Developing a Method Based on EMG to Assess Muscle Fatigue during Manual Lifting in a Simulated Laboratory Environment

by

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Développement d'une technique analytique basée sur l'électromyographie pour l'évaluation de la fatigue musculaire durant des tâches de levage manuel dans un environnement de laboratoire simulé

Faezeh SEHATI

RÉSUMÉ

La fatigue musculaire est considérée comme un problème à haut risque de blessures au dos entraînant des troubles musculosquelettiques (TMS) et des douleurs chroniques au bas du dos. Le but de la recherche actuelle est d'analyser les données électromyographiques de surface (sEMG) de huit muscles du dos durant les tâches répétitives de levage manuelle à quatre niveaux de hauteur induisant une fatigue musculaire.

On a demandé à quatre sujets en bonne santé de soulever et de déposer 24 boîtes de 10 kg pendant près de 16 minutes dans un environnement de laboratoire simulé afin d'évaluer la fatigue musculaire Les données EMG pour dix muscles ont été collectées et coupées à chaque cycle (portance plus dépôt) par le magnétomètre et évaluées à l'aide d'une procédure d'analyse temps-fréquence (STFT) pour extraire le calcul des fréquences moyennes et médianes.

La fréquence médiane et moyenne (MDF / MNF) et la racine carrée moyenne (RMS) ont été mesurées et utilisées pour analyser les changements du signal EMG de tous les muscles testés pour quatre hauteurs différentes. Les résultats ont montré que le MDF / MNF diminue et le RMS augmente en signe de facteur de fatigue musculaire. Les résultats de cette expérience ont révélé que le plus grand taux de fatigue musculaire était démontré par les muscles deltoïdes postérieurs par rapport aux autres muscles. Sur la base des résultats, pendant toute la tâche de levage manuel, la hauteur 2 et la hauteur 1 (au niveau du sol) ont présenté le plus grand nombre de répétitions de fatigue par rapport à toutes les autres hauteurs. Il est évident d'après les résultats que divers muscles avaient leur propre schéma de fatigue unique entre les quatre hauteurs différentes et on peut s'attendre à ce que la fatigue se produise environ 6 à 14 minutes de toute l'expérience.

Cette recherche serait également importante car elle permettra aux employés de l'entrepôt de construire une structure pour une configuration correcte des boîtes à des hauteurs acceptables pour éviter la fatigue musculaire et éventuellement réduire les TMS ou les douleurs lombaires.

Mots-clés: fatigue musculaire, sEMG, levage manuel en laboratoire simulé, fréquence moyenne / médiane, carré moyen et différentes hauteurs

Development of an analytical technique based on EMG to assess muscle fatigue during manual lifting in a simulated laboratory environment

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ABSTRACT

Muscle fatigue has been recognized and considered as a high-risk issue for back pain injuries resulting in MSDs and chronic lower back pain. The aim of current research was to investigate differences in surface electromyography (EMG) data of ten back muscles performing a manual lifting task inducing muscle fatigue with respect to four different heights.

Four healthy subjects were asked to lift and deposit twenty-four 10-kg boxes for almost 16 minutes in a simulated laboratory environment in order to assess muscle fatigue. EMG data for ten muscles was collected and cut off for each cycle (lift plus deposit) by the magnetometer and evaluated using a time-frequency analysis procedure (STFT) for extracting the mean and median frequency calculation.

Median and mean frequency (MDF/MNF), and root mean square (RMS) were measured and used to analyze the changes in the EMG signal of all the tested muscles for four different heights. The results showed that MDF/MNF decreases and RMS increases as a sign of muscle fatigue factor. The results obtained from this experiment revealed that the greatest rate of muscle fatigue was demonstrated by the posterior deltoid muscles compared to the other muscles. Based on the results, during the entire manual lifting task, height 2 and height 1 (at ground level) presented the highest number of fatigue repetitions compared to all other heights. It is evident from the findings that various muscles had their own unique fatigue pattern between the four different heights, and it can be expected that fatigue occurs from approximately 6 to 14 minutes of entire experiment.

This research is also important because it will enable warehouse employees to build a structure for proper box setup at acceptable heights to avoid muscle fatigue and eventually reduce.

Keywords: Muscle fatigue, sEMG, manual lifting in simulated laboratory, mean/median frequency, root mean square and different heights

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LIST OF ABREVIATIONS

CNSST	Commission des normes, de l'équité, de la santé et de la sécurité du travail
CRCHUM	Centre de Recherche du CHUM
DTS	Desktop Direct Transmission System
EMG	ElectroMyoGraphy
ES	Erector Spinae
ESL	Erector Spinae Left
ESR	Erector Spinae Right
ÉTS	École de Technologie Supérieure
FD	Frequency Distribution
FFT	Fast Fourier Transform
IEMG	Integrated EMG
LT	Lower Trapezius
LTL	Lower Trapezius Left
LTR	Lower Trapezius Right
MAV	Mean Absolute Value
MDF	Median Frequency
MMG	MechanoMyoGraphy
MNF	Mean Frequency
MSDs	MusculoSkeletal Disorders
MT	Middle Trapezius
MTL	Middle Trapezius Left

MTR	Middle Trapezius Right
NIOSH	National Institute for Occupational Safety and Health
NIRS	Near InfraRed Spectroscopy
OHS	Occupational Health and Safety
PD	Posterior Deltoid
PDL	Posterior Deltoid Left
PDR	Posterior Deltoid Right
PKF	Peak Frequency
PSD	Power Spectral Density
RMS	Root Mean Square
SC	Slope Coefficient
SENIAM	Surface EMG for Non-Invasive Assessment of Muscles
SMG	SonoMyoGraphy
STFT	Short Time Fourier Transform
TD	Time Distribution
TFD	Time-frequency Distribution
TTP	Total Power
UT	Upper Trapezius
UTL	Upper Trapezius Left
UTR	Upper Trapezius Right

INTRODUCTION

In Quebec, data from the Commission des normes, de l'équité, de la santé et de la sécurité du travail (CNESST) reveal that back injuries have frequently been observed in the warehousing and manufacturing activities that involves handling, picking, moving, and lifting boxes (St-Vincent, et al., 2005). Moreover, in the U.S.A., based on Bureau of Labor Statistics 2014, musculoskeletal disorders have been responding to 32% of all reported occupational injuries in 2014. In these cases of injury, stock and material handlers have been recorded as the most common sufferers. Manual lifting is one of the common practices for handling or moving objects to various locations within industries. In the manufacturing industry, the manual lifting task is related to multiple risk factors for the employee and therefore, increased long-term work-related absences occur due to sickness (Andersen, et al., 2016; Lund, et al., 2006), early retirement (Van den Berg, et al., 2010) and disability salary (Ropponen, et al., 2014).

Even though robotics and high-tech equipment like forklift trucks, pallet trucks, lifting gear, cranes and conveyors are commonly available nowadays, manual lifting is still considered as a frequent technique to perform material handling tasks. Manual lifting tasks leading to Musculoskeletal Disorders (MSDs) have been recognized for a period of time as one of the principal work-related injuries that affects the personal satisfaction of workers all over the world (Eatough, et al., 2012). Manual handling is known to be a contributor to occupational musculoskeletal disorders and the prevalence of this disorder can be categorized as one of the significant health problems that are associated with work requiring manual handling (Balasubramanian, et al., 2018; Punnett, & Wegman, 2004), especially in the transportation and warehousing sectors which necessitate more than twofold the average in the industry. To date, several studies have stated that manual handling or lifting can lead to severe accidents and irreversible impacts on employees' health.

Common causes of MSDs in manual handling are due to improper lifting and muscle fatigue. Granata et al., (2004); Balasubramanian et al., (2018) indicated that the potential reason for lower back pain and MSDs has been attributed to muscular fatigue. However, according to

Anthony & Aghazadeh (2009), muscle fatigue can be associated with increasing the risk of low back pain and MSDs during a repetitive lifting task. Moreover, the existence of a remarkable level of muscle fatigue can lead to increasing the unsafe actions, human errors, incidence of accidents, work-related musculoskeletal disorders, and reduced productivity (Hallowell, 2010). A few experiments have examined how, in manufacturing industries, fatigue leads to human errors; their analysis showed a total of 48.8 percent of human errors happen because of muscle fatigue (Yeow, et al., 2014).

However, regarding the monitoring of muscle fatigue, researchers are still seeking to discover the best processing and analytical method to evaluate human musculoskeletal conditions. Hence, the assessment and evaluation of muscle fatigue in the warehousing and manufacturing environment remains a challenging problem, as this influences worker health and the productivity of the organization.

EMG is selected as the appropriate evaluation technique in our study as it is the most commonly used tool to assess muscle fatigue that has been well reported by many researchers (Hargrove, et al., 2007). Nowadays, current assessments for muscle fatigue monitoring during dynamic contractions are usually based on body sensor attachment such as surface electromyography (SEMG). Most of researches focuses on the use of EMG for analyzing fatigue in the workplace. Hence, this approach could be utilized in a wide range of different applications such as manual lifting tasks, which all derived from human efforts alone. To overcome MSDs and to avoid overexertion, the EMG signal will be used to monitor the muscular condition of the workers in order to find the number of repetitions that the workers are able to handle before experiencing fatigue. In addition, muscle fatigue assessment would be highly crucial in order to improve rehabilitation programs and to mitigate the risk of MSDs for manual workers in the manufacturing and the warehousing activities.

In this study, we aim to apply an analytical method based on EMG techniques in order to find the best way of assessing muscle fatigue during manual handling. To achieve this goal, time-frequency distribution (TFD) is used for fatigue monitoring in EMG techniques, in which the progression of obtaining a signal via EMG can be monitored in time and frequency (Shair, et al., 2017). Analyzing time-frequency distribution can help us to show the time once any variation happens in EMG frequency. Hence, considering both time and frequency together leads us to obtain higher accuracy compared with considering time or frequency distribution alone. Figure 1, shows the overall workflow of fatigue assessment based on EMG.

Despite the use of traditional methods such as time distribution and frequency distribution, time-frequency distribution is utilized for better monitoring since it enables the user to observe the progress of the signal in time and frequency simultaneously.

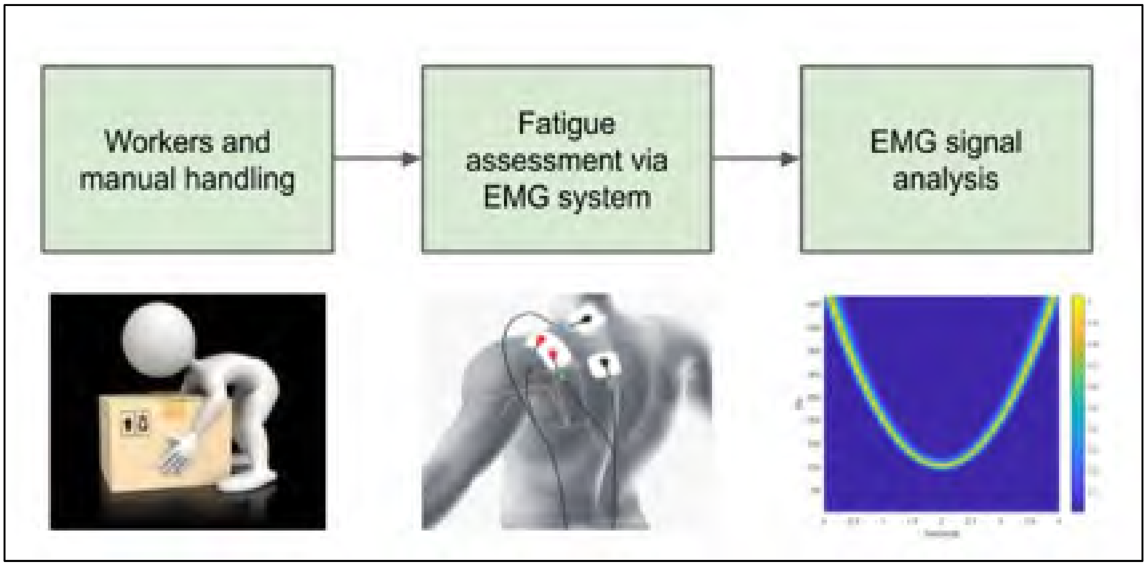


Figure 0.1 Schematic workflows of fatigue assessment

In spite of the fact that all manual lifting tasks are particularly dynamic, most of the time, mean or median frequency of isometric contractions has been analyzed only before and after a manual lifting task by previous researchers (Dolan, P., & Adams, M. A. 1998; Bonato, P., et al, 2002; Shin, H. J., & Kim, J. Y., 2007; Plamondon, et al, 2014). Furthermore, the effects of muscle fatigue are also measured regularly after completion of fatigue cycle, which results in restriction of our awareness of the muscle fatigue processes contributing to the presence of fatigue throughout the repetitive lifting task. According to the literature, up to the present, there are few studies assessing muscle fatigue by EMG signals during the repetitive lifting task to prove the existence and quantify muscle fatigue (Sundelin, 1992; Plamondon, et al, 2014; Spyropoulos, E., et al, 2015). Moreover, and most importantly, there is no research analyzing muscle fatigue by EMG signal throughout this lifting task with respect to different heights of handling boxes. Since we aim to assess muscle fatigue during manual handling to overcome MSDs, our study requires monitoring the muscular conditions of the workers and understanding how the back muscles respond to a powerful stimulus of fatigue arising from dynamic contractions through repetitive lifting tasks in different heights.

This thesis is divided in four chapters. Chapter 1 provides background information and a literature review of the existing methods by EMG signals for assessing muscle fatigue. The main aim of the first chapter is to point out the existing barriers and challenges in applying different methods of electromyography signal processing for muscle fatigue assessment.

The research methodology adopted in this thesis is discussed in Chapter 2. Formulating the research hypothesis and the objectives of this study are included in this chapter. Consequently, three objectives are defined.

Defining the approach and the required tools for addressing the three objectives of this thesis are the main goals of this chapter. All data analysis and results are described in Chapter 3. Finally, in Chapter 4, provides conclusion with a summary of study, limitations and future work.

CHAPTER 1

LITERATURE REVIEW

This review of the literature presents the manual handling/lifting, statistical profile of low back injuries in industry, repetitive lifting task, muscle fatigue, the relation between repetitive lifting task and muscle fatigue, muscle fatigue assessment, electromyography (EMG) signal, electromyography processing, Time Distribution (TD), Frequency Distribution (FD), Time-Frequency Distribution (TFD), Short Time Fourier Transform (STFT) and Mean/Median Frequency. Figure 1.1, shows the classification of the literature review in different categories.

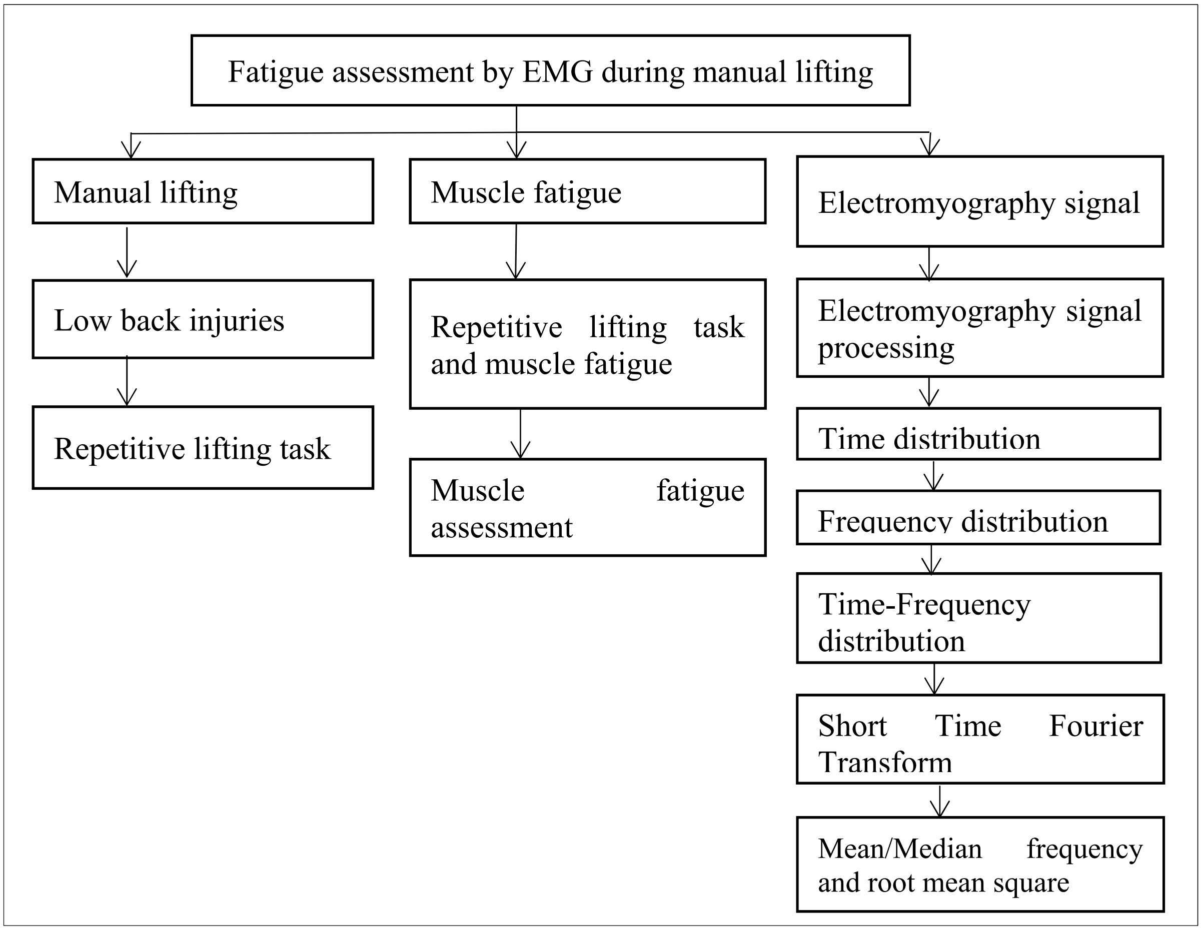


Figure 1.1 Classification of the literature review

1.1 Manual lifting

Even though machines are widely used in modern industries, these days there are still several tasks in industry that are carried out physically by humans. Manual handling is one of the preponderant manual activities in traditional and non-automated warehouses.

Manual handling is the most extensively utilized method. It commonly consists of dragging the object to the puller, lifting, carrying, lowering, and positioning with pushing (Taboun & Dutta, 1984; Murphy & Courtney, 2000). Manual handling, which includes transferring boxes, is accomplished during different steps such as pre-grip, pick-up, move/carry, and deposit (Drury, et al., 1982). It has, however, been identified that manual handling of an object is performed by a combination of lifting, carrying and lowering (Straker, et al., 1996).

Previous studies (McCormick, E. J., & Sanders, M. S., 1982; Murphy & Courtney, 2000; Ciriello, 2007) have shown that manual material handling is not only the most commonly reported, but also the costliest group of compensable loss at workplace. Based on the study of St-Vincent et al., 2005, on average, 74% of the work shift is performed by manual materials handling activities and the stockers carry out, on average, around two hundred handling operations per shift.

1.2 Statistical profile of low back injuries in industry

Manual handling is known to be a contributor to occupational Musculoskeletal Disorders (MSDs) accidents and the prevalence rate of MSDs associated with work in the transport and storage sector is more than twice the average of the industry. However, the Kraus et al, 1997 studies stated that by increasing handling operations demands with considering frequency and weight of merchandise, low-back injuries would increase. MSDs are known as a main cause of pain, suffering, and disability at the workplace. It has been estimated that more than 380,000 lost workday injuries have been assigned to work-related MSDs.

According to St-Vincent et al., 2005 & NIOSH (1997), one out of every three dollars goes toward MSDs to compensate workers. Moreover, it is estimated that $20 billion per year will be spent directly on MSDs compensation to workers with five times as much spent on indirect costs. Obviously, for U.S. industry, preventing work-related MSDs is an important priority. In the United Kingdom, more than 43 percent of all work-related diseases contributed to the overall amount of MSD reports in 2013/14 (Buckley, 2014). MSDs reported over 62 per cent of all work-related health issues in 2007 in the European storage and distribution market (European, 2009), with around 40% of confirmed cases of workplace diseases in warehouses in the US in 2014 (Ma, et al, 2018). The National Institute of Occupational Safety and Health in USA stated that large amounts of musculoskeletal disorders are reported annually in the United States for manual material handling activities. Different sources of data indicate that the currently expanding warehouse-superstore sector is a potentially hazardous sector due to its widespread handling activities, particularly for stockers and receivers. A warehouse superstore is a store where most of the merchandise is stored in the sales area. In Québec, data from the Commission des normes, de l'équité, de la santé et de la sécurité du travail (CNESST) reveal that back injuries have frequently been observed in warehouses.

Back in the U.S.A., based on Bureau of Labor Statistics 2014, musculoskeletal disorders have responded to thirty-two percent of all reported occupational injuries in 2014; in these injury cases stock and material handlers have been recorded as the most common sufferers. NIOSH (1997) revealed that the primary focus was placed on lower back injuries. In 2000, Shri Mathur, indicated that strains and sprains, fractures, as well as joint inflammation (mostly L4/L5 and L5/S1; sometimes other joints such as the shoulder and hip), dislocation (herniation) of the lumbar disc, laceration of muscle tissue, contusion, and nerve (sciatic) involvement were the types of back injuries often reported; they often lead to movement constraints and workplace accidents.

Regarding the relation between manual handling, of course, not only in North America, but also European countries have recorded cases of occupational diseases. Based on Eurostat, in

2009 the European transport and storage sector recorded more than sixty-two percent of all work-related health disease in 2007. Lidgren et al (2014) concluded that 100 million Europeans are exposed to MSDs.

1.3 Repetitive lifting task

Repetitive movement is a simple harmonic movement by moving back and forth positioned at the equilibrium or center point where the optimum displacement on one side is equivalent to the optimum displacement on the other side as well (Colombini, 2002). Repetitive movements are the most common risk in the workplace and nearly 62 percent are reported for that (Bernardo, 2017).

Most of the time, distribution center workers are required to perform manual handling or lifting boxes and act in repetitive movements (Kamat, et al, 2017). According to what warehouse workers say, they tend to feel fatigued halfway through their shift after moving boxes and inventory for the first half of their workday. Referring to this statement, Kamat et al (2017) expressed that, based on data collections like questionnaires, most workers have already experienced back pain and muscle fatigue-related pains when too many boxes need to be lifted.

1.4 Muscle fatigue

The term muscle fatigue refers to the transient decrease in the capacity to perform physical actions and the decrease in the maximal force or power (velocity of muscle contraction) that the involved muscles can produce.

Muscle fatigue might occur through repetitive and continuous work (De Luca, 1997). Some serious injuries are a result of undetected fatigue over time, which is unavoidable. Hence, the existence of an automated muscle fatigue detection mechanism might be deployed to decrease the risk of these injuries. In this regard, EMG signals are utilized through a specific muscle involved in a defined task in order to assess fatigue (Phinyomark, et al., 2012).

Muscle fatigue can be classified into three stages: first, non-fatigue (the fresh muscle can impose its maximum strength), second, shift to fatigue (only after the fresh muscle begins to fatigue, new muscle fibers are recruited) and third, fatigue (development of muscle fatigue throughout muscle contraction) (Al-Mulla, et al., 2011). Halim et al (2014) stated that the shift-to-fatigue phase can be prolonged by performing the appropriate working/rest time and monitoring the lifting parameters while conducting manual handling, consisting of any of the conditions for instance lift, hold, put down, push, pull and transfer a load.

According to the Hallowell (2010), a remarkable level of muscle fatigue can lead to loss of productivity, human errors, dangerous behavior, injury and work-related musculoskeletal problems and back pain.

1.4.1 Relation between repetitive lifting task and muscle fatigue

Granata et al (2004) showed that advancements in science indicate that a potential reason for lower back pain is known to be muscle fatigue. Due to muscle fatigue, the long-lasting degradation of the human operator’s performance occurs to produce force (Troiano, et al., 2008). Muscle fatigue is often created by repetitive or persistent work and occurs due to a chain of metabolic, structural and energy changes in the muscle, because of the lack of oxygen and nutrient substances that are transmitted through the bloodstream, also because of changes in efficiency of the nervous system (Cifrek, et al., 2009).

According to Plamondon, et al (2014) longissimus muscle right and left fatigue is assessed by median frequency (MDF) and root mean square (RMS). The percentages of median and RMS changes during entire lifting task for longissimus muscle right were decreased by 12% and increased by 23% respectively. For this muscle in the left side the percentages of changes were nearly 10% decrease in MED and 38% increase in RMS. However, these results verified that transferring multiple boxes in a simulated warehouse will lead to muscle fatigue.

1.4.2 Muscle fatigue assessment

Many characteristics of muscle fatigue have been highlighted by former researchers as the increase in amplitude and the shift from high to low frequencies (Merlo & Campanini, 2010). Different techniques are available to determine these muscle fatigue characteristics, depending on the utilization. Currently, although assessing muscle fatigue by means of intramuscular technique to assess muscle fatigue such as blood test which measures lactate level of blood and muscle biopsies that show muscle pH, provides greater precision than non-intramuscular methods. Based on Kamavuako et al., 2013, it is still unsuitable for certain fields like ergonomics, sports, and occupational therapy.

Compared to non-invasive methods that are sometimes difficult to utilize, applying several non-invasive techniques to gain muscle fatigue signals like electromyography (EMG) signals, mechanomyography (MMG), near-infrared spectroscopy (NIRS), and sonomyography (SMG) considered for research approaches can be more comfortable and more easily done (Smith & Hargrove, 2013). However, based on Hargrove, et al., (2007) and many studies that have been well reported, electromyography (EMG) signals are the most popular tool that is applied with the aim of assessing muscle fatigue during manual lifting.

1.5 Electromyography signal

Electromyography (EMG) is the measurement of the electrical signals generated by motor units as a result of a muscle contraction expressing neuromuscular action (Merlo & Campanini, 2010).

Electromyography (EMG) signal recording methods have been introduced as an intramuscular or invasive method which is essential to apply needles by inserting into the muscle under study to try to measure muscle EMG activity (Henneberg, 2000). Due to its features, the limitation of the diffusion because of the needle type electrode characteristic, it can potentially well-equip potential measurement for active muscle fibers and it is supposed this technique is a classic tool for examining the properties of motor units, especially clearly in the clinical examination (Troiano, et al., 2008). Despite the fact that the invasive method is an appropriate instrument for electromyography (EMG) signal analysis, in some cases, placing needles into the muscle is not desirable or easy to use, for instance, for examining some activities which require motion like sports or ergonomics (Troiano, et al., 2008).

Surface electromyography (sEMG) is a measure of the electrical potential present on the skin as a consequence of a muscle contraction. This voltage is detected by electrodes placed on the skin. Under certain limitations, when a proper protocol for electrode placement is used, the voltage measured on the skin can be related to the activity of a single specific muscle. The signal is represented as a trace that develops during time, increasing from zero up to tenths or hundreds of microvolts as the muscle becomes activated (Reaz, et al., 2006).

Even though the changes in sEMG readings will be directly associated with the functional condition of the measured muscles, it's essential to utilize sEMG for measuring muscle activity (Zhou, et al., 2011; Martins, et al., 2008). This technique has frequently been employed in measurement of muscle fatigue rates by measuring variables such as median frequency (Lomax et al., 2015; De Luca, 1997).

1.6 Electromyography (EMG) processing

In an especially useless form, raw EMG signal gives us useful information. This information is only valuable if the knowledge can be quantified. To obtain the exact and real EMG signal, different signal processing methods are implemented on raw EMG. This section provides a study of EMG signal processing by means of various methods (Reaz, et al., 2006).

1.6.1 Time distribution (TD)

Extraction of time domain fatigue indices in comparison with other methods is extremely simple and uncomplicated, and this technique does not implicate any transformation (Du &

Vuskovic, 2004). The time representation of the raw EMG can be achieved directly by performing some easy mathematical statistics. The conception of fatigue is closely linked with the amount and the rate of change of certain variables and muscle changes in prolonged contractions (Enoka & Duchateau, 2008). Former researches (Malinzak, et al., 2001; Suetta, et al., 2004; Plamondon, 2014) have explored multiple fatigue indices such as Integrated EMG (IEMG), Mean Absolute Value (MAV) and Root Mean Square (RMS) respectively, in the time domain base of Table 1.1. The analysis according to time domain is formerly well-established and has been broadly applied for the last decade.

The drawback of this time domain feature, which has an impact on the integrity of data, comes from non-stationary property of the EMG signal where the statistical properties alter over time, however time domain specification presumes the data as a stationary signal (Reaz, et al., 2006).

Some researchers applying time-distribution just concentrate on discovering new fatigue indices with more strength, while the majority of researchers apply time-frequency analysis which is considered to be more precise compared to time-distribution alone (Shair, et al., 2017).

Table 1.1 Fatigue indices in time domain

References	*Year*	*Fatigue indices*
Malinzak et al	2001	Integrated EMG (IEMG)
Suetta et al	2004	Mean absolute value (MAV)
Plamondon et al	2014	Root mean square (RMS)

1.6.2 Frequency distribution (FD)

In numerous studies of muscle fatigue, frequency domain features are most often utilized to exploit data from a signal. In the present period, more than 20 fatigue indices exist in the frequency domain, in which the mean frequency (MNF) and median frequency (MDF) are frequently used parameters (Georgakis, et al., 2003).

A few methods have been utilized to extricate data from EMG signals such as Fast Fourier Transform (FFT) and power spectral density (PSD).

In order to illustrate the signal in frequency domain, the EMG signal must undergo FFT. As pointed out by Shair, et al., 2017, the FFT concept in the form of the power spectrum is seen in the formula below where x (t) is the signal in time domain and T is time period:

$$Sx\,(\mathrm{f}) = \frac{1}{\mathrm{T}} \left| \int_{-\infty}^{\infty} x\,(t).\quad e^{-2\pi f t} dt \right| \tag{1.1}$$

In any case, the changes of the EMG frequency component is because of the adjustments in muscle force, length and contraction speed throughout time and provide challenges in the utilization of FFT and other traditional processing techniques. The basic limitation of an FFT is that it is unable to provide simultaneous time and frequency localization (Vitor-Costa, 2012). Using these techniques for examination of the EMG signal in dynamic contraction (i.e., repetitive lifting) may not be successful because the signal needs to be stationary. Table 1.2, listed a few fatigue indices in the frequency domain.

Table 1.2 Fatigue indices in frequency domain

References	*Year*	*Fatigue indices*
Thongpanja et al	2013	Mean frequency
Plamondon et al	2014	Median frequency
Khanam & Ahmad	2015	Peak frequency
Khanam & Ahmad	2015	Mean power
Khanam & Ahmad	2015	Total power

1.6.3 Time-Frequency Distribution (TFD)

A signal's time frequency representation transforms a single-dimensional signal into a two-dimensional of time and frequency. Time-frequency representation is broadly utilized in analyzing, improving and synthesizing non-stationary signals since both representations of time and frequency are taken into consideration, hence direct to higher accuracy compared to FFT (Wacker & Witte, 2013).

