Objective Methods for Characterizing Physical Exposures which may contribute to Work-related Musculoskeletal Disorders in Agricultural Workers

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A dissertation
submitted in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy

University of Washington

2016

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Program Authorized to Offer Degree:
Industrial & Systems Engineering

University of Washington

Abstract

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Migrant farmworkers in the United States often perform physically-demanding work but are less likely to report poor working condition, which exposes them to the physical risks of work-related musculoskeletal disorders including prolonged non-neutral postures, repetitive motions and forceful exertions. In industrialized countries, such technology as the harvest-assisted mobile orchard platform has been introduced to increase efficiency; however, research on potential musculoskeletal health effects associated with the introduction of the mobile platforms on the workers is lacking. The existing methods to assess ergonomic risk factors in laboratories or other industries are not suitable to agricultural work due to the variability of the work in the field-based settings. The goal of this study was to develop methods to characterize these musculoskeletal health risk exposures from data directly collected in the field. Kinematic measures included static non-neutral postures of upper arms and back and work repetition rates of upper arms derived from accelerometer data. Physiological measures included muscle fatigue and muscle activity of upper trapezius obtained from surface electromyography (EMG). Muscle fatigue was investigated in terms of the EMG median power frequency shift and changes in EMG amplitude over time. Muscle

activity was characterized as EMG amplitudes normalized to reference activity and maximal dynamic activity. Moreover, subjective Borg RPE and Borg CR10 scales were used to assess perceived overall exertion and local body part fatigue, respectively. Then the exposure assessment methods were implemented to compare different apple harvesting methods in Washington State. Lastly, correlations between objective and subjective measures were calculated to study whether one measure can replace the other. The outcomes from this dissertation and its implications for future studies could potentially lead to the improvement in work environment for farmworkers and will ultimately improve their health and well-being.

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Acknowledgement

First and foremost, I would like to thank Dr. Peter Johnson for his guidance and trust in me throughout my graduate studies. The experience in working as his student helped me establish a great foundation on becoming a researcher. His expertise undoubtedly helped ensure the quality of research. His passion and intellect helped push me to overcome barriers on my seven-year journey here at UW and to become a lifelong learner.

I would like to deeply thank Dr. Linda Ng Boyle for her great intellectual and emotional support. This dissertation would not have been completed without her selfless help especially during the last seven months with her suggestions, encouragement and confidence in me.

My gratitude to Dr. Randal Ching for his suggestions, encouragement, kindness and patience since developing the dissertation proposal.

Also thank to Dr. Kevin McQuade for his inputs beyond the GSR role. His expertise greatly merited this research as an additional yet important consideration from the clinical perspective.

This research would not have been possible without Stemilt – the cooperating orchard – and Automated Ag Systems – the manufacturer of the agricultural equipment in use in this research.

Many thanks to the Pacific Northwest Agricultural Health and Safety (PNASH) Center at the Department of Environmental and Occupational Health Sciences and the team of researchers – Kit Galvin, Maria Tchong-French, Maria Negrete and Pablo Palmández. During three harvesting seasons of fieldwork with PNASH, I learned so much from shadowing the fieldwork, participating as a team member, and leading the team.

Also I would like to thank my co-workers at the Ergonomic Laboratory – Margaret Hughes, Katherine Gregersen and Monica Zigman for their help with the fieldwork, Lovenoor Aulck and Patrik Rynell for their help in computer programming, and Fangfang Wang, Frank Ryou, Dawn Ryan and Jeong Ho Kim for their feedback about this research.

Thank to the Industrial and Systems Engineering (ISE) staffs – Kellus Stone, Jennifer Tsai, Jenny Dutton, Sheila Prusa and Deborah Fromm – for all their hard work and support through my time at UW. Thank to my ISE fellow graduate students – Penny Hu, Sirirat Sujitnapitsatham, Tolu Abe, David Linz, Shuoqi Wang, Chun-Cheng Chang, Gavan Kaizawa, Haixu Mei, Tin-Yu Ho, Larissa Guimaraes Petroianu, Peeyush Kumar, Abdul-Aziz Aldawood, Hao Huang and Philip Placek – for their numerous support and friendship.

I am very thankful for the powerful support and encouragement from my close friends along this adventurous road – Barbara Pizacani, Jitpicha Jarayapun, Wilawan Thanatemaneerat, Manisa Veeravigrom, Charles Warner, Rocio Chueco Montilla, Evaldo Primo, Minhtu Nguyen, Mylinh Nguyen, Antonin Della Noce, Harikrishnan Murali, Gabriela Alban Hidalgo, Mohamed Bashir Mobasher, Krissana Clark, Pranee Oupako, Amy Phillips, Brian Jacobs and my Spanish teacher Donally Kennedy.

Thanks so much to all the research participants. Their contributions are much appreciated.

Much gratitude to all the migrant farmworkers. Their lives motivated me to invest myself into them and reminded me to be truthful to the work with good intention.

Last but not least, I am grateful to my family, especially my mother – Areerat Thamsuwan – for her strength and unconditional love that inspired me to choose a research topic that will help the underprivileged and to keep on working hard. I promise to her that I will use my privilege of education to bring equity to society.

This research was supported by Washington State Medical Aid and Accident Fund and CDC/NIOSH Grant (2 U54 0H007544-11).

Chapter 1 Introduction

This chapter provides background information on the problems addressed by this dissertation; that is, how challenges in agricultural industry in United States and Canada have been contributing to health disparities, in particular, the risks for work-related musculoskeletal disorders (WMSDs) in migrant agricultural workers. This dissertation attempts to identify ergonomic interventions that will reduce the risk of WMSDs among migrant farmworkers due to physical exposure. Currently, there are still gaps in applying existing ergonomic methods for improving work in agricultural settings. The chapter will discuss the challenges with using current ergonomic methods in agricultural settings, identify gaps in knowledge, and will end with the overview of the proposed research in how to intervene these gaps.

1.1 Background and Motivation

1.1.1 Emerging Technology in North American Agricultural Industry

Agriculture has been an important industry in North America. Among agricultural products, tree fruit ranks first for market value and accounts for almost one-third of agricultural product sales in the United States (USDA 2012). Apple production has increased over time and more than half of the apples produced in the Unites States come from Washington State (USDA 2014).

In the past 20 years, the U.S. tree fruit industry has been facing challenges in price competition from foreign producers, especially China and Chile. In an attempt to respond to the international market situation, in 2004, the Washington State Tree Fruit Research Commission issued the National Technology Roadmap for Tree Fruit Production. The goal of this roadmap was to reduce production costs of its highest quality fruit by 30% by the year 2010 and, in the long run, focus on technological innovations towards automated orchard systems (Seavert 2005).

Mechanical, semi-automated harvesting, as a part of the technology roadmap for tree fruit production, has been introduced to make harvesting more robust and economical. Two key components of the mechanical harvesting component involving the tree fruit technology roadmap are an end-effector, semi-automated fruit harvesting methods and harvest-assist mobile platforms. The end-effector technology is being proposed for better harvesting efficiency but as yet, has not been put into practice. It consists of a robot arm that semi-automatically removes apples from the tree. The harvest-assist mobile platform (Figure 1) is an elevated platform that semi-autonomously moves through two rows of trees and has already been adopted by some industrialized orchards. With the introduction of the mobile platforms, workers can now stand on the platform and continuously pick apples while the platform semi-autonomously transports workers through the orchard. This is in contrast to their previous method of walking up and down and standing on ladders. In order for the implementation of the mobile platforms to become effective, trees have to be grown in parallel rows with room for the mobile platform and the workers to pass through the trees (WTRFC 2011). In Washington State, on average, there are 1.3 (range 0-4) platforms in an orchard and 3.8 (range 0-10) workers per platform (WTRFC 2011). The adoption of mobile platform depends on orchard size, apple variety and topography of the orchard.

Figure 1 – Harvest-assisted mobile orchard platform

1.1.2 Latin American Migrant Farmworkers

Labor cost and agricultural worker availability has been an issue in the U.S. tree fruit industry. Most of the children of farmers prefer to work in higher paying jobs in cities. Since 1994, the North American Free Trade Agreement (NAFTA) has jeopardized Mexican farms and food self-sufficiency. Mexico's small farmers have experienced a drastic decrease in subsidies that they had previously received and; therefore, can no longer continue to grow and sell their agricultural produce competitively. Since job opportunities in Mexican farmlands have become rare, some of the people who used to work on these farms now have to migrate to work in the United States and Canada.

In the United States, Latino migrant workers have been seasonally employed to fill in jobs that American workers are not willing to do for the wages that farm owners can afford to pay (Blank 1998). In California and Washington State, migrant farm workers have been recruited through farm labor contractors (Krissman 1999). Coming from Mexico and Central American countries, migrant farm workers have to face several hardships because of their low socioeconomic status. During harvesting season, they are employed to pick fruits and are paid either an hourly rate or more likely, piece rate, based on the amount of fruit they pick. They are often required to pick a minimum aggregate weight of fruit, that is often difficult to achieve; and as a result, typically work seven days a week; in other words, with little to no rest. Due to the high work demands and tenuous work status, if the migrant workers have a work-related illness or injury, they may underreport their health conditions because of their legal work status, lack of health insurance, or fear of being fired by their employers for a reason of not being able to meet job requirements. As a result of these circumstances, migrant workers complain less and use fewer public resources such as clinic services, welfare, and worker compensations (Holmes 2013). Above all, due to a higher physical work demand, they are more susceptible to work-related musculoskeletal disorders (WMSDs) than the non-Hispanic American farmworkers.

1.1.3 WMSDs Prevalence and Occupational Risk Factors

During 2010-2014, the incidence rate of recorded nonfatal workplace injuries and illnesses among the US crop production was 5.5 cases per 100 full-time workers, which is higher than the average rates across all industries at 3.4 cases per 100 full-time workers (US-BLS 2015a). Among the total incidence cases, 3.3 cases per 100 full-time workers were with days away from work or job transfer or restriction. In 2014, farmworkers had a median of 7 days away from work due to MSDs (US-BLS 2015b). Notwithstanding, the number of cases in crop production was estimated to be undercounted by 73.7% (Leigh et al. 2014).

Work-related musculoskeletal health outcomes can be classified into two categories: acute injuries and work-related musculoskeletal disorders (WMSDs) resulting from cumulative trauma. While both have significant consequences to the long-term health of farmworkers, research on WMSDs in agricultural settings is still lacking. In general, the WMSDs that farmworkers experience the most are in the regions of the low back, shoulder, and upper extremities, respectively (Davis & Kotowski 2007; Osborne et al. 2012). Based on self-reported pain in the past year in the United States (Walker-Bone & Palmer 2002), the prevalence of low back pain was greater in farming (41%) than other manual (38%) and non-manual (27%) occupations and the prevalence of shoulder pain was greater in farming (14%) than other manual labor (9.7%) and non-manual labor (7.1%) occupations. Epidemiological studies have been conducted on the working conditions of migrant seasonal farmworkers in California (McCurdy et al. 2003; Xiao et al. 2013). In apple orchards, manual harvesting was the most frequency engaged in task (34.5%) and the median duration of the apple harvest was 4 weeks (McCurdy et al. 2003). When looking at the gender distribution, due to the high physical demands associated with the apple harvesting work, the number of male workers performing the harvesting task was roughly six-fold greater than the number of females (Xiao et al. 2013). This gender distribution is similar to the apple harvesting population in

Washington State. Notwithstanding, these previous studies did not present any specific associations between tree fruit harvesting, musculoskeletal discomfort and the prevalence of WMSDs.

Typically, WMSDs develop over time during exposure to one or a combination of physical risk factors including forceful exertions, awkward postures and repetitive work. Occupational risk factors for low back and shoulder pain include working with moderate to high forces, prolonged elevated postures with the back and arms and repetitive use of the arms (English et al. 1995; van der Windt et al. 2000; Leclerc et al. 2004). In apple harvesting, workers are exposed to shoulder stresses while reaching to pick apples (62.9% of the time) and to both back and shoulder stress while carrying apple bags or ladders (78.5% of the time) (Fulmer et al. 2002). The period of awkward postures in this population was found greater than those in construction workers and nurses, two groups with the highest WMSD risk (Earle-Richardson et al. 2004).

1.1.4 Summary of Current Methods in Ergonomic Evaluation

With the recent introduction of the mobile platform, workers are constantly working as the mobile platform transports them through the tree canopy. Compared to traditional apple harvesting with ladders, the major potential benefit of the mobile platform is the potential productivity increase by always being in and slowly moving through the tree canopy. If there is a productivity increase compared to harvesting fruit from ladders, then mobile platforms may be an available alternative to replace ladders. In addition, falls from ladders are not uncommon (Fathallah 2010) and the mobile platform may help reducing some of the fall-related injuries associated with ladder use. Finally, relative to work on ladders, mobile platforms may reduce low-back and shoulder pain associated transporting and unloading picked fruit into larger, centrally-located, harvesting bins. Both mobile platform and ladder workers wear front mounted fruit bags which are strapped to their shoulders; however, the harvesting bin is just a few steps away in the mobile platform whereas ladder workers have to descend the ladder and walk varying distances (10 to 50 meters) to a centralized fruit bin to unload and deposit the fruit they picked. There appears to be many positive benefits associated with the mobile platforms. However, a major unanswered question and concern is, whether the mobile platform workers will (1) be able to consistently move through the tree canopy when compared to ladder worker, (2) whether the mobile platforms be able to promote and contribute to higher repetitive or prolonged static loading in the shoulders and back or put the workers at greater risk for shoulder- and/or back-related discomfort and injury.

Physical exposures (non-neutral posture and repetition) in the upper extremities can be characterized based on the change of upper-arm angle relative to the shoulder joint, i.e. glenohumeral joint. These kinematic exposures can be assessed either by observation and subjective scoring, for example RULA (McAtamney & Nigel Corlett 1993) and REBA (Hignett & McAtamney 2000), or by objective, direct measurements that incorporates either some sort of computerized system with markers on the relevant body segments or self-contained, battery powered sensors with built-in memory (Spielholz et al. 2001; Scibek 2012). Very few studies have collected objective measurements of repetition and posture from agricultural workers in field settings. Although repetition can be assessed using time and motion study methods (Lowe 2004), which is widely used in other industries involving cyclic work like manufacturing, there is no method readily available to quantify work-related repetition, or posture for that matter, in field-based agricultural settings. For example, a camera-based motion capture system often requires access to several views to accurately characterize the body segment movements, and this is difficult if not impossible to obtain in the field where workers keep moving from one place to the other. Another reason is due to the diverse and unpredictable nature of agricultural work. For example, in the fruit harvesting case, the height of the fruits from the ground and location of fruits within the trees varies, and the trees can often obstruct the view of the workers.

One physiological method for evaluating work-related exposures during agricultural work is electromyography (EMG), which measures the electrical activity of the muscle. The simplest way to assess a muscle's electrical activity is to use skin mounted surface electrodes and measure the electrical activity from the targeted muscle or muscles underneath the electrodes. In many ergonomic assessments evaluating work-related physical exposures, the trapezius muscles in the shoulder are often targeted. However, surface EMG may be difficult to apply in orchards as equipment including data logger and electrode cables may interfere with harvesting tasks and perspiration may interfere with how well the electrode stays in contact with the skin. In a previous study, (Earle-Richardson et al. 2006), noted that it was not feasible to collect muscle activity in orchard workers due worker perspiration and the electrodes sliding off. To date, the only objective measures of agricultural worker muscle activity have been conducted in laboratory-based studies (Freivalds et al. 2006; Jin et al. 2009).

Physical or kinematic measures of body segments and physiological measures like EMG may be related. A previous study (Vasseljen & Westgaard 1997) found concurrent increases in the angle of arm elevation and trapezius EMG at non-neutral postures (> 45^{o}). Also, a relationship between the repetition rate of reaching above shoulder and EMG was evidenced in laboratory studies (Ebaugh et al. 2006; Fuller et al. 2009). A study of this relationship in the field may also provide information on whether kinematic measures (e.g., work postures and repetition rate) are sufficiently meaningful to represent muscle activity.

1.2 Proposed Research

While the mobile orchard platform technology has been developed and implemented to improve productivity in the tree fruit industry, the prolonged health effects on orchard workers are still uncertain. Although many ergonomic evaluation techniques have been developed, they have primarily been applied under controlled laboratory-based settings, which did not truly mimic working conditions in the field. This research aims to fill these gaps by evaluating field-based posture and EMG measurement methods for evaluating agricultural work in actual field settings. In addition, these methods are to be used for evaluation and comparing WMSD-related risk factors associated with harvesting fruit using mobile platforms and ladders. Particularly, this research focuses on quantifying the posture and repetition of upper arms and back using accelerometers and the physical load in shoulder muscles using surface EMG.

Chapter 2 Literature Review

This chapter extends the review of the ergonomics literature for methods of evaluating physical risk exposures for WMSDs, i.e. prolonged non-neutral postures, repetitive motion and forceful exertion. In summary, kinematic exposures, posture and repetition, can be evaluated both objectively and subjectively. Forceful exertions can be measured in selected muscles in the upper extremities using electromyography and measures of local and whole body perceived exertion could be measured subjectively. Finally, the associations between the objective and subjective measures are reviewed.

2.1 Measures of Kinematic Exposures

2.1.1 Postures

Previous studies have presented several techniques that can be used to assess non-neutral work postures through observational methods. Among the observational upper extremity-based assessment tools, the Rapid Upper Limb Assessment (RULA) (McAtamney & Nigel Corlett 1993) and REBA (Hignett & McAtamney 2000) is popular due to its simple, user-friendly assessment method. The RULA method assesses the postural exposures based on the presence of the upper arm elevation angle exceeding certain thresholds and combines the hazard levels at upper arm with hazards estimated from the other parts of the body (neck, back and legs). The REBA method assesses the postural exposure by taking account of neck, trunk, legs, upper arms and lower arms. One concern with the RULA method is how the misclassification of upper arm posture can lead to the misclassification of the overall musculoskeletal risk rating and, similarly, the concern for REBA method is that the trunk and upper arm misclassification affect the overall rating of risk (Escobar 2006).

Other studies that quantified upper arm and back postural exposures by observation have described the exposure as the percentage of time that the upper arm is elevated above certain anatomical threshold values and when back bending exceeds certain angular threshold values (Karhu et al. 1977; Keyserling et al. 1993; Paquet et al. 2001) as well as temporal distributions of upper arm elevations and back bending over ranges of angle categories (Keyserling 1986; Occhipinti 1998; Occhipinti & Colombini 2007; Ohlsson et al. 1995; Sakakibara et al. 1995).

Ovako Work Posture Analysis Systems (OWAS) (Karhu et al. 1977) classifies postural exposure using photographic images of the worker. When applying the OWAS across each desired work task, the upper arm posture is categorized as: 1) both limbs below shoulder, 2) one limb above shoulder or 3) both limbs above shoulder; and back posture is classified 1) straight, 2) bent, 3) straight-and-twisted, or 4) bent-and-twisted. Although the OWAS method may not have high measurement resolution, it is practical and more likely to be accurate as the choices of upper arm and back posture categories are very clear and easy to recognize and evaluate.

Characterizing postures using the presence or percentage of time when upper arm elevation angle passes an anatomical cut-point, like the RULA, REBA and OWAS method, may be applicable for identifying where and when to introduce an intervention. On the other hand, when upper arm and back posture is characterized using angle ranges, the exposures are simpler to characterize and better suited for epidemiological studies. A cross-sectional study in female industrial worker population (Ohlsson et al. 1995) categorized upper arm postural exposures into ranges of angles and found association between the increases in arm flexion and abduction and the prevalence of diagnosed neck and shoulder disorders. Another study which assessed female Japanese workers who bagged apples and pears (Sakakibara et al. 1995) also evaluated the time the arm elevation was in different angle ranges to show there was a relationship between arm elevation and the prevalence of neck and shoulder pain.

