figure demonstrates how total cost changes with “ T_p ” and “ T_r ”. Results showed that the optimal work duration “ T_p ” is 1.1 minutes, the optimal recovery time “ T_r ” is 1.8 minutes. With this schedule the 50 minutes weight lifting task will be finished in 131.8 minutes (including both task performance and recovery time) with minimum total cost of \$55.3. The corresponding peak HR and peak MF at the end of each task performance are 24.1 beats/min and 17.9 Hz (below resting level) respectively. The HR and MF recovery targets at the end of each recovery section are 11.8 beats/min and 10.5 Hz (below resting level) respectively. Figure 38 demonstrates the corresponding total cost with the changes of task performance duration “ T_p ” and recovery duration “ T_r ”.

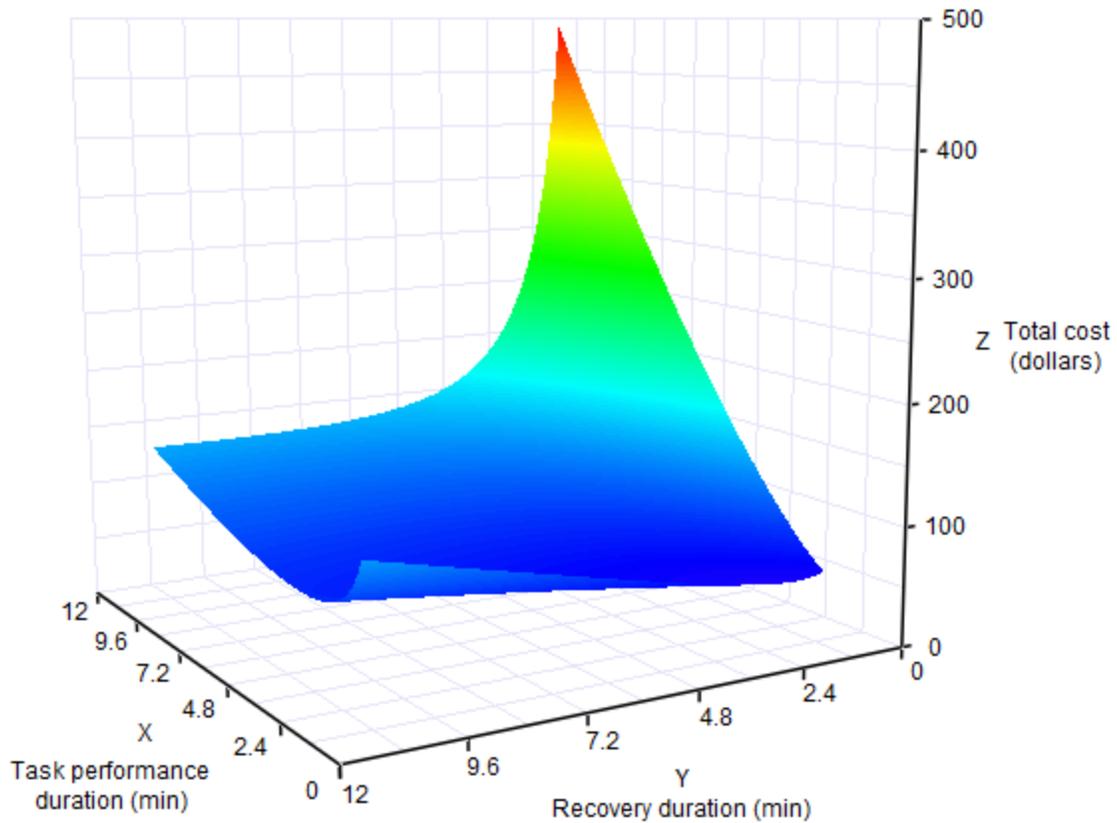


Figure 38: The task duration, recovery duration and total cost relation curve when

$T_n=50\text{min}$, $M=0.05/\text{person}$, $W=0.2/\text{min}/\text{person}$ $a=1\times 10^{-5}$ and $b=6.9\times 10^{-4}$.