The most fundamental form of time-frequency distribution method is the Short Time Fourier Transform (STFT).

1.6.3.1 Short Time Fourier Transforms (STFT)

It is normal to divide the long signals into blocks of smaller fragments in order to resolve the disadvantages of time distribution and frequency distribution and fulfill the stationary condition (Karlsson, Yu, & Akay, 2000). This shortening would help us to evaluate the signals over the specific time-slice which can be considered as the stationary segments. With respect to basic idea and implementation of STFT, in most research, STFT is used to differentiate the pattern of muscle fatigue which makes this method very eligible and handy for the applications demanding simple analysis and desirable results (Shair, et al., 2017).

1.7 Evaluation parameters for muscle fatigue assessment

To date, there have been many fatigue indices in the domain frequency that have been widely used. Among all those techniques, some parameters such as root mean square (RMS), mean frequency (MNF), and median frequency (MDF) have been appointed as the gold standard to assess muscle fatigue along with EMG signals (Phinyomark, A., et al, 2012).

1.7.1 Root Mean Square (RMS)

The square root of the average power of each EMG signal over a given period of time is shown by RMS parameter. Since the amplitude of the signal is measured as a function of time, it can be considered as a time domain variable.

$$x_{\text{rms}} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} [f(t)]^2 \; dt} \tag{1.2}$$

where the integrals got over the distribution domain and also for f(t) as a function over the time interval [T_1 and T_2],

For muscle fatigue assessment, the changes of EMG signal of all selected muscles are evaluated by computing RMS values (Sundelin, 1992, Niu, H., 2008). In this study the RMS value is a representation of the signal in terms of power.

1.7.2 Mean Frequency (MNF)

According to the equation below, MNF is average frequency calculating the sum of product of the EMG power spectrum and the frequency divided by the total sum of the power spectrum (Oskoei & Hu, 2008; Phinyomark et al., 2012). Moreover, MNF is also known as mean power frequency and mean spectral frequency in some other research that have been done so far.

$$\text{MNF} = \frac{\sum_{i=1}^{M} Fi\, Pi}{\sum_{i=1}^{M} Pi} \tag{1.3}$$

where Fi represents frequency value of EMG power spectral at point *i*, and Pi represents power spectrum at the frequency of point *i* and *M* is the length of frequency bin.

Mean frequency (MNF) has been applied by MacIsaac et al. 2001 as fatigue indices and has concluded three significant outcomes. 1) It does not appear that the non-stationaries in EMG impact on MNF values derived by Fourier transform. 2) The effect of non-stationaries in dynamic compressions has effectively been midpoint by applying the STFT method to measure mean frequency. 3) The STFT is able to detect a downward trend with fatigue in dynamic contraction, so long as the motion spectrum remains constant over a continuous time interval (MacIsaac, et al., 2001).

1.7.3 Median Frequency

MDF (Median Frequency) is known as a frequency in which the EMG includes two equal parts and similar amplitude (e.g., Oskoei & Hu, 2008; Phinyomark et al., 2012). The definition of MDF is represented by:

$$\sum_{i=1}^{MDF} Pi = \sum_{i=MDF}^{M} Pi = \frac{1}{2} \sum_{i=1}^{M} Pi \tag{1.4}$$

where *Pj* is the EMG power spectral at point *j* and *MDF* is the number of frequency bin that *MDF* happens.

Both parameters MNF and MDF are types of average in statistics and there is no big difference between MNF and MDF in terms of their behavior; the only distinction is related to the performance of those parameters, in which the performance of MNF versus MDF might differ in any application.

Mean and median frequency parameters have been depicted on the typical diagram of power spectrum at Figure 1.2.

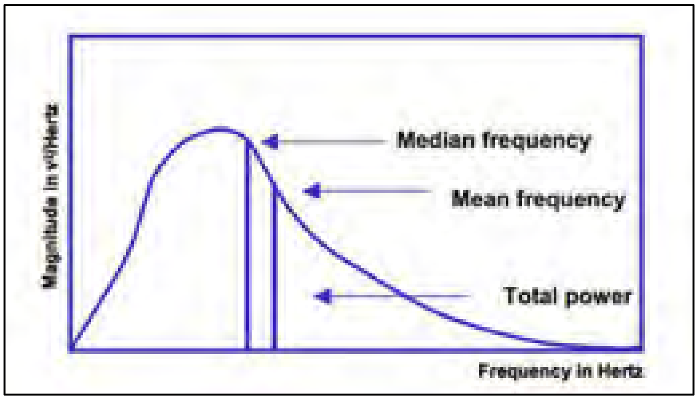


Figure 1.2 Standard frequency parameters derived from EMG relying on FFT calculations taken from Konard (2005)

Fatigue is presented while the frequency outputs are shifted to lower in the spectrum during the analysis of EMG signal (Winter, 1990). Figure 1.3 clearly shows these changes over time. Based on this Figure, it is easy to understand that muscle fatigue is happened when median frequency of the power spectral (Fatigue index) goes to the lower.

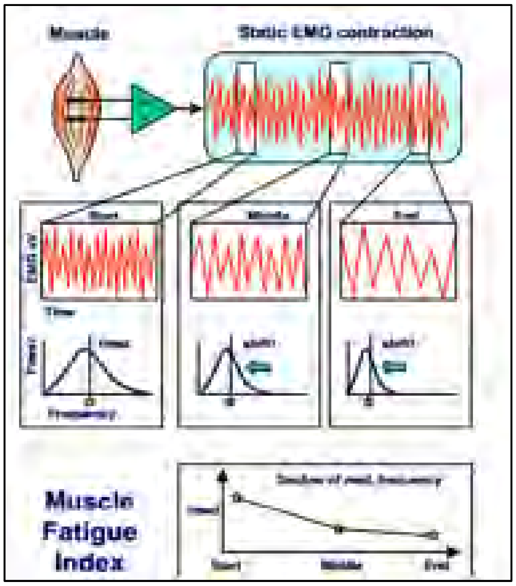


Figure 1.3 Schematic description of the frequency change in continuous contractions towards lower frequencies and estimation of the index of muscle fatigue taken from Konard (2005)

Researchers have analyzed the slope values of the MDF's. However, if a negative value is calculated in the slope of the MDF, this means that the muscle has fatigue for a certain period of time. This is the same if there is no incline or a positive slope value for MDF, there is no fatigue presence in reading the EMG signal for that particular analysis. The greater the negative slope, the more fatigue is shown in the EMG reading (Shair, 2017).

Sundelin & Hagberg (1992) performed regression analysis for the analysis of changes in the mean frequency and RMS with time as the independent variable and mean frequency and RMS as dependent variables. The results of this study showed that the muscle fatigue with a decrease in the mean frequency and an increase in root mean square amplitudes. In addition, Plamondon et al (2014) determined the EMG power spectrum median frequency (MDF) using the middle 3s of the 5s EMG signal duration obtained during the sub-maximum isometric contractions, and a decrease in the median frequency of the back muscles was observed between the pre-test and the post-tests.

The studied paper regarding muscle fatigue assessment during manual handling is listed in Table 1.3. This table gives us some information regarding the three papers related to current study. The number of samples, muscle group, equipment that they used, task description, parameter, method and finally results of each paper have been described in this table. So, with looking at this table we will easily be able to compare the results and methods of each study with our study.

Table 1.3 Studied papers on muscle fatigue assessment during manual lifting

No	Reference	Year	Sample	Muscle Group	Equipments	Task	Parameters	Method	Outcomes and Remarks
1	Gunnevi Sundelin and Hagberg	1992	6 females	Trapezius and infraspinatus muscles	sEMG (Bipolar surface silver-silver electrodes)	Repetitive arm work for 1 hour (grasping a small cylinder with the right hand and then releasing it through a hole in a table)	Root-mean square amplitudes (RMS) and mean frequency (MNF)	Fast fourier transform (FFT) for 250 ms window size during 1-hour repetitive arm task	Trapezius muscle showed fatigue with a decrease in the MNF and an increase in RMS simultaniously. The slope of MNF regression line was between -1.0 to -3.1 Hz/s * 10^-3 and the RMS slope was between 2 to 27 µv^2/s * 10^-3
2	Plamondon, et al	2014	30 males	Right and left longissimus muscles (Back mucsle)	photogrammetric systems + video cameras + force platform + sEMG system	The manual handling task consisted in transferring 24 15-kg boxes from one pallet to another, and back	Root mean square (RMS) and median frequency (MDF)	RMS and MDF was calculated form EMG signal with windows size of 100 ms for 3 seconds first, middle and the lifting task.	The percentages of median and RMS changes for longissimus muscle right (Novice workers) were decreased 12% and increased 23% respectively. For this muscle in the left side the changes percentages were nearly 10% decrease in MED and in RMS, 38% increase was shown.
3	Spyropoulos , et al	2015	8 males	erector spinae (Right)	MG recorder (Dantec-Keypoint, 6-channel amplifier) with a pair of surface Ag/Agcl electrodes.	The participants stand at a distance of 30 cm from the table and there were 64 lifts with a frequency of 4 lifts per minute	Mean and median frequency (MNF and MDF)	Fast FourierTransform (FFT) with a 50 ms window size.	The maximum percentage of changes in MNF for 16 lifting loads was 6% and for MDF it was 11%.

CHAPTER 2

THESIS RESEARCH METHODOLOGY

In this chapter, we discuss the research methodology of this thesis. We will define the approach and the tools that will be utilized to address two objectives of this thesis, which were set out below. In a first step, the research hypothesis is described in Section 2.1 and, following that, Section 2.2 including research objectives is identified. Afterwards, subject demographics, recruiting participants and then subject preparation will be discussed respectively (Sections 2.3 and 2.4). In the following section, (Section 2.5) the experimental session will be described. Different data-gathering methods used in this study will be presented afterwards (Section 2.6). Finally, statistical methods for analyzing obtained data will be described (Section 2.7).

2.1 Research hypothesis

Underlying the muscle fatigue assessment of workers during manual lifting derived from EMG signals by attaching sensors (Noraxon) can allow evaluation of muscle fatigue in the working environment and provide insights into the characterization and motion changes by analyzing fatigue in the workplace. This can help to determine the eligibility of the analytical method for fatigue assessment amid manual handling based on EMG and consequently increasing organization productivity by mitigating the risk to human health.

2.2 Research objectives

The current study strives to attain a main objective and three sub-objectives as follows:

1. Investigating the effect of lifting height on muscle fatigue during repetitive manual lifting task.

2. Testing muscle fatigue patterns by the EMG in the muscles of the posterior deltoid (PD), upper trapezius (UT), middle trapezius (MT), and lumbar erector spinae (ES) for left and right side of the body by analyzing mean/median frequency (MNF/MDF) and RMS values.
3. Identifying the muscles that induce fatigue greater than others during manual lifting based on observing the mean/median frequency values over the time.

2.3 Subject demographics and recruiting participants

This study took place in the LIO laboratory at CRCHUM and École Technologie Supérieure (ÉTS). Before recruiting the subjects, the protocol (Attached in Appendix III) and procedure of the experiment was explained in detail and then the document was sent to the ÉTS ethics committee. After getting the approval of ÉTS, the approved document was sent to the CRCHUM ethics committee for final approval. Eventually, after obtaining the CRCHUM and ÉTS ethics committees' approval (Attached in Appendix I), recruiting the subject was begun.

Since the previous studies recorded EMG data between 6 and 30 subjects with 20 and 30 years of age (young subjects), we aimed to select fifteen healthy volunteer participants Potvin, (1997) aged between 18 and 35 years old to complete this study, but the number of subjects for the experiment was limited to 4 subjects because of the urgent situation created in the world (COVID-19). Participant recruitment was done among members of the LIO laboratory at CRCHUM and École Technologie Supérieure (ÉTS). An advertisement of the research was posted on the interior walls of the different departments of ÉTS and CRCHUM. Individuals interested in participating in this project contacted the research team by email or phone.

2.4 Subject preparation

An appointment was fixed once the eligible subject agreed to participate in this research. On the day of the experiment, the informed consent and data bank form (Appendix II) were given to the subject to read again, as well as the potential risks were explained to him. The subjects who had any injuries or limitations that could restrict or modify their ability to perform the required tasks were excluded. However, if the subject met any one of the following criteria, he was excluded from the experiment. The criteria consisted of any significant health problems that may affect the ability to perform a lifting task, such as heart disease, breathing problems, bone fractures, severe arthritis or osteoarthritis, chronic pain that does not allow the participant to perform the prescribed tasks, a history of musculoskeletal injuries including shoulder, back, knee, elbow and wrist injuries, balance problems and discomfort while performing the lifting task. Finally, the eligible subject signed the information and consent forms, and data bank form. Afterwards, a general information questionnaire including personal data like age, weight, height and past medical history was given to the subject to fill out to validate the general health status of each and his ability to participate in the study. (Appendix IV). A member of the team will be ready to assist the participant in obtaining certain data and answering the participant’s questions. Finally, the eligible participant was ready to begin the experimental part. Table 2.1 shows the demographic details of the one subject who did the experiment.

Table 2.1 Demographic details of subjects

	Sex	*Age*	*Height (cm)*	*Weight (Kg)*
Subject 1	Male	34	186	91
Subject 2	Male	32	184	84
Subject 3	Male	26	168	71
Subject 4	Male	24	168	73

2.5 Experimental session

This study was divided into one main experimental session, including 3 phases. The first is the eligibility determination phase, the second is the preparation phase, and the third is the experimental acquisition/task description respectively.

2.5.1 Eligibility determination phase

Before starting formal measurements, the experimental procedures of the study were explained to the subject and the subject was trained to become familiar with the assessment procedures and to ensure correct execution of the lifting tasks. Then, the participants went to the R07.402, Laboratoire de recherche en imagerie et orthopédie to perform the manual lifting task as an optional trial. Depending on the subject's being comfortable with lifting task, the experiment was started. The duration of this phase was estimated at 15 minutes.

2.5.2 Preparation phase & electromyography setup

This phase takes just 25 minutes to be completed. If the verified criteria during the eligibility determination phase demonstrated that the participants are eligible to participate in this project, we asked them to present the following arrangements:

1. The experimental procedures of the study were explained to the subject and the subject was shown how to perform the manual handling tasks correctly (Figure 2.1). First, the subject was briefed on the experimental procedures of the study and familiarized with the evaluation procedures and the proper performance of the lifting tasks. The subject was asked to perform a manual lifting task as a test-training.

Figure 2.1 Correct techniques of manual lifting task (https://employsure.com.au/blog/reduce-risks-associated-manual-handling/)

2. After becoming familiar with lifting tasks, the subject was led by the research team to a locker room at the CRCHUM Imaging and Orthopedics Research Lab R07.402 to change clothes.
3. As a preparation process, the subject's skin was cleaned by alcohol swap to ensure that there was the least amount of impedance during the manual handling (Xiao, et al., 2014). Then the skin was allowed to dry before attaching the electrodes. If necessary, his skin was shaved in some places to promote the adhesion of the sensors. A measured tape was attached to the sensors to be fixed on the body during the lifting task to record signal completely for uninterrupted analysis.
4. The procedure for the EMG electrode placements was done as a SENIAM (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) recommendation to acquire stable and optimum pick-up area of the EMG signals from each participant. SENIAM provides recommendations for sensor locations in thirty single muscles. Recommendations for each muscle include description of muscle anatomy like origin, placement and function, description of sEMG sensors, description of electrode location and direction, and description of onset and clinical trial status for recording sEMG specific muscle. Figure 2.2 shows an example of placement of EMG electrodes on the body.

Figure 2.2 Example of placement of EMG sensors on the back muscles

Electromyography set-up: Surface electromyography (sEMG) is a technique which is non-invasive and commonly used to assess muscle fatigue and quite a few characteristics of the sEMG signal can be markers of muscle fatigue (Cifrek, 2009).

In the current study, surface electromyography (sEMG) has been utilized to check ten different posterior muscles involved in upper extremity movement (Uhl, et al. (2003). The EMG sensors were placed bilaterally to collect the muscular activity of the subjects on the different back muscles for the left and right sides of the upper body (Figure 2.2), including posterior deltoid (PD), upper trapezius (UT), middle trapezius (MT), lower trapezius (LT) and the erector spinae (ES) (Uhl, et al. 2003). According Uhl et al (2003) these muscles were chosen because of their role as trunk extensors.

The SENIAM technique was used to find the placement measurement of electrodes for ten specified muscles that would have to be analyzed. To find the right location of the identified muscles a physiologist was asked to help as well. Based on SENIAM and the physiologist, the PD electrodes were positioned 3 cm below the acromion-process angle; the UT electrodes were mounted on the vertebra C7 at 50 per cent on the line from the acromion to the spine;

the MT electrodes were positioned at the T3 stage at 50 per cent between the scapula's medial boundary and the spine. To properly position the electrodes in the above guidelines, a measuring tape (Figure 2.3) was utilized, and the identified areas were marked before the positioning of the electrodes (Uhl et al., 2003). Owing to have minimum impedance during the analysis, the alcohol swab was used after shaving (Xiao et al., 2014).

The surface EMG program system used throughout the experiment was NORAXON model MR 3.14., with ten wireless sensors and associated electrodes and 2000 Hz sampling rate was used to collect EMG signals, which consists of a parallel-bar-based EMG measurement device. Bipolar surface electrodes were positioned at an inter-electrode distance of 20 mm, adjacent to the muscle fibers being measured. In order to make sure that combined electrodes and EMG sensors remain in place throughout the experiment, a piece of measuring tape (10 cm) was pasted on the area which permitted the extremities to move (Figure 2.3).

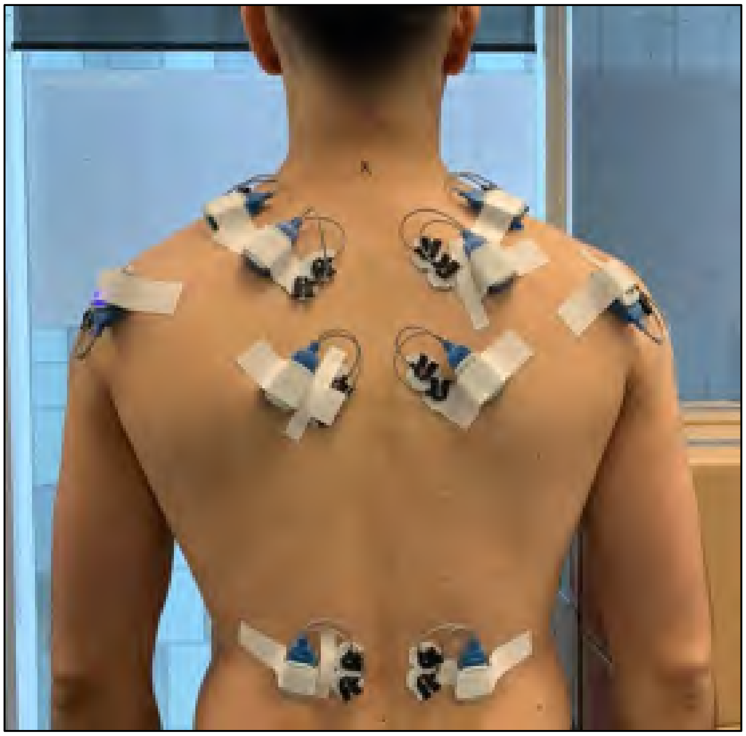


Figure 2.3 Pasting measuring tape over the electrodes and EMG sensors.

Following the location of the electrodes, muscles were tested by watching signals on the computer screen connected to the wireless network for proper positioning. The subject was asked to move or bend from his waist to be able to capture a test for each muscle group and verify that the activation is clearly legible by each electrode for the muscles in the group.

Before starting the experiment, the subject was asked to participate in benchmark for one column to be able to cutoff the lifting cycles. In this way, the subject had to take a first, second, third and fourth box in a column respectively, with a pause of 5 seconds for lifting and depositing tasks which were recorded in the computer. Once the subject had finished the benchmarks, he was explained in depth about the testing process and the experimental acquisition was started.

2.5.3 Experimental Acquisition/Task description

After placement of electrodes in the defined muscles, the subject executed the manual lifting task. The experimental acquisition phase involved moving 24 boxes. Each box weighed about 10 kg. The lifting tasks were performed in a correct posture – body is aligned and balanced placing minimal stress on muscles, tendons, nerves, and bones and allowing for maximum control (Moore, et al., 2011). The manual handling task included transferring 24,10-kg boxes from one side (depalletizing) to another (palletizing), and back, 3 roundtrips (6 single trips) over a period of 16 min (total box transfers: 144). The box dimensions are 30.4 cm deep by 40.6 cm wide by 30.4 cm high. The subject was instructed to stand on the floor, in front of the boxes and move to a piling model in columns of four layers of height (first layer = on the ground, 2nd = 30.4 cm, 3rd = 60.8 cm, 4th = 91.2 cm) by six boxes/layer (3 in the front row, 3 in the back row). The moving distance between current location of the boxes and the location where they were to be stacked was two meters.

The lifting task (imposed pace) consisted of three round trips (6 go and back trips) for all 24 boxes on the floor (144 boxes) at the imposed pace of nine-boxes-per-minute (Garg & Saxena, 1979) to increase the challenge and potential fatigue. Based on Snook & Ciriello (1991), 75% of men can bear this workload. The participant should follow the sound of a metronome, which was heard as a trial for one minute with an empty box. During transferring the boxes, the pace or speed will be controlled and they will be notified by a team member if they are regularly too fast or too slow. The goal is to make the task more difficult than at regular speed to achieve participants' fatigue. The full definition of the function for manual handling was as follows:

The subject began the depalletizing task by grabbing and lifting the first box in front of the top row as instructed by the research team member at the beginning of the session. He stood in an upright position in front of the boxes and lifted the box in his own way and rotated with a 90° step. The subject would do the palletizing task of lowering and depositing the box on the floor until all the boxes were moved to their destination. The subject was instructed to lift boxes from the top (fourth row) and deposit that box to the destination on the floor (First row) and when he had put all boxes from the fourth row to the first row, he started to lift third row and deposit them on the top of the first row (second row) of the destination area. He was forced to continue this task for two the remaining rows.

Upon completion, he immediately moved to the first location, and he would repeat this job for two more round trips to complete the task. Figure 2.4 shows the boxes set up in the laboratory.

Figure 2.4 Boxes set up in the laboratory

2.6 Proposed method

Sequential steps of the proposed method for estimating mean/median frequency are demonstrated by the flowchart below:

Figure 2.5 Procedure of MDF & MNF calculations

2.7 Signal analysis

After collecting, EMG signal filtering will be applied (band pass). This filtering allows us to have frequency of all active muscles that were measured by EMG signals in a specific range between 10 - 450 Hz. Thus, the only frequency that will be taken into account will be in between 10 – 450 Hz range (In the other frequency levels, noise will be considered irrelevant). As I explained in detail in the experiment acquisition, the entire of lifting task is 16 minutes consisting 144 cycles (each cycle including lift, walking and deposit task equal to 4-6 seconds), we aimed to assess muscle fatigue only for lift, walking and deposit task. However, for addressing objectives of the current study, I needed to extract just lift, walking and deposit. So, lift, walking and deposit task from the whole EMG signal were split or cut-off by using magnetometer signal from the recorded surface EMG signals.

As the EMG signals are non-stationary, during dynamic contractions, using discrete-time STFT technique means the power spectrum calculated for every window. STFT was computed by use of FFT. Afterwards, the mean and median frequency analysis for each epoch or window was calculated.

The mean and median frequency value of power spectral was also calculated over each consecutive 4-6 seconds (each cycle). However, data were extracted for sub-calculation epoch via the window of 500 ms with 20% overlapping with each other (Fs = 2000 Hz; 1 sample 0.5 ms; 500 ms = 1000 samples plus with 20% overlapping). Such split and overlapping windows were designed to achieve as much smoothness as possible of an output frequency spectrum, and also to prevent outliers of the results.

Then mean frequency (MNF) and median frequency (MDF) analysis is computed by power spectrum analysis of each task (SFTT). Moreover, root mean square (RMS) was calculated for each EMG signal for each window. Finally, we compute a regression analysis between MNF/MDF and RMS with respect to four different heights. However, changes in the frequency (Median and Mean frequency) will be used to determine local muscle fatigue.

2.7.1 The method of cutting cycles

The cycles (144 lift+walk+deposit carried out during 4-6 seconds) are determined using the Y component of the magnetometer of the sensor attached to the right lumbar muscle (medial-lateral). We tried to determine the width between the rising and falling edges of the magnetometer. It is necessary to reset the baseline to 0 (when the participant is static). Then the pulse-width function of Matlab was used. However, the average reference level at 5% and the high states of the signal at 200 mGauss and the low states at 10 mGauss was chosen.

The times of the rising and falling edges were recovered. We used these times to cut the EMG of the right lumbar and also of all the other muscles within this method.

Due to lack of detecting cycles by the magnetometer signal, we had to exclude a few cycles. The reasons for the magnetometer not detecting these cycles could be such as de-attaching the sensors from the subject's skin because of perspiring a lot during lifting task and pausing subject to attach the sensors on the body again, perhaps the magnetometer signal could not work well. Because of these mentioned reasons, we had no data from subject 4 for 2 muscles such as MTL and ESL that were omitted from the study.

2.7.2 The method of finding heights

Height was calculated based on their sequences. Because subject lift the 3 boxes from the first row from the top that was considered as a height 4 and then second row as a height 3. The third and fourth respectively were considered as a height 2 and height 1. The subject did 3 round trips (6 go and back trips) in 16 minutes. He did this procedure (lifting and depositing the boxes from height 4 to height 1) and, according to this sequence, that means 3 boxes in each height. We differentiate these four heights.

2.7.3 Linear regression

In statistical data analysis, after having the data with multiple variables, one of the important questions would be how the variables are related. To address such a question, we need regression analysis. In this section we focus on the simplest type of regression named linear regression. More specifically, assume a set of data including N samples $\{(x_i, y_i)\}_{i=1}^{N}$ are given and we aim at fitting a linear line (such as the one in eq. 2.1) to the data.

$$y = \alpha x + \beta \tag{2.1}$$

where x and y are called the independent and dependent variables, respectively. In this equation α is the slope of the line while β is the intercept. The goal of the linear regression algorithm is to find the best values for the α and β for the given data set in such a way that the error of fitting is minimized.

2.7.4 Least-squares linear regression

For the data samples $\{(x_i, y_i)\}_{i=1}^{N}$ considering the fitted linear line in eq. 2.1, the dependent variable can be estimated as follows:

$$\hat{y}_i = \alpha x_i + \beta\,, \qquad i = 1,2,\dots,N \tag{2.2}$$

Therefore, the amount of error due to the linear relation assumption can be found as follows:

$$\varepsilon_i = y_i - \hat{y}_i = y_i - (\alpha x_i + \beta)\,, \qquad i = 1,2,\dots,N \tag{2.3}$$

where ε_i is the amount of error associated to the sample i. The unknown coefficients α and β can be calculated by minimizing the total squared error in eq. (2.3) by solving the following minimization problem:

$$\min \sum_{i=1}^{N} \varepsilon_i^2 = \min \sum_{i=1}^{N} [y_i - (\alpha x_i + \beta)]^2 \tag{2.4}$$

where minimization is done based on the unknowns α and β. Solving the optimization problem (2.4), the optimum coefficients α^* and β^* can be calculated as follows (Devore, 2011; Seber G.A & Lee A.J 2012):

$$\alpha^* = \frac{\sum_{i=1}^{N} x_i y_i - \frac{1}{N} \sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{\sum_{i=1}^{N} x_i^2 - \frac{1}{N} (\sum_{i=1}^{N} x_i)^2} \tag{2.5}$$

$$\beta^* = \overline{y} - \alpha^* \overline{x} \tag{2.6}$$

where the $\overline{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$ and $\overline{y} = \frac{1}{N} \sum_{i=1}^{N} y_i$ are the sample means for variables x and y, respectively.

2.7.5 Confidence interval for slope

After estimating the optimum slope α^* of the linear line in eq. (2.1) from the samples $\{(x_i, y_i)\}_{i=1}^{N}$, we would like to know a lower and upper bound (for the estimated value), named as confidence interval, which guarantees with probability $100(1-\alpha)\%$ to encompass the true value of the population parameter. In other words, it ensures that with probability $100(1-\alpha)\%,$ the estimated parameter for the any future experiment would fall within that interval. For the slope parameter of the linear regression proposed in the previous section, the $100(1-\alpha)\%$ confidence interval can be found as follows:

$$\alpha^* - t_{\alpha/2,N-2}\sqrt{\frac{\hat{\sigma}^2}{S_{xx}}} \leq \alpha \leq \alpha^* + t_{\alpha/2,N-2}\sqrt{\frac{\hat{\sigma}^2}{S_{xx}}} \tag{2.7}$$

where the $S_{xx} = \sum_{i=1}^{N}(x_i - \bar{x})^2$, $\hat{\sigma}^2 = \frac{\sum_{i=1}^{N}\varepsilon_i^2}{N-2}$, and $t_{\alpha/2,N-2}$ can be calculated from the t-table. For more information on how to find the eq. (2.7) and t-table the reader is referred to (DeGroot MH & Schervish MJ, 2012).

2.7.6 MNF/MDF and RMS regression line

In this dissertation, before doing regression analysis on the given MNF/MDF and RMS data, the outliers for each dataset should be found and removed. To this end, several statistical methods are proposed in the literature (Hodge V & Austin J, 2004; Chandola V et al, 2007). In this work we simply use the histogram (distribution) analysis of each dataset (at each height) and those data points that differ significantly from other data are determined as outliers and removed. Figure 2.6 shows an example for outliers detected for our dataset.

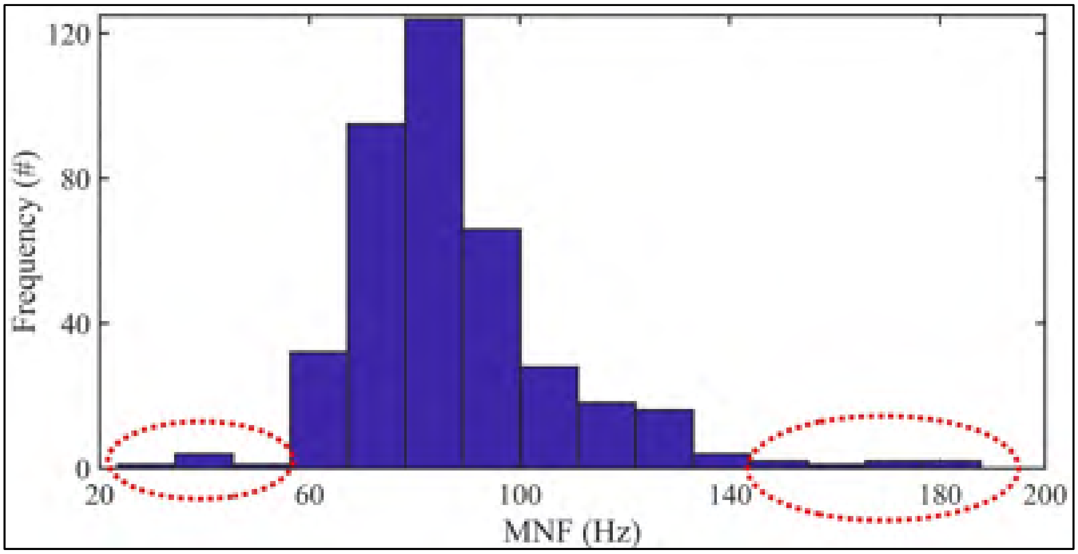


Figure 2.6 Example of the outlier detection by observing the histogram of the data samples.