Although subjective, observational measurements can be done quickly and at low cost, the accuracy, i.e. the internal validity of the subjective measures may be questionable. In a study that compared subjective postural classifications by ergonomists watching videos to direct measurements made with an optical motion capture system (Lowe 2004); relative to the direct measurements, the subjective, video-based observational methods resulted in a great deal of misclassification. When the ergonomists categorized the most frequent shoulder angle (mode) into three bins within in the coronal and traverse planes (abduction and outward rotation), posture misclassifications occurred for 25% and 8.3% of the time, respectively. When the posture was classified based on the extreme (peak) shoulder angle, posture misclassifications occurred for 22.2% and 38.9% of the time, respectively. Also, the subjective visual analysis by ergonomists resulted in a trend towards an overestimation of the percentage of the work cycle in the low- (neutral) and high- (extreme) exposure categories but an underestimation of the percentage in the middle category. Since the ergonomists are likely to lean towards recognizing postural extremes, this subjective method may not be as accurate as direct measurement methods.

2.1.2 Repetitions

Repetitive work with the upper extremities can be counted in real time through direct observation in the field with activities videotaped for remotely analysis later in a lab. Motion capture based systems can also monitor and measure repetitions in lab-based settings. Video and motion capture-based methods are considered the “gold standard” for measuring posture and repetition since the continuous record of the movement can be monitored, captured and analyzed. Observational-based methods include work sampling techniques like “PATH: posture, activity, tools and handling” (Buchholz et al. 1996) which can be used to determine repetition cycles at certain time stamps or as snapshots of ergonomic assessment. In the original version of PATH, observations were randomly distributed across fixed intervals of usually 45 or 60 seconds. Also, time-motion studies may be performed in a finer detail. However, these observational methods can be time consuming. Moreover, both observational methods, with and without videotaping, may lead to systematic biases; that is, workers could change the way they normally work due to the presence of a researcher or camera or there may be differences in how observers perceive movements and postures. To overcome the drawback of these observational methods, direct measurements are often preferred.

There are some studies that have developed methods to characterize repetition cycles based on direct measurement. One commonly used method to measure repetition as well as posture is a motion tracking system of which videos, optical or electromagnetical sensors follow markers placed on a subject. Even though these systems have been used with high accuracy (Lowe 2004; Ebaugh et al. 2006; Fuller et al. 2009), the methods are limited to laboratory or controlled indoor settings.

Another way to directly measure the movement of upper arms as well as other body segments is to use accelerometers where the device measures angles with respect to gravity. This technique has been used in clinical assessment of shoulder range of movement (Green et al. 1998; Triffitt et al. 1999; Johnson et al. 2001; Kolber & Hanney 2012) but has yet to be explored for investigating work repetition. Currently, there are no accelerometer-based studies that have taken advantage of continuously-monitored upper arm angles to measure repetition rates. However, there is a previous (Spielholz et al. 2001) that collected the postures of distal upper extremity (hand, wrist and forearm) using electrogoniometers and electrotorsiometers, and then derived repetition rates from the postural excursion data. One repetition was defined as a movement passing a pre-defined neutral postural cut-point, ending in a non-neutral posture, and then passing through the neutral posture cut-point. This method has been shown to be reliable for assessing repetitive motions of the distal upper extremities.

Generally, repetitive cycles can be studied not only in the time domain, i.e. counting cycles in a certain time window, but also in the frequency domain, i.e. spectral analysis, looking at the most common frequency or frequencies of the movements. For characterizing cyclical tasks through spectral analysis, a previous experimental study (Radwin & Lin 1993) used electrogoniometer to collect wrist postures in a task involving primarily wrist flexion/extension, a task involving repetitive ulnar/radial deviation while sustaining constant wrist flexion and a task containing sub-cycles within a fundamental cycle. The DC component of the spectrum indicated average sustained posture, representing postural stress. The AC component's harmonic peak frequencies indicated the frequencies of the cycle. This method was able to capture the frequencies of both the fundamental cycle and the sub-cycle. The root-mean-square magnitude of each spectral component indicated postural deviation for its corresponding repetition rate. This spectral analysis technique was extended to evaluate the frequencies of repetitive upper arm motions in a reaching-and-grasping task, involving shoulder flexion/extension and shoulder abduction/adduction, and was found to provide the same information as a time-motion study (Yen & Radwin 2000). Furthermore, the spectral analysis can benefit the posture analysis as it saved a great amount of time compared a parallel postural classification performed by ergonomist (Yen & Radwin 2002).

2.2 Electromyography as Physiological Measure

2.2.1 Surface EMG Measurement Systems

Surface EMG is a non-invasive technique for measuring electrical activity from muscle contraction and relaxation. With this technique, surface electrodes are placed on the skin over the muscle or muscles of interest. Proper skin preparation and electrode positioning are key prerequisites in acquiring quality EMG signals. Since the impedance of skin can diminish the magnitude of EMG reading, it is necessary to remove dead skin to lower the impedance. This can be done by using alcohol wipe or fine sandpaper to abrade the skin. Electrode pairs are always placed along the direction of the muscle fibers. A reference (ground) electrode should be placed away from the differential electrode pair and on electrically neutral tissue, i.e. over bones or tendons. These electrodes are generally wired to a digital recording system.

2.2.2 EMG Analysis and Signal Quality

The amplitude of EMG signal is often used as an estimator of muscular load; however, the EMG amplitude depends on the muscle and movement type. The EMG signal can be evaluated in terms of raw and root-mean-squared (RMS) signals. While both raw and RMS signals can provide information about the contraction and resting states, which are useful for the study of muscle activation time and for detecting signal artifacts, RMS signals are more useful for quantifying the level of muscle activity. The RMS signals based upon an averaging time window of 0.25-0.75 seconds have been shown to have a relationship with developed static force, which is a sign of fatigue (National Institutue for Occupational Safety and Health 1992). Using percentile ranges or amplitude probability distribution function (APDF), the static component, central tendency and peak components of EMG can be evaluated.

In addition, the frequency content of the raw muscle activity signals such as mean power frequency and median power frequency can provide information about muscle fatigue (DAUBE 1981). A significant change in one of these spectral parameters can be an indication of muscle fatigue. The mean and median power frequencies are generally calculated over a series of short windows of 0.25-2 seconds over the measurement period of time (Öberg 1995; Potvin & Bent 1997; Chesler & Durfee 1997; Yassierli & Nussbaum 2007; Ferguson et al. 2013).

One common artifact in EMG signals is a 50-60-Hz power line interference, caused by electrical devices. Another type of signal artifacts is EKG artifacts generated by the heart muscle, which can be avoided by placing electrodes off axis from heart activity. A high-pass filter may also be used to remove these artifacts but there is a trade-off that some of the power of the EMG is lost if this high-frequency cut-off is used. Additionally, low-frequency movement artifacts can occur when electrodes are disturbed or cables are pulled. The movement artifacts can be reduced through high pass filtering, setting a high pass frequency cutoff between 10-20 Hz.

2.2.3 EMG Amplitude Normalization

The magnitude of EMG varies by individual and can be dependent on muscle depth, the amount of body fat tissue below the skin and muscle fiber recruitment. Also, even within the same subject, distance between the electrode pairs affects the depth at which the muscle activity is measured and can affect the magnitude of the signals. Therefore, when comparing individuals, EMG normalization is mandatory.

EMG can be normalized as a percentage of maximal voluntary contraction (%MVC) (Westgaard 1988), at some level of submaximal voluntary contraction (Attebrant et al. 1995; Jackson et al. 2009) or as a percentage of dynamic muscle activity (Fernández-Peña et al. 2009; Nishijima et al. 2010). According to previous literature, for an MVC normalization of the upper trapezius, subjects have been asked to perform three maximal shoulder elevations for at least 3 seconds with at least a 4 minute break in between. Then the highest 3-second-average amplitude among these three contractions is used as MVC. Two different procedures for performing submaximal MVC contractions have been developed and tested (Attebrant et al. 1995): 1) a ramp procedure and 2) a constant two-force procedure. First the subject MVC value has to be determined. Then, in the ramp procedure, subjects perform isometric shoulder elevations with increasing force from rest to 30%MVC, lasting about 10 seconds. In the constant two-force procedure, subjects perform steady isometric shoulder elevations, one at 15%MVC and the other at 30%MVC. EMG is recorded for 15 seconds of contractions with 15 seconds of relaxation between the submaximal contractions and the middle 10 seconds is used to calculate the submaximal MVC reference value.

The disadvantage of using and MVC or submaximal MVC is that a maximal contraction is necessary but may be difficult to perform and there is a risk for injury when performing maximal contractions. To avoid these issues, EMG amplitude can be expressed in the percentage of the amplitude during a standardized submaximal reference voluntary contraction (%RVC) (Mathiassen et al. 1995). In a study comparing EMG amplitude distribution between a 10-seccond ramp contraction from 0% to 90%MVC and a 30-minute sustained contraction at 25%MVC of upper trapezius muscle, the amplitude distribution at sustained contraction became close to the contraction at higher force (Holtermann & Roeleveld 2006). Experimental protocols in previous studies (Mathiassen & Winkel 1990; Veiersted et al. 1990; Bao et al. 1995) consider both unilateral and bilateral contractions, with various postures including shoulder elevation, arm flexion and arm abduction, and with and without loads. In a later study applying the reference contraction technique to upper trapezius muscle (Farina et al. 2002), the recording procedure involved having subjects stand in an erect posture with simultaneously moving the upper arms in five positions (arms at the side of body, 45^o and 90^o flexion and 45^o and 90^o abduction) with elbow straight and hand 90^o pronated. At all five postures, subjects held no load, 0.5 kg and 1 kg load.

Furthermore, an alternative method for EMG normalization can be obtained using a dynamic normalization, i.e. normalizing to a mean or peak (maximum level) of amplitude during activity during dynamic contraction. This method has been used for gait analysis during walking (Yang & Winter 1984) and cycling (Chapman et al. 2010). Normalization using dynamic contraction was found to have higher reproducibility than MVC in a study of gastrocnemius muscle (Knutson et al. 1994). However, another study in biceps brachii muscle found that the dynamic contraction method was unable to distinguish the changes in the same force as the MVC method could (Burden & Bartlett 1999). Moreover, since the denominators (mean or peak muscle activities) are relative to the task but not to the maximum capacity of the muscle, the normalized muscle activities cannot be compared between muscles, tasks or other studies that don't use a dynamic normalization (Halaki & Ginn 2012).

Muscle fatigue can be quantified with EMG mean power frequency (MNF) or median power frequency (MDF). A previous study using surface EMG on the biceps brachii muscle during repetitive elbow flexion and partitioning time into 250-ms segments found a significant effect of time on both amplitude and frequency of the signals, i.e. the average amplitude increased by 34.2±14.7% and the MNF values decreased 27% from 72.6±8.4 Hz under rested conditions to 53.0±9.9 Hz when muscle was fatigue (Potvin & Bent 1997). Another study on descending trapezius separated muscle activity into 5-minute periods also found an increase in RMS amplitude and a decrease in MNF (Sundelin & Hagberg 1992). Finally, as the amplitude of EMG rises due to muscle fatigue, the contraction used for the normalization of the EMG should be of limited duration (Öberg 1995).

2.3 Subjective Measures

2.3.1 Ratings of Perceived Exertion and Pain Scale

Psychophysical evaluation of perceived exertion has been a complement to physiological evaluation in sport medicine and ergonomics. Methods that have been widely-used were developed by Borg. Two of the most well-known scales are the 6-20 Ratings of Perceived Exertion - RPE (Borg 1970), and the 0-10 Category scale with Ratio properties - CR-10 (Borg 1982). The definitions of the ratings (numbers) of the Borg RPE and Borg CR-10 scales are shown in Appendix D. The RPE scale was constructed to give data that increase linearly with the intensity of stimulus during aerobic exercise on a bicycle ergometer. Correct, consistent instructions on how to give a rating score from the RPE scale are always necessary. The Borg RPE score was designed to be associated with heart rate and blood lactate concentration (Scherr et al. 2013). Heart rate is correlated with oxygen demands in muscles (Huckabee & Judson 1958). Lactate is produced in the muscles during carbohydrate metabolism and has a major effect on muscle fatigue and pain experienced during exercise (Miles & Clarkson 1994). For the CR-10 scale, numbers with verbal-anchors were modified from the RPE scale. The Borg CR10 has been used mainly as a pain and perceived exertion scale in localized body parts. A study of arm-cranking exercise (Capodaglio 2001) found linear relationships between Borg CR-10 and heart rate and blood lactate.

2.4 Relationships among Kinematic Measures, EMG and Subjective Measures

2.4.1 Kinematic Measures versus EMG

Upper arm posture and trapezius EMG are used to indicate biomechanical exposure: internal force generated to meet the work demands (Westgaard 1988); postures as physical measures, and EMG as a physiological measure representing of internal loads, may be correlated. In a previous study (Mathiassen & Winkel 1990), trapezius EMG and shoulder flexion were found to be positively correlated. Moreover, according to a laboratory study (Wickham et al. 2010) that created intensity profiles of EMG amplitude in %MVC during entire range of abduction-adduction movement, the peak intensity (the highest EMG amplitude) occurred when the upper arm was slightly above shoulder level. A similar response was seen in the fourteen other shoulder muscles.

Upper arm repetition could also be related to EMG. In a study of temporal pattern of arm elevation (Vasseljen & Westgaard 1997), the number of movements in small angles ($< 45^{o}$) of excursion did not affect static EMG; however, weak correlations were found between the number of larger movements ($> 30^{o}$) and peak EMG. In the study of force and EMG power spectrum, the speed of arm movement was shown to have a great effect on internal loading (Linnamo et al. 2000). In particular, the velocity of dynamic upper arm abduction movement was shown to have an effect on the EMG amplitude of the upper trapezius muscle in the shoulder; that is, dynamic shoulder muscle activity resulted in the doubled EMG activity compared to isometric contractions (Antony & Keir 2010).

Finally, in a more recent study (Ferguson et al. 2013), demonstrated that not only was shoulder flexion angle and repetition were significantly associated with trapezius EMG, but there was also an interaction effect between the angle and repetition on oxygenated hemoglobin in trapezius muscles, measured by NIRS. This demonstrates the importance of measuring both work posture and repetition.

2.4.2 Subjective Measure versus EMG

Relationships between the subjective measures of perceived exertion and objective measures of muscle activity have been widely studied. A previous study (Hummel et al. 2005) found a linear correlation between Borg CR-10 and the slope of the regression of the normalized mean power frequency (MPF) of the upper trapezius EMG over time during an isometric shoulder elevation ($R = 0.76$, $p < 0.01$). Additionally, a strong correlation ($R = 0.99$) was found between Borg CR-10 and the RMS amplitudes of the upper trapezius EMG during isometric contraction of shoulder elevation in a controlled lab setting (Troiano et al. 2008). In another study investigating a relationship between EMG and Borg CR-10 scores during the full day of lifting tasks, the CR-10 score appeared to be a good indicator for high muscular loading (Jakobsen et al. 2014).

Chapter 3 Specific Aims

The purpose of this dissertation is to develop methods for the ergonomic assessment and physical evaluation of agricultural activities with the ultimate goal to identify WMSDs and the physical risks that may contribute to WMSDs among agricultural workers and reduce their occurrence. The research primarily focuses on assessing physical exposures to the shoulder, upper arms and back by comparing traditional ladder-based fruit harvesting methods to recently-introduced harvesting methods associated with the introduction of mobile platforms. This chapter includes the specific aims of the dissertation and the proposed activities for each of the four aims.

Aim 1: To determine whether the postures in the back and shoulders are different between ladder- and mobile platform-based fruit harvesting methods.

Using the programs developed for characterizing postures from data collected in the field, the exposures to non-neutral back and upper arm postures of orchard workers were compared between ladder- and mobile platform-based fruit harvesting methods. The postural exposures were characterized in two ways: (1) the fractions of work time when angles of the back and upper arms are greater than certain postural thresholds and (2) the fractions of work time when the angles of the back and upper arms are within certain angle ranges.

Aim 2: To develop a systematic method for quantifying the repetition in the upper arms and determine whether there are differences in upper arm repetition between ladder- and mobile platform-based fruit harvesting methods

The systematic method for quantifying the repetition in the upper arms was tailored to be suitable for field-based assessments, which involved a wide range of unconstrained movements of arms throughout the day. Using accelerometers mounted to the upper arms, a computer program was developed to characterize upper arm posture and count cyclic upper arm motions (repetitions) while orchard workers are harvesting fruit. The repetition results from this systematic method were compared to a subset of time-motion analysis data from videotape which will be considered as the gold standard for assessing repetitions.

Aim 3: To use surface electromyography (EMG) to determine whether there are differences in the physiological load in upper trapezius muscles in the shoulder between ladder- and mobile platform-based fruit harvesting methods.

Surface EMG in the upper trapezius muscles of orchard workers was collected under actual field conditions. Previous works showed that field collection of EMG data was extremely difficult primarily due to perspiration interfering with surface electrodes staying attached to the body and the wires to the electrodes getting caught in tree branches and inadvertently removed. Muscle activity will be characterized based on Amplitude Probability Distribution Functions (APDF); that is, static (10^{th} %tile), median (50^{th} %tile) and peak activities (90^{th} %tile) were determined. In addition, muscle fatigue was assessed in terms of determining whether there are shifts in median power frequencies over time. Then the EMG data were compared between ladder- and mobile platform-based fruit harvesting methods. The results might provide additional insight on the physical loading on the muscles associated with fruit harvesting.

Aim 4: To determine whether there are associations between the objective measures of work posture, repetition, muscle activity and the workers' subjective self-assessment of the effort to do the work.

The objectively assessed measures include the time of exposure to non-neutral postures in upper arms and back, the rate of repetition in upper arms and the shoulder muscle activity measured by EMG.

In addition to finding whether there was any association between objective and subjective measures, differences in workers' subjective self-assessments of effort were compared between the ladder- and mobile platform-based fruit harvesting methods.

If a strong association between objective and subjective measures existed, the research might determine whether the posture, repetition and/or EMG were necessary to characterize the physical nature of the work and/or identify differences between work methods. The findings might show whether it would be necessary to conduct a posture and EMG assessment of work in field settings or whether physical exposures can be relatively and efficiently assessed via the workers' subjective self-assessment of their work-related efforts.

Chapter 4 Work Postures in Apple Harvesting Activity

This chapter discusses the approach to characterize kinematic exposures, particularly the static upper arm and back postures, associated with ladder- and mobile platform-based fruit harvesting work. The method section provides the description of the orchard work activity – apple harvesting – to address the task requirements that may affect work postures. Then the methods used demonstrate how the accelerometers can be used to characterize upper arm postures in terms of geometry and the mathematical derivation to obtain postural exposures over work time. In the results section, static postural exposures are characterized both in categories for epidemiological purpose and in terms of exposure limits for WMSDs prevention. The static postural exposures are compared to another study of workers performing apple harvesting in New York State.

4.1 Methods

4.1.1 Defining Fruit Harvesting Task Requirement

The conventional way of harvesting apples is to have workers carry an empty bag on their front side which is attached to the worker via shoulder straps (Figure 2), climb up the ladder and pick apples from the highest point of the tree and move down the tree until the apple bag is filled. With the filled bag, the workers then walk to an apple bin (Figure 3), dimension: 120 cm x 120 cm x 70 cm, and bend over and open the bottom of the apple bag and gently release and disperse the apples into the bin. The workers can usually carry up to 20 kg of apples in their bag before they go to deposit the apples into the bin. As soon as the bag is empty, the work cycle starts again. When working on ladders, this work cycle typically takes about 2.5 to 3 minutes. When the workers finish picking apples from one tree, they move to another tree while carrying the ladder along with them.