7.6.1.2 Sensitivity analysis

A sensitivity analysis was also conducted to demonstrate the changes in optimal solutions with different model input. Same as single risk factor model in the new multi risk factor model, a fixed set of “M”, “W”, “a” and “b” values generates one unique optimal work-rest schedule. Table 18 demonstrates how changes in setup up cost “M”, wage cost “W” HR holding cost parameter “a” and MF holding cost parameter “b” affect the selection of optimal task performance and recovery duration “Tp” and “Tr”, HR recovery target “R_{thr}”, MF recovery target “R_{mf}” total job finishing time (in this example that’s the total time to finish

50 minutes of weight lifting) and the minimum total cost " C_{total} ". After analyzing the data in Table 18 we can find that when wage cost and setup cost are constant the optimal work duration and HR, MF recovery targets will decrease with the increase of holding cost parameter "a" and "b", which means our model tried to reduce the level of HR and drop in MF in order to reduce the holding cost. For the setup cost "M" we have tested three different levels: $M=\$0$ means there is no setup cost from the Table 18 we can see that because there is no penalty for taking multiple breaks the optimal task duration when $M=\$0$ is the lowest among all conditions. In the second level $M=\$0.05/\text{person}$ which means each time a person takes a break there is 5 cents cost associated with it, this 5 cents could represent the cost of time that workers wasted in the transaction between work area and rest area. In this condition the optimal work duration become longer compare with the $M=\$0$ condition. In the third condition $M=\$0.5/\text{person}$ for each break. This cost represents the scenario that a machine operator turns off a machine or shuts down a conveyor belt, the cost associate with the machine tear-and-wear, could generate a much higher cost. In this $M=\$0.5/\text{person}$ condition we can observe the highest optimal work durations which means that our work-rest model tried to increase work duration in each cycle and reduce the number of breaks. Finally we have also tested the effect of different salary level. Table 18 shows that with the increase of worker's wage the optimal work duration slightly increased, but recovery duration decreased (which generated a higher HR and MF recovery target), these changes generated a decreased total time which has a direct impact on the total wage cost.

Model input				Model output					
W	M	a	b	T	T _r	R _{thr}	R _{tmf}	Total Time	C _{total}
0.1	0	5.00E-06	3.45E-04	0.6	1.0	14	12	133.3	25.8
0.1	0	1.00E-05	6.90E-04	0.6	1.4	11	9	166.7	36.9
0.1	0	1.50E-05	1.04E-03	0.6	1.7	10	7	191.7	46.5
0.1	0.05	5.00E-06	3.45E-04	1.2	2.0	11	10	133.3	28.8
0.1	0.05	1.00E-05	6.90E-04	0.9	2.0	10	8	161.1	40.7
0.1	0.05	1.50E-05	1.04E-03	0.7	2.0	9	7	192.9	50.6
0.1	0.5	5.00E-06	3.45E-04	2.9	4.2	6	7	122.4	39.6
0.1	0.5	1.00E-05	6.90E-04	2.1	4.2	6	6	150.0	55.6
0.1	0.5	1.50E-05	1.04E-03	1.7	4.1	5	5	170.6	68.8
0.2	0	5.00E-06	3.45E-04	0.6	0.7	18	16	108.3	37.9
0.2	0	1.00E-05	6.90E-04	0.6	1.0	14	12	133.3	51.7
0.2	0	1.50E-05	1.04E-03	0.6	1.2	13	10	150.0	63.3
0.2	0.05	5.00E-06	3.45E-04	1.3	1.5	15	14	107.7	40.7
0.2	0.05	1.00E-05	6.90E-04	0.9	1.5	13	11	133.3	55.2
0.2	0.05	1.50E-05	1.04E-03	0.8	1.6	12	9	150.0	67.3
0.2	0.5	5.00E-06	3.45E-04	3.0	3.3	9	11	105.0	50.8
0.2	0.5	1.00E-05	6.90E-04	2.2	3.3	8	9	125.0	69.2
0.2	0.5	1.50E-05	1.04E-03	1.8	3.3	8	7	141.7	84.2
0.3	0	5.00E-06	3.45E-04	0.6	0.6	19	18	100.0	48.4
0.3	0	1.00E-05	6.90E-04	0.6	0.8	16	14	116.7	64.3
0.3	0	1.50E-05	1.04E-03	0.6	1.0	14	12	133.3	77.5
0.3	0.05	5.00E-06	3.45E-04	1.4	1.4	16	16	100.0	51.1
0.3	0.05	1.00E-05	6.90E-04	1.0	1.4	14	13	120.0	67.7
0.3	0.05	1.50E-05	1.04E-03	0.8	1.3	13	11	131.3	81.4
0.3	0.5	5.00E-06	3.45E-04	3.1	2.9	11	13	96.8	60.8
0.3	0.5	1.00E-05	6.90E-04	2.3	2.9	10	10	113.0	81.1
0.3	0.5	1.50E-05	1.04E-03	1.9	2.9	9	9	126.3	97.6