The dotted ellipses in Figure 2.6 represent the data points that clearly differ from the other (majority) data points and so can be considered as outliers.

After removing the outliers at each height, the regression analysis can be done as follows: Starting from the time zero (first sample in the dataset), the average mean/median frequency and root mean square is calculated every 1 minute (for 30 samples before and 30 samples after that time) all over the experiment. Then the average mean/median frequencies are plotted versus the time and a linear regression line is fitted to align with the 95% confidence interval for the slope of the line.

CHAPTER 3

RESULTS

This chapter provides the analysis results of electromyography data using three different measures, namely, mean frequency (MNF), median frequency (MDF) and root mean square (RMS) of the EMG signal data during a lifting task.

This chapter gives the regression analysis of the EMG amplitude and frequency versus time during each lifting task condition which corresponds to four different heights. In addition, muscle fatigue patterns of EMG signal will be analyzed during the 1-minute period. At the end of this chapter, the muscles and heights that display back muscle fatigue better than others during the manual lifting task will be addressed.

3.1 Muscle fatigue during entire lifting task in terms of four different heights

The first objective of this study is to investigate the effect of lifting height on muscle fatigue during repetitive manual lifting task. We have considered four different height levels for analysis namely: H1 to H4 in the upward vertical direction. H1 is the ground layer, H2 is at 30.4 cm, H3 is at 60.8 cm and finally H4 is at 91.2 cm.

Regression analysis has been applied to the MDF, MNF and RMS parameters for the ten back muscles and for all of the subjects. In order to compare MDF, MNF and RMS regression, ten tables including the number of subjects, four different heights for each subject, MDF, MNF and RMS intercept, slope coefficient and 95% confidence interval (CI) for each muscle have been calculated for each muscle that will be shown below.

3.1.1 Posterior deltoid right (PDR)

Based on Merletti, et al., 1990 and Sundelin, 1992, muscle fatigue will happen once the slope of MDF and MNF is negative and slope of RMS is positive. Therefore, regression analysis of the EMG amplitude (RMS) and frequency (MDF and MNF) versus time for 10 muscles in this study indicated signs of fatigue by negative slopes of MDF and MNF and positive slopes of RMS (Grey highlighted numbers in tables).

Table 3.1 Regression analysis of the MDF, MNF and RMS for the PDR muscle of 4 subjects based on four heights

		Median			***Mean***			***RMS***		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*
1	H1	52.42	-0.63	[-4.08 , 2.81]	69.77	-4.69	[-8.61 , -0.77]	32.23	4.99	[-1.74 , 11.72]
	H2	53.96	-6.89	[-11.78 , -2.01]	71.18	-9.68	[-14.74 , -4.61]	29.9	18.53	[3.68 , 33.37]
	H3	55.15	-6.04	[-9.99 , -2.1]	70.56	-9.56	[-14.7 , -4.43]	29.35	6.85	[3.31 , 10.39]
	H4	56.02	-6.93	[-9.44 , -4.43]	71.3	-8.92	[-12.19 , -5.65]	31.01	4.54	[2.15 , 6.92]
2	H1	41.46	-3.66	[-7.68 , 0.36]	54.88	-1.39	[-4.72 , 1.95]	25.94	15.23	[2.09 , 28.36]
	H2	42.76	-3.13	[-7.15 , 0.88]	58.67	-4.55	[-9.86 , 0.76]	27.03	20.59	[5.08 , 36.09]
	H3	39.65	-2.1	[-6.52 , 2.33]	56.69	-3.47	[-10.59 , 3.64]	30.27	2.44	[-1.61 , 6.49]
	H4	42.37	-4.64	[-8.84 , -0.44]	59.59	-7.27	[-15.03 , 0.48]	28.05	1.14	[-9.83 , 12.1]
3	H1	57.54	-6.23	[-8.21 , -4.25]	83.37	-24.27	[-29.8 , -18.74]	21.37	14.77	[10.15 , 19.39]
	H2	55.26	-4.06	[-8.11 , -0.02]	81.45	-22.41	[-29.18 , -15.63]	22.69	15.29	[8.93 , 21.66]
	H3	54.3	0.08	[-4.85 , 5.01]	80.94	-21.46	[-31.3 , -11.63]	20.64	13.15	[6.53 , 19.77]
	H4	53.81	1.41	[-3.24 , 6.07]	78.43	-13.07	[-19.52 , -6.62]	24.23	6.07	[0.38 , 11.75]
4	H1	56.71	-7.49	[-12.14 , -2.85]	91.03	-20.17	[-31.27 , -9.08]	23.83	9.01	[-1.21 , 19.24]
	H2	59.23	-13.91	[-19.32 , -8.49]	104.5	-36.05	[-51.88 , -20.23]	19.72	12.94	[6.92 , 18.96]
	H3	55.03	-8.22	[-11.89 , -4.54]	95.82	-38.24	[-51.95 , -24.53]	24.49	1.73	[-9.11 , 12.57]
	H4	60.17	-11.21	[-19.06 , -3.37]	96.81	-24.63	[-36.92 , -12.34]	23.31	4.52	[-3.21 , 12.26]

As is evident from Table 3.1, signs of muscle fatigue were shown for all four different heights for all subjects for posterior deltoid muscle on the right side with negative slope of MDF/MNF and positive slope of RMS. Based on 95% CI [LL, UL] where LL is the lower limit of the confidence interval and UL is the upper limit, we ensure that if we redo the experiment, the estimated slope will be placed into that interval with a confidence of 95%. So, among all these highlighted slopes that show muscle fatigue, those who have negative 95% confidence interval range for frequency (MDF and MNF) and positive range for amplitude (RMS) illustrate a higher chance of muscle fatigue in any other same experiment.

In other words, if the experiment is repeated several times by the subject, with a higher chance the muscle fatigue will happen.

Based on these findings, the presence of muscle fatigue happened for all subjects at all heights. Among the data, a greatest decrease was seen at all heights for subject 4. However, based on Merletti, et al., 1990, Sundelin, 1993 dropping in instantaneous MDF and MNF versus time (minute) in the EMG data and increasing RMS as a fatigue factor for all heights and all subjects illustrated that PDR is a remarkable back muscle showing muscle fatigue obviously.

In addition, the changes in instantaneous MDF and MNF (represented by the blue line) and RMS (represented by the red line) versus time (minute) of posterior deltoid right for four heights is shown in Figures 3.1 and 3.2. The trend of median and mean frequency and RMS in these figures depicts changes in slope clearly. As stated in Table 3.1, subject 4 has the most decrease in mean frequency and increase in RMS for all heights, and this decrease and increase can easily be seen in Figure 3.1. The remaining figures given for various subjects can be seen in Appendix V.

As can be seen from Figures 3.1 and 3.2, in addition to defining the downtrend of MDF and MNF (blue line) as well as the uptrend of RMS (red line), patterns of the EMG were seen in all four different heights during a 1-min lifting task time (16 minutes). In these graphs, the blue dots represented the MDF/MNF and the RMS was represented by red dots.

The patterns (represented by the blue dots) of median and mean frequency and increasing RMS were different during time interval i.e., 16 minutes. Furthermore, as is seen in Figure 3.1 after upward direction of the MNF, decreasing the frequency happened for all heights. In Figure 3.2, this trend (upward and downward) was also shown for H1 and H2 in MDF.

As can be seen in Figure 3.1 (MNF changes), after almost 7 minutes, decreasing mean frequency and increasing RMS occurred in all heights and continued until the end of the lifting task (16th minute). Furthermore, decreasing mean frequency and increasing RMS happened after 8 minutes for MDF, as can be seen in Figure 3.2 and continued by the end of lifting task in H1 except H2, H3 and H4 that had increasing median frequency and decreasing RMS almost in the last 1 and half minutes of the experiment.

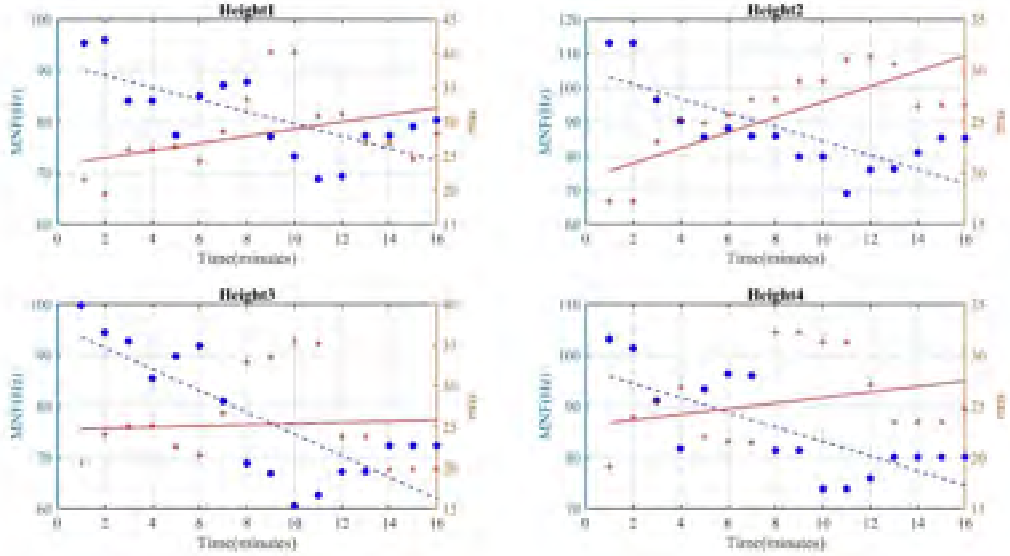


Figure 3.1 Changes in mean frequency (MNF) versus time (minutes) of PDR muscle for four heights (Subject 4)

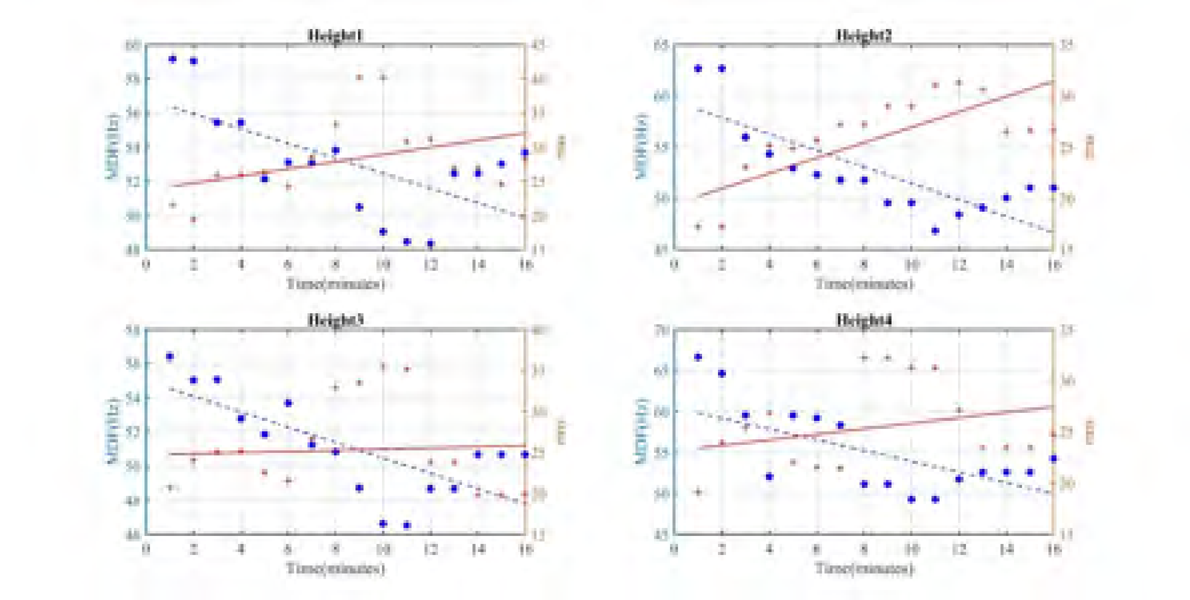


Figure 3.2 Changes in median frequency (MDF) versus time (minutes) of PDR muscle for four heights (Subject 4)

3.1.2 Posterior deltoid left (PDL)

Table 3.2 Regression analysis of the MDF, MNF and RMS for the PDL muscle of 4 subjects based on four heights

		Median			**Mean**			**RMS**		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*
1	H1	58.34	-9.66	[-15.35 , -3.96]	76.4	-13.67	[-21.91 , -5.43]	32.32	1.49	[-1.53 , 4.51]
	H2	60.01	-10.83	[-17.76 , -3.9]	76.04	-12.63	[-19.31 , -5.95]	36.91	0.13	[-5.66 , 5.91]
	H3	57.83	-6.97	[-9.33 , -4.62]	74.03	-11.66	[-14.87 , -8.45]	35.3	2.86	[-2 , 7.73]
	H4	59.08	-8.35	[-12.43 , -4.26]	76.68	-14.17	[-19.7 , -8.65]	31.66	9.48	[5.27 , 13.69]
2	H1	40.12	-5.83	[-10.38 , -1.29]	53.79	-6.9	[-11.47 , -2.34]	24.95	3.97	[-3.15 , 11.08]
	H2	38.73	-2.43	[-7.8 , 2.95]	51.78	-0.96	[-5.74 , 3.82]	23.82	5.55	[-7.72 , 18.81]
	H3	40.61	-8.39	[-12.45 , -4.33]	56.41	-11.65	[-16.92 , -6.38]	26.91	-1.06	[-8.94 , 6.83]
	H4	38.3	-4.9	[-9.75 , -0.05]	54.6	-8.18	[-16.15 , -0.21]	26.96	-2.44	[-10.13 , 5.25]
3	H1	74.31	-13.75	[-20.47 , -7.03]	122.72	-60.23	[-75.86 , -44.59]	22.38	63.67	[46.09 , 81.26]
	H2	82.05	-26.63	[-35.36 , -17.9]	129.17	-62.92	[-80.75 , -45.09]	29.77	24.01	[2.47 , 45.55]
	H3	94.57	-44	[-58.77 , -29.23]	141.39	-73.01	[-94.59 , -51.43]	25.84	23.57	[15.01 , 32.13]
	H4	76.23	-16.99	[-27.69 , -6.3]	124.39	-53.93	[-73.25 , -34.61]	31.82	3.71	[-2.84 , 10.27]
4	H1	51.28	-3.16	[-8.49 , 2.17]	71.32	-0.23	[-8.74 , 8.28]	26.57	0.49	[-7.9 , 8.88]
	H2	48.89	-6.53	[-10.2 , -2.86]	71.39	-8.85	[-13.29 , -4.42]	25.68	-3.35	[-11.62 , 4.93]
	H3	45.85	-5.44	[-8.75 , -2.12]	65.45	-4.1	[-9.2 , 1]	23.79	1.65	[-3.59 , 6.88]
	H4	47.64	0.56	[-2.46 , 3.58]	66.61	6.28	[0.64 , 11.91]	25.52	0.58	[-3.93 , 5.1]

The regression analysis of EMG signal has been shown in terms of MDF/MNF and RMS for four different heights for each subject in Table 3.2. As seen in the above table, for the posterior deltoid muscle on left side, the slopes of the MDF/MNF values were negative and RMS slopes were positive for four heights for two subjects namely S1 and S3. For the subjects 2 and 4, the signs of muscle fatigue were seen in just two heights. Subject 2 showed fatigue in just H1 and H2. Although the slope of MDF and MNF were negative for H3 and H4, the slopes of the RMS were negative in combination with negative slopes of the MDN and MNF. The posterior deltoid left muscle of subject 4 experienced fatigue in heights 1 and 3. Based on the results, subject 4 showed fatigue in two heights of H1 and H3. Second height for this subject had a negative slope, and H4 had a positive slope for all three parameters (MDF/MNF and RMS).

As it turns out in Figure 3.3, these decreases in MNF and increasing RMS for all four heights can clearly be seen. By looking at Figures 3.3 and 3.4, it will be clear seen how the mean and median frequency (Blue line) goes to the negative slope and root mean square (Red line) to the positive slope for all four heights. The remaining figures produced for different subjects can be seen in Appendix V.

The patterns (blue dots) of median and mean frequency were different during time interval i.e., 16 minutes. As can be seen in Figure 3.3, in all heights, decreasing mean frequency and increasing RMS happened after 7 minutes on average and continued by the end of the lifting task (16th minute). For the MDF (Figure 3.4), in all heights except H4, this pattern was seen by the end of the experiment.

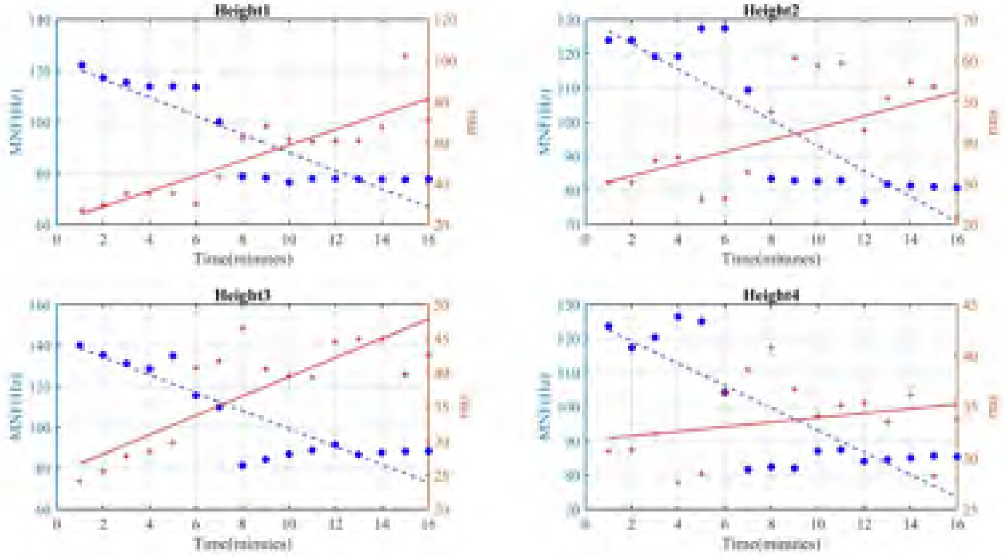


Figure 3.3 Changes in mean frequency (MNF) versus time (minutes) of PDL muscle for four heights (Subject 3)

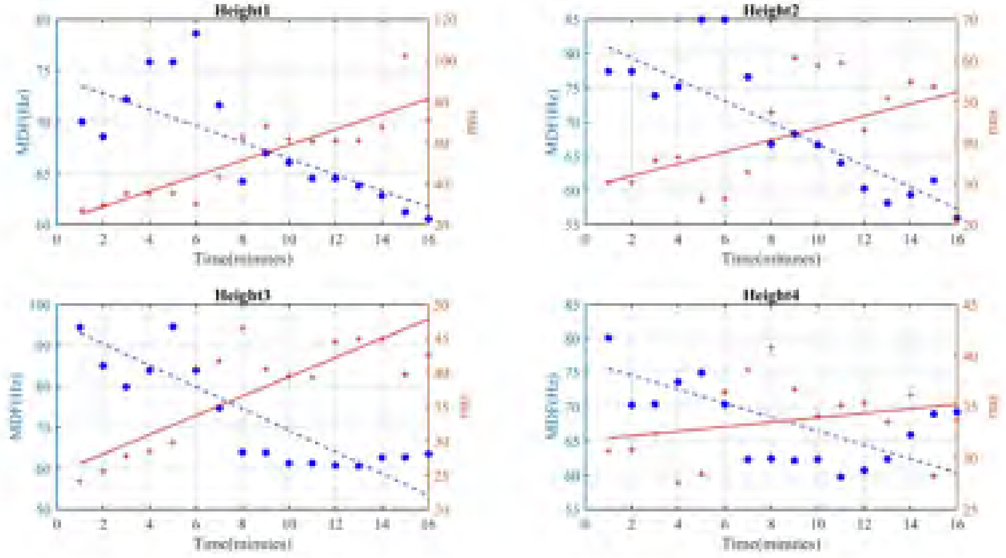


Figure 3.4 Changes in median frequency (MDF) versus time (minutes) of PDL muscle for four heights (Subject 3)

3.1.3 Upper trapezius right (UTR)

Table 3.3 Regression analysis of the MDF, MNF and RMS for the UTR muscle of 4 subjects based on four heights

		Median			***Mean***			***RMS***		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*
1	H1	53.6	-11.75	[-18.12 , -5.38]	66.36	-10.93	[-17.06 , -4.8]	47.43	-1.2	[-11.55 , 9.15]
	H2	54.06	-10.3	[-15.12 , -5.49]	67.04	-10.73	[-15.96 , -5.5]	50.72	0.37	[-10.96 , 11.7]
	H3	53.85	-10.65	[-14.08 , -7.22]	66.52	-11.43	[-16.31 , -6.54]	42.67	13.65	[7.68 , 19.61]
	H4	54.11	-8.72	[-12.86 , -4.58]	68.39	-12.74	[-17.73 , -7.74]	45.91	7.81	[1.3 , 14.33]
2	H1	79.39	-11.53	[-15.25 , -7.81]	93.93	-5.3	[-9.47 , -1.12]	60.34	-22.16	[-43.9 , -0.41]
	H2	70.44	-1.74	[-10.73 , 7.24]	95.35	-3.71	[-11.16 , 3.73]	37.7	14.7	[-14.36 , 43.76]
	H3	70.14	-9.1	[-16.22 , -1.98]	96.95	-6.12	[-13.92 , 1.68]	30.51	0.92	[-6 , 7.85]
	H4	74.44	-13.62	[-18.43 , -8.81]	95.77	-7.36	[-13.03 , -1.69]	45.47	-27.85	[-35.49 , -20.22]
3	H1	64.44	-4.03	[-6.19 , -1.88]	72.72	-7.06	[-8.96 , -5.16]	101.28	0.21	[-33.01 , 33.44]
	H2	62.86	-6.3	[-10.11 , -2.49]	70.98	-7.35	[-11.09 , -3.61]	85.57	-6.27	[-24.72 , 12.17]
	H3	61.85	-7.65	[-10.95 , -4.35]	70.28	-6.61	[-9.76 , -3.45]	63.39	7.92	[-8.44 , 24.28]
	H4	63.88	-6.49	[-10.84 , -2.14]	71.53	-6.27	[-9.93 , -2.62]	89.71	10.02	[-2.37 , 22.42]
4	H1	55.22	0.28	[-2.78 , 3.33]	67.72	-0.83	[-3.9 , 2.24]	41.32	-9.51	[-18.54 , -0.48]
	H2	54.67	-0.99	[-5.07 , 3.09]	72.11	-6.89	[-11.44 , -2.34]	22.07	19.87	[2.63 , 37.11]
	H3	53.08	-1.65	[-7.29 , 4]	70.86	-7.39	[-10.2 , -4.57]	16.86	17.79	[12.35 , 23.24]
	H4	56.75	0.04	[-5.27 , 5.35]	71.14	-1.95	[-6.72 , 2.82]	22.61	19.9	[13.04 , 26.77]

The EMG signal regression analysis was shown in Table 3.3 in terms of MDF/MNF and RMS at four different heights for each subject. As implied by the findings, it displays signs of fatigue due to negative MDF/MNF slopes and positive RMS slope with a 95% confidence interval for 4 subjects at four different heights for the upper trapezoidal muscle on the right side (Table 3.3).

As can be seen above in the table, muscle fatigue occurred in subjects 2 and 4 at the same heights such as H1 and H4 as each other. Moreover, 3 of the subjects (Subject 1, subject 2 and subject 4) did not encountered muscle fatigue during the whole lifting task in H1. So, it was supposed that H1 was not a remarkable height for upper trapezius right muscle. And, as pointed out in the results, the important heights for this back muscle were H2 and H3, because in all subjects they displayed fatigue.

Subject 1 had the largest frequency decrease in three heights (H2, H3 and H4), and muscle fatigue was found in this subject rather than in others, as pointed out by Shair, 2017. Figures 3.5 and 3.6 have been plotted to illustrate the pattern of decreasing frequency and rising RMS clearly. And as can be seen, the H3 and H4 have depicted this decline and increase trend for both mean and median. The remainder of the figures presented for other subjects can be seen in Appendix V.

According to the results obtained, however, it is clear that fatigue occurred in the upper trapezius right muscle during the 16-minute lifting task for all subjects, at all four different heights. But subjects 1 and 4 in H3 and H4 had the greatest decrease and increase in frequency and RMS respectively, and showed muscle fatigue more than other heights. Figures 3.5 and 3.6 depicted these drops and rises clearly. As is seen in these figures, H3 and H4 had a steady trend of decreasing MDF/MNF and increasing RMS during entire lifting task rather than at 2 other heights. The remainder of the figures presented for other subjects can be seen in Appendix V.

The fatigue pattern based on MNF and MDF showed the same direction. However, UTR muscles at H1 and H4 began to fatigue (MDF/MNF decreases and at the same time the RMS increases) approximately after around 6 minutes respectively, while H3 reported being fatigued after around10 minutes (Figure 3.5 and 3.6).

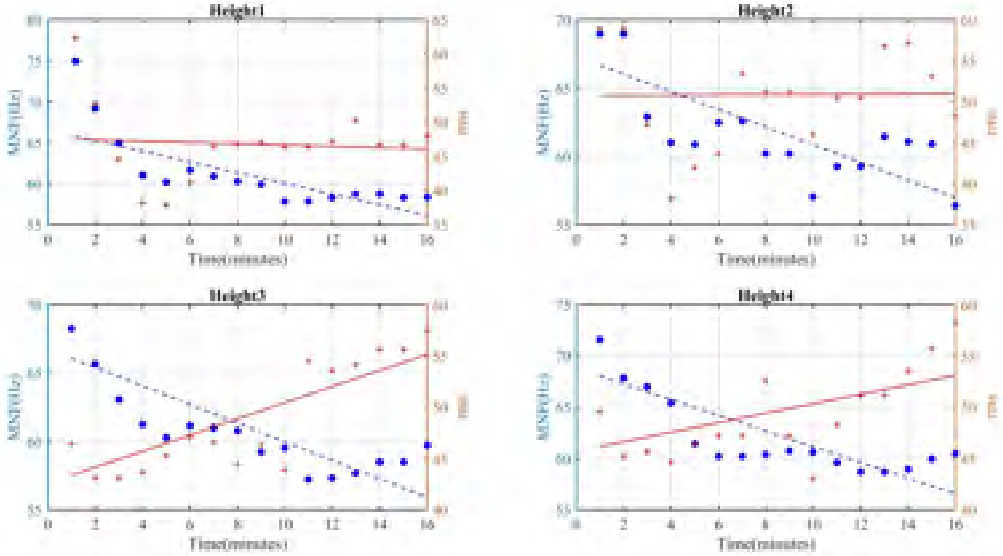


Figure 3.5 Changes in median frequency (MNF) versus time (minutes) of UTR muscle for four heights (Subject 1)

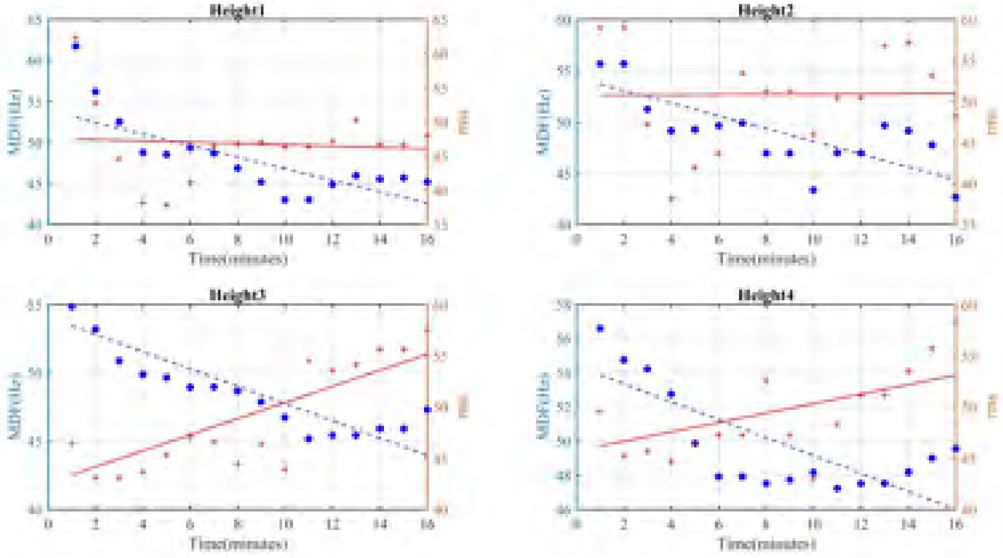


Figure 3.6 Changes in median frequency (MDF) versus time (minutes) of UTR muscle for four heights (subject 1)

3.1.4 Upper trapezius left (UTL)

Table 3.4 Regression analysis of the MDF, MNF and RMS for the UTL muscle of 4 subjects based on four heights

		Median			**Mean**			**RMS**		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*
1	H1	58.51	-5.52	[-8.51 , -2.53]	79.82	-8.24	[-14.04 , -2.43]	21.38	6.31	[2.35 , 10.27]
	H2	57.68	-3.48	[-6.9 , -0.05]	79.9	-5.31	[-10.56 , -0.06]	18.78	7.04	[4.46 , 9.61]
	H3	56.88	-3.88	[-7.21 , -0.54]	80.75	-11.91	[-17.75 , -6.06]	17.84	10.37	[6.79 , 13.94]
	H4	59.97	-8.52	[-13.79 , -3.24]	81.59	-11.79	[-19.29 , -4.29]	19.98	4.37	[1.14 , 7.6]
2	H1	74.25	-4.34	[-7.14 , -1.55]	86.09	-3.29	[-6.35 , -0.23]	44.01	-18.26	[-26.49 , -10.03]
	H2	68.91	0.24	[-4.5 , 4.98]	82.61	-0.61	[-3.23 , 2.01]	21.47	16.14	[1.3 , 30.99]
	H3	67.96	-7.77	[-15.08 , -0.47]	82.78	-9.36	[-13 , -5.71]	20.24	-0.94	[-7 , 5.11]
	H4	74.81	-21.34	[-28.96 , -13.73]	85.93	-11.14	[-15.29 , -6.98]	30.7	-12.41	[-23.29 , -1.53]
3	H1	68.48	-10.87	[-16.03 , -5.72]	83.58	-17.58	[-24.71 , -10.44]	40.14	25.21	[11.23 , 39.2]
	H2	61.93	-0.36	[-2.77 , 2.05]	76.12	-6.15	[-7.64 , -4.67]	39.69	42.99	[27.89 , 58.08]
	H3	60.98	-1.76	[-4.84 , 1.32]	72.93	-3.85	[-6.18 , -1.52]	34.11	23.44	[8.58 , 38.3]
	H4	62.93	-2.13	[-7.68 , 3.43]	76.04	-5.47	[-10.79 , -0.16]	47.2	8.74	[-4.56 , 22.04]
4	H1	75.08	-15.71	[-21.19 , -10.22]	93.95	-10.76	[-15.27 , -6.25]	22.06	-0.66	[-5.01 , 3.7]
	H2	67.11	-17.55	[-24.15 , -10.95]	89.93	-11.4	[-14.95 , -7.84]	15.15	-1.2	[-3.72 , 1.33]
	H3	62.53	-12.83	[-20.26 , -5.39]	87.99	-10.27	[-15.6 , -4.94]	12.52	4.32	[1.86 , 6.78]
	H4	66.52	-7.94	[-13.63 , -2.24]	87.64	-2.82	[-8.58 , 2.93]	19	1.47	[-1.45 , 4.4]

In Table 3.4, the EMG signal regression analysis elaborates the MDF and MNF and RMS against the time for four different heights for four subjects, and highlighted cells showed muscle fatigue during whole lifting task for UTL muscle for each height.