Figure 2 – A worker picking apples while carrying an apple bag and standing on the ladder

Figure 3 – Apple bins

With the new mobile platform technology, workers do not have to climb the ladder or walk to the bins to unload the harvested apples. They stand on the mobile platform, which slowly moves through the tree canopy. They use the same apple bag, pick apples until their bag is full and deposit the apples into a bin located on the mobile platform. A foreman or one of the mobile platform workers may control the movement of the mobile platform. In this study, the workers controlled the platform themselves; thus, they were able to control their own work pace. The mobile platform operator only has to control the platform movement intermittently; therefore, this additional task of operating and controlling the platform takes a little time and does not distract the workers from their picking task.

Washington State has requirements for the quality of apples. One restriction is to have a stem attached to the apple (Figure 4 right). If the stem is pulled out (Figure 4 left), the apple cannot be sold as fresh produce. When harvesting apples, the way to keep the stem intact on the apple is to twist the apple about the stem when harvesting rather than directly pulling from the branch. Considering the arm motion of the worker, picking an apple has a small but distinct sub-movement of twisting the apple within the major apple picking movement. That is, workers reach their arm to an apple on a tree, and slightly twist their arm (pronate their forearm and internally rotate their shoulder) to remove the apple with its stem intact. For some apple varieties, including the Fuji apples which were harvested in the study, the other requirement is to use a clipper to cut the stem so it is short enough that the stem does damage the skin of the other apples when the apples are dumped into the centralized storage bins. This clipping task only requires fine finger motions rather than gross movements of the arm. The clipper is small enough that workers can hold and pick apples with the same hand.

Figure 4 – Fruit removal conditions: (left) stem-pulled, (right) stem-intact

4.1.2 Subjects

Twenty-four workers having at least one season (three months) of harvesting experience were selected to participate in the study. All the participants were males of Hispanic origin and native Spanish speakers. The participants were equally divided into three groups: (1.) platform workers who picked apples at the upper and mid-level of the trees while standing on a moving platform, (2.) ground workers, who worked in front or behind the mobile platform and picked apples only at the lower level of the trees and (3.) a separate group of ladder workers who picked apples over the full height of the trees. Four platform workers worked together on the same platform each day. Similarly, four ground workers worked as a team in front or behind the mobile platform. Accordingly, there were two teams of the platform workers (n = 4 each team) and two teams of the ground workers (n = 4 each team). However, the ladder workers (n = 8) worked individually. All subjects participated in the study for one day and only performed their dedicated harvesting task. Therefore, the study is not a repeated-measure design. Subject weight, height, arm length, upper arm length and forearm length were measured at the end of the work day. Arm lengths were measured when subjects stood up and held their arms out straight out in front of their body (Figure 5 left). Arm length was measures as the length is from the proximal head of the humerus to the fist. Upper arm and forearm lengths were measured when subjects were rested their upper arms comfortably at their side and bending their forearms creating a right angle at the elbow (Figure 5 right). The upper arm length was the length from the proximal head of humerus to the distal head of the humerus measures at the end of the lateral epicondyle. The forearm length was measured from the proximal head of radial to the end of the hand when the subjects created a fist. Figure 5 shows how the anthropometric parameters were measured.

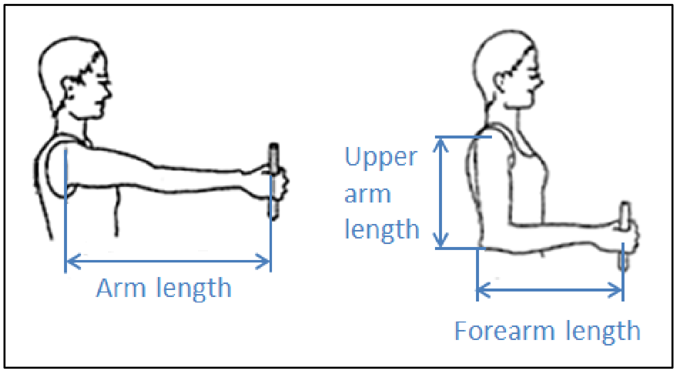


Figure 5 – Measuring arm length, upper arm length and forearm length

4.1.3 Approach in characterizing upper arm and back postures

Upper arm posture is generally defined based on three anatomical planes; i.e. flexion (arm forward) and extension (arm backward) in the sagittal or lateral plane, abduction (arm movement toward the side of the body) and adduction (arm movement away from the side of the body) in the frontal or coronal plane and horizontal abduction and adduction in the plane of shoulder elevation (top view or traverse plane). As the nature of apple picking activity involves the movement of the upper arm relative to gravity, this study focuses on the arm postures characterized in the lateral and frontal planes (Figure 6). The angles of flexion (Θ_{FL}) and abduction (Θ_{AB}) are determined by equation 1 and 2, respectively. The x, y and z represent the accelerations of upper arm in forward, sideway and vertical directions, respectively. Instead of using displacement vectors by the double integration of continuous acceleration data, the acceleration signals obtained directly from the accelerometers were used for calculating the angles. This calculation is validated in Appendix A.

$$\theta_{FL} = \tan^{-1}\left(\frac{x}{z}\right) \qquad \text{eq. 1}$$

$$\theta_{AB} = \tan^{-1}\left(\frac{y}{z}\right) \qquad \text{eq. 2}$$

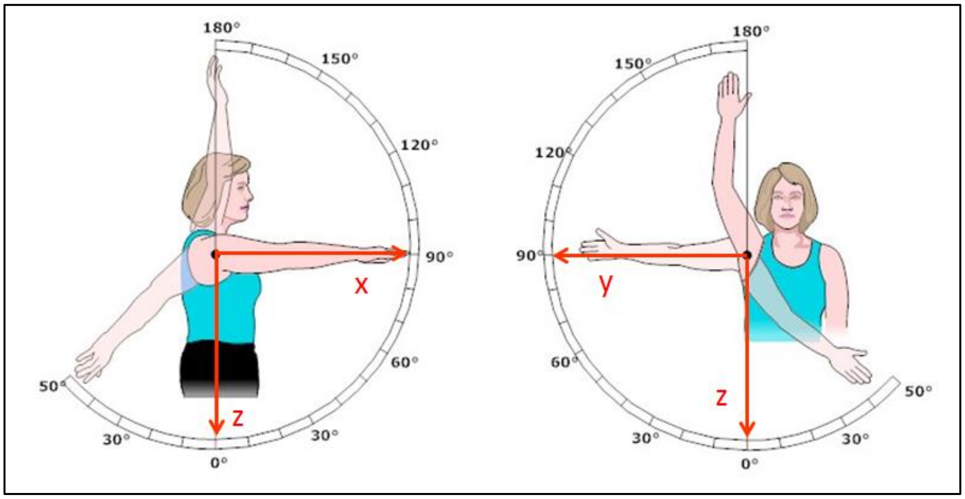


Figure 6 – Upper arm range of motion and corresponding angles: (left) flexion/extension in side view or sagittal plane, (right) abduction/adduction in front view or coronal plane

Besides these standard definitions, upper arm posture can be characterized as a concentric cone of the upper arm about the shoulder, relative to the vertical line, and denoted as inclination angle (Θ_{VS}) (Figure 6). To compute Θ_{VS}, firstly, the sum of the arm acceleration vectors in forward (x) and sideway (y) direction is calculated. Then Θ_{VS}, defined as the angle between the calculated inclination and the vertical (z) acceleration of the arm as shown in Figure 6, is calculated using equation 3.

$$\theta_{VS} = \tan^{-1}\left(\frac{\sqrt{x^2+y^2}}{z}\right) \qquad \text{eq. 3}$$

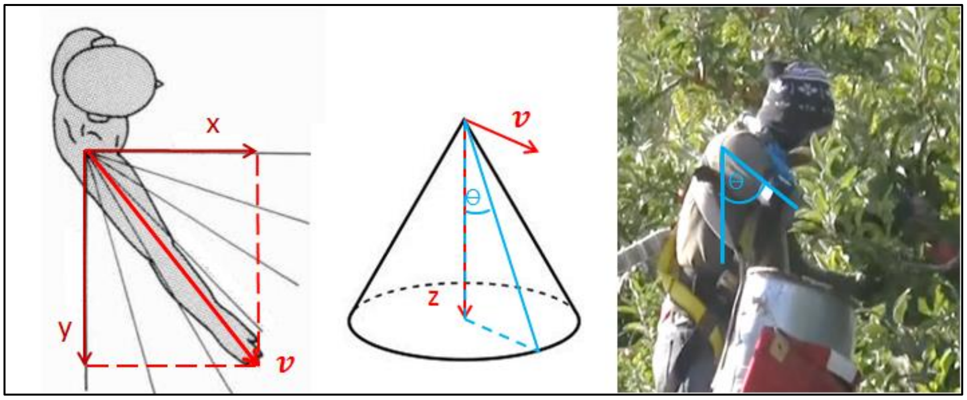


Figure 7 – Upper arm elevation angle

Similar to upper arm angles, back bending is defined in terms of the degree deviated from vertical line. The study combined forward bending (trunk flexion) and side (lateral) bending as a conic angle relative to the vertical line. The back bending angle is calculated according to equation 3, with the axes shown in Figure 8. Thus, the back angle is the arctangent of the ratio between the vector sum of the forward (x) and the lateral (y) movement, and the vertical movement (z).

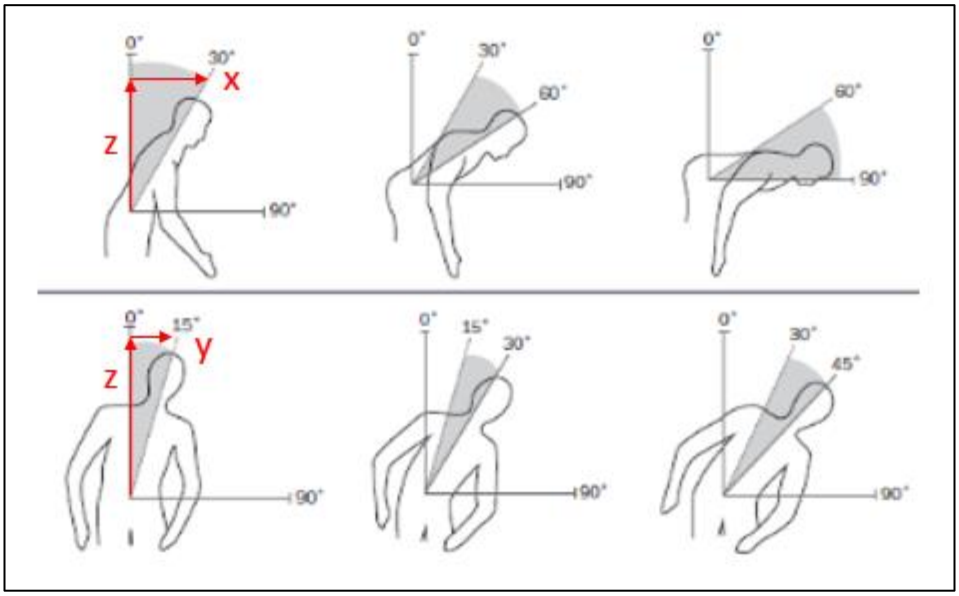


Figure 8 – Axes for calculating back angle

4.1.4 Parameters of Interest

The study evaluated two different general types of apple harvesting methods: harvesting from ladders and harvesting from mobile platforms. In addition to the workers working on the mobile platform picking apples from the top of the trees, there is also a second set of works pick apples on the lower portion of the trees from the ground. As a result, the workers were categorized into three groups: “platform”, “ladder” and “ground”.

The dependent variables were the exposures to non-neutral upper arm and back postures. The postural exposures were characterized in terms of the percentage of work time the upper arm is above designated threshold values. Two alternatives were used in characterizing postural exposures, namely the percentages of time above “angle limits” and the percentages of time in designated “angle bins”. Considering the percentages of time above “angle limits”, the parameters of interest were selected to be the percentage of time when the upper arm angle exceeds 30^o, 60^o and 90^o for upper arm inclination, flexion and abduction. Considering the percentages of time in designated “angle bins”, the parameters of interest were selected to be the percentage of time when the upper arm angles were between $0\text{-}30^o$, $30\text{-}60^o$ and $60\text{-}90^o$. Note that characterizing the time when angles are in $0\text{-}30^o$ has the similar meaning to the angle not exceeding 30^o. The exposure to back bending was characterized in terms of the percentages of time when the bending exceeded 10^o, 20^o and 30^o for the “angle limits” approach and the percentages of time when the back angles were in the range of $0\text{-}10^o$, $10\text{-}20^o$ and $20\text{-}30^o$ for the “angle bins” approach.

4.1.5 Instrumentation protocol

All the participants picked the same type of apples at the same orchard blocks with the same picking instructions. All the workers were assigned to pick Fuji apples in a trellised-tree block where all the trees were 7.5 years old. The picking instructions were “to pick for color”, which is the first pass picking apples from the orchard where only apples of a desired color and size are picked. The platform (*Bandit Xpress, Automated Ag Systems, Moses Lake, WA, USA*) had two raised levels: a lower level in the front and higher level in the back (Figure 1). Two workers stood on each side (left-right) of the platform, one on the lower level and the other on the upper level. A bin for collecting the picked apples was positioned in the middle of the platform between all the four workers. Therefore, unlike the ladder and ground workers, the platform workers did not have to walk for a long distance to fill up the bin and could continuously pick apples. On the contrary, for the ground and ladder workers, the bins were placed along the tree rows; thus, walking to and unloading their apples into these bins were a part of their work activity. In addition, ladder workers had to carry and re-position their ladders. All the participants were paid by the amount of apples they picked. The study was conducted at a cooperating orchard in the West of Quincy, WA, USA, over a six day period in October 2014. Due to the number of data loggers and field researchers and the limited time to instrument the subjects, there were four participants on each study day. The schedule of the study days is shown in Table 1.

Table 1 – Study schedule

2014								
9 Oct Day 1	10 Oct Day 2	11 Oct Day 3	12 Oct Day 4	13 Oct Day 5	14 Oct Day 6	15 Oct Day 7	16 Oct Day 8	17 Oct Day 9
Subject Recruitment & Consent	Platform n = 4	Ground n = 4	Break	Ladder n = 4	Ladder n = 4	Break	Platform n = 4	Ground n = 4

To record upper arm and back postures over a full work shift (8 hours), the participants wore arm bands and torso strap with a small wireless tri-axial accelerometer *(G-Links; MicroStrain® Sensing Systems; Williston, VT, USA*) attached on their left and right upper arms and torso, respectively (Figure 9). The tri-axial accelerometers were battery powered and had 2 MB of built-in memory. Posture data were continuously recorded with the units at the sampling frequency of 5 Hz.

Figure 9 – Upper arm accelerometers: (left) side view, (right) front view

The data collected from the tri-axial accelerometers were processed and analyzed using an interactive graphical software program (*LabVIEW 2014; National Instruments; Austin, TX, USA*). To reduce instrumental noise, raw data were filtered using a dual-pass 1-Hz low-pass Butterworth filter. After obtaining the filtered signal of the upper arm displacements in each of the three directions (x-y-z), the upper arm angle was calculated using equation (1), (2) and (3), as described in the previous section. For each subject, two time segments (before and after lunch break) of the data were extracted from the full signal of the upper arm angle in order to further calculate the percentage of time in the postural exposure categories.

4.1.6 Statistical Analysis

The measures at dominant and non-dominant arms were compared using paired t-test with type I error of 0.05. When there is no difference, two sides of arms were pooled together in the analysis. The effects of harvesting method on each posture category were analyzed using RANOVA method with dominant or non-dominant arm being a fixed effect and participants being random effect. If there were statistically significant differences between dominant or non-dominant arm, the body sides were analyzed separately. Since the three harvesting methods consisted of different groups of participants, the effect of harvesting method was analyzed using ANOVA methods.

4.2 Results

4.2.1 Participant's demographic and anthropometry

Table 2 shows the descriptive statistics of the demographic and anthropometric measures from the participants. There were no statistically significant difference in age, weight, stature and experience among the three groups of workers.

Table 2 – Participant's demographics and anthropometry

	Mean (SE)			
	Ground N = 8	Ladder N = 8	Platform N = 8	p-value
Age (years)	23.9 (1.4)	32.5 (3.0)	28.3 (3.0)	0.09
Weight (kg)	83.9 (4.9)	71.4 (4.5)	74.7 (2.4)	0.11
Height (cm)	177.0 (3.3)	169.6 (2.4)	171.3 (2.4)	0.16
Arm length (cm)	65.6 (1.6)	63.6 (1.0)	66.1 (1.3)	0.36
Upper arm length (cm)	37.1 (1.0)	35.4 (0.4)	35.7 (0.6)	0.26
Forearm length (cm)	35.4 (1.1)	34.7 (0.5)	35.4 (0.9)	0.80
Number of right-handed workers	7	6	8	-
Experience at study site (seasons)	1.38 (0.26)	2.00 (0.27)	1.25 (0.16)	0.08

4.2.2 Upper arm postures

The postural exposures at the dominant and non-dominant upper arms were not significantly different (p-values = 0.37, 0.30 and 0.13 for flexion, abduction and elevation, respectively); however, there were interaction effects between the dominant side of the arm and the harvesting method for the mean flexion angle and a trend indicating a potential interaction for mean abduction angles (p-values = 0.008, 0.08 and 0.49 for flexion, abduction and elevation, respectively), particularly with respect to upper arm flexion and inclination angles (Table 3) so the postural data of dominant and non-dominant arms were also analyzed separately. As shown in Figures 10 to 12, the platform group generally experienced the least exposure to non-neutral upper arm postures in terms of the percentage of exposure time as compared to the ground and ladder groups.

Table 3 – Mean upper arm postural exposures across harvesting methods

	Mean (SE)			p-value	
	Ground N = 8	Ladder N = 8	Platform N = 8	Method each arm	Between two arms
Flexion: non-dominant arm	20.2° (4.5)	0.6° (3.9)	21.7° (5.0)	0.01	0.33
Flexion: dominant arm	13.5° (1.9)	17.9° (2.7)	14.9° (3.0)	0.52	
	p-value = 0.12				
Abduction: non-dominant arm	8.0° (3.0)	10.0° (3.2)	5.1° (4.1)	0.02	0.28
Abduction: dominant arm	18.7° (3.4)	4.5° (3.9)	9.0° (2.4)	0.63	
	p-value = 0.15				
Elevation: non-dominant arm	32.4° (2.4)	27.8° (1.4)	32.1° (2.3)	0.54	0.13
Elevation: dominant arm	30.2° (1.9)	27.8° (2.2)	27.0° (1.9)	0.27	
	p-value = 0.28				

For upper arm flexion (Figure 10), the platform significantly reduced the percentage of the work time when the non-dominant upper arm was above the various angle thresholds. That is, when working on the platform, workers spent less time with flexion angles above 30°, 60° and 90° (p-value = 0.06, 0.02 and 0.03, respectively). In the dominant upper arm, on the other hand, there were no statistically significant differences in time of flexion higher than small angle thresholds (p-value = 0.91 and 0.78 for the percentage of time above 30° and 60°, respectively). However, at the angle thresholds of 90°, which are at the work posture of upper arm above shoulder level, the platform workers had significantly less exposure (p-value = 0.004).