Table 18: Changes of optimal work duration “T”, recovery duration “T_r”, heart rate recovery target “R_t”, total job finishing time and total cost “C_{total}” with different setup cost “M”, holding cost parameter “b” and wage cost “W”.

CHAPTER 8. DISCUSSION

8.1 Achievement

The results of the current study have shown that modeling the development and recovery of muscle fatigue during a physical work task using some basic inventory control theory modeling techniques is appropriate. In the current study, the changes of three physiological variables: trunk sway speed (a measure of whole body stability), EMG median frequency (a measure of local muscle fatigue) and heart rate (a measure of cardiovascular exertion level) during the performance of two typical low back muscle fatiguing tasks (static weight holding and dynamic weight lifting) were modeled. Two experiments with four participants each were conducted. Experiment I was dedicated to generate a series of regression equations for tracking the changes in physiological variables during the performance and recovery of fatiguing exertions. Results from Experiment I demonstrated that most of the development and recovery curve followed non-linear relationship with time. This is expected from our understanding of muscle physiology and cardiovascular functions. Previous research has demonstrated that the increase of postural sway introduced by low back muscle fatigue gradually recover in a non-linear curve during the time of resting (Davidson et al., 2004). An exponential time dependence model has been used to fit the recovery profile of EMG median frequency during the recovery of low back muscle fatigue (Elfving et al., 2002). Similar profile was also found in the recovery of heart rate, researchers reported exponential heart rate recovery curve after exercise (Bosquet et al., 2008). These results are all in-line with our observations in the current study.

Experiment II was conducted to test the validity of these equations by using different participants and performing three different categories (including “Moderate two-work-rest-cycle”, “Moderate four-work-rest-cycle” and “Hard two-work-rest-cycle” protocols) of task protocols. Results from Experiment II (as shown in Table 14) demonstrated that HR preformed best in predicting the development and recovery of HR. It had the lowest mean MAPE value (5.5%) among all three physiological variables, which means that the predicted values from the regression equations were on average only 5.5% different from the actual HR measurement. MF had a higher MAPE value (11.7%) than HR and SS had the highest MAPE value (15.0%) among all three variables.

Comparing the MAPE values between different categories of tasks we can see that the “Moderate two-work-rest-cycle” trials and the “Moderate four-work-rest-cycle” trials have very close average MAPE values, whereas in the “Hard two-work-rest-cycle” trials these values were slightly higher. This is very understandable, we can imagine that our regression equations should have a near zero MAPE value when predicting a protocol where no exertion tasks were performed (then the physiological variables should all be assumed to stay at the resting level) on the other hand when performing intensive physical exertion tasks the physiological responses will be exaggerated and more variance will be introduced which may cause a higher degree of disagreement (higher MAPE value). In addition one reason for HR and MF being the two better-performer is that HR and MF are two objective measures which are not affected by individual’s will, whereas SS is a “semi-objective” measure which means that it is not only affected by low back muscle fatigue but also subjective factors (such as

participants' willingness to cooperate, the degree of focus utilized, etc.). With this consideration only MF and HR were selected to be involved in the modeling.