As indicated by the results, subject 1 and subject 3 showed signs of fatigue due to negative MDF/MNF slopes and positive RMS slope for 4 subjects at four different heights for the upper trapezoid muscle on the left side with a 95 percent confidence interval. According to the findings, for subject 2, three heights (H1, H3 and H4) had a negative frequency slope with a negative RMS slope. For this subject there was a little decrease of mean frequency in just H2, equal to -0.6 Hz with positive RMS that shows fatigue in this height. Although the mean frequency slope is negative for this height, it is not very significant. In other words, this value is so small that it can be assumed to be positive. And in general, it shows that the second subject's muscle did not show fatigue at any height. For better visualization, Figures 3.7 and 3.8 have been made, and you can see them below. The pattern of declining mean and median frequency in three heights such as H1, H3 and H4 can be clearly seen from the figures. For other subjects in Appendix V, the remaining plots given can be seen.

As shown in the table, subject 4 met the muscle fatigue parameters (decreasing MDF/MNF and increasing RMS) only in H3 and H4. The slopes of the RMS in combination with the negative slopes of the median and mean frequency in H1 and H2 have been negative for this subject.

It can be inferred by observing these results that H3 has shown upper trapezius left muscle fatigue among 3 subjects. This will be visualized better at the added plots in Appendix V.

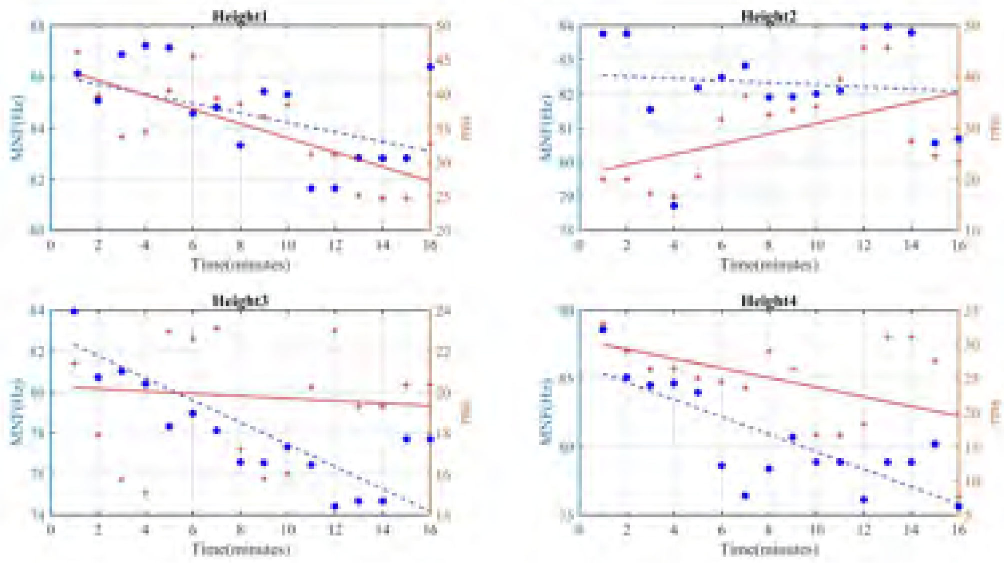


Figure 3.7 Changes in median frequency (MNF) versus time (minutes) of UTL muscle for four heights (Subject 2)

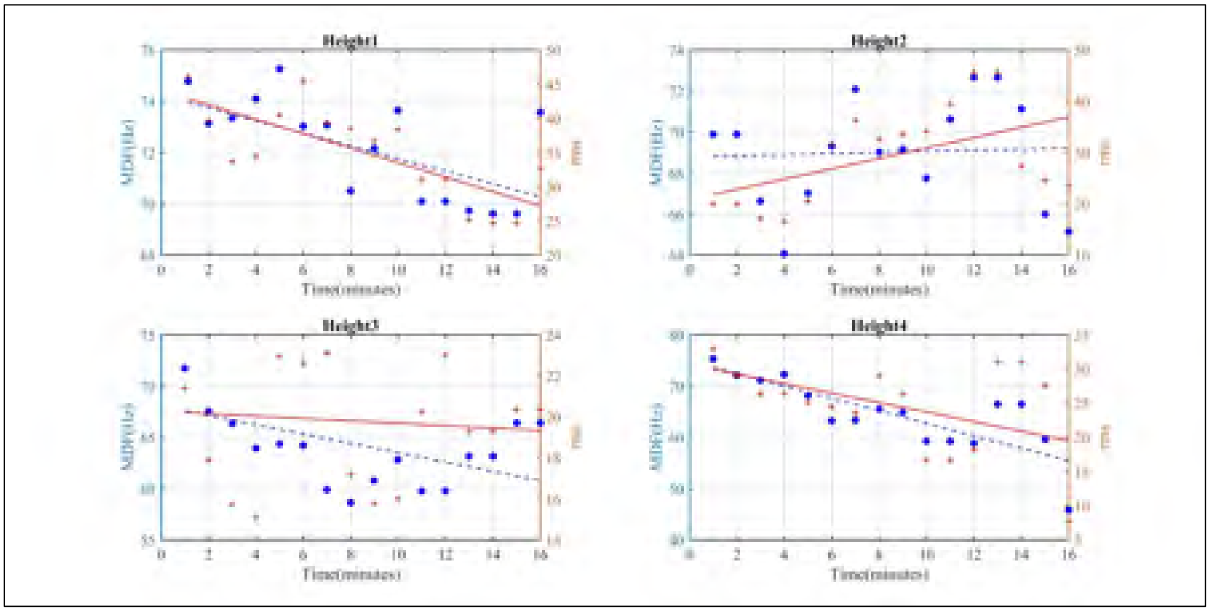


Figure 3.8 Changes in median frequency (MDF) versus time (minutes) of UTL muscle for four heights (subject 2)

3.1.5 Lower trapezius right (LTR)

Table 3.5 Regression analysis of the MDF, MNF and RMS for the LTR muscle of 4 subjects based on four heights

		Median			***Mean***			***RMS***		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*
1	H1	64.14	-1.85	[-5.59 , 1.88]	94.69	0.85	[-2.33 , 4.02]	12.92	0.62	[-1.59 , 2.83]
	H2	65.18	-13.25	[-18.97 , -7.54]	98.42	-12.73	[-22.19 , -3.26]	10.96	1.64	[-0.4 , 3.68]
	H3	65.29	-17.23	[-23.62 , -10.83]	100.33	-19.47	[-25.33 , -13.62]	10.96	1.46	[0.15 , 2.76]
	H4	66.43	-9.87	[-13.24 , -6.5]	97.64	-10.3	[-15.65 , -4.94]	14.12	-2.72	[-4.09 , -1.34]
2	H1	60.44	-15.92	[-19.79 , -12.06]	79.97	-16.67	[-25.12 , -8.22]	-2.01	114.7	[57.83 , 171.57]
	H2	64.04	-23.74	[-29.1 , -18.38]	79.53	-15.93	[-25.47 , -6.39]	8.83	161.38	[-12.17 , 334.92]
	H3	62.86	-24.56	[-31.18 , -17.93]	77.57	-17.95	[-24.58 , -11.31]	27.61	28.01	[8.53 , 47.49]
	H4	63.07	-22.47	[-28.41 , -16.53]	78.52	-16.57	[-27.26 , -5.89]	23.93	34.6	[17.36 , 51.83]
3	H1	64.26	-10.36	[-13.55 , -7.17]	74.63	-14.84	[-19.14 , -10.55]	64.95	12.2	[-14.08 , 38.48]
	H2	63.98	-8.35	[-11.85 , -4.84]	76.2	-16.43	[-20.6 , -12.26]	58.13	-3.71	[-20.29 , 12.87]
	H3	61.92	-6.32	[-9.35 , -3.29]	74.11	-15.31	[-19.79 , -10.83]	61.28	-18.2	[-41.04 , 4.63]
	H4	61.28	-3.21	[-4.6 , -1.82]	73.51	-10.33	[-16.23 , -4.42]	56.81	-1.18	[-31.21 , 28.85]
4	H1	60.53	2.42	[0.32 , 4.52]	85.64	3	[-2.51 , 8.51]	35.47	1.51	[-7.49 , 10.5]
	H2	59.27	3.74	[1.61 , 5.87]	82.17	3.19	[-3.31 , 9.68]	35.67	-1.71	[-5.84 , 2.43]
	H3	60.78	-0.94	[-4.25 , 2.38]	83.09	-1.26	[-9.5 , 6.98]	32.06	2.11	[-5.13 , 9.34]
	H4	59.35	1.22	[-3.38 , 5.81]	83.09	0.78	[-13.03 , 14.59]	34.28	-0.42	[-10.65 , 9.8]

For the lower trapezius right muscle, the regression analysis of frequency versus the time for four heights was applied. In this muscle, for subjects 1 and 2, presence of muscle fatigue was seen for 3 heights as H1, H2 and H3, while for subjects 3 and 4, just one height (H1 for subject 3 and H3 for subject 4) showed fatigue with showing negative MDF/MNF slope and positive RMS slope.

As obtained from the findings, in fatiguing this muscle, H4 had almost the least impact. On the other hand, for the lower trapezius on the left side of the body just 2 subjects presented muscle fatigue (Subject 1 for H1, H2 and H3 and subject 2 for all heights). Moreover, the lower trapezius left muscle for subjects 3 and 4 did not show too much muscle fatigue because only one height for each of them (H1 for subject 3 and H3 for subject 4) had a negative frequency slope and a positive RMS slope.

The changes in MNF and MDF for the second subject who had the most muscle fatigue in lower trapezius right can be clearly seen on the Figures 3.9 and 3.10. These figures dropping frequency and rising RMS can be seen for all heights. The rest of the figures provided for other subjects can be seen in Appendix V.

Based on Figures 3.9 and 3.10, the pattern of frequency and RMS showed muscle fatigue was happening at a quarter of last minutes of the lifting task after nearly 12 minutes in this muscle (LTR).

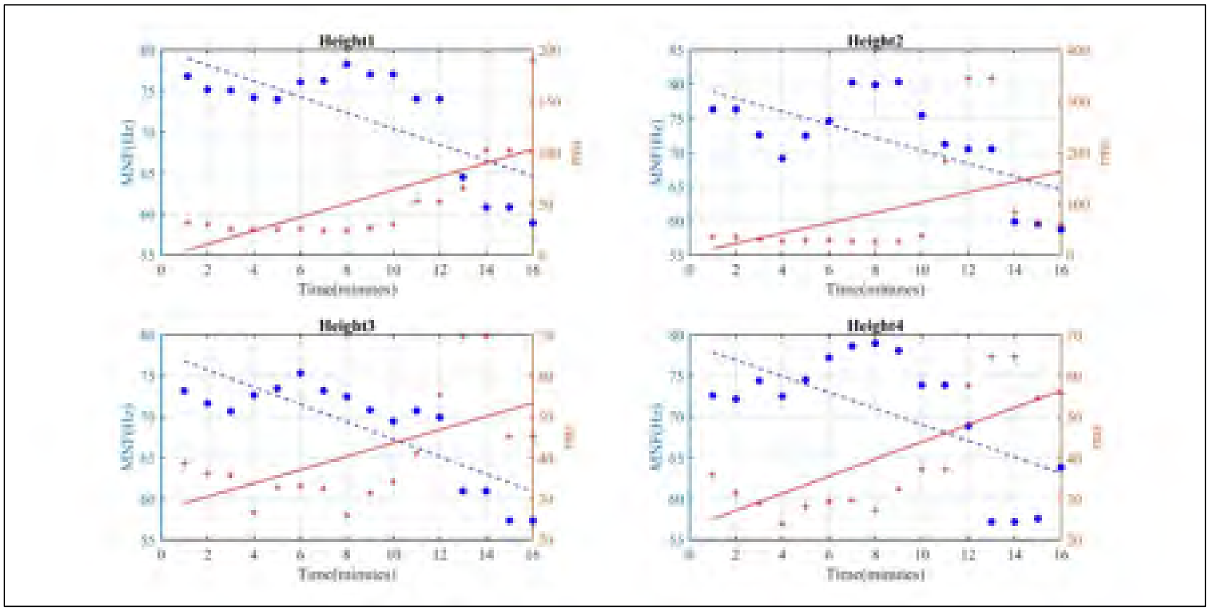


Figure 3.9 Changes in median frequency (MNF) versus time (minutes) of LTR muscle for four heights (Subject 2)

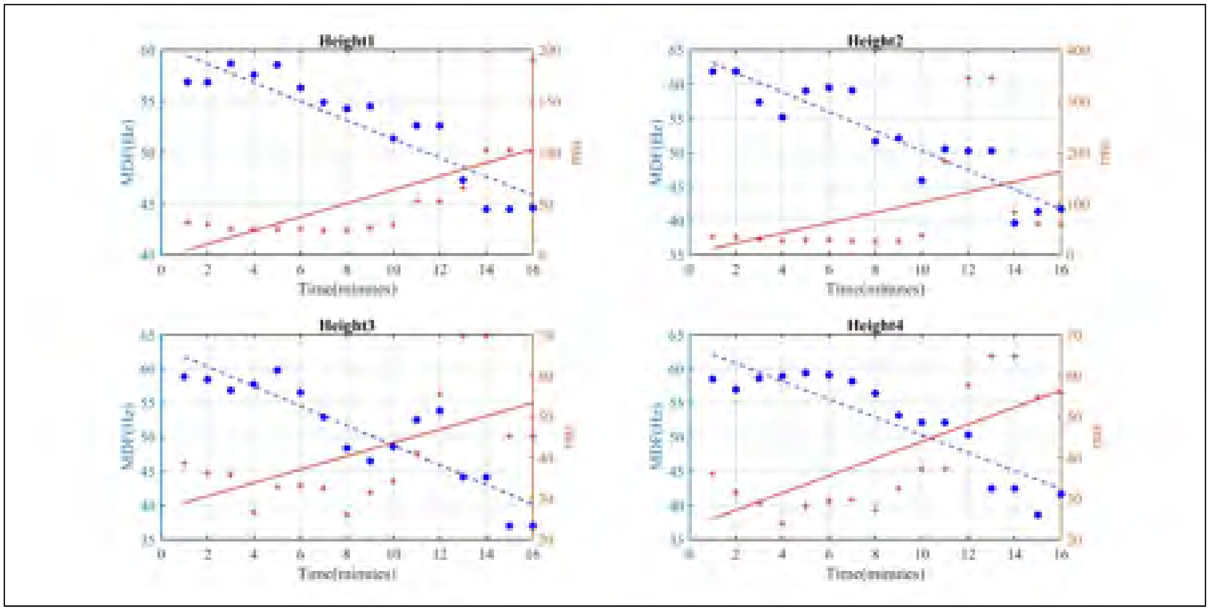


Figure 3.10 Changes in median frequency (MDF) versus time (minutes) of LTR muscle for four heights (subject 2)

3.1.6 Lower trapezius left (LTL)

Table 3.6 Regression analysis of the MDF, MNF and RMS for the LTL muscle of 4 subjects based on four heights

		Median			**Mean**			**RMS**		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*
1	H1	59.82	0.61	[-4.6 , 5.82]	97.34	-2.21	[-5.5 , 1.07]	18.42	0.62	[-2.55 , 3.8]
	H2	59.58	-10.69	[-16.31 , -5.07]	100.22	-8.39	[-12.54 , -4.24]	15.08	2.03	[1 , 3.05]
	H3	56.7	-5.69	[-10.32 , -1.05]	104.57	-18.72	[-25.26 , -12.18]	14.9	3.73	[0.82 , 6.65]
	H4	54.92	-6.48	[-9.12 , -3.84]	97.63	-9.46	[-12.32 , -6.6]	16.82	-0.36	[-1.73 , 1.01]
2	H1	63.01	-3.4	[-8.42 , 1.63]	79.75	12.24	[6.19 , 18.3]	38.93	-24.53	[-29.3 , -19.76]
	H2	60.38	-0.26	[-4.72 , 4.21]	79.03	14.73	[8.56 , 20.9]	37.08	-24.31	[-27.97 , -20.64]
	H3	61.16	-6.15	[-9.74 , -2.57]	81.78	2.18	[-1.38 , 5.74]	33.07	-15.47	[-20.52 , -10.42]
	H4	58.19	2.29	[-1.38 , 5.96]	77.75	12.81	[8.45 , 17.17]	34.96	-21.52	[-25.7 , -17.35]
3	H1	57.24	-7.64	[-11.27 , -4.01]	72.62	-19.27	[-23.79 , -14.76]	41.16	6.49	[-3.97 , 16.96]
	H2	58.3	-12.61	[-15.97 , -9.26]	74.58	-23.31	[-31.28 , -15.34]	40.26	2.36	[-4.12 , 8.84]
	H3	57.86	-13.77	[-17.57 , -9.96]	74.97	-28.02	[-36.17 , -19.86]	44.62	-13.82	[-25.51 , -2.12]
	H4	58.27	-13.24	[-16.02 , -10.46]	73.96	-23.03	[-30.19 , -15.87]	42.59	-11.27	[-22.69 , 0.16]
4	H1	70.89	22.46	[15.07 , 29.85]	54.78	6.35	[-0.18 , 12.89]	50.94	-34.02	[-43.49 , -24.54]
	H2	67.14	30.55	[23.42 , 37.68]	52.2	11.05	[5.23 , 16.87]	43.04	-27.9	[-32.32 , -23.48]
	H3	68.16	25.87	[18.24 , 33.5]	52.93	8.09	[4.56 , 11.62]	45.94	-32.48	[-40.59 , -24.36]
	H4	67.71	24.9	[18 , 31.79]	52.03	10.33	[6.58 , 14.08]	46.4	-28.79	[-40.41 , -17.17]

Regression analysis of EMG amplitude and frequency for the lower trapezius left side of the body was done for four different heights (Table 3.6). According to the results, during the 16-minute lifting test, only 2 subjects (1 and 3) showed presence of muscle fatigue. For subject 1, H2 and H3 had a negative slope in both MDF and MNF and positive slope of RMS, while H1 for this subject just illustrated negative MNF slope along with positive RMS slope. Although the negative slope and positive for RMS is shown by H1 for MNF, it is not too much, which means that there is not too much muscle fatigue at this height. These small changes for MNF in H1 can be seen in Figure 3.11.

Moreover, H1 and H2 were the signs of the muscle fatigue for subject 3. However, based on the findings, H2 was a remarkable height among other heights that showed signs of fatigue for these two subjects. As is obvious from the results, no fatigue occurred during manual lifting for subjects 2 and 4.

The shifts in MNF and MDF for subject 1 for four different heights can be clearly seen in Figures 3.11 and 3.12. As can be seen in the plots, H2 and H3 displayed these declining and rising trends as the table results showed. The remainder of the figures plotted for other subjects can be seen in Appendix V.

Looking at the height pattern, we can see that between 11 and 14 minutes of fatigue took place. And after 14 minutes, the frequency almost began to increase and RMS started to decrease (Figure 3.11 and 3.12).

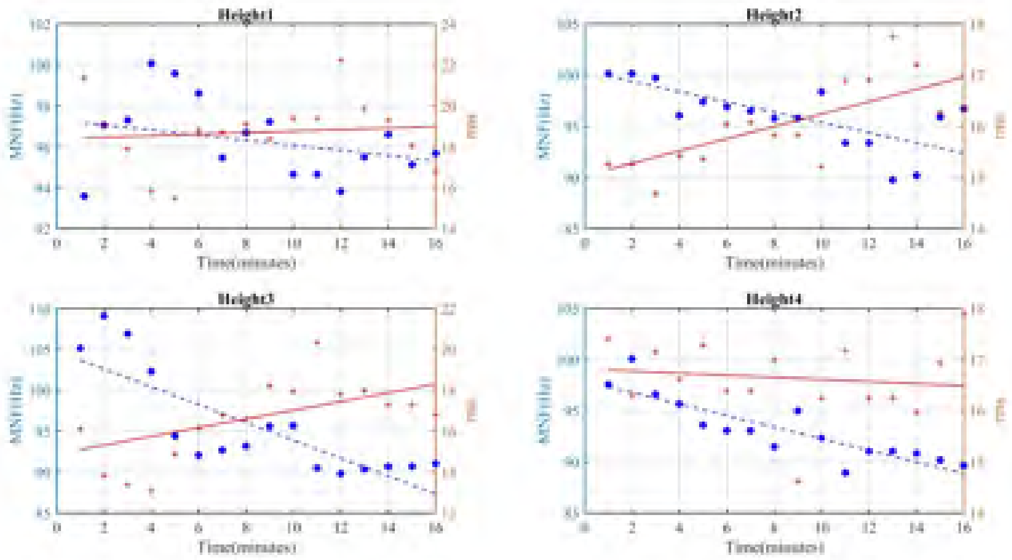


Figure 3.11 Changes in median frequency (MNF) versus time (minutes) of LTL muscle for four heights (Subject 1)

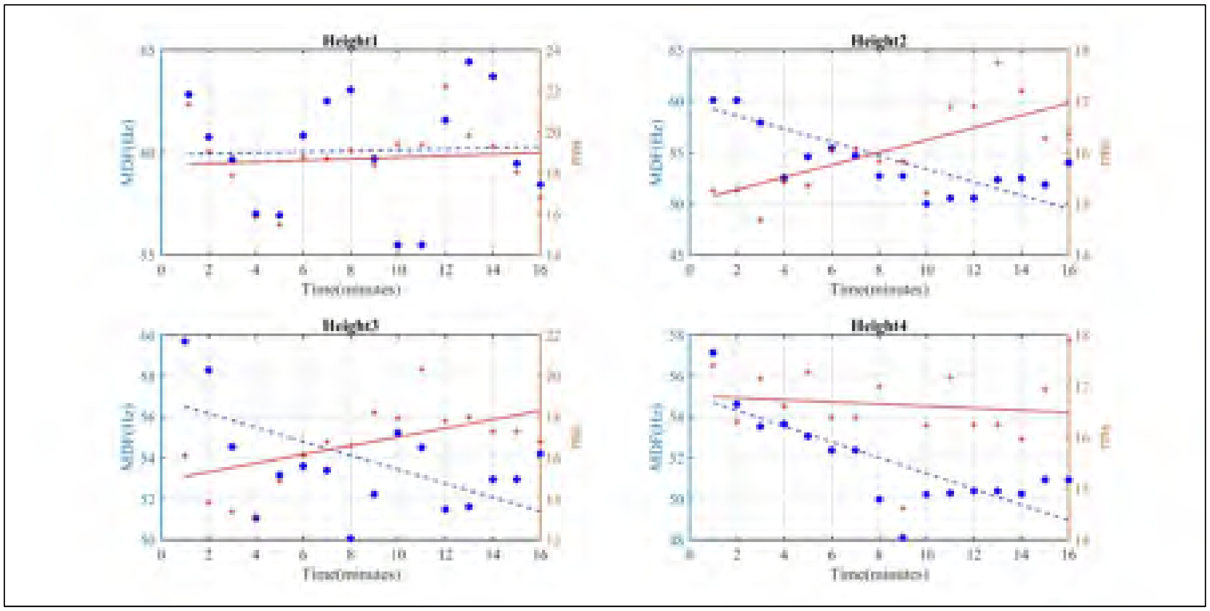


Figure 3.12 Changes in median frequency (MDF) versus time (minutes) of LTL muscle for four heights (subject 1)

3.1.7 Middle trapezius right (MTR)

Table 3.7 Regression analysis of the MDF, MNF and RMS for the MTR muscle of 4 subjects based on four heights

		Median			***Mean***			***RMS***		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% CI [LL,UL]*
1	H1	51.53	-6.71	[-9.47 , -3.95]	68.1	-7.57	[-10.65 , -4.48]	24.93	-3.72	[-8.86 , 1.42]
	H2	49.06	-2.46	[-4.36 , -0.56]	67.05	-9.72	[-12.58 , -6.87]	22.13	-1.4	[-4.87 , 2.08]
	H3	48.09	-3.65	[-7.89 , 0.59]	67.33	-10.69	[-15 , -6.37]	23.33	-1.84	[-4.9 , 1.23]
	H4	48.9	-5.2	[-7.28 , -3.12]	70.42	-10.84	[-13.98 , -7.69]	15.85	3.7	[0.26 , 7.14]
2	H1	57.3	-9.47	[-13.05 , -5.88]	74.56	-14.68	[-20.23 , -9.13]	30.23	4.49	[-8.43 , 17.41]
	H2	56.04	-8.69	[-12.14 , -5.23]	72.95	-11.17	[-16.21 , -6.14]	26.59	11.75	[0.33 , 23.16]
	H3	54.87	-7.61	[-9.95 , -5.27]	71.84	-12.23	[-15.81 , -8.65]	26.98	4.05	[-2.98 , 11.08]
	H4	52.43	-5.31	[-7.69 , -2.92]	70.01	-9.32	[-14 , -4.64]	24.54	7.93	[3.03 , 12.83]
3	H1	62.68	-5.75	[-9.74 , -1.76]	78.3	-13.38	[-18.2 , -8.56]	85.72	17.15	[-11.67 , 45.96]
	H2	60.74	-5.59	[-8.86 , -2.32]	77.2	-11.02	[-15.1 , -6.93]	66.99	-9.75	[-32.66 , 13.16]
	H3	60.86	-8.45	[-11.48 , -5.42]	78.29	-17.82	[-21.89 , -13.75]	67.35	-26.17	[-50.88 , -1.46]
	H4	61.82	-6.72	[-9.48 , -3.96]	77.67	-13.47	[-17.99 , -8.95]	70.22	-2.42	[-34.01 , 29.17]
4	H1	67.66	-6.75	[-15.41 , 1.9]	84.74	8.75	[-2.35 , 19.85]	20.29	-10.55	[-14.83 , -6.27]
	H2	67.61	-5.48	[-15.79 , 4.84]	86.97	4.27	[-7.12 , 15.65]	18.08	-10.13	[-13.03 , -7.23]
	H3	59.12	7.71	[1.32 , 14.11]	77.08	17.31	[8.23 , 26.38]	17.77	-12.08	[-16.26 , -7.9]
	H4	66.83	5.22	[-1.95 , 12.4]	85.69	17.04	[8.07 , 26.02]	19.38	-13.59	[-16.27 , -10.91]

Table 3.7 illustrates the regression analysis of EMG amplitude and frequency for 4 heights for the middle trapezius right muscle. Based on these results, fatigue has occurred by negative slopes of MDF and MNF and positive slope of RMS for all four heights for subject 2. As seen in the table, for subjects 1 and 3, only one height (H4 for subject 1 and H1 for subject 3) showed muscle fatigue, and for subject 4, there was no muscle fatigue at each height.

Figures 3.13 and 3.14 illustrated the decrease in MDF and MNF and increase in RMS for each height for subject 2 who had fatigue during each height. Based on the findings derived from above table, the trend of drop and rise of the frequency and EMG amplitude for four heights was displayed perfectly on these figures as well. The remainder of the plots for other subjects can be seen in Appendix V.

As can be observed from Figures 3.13 and 3.14, the trend showed that muscle fatigue in MTR occurred between 7 and 10 minutes, and then the frequency started to increase after this point, and by the end of the lifting task, RMS began to decrease.