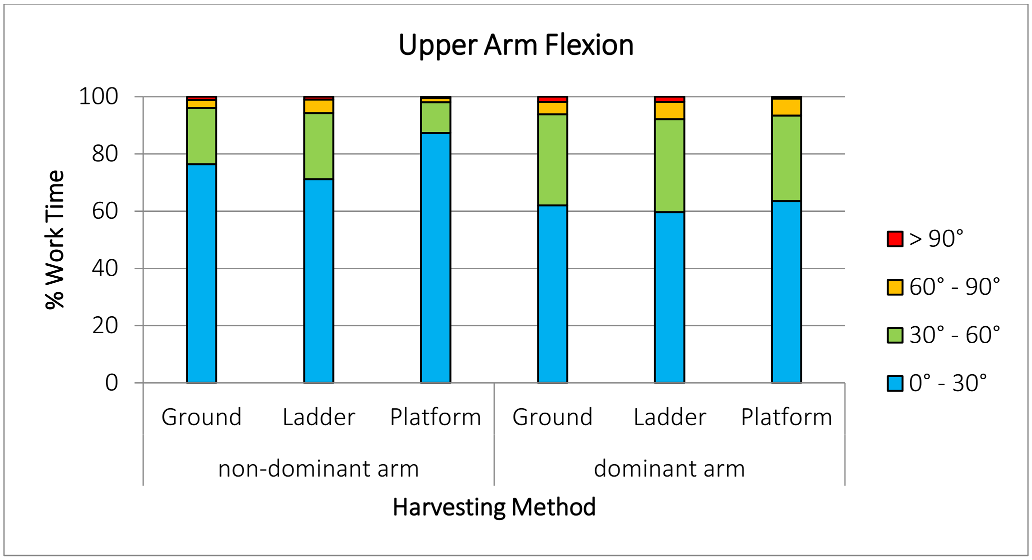


Figure 10 – Exposure to upper arm flexion in terms of percentage of work time

For upper arm abduction (Figure 11), there were no differences across harvesting methods for the time spent in abduction less than 30^{o} (p-value = 0.72 and 0.33 for non-dominant and dominant arm, respectively). However, considering larger angle thresholds, working with platform had less extreme postural exposure (p-value = 0.01 and 0.001 for non-dominant arm abducted above 60^{o} and 90^{o}, and p-value = 0.04 and 0.007 for dominant arm abducted above 60^{o} and 90^{o}).

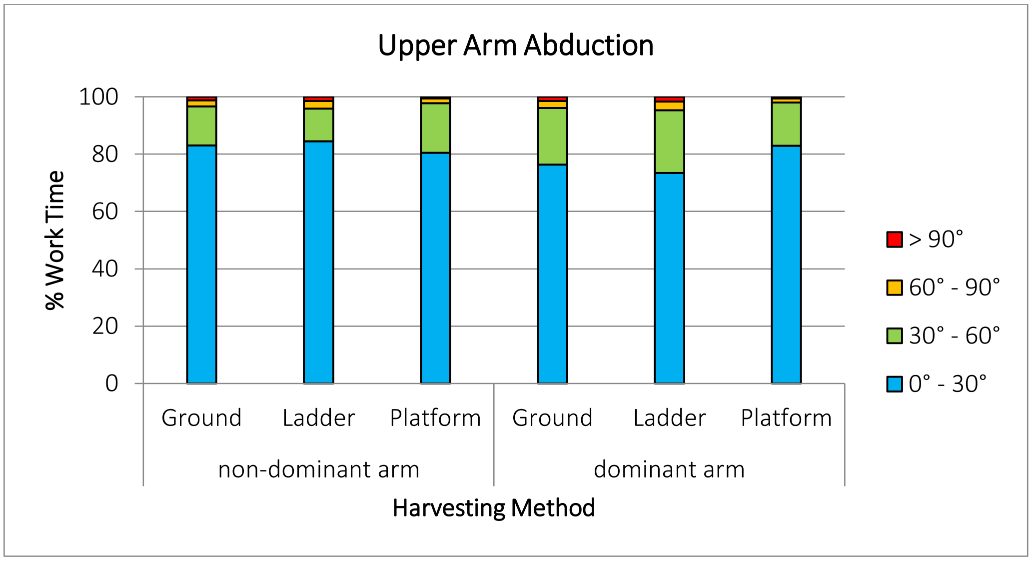


Figure 11 – Exposure to upper arm abduction in terms of percentage of work time

Figure 12 shows the postural exposures in terms of elevation angle, i.e. considering the conic angle relative to vertical line regardless of whether it was flexion or abduction. The non-dominant arm in the ladder group was exposed to a greater portion of work time with upper arm elevation above 60° and 90° than the platform and ground groups (p-values < 0.001) but the difference was insignificant when compared to the arm elevation above 30° (p-value = 0.26). The ground and ladder groups were exposed to the greater percentages of time with the dominant upper arm working overhead, i.e. arm elevation > 90°, than the platform group (p-value = 0.002) but there was no significant differences found for the arm elevation above 30° and 60° (p-value = 0.39 and 0.71, respectively).

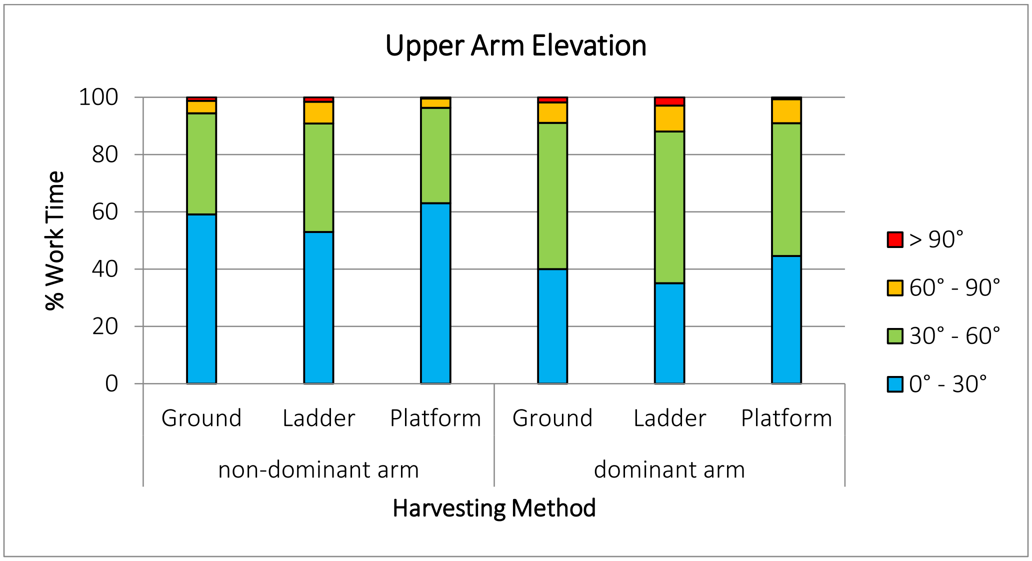


Figure 12 – Exposure to upper arm abduction in terms of percentage of work time

4.2.3 Back postures

The average (standard error) angles of back bending were 26.5 (2.4), 27.9 (4.4) and 27.8 (3.2) degrees for the ground, ladder and platform, respectively. There was no statistically significant difference among the three groups (p-value = 0.90). Figure 13 shows the percentages of work time when back bending was in the various angle ranges. There was no statistically significant difference among the three groups (p-value = 0.20, 0.26 and 0.52 for thresholds of 30°, 60° and 90°, respectively).

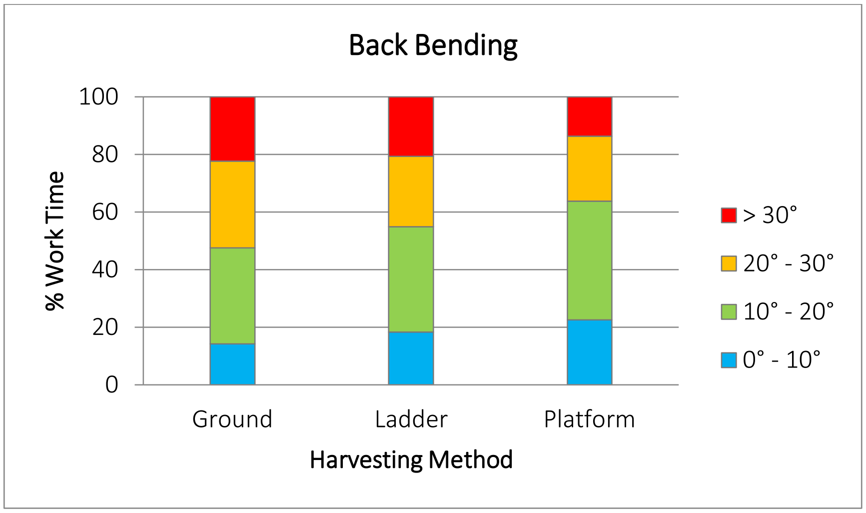


Figure 13 – Exposure to back bending

4.3 Discussion

4.3.1 Application of research findings

This study presented an objective method for measuring work postures using accelerometers. Non-neutral postures of upper arms and back could be assessed using different angular thresholds of upper arm inclination and back bending angles. By analyzing the time spent above various angle thresholds, differences were identified across the various harvesting methods, especially in the upper arm. Mobile platform use reduced the exposures to overhead work but it did not substantially change the percentage of time the upper arms were used at the lower levels of arm elevation.

Although the platform was found to significantly improve postural exposure, the difference may not always been meaningful, in particular to the upper arm angle at higher thresholds. For instance, considering the overhead work i.e. upper arm angle above 90°, the percentage of time differences were very little around 1-2%. Accordingly, the practical interpretation of these results has to be made carefully. However, the results also indicate the platforms do not appear to increase the postural risks which was a concern given the platform workers are almost constantly working in the tree canopy. Some further work is merited; however, since there may be some differences in apple harvesting productivity between the groups which may affect postural results. Due to the intensive nature and cooperation needed from the grower to measure productivity, productivity assessment was beyond the scope of the postural assessment in this dissertation.

Although the platform could reduce the time spent working with back bent compared to working on the ladder, the platform also requires a group of ground workers to walk and pick apples from the lower levels of the tree. This study demonstrated that the ground workers had the greatest exposures in terms of the percentage of time bending their back. Therefore, in order to provide the workers benefit from the platform, job rotation between the platform and ground work would be advisable to reduce the exposures to back bending in each individual.

4.3.2 Comparing results to previous studies

Upper arm results were somewhat different from a previous study among the apple orchard workers in New York State (Earle-Richardson et al. 2005). In the previous study, different apple bucket design were evaluated while harvesting apples from ladders, and the researchers observed, sampled and tracked the various work postures of the workers. In their study, approximately 40% of work time both upper arms were in a neutral region (< 60°), about 30% of the time one upper arm was above 60° and about 30% of the time two upper arms were above 60°. The non-neutral upper arm postures assessed through this visual observation method indicated the arms were elevated above 60° for greater percentages of time than found in this dissertation, greater than 30% as compared to less than 10%. In other words, upper arm angles were less than 60° for more than 90% of the time in our study. This suggests the threshold of 60° for defining non-neutral upper arm position may not be appropriate and smaller angles, such as the time the arms are above 30° should also be considered.

The results of the back postural exposure among ladder workers were very similar to the New York study. In the current study, the ladder workers bent their back more than 20° for 45% of work time (24.4% in 20°-30° region and 20.7% in > 30° region). In the New York study, the exposure to back bending for more than 20° was 23% of their work time. The higher exposures observed in this study suggest that the ladder workers might have bent their back to put apples from the bag to the bin more frequently than the previous study due to the fact that the trellised orchard settings might have eased the harvesting activity. This could have helped them pick faster. Therefore, further studies on work repetition would be of interest to examine the differences in picking.

Chapter 5 Repetitive Motions in Apple Harvesting Activity

This chapter discusses the approach to characterize kinematic exposures, particularly the repetitive motions of the upper arms, associated with the use of ladder and mobile platform in fruit harvesting work. The method section describes how repetition rates can be derived from the postural data collected in the field in Chapter 4 as well as how the algorithms were validated with the video recordings. Various styles of fruit picking were taken into consideration to validate the computational methods. In the discussion, the repetition rates calculated from this study were also compared to the reported productivity in Washington State as well as the information from the cooperating orchard about the overall productivity of the same workers on the same day the measurement was taken.

5.1 Methods

5.1.1 Subjects

Similarly to the study of static postures in Chapter 4, 24 workers having at least one season (three months) of harvesting experience were invited to participate in the study. All the participants were males of Hispanic origin and native Spanish speakers. The participants were equally divided into three groups: (1) platform workers who picked apples at the upper and mid-level of the trees while standing on a moving platform, (2) ground workers, who worked in front or behind the mobile platform and picked apples only at the lower level of the trees and (3) a separate group of ladder workers who picked apples over the full height of the trees. Four platform workers worked together on the same platform each day and four ground workers worked as a team in front or behind the mobile platform. Accordingly, there were two teams of the platform workers (n = 4 each team) and two teams of the ground workers (n = 4 each team). However, the ladder workers (n = 8) worked individually.

5.1.2 Parameters of Interest

The repetition rates were compared across the three methods for harvesting apples: the traditional method using ladders, an alternative new method picking apples from the mid- to upper levels of the trees using a mobile platform, and a group of workers who pick apples from the lower portion of the trees from the ground without using platforms or ladders. Therefore, the three groups for comparison were “platform”, “ladder” and “ground” workers.

Repetition rate was the dependent variable and the numbers of upper arm movement cycles per minute were compared between two methods: 1) a computer program designed to count upper arm repetitions from accelerometer data and 2) the repetition rates counted from video observation.

5.1.3 Instrumentation protocol

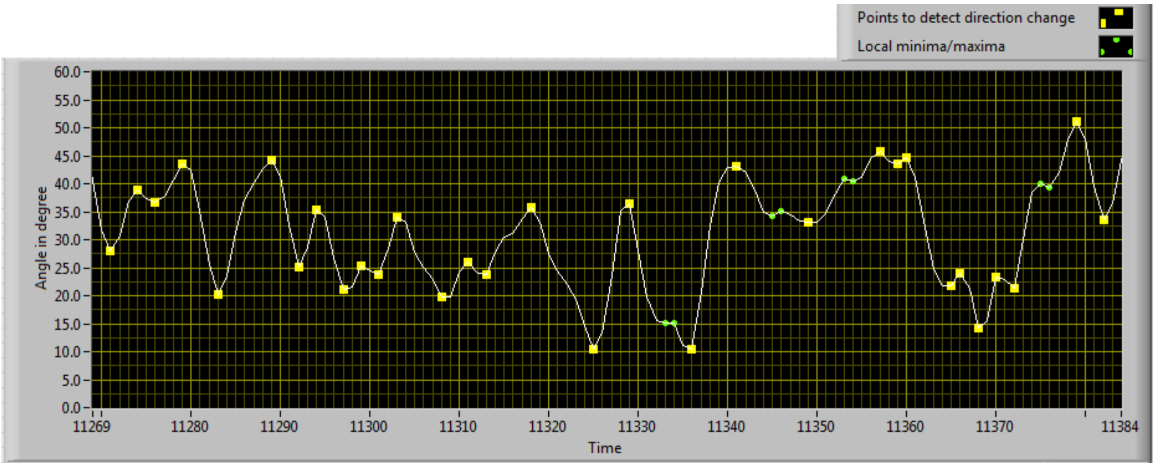
In addition to collecting postural data using accelerometers, the workers were videotaped five times for roughly 5-6 minutes while performing their work, which is the time it took to fill up and empty two consecutive bags of apples. The video recording times started when a subject finished emptying a bag of apples into a bin and ended after two bags of apples were filled and the second bag of apples was emptied into the bin.

At the beginning of the video recording, the subject number and start time were recorded on the video and this process was repeated at the end of the recording where the finish time and subject number were recorded to the video. The subject number and timer were used to prevent human errors and to find the beginning and ending time of the subject’s videotaped activities within the simultaneously recorded accelerometer data. The video-based upper arm repetition measured during apple harvesting activity was considered gold standard.

5.1.4 Characterizing repetition cycles from accelerometer data

Repetition rate was characterized on the basis of the changes in inclination angles in the time domain. That is, the numbers of cycles that were counted over a defined timeframe and then normalized to a unit of cycle of repetitions per minute.

As shown in Figure 14, after obtaining the arm elevation signal (Θ_{VS} in eq. 3, Chapter 4), local maxima and minima were determined when the slope of the signal changes from positive to negative or vice versa. One cycle of motion was counted when a difference in the Θ between successive local maxima and minima was greater than a movement threshold, denoted as Φ. One of the aims of this study was to develop a computational method for quantifying work repetition; therefore it was necessary to validate the computational program by determining an appropriate value of Φ which matched a video based gold standard for upper arm repetition during apple harvesting activity. The various Φ thresholds will be compared to one another and to the gold standard for repetition from the video-based observations. The values of Φ evaluated in this study ranged from 5° to 45° in the increments of 5°.



Remarks: green dots were the twisting motion (stem breaking) that were not included in detecting cycle, yellow squares are the rest of the local minima and maxima that were considered in detecting cycle

Figure 14 – Upper arm angle signal showing repetition cycles of one subject picking apples for 115 seconds

Apple picking is achieved through two movements: a major movement of reaching to an apple and a smaller sub-movement of removing the apple and its stem from the tree (Figure 15). In many cases, there can be two local maxima and minima corresponding to these two movements associated with the apple picking task within one cycle. Thus, it will be necessary to prevent counting sub-movements of breaking the stem from a tree as independent repetitions.

Figure 15 – Upper arm movement illustrating two-step picking

5.1.5 Counting repetition cycles from video

To synchronize the accelerometer's data collection with the data collection based on the video recordings, the repetition data using both methods were also extracted from five short (5-6 minutes) sessions from each subject. Since a cycle began and ended with a worker roughly bending 90^o at the torso to empty their apple bag into a bin, the synchronized data from torso accelerometer was used to verify the beginning and ending periods of the 5-6 minute two bag loading cycle in the arm-collected accelerometer data.

The result from video analysis yielded the true group average for the repetition rate and this information was used for identifying the threshold of angle difference (Φ) used in the computational program for counting upper arm repetitions.

5.1.6 Statistical Analysis

The measures in the dominant and non-dominant arms were compared using paired t-test with Type I error, α, of 0.05. If there was no difference, the measures from the two sides of upper arms were average together in the analysis. If the repetition rates were significantly differences between dominant and non-dominant arm, the body sides were analyzed separately. Then the effect of harvesting method was analyzed using ANOVA for the accelerometer data and RANOVA for the video data since each participant was videotaped over multiple sessions.

5.2 Results

5.2.1 Repetition from video data

From the paired t-test for the differences between dominant and non-dominant arms, the non-dominant arms were found to have higher repetition rates (p-value = 0.016) for all subjects. The differences were particularly significant among workers using platform (p-value = 0.047) and those working on the ground (p-value = 0.036). However, considering the ladder workers, their repetition rates in dominant and non-dominant arms were not different (p-value = 0.36). Since there were different picking styles and the previous statistical test varied by the type of harvesting, repetition rates were analyzed for the non-dominant and dominant arms as well as the average of both arms.

By counting the number of reaching movements to pick apples and disregarding other non-picking-related activities, the upper arm repetition rates were higher in the platform-related harvesting (platform and ground workers) than the ladder group especially in the non-dominant arms. However, the differences based on the sub-sample of the videos were found to be insignificant (Table 4).