The modeling technique of Economic Production Lot (EPL) model from inventory management was adapted to create the new work-rest model. All variables involved in the EPL model were redefined (as shown in Table 6). The production rate and demand rate were translated to the changes in physiological variables during the development and recovery of muscle fatigue. The "Unit production cost" was not included in the new model, but a new variable "workers' wage cost" was included in our work-rest model. "setup cost" was modeled as the cost to initiate each recovery section; "holding cost" represents the estimated potential injury cost for maintaining a certain level of physiological stress (in current study these stresses were represented as MF and HR); finally "Lot size" was translated to the upper and lower limit of muscle fatigue level (the stress target S_t and recovery target R_t in terms of SS, MF and HR as defined in the modeling section). Each set of "upper and lower limit of muscle fatigue level" would also correspond to a specific task performance time and resting time (a work-rest schedule) which is the decision variable that we want to obtain based on the other parameters described above. With the assistant of the current model an ergonomist can easily setup a work-rest schedule by using the optimal working duration "T" and recovery duration " T_r ". Alternatively he/she can also use the corresponding stress target S_t and recovery target R_t as the indicator for starting a resting section or a physical exertion respectively.

The sensitivity analysis in all three models (HR model, MF model and the combined model) indicated that when wage cost and setup cost are keep unchanged, the optimal work duration and stress (in terms of HR and/or MF) recovery target both decrease with the increase of holding cost parameter “a”, which means that the model algorithm tried to reduce the level of stress in order to reduce the holding cost. For the setup cost “M” when there is no penalty for taking multiple breaks (M=0) the optimal task duration reaches to the lowest level. With the increase of setup cost “M” the optimal work durations become longer in order to reduce the number of breaks which in turn reduce the total setup costs. Finally the increase of worker’s wage will slightly increase the optimal work duration, but significantly reduce the recovery duration (which generated a higher stress recovery target “ R_t ”), these changes generated a decreased total time which reduces total wage cost. From Table 16, 17 and 18 we can observe that the work-rest model was “smart” enough to select different strategies responding to the dynamic changes of all three cost factors.

In the traditional EOQ and EPL models both the production and consumption have fixed rate of change (linearly related with time) however in our current work-rest model the physiological variables do not change linearly. As shown in the Methods section, much effort has been dedicated to finding good non-linear response curves for all three physiological variables during both the task performance and recovery. These non-linear responses made the simple optimization methods used in the traditional models not applicable to our new model. A much more sophisticated modeling technique has been developed (as shown in the MODELING section) to fit the requirements of our new model. One unique component of our new work-rest model is that we were able to value the potential risk of holding high level

of physiological variables (HR, MF) on a monetary base. The benefit of this approach is that we were able to combine all the costs (holding cost for potential risk of injury, wage cost, setup cost...) under the same unit (\$/person). This is also one of the most critical components of current model, without this approach the optimization procedure would not be able to work.

As we have demonstrated in the MODELING section, similar to the idea that keeping product in the warehouse (inventory) will generate a holding cost, keeping certain level of physiological stress would increase the risk of injury and in turn generate a “holding cost”. In each work-rest cycle the holding cost is calculated as the total area under the “Increase of heart rate” or “Change in median frequency” profile and multiplies by a cost factor “h”. In the traditional EPL model “h” is a constant value (does not change with the level of inventory) with an unit of dollar per item per year, however in our model, the holding cost factor for HR changes in quadratic function with the amount of increase of HR, namely $h = a \times y^2$ where “y” is the amount of HR increase from resting level and “a” is a constant parameter that determines the magnitude of cost factor. The reason we have selected a quadratic function is based on the consideration that moderate increase in heart rate during short amount of time would not be harmful to human health (e.g. regular exercise), the increase in HR become harmful only when keeping high level of heart rate for a relatively long period of time. So when we define the holding cost factor for HR we wanted it to reflect low rate of cost at beginning of the heart rate increase and increase significantly when the HR level reaches to higher level. After the format of the function was defined the next step was to find the value of parameter “a” which has a direct impact on the magnitude of the cost. As shown in the

MODELING section we were able to find the cost for keeping certain amount of HR through a study of marathon runners. By connecting marathon runners' rate of sudden cardiac death, the average heart rate and duration of their exercise and the general cost of human life we were able to calculate the value of "a" (detailed calculations are showing in Equation 6 and 7). The holding cost function for MF was developed in a similar fashion. A linear correlation was assumed between the holding cost rate and the changes in MF namely $h=b \times y$ where "y" is the amount of MF decrease (a positive value) from resting level and "b" is a constant parameter that determines the magnitude of the holding cost rate. This linear function was selected because previous researchers have found a linear correlation between the change in MF and change in Borg scale (which reflect reporter's subjective perception of the hardship of the task) during the performance of low back fatiguing tasks (Dedering et al 1999; Kankaanpaa et al 1997). Similar to what we did in finding the holding cost parameter "a" for HR, the holding cost parameter "b" for MF was calculated by finding a relationship between the work related LBP incident rate among geriatric nurses, the change in MF these nurses experienced during their daily shift and the average cost of each LBP case (detailed calculations are shown in Equation 8 and 9).