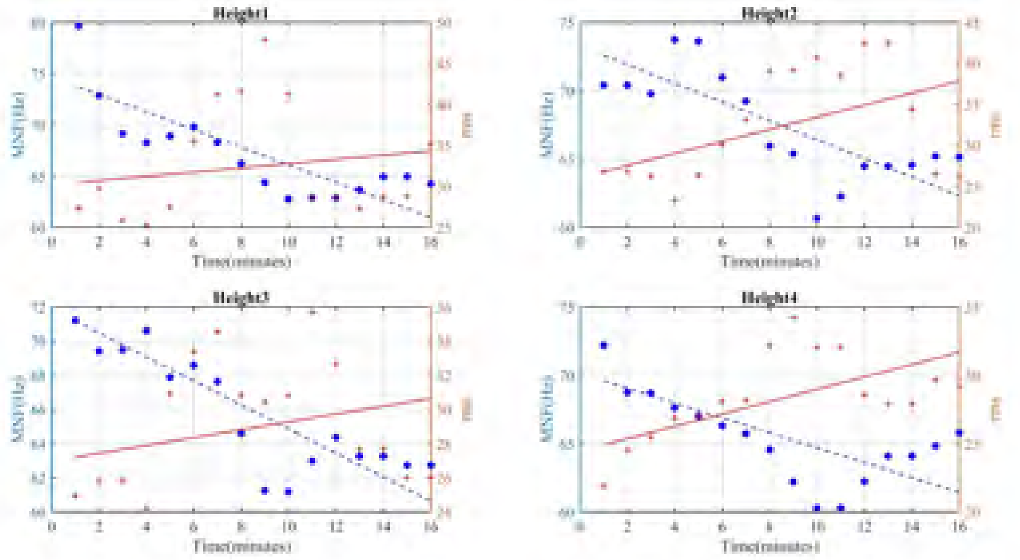


Figure 3.13 Changes in median frequency (MNF) versus time (minutes) of MTR muscle for four heights (Subject 2)

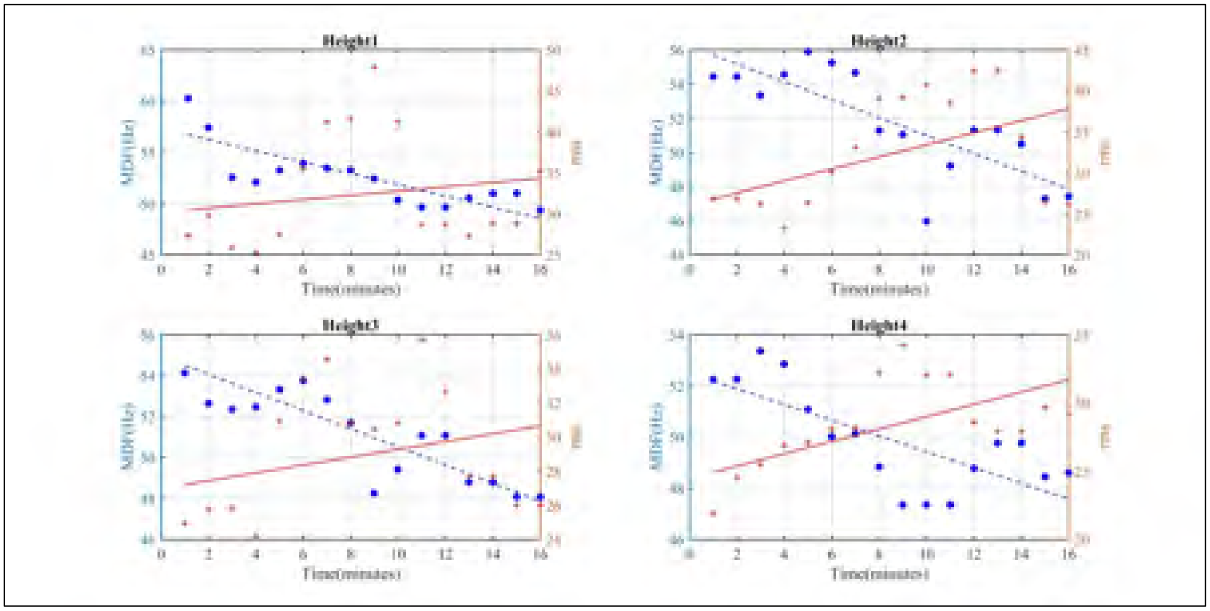


Figure 3.14 Changes in median frequency (MDF) versus time (minutes) of MTR muscle for four heights (Subject 2)

3.1.8 Middle trapezius left (MTL)

Table 3.8 Regression analysis of the MDF, MNF and RMS for the MTL muscle of 4 subjects based on four heights

		Median			Mean			RMS		
Subject	Height	Median Intercept	Slope coefficient 10^{-3}	95% CI [LL,UL]	Mean Intercept	Slope coefficient 10^{-3}	95% CI [LL,UL]	rms Intercept	Slope coefficient 10^{-3}	95% CI [LL,UL]
1	H1	49.53	-2.18	[-3.59 , -0.77]	63.42	-1.62	[-2.92 , -0.32]	20.58	14.92	[9.48 , 20.35]
	H2	50.2	-2.94	[-5.6 , -0.28]	62.47	-2	[-5 , 0.99]	21.1	20.52	[14.22 , 26.82]
	H3	47.03	2.59	[-1.28 , 6.46]	60.56	0.23	[-3.49 , 3.96]	19.46	34.22	[27.11 , 41.33]
	H4	49.43	-2.47	[-6.72 , 1.77]	61.92	-1.43	[-5.8 , 2.94]	20.47	23.15	[18.16 , 28.14]
2	H1	60.98	-20.87	[-27.27 , -14.47]	81.57	-19.5	[-25.77 , -13.24]	23.92	5.76	[1.65 , 9.87]
	H2	55.61	-13.09	[-17.26 , -8.93]	80.56	-18.02	[-24.33 , -11.71]	18.56	11.79	[7.35 , 16.22]
	H3	56.14	-12.38	[-17.64 , -7.12]	80.89	-16.33	[-23.1 , -9.55]	19.14	16.58	[11.85 , 21.3]
	H4	55.55	-14.84	[-18.8 , -10.89]	78.37	-15.71	[-22.49 , -8.94]	21.07	5.89	[0.01 , 11.77]
3	H1	56.12	0.21	[-4.72 , 5.14]	72.27	-6.28	[-11.18 , -1.38]	50.83	10.91	[-3.1 , 24.92]
	H2	62.98	-4.37	[-10.14 , 1.41]	77.53	-11.72	[-16.89 , -6.56]	47.75	12.18	[-1.9 , 26.27]
	H3	68.1	-14.18	[-17.7 , -10.65]	79.52	-14.4	[-18.2 , -10.6]	51.58	-8.73	[-27.42 , 9.96]
	H4	63.56	-10.21	[-15.52 , -4.91]	76.97	-13.82	[-18.04 , -9.6]	52.38	-15.58	[-32.69 , 1.52]
4	H1									
	H2									
	H3									
	H4									

The regression analysis of EMG signal in Table 3.8 elaborates the MDF and MNF and RMS of middle trapezius left (MTL) muscle for four different heights for 4 subjects. The gained results show muscle fatigue by negative slopes of MDF and MNF and positive RMS with 95% confidence interval for MTL muscle of 4 subjects for each height during the entire 16 minutes of lifting task.

As can be observed in the table above, in all four heights, the second subject indicated MTL muscle fatigue. In addition, the first subject showed fatigue of the MTL muscle in all four heights, except the third height. Although, these 2 subjects illustrated muscle fatigue, based on the results it was found the amount of frequency reduction for subject 1 is not too much. According to Figures 3.15 and 3.16, this slight change can be easily understood. The remainder of the plots for other subjects can be seen in Appendix V.

Subject 3 only showed muscle fatigue at H1 (mean frequency) and H2. As you can see in the table, no data has been recorded for subject 4 for the reason of de-attaching the sensors on the participant's body due to perspiring a lot during the experiment (Black box in the table).

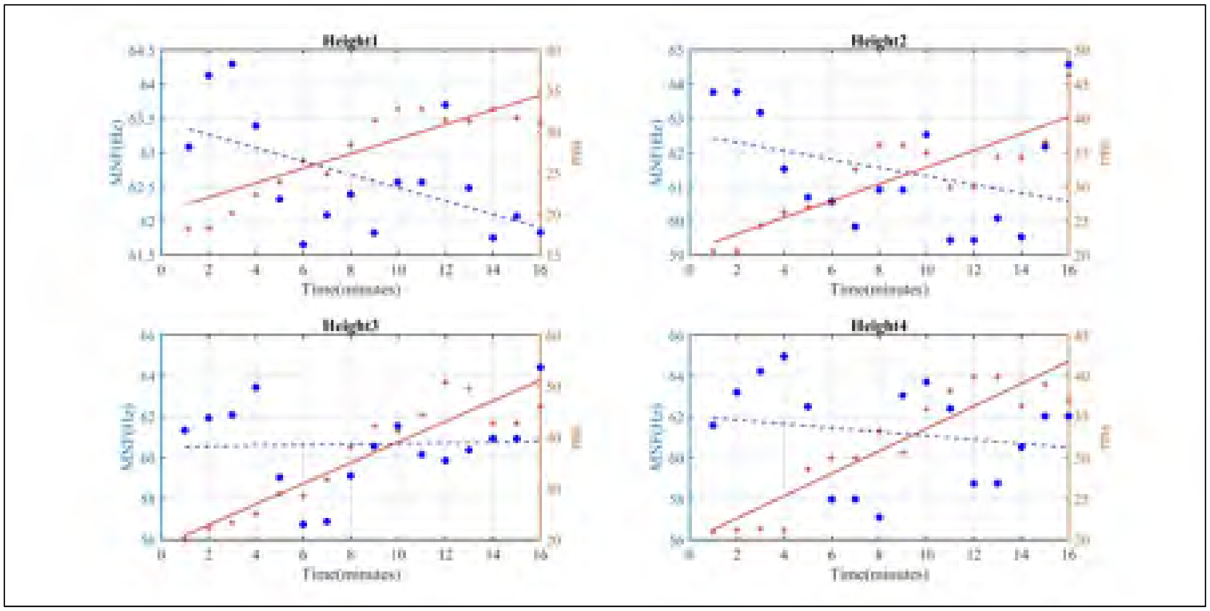


Figure 3.15 Changes in median frequency (MNF) versus time (minutes) of MTL muscle for four heights (Subject 1)

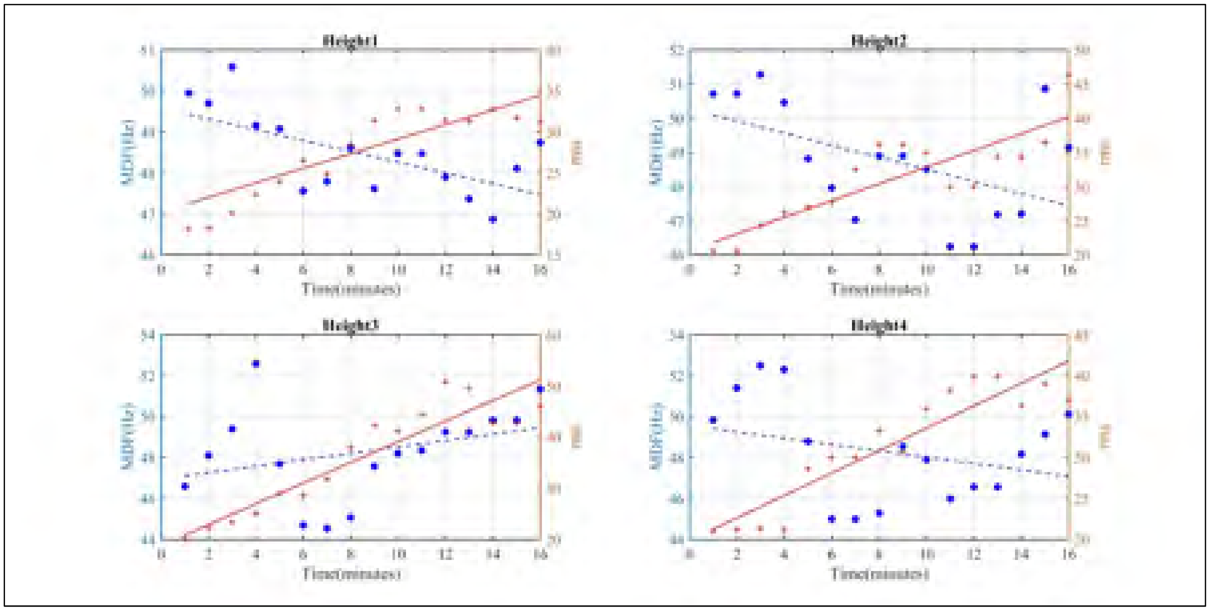


Figure 3.16 Changes in median frequency (MDF) versus time (minutes) of MTL muscle for four heights (Subject 1)

3.1.9 Erector espinae right (ESR)

Table 3.9 Regression analysis of the MDF, MNF and RMS for the ESR muscle of 4 subjects based on four heights

		Median			***Mean***			***RMS***		
Subject	*Height*	*Median Intercept*	*Slope coefficient 10^{-3}*	*95% confidence interval 10^{-3}*	*Mean Intercept*	*Slope coefficient 10^{-3}*	*95% confidence interval 10^{-3}*	*rms Intercept*	*Slope coefficient 10^{-3}*	*95% confidence interval 10^{-3}*
1	H1	56.05	-3.68	-7.21 < SC < -0.15	80.17	-3.5	-6.78 < SC < -0.22	24.34	6.01	3.29 < SC < 8.73
	H2	54.88	2.19	-2.58 < SC < 6.97	84.86	-7.52	-12.24 < SC < -2.81	18.24	11.64	8.84 < SC < 14.43
	H3	54.36	0.62	-2.23 < SC < 3.47	82.87	-6.68	-11.39 < SC < -1.97	18.99	10.62	7.7 < SC < 13.54
	H4	54.6	1.69	-1.09 < SC < 4.48	84.06	-5.8	-8.23 < SC < -3.36	19.88	7.2	4.01 < SC < 10.39
2	H1	66.44	-2.7	-7.28 < SC < 1.88	84.53	-4.67	-10.86 < SC < 1.51	75.82	-8.16	-21.83 < SC < 5.51
	H2	64.94	-2.38	-8.87 < SC < 4.11	81.44	-4.12	-13.04 < SC < 4.81	80.77	-5.57	-15.79 < SC < 4.64
	H3	60.44	6.67	4.13 < SC < 9.21	76.6	6.97	3.25 < SC < 10.7	85.63	-27.78	-35.64 < SC < -19.91
	H4	62.15	5.94	1.6 < SC < 10.29	78.31	5.53	-0.28 < SC < 11.35	80.07	-23.53	-38.63 < SC < -8.44
3	H1	68.76	-14.1	-18.13 < SC < -10.08	90.68	-30.58	-39.07 < SC < -22.08	76.61	21.98	-1.4 < SC < 45.36
	H2	67.92	-11.78	-14.88 < SC < -8.68	89.12	-25.62	-30.4 < SC < -20.84	54.81	69.71	41.42 < SC < 98.01
	H3	62.4	-2.79	-4.43 < SC < -1.16	83.93	-13.44	-17.71 < SC < -9.16	75.64	13.68	-10.1 < SC < 37.46
	H4	62.03	-1.68	-4.33 < SC < 0.98	81.62	-10.41	-16.64 < SC < -4.18	83.31	-4.1	-31.66 < SC < 23.45
4	H1	64.43	-6.58	-15.96 < SC < 2.8	83.76	-5.9	-16.57 < SC < 4.76	55.18	-7.57	-22.18 < SC < 7.05
	H2	60.1	-1.77	-5.41 < SC < 1.87	79.89	1.65	-3.58 < SC < 6.88	53.06	-9.53	-13.72 < SC < -5.34
	H3	59.85	-3.14	-4.76 < SC < -1.51	77.53	-0.91	-3 < SC < 1.18	51.81	-9.72	-17.08 < SC < -2.36
	H4	59.58	-1.97	-4.44 < SC < 0.51	79.54	-1.47	-4.11 < SC < 1.16	45.52	5.19	-2.24 < SC < 12.61

As can be seen in above table (Table 3.9), the regression analysis of EMG signal is shown in terms of MDF and MNF and RMS versus the time for four different heights. According to the results, the negative value of the MDF and MNF indicates induced fatigue in ESR muscle within the entire 16-minute lifting task.

For this muscle, H1, H2 and H3 somehow showed the presence of muscle fatigue in 2 subjects (Subject 1 and 3). For first subject, H1 showed signs of muscle fatigue simultaneously in mean and median frequency. For the third subject, muscle fatigue was shown in first three heights (H1, H2 and H3). Subject 4, just had a muscle fatigue in H4 that was a negligible amount compared to the other heights.

Considering the trend shown in Figures 3.17 and 3.18 for the instantaneous MDF/MNF and RMS against time (minute) for four heights are different during time interval i.e., 16 minutes for third subject's ESR muscle that showed greater decrease in frequency. The remainder of plots for 3 other subjects are found in Appendix V.

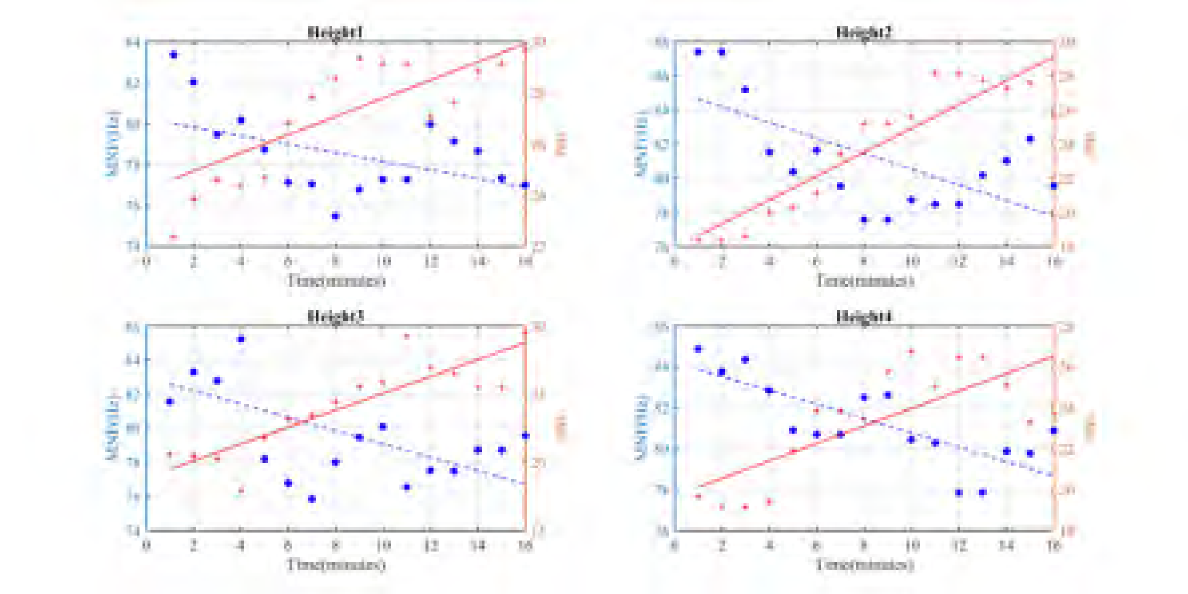


Figure 3.17 Changes in median frequency (MNF) versus time (minutes) of ESR muscle for four heights (Subject 1)

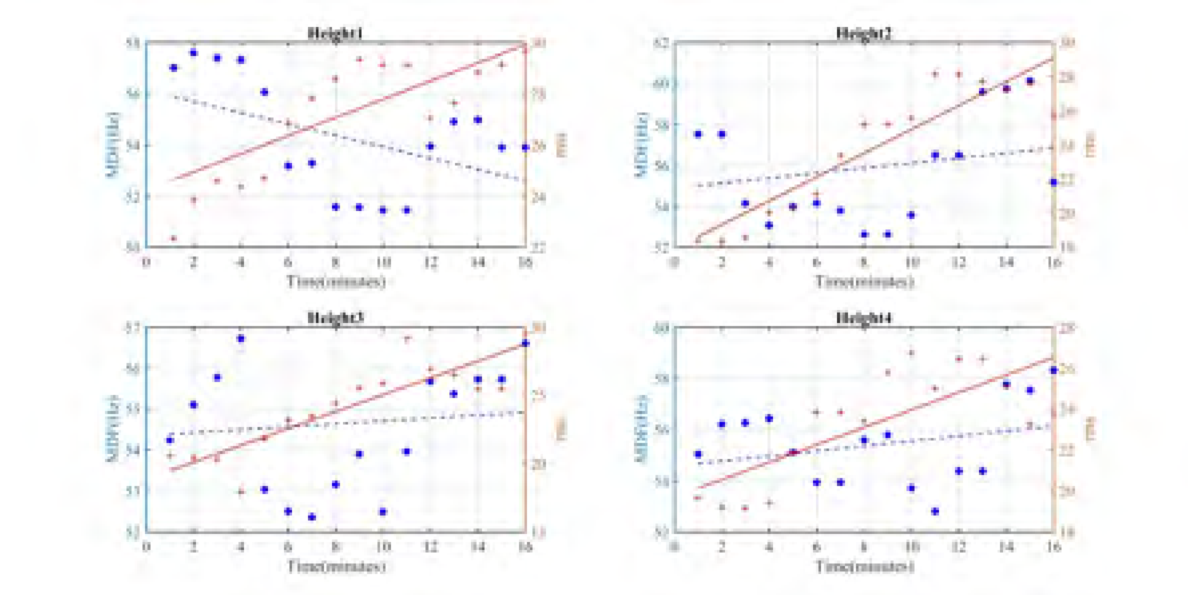


Figure 3.18 Changes in median frequency (MDF) versus time (minutes) of ESR muscle for four heights (Subject 1)

3.1.10 Erector espinae left (ESL)

Table 3.10 Regression analysis of the MDF, MNF and RMS for the ESL muscle of 4 subjects based on four heights

		Median			***Mean***			***RMS***		
Subject	*Height*	*Median Intercept*	*Slope coefficient* 10^{-3}	*95% CI [LL,UL]*	*Mean Intercept*	*Slope coefficient* 10^{-3}	*95% CI [LL,UL]*	*rms Intercept*	*Slope coefficient* 10^{-3}	*95% CI [LL,UL]*
1	H1	50.36	-2.34	[-4.73 , 0.05]	63.48	-4.76	[-8.45 , -1.08]	29.94	35.47	[19.58 , 51.37]
	H2	52.38	-4.38	[-7.68 , -1.08]	64.2	-4.48	[-7.76 , -1.19]	28.91	16.52	[11.56 , 21.47]
	H3	50.56	-3.1	[-5.22 , -0.98]	62.69	-4.4	[-8.24 , -0.57]	28.88	13.42	[5.27 , 21.57]
	H4	49.96	-0.84	[-2.9 , 1.23]	61.78	0.86	[-3.32 , 5.03]	31.21	10.88	[-4.62 , 26.38]
2	H1	64.98	-3.81	[-10.16 , 2.54]	82.68	-11.29	[-21.59 , -0.99]	68	-4.46	[-13.61 , 4.7]
	H2	65.74	-4.48	[-11.46 , 2.5]	79.22	-4.87	[-14.06 , 4.32]	80.21	-16.67	[-26.79 , -6.55]
	H3	64.47	-0.51	[-9.9 , 8.87]	78.35	-1.94	[-12.65 , 8.77]	78.66	-12.85	[-18.43 , -7.28]
	H4	62.47	5.84	[-1.31 , 12.98]	78.82	-0.16	[-9.58 , 9.27]	70.09	-9.83	[-17.38 , -2.28]
3	H1	62.29	-6.61	[-10.63 , -2.6]	82.13	-22.91	[-28.83 , -16.99]	64.01	50.47	[27.09 , 73.86]
	H2	59.31	-3.16	[-5.28 , -1.04]	78.04	-15.4	[-18.71 , -12.1]	83.04	25.81	[9.38 , 42.25]
	H3	58.77	-4.27	[-6.1 , -2.44]	72.47	-5.1	[-9.36 , -0.83]	99.62	-27.89	[-49.89 , -5.89]
	H4	59.17	-0.75	[-4.18 , 2.68]	74.62	-9.13	[-14.74 , -3.52]	88.31	-33.95	[-55.25 , -12.64]
4	H1									
	H2									
	H3									
	H4									

As can be shown in the Table 3.10, the EMG signal regression analysis is seen in terms of MDF, MNF and RMS versus time for four different heights. According to the results, the negative value of the MDF and MNF indicate induced fatigue in the ESR muscle within the entire 16 minutes of the lifting task for subjects 1 and 3.

As the outcome shows, it can be seen that H1 and H2 for both MDF and MNF has decreased for two subjects (subjects 1 and 3). Based on the findings, for subject 1 there was decreasing frequency in H3 and H4, but there was a drop in MDF for H4, not MNF. As can be seen in Figure 3.19, positive slope of the MNF for H4 has been presented clearly. However, as shown in Figures 3.19 and 3.20, all heights showed an upward trend of RMS and downward trend of MDF/MNF for first subject which confirmed the results obtained from Table 3.10. The other plots for three other subjects are located in Appendix V.

As can be seen in the table, no data was collected for subject 4, for reasons such as de-attaching the sensors to the body of the participant due to a lot of perspiring during the experiment (The black box at the table).

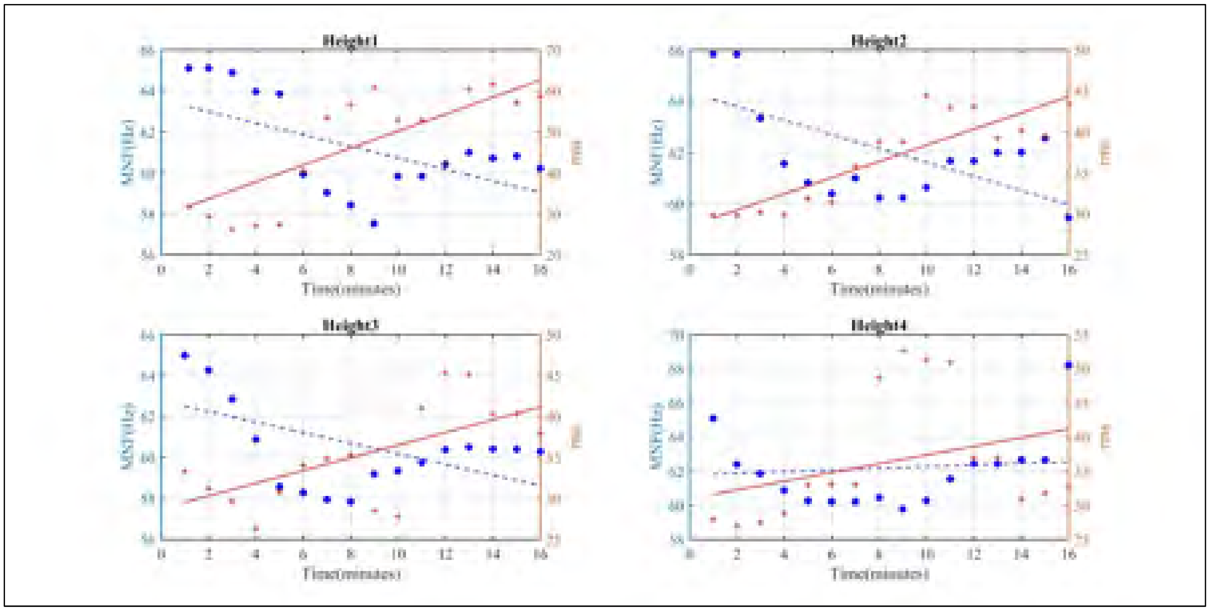


Figure 3.19 Changes in median frequency (MNF) versus time (minutes) of ESL muscle for four heights (Subject 1)

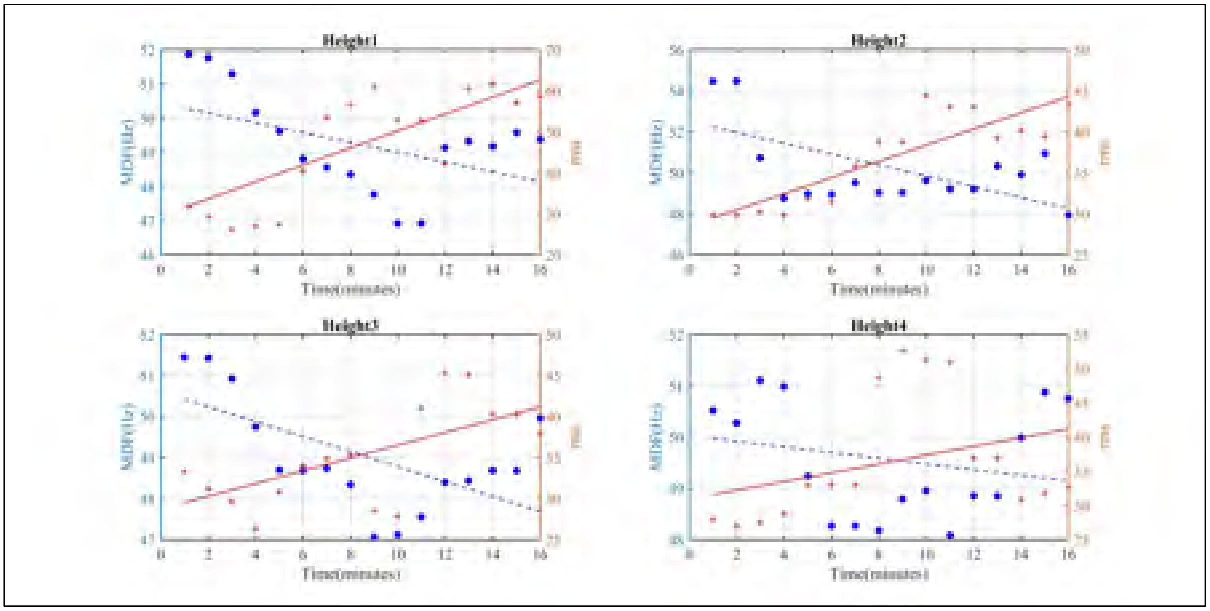


Figure 3.20 Changes in median frequency (MNF) versus time (minutes) of ESL muscle for four heights (Subject 1)

3.2 Significant muscle and height based on MDF and MNF entire lifting task

Based on observation of the mean/median frequency values over time, we aimed to identify the muscles and heights that cause more fatigue during manual lifting than others. Due to this purpose, two tables (Tables 3.11 and 3.12) have been established to show the results of this analysis. The tables are explained below.

Table 3.11 Percentage of number of cases where fatigue occurs in ten different muscles at different heights for the 4 subjects (MDF).

Height / Muscle	PDR	PDL	UTR	UTL	LTR	LTL	MTR	MTL	ESR	ESL	Average
H1	100%	100%	25%	50%	75%	25%	50%	50%	50%	50%	57.5
H2	100%	75%	75%	50%	50%	50%	25%	75%	25%	50%	57.5
H3	75%	75%	100%	75%	75%	25%	25%	25%	25%	25%	52.5
H4	75%	50%	50%	75%	25%	0%	50%	50%	25%	25%	42.5
Average	**87.5**	75	62.5	62.5	56.25	**25**	37.5	50	31.25	37.5	

Table 3.11 displays the percentage of number of cases where fatigue occurred in ten different muscles and at different heights, resulting from the median frequency (MDF) for the four subjects.

As can be shown, 10 different muscles called posterior deltoid right (PDR), posterior deltoid left (PDL), upper trapezius right (UTR), upper trapezius left (UTL), lower trapezius right (LTR), lower trapezius left (LTL), middle trapezius right (MTR), middle trapezius left (MTL), erector spinae right (ESR) and erector spinae left (ESL) in the first row of orange cells and four different heights called H1, H2, H3 and H4 in the first column of blue cells were included in Table 3.11. Furthermore, the average was calculated for each height and placed in the blue cells. Moreover, orange cells in the last row of the table displayed an average of all muscle fatigue repetition numbers for each muscle at any height.

Based on the table shown above obtained from MDF results, Posterior deltoid right (PDR) with average percentage value 87.5% had the highest number and lower trapezius left (LTL) with average percentage value 25% had the lowest number of repetitions of all muscles during the entire lifting task, which indicated muscle fatigue. According to the findings, the important heights between the four heights were H1 and H2, with the same average percentage value 57.5%. And the lowest number was equivalent to 42.5% for H4.

Table 3.12 Percentage of number of cases where fatigue occurs in ten different muscles at different heights for the 4 subjects (MNF)

Height / Muscle	PDR	PDL	UTR	UTL	LTR	LTL	MTR	MTL	ESR	ESL	Average
H1	100%	100%	25%	50%	50%	50%	50%	75%	50%	50%	60
H2	100%	75%	75%	75%	50%	50%	25%	75%	50%	50%	62.5
H3	100%	75%	100%	75%	75%	25%	25%	25%	50%	25%	57.5
H4	100%	50%	75%	75%	25%	0%	50%	50%	50%	0%	47.5
Average	**100**	75	68.75	68.75	50	**31.25**	37.5	56.25	50	**31.25**	

The percentage of number of fatigue cases occurred in ten different muscles and at different heights resulting from the mean frequency (MNF) for the four subjects is shown in table 3.12.

As illustrated in Table 3.12, ten different back muscles as PDR, PLD, UTR, UTL, LTR, LTL, MTR, MTL, ESR and ESL were marked orange at the top of the table. In addition to the muscle, the height with blue cells on the left side of the table was also listed in this table. Moreover, in this table, like Table 3.11, the average of each height (Blue) and repetition numbers of each specific muscle (orange) were placed.