Table 4 – Repetition rates in cycles per minute from the video recordings

	Mean (SE)			p-value
	Ground N = 5	Ladder N = 5	Platform N = 5	
Repetitions of non-dominant arms	15.1 (0.9)	13.1 (0.9)	16.4 (1.2)	0.18
Repetitions of dominant arms	13.6 (0.9)	12.8 (0.7)	11.3 (1.8)	0.55
Average repetitions of both arms	14.4 (0.8)	13.0 (0.7)	13.9 (0.8)	0.61

Remarks: N = 5 is the number of subjects. In this repeated measure design, each subject had 1-2 recordings that were used for analysis and the total number of measurement was 8 in each group.

5.2.2 Repetition from accelerometer data

Repetition rates in the dominant and non-dominant upper arms were not significantly different for all the Φ's of 5°-45° (p-values = 0.99, 0.38, 0.19, 0.14, 0.19, 0.32, 0.73, 0.71 and 0.26, respectively). Since the differences were insignificant, the repetition rates from dominant and non-dominant arms were pooled together for the analysis of the effect from harvesting methods (ladder, platform or ground).

Using the computational program, as the angle change threshold (Φ) decreased from 45° down to 5°, the calculated repetition rates increased as shown in Figure 16 (error bars were omitted for simplicity). Regardless of the Φ used in the analysis, the repetition rates were greater in the workers using ladders compared to those who picked apples from the platform or the ground level; in particular, the differences were statistically significant when Φ = 15°-45° (respective p-values for Φ's of 5°-45° = 0.26, 0.07, 0.02, 0.004, 0.0005 and less than 0.0001 onwards).

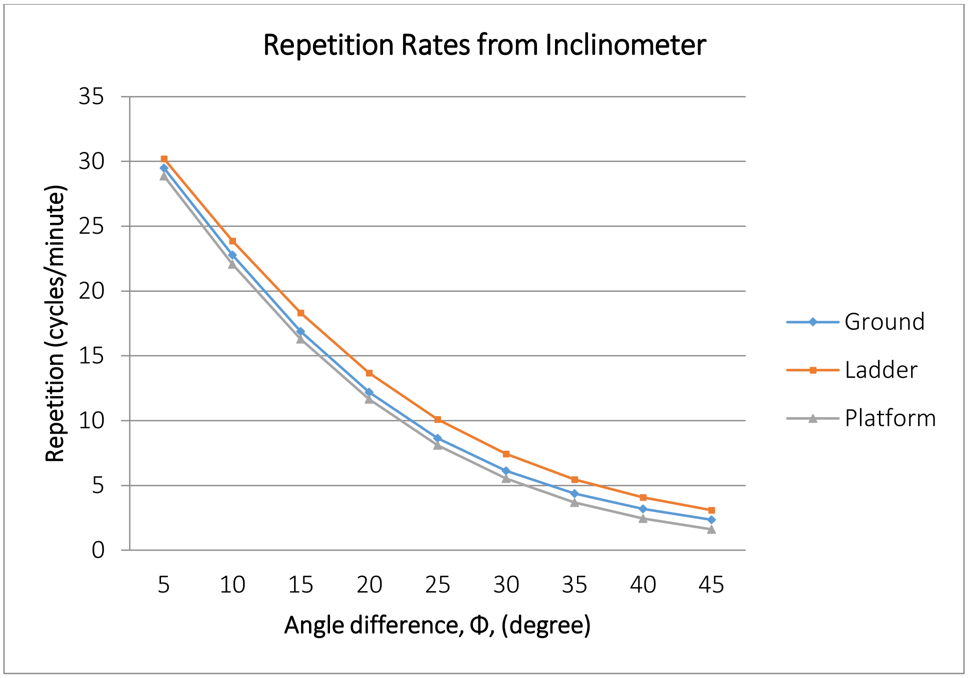


Figure 16 – Mean repetition rates from the accelerometer data using angle thresholds (Φ) between 5° and 45°

5.2.3 Comparing repetition rates between video and accelerometer data

Comparing the repetition rates counted from the video which was used as the gold standard for repetition rates and from the computational program, the value of Φ = 20° was found to best approximate the video-based repetition rate for the platform-related work (platform and ground workers) whereas, among the ladder workers, the program captured other movement besides picking such as climbing up and down the ladders. Repetitions computed from the program using Φ = 20° were 12.2, 13.7 and 11.7 cycles per minute for the ground, ladder and platform groups, respectively. Moreover, interpolating for Φ = 17.5°, the repetition rates were 14.5, 16.0 and 14.0 cycles per minute for the ground, ladder and platform, respectively. By increasing the resolution of Φ and interpolating the repetition rates Φ = 17.5°, the results for the ground and platform workers were very close to the video-based repetition (14.4 and 13.9 cycles per minute, respectively). The repetitions from the accelerometer data were different from the video-derived repetition results in the ladder workers.

5.3 Discussion

5.3.1 Findings and methodological considerations in video observation

Through visual observation, different workers had different picking styles. At least three main picking methods were found. The first method was quite bilateral: two arms reaching out to apples around the same time, once bringing apples close to body then the non-dominant arm held the two apples and the dominant arm clipped the stem. The other two methods were unilateral. One was when the non-dominant arm reached out to pick apples and the dominant hand was only for clipping the stems. The other way was when the dominant arm reached out to pick apples, brought the apples passing to the non-dominant hand to hold them, and then the stem was clipped using the dominant hands. Note that the dominant body side was defined as the one used for holding the clipper.

The study did not find statistically significant differences in the subsamples of the video data but rather in the accelerometer data. Using the subsample of the video collected data, a power analysis indicated the sample size was sufficient. A priori study using six measurements total (N = 2 for each group, different subjects) suggested that, in order to have a power at least 0.80, the total sample size had to be 9 for non-dominant arms and 24 for dominant arms. Therefore, at least 8 data points, i.e. eight, five-minute video sessions, were used for counting the repetitions. Post hoc statistical power obtained from this subsample were 0.99 for non-dominant arm, 0.51 for dominant arm and 0.79 for the average between the two arms.

5.3.2 Findings and methodological considerations in using accelerometer data

The repetition assessment method developed in this study differs from other studies that used the number of movements passing an anatomically-based cut-point (Spielholz et al. 2001). Most previous studies have been conducted in a well-control laboratory settings, in which the subjects performed designated, postural-constrained tasks rather than their daily activities. However, the repetitions evaluated in this study were from actual field work, which involves a great deal of postural variation due to the nature of the apple picking task (i.e. apples on trees were at various heights and upper-arm postures do not return to the same set angle every cycle). Assessing repetition through changes in posture was more applicable.

The computational methods may not work for the tasks using ladders due to the variety of the tasks. In addition to picking, workers were also required to climb up and down the ladders, moving and positioning the ladder. These tasks involved the other types of upper arm movement. When counting the repetition using the accelerometer data, those movements were not separated from the picking motions. As a result, the trend of repetitions counted from the accelerometers across the three tasks were different than the trends from the video.

5.3.3 Comparing results to work productivity

The results were compared to previous work where overall productivity was counted. The previous report in Washington State found that the average apple harvesting rate of a worker performing a first-pick (picking apples for the first stime based on color and size – the same as the current study) on a mobile platform was 45 apples per minute (WTRFC 2014). In other words, approximately 22.5 apples were picked by each hand in a one minute period. This is much higher than the results in this dissertation. This could be due to the fact that the harvesting task observed in this study required stem-clipping and that slowed down the repetition rate. The previous work did not indicate the type of picking instruction, which could be strip picking that is the fastest among all picking instructions. Also, both repetition and productivity could have been impacted by the speed of the moving platform. In this dissertation, workers operated the platform by themselves and the speed of the platform depended on the picking speed of the slowest person in the team. In other orchards, the platforms might be operated by a supervisor or a worker designated to only operate the platform so the speed of the platform could be faster than in this dissertation.

With respect to the work productivity collected as the number of bins of apples picked per hour (Appendix B), the repetition rates calculated from the accelerometer data showed a similar pattern. That is, the productivity rank from the highest to the lowest was ladder, ground and platform. Therefore, although the repetition rate calculated from the program could be higher than the actual rate for the ladder workers, the increase of the rate might be marginal. Thus, the computational program can still be used for calculating repetition rates for the comparison of harvesting methods.

Chapter 6 Trapezius EMG in apple harvesting

This chapter presents the theoretical and experimental methods and results of the muscle activity (EMG) measurements of the trapezius muscle in the upper extremities. EMG was characterized in the time domain to enable the comparison of muscle activity levels between working with ladders and mobile platforms; and in frequency domain to verify signal quality and determine whether muscle fatigue occurs and whether there are differences in muscle fatigue between the work methods.

6.1 Methods

6.1.1 Subjects

Similar to Chapters 4 and 5, the study had the same 24 participants with at least one season (three months) of harvesting experience. All the participants were males of Hispanic origin and native Spanish speakers. The participants were divided into two groups: ladder workers (n = 8) and mobile platform workers (n = 16), and the mobile platform workers were further subdivided into two subgroups: those who worked on the mobile platform (n = 8) and those who worked on the ground (n = 8).

6.1.2 Parameters of Interest

The independent variable was the harvesting methods (with 3 levels): harvesting apples using ladder, harvesting apples on the platform and harvesting apples while walking on the ground picking apples.

Muscle activity was defined in terms of static (10th %tile), median (50th %tile) and peak (90th %tile) activity of the normalized root-mean-square (RMS) amplitude in the upper trapezius muscles EMG (de Luca 1997; El Ahrache et al. 2006; Rash 2008).

6.1.3 Instrumental Protocol

Upper trapezius EMG was collected at 1,000 Hz using a battery-powered portable data logger for the entire 8-hour work day. The differential electrode pairs were placed one-centimeter distally from the midpoint between the spine level C7 and the acromion. For the electrode pairs, the two bi-polar electrodes were placed next to each other with the approximate inter-electrode distance of 2 centimeters. This distance between the two differential electrodes is 1 centimeter, which has been recommended by a previous study on shoulder muscle activity (Jensen et al. 1993). The ground electrodes were placed over the bone and tendons of the acromion. Figure 17 shows the scheme of the electrode placement.

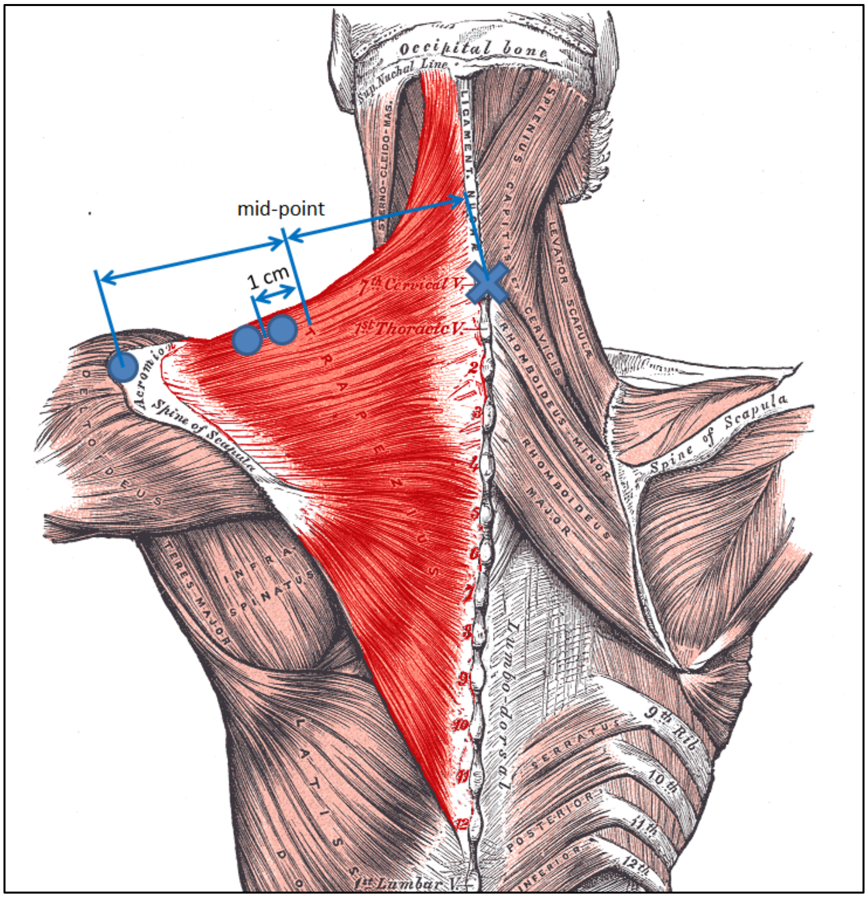


Figure 17 – EMG electrode location at upper trapezius

The skin-electrode interface (Figure 18) included skin preparation by cleaning the skin with alcohol wipe to remove dead skin cells, covering the two circular regions of the skin that would be in contact with the active potion of electrode with tape, applying sweat-resistant adhesive (*Benzoin Compound Tincture; Humco Holding Group Inc.; Texarkana, TX, USA*) over the area the electrodes were going to adhere to, removing the two circular portions of tape to expose the two clean circular clean areas of skin, and attaching the electrodes so the active areas of the electrodes were in contact with the two clean areas of skin. Single-use disposable pre-gelled electrodes (*Blue Sensor N; Ambu; Ballerup, Denmark*) were placed and secured to the subject with two types of medical tape (*Tegaderm and Transpore; 3M; Saint Paul, MN, USA*). The electrodes were connected to a data logger (*Biomonitor ME6000; Mega Electronics Ltd.; Kuopio, Finland*) through cables. The logger was powered by four AA batteries. The data were recorded to 2 MB compact flash memory card contained in the logger. Subjects carried the logger using a waist strap which contained a small pocket. The logger was placed in the small pocket which was positioned in the lumbar region of the spine. The full EMG data collection system is shown in Figure 19.

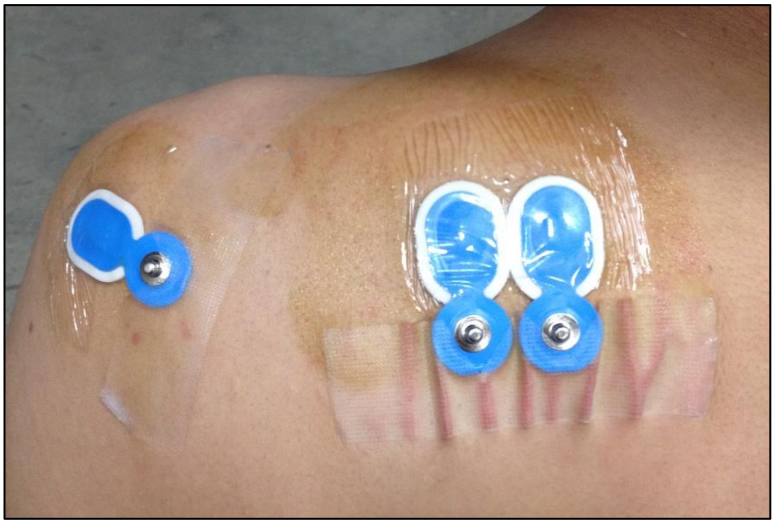


Figure 18 – Preparation of skin-electrode interface

Figure 19 – EMG data collection system

Instrumental factors; for instance, distance between differential electrodes and individual factors such as skin impedance, adipose tissue and the cross-sectional area of muscle fibers could influence the EMG levels measured at the electrodes; thus, the EMG amplitude had to be normalized. Since performing maximum voluntary contractions (MVCs) trials could be harmful to the workers, this study used alternative methods for EMG normalization including a submaximal reference voluntary contraction (RVC) and a dynamic normalization referred to as the "peak(d)".

Three RVC trials were collected before each participant started working. During the RVC trials, the participants stood upright, held their two arms straight forward (at 90° flexion) in from of their body at shoulder level, and held a 0.91-kg dumbbell each in each and. The forearms were in a neutral pronation/supination position so the dumbbells were in a vertical orientation when grasped. The RVC trials lasted for 30 seconds with an approximately 5-second break in between each trial. Before and after each trial, subjects were asked by a native Spanish-speaking researcher to elevate and lower their shoulder; this dynamic muscle activity was used as a marker to identify the beginning and ending of each RVC trial when analyzing the data. In addition, signals were marked using a button on the instrument, which would place an event mark in the collected data to identify where the reference contractions are. For the dynamic normalization (peak(d)), the 95th percentile EMG activity was taken during the first 90 minutes of work and used as the denominator value for the EMG normalization.

6.1.4 Frequency Domain Analysis

An analysis in frequency domain of the EMG signals can provide insight on whether or not the muscle may be fatigued. A shift in mean power frequency (MNF) and/or median power frequency (MDF) over time is often used as a measure to indicate when muscle fatigue is starting to develop. Alternatively, given the challenge of EMG electrodes staying attached to the body due to perspiration, a change in the MPF or MDF may indicate when electrodes were becoming detached from the body. A decrease in MNF or MDF is an index of muscle fatigue in dynamic contractions (Potvin & Bent 1997). However, when MNF or MDF increases during work, it could be a sign of errors associated with the electrodes falling off or non-work (rest) periods.

In this study, EMG signals through the entire day were partitioned into several 10-minute sub-intervals. This interval was selected because it could capture 2-3 work cycles of bin filling (one cycle is identified as when participants picked apple until the bag was full then put all the apples into the bin) and allows 15 data points during work session before lunch and at least 15 data points after lunch. Within each sub-interval, EMG power spectrum was obtained using Fast Fourier Transform (FFT). MNF was calculated according to equation 4, where f_j is the frequency value at frequency bin *j*, P_j is the EMG power spectrum at frequency bin *j* and M is the length of the frequency bin. MDF was determined as the frequency at which EMG power spectrum was equally divided into two regions i.e. half of the total power.

$$MNF = \sum_{j=1}^{M} f_j P_j / \sum_{j=1}^{M} P_j \qquad \text{eq. 4}$$

$$\sum_{j=1}^{MDF} P_j = \sum_{j=MDF}^{M} P_j = \frac{1}{2} \sum_{j=1}^{M} P_j \qquad \text{eq. 5}$$

As shown in Figure 20 and 21 (examples from two subjects), the MDF EMG data and the 1st percentile of the amplitude in µV were first analyzed second-by-second for determining signal quality. A sudden and prolonged increase or decrease in MDF or 1st percentile EMG values was used to indicate when skin-electrode interface was compromised and the electrodes were losing contact with the skin, compromising the integrity of the EMG signal. The MDF and the 1st percentile of the amplitude were explicitly plotted for each individual subject in Appendix C. When there was a systematic shift in MDF or 1st percentile EMG values then the EMG data from the point of the shifts were excluded from the data analysis. With the remaining intact EMG data, any systematic shift could indicate the onset and presence of muscle fatigue.