The current work expands on previous studies in a number of ways. First, previous risk assessment models were not able to provide delicate measurement of cumulative work stresses especially within a short duration of task performance (in minutes). Second, to represent the level of risk, most of the previous risk assessment models were developed using arbitrarily defined variables such the Job Severity Index (JSI) (Liles et al., 1984) and lifting index (Waters et al., 1993) or coding systems that were used in the OWAS model (Karhu et

al., 1977) and PATH model (Buchholz et al., 1996). These risk assessment tools are great for evaluating the risk level of certain tasks; however it is very difficult for these tools to demonstrate the dynamic changes of physiological stress. In current study we were able to connect the physiological stresses (SS, HR and MF) directly to the risk of injury and predict the accumulation of these stresses with relatively high accuracy (especially for HR and MF as shown in the model validation section). In the history of work-rest modeling, operations research methodologies (optimization) have been used to create work-rest model. However none of the previous work-rest models was able to precisely model the work stress. For instance one model developed by Bechtold and colleagues in 1984 (Bechtold et al., 1984) used an optimization approach with the objective of maximizing labor productivity. This model utilized a mixed-integer quadratic programming formulation to decide the optimal scheduling. However, in this model the type of work was not specified; the overall work stress included physical stress and mental stress and/or any other stress factors that would reduce the productivity. The impact of work exposure on productivity uniformly considered as “work decay”. A resting time was considered to provide recovery to the work decay and also the productivity. In this model, productivity (not the actual work stress) was modeled in a circular fashion (decrease during work and recover during rest) the rates of decreasing work productivity and its recovery are assumed to be linearly related with exposure time. A recent review on work-rest models stated that the existing operation research oriented work-rest modeling literature lacks a sense of realism (Lodree et al., 2009). The author concluded that “nonlinear and time varying decay and recovery rates” and “the introduction of more realistic representations of work rate decay and recovery...is likely to result in further performance improvements in practice.” In the current study, our new work-rest model have both provided

a realistic methodology for tracking the physiological changes during task performance and also a sound theoretical model that is able to generate reliable optimal work-rest schedule solutions.

As we have demonstrated in the modeling section the traditional inventory control model provided theoretical foundation for the new work-rest model. In the traditional EOQ and EPL model one product was modeled at each time. In production management if multiple products need to be model at the same time each can be modeled independently. However in the current work-rest scheduling model we are trying to calculate the cost of potential risk of injury (holding cost) by evaluating the level of physiological stresses. In some tasks there might be a dominant risk factor. For example one task may only generate significant increase in heart rate but not severe muscle fatigue or any other additional risk. In this case our work-rest model could only focus on evaluating the holding cost generated by HR (as shown in the first model in the modeling section). However in other cases the task may generate both increase in HR and also significant muscle fatigue, then the potential risk for both LBP and cardiovascular dysfunction should both be considered (as shown in the third model in the modeling section). Our model has demonstrated its ability to handle both single risk factor analysis and also multi-risk factor analysis.

The same modeling technique can be easily applied to different work conditions and jobs. In current study, low back muscle fatigue tasks were investigated and SS, MF, and HR were selected as the stress variable to be modeled. The same technique can also be used to model other physical or mental stress factors as long as the development and recovery functions can