Based on the results obtained from the table above, the highest average percentage value among all the muscles allocated to the PDR muscle with a value equal to 100% and the lowest one was regards to LTL and ESL with the same value of 31.25%.

In accordance with the results gained from MNF data, the significant heights between the four heights were H2, with average percentage value 62.5%. On the other hand, the lowest number, equals to 47.5%, was assigned to H4.

CHAPTER 4

DISCUSSION

The aim of current study was to develop an analytical method to assess muscle fatigue by the EMG during manual lifting in a simulated environment and to discover the significant back muscles during the lifting task. For this purpose, EMG sensors were attached to the 10 different posterior muscles of the subject's body that are involved in upper extremity movement during the lifting task (Uhl, et al. 2003).

Median frequency (MDF), mean frequency (MNF) and root mean square (RMS) were determined and used to assess the EMG signal changes of all the muscles tested. The results have shown a simultaneous decrease in MDF/MNF and increase in RMS as signs of muscle fatigue factor, from the beginning to the end of the lifting task (Merletti, et al., 1990, Sundelin, 1993) with time during repetitive lifting task at four different heights for all measured muscles. What is known in this study is that the incidence of fatigue is differed from person to person.

In this study the analysis data in terms of muscles and heights (Tables 3.11 and 3.12) showed that posterior deltoid right (PDR) was the most remarked muscle that has been contributed to muscle fatigue assessment among all evaluated back muscles with an average percentage value 100% (which is the average number of cases where fatigue occurs for each muscle at four different heights) for MNF and 87.5% for MDF (according to the Tables 3.12 and 3.11). The second rate of muscle fatigue went to posterior deltoid left (PDL) with rate of average percentage value 75% for both MNF and MDF. The lowest recurrence of muscle fatigue was observed in the lower trapezius left (LTL) for both MDF and MNF with average percentage value 25% and 31.25%, respectively. In addition, erector spinae left (ESL) also showed the presence of fatigue in MNF with average percentage value 31.25%. According to the findings of the study, overall, PDR, PDL, UTR and UTL displayed the highest rate of fatigue. Therefore, it can be concluded that the shoulder muscles show fatigue more than the lumbar muscles.

In addition, referring to the Tables 3.1 and 3.2, a notable drop in instantaneous MNF versus time in the EMG data was seen in posterior deltoid muscles and allocated by the highest regression line slope of mean frequency spectrum of EMG signal among all muscles. Therefore, it can be confirmed that posterior deltoid muscle became fatigued during lifting task (Phinyomark, A., et al, 2012).

Regarding the height, as was concluded from the analysis (Tables 3.11 and 3.12), except of H4 (highest level from the ground level) almost all heights showed muscle fatigue with a small difference. Thus, what was obtained from the results, H2 and H1 in order (on the ground level) presented highest numbers of fatigue repetitions as compared to all other heights during entire manual lifting task. However, it could be associated to the posture-related variables such as lumbar flexion angle, trunk inclination in these heights and can be the reason for being more fatigued compared to the other heights (Plamondon, 2014).

It is noticeable that based on our results, in the different regression analysis of each specific muscle on both sides of the body, each person's right and left muscles can have a different and specific fatigue function.

As can be seen from Figures 3.1 to 3.20 and the attached ones in Appendix V, in addition to identifying downtrend of MDF and MNF (blue line) and uptrend of RMS (red line), patterns of each muscle in each four different heights during 1-min period of lifting task (16 minutes) has been depicted. The blue dots have represented the MDF/MNF and RMS has been represented by red dots in these plots. With regard to the variability of muscle features, it is clear from the findings that different muscles in each subject and in four different heights had their own specific fatigue pattern. As pointed out by Sundeline, 1992, also EMG signs of fatigue patterns were different between muscles and between subjects.

Moreover, as can be seen in these plots, each of the muscles in periods of times has started decreasing MDF/MNF and increasing RMS simultaneously which are signs of fatigue (Sundeline, 1992). Based on our analysis, by looking at the pattern of all the muscles in which fatigue has taken place, it can be assumed that fatigue occurred in the evaluated muscles between approximately 6 to 14 minutes (around the intersection of the fitted regression lines). Growing frequency and decreasing RMS occurred at the end of the lifting task (after 14 minutes to the end) because this may be attributed to an adaptation to the work pace and work task, facilitating an alternating recruitment of motor units within the muscle as revealed by Sundeline, 1993.

CONCLUSION

Summary of work

One of the most common diseases in the warehouse during manual handling is musculoskeletal disorders (MSDs), particularly chronic lower back pain, causing enormous costs for the company, the healthcare system and contributing to the lifetime of the disability. Muscle fatigue has been recognized to consider as a high-risk issue for back pain injuries resulting in MSDs and chronic lower back pain. Current research aimed to investigate differences in surface electromyography (EMG) data performing a manual lifting task that induces fatigue in the muscles. Four healthy subjects were asked to lift and deposit 24 boxes with 10kg for almost 16 minutes in a simulated laboratory environment in order to simulate muscle fatigue. EMG data for ten muscles was collected, cut off each cycle (lift plus deposit) by the magnetometer and evaluated using a time-frequency analysis procedure (STFT) for extracting the mean and median frequency calculation. All computations were carried out in MATLAB. Median and mean frequency (MDF / MNF) and root mean square (RMS) were calculated and are used for four various heights to analyze the changes in the EMG signal of all the muscles evaluated. The results showed that as a sign of muscle fatigue factor, MDF / MNF was decreased while RMS increased. The findings obtained from this experiment showed that the greatest rate of muscle fatigue was demonstrated by the posterior deltoid muscles compared to the other muscles. Height 2 and height 1 displayed the highest number of fatigue repetitions compared to all other heights during the entire manual lifting task. From the results, it is apparent that different muscles have their own particular fatigue pattern between the four different heights.

Limitations

In the road map of this study, initially we aimed at considering fifteen subjects to increase our confidentiality mainly in the statistical analysis sections. However, due to the urgent condition created in the world, the number of subjects for the experiment was reduced to four subjects. Still testing these four subjects leaded to high confidential results that are comparable with the literature. For sure including more subjects and so having more data will enable the use of other techniques such as ANOVA technique and T-test.

Experimental errors are other limitations in this sort of research that can lead to differences between muscle’s results.

In addition, as we mentioned in the protocol, we aimed at applying these analytical methods to ten muscles but because of the created situation and time limitation for acquisition of the data for more subject, we missed the data for the lower trapezius left and right muscles, in order to they had not been recorded correctly and thus we excluded these two muscles. The results of this study must therefore be interpreted and used in light of these limitations.

Future work

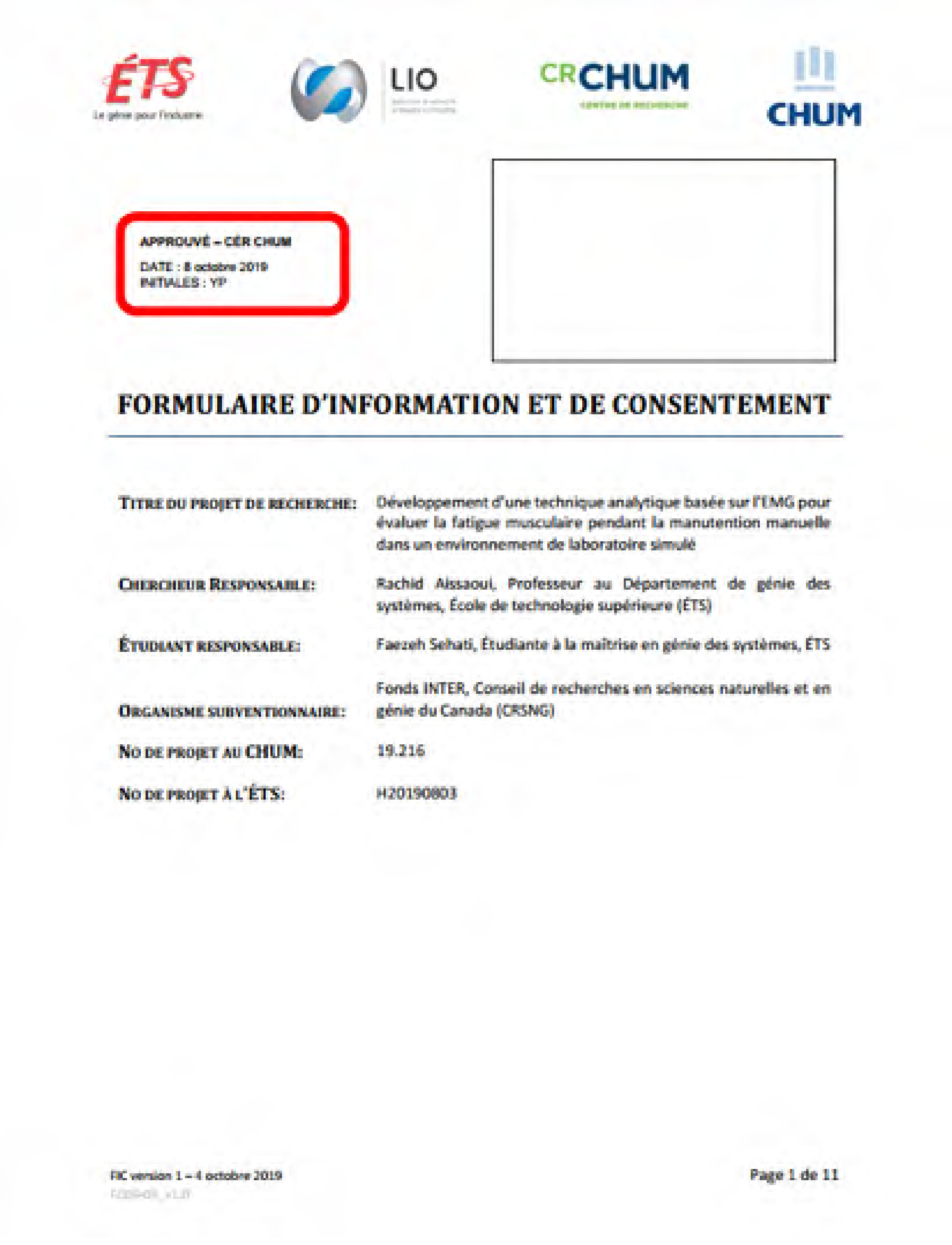
The study and results presented in this work can raise the following suggestions as the future work:

- The associations between lumbar and shoulder muscles fatigue, and changes in the biomechanics of motion during a repetitive lifting task in four different heights for subjects with no background of lower back problem, could be investigated in the future.
- Moreover, assessing muscle fatigue by the EMG during manual lifting in among warehouse employees could be applied to see the difference between the muscle fatigue results.
- In addition to the MNF, MDF, and RMS, probably some other parameters can be extracted from the EMG signals using artificial intelligence (AI) techniques. More specifically, a neural network can be trained to learn which parameters (from the EMG signals) are more correlated with the fatigue.

- A smarter fatigue monitoring technique based on AI approaches can be considered. For example, a recurrent neural network (RNN) can be trained to monitor the real-time fatigue occurrences based on MNF, MDF, RMS, and some other parameters extracted from the EMG signals.

APPENDIX I

APPROVAL OF ETHIC COMMITTEE FOR RESEARCH



APPROUVÉ – CÉR CHUM
DATE : 8 octobre 2019
INITIALES : YP

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

TITRE DU PROJET DE RECHERCHE:	Développement d'une technique analytique basée sur l'EMG pour évaluer la fatigue musculaire pendant la manutention manuelle dans un environnement de laboratoire simulé
CHERCHEUR RESPONSABLE:	Rachid Aissaoui, Professeur au Département de génie des systèmes, École de technologie supérieure (ÉTS)
ÉTUDIANT RESPONSABLE:	Faezeh Sehati, Étudiante à la maîtrise en génie des systèmes, ÉTS
ORGANISME SUBVENTIONNAIRE:	Fonds INTER, Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG)
NO DE PROJET AU CHUM:	19.216
NO DE PROJET À L'ÉTS:	H20190803

FIC version 1 – 4 octobre 2019

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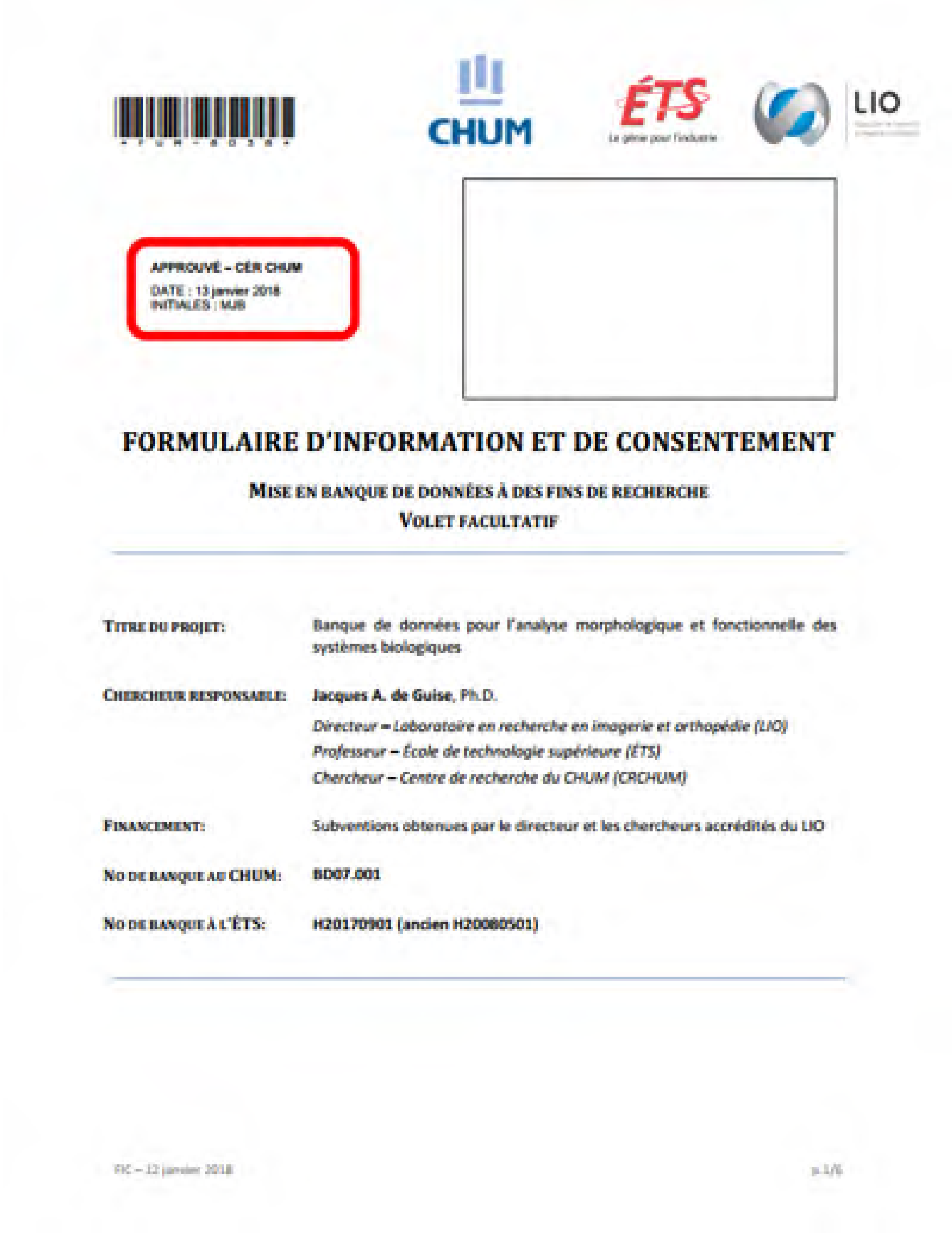
APPENDIX II

APPROVAL OF DATABASE FOR OPTIONAL SEARCH PURPOSES



APPROUVÉ – CÉR CHUM
DATE : 13 janvier 2018
INITIALES : MJB

FORMULAIRE D'INFORMATION ET DE CONSENTEMENT

MISE EN BANQUE DE DONNÉES À DES FINS DE RECHERCHE
VOLET FACULTATIF

TITRE DU PROJET: Banque de données pour l'analyse morphologique et fonctionnelle des systèmes biologiques

CHERCHEUR RESPONSABLE: **Jacques A. de Guise**, Ph.D.
Directeur – Laboratoire en recherche en imagerie et orthopédie (LIO)
Professeur – École de technologie supérieure (ÉTS)
Chercheur – Centre de recherche du CHUM (CRCHUM)

FINANCEMENT: Subventions obtenues par le directeur et les chercheurs accrédités du LIO

NO DE BANQUE AU CHUM: **BD07.001**

NO DE BANQUE À L'ÉTS: **H20170901 (ancien H20080501)**

FIC – 12 janvier 2018

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APPENDIX III

DETAILED PROTOCOL

ÉTS Le génie pour l'industrie

LIO

CRCHUM CENTRE DE RECHERCHE

CHUM

DETAILED PROTOCOL

TITLE OF RESEARCH PROJECT	Development of an analytical technique based on EMG to assess muscle fatigue during manual handling in a simulated laboratory environment
RESPONSIBLE RESEARCHER	Professor Rachid Aissaoui, École de technologie supérieure (ÉTS), Chercheur LIO, CRCHUM,
CO-RESEARCHER	Professor Mustapha Ouhimmou, École de technologie supérieure (ÉTS)
RESPONSIBLE STUDENT :	Faezeh Sehati, École de technologie supérieure (ÉTS)
SUBSIDIARY ORGANIZATIONS	Fonds INTER, Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG)
PROJECT NUMBER AT CHUM	
PROJECT NUMBER AT ETS	H20190803

APPENDIX IV

CLINICAL HISTORY QUESTIONNAIRE

General Information and Clinical History Questionnaire

The purpose of this questionnaire is to help the research team better distinguish of the study population. In some cases where the information reported is inaccurate or incomprehensible, the research team may contact you to validate certain information.

Do not hesitate to ask for help if questions seem ambiguous or if you prefer not to answer.

Personal details			
#IC: P0104205	Date:	Profession:	
Sex: M / F / X	Age:	Weight(kg):	Height(cm):
Start time:	End time:	Responsible person:	

Preparation	Yes	No
Do you have any disability that could prevent you from performing tasks such as performing gripping tasks? If yes, explain:	☐	☐
Do you have any health problems that you feel are important that could impact your ability to apply a load (e.g. lifting an object) or performing a physical task? If yes, explain:	☐	☐
Do you have balance problems?	☐	☐

Do you have any chronic pain, forcing you to consume medications? (Acetaminophen, Anti-inflammatories, Muscle Relaxants, Anti-Pain, Cortisone Injections, Antidepressants or other)	☐	☐
Do you do regular physical activity? If Yes, on average how many hours per week:	☐	☐
In the last 24 hours did you perform any activity that required more physical effort? If yes, explain:	☐	☐
Have you consumed any psychoactive substances (Alcohol, Opioids, Cannabis, etc.) 24 hours before the experiments?	☐	☐
Clinical history		
Is there any type of medical condition diagnosed (disease / injury / allergy)? If so, which one?	☐	☐
Are you taking any medications? If so, which one?	☐	☐
Are you currently experiencing any problems with fatigue or muscle pain? If so, which area of the body?	☐	☐
Are you anxious or stressed right now?	☐	☐

APPENDIX V

REMAINED FIGURES OF MNF AND MDF CHANGES FOR EACH MUSCLE

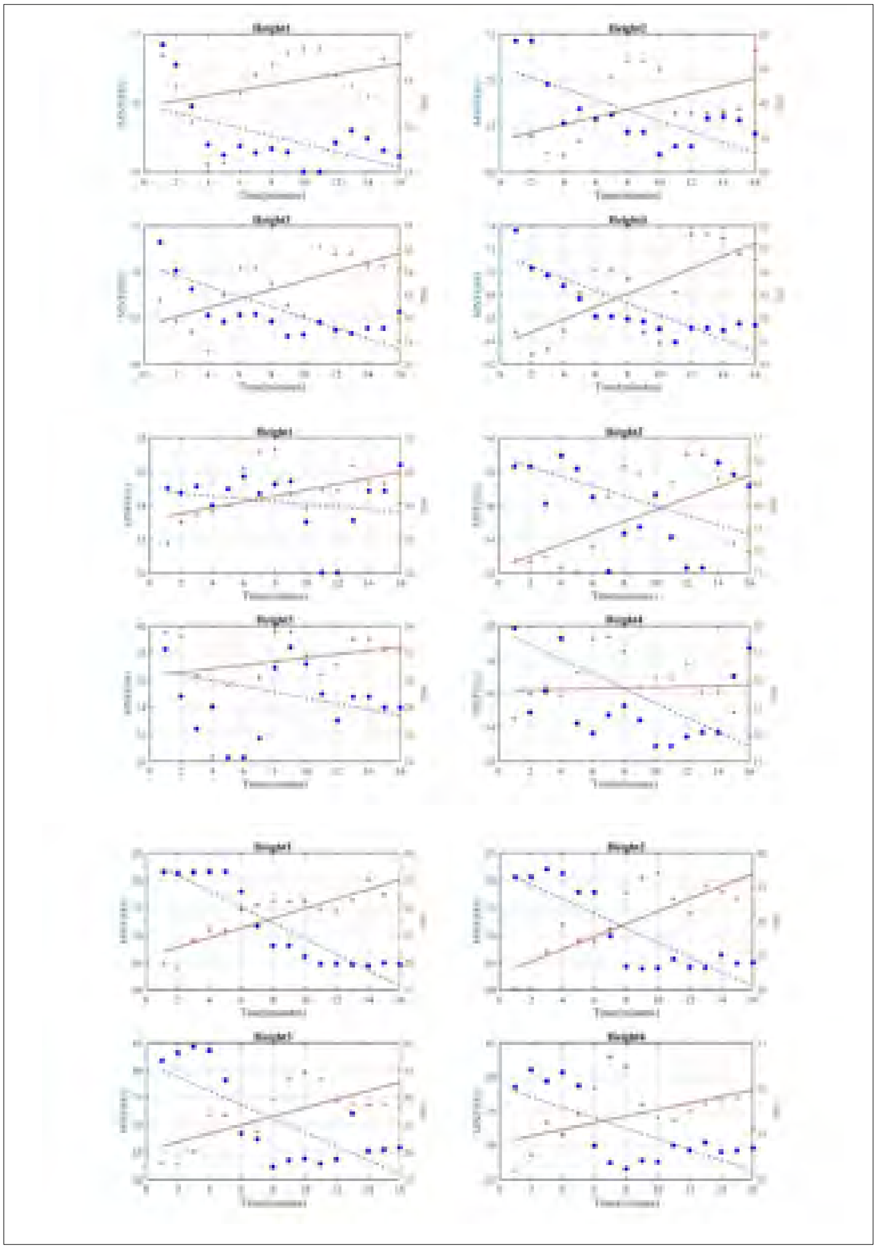

Figure-A V-1 Changes in mean frequency (MNF) versus time (minute) of PDR muscle for four heights (Subject 1, 2 and 3)

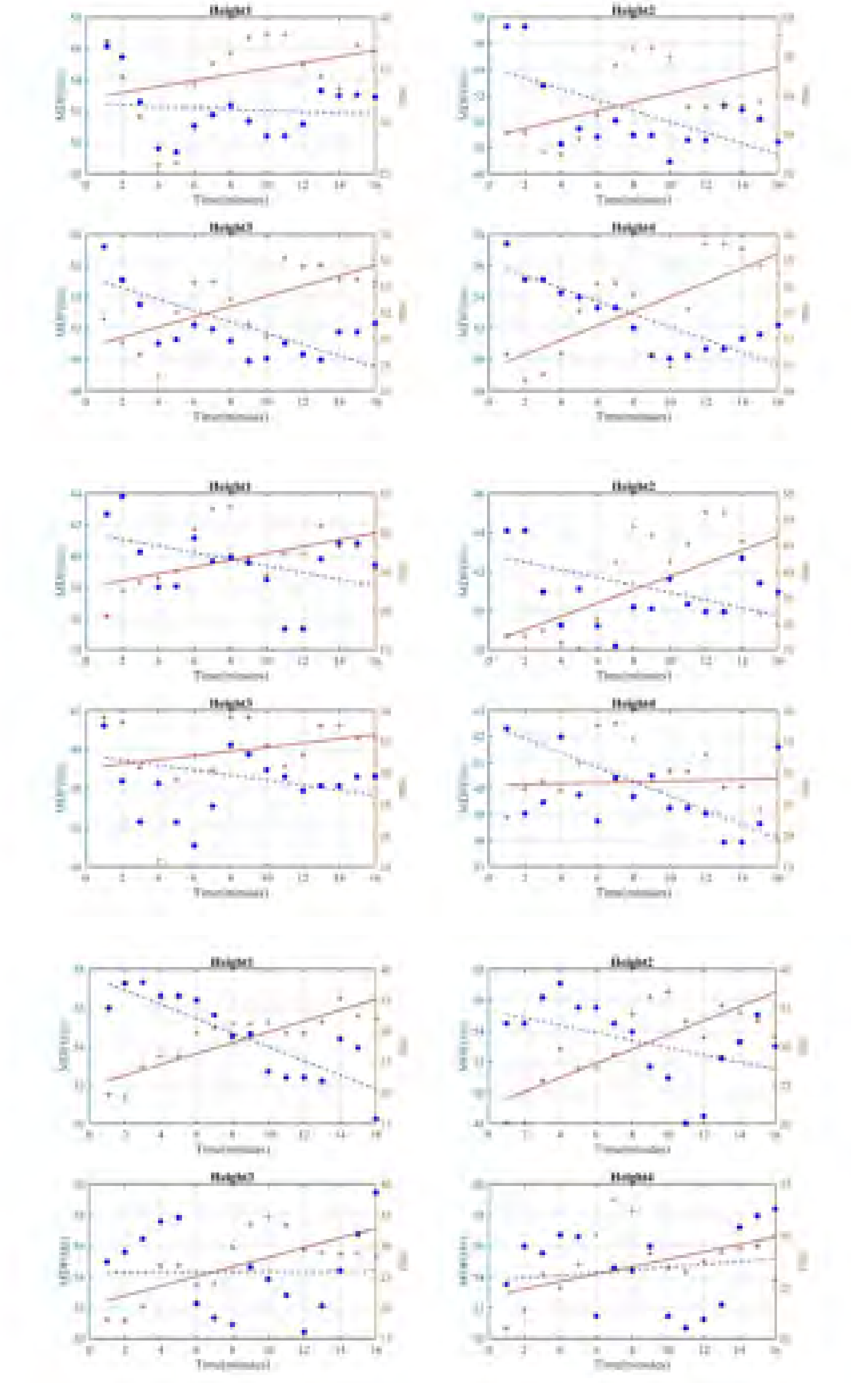

Figure-A V-2 Changes in median frequency (MDF) versus time (minute) of PDR muscle for four heights (Subject 1, 2 and 3)

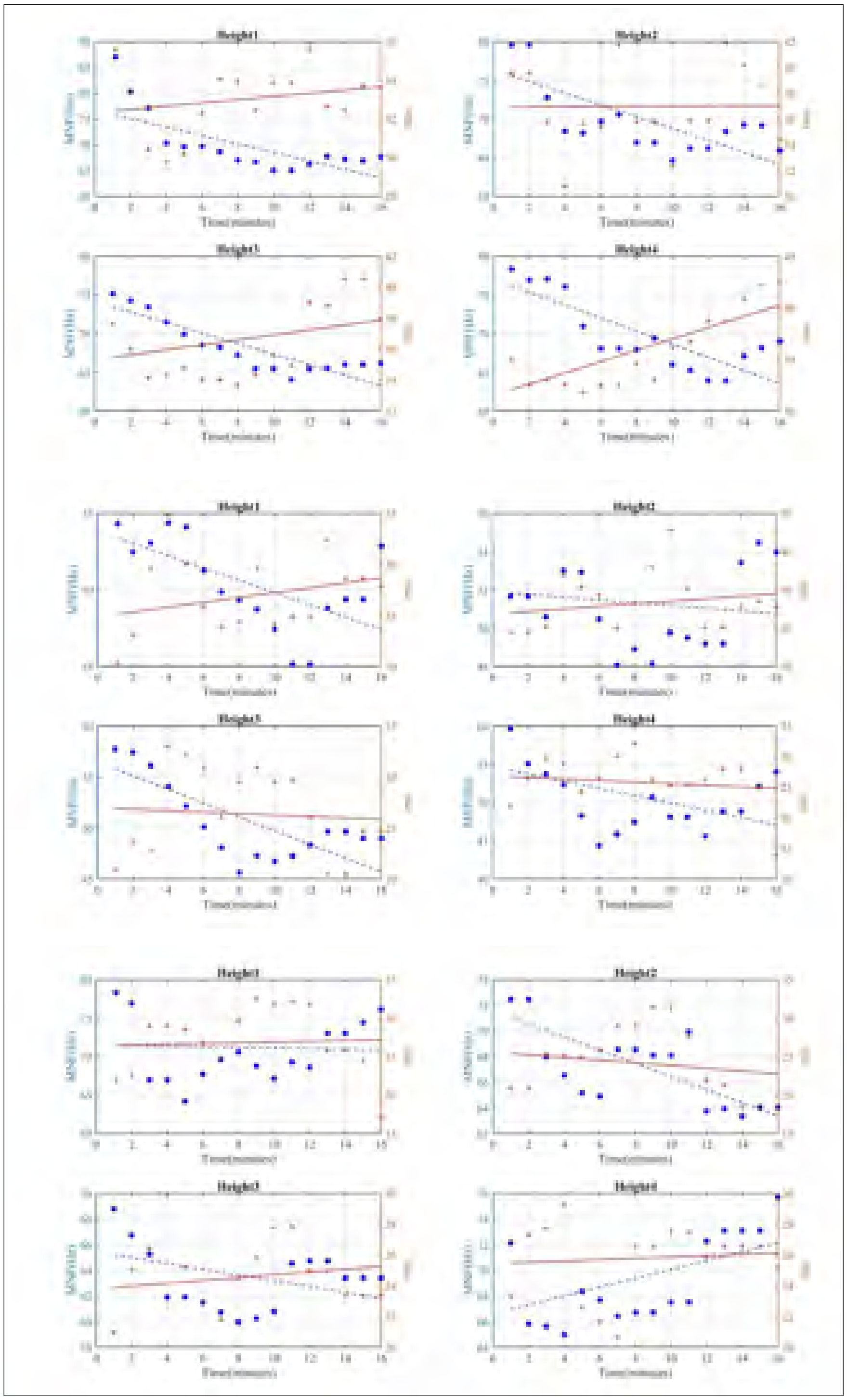

Figure-A V-3 Changes in mean frequency (MNF) versus time (minute) of PDL muscle for four heights (Subject 1, 2 and 4)