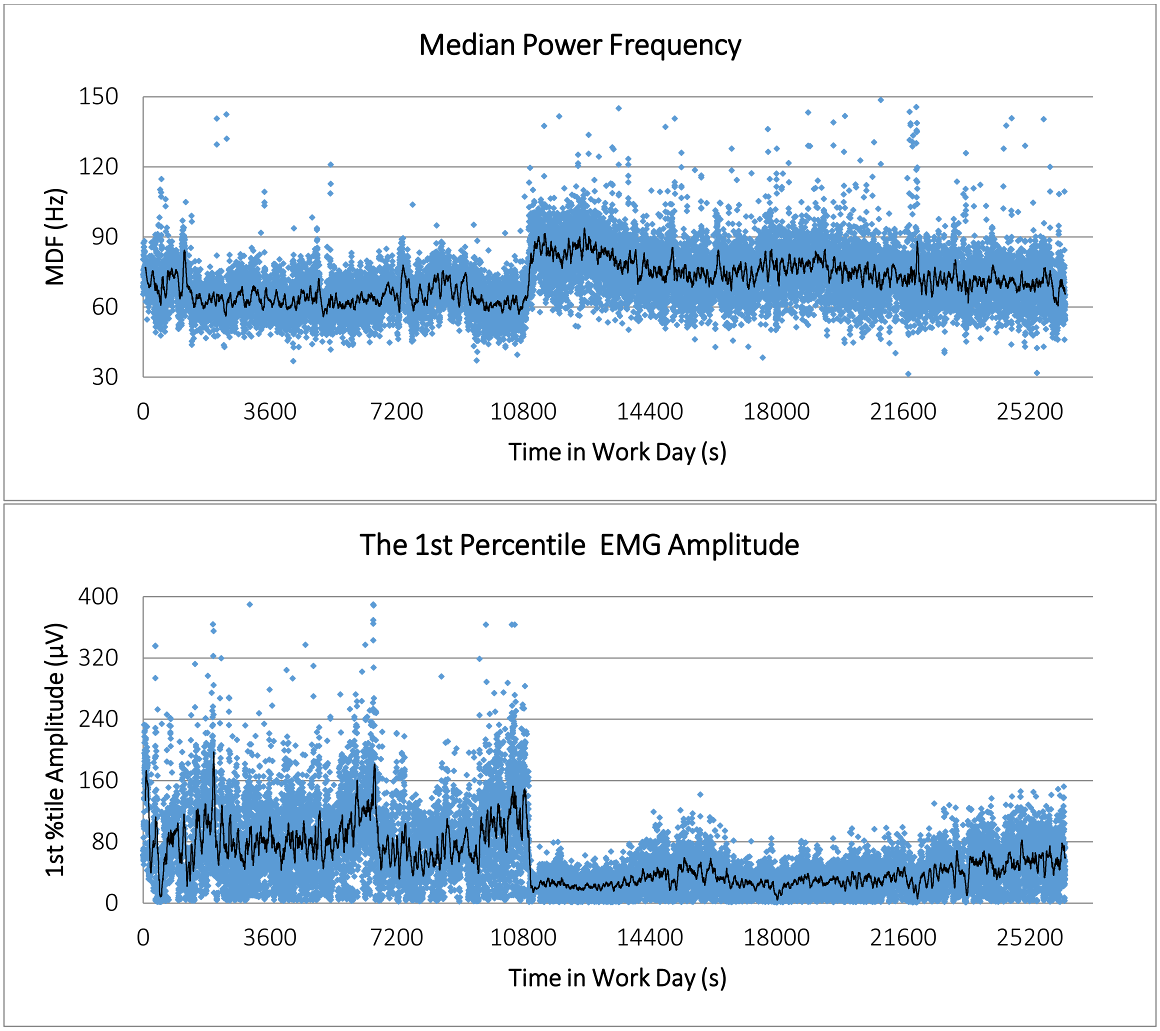
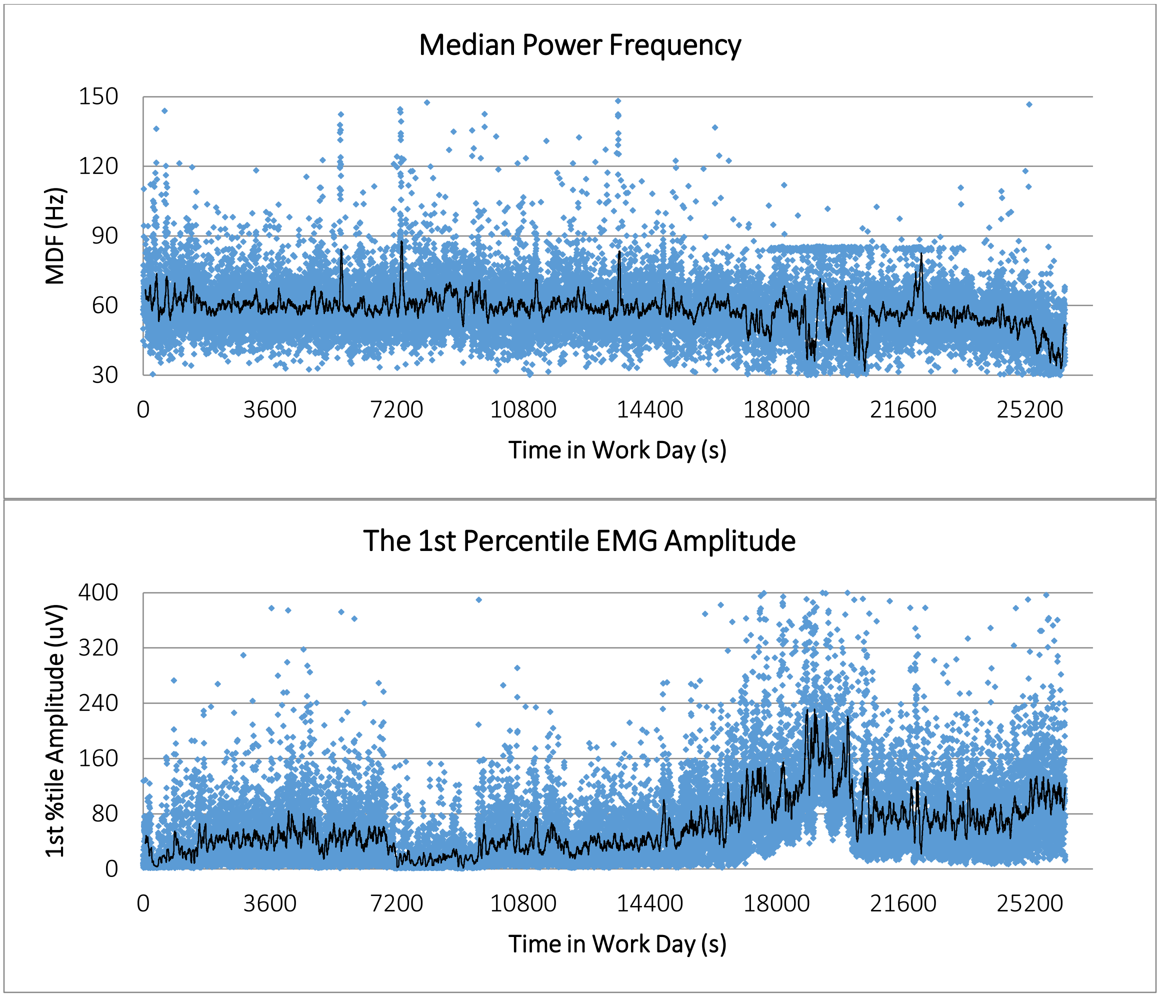


Figure 20 – EMG error detection, Top: Median Power Frequency (Hz); Bottom: the 1st Percentile of EMG Amplitude (µV) by Time in Work Day (s) Plot, trend line is one minute average, from the right trapezius of one subject


Median Power Frequency

The 1st Percentile EMG Amplitude

Figure 21 – EMG error detection, Top: Median Power Frequency (Hz); Bottom: the 1st Percentile of EMG Amplitude (µV) by Time in Work Day (s) Plot, trend line is one minute average, from the right trapezius of one subject

6.1.5 Time Domain Analysis

The Amplitude Probability Distribution Function (APDF) of the EMG signal at various set levels was used to represent different types of muscle activity. Parameters such as the 10th, 50th and 90th percentile represent static, central tendency and peak activities of the muscle (Iridiastadi et al. 2008). In the time-domain analysis, EMG signals were processed in the steps in Figure 22.

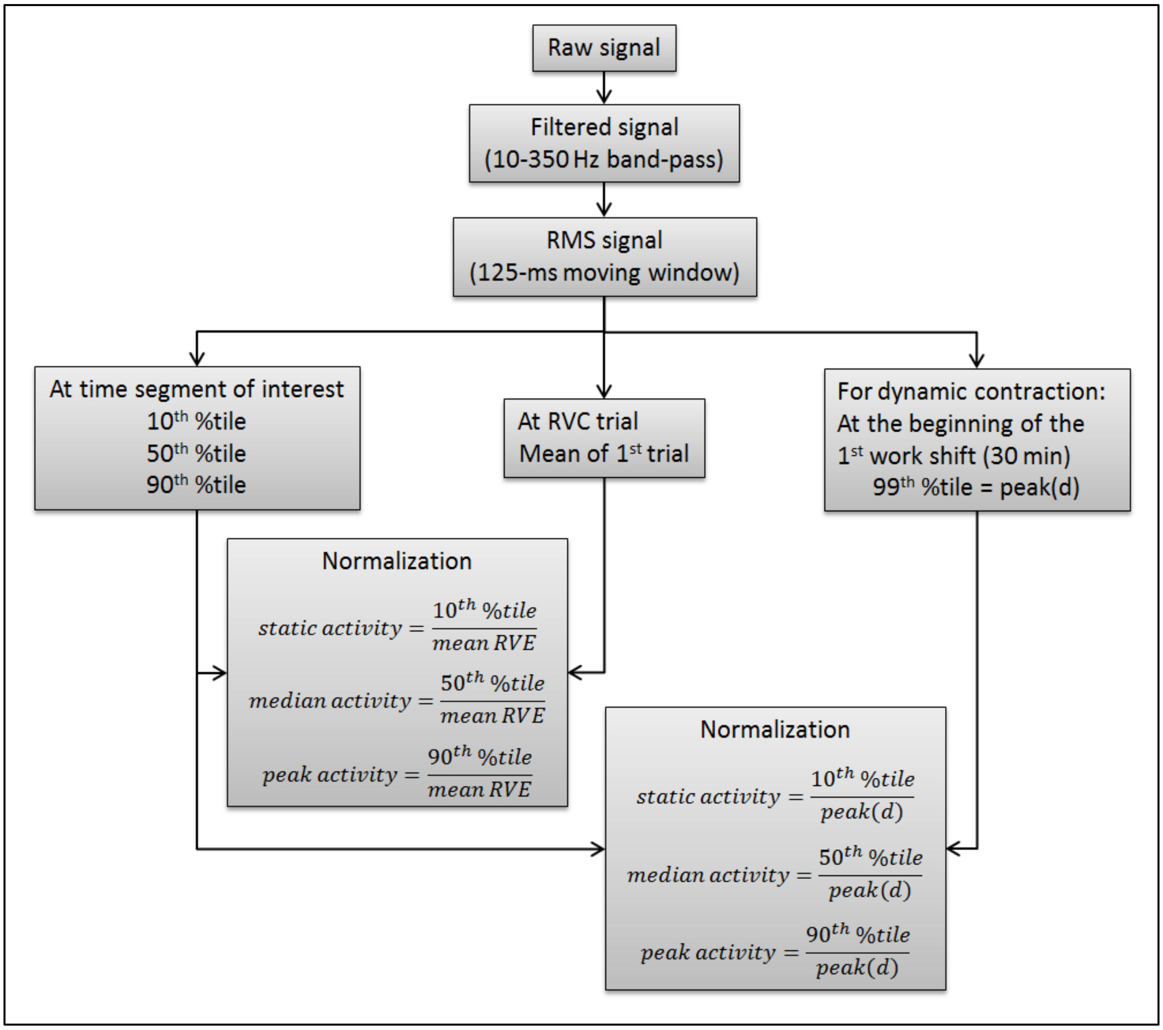


Figure 22 – EMG signal processing and parameter calculation

EMG raw signals collected at 1,000 Hz were passed through a second-order Butterworth dual-pass 10-350 Hz band-pass filter. This band pass is selected based on the requirements outlined in the Journal of Electromyography and Kinesiology (1996) although the high-pass 10-Hz low cutoff is different from the more recent evidence that surface EMG signals below 20 Hz may be unstable (De Luca et al. 2010).

With the EMG, a root-mean-square (RMS) window with a 125-millisecond duration with no overlap was used as shown in equation 6 to calculate levels of muscle activity where S is the window length (0.125 second x 1,000 points/sec) and f(s) is the data in each window.

$$RMS = \left(\frac{1}{S}\sum_{1}^{S} f^2(s)\right)^{\frac{1}{2}} \qquad \text{eq. 6}$$

This RMS signal represented the level of muscle activity in time-domain. Within a certain time interval of interest, e.g. from beginning to finishing a work shift, the 10th, 50th and 90th percentile of all the RMS data points were determined as shown in Figure 23.

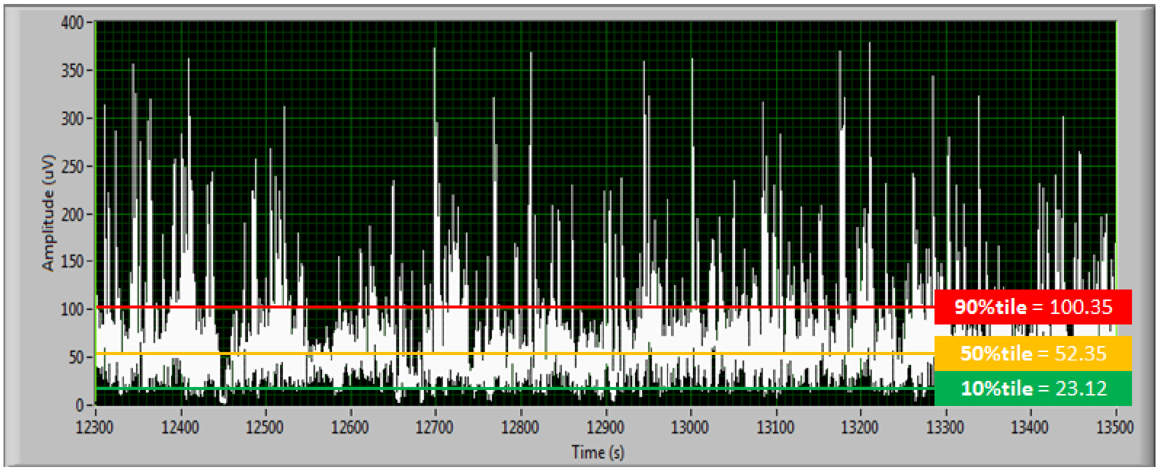


Figure 23 – Muscle activity (static, median and peak) from RMS signal

Reference Voluntary Contraction (RVC) values from the EMG were extracted from the mean of the 30-second RMS signal during the RVC (Figure 21). Dynamic Voluntary Contraction (DVC) reference values were the near maximal EMG values measured during actual work, and denoted as peak-d. The denominator of the DVC was the 95th percentile of the RMS value during the first 1.5 hour of work. In this study, the 95th percentile was used for the dynamic normalization instead of the maximum EMG to ensure the true muscle activity levels were used rather than noise or erroneous, which could be part of the maximal 100th percentile.

For each participant and each muscle (left and right upper trapezius), the median value of the three RVC mean activity levels was used as denominator for EMG normalization. As shown in Figure 24, the digital marks and shoulder shrugs were used to mark the beginning and the end of the reference contractions.

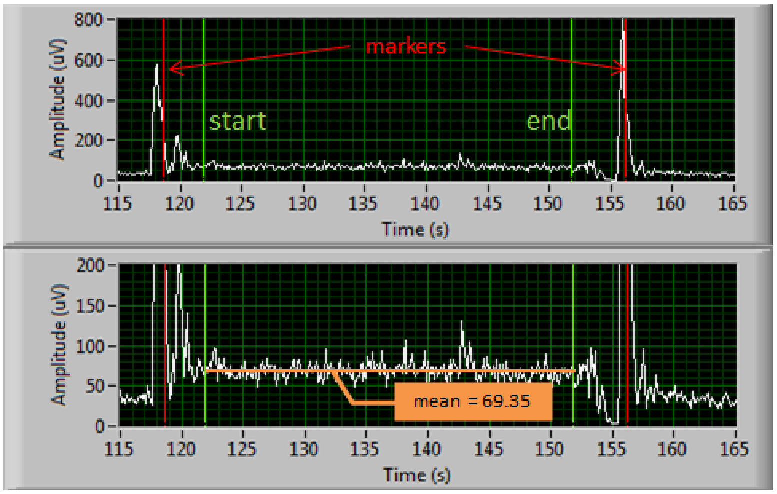


Figure 24 – Mean RVE signal

Finally, the 10th, 50th and 90th percentiles of the normalized EMG data were calculated as a function of: (1.) the sub-maximal or reference voluntary electrical activation (%RVE), and (2.) the peak RMS in dynamic normalization period (peak-d). Figure 21 summarizes the steps of EMG signal processing to obtain the static, median and peak levels of muscle activity.

6.1.6 Statistical Analysis

The differences in muscle fatigue and muscle activity levels in the first work hour given harvesting method and the body side (dominant or non-dominant arm) were examined using a 3 (harvesting method) x 2 (body side) ANOVA, with subjects as random effect and significance assessed at α =

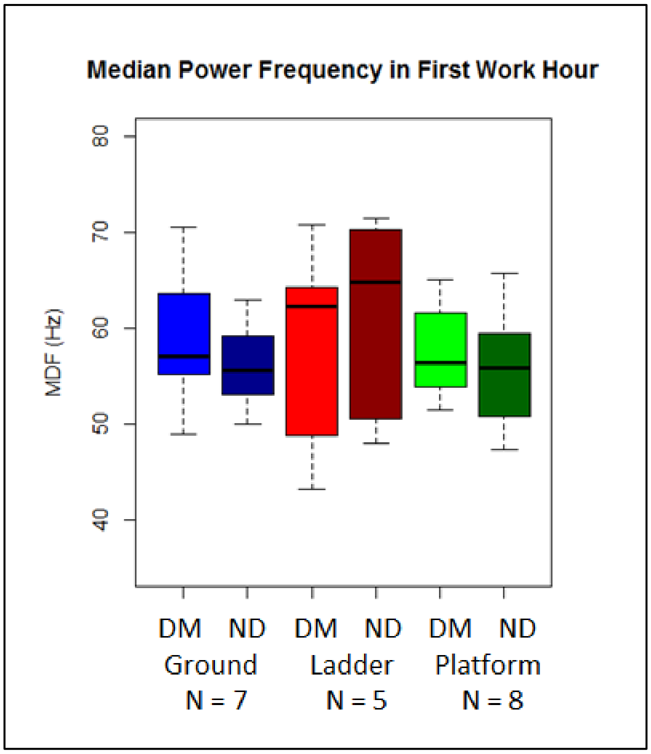
0.05. In addition, a time effect on muscle fatigue and muscle activity (data in 10-minute windows through the entire work day) was analyzed.

6.2 Results

6.2.1 Muscle Fatigue

Analyzing EMG in frequency domain, the MNFs and MDFs were calculated over time. Since the values of MNF and MDF were quite similar, only the MDFs were used in further analysis. The plots of MDFs and 1st percentile of RMS muscle activity in left and right (non-dominant and dominant) muscles for each participant were shown in Appendix C. To obtain the maximal amount of good data, a 60-minute period was selected within the first 90 minutes of work for analysis in order to ensure that all the selected times were during work, not when the participants were getting used to the work rhythm at the beginning nor when they started to slow down after the first work hour. As shown in the graphs, the data with errors (signals with significant, sudden increases or drops) were excluded from the analysis. The ground worker group included seven participants, both dominant and non-dominant muscles. The ladder worker group included four participants with both dominant and non-dominant muscles. Of the original 8, one participant had only a dominant trapezius data and one had only non-dominant trapezius data that are usable for comparison. Thus, there were the totals of five subjects per muscle side. The platform worker group included all the eight participants and both muscles that were measured.