be obtained and the corresponding holding cost can be appropriately defined. At the same time there are also some challenges when applying this methodology to a real work site. In the current study, to be able to develop sufficient low back muscle fatigue the two fatiguing exertion tasks we have selected were very intense tasks leading to exhaustion in a short period of time. In most real world work settings, workers are performing much less intense tasks but over a long period of time. In addition, during the work shift workers often take “micro breaks” instead of constantly working. These factors will introduce much more variance in the development of physiological stress and will make the modeling of time-dependent physical stress a bit more difficult. In those cases, it may be the case that precise physical stress profiles are neither practical nor necessary; rather a “rough” estimation of the physiological stresses within a long period of time (eight hours) could be more appropriate. In addition our model assumed that the work-rest cycle is a memory-less process implying that the set of regression equations can always be applied no matter how many work-rest cycles have been performed. This assumption was also tested to be true in our model validation section. However, given the fact that the longest task performance protocols we have tested included only four work-rest cycles. It is possible that over 8 hours of work the cumulative effect of muscle fatigue may alter the development and recovery profiles of physiological variables.

8.2 Limitations

There are several limitations that limit the generalizability of this work-rest model. First of all, as we have demonstrated in the data collection section our summarized regression equations were precisely predicting the physiological stresses (in terms of SS, HR and MF) at

different stage of work cycle. However, the development and recovery of these physiological variables may not truly reflect the development and recovery of physical stress. For instance previous studies have demonstrated that full recovery of median frequency of an EMG signal does not necessarily transfer to full recovery of muscle strength and/or muscle endurance (Elfving et al., 2002). On the other hand, other studies have showed that the speed of this median frequency drop may increase after several episodes of muscle fatigue and recovery (Hui et al., 2001). All of these pieces of evidence indicate that there might be micro damages to the muscle tissues during the development of muscle fatigue and these damages may not be reflected in the muscle's EMG median frequency.

Another limitation is that to be able to use this model, there were a number of assumptions that have to be satisfied: 1. Assume there is a fixed duration of certain task to be performed. 2. Assume this task can be cut into infinite small sections (this task can be stopped at anytime). 3. Assume all work-rest cycles to be identical (in terms of HR and MF profile). 4. Assume this is a memoryless process, which means the regression equations can always be applied no matter how many work-rest cycles have been performed. Among these 4 assumptions the Assumption 3 and 4 are the most strictly applied, the Assumptions 1 and 2 can be loosened to a certain degree. For example, for Assumption 1, a worker can perform different tasks in one cycle, as long as the performance schedule are the same in all work cycles our work-rest model would still work. For Assumption 2, we can observe from Figure 36-38 that our optimal work schedule is located at a fairly flat and smooth area on the solution curve which means that the total cost are quite stable in the neighborhood of our optimal choice. If one job has a restricted task duration or limited numbers of resting period, our model can still find a

sub-optimal schedule that would work for this particular job. If this job only has several work-rest duration options, our model can also test which one is the best.

The current model only modeled two specific low back fatiguing tasks (static weight holding and dynamic intermittent weight lifting), the regression equations that summarized in current study are only valid for these two specific tasks but do not apply to other tasks. One of the challenges for the future application of this model is that before modeling a job one has to evaluate the tasks and have a good understanding of the work stress development and recovery profile.

In this study the holding cost parameters (input variable “a” and “b” in the model) were estimated by connecting physiological stresses (in terms of HR and MF), occurrence rate of injury and the average cost of the injury (or death), however current estimation methods may not be the only way to model these parameters. In reality the holding cost may change based on the specific tasks workers perform, personal characters (health condition, fatigue tolerance, injury history...) of the worker and other factors. There are many other ways to calculate holding cost, more efforts are still needed in this perspective.

Finally, in the current model only the risk of low back pain (caused by muscle fatigue) and cardiovascular stress were considered. The stability indicator “SS” was not further investigated in the modeling section because it was shown to have a higher variability compared with the other two (HR and MF) variables. In term of model prediction our summarized regression equations performed well in predicting the changes of all three

physiological variables (results of MAPE values are showing in Table 14) however SS was the worst among these three. Also compared with HR and MF, SS is “semi-subjective” measure; its output not only depending on the level or muscle fatigue but also depending on human performance, environment influence and so on. Other injury risks were not considered in the current model (such as noise, vibration, neck and shoulder problems...); however the same modeling technique may hold promise to be applied in modeling other factors.