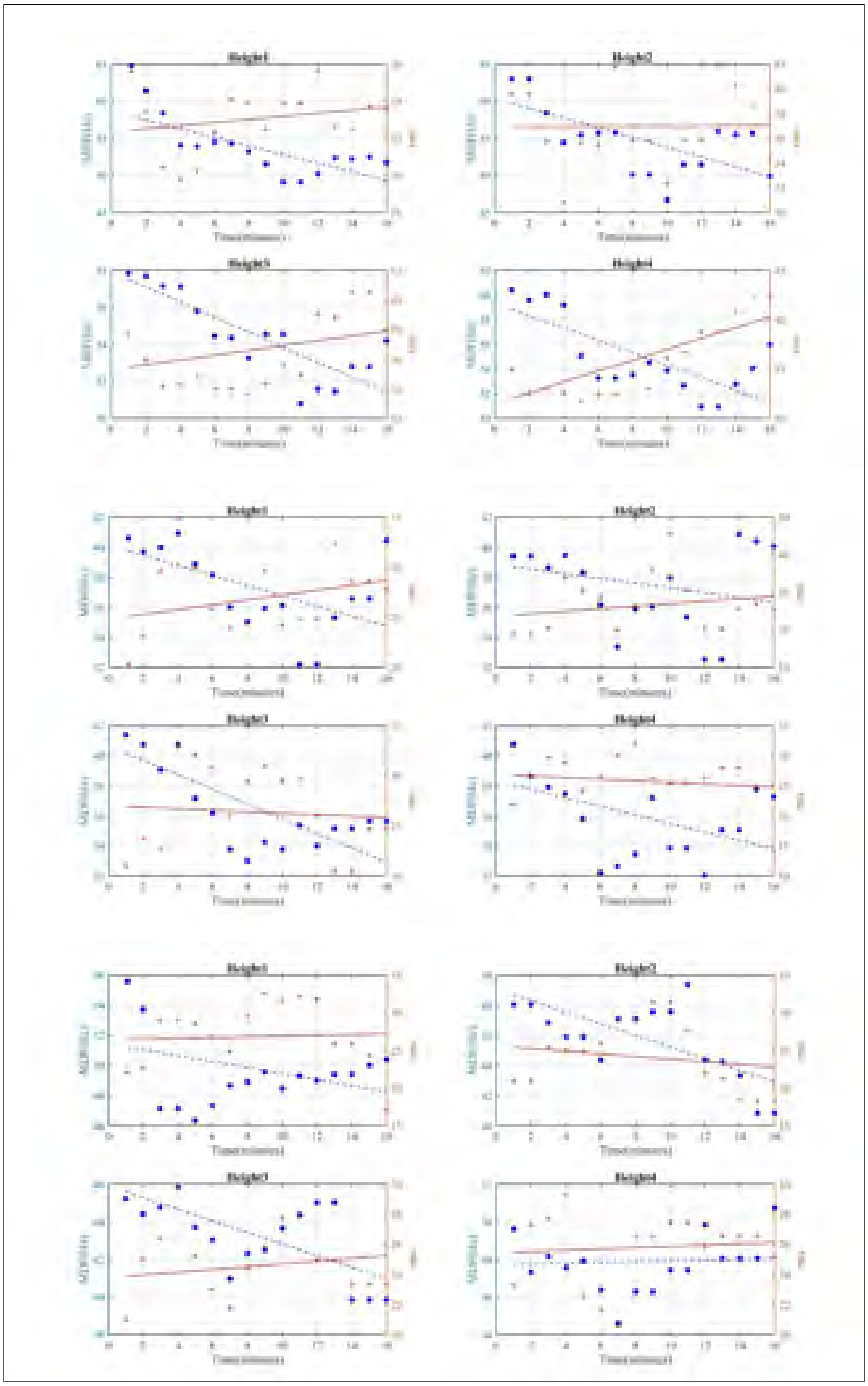

Figure-A V-4 Changes in median frequency (MDF) versus time (minute) of PDL muscle for four heights (Subject 1, 2 and 4)

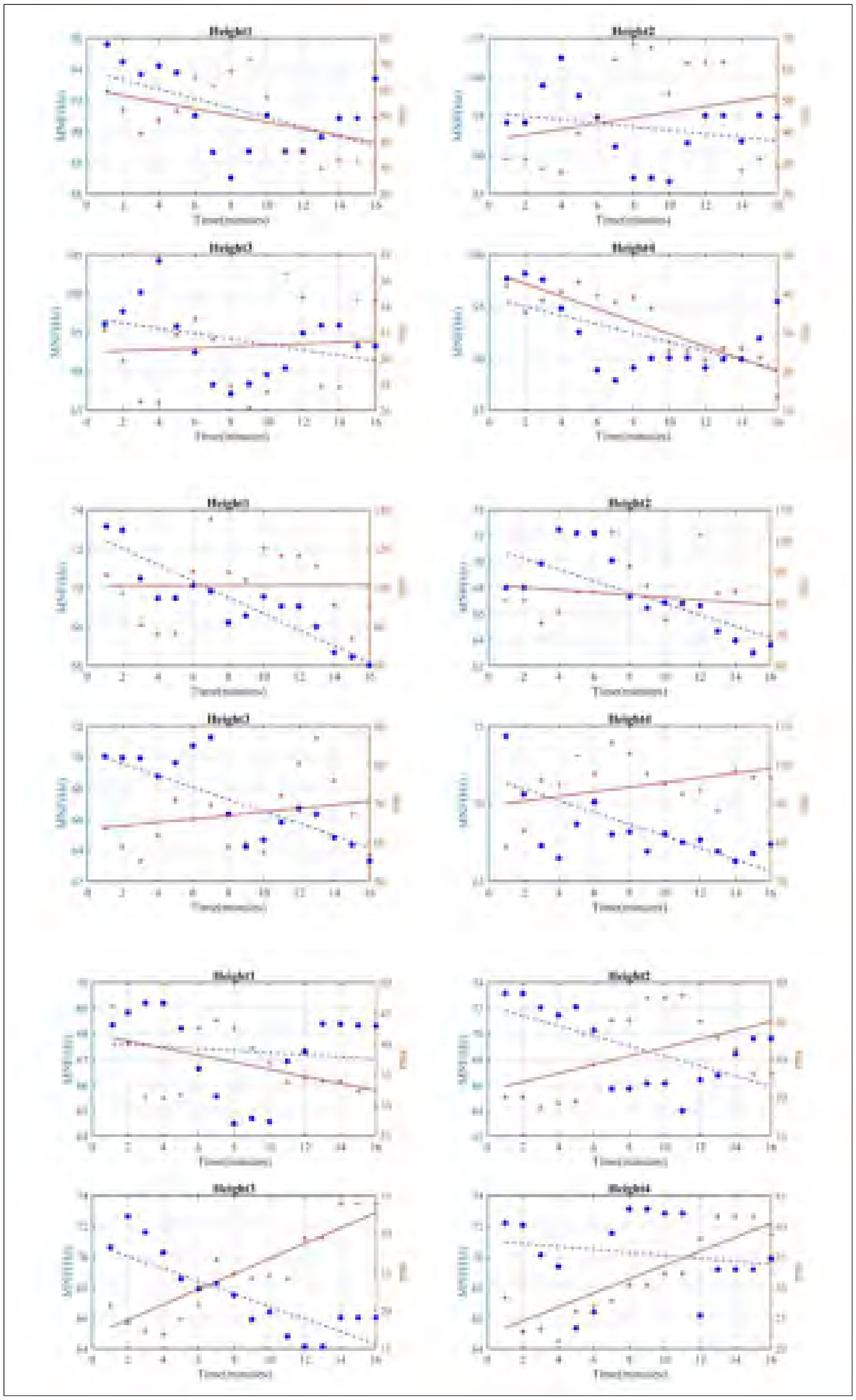

Figure-A V-5 Changes in mean frequency (MNF) versus time (minute) of UTR muscle for four heights (Subject 2, 3 and 4)

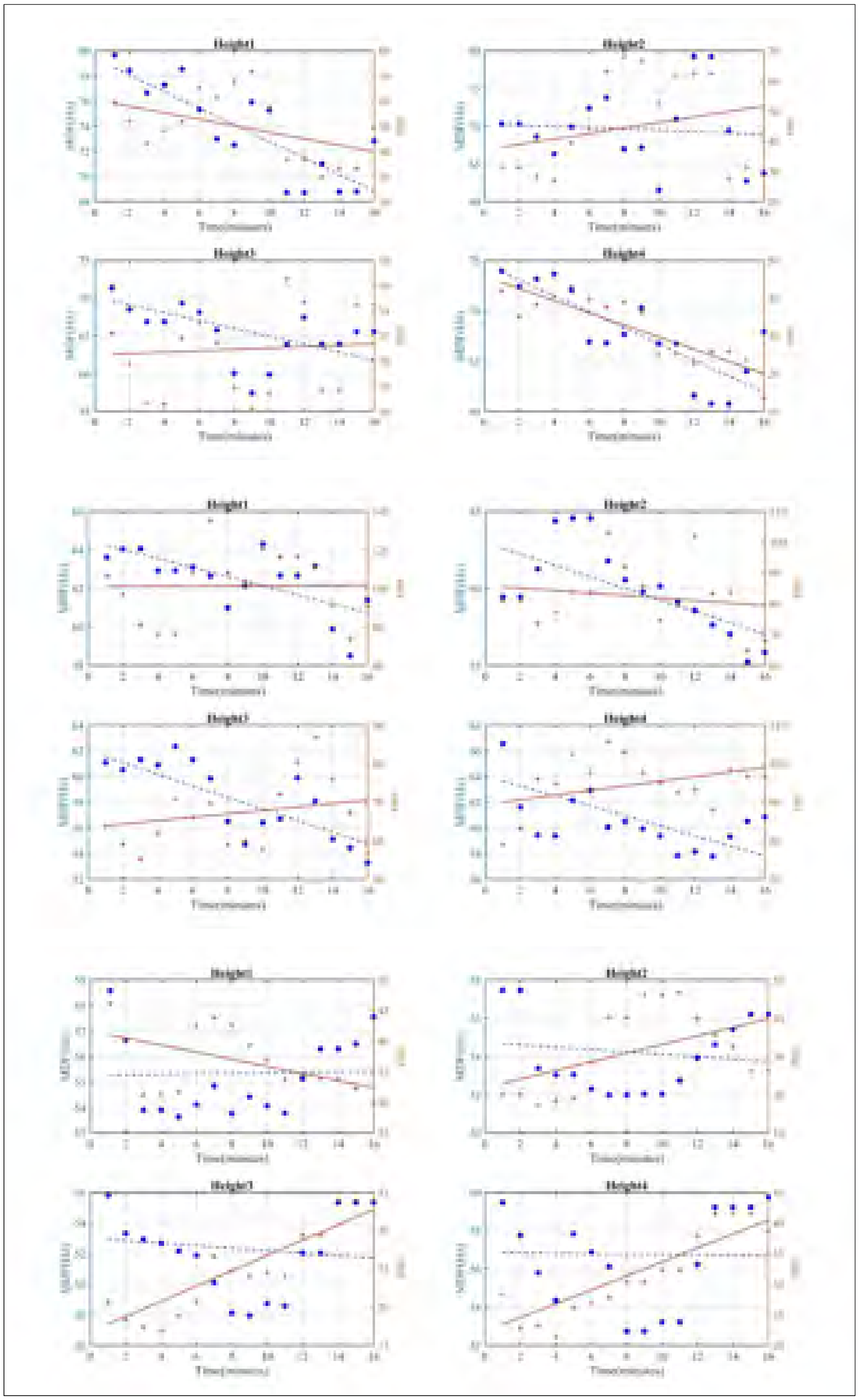

Figure-A V-6 Changes in median frequency (MDF) versus time (minute) of UTR muscle for four heights (Subject 2, 3 and 4)

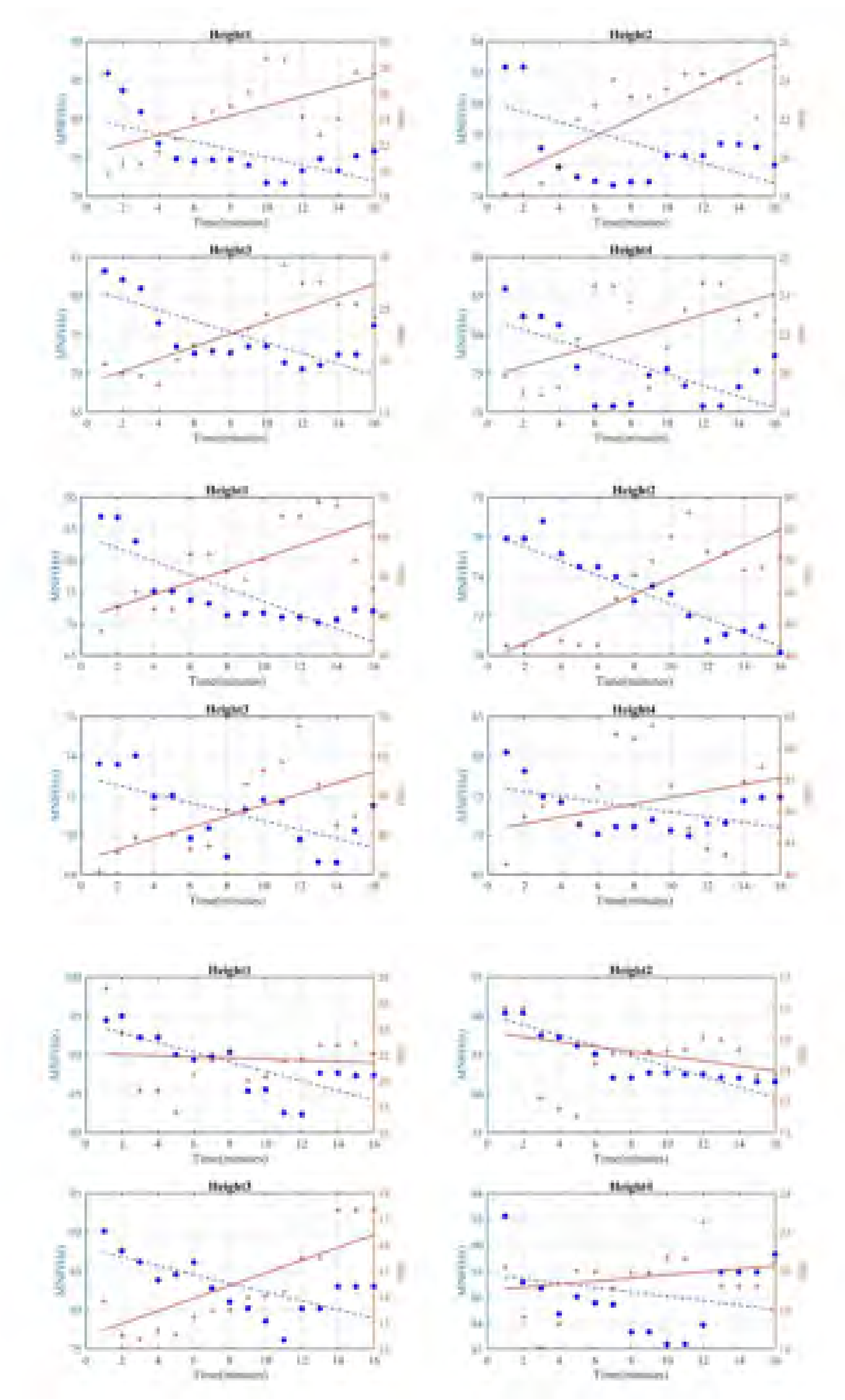

Figure-A V-7 Changes in mean frequency (MNF) versus time (minute) of UTL muscle for four heights (Subject 1, 3 and 4)

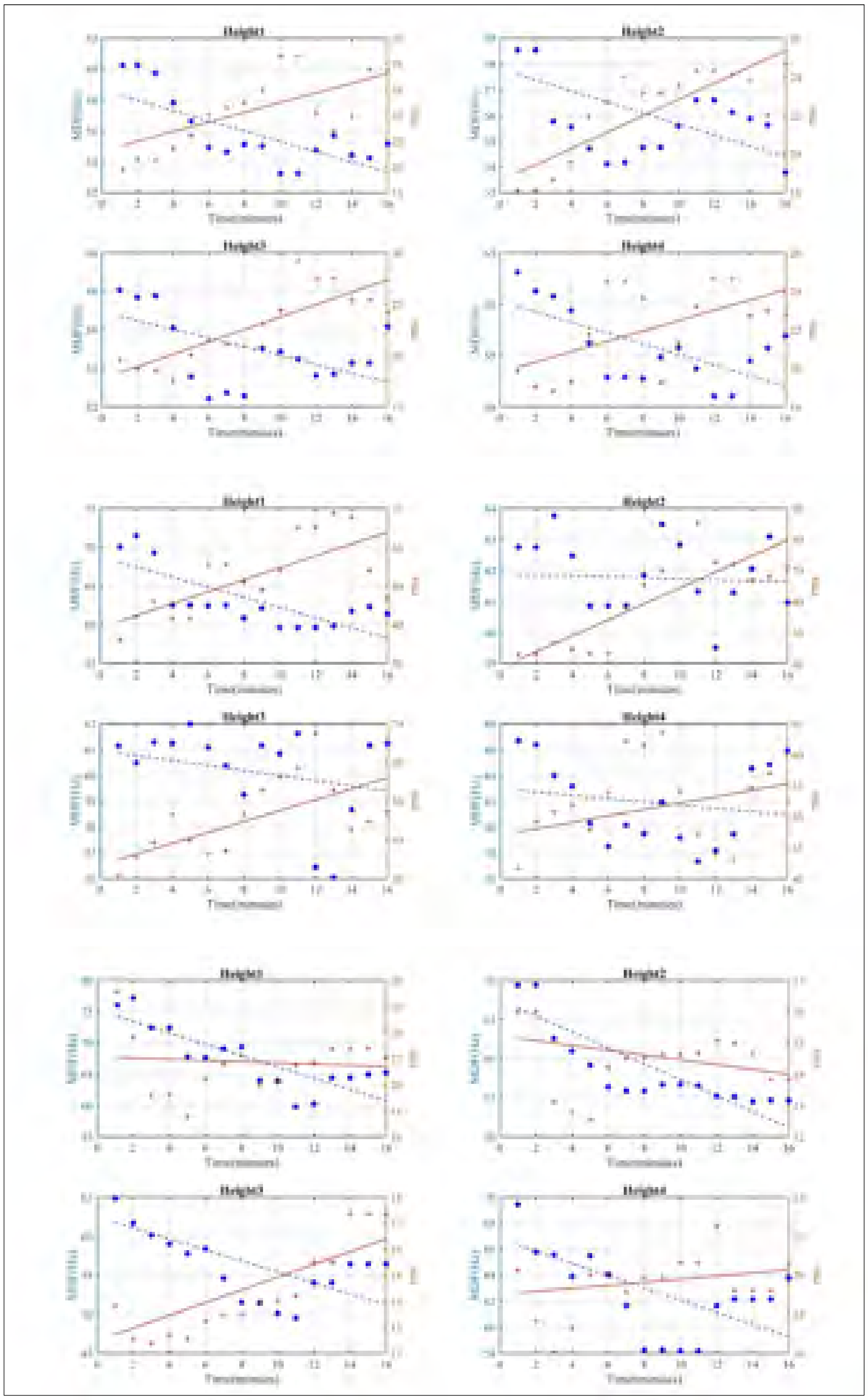

Figure-A V-8 Changes in median frequency (MDF) versus time (minute) of UTL muscle for four heights (Subject 1, 3 and 4)

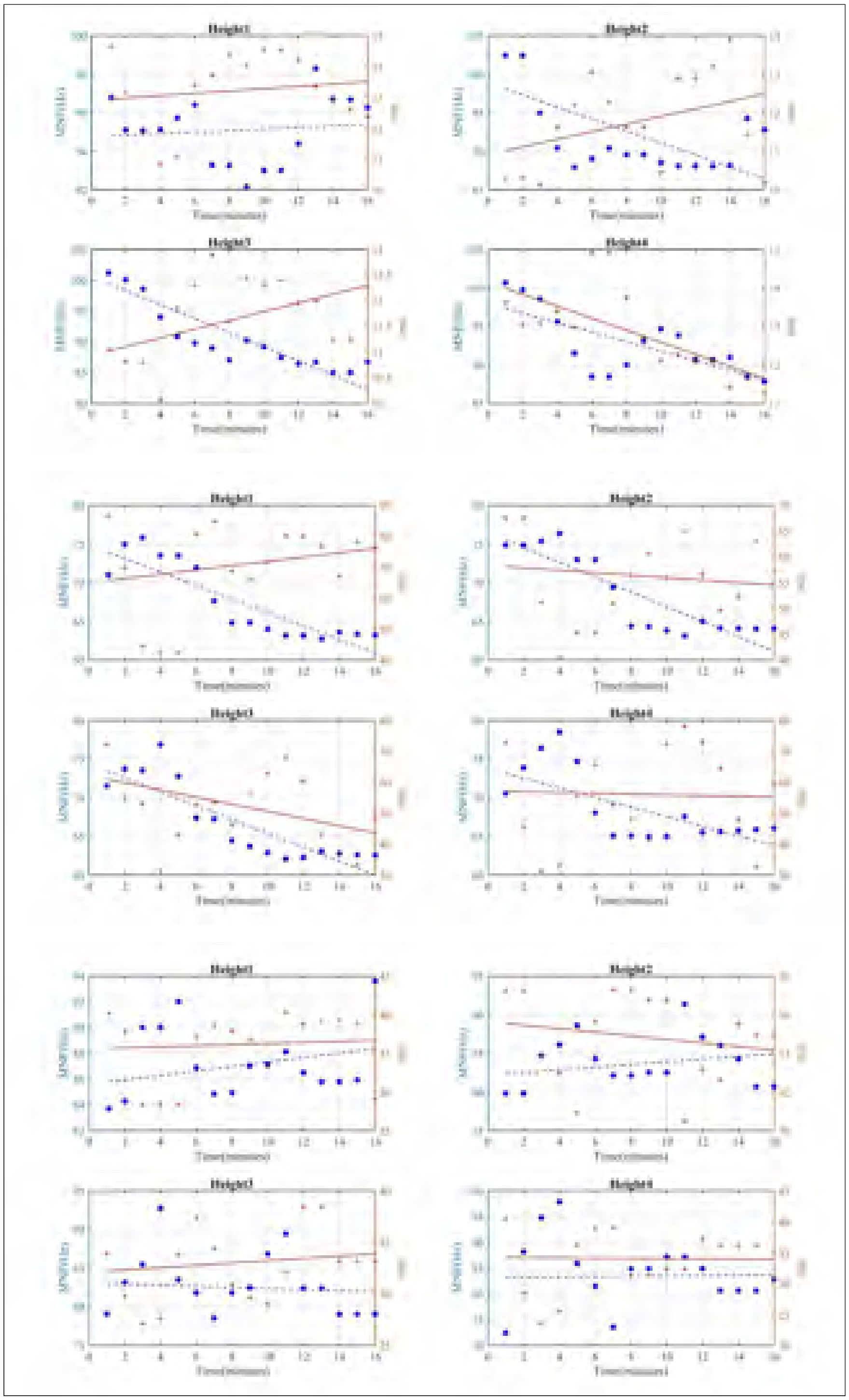

Figure-A V-9 Changes in mean frequency (MNF) versus time (minute) of LTR muscle for four heights (Subject 1, 3 and 4)

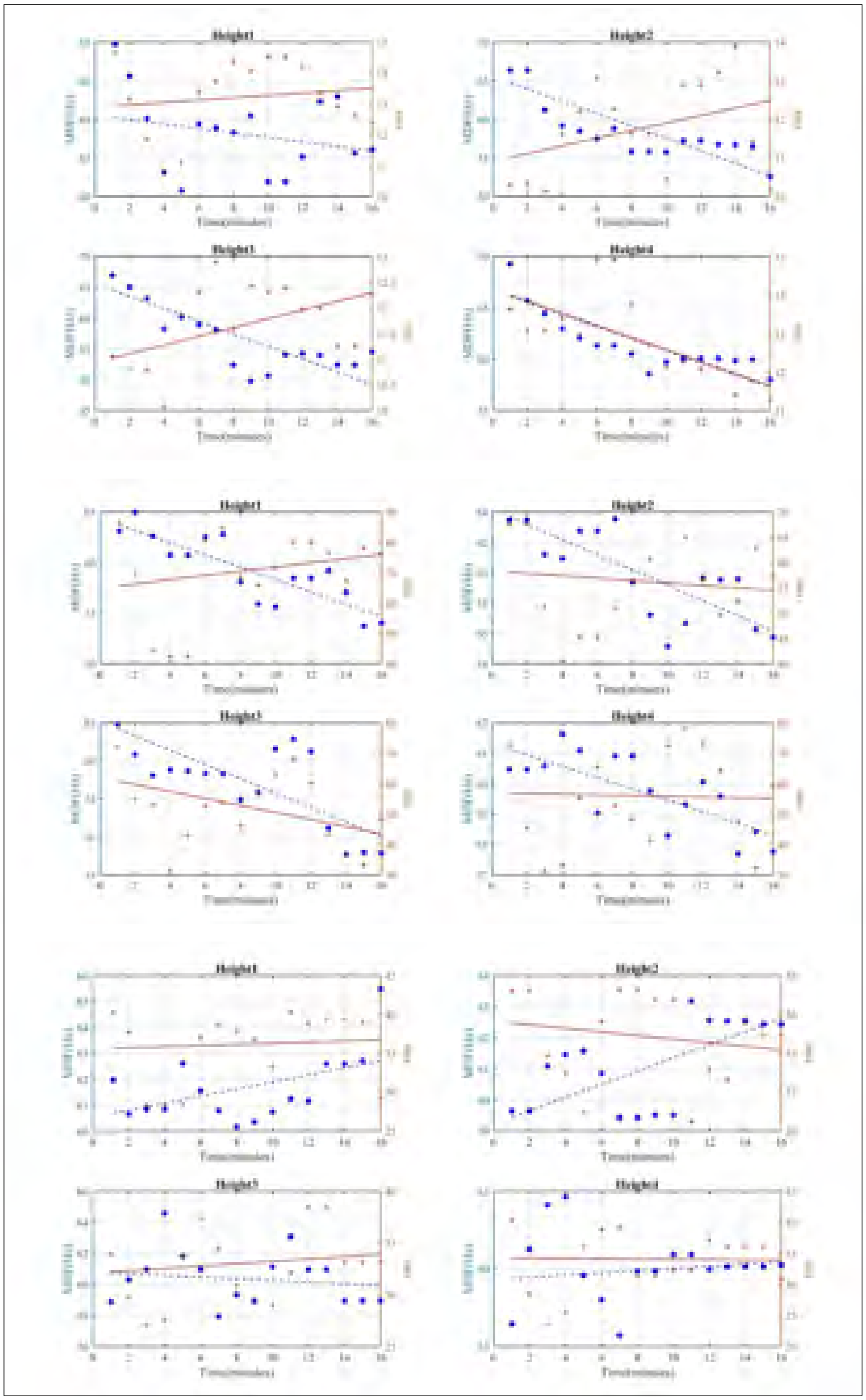

Figure-A V-10 Changes in median frequency (MDF) versus time (minute) of LTR muscle for four heights (Subject 1, 3 and 4)

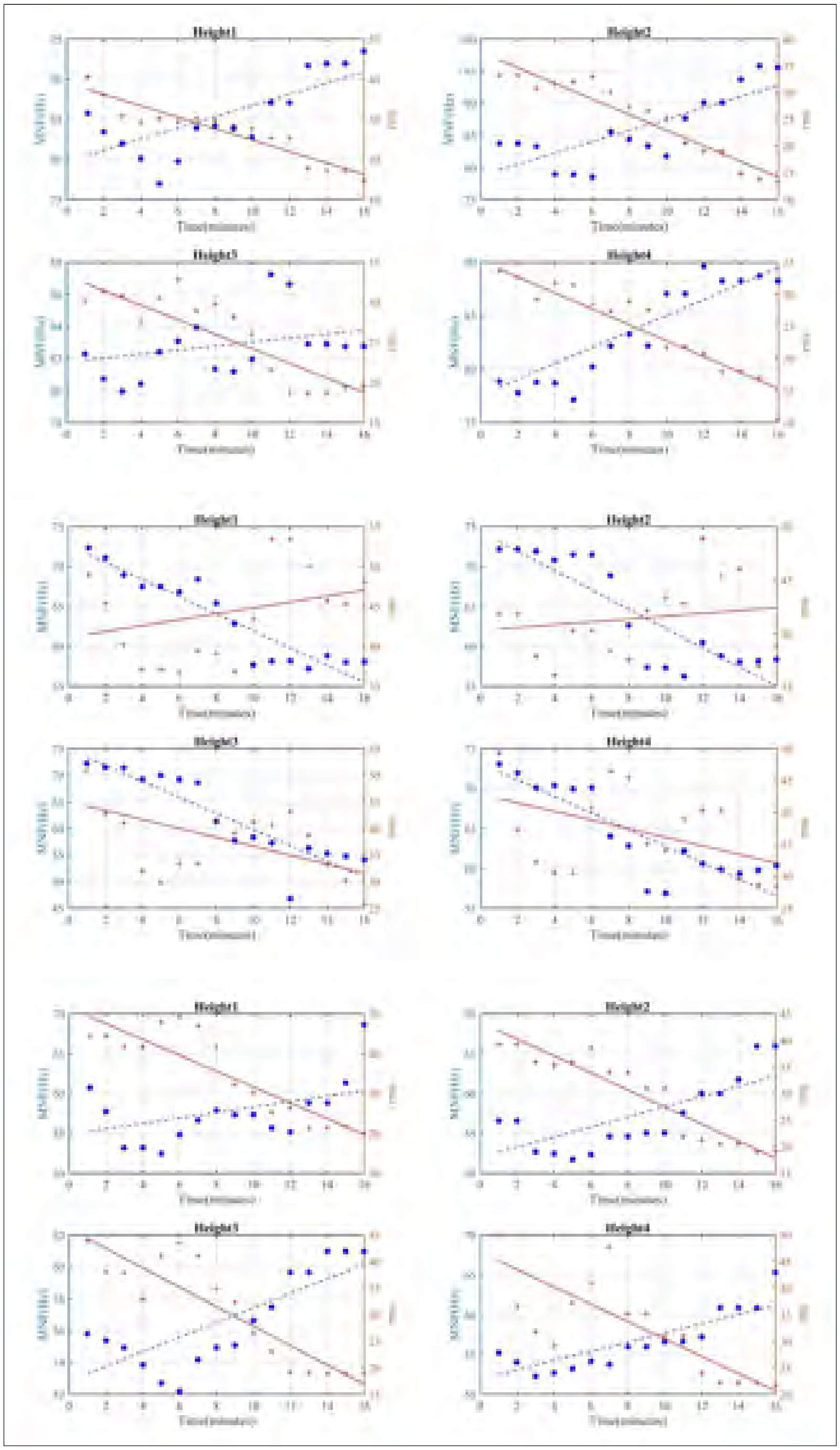

Figure-A V-11 Changes in mean frequency (MNF) versus time (minute) of LTL muscle for four heights (Subject 2, 3 and 4)