Figure 25 shows the boxplot of MDFs during the first hour of work across the four categories of the combined factors of the dominant side and harvesting method. It appeared that the ladder workers had the higher average value of MDFs, i.e. muscle worked at higher frequencies than the platform-related group. This was particularly prevalent in the non-dominant side of the upper trapezius. The higher MDFs with the ladder workers indicated some aspect of the ladder work caused the muscles to fire at a higher rate. However, the ANOVA did not show any significant differences between the dominant sides (between-subject F (1, 17) = 0.002, p = 0.96; within-subject F (1, 18) = 0.735, p = 0.40). There were also no significant differences observed in harvesting method (F (2, 17) = 0.26. p = 0.78).



* DM: dominant body side, ND: non-dominant body side, Ground N =7, Ladder N = 5, Platform N = 8

Figure 25 – Boxplot of EMG median power frequency by dominant and non-dominant body side and harvesting method

The boxplots of MDFs over time, separated for each harvesting method and dominant side, are shown in Figure 26 – 31. The MDFs in ground and ladder workers increased at the tail or the end of the workday. The MDFs dropped during the lunch break, i.e. non-work period, for the non-dominant side of trapezius; therefore, the statistical analyses were done with and without the break time. When break time was included, the time of the day and the dominant body side had significant effect on the MDFs (Table 5). When excluding break time, time of the day became less significant and the effect of the dominant body side became insignificant (Table 6).

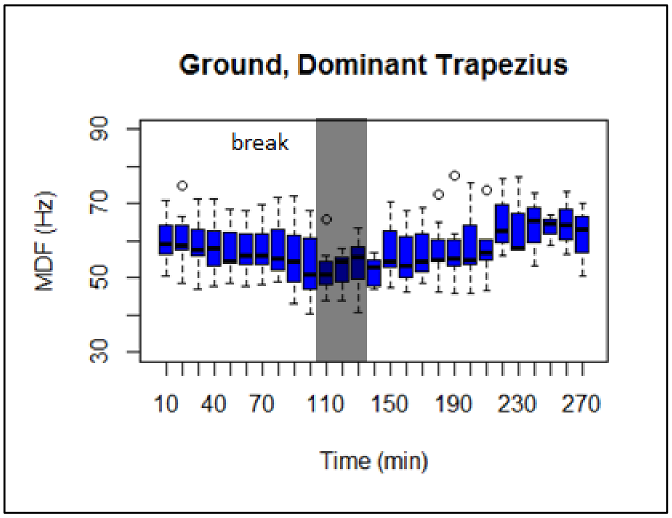


Figure 26 – Boxplot of EMG median power frequency by time, ground, dominant trapezius (n = 7) with the shaded areas being the lunch period.

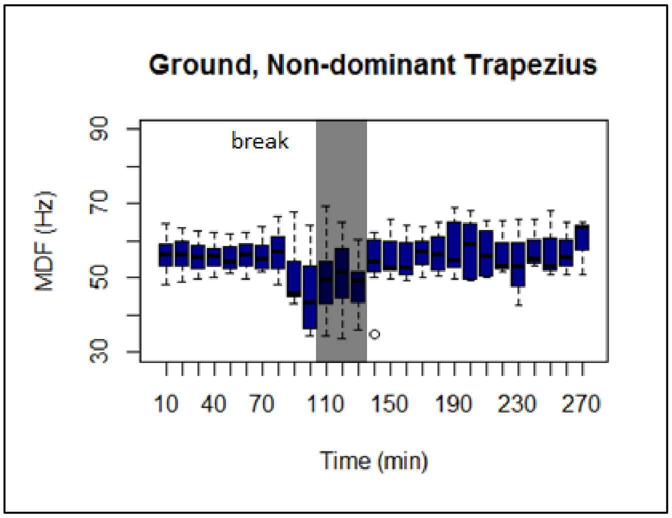


Figure 27 – Boxplot of EMG median power frequency by time, ground, non-dominant trapezius (n = 7) with the shaded areas being the lunch period.

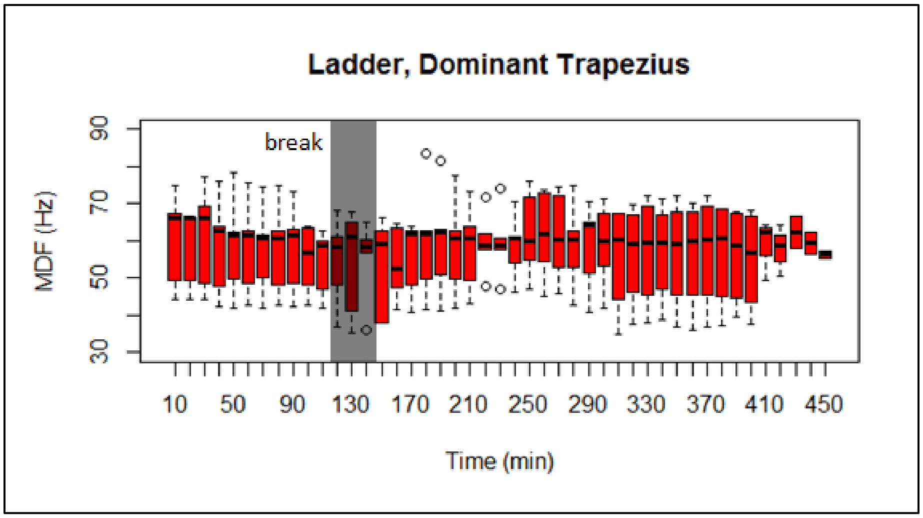


Figure 28 – Boxplot of EMG median power frequency by time, ladder, dominant trapezius (n = 5) with the shaded areas being the lunch period.

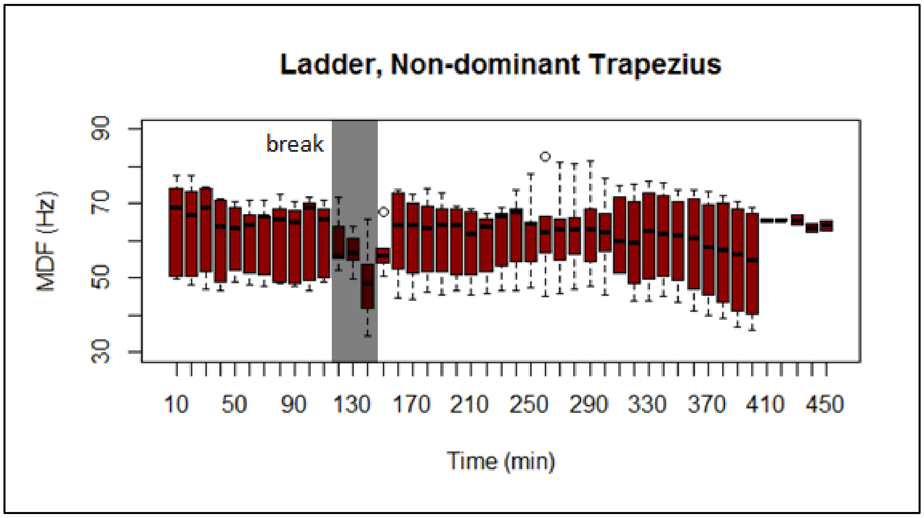


Figure 29 – Boxplot of EMG median power frequency by time, ladder, non-dominant trapezius (n = 5) with the shaded areas being the lunch period.

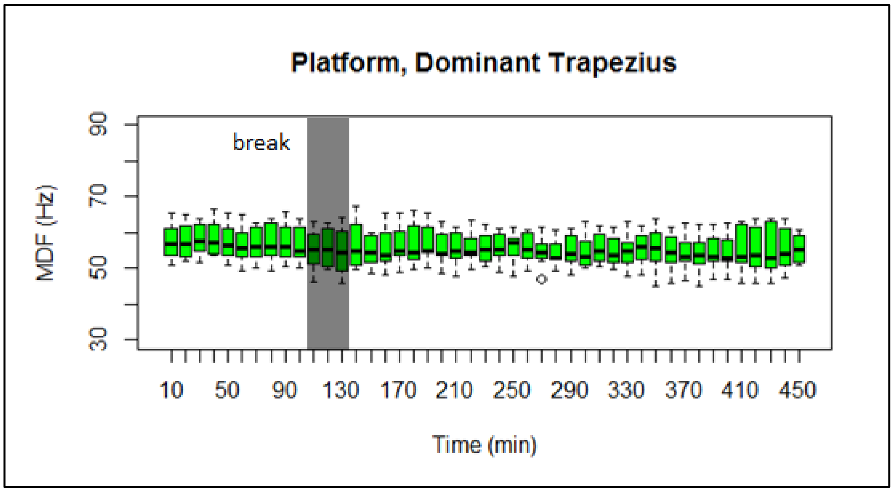


Figure 30 – Boxplot of EMG median power frequency by time, platform, dominant trapezius (n = 8) with the shaded areas being the lunch period.

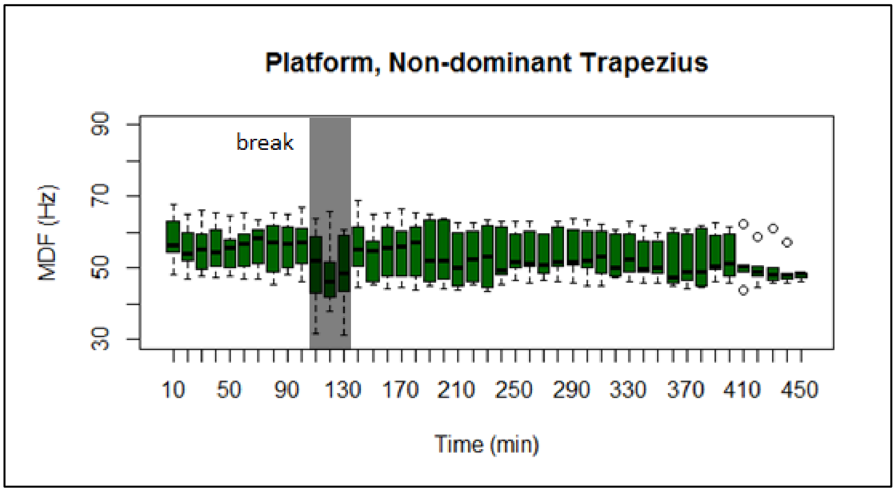


Figure 31 – Boxplot of EMG median power frequency by time, platform, non-dominant trapezius (n = 8) with the shaded areas being the lunch period.

Table 5 – ANOVA tables for MDFs including break time

Error: between-subject	df	Sum Sq	Mean Sq	F-value	p-value
Harvesting Method	2	4,478	2,239	0.575	0.58
Dominant Side	1	177	177	0.045	0.84
Time	8	28,026	3,503	0.900	0.55
Residuals	9	35,048	3,894		

Error: within-subject	df	Sum Sq	Mean Sq	F-value	p-value
Dominant Side	1	201	201	9.232	*0.002*
Time	44	3,290	75	3.426	< *0.001*
Residuals	1,285	28,046	22		

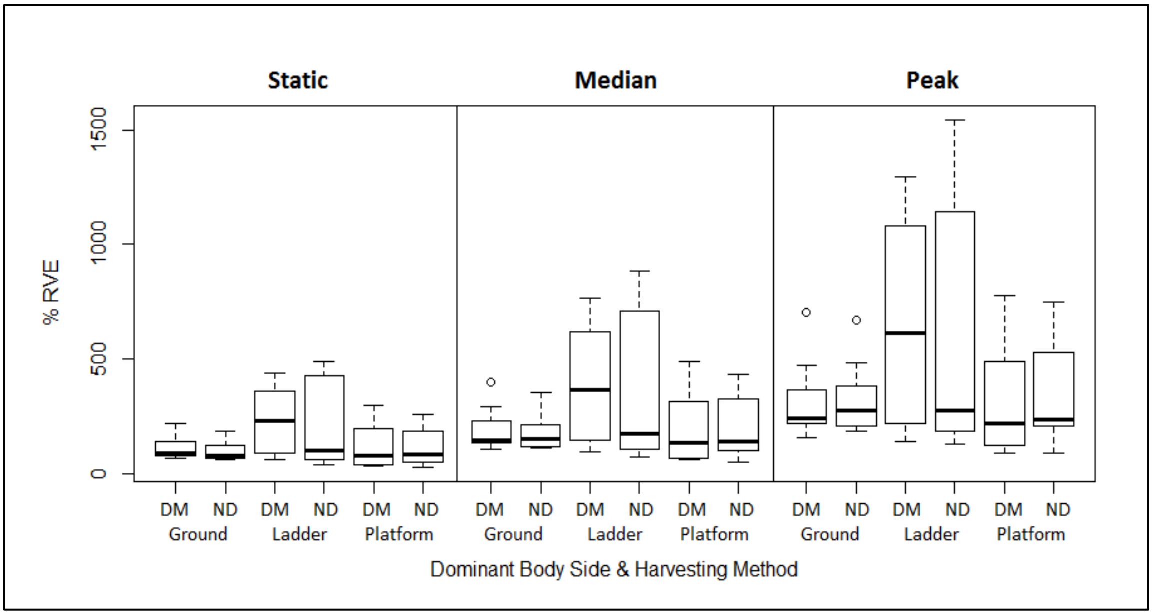
Table 6 – ANOVA tables for MDFs excluding break time

Error: between-subject	df	Sum Sq	Mean Sq	F-value	p-value
Harvesting Method	2	4,819	2,409	0.608	0.57
Dominant Side	1	159	159	0.040	0.85
Time	9	28,487	3,165	0.799	0.63
Residuals	8	31,692	3,961		

Error: within-subject	df	Sum Sq	Mean Sq	F-value	p-value
Dominant Side	1	53	53	3.341	*0.07*
Time	41	963	24	1.472	*0.03*
Residuals	1,168	18,647	16		

6.2.2 Muscle Activity

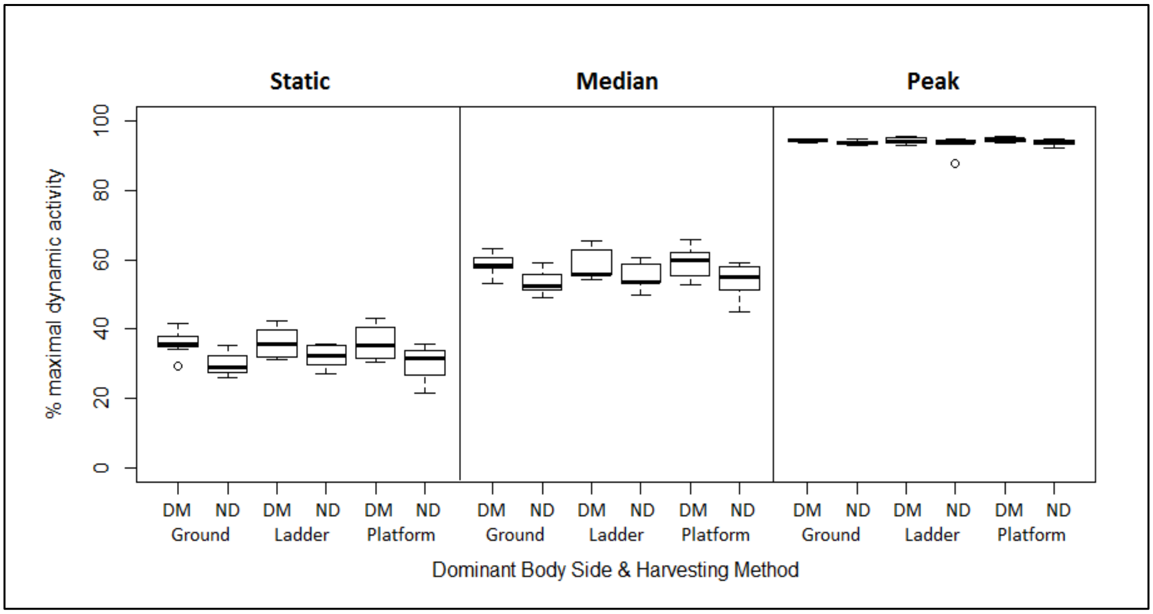
The muscle activity levels (static 10th%tile, median 50th%tile, and peak 90th%tile) normalized using the reference contractions and the dynamic voluntary contraction are shown as boxplots in Figure 33 – 34, respectively.



* DM: dominant body side, ND: non-dominant body side, Ground N = 7, Ladder N = 5, Platform N = 8

Figure 32 – Boxplot of the first work hour of muscle activity (in EMG amplitude as a %RVE) by dominant body side and harvesting method

Muscle activities normalized as %RVE were relatively higher in the dominant trapezius of the ladder workers as compared to the other groups (Figure 30). Still, the variability of the data was quite high especially among the ladder workers; thus, muscle activity differences among the three harvesting methods were not statistically significant (static: F (2, 17) = 1.95, p = 0.17; median: F (2, 17) = 1.85, p = 0.19; peak: F (2, 17) = 1.78, p = 0.20). The dominant body side did not have significant effect on muscle activities either (static, median and peak activities: $p > 0.05$ for both between- and within-subject).



* DM: dominant body side, ND: non-dominant body side, Ground N = 7 Ladder N = 5, Platform N = 8

Figure 33 – Boxplot of the first work hour of muscle activity (in EMG amplitude normalized to maximal dynamic activity) by dominant body side and harvesting method

Muscle activity normalized to the maximal dynamic activity appeared to be more robust given substantially reduced variability. Static muscle activity ranged from about 20-40% of peak dynamic activity (peak(d)). Median muscle activities ranged approximately at 45-65% of peak(d). Peak muscle activities ranged approximately at 90-100% of peak(d) and was not further considered in analyses for effects from harvesting method or dominant body side because the values were derived from the 90th and 95th percentile of the same work activities, which could be very close. As shown in Figure 31, for the three harvesting methods, static and median muscle activities were higher in the dominant body side than the non-dominant side (static: between-subject F (1, 17) = 0.153, p = 0.70; within-subject F (1, 18) = 38, p < 0.0001; median: between-subject F (1, 17) = 0.072, p = 0.91; within-subject F (1, 18) = 29, p < 0.0001). The effects from harvesting method were not significant (static: F (2, 17) = 0.139, p = 0.87; median: F (2, 17) = 0.094, p = 0.91).

Static, median and peak muscles activities normalized as %RVE were shown in Figures 48 – 65 (including break) in Appendix C. Static and median muscles activities normalized to maximal dynamic activity for ground, ladder and platform workers were shown in Figures 66 – 77 (including break) in Appendix C. With an exception of the lunch break, the figures do not show any clear trends in time effect on muscle activities.

Within subject, time excluding the break period significantly impacted muscle activity (p-values < 0.0001). However, between subjects, time effects (also excluding break) were not significant. For the differences among the three harvesting methods, significant differences were found in only the static and median muscle activities of dominant muscles (p-values = 0.03 and 0.02, respectively). There is interest in the static muscle activities as this is an indicator of the repetitive nature of the picking task. The median muscle activities provide indicators of central exertion.

6.3 Discussion

6.3.1 Instrumental Errors

Before evaluating the group summary muscle activity data, the individual data of MDFs and the first percentile of non-normalized muscle activity were plotted over time to identify the time portion to be included. This helped identify the time when the interface between the skin and EMG electrodes started to interfere due to mechanical factors (pressure or external shear forces on the electrodes) or the electrodes lose contact due to skin sweat. There was an issue in recording data in one ladder worker so the data was not successfully recorded. There were also errors in electrode connection where the signals greatly fluctuated for one ground workers in both shoulders, two ladder workers in one shoulder, and one ladder worker in both shoulder. The mechanically-related electrode problems primarily occurred with the ladder workers were beacause they carried a ladder on their shoulder while moving the ladder. The problem was discovered at the end of the first day when the electrodes were removed and the EMG data were preliminarily processed and indicating the portion of data were lost. Only data from two participants, one body side each, were not errors and were included. At the beginning of the second day of the measurement of the ladder workers, the research team members asked the workers to move and carry the ladder in the way that would not interfere the skin-electrode connection. As a result, the data for all the four participants on the second day were usable.