8.3 Future work

In the future, in order to build a comprehensive work-rest model that is able to analyze different kinds of jobs and tasks, a database of regression equations must be developed; these regression equations should have the ability to track the development and recovery of physiological stresses during the task performance and resting. One possible way of obtaining this information is to divide different tasks into a number of task categories and generalize one format of regression equations to each particular category. Then the parameters involved in the equation would change depending on different factors that define the particular job. For example, the HR development profile during weight lifting can have a general function such as $HR = a \times t^b$ where “a” and “b” are parameters that could be determined by investigating the requirement of the lifting (e.g. weight of the load, lifting frequency...).

In current study three physiological variables (SS, HR and MF) were investigated. Each variable represents one different kind of factor that may be influenced by the development of low back muscle fatigue. Sway speed demonstrates the level of spinal stability, heart rate

presents the cardiovascular stress and median frequency indicates the muscle fatigue level which is related to the risk of developing low back pain. Two of these three variables namely HR and MF were further used to develop the work-rest model. Future research may investigate other risk factors that involved in the working environment (e.g. vibration, noise control...). This modeling technique can be applied in the investigation of a variety of different risks. To be able to model other risk factors it is critical to investigate their corresponding holding cost parameter. In the current study we were able to find evidence that link the physiological variables (HR and MF) to the prevalence of injury (or death) and the average cost. Similar approaches can be also adapted in the investigation of other variables.

CHAPTER 9. CONCLUSION

Work stresses developed during an eight-hour workday have the potential for causing low back injury and cardiovascular stress. A work-rest scheduling model that is able to predict the physiological changes of human body and generate optimal work-rest schedules was the goal of the current research. In the current study two types of low back muscle fatiguing tasks were considered. Regression equations predicting heart rate and drop in median frequency of the EMG signal of the erector spinae muscles were generated and tested. A modeling technique adapted from inventory management literature employed these regression equations along with the cost of work stress (holding cost) with other direct monetary costs (wage costs, setup costs). This modeling technique was able to generate an optimal work-rest scheduling solution by minimizing total cost. Sensitivity analysis demonstrated the model outputs (the optimal work-rest schedule) have clear and reasonable interactions with the dynamic changes of all cost factors. Future applications of this modeling approach are not limited to modeling low back muscle fatiguing tasks. This new work-rest model has great practicality in real work conditions, it is very flexible in terms of model inputs and is easy to customize based on user's specific needs. It is hoped that this model will soon gain attention in the academia and industry and be utilized to reduce the workplace injury and benefit the business owners at the same time.

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APPENDIX: INFORMED CONSENT DOCUMENT

Title of Study: Changes in human performance due to low back muscle fatigue

Investigators: Xiaopeng Ning, Gary Mirka

This is a research study. Please take your time deciding if you would like to participate. Please feel free to ask questions at any time.

INTRODUCTION

The purpose of this study is to explore changes in human performance due to low back muscle fatigue (under two different types of fatiguing tasks: weight holding and weight lifting) and its recovery. You are invited to participate in this study because you are a healthy individual, between the ages of 18 and 34 years old and have no history of chronic or current lower back, hip or upper/lower extremity injuries.

DESCRIPTION OF PROCEDURES

Tasks performed in this experiment include fatiguing protocols and measurement protocols. There are two types of fatiguing protocols: weight holding protocol and weight lifting protocol. In a weight holding protocol you will be asked to hold a 45 deg forward trunk flexion posture for up to 4 minutes. In a weight lifting protocol you will perform lifting a 35-lb crate from ground level to about knuckle height and lowering it down to the ground at a rate of one lift every 8 seconds for up to 3 minutes. There are also two measurement protocols: the first measurement protocol requires you to maintain a 45 deg forward trunk flexion posture with additional instructions of closing eyes and restricting trunk movement for 6 seconds. In the second measurement protocol 20lbs more weight will be put on shoulder and a 45 deg forward trunk flexion posture will be maintained for 6 seconds.

This experiment will be divided into two sections. In section one, you will be required to perform 4 minutes of weight holding protocol and 3 minutes of weight lifting protocol in different days. Measurement protocols will be performed during the fatiguing protocol and recovery section. In section two, you will perform two sequences of tasks each includes four consecutive “fatiguing protocol + resting” tasks (e.g. 3min of weight lifting + 5min of resting + 2min of weight holding + 10min of resting + 4min of weight holding + 4min resting + 1min of weight lifting + 8min of resting)

all of the fatiguing protocols and resting periods will be pre-selected from a pool of tasks (Including different durations of weight holding task, weight lifting task and resting). Two sequences of tasks will be performed at least 5 days apart to ensure a full recovery from muscle fatigue.