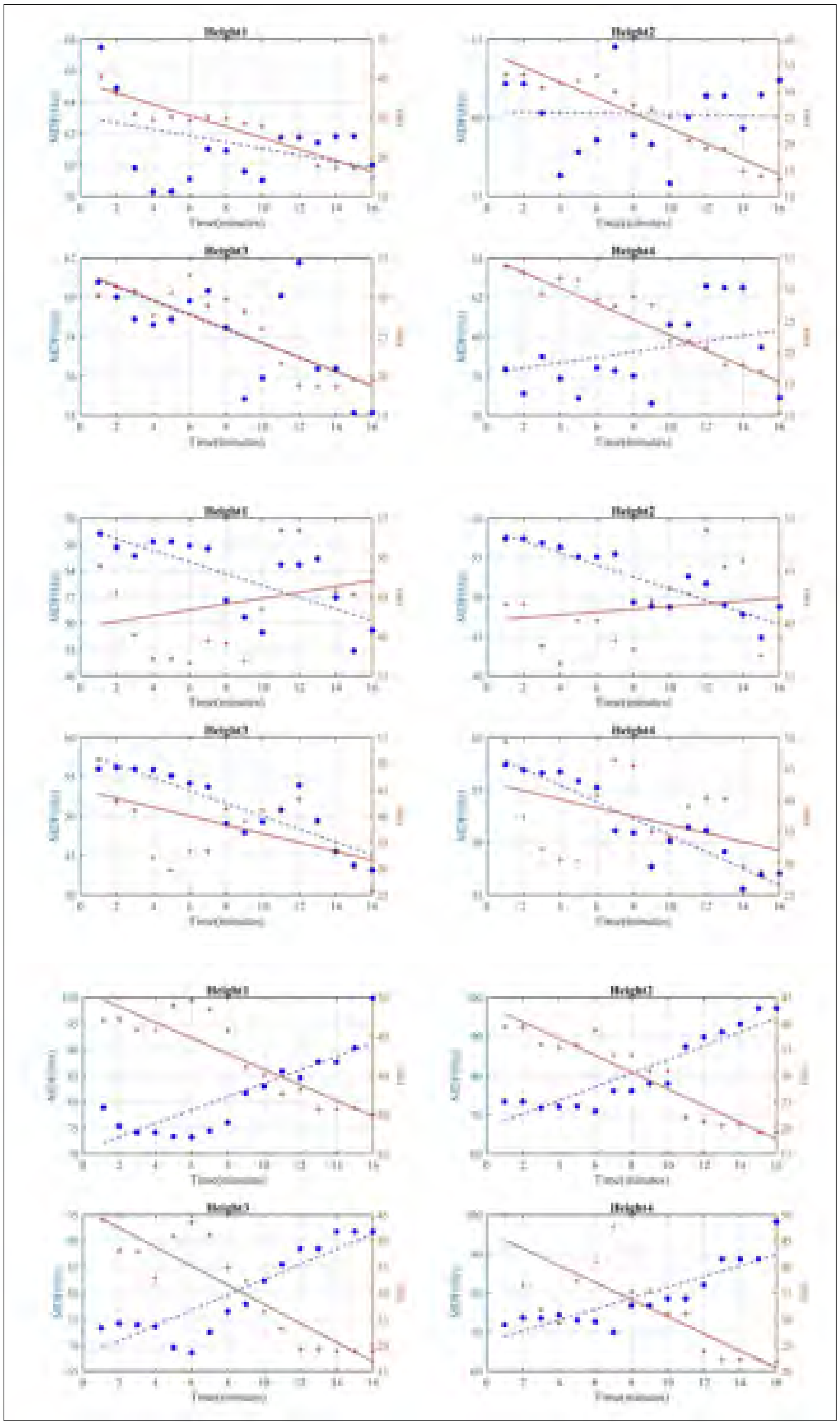

Figure-A V-12 Changes in median frequency (MDF) versus time (minute) of LTL muscle for four heights (Subject 2, 3 and 4)

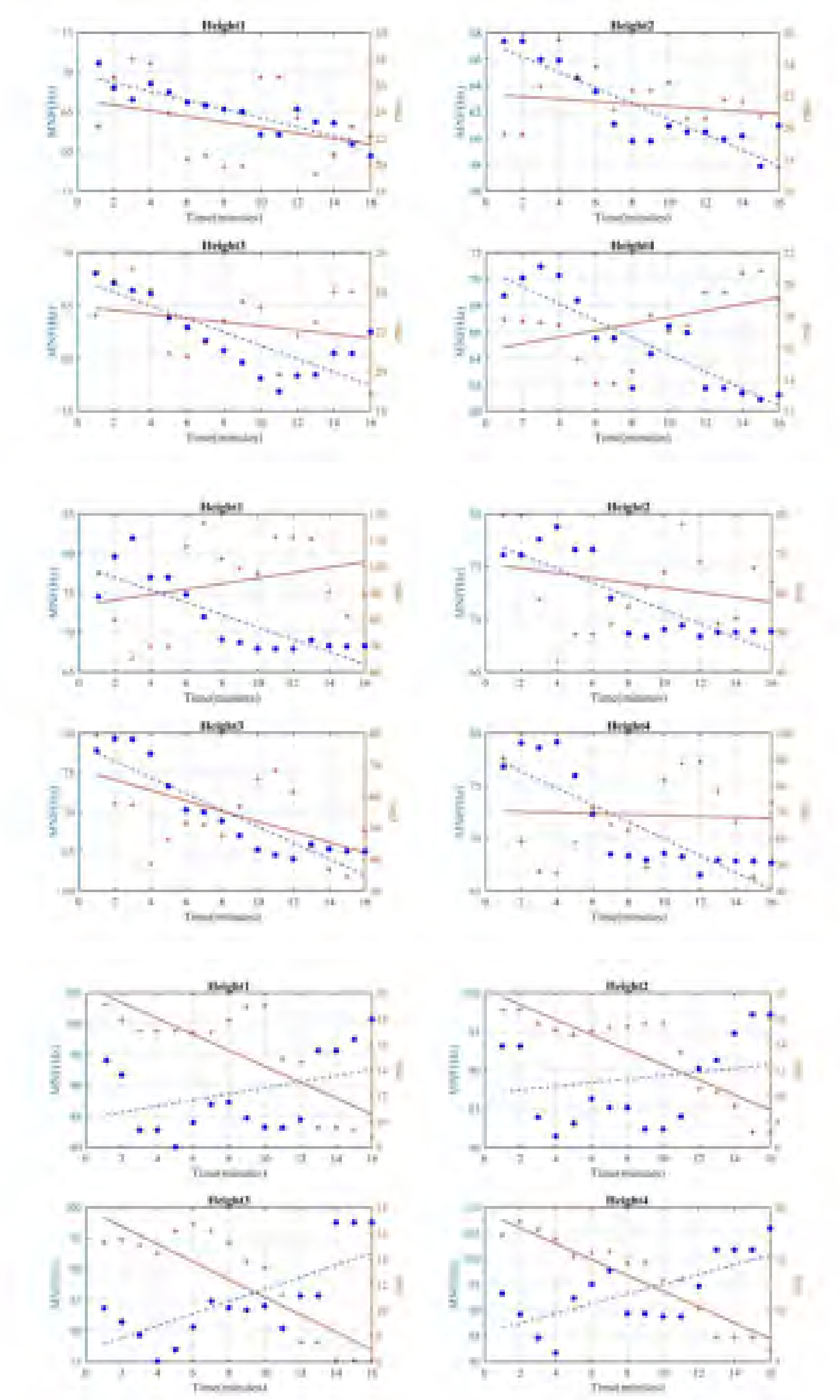

Figure-A V-13 Changes in mean frequency (MNF) versus time (minute) of MTR muscle for four heights (Subject 1, 3 and 4)

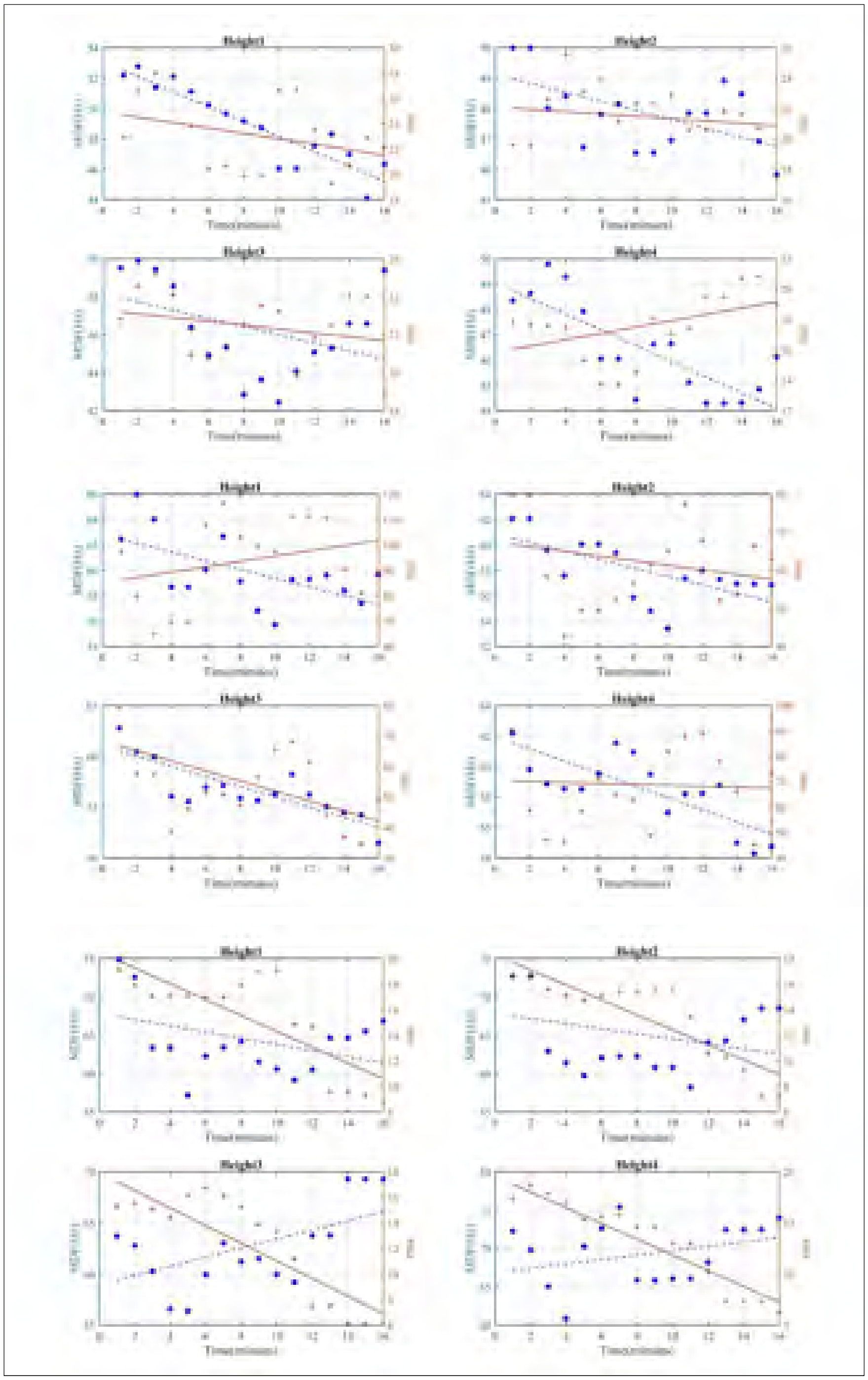

Figure-A V-14 Changes in median frequency (MDF) versus time (minute) of MTR muscle for four heights (Subject 1, 3 and 4)

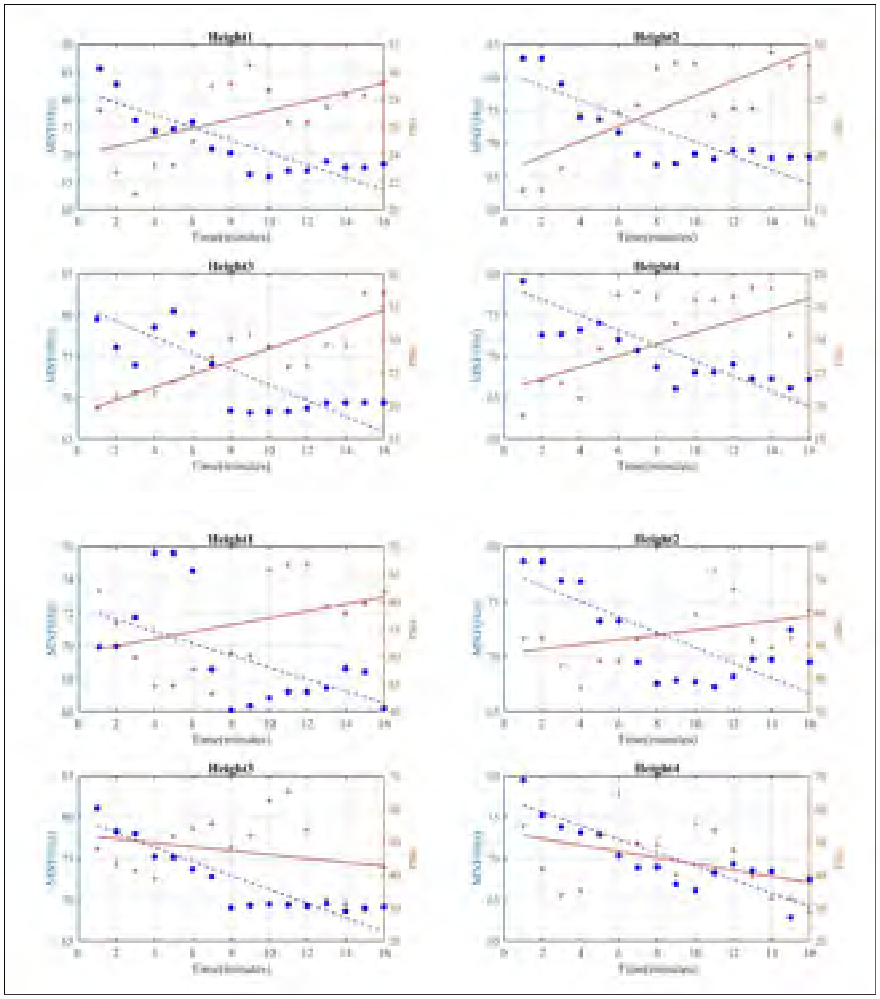

Figure-A V-15 Changes in mean frequency (MNF) versus time (minute) of MTL muscle for four heights (Subject 2, 3)

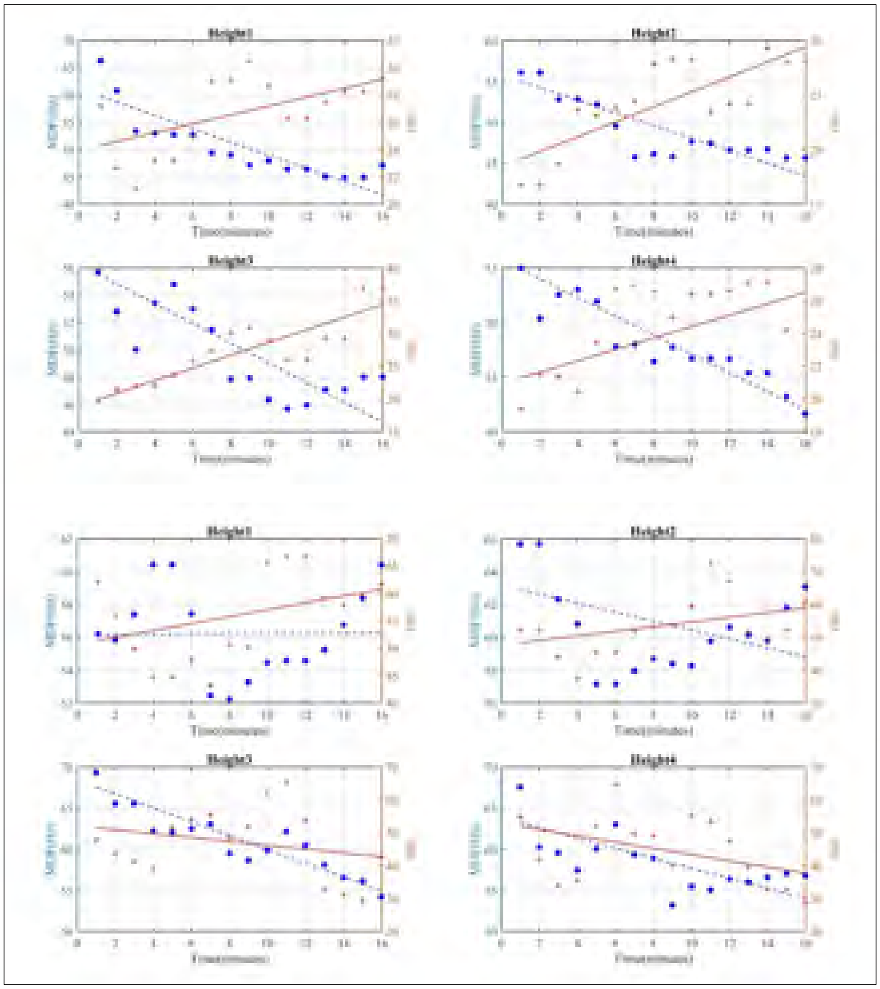

Figure-A V-16 Changes in median frequency (MDF) versus time (minute) of MTL muscle for four heights (Subject 2, 3)

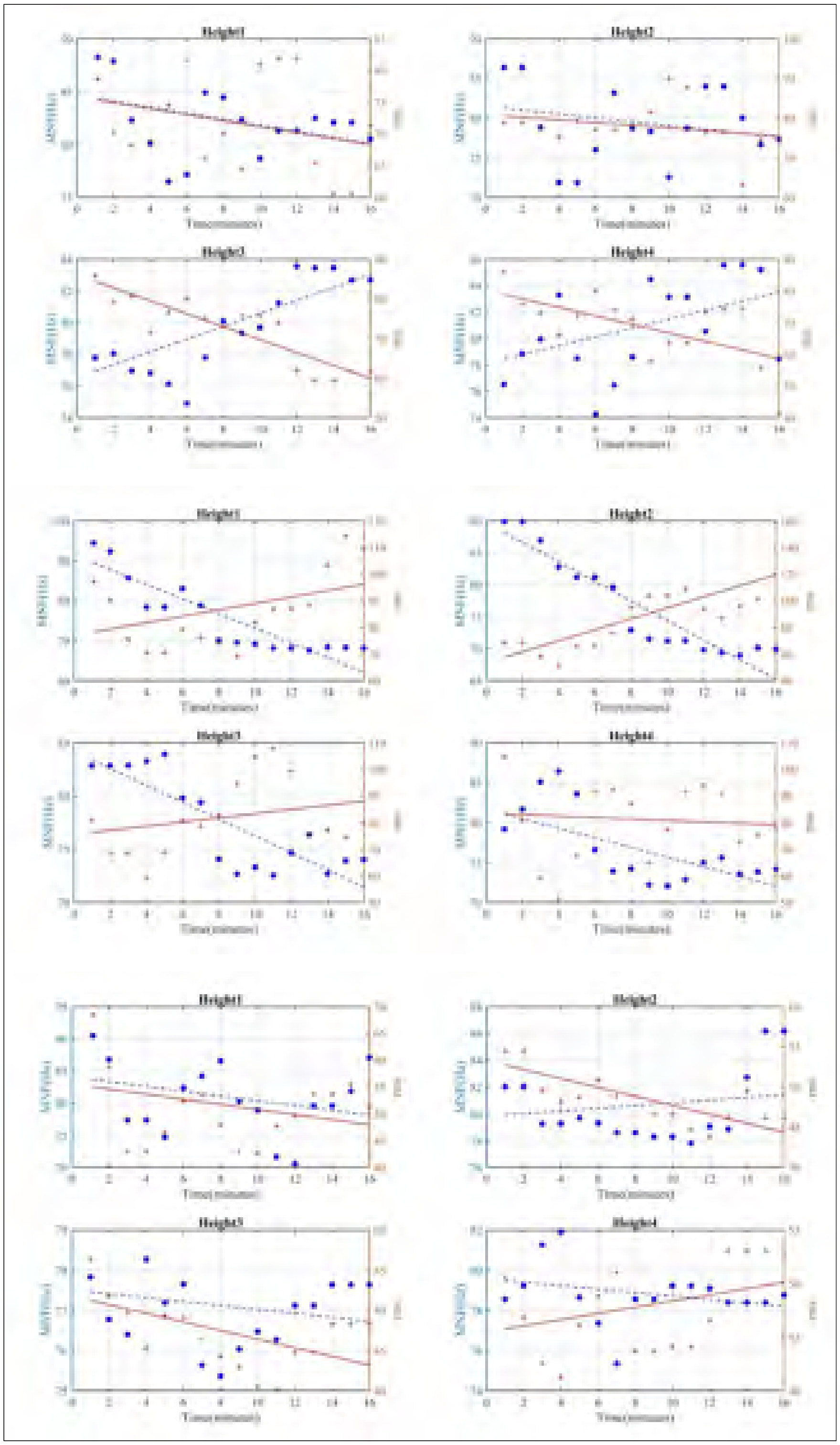

Figure-A V-17 Changes in mean frequency (MNF) versus time (minute) of ESR muscle for four heights (Subject 2, 3 and 4)

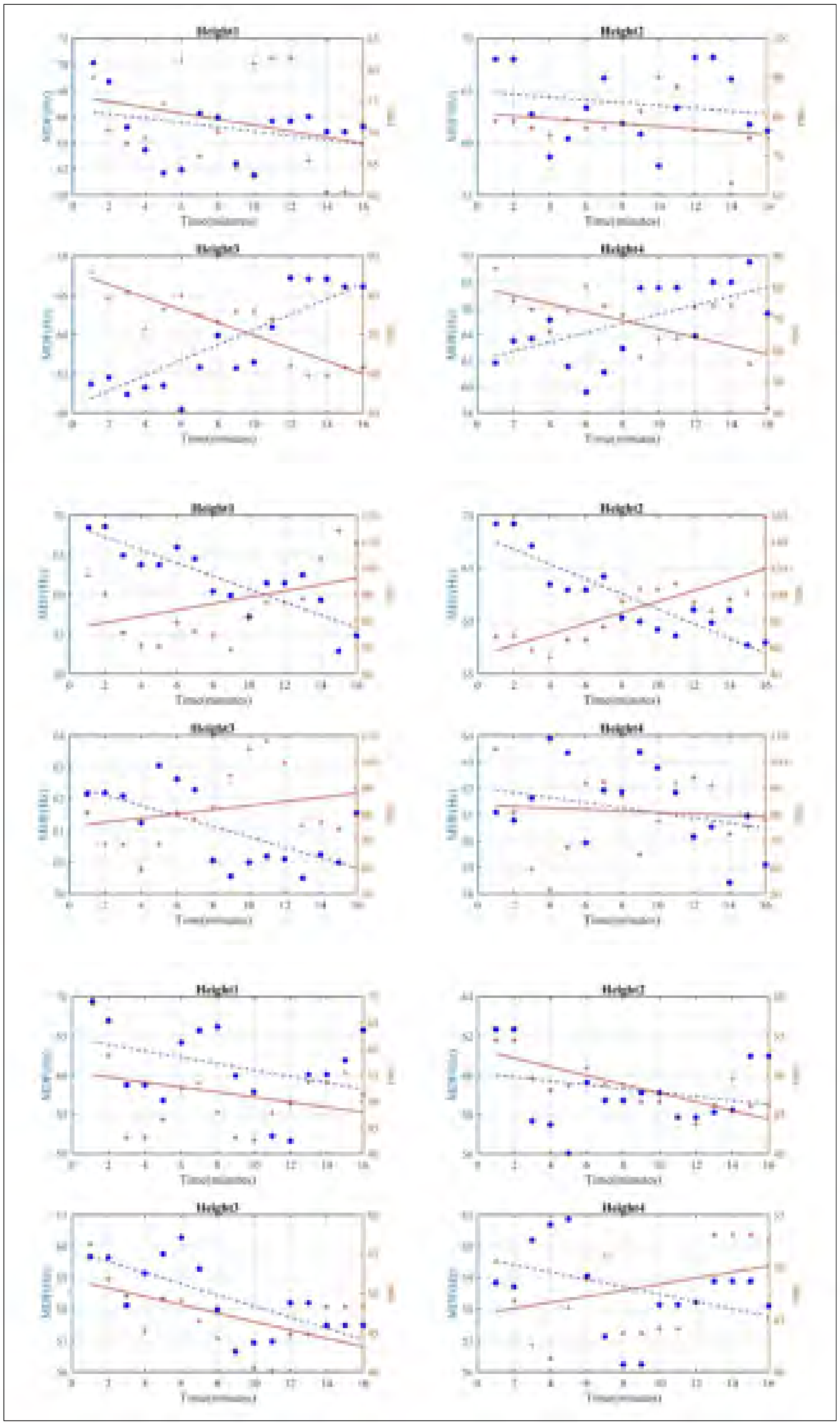

Figure-A V-18 Changes in median frequency (MDF) versus time (minute) of ESR muscle for four heights (Subject 2, 3 and 4)

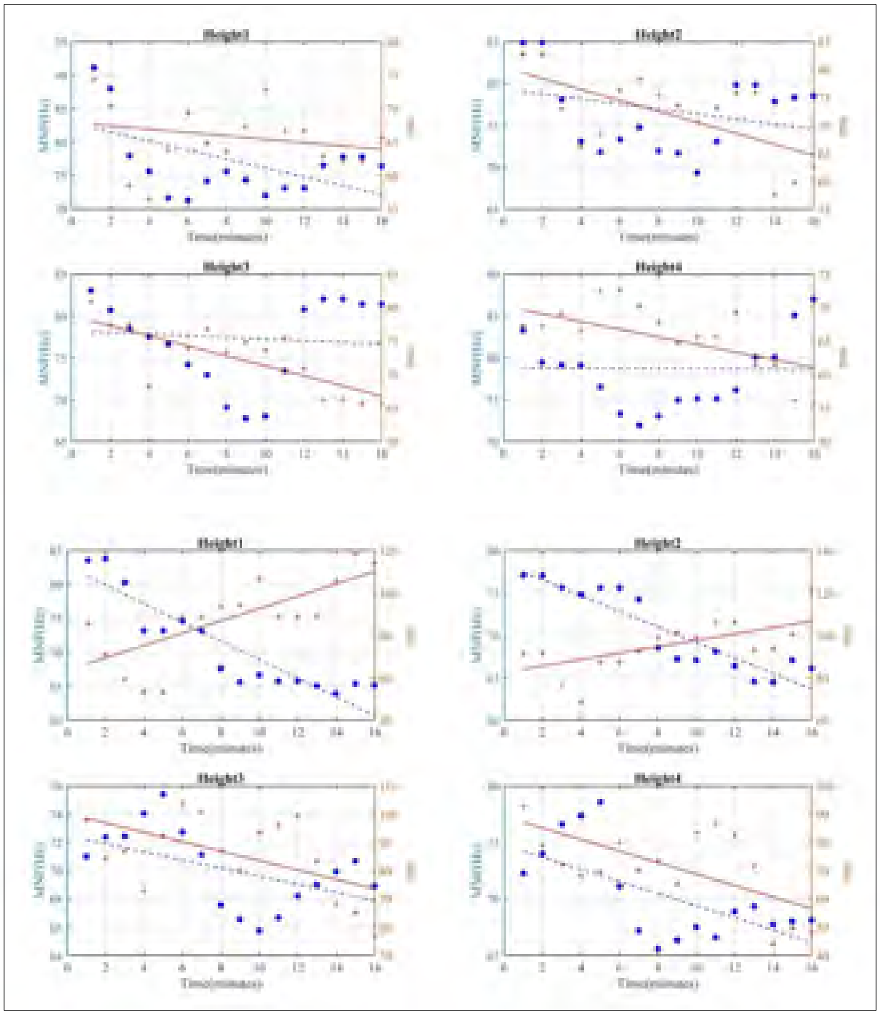

Figure-A V-19 Changes in mean frequency (MNF) versus time (minute) of ESL muscle for four heights (Subject 2, 3)

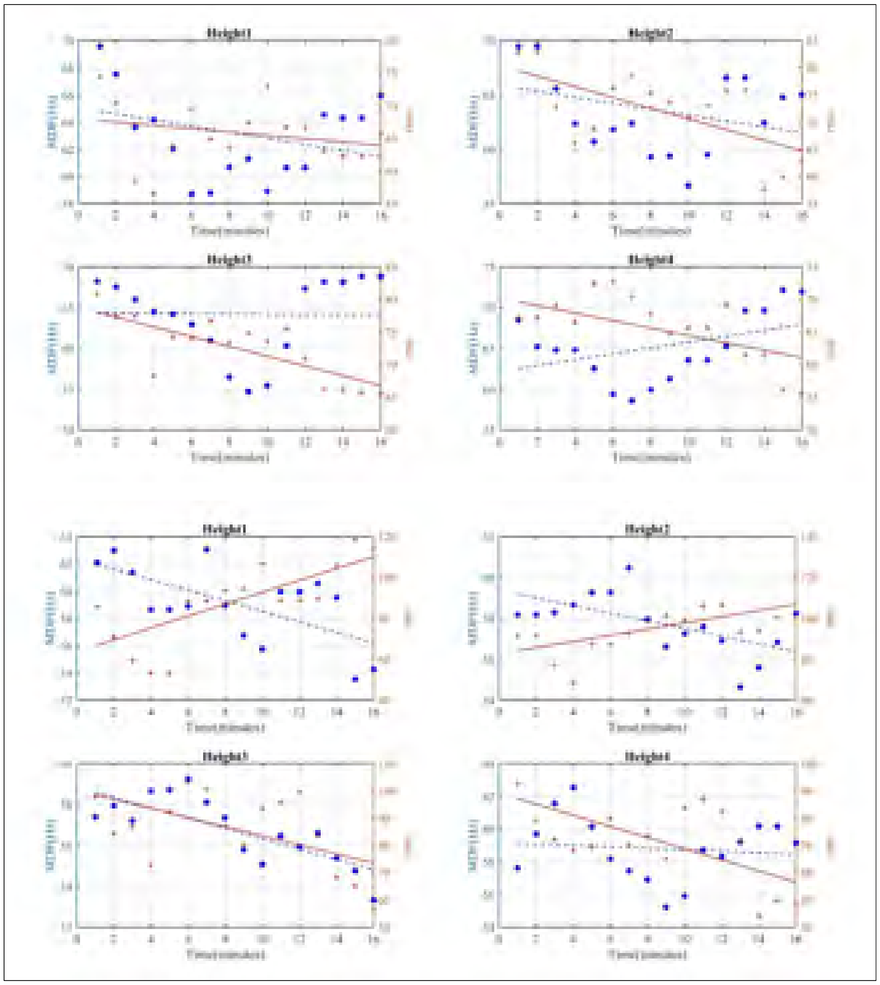

Figure-A V-20 Changes in median frequency (MDF) versus time (minute) of ESL muscle for four heights (Subject 2, 3)

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