If you agree to participate in this study, we will first collect some anthropometric measurements of your body (including whole body height and weight, trunk width and depth at navel level) and then put some sensors (EMG electrodes and heart rate monitor) on your skin. We will ask you to stand on a wood platform with your waist secured by a nylon belt and then perform designated task protocols. The detail of the tasks will be explained to you prior to the task performance. During the data collection you can stop the experiment at any time if you experience excessive amount of fatigue or just feel uncomfortable. Upon completion heart rate monitor and EMG surface electrodes will be removed and you will be free to go. The total time for each data collection is anticipated to be less than 40 minutes.

RISKS

While participating in this study you may be exposed to certain risks of injury. Participants may experience minor skin irritation from the attached sensors. There is a potential risk for lower back injuries as well as some muscle or joint discomfort while performing the weight lifting task. To help reduce the risk of these activities you will be required to complete a warm up session before these experimental tasks. Also, investigators will teach you the proper method to complete each lifting technique and will allow you time to practice each. You should not participate in this study if you have a history of chronic low back pain or chronic injury to the upper/lower extremity or if you are currently experiencing problems/discomfort/pain in these regions.

Please initial here to indicate that you do not have a chronic or current pain/injury in the low back or lower extremities _____.

BENEFITS

If you decide to participate in this study there may be no direct benefit to you. It is hoped that the information gained in this study will benefit society by providing a new risk assessment and work-rest scheduling model that may benefit industrial workers by reducing their risk of injury.

ALTERNATIVES TO PARTICIPATION

The only alternative is to not participate in this study

COSTS AND COMPENSATION

You will receive an Ergonomics Lab t-shirt for participating in this study.

PARTICIPANT RIGHTS

Your participation in this study is voluntary and you may refuse to participate or leave the study at any time. If you decide to not 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.

CONFIDENTIALITY

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, 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 your 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. The biomechanical analysis is numerical and does not contain video that could identify the participant. Your data will be kept confidential by using alphanumeric identifiers that are unrelated to your name. Your name and information/data will be kept in separate locations. Your informed consent document will be kept in a locked file cabinet. The research team will keep private all research records that identify you to the extent allowed by law. When the results of the study are reported, the combined information that has been gathered will be presented. If the results are published, your identity will remain confidential.

QUESTIONS OR PROBLEMS

You are encouraged to ask questions at any time during this study.

- For further information about the study contact Xiaopeng Ning at 5155201951 or Gary Mirka at 5152941309
- 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.

PARTICIPANT SIGNATURE

Your signature indicates that you voluntarily agree to participate in this study, that the study has been explained to you, that you have been given the time to read the document and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant's Name (Printed): _____

(Participant's Signature)

(Date)

INVESTIGATOR SIGNATURE

I certify that the participant has been given adequate time to read and learn about the study and all of their questions have been answered. It is my opinion that the participant understands the purpose, risks, benefits and the procedures that will be followed in this study and has voluntarily agreed to participate.

(Signature of Person Obtaining
Informed Consent)

(Date)

BIOGRAPHY

Xiaopeng Ning was born in Beijing, China in 1983. He received the Bachelor of Science in Electronics Engineering from Beijing Institute of Technology in 2005. After graduation Xiaopeng worked for China Great Wall Computer Group as an IT consultant for one year. In the year of 2006 he came to the United States and started his Master of Science degree in Agricultural Engineering at Iowa State University. In 2008, after receiving his M.S. degree Xiaopeng stayed at ISU and joined the department of Industrial and Manufacturing Systems Engineering to pursue his Ph.D degree in the study of ergonomics and spine biomechanics under the guidance of Dr. Gary Mirka. On December 29th 2010 Xiaopeng married his lovely wife Chunyan who is from Nanjing, China. Toward the end of his Ph.D study Xiaopeng gained employment as an assistant professor at West Virginia University.

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