6.3.2 Muscle Fatigue from Frequency Domain Analysis

MDF increased over the work day in several participants: five ground workers, one ladder worker and two platform workers. MDF increases were observed in the afternoon work period. However, the increase may be related to the fact that the electrodes might have come off at different times in the afternoon for some participants. Hence, only the data during the first work hour were initially included for the comparison among harvesting methods and dominant body side.

When comparing the MDFs during the first work hour, there was no effect across the harvesting methods nor the dominant body side. This might have been because the selected time portion was during the beginning of the work (7:30-9:00) and with an assumption that the participants had rested before coming to work in the morning.

Besides the shift in MDF observed in many participants, there was a drop in MDFs during their lunch break (as expected as they are no longer working). The MDF then increased back when workers started working again. This obvious MDF drop appeared in 14 participants for non-dominant trapezius and 8 participants dominat trapezius. Even within the same individual, the MDF drops were more clear in the dominant trapezius than the non-dominant one for all the eight participants that had MDF drop in dominant trapezius. This confirms that the muscle was rested during the break, especially for the non-dominant trapezius. For many participants, the dominant trapezius were still used during the break, i.e. for non-harvesting activities, indicated by constant (non-dropping) MDFs.

Time effect initially observed when analyzing the MDFs over time (Table 30) might have been due to the break when MDFs dropped in some of the participants. Since only work activities were considered, the break portions was removed and data were reanalyzed. The time effect on MDFs was still observed (Table 31) indicating muscle fatigue. Particularly, the MDF increases among the ladder and ground workers started around the middle or the end of work day.

6.3.3 Muscle Activity and Normalization Technique in Time Domain Analysis

The normalization method may not affect the muscle activity in the time domain within each individual. However, using different denominators in normalization may greatly affect the comparison across subjects and between the dominant and non-dominant sides. Normalization technique, therefore, plays an important role in this study. In this case, the RVC method presents much greater variations compared to the method using dynamic contraction. This may be due to the fact that the measured work activity was the same as and the part of the dynamic activity.

The purpose of using the RVC normalization technique was to ensure that the method to create the muscle activity for denominator was the same across all the participants, these participants were guided by the same research team member and performed the reference contractions with the same controlled procedure. This allowed a comparison among the harvesting methods when harvesting activity was different from the reference activity (holding static load). The differences between the harvesting methods were found statistically significant.

Using the maximal dynamic activity as a denominator gave the EMG values within a 0-100% range, which is more intuitive. However, the denominator itself was similar to the work activity; thus, the difference between the harvesting methods was not found. Meanwhile, the greater muscle activities in dominant trapezius than the non-dominant trapezius were already expected because the work activities appeared to be unilateral rather than bilateral according to the video analysis in Chapter 5.

Regardless of normalization technique, muscle activity levels did not significantly change over time. That suggested that muscle activities might not change temporally. On the other hand, muscle fatigue, i.e. the shift in MDFs, appeared to be a better indicator of muscle fatigue over time.

Chapter 7 Associations between Subjective and Objective Measures

This chapter explored various measures of the exposures to risk factors to WMSDs and studied whether any low-cost subjective measures can replace subjective measures such as EMG and/or accelerometer data. The subjective measures included Borg RPE and Borg CR10 modified and translated from English to Spanish. The objective measures included kinematic parameters like postures and repetitions described in Chapter 4-5 and EMG parameters described in Chapter 6.

7.1 Methods

7.1.1 Borg Scales as Subjective Measures

Subjective measures may be complimentary or even a substitute for objective measures. This study used Borg RPE as the perceived exertion of overall body and Borg CR10 s the perceived exertion at local body parts. The instructions and questions of modified Borg RPE and Borg CR10 were translated from English to Spanish, by a bilingual-bicultural research team member (Appendix D). The questionnaires were administered at four time points throughout the workday. The four times included (1.) before the start of work in the morning (data collected during 6:30-7:00), (2.) after the end of the first work shift (start lunch break at 9:00), (3.) before the start of the second work shift (end of lunch break at 9:30) and (4.) at the end of work day (3:30).

7.1.2 Parameters of Interest

Basic information such as the demographics and anthropometry may be identified as confounding factors and, thus, were included in the correlation matrix. As part of parameters described in Table 2, Chapter 4, anthropometric and demographic data included age, weight, height, arm length, upper arm length, forearm length and years or seasons of experience working in harvesting activity.

Postural exposures included the percentage of work time when dominant and non-dominant arm flexion, abduction or elevation exceeded 30^o, 60^o and 90^o and the percentage of work time when back bending more than 10^o, 20^o and 30^o. These values were already computed in Chapter 4.

Parameters indicating repetitive motions were the repetition rates from accelerometer data. The values were derived in the same way as described in Chapter 5 to obtain the values in Figure 15 with the interpolated value of Φ between 15° and 20° but the rates were separated into two arms rather than the average of both arms.

Muscles fatigue was the median power frequency, calculated the same way for Figure 23 in Chapter 6. Muscle activities included the 10th, 50th and 90th percentile of normalized amplitude similarly to the value shown in Figure 24 and 25.

Subjective ratings were collected from modified Borg RPE and Borg CR10 at left and right shoulders and lower back at four time points as described in part 7.1.1. In addition, the correlation of Borg CR10 between each of other body parts – neck, upper back, wrist/hand, thigh/calf, knee, and ankle/foot – were investigated. The subjective scores used for creating the correlation matrix with other objective parameters were the incremental scores from the beginning to the end of the workday of Borg RPE, Borg CR10 in both shoulders and back.

7.1.3 Statistical Analysis

Borg RPE and Borg CR10 were analyzed using ANOVA ($\alpha = 0.05$) of which factors were three harvesting methods, four time points of the day and the interaction between harvesting method and time of the day.

After all the parameters are obtained, correlation coefficients between each pair of postures, repetitions, EMG and subjective measures were calculated in order to determine whether there is any relationship between the measures. This was used to determine whether high-level kinematic exposures - posture and repetition - could be causal to high muscle activity, and to determine whether the muscle activity and/or muscle fatigue can be predicted by any subjective measures.

7.2 Results

7.2.1 Borg Scales as Subjective Measures

The subjective measures: Borg RPE, Borg CR10 at non-dominant and dominant shoulders and lower back were shown in Figures 64 – 67, respectively. Borg RPE of the ground and platform workers increased during work period, reduced during the break then increased again during the work session after lunch break. Borg RPE of the ladder workers started slightly higher than the other groups at the beginning of the day, decreased by the start of lunch break then increased again through the workday. Most of the Borg CR10 scores were quite low, mostly lower than 1 at the first three time points and lower than 5 at the end of the day. Observing the figures, Borg CR10 in lower back and both shoulders were higher in the platform workers than the other two groups at the end of workday.

Moreover, ANOVA tables are provided in Tables 7 to 10. Time of the day significantly affected all the Borg scores (i.e., Borg RPE, Borg CR10 at both shoulders and back). Harvesting method and the interaction between harvesting method and time of the day significantly affected Borg CR10 at both shoulders but did not significantly affect Borg RPE and Borg CR10 at lower back.

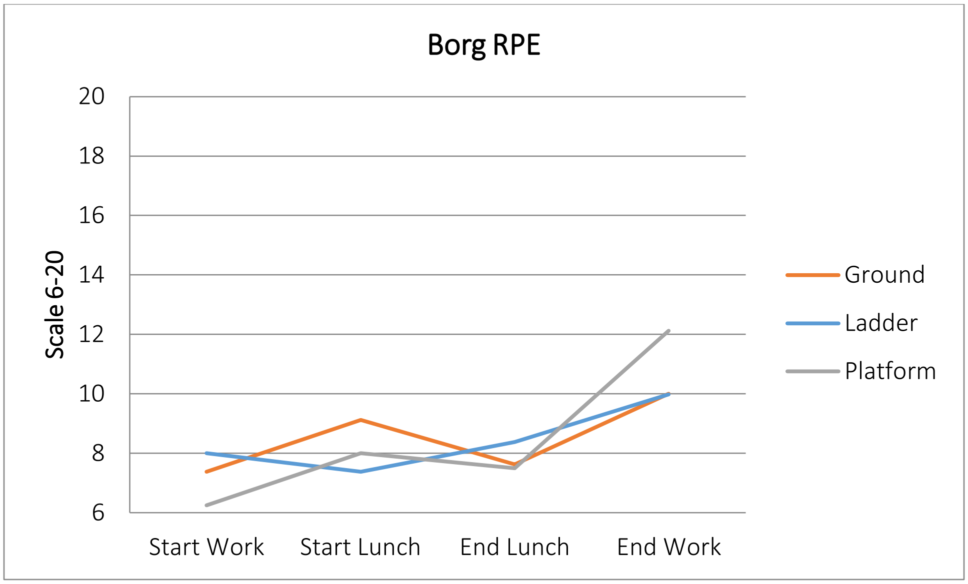


Figure 34 – Borg RPE by harvesting method and time of the day (Ground n = 7, Ladder n = 5, Platform n = 8)

Table 7 – ANOVA tables for Borg RPE with two factors: harvesting method and time of the day

	df	Sum Sq	Mean Sq	F-value	p-value
Harvesting Method	2	0.400	0.198	0.043	0.96
Time of Day	3	214.7	71.57	15.50	*< 0.0001*
Harvesting Method x Time of Day	6	44.86	7.476	1.619	0.15
Residuals	84	387.9	4.617		

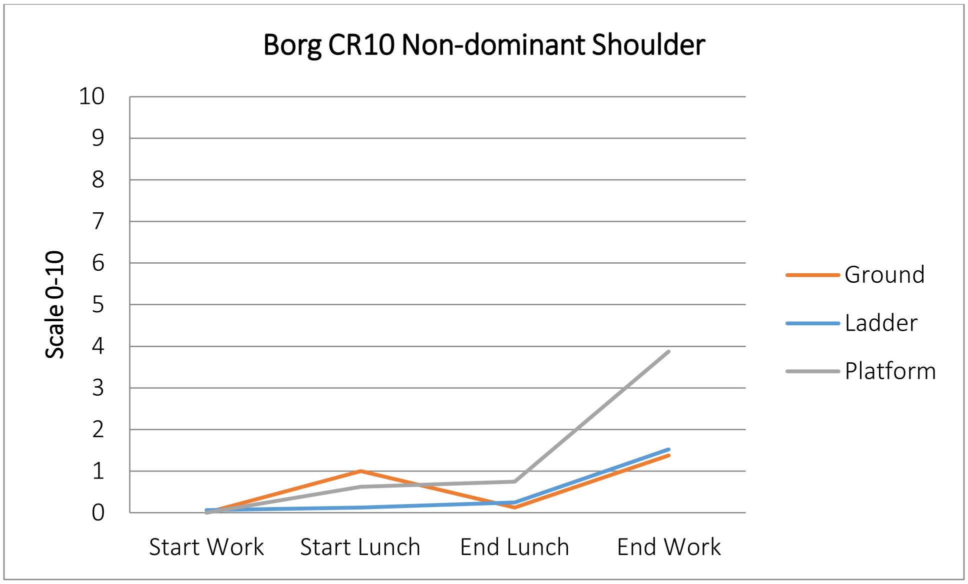


Figure 35 – Borg CR10 at non-dominant shoulder by harvesting method and time of the day (Ground n = 7, Ladder n = 5, Platform n = 8)

Table 8 – ANOVA tables for Borg CR10 at non-dominant shoulder with two factors: harvesting method and time of the day

	df	Sum Sq	Mean Sq	F-value	p-value
Harvesting Method	2	12.56	6.28	3.58	***0.03***
Time of Day	3	74.44	24.8	14.2	***< 0.0001***
Harvesting Method x Time of Day	6	22.60	3.77	2.15	***0.05***
Residuals	84	147.1	1.75		

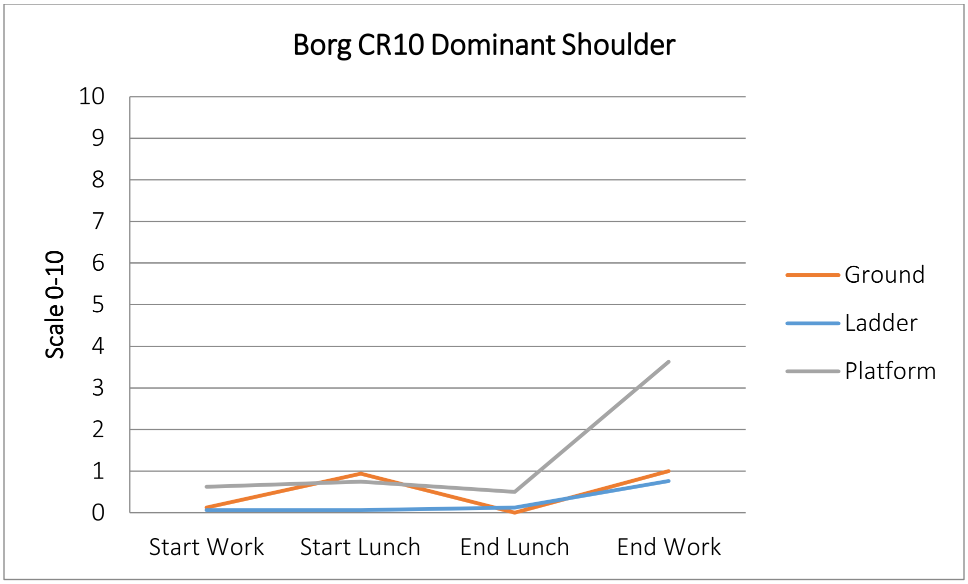


Figure 36 – Borg CR10 at dominant shoulder by harvesting method and time of the day (Ground n = 7, Ladder n = 5, Platform n = 8)

Table 9 – ANOVA tables for Borg CR10 at dominant shoulder with two factors: harvesting method and time of the day

	df	Sum Sq	Mean Sq	F-value	p-value
Harvesting Method	2	22.13	11.1	7.59	*0.0009*
Time of Day	3	40.97	13.7	9.36	*< 0.0001*
Harvesting Method x Time of Day	6	23.25	3.87	2.66	*0.02*
Residuals	84	204.3	1.46		

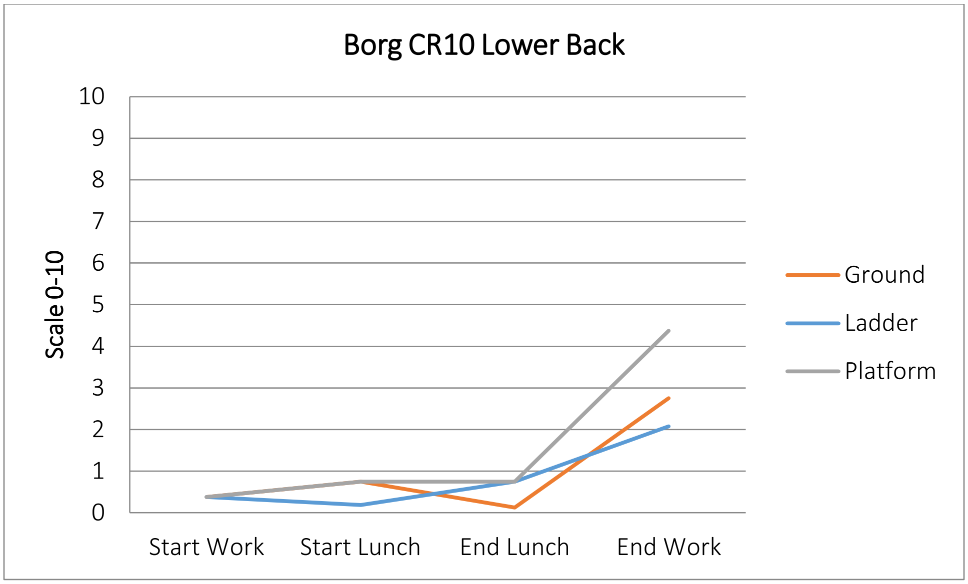


Figure 37 – Borg CR10 at lower back by harvesting method and time of the day (Ground n = 7, Ladder n = 5, Platform n = 8)

Table 10 – ANOVA tables for Borg CR10 at lower back with two factors: harvesting method and time of the day

	df	Sum Sq	Mean Sq	F-value	p-value
Harvesting Method	2	9.443	4.72	1.94	0.15
Time of Day	3	125.3	41.8	17.2	***< 0.0001***
Harvesting Method x Time of Day	6	14.06	2.34	0.96	0.45
Residuals	84	204.3	2.43		

7.2.2 Correlation Matrix of Subjective Measures

The correlations between each pairs of two Borg scores were calculated. The correlation matrix of Borg RPE and Borg CR10 for each body parts is shown in Table 11. The Borg CR10 scores were somewhat correlated among one another. More specifically, lower back and both shoulders had correlation coefficient greater than |0.60| with other body parts except the lower body parts such as dominant calf, knee and foot. However, Borg RPE did not have strong correlations with the local body part Borg CR10 (less than |0.50|) except at the upper back.

Table 11 – Correlation matrix of subjective measures

	Neck	Upper Back	Lower Back	Dominant Shoulder	Dm Hand	Dm Thigh	Dm Knee	Dm Calf	Dm Foot	Non-dominant Shoulder	Nd Hand	Nd Thigh	Nd Knee	Nd Calf	Nd Foot	RPE
Neck	1															
Upper Back	0.59	1														
Lower Back	0.73	0.77	1													
Dominant Shoulder	0.60	0.61	0.72	1												
Dm Hand	0.64	0.57	0.62	0.79	1											
Dm Thigh	0.42	0.69	0.64	0.62	0.62	1										
Dm Knee	0.51	0.61	0.59	0.53	0.71	0.72	1									
Dm Calf	0.52	0.51	0.42	0.47	0.49	0.40	0.34	1								
Dm Foot	0.36	0.49	0.34	0.35	0.46	0.55	0.54	0.71	1							
Non-dominant Shoulder	0.64	0.66	0.81	0.77	0.78	0.64	0.63	0.51	0.43	1						
Nd Hand	0.57	0.65	0.65	0.69	0.89	0.69	0.84	0.39	0.56	0.77	1					
Nd Thigh	0.61	0.62	0.73	0.64	0.74	0.81	0.77	0.47	0.56	0.79	0.84	1				
Nd Knee	0.48	0.56	0.57	0.56	0.78	0.73	0.92	0.46	0.59	0.68	0.88	0.87	1			
Nd Calf	0.53	0.55	0.59	0.64	0.69	0.67	0.65	0.64	0.46	0.71	0.71	0.86	0.79	1		
Nd Foot	0.46	0.54	0.56	0.63	0.78	0.70	0.82	0.43	0.61	0.73	0.91	0.85	0.92	0.74	1	
RPE	0.35	0.69	0.48	0.50	0.50	0.46	0.39	0.47	0.45	0.46	0.52	0.40	0.40	0.41	0.41	1

* 24 subjects, 4 time points each subject, 96 data points, Dm = dominant, Nd = non-dominant

7.2.3 Objective Measures represented by Subjective Measures

The correlation matrices for upper arm/shoulder and back exposure variables are shown in Tables 12 and 13, respectively. The demographic and anthropometry variables were not shown and their correlations with exposure measures were small.

There was no strong correlation between Borg scores and objective measures. All the correlation coefficients between Borg CR10 at any shoulder or back and other parameters were less than |0.40|. Neither were the correlations between repetition rate and other variables. Still, repetition had small positive correlations with arm elevation and flexion parameters as well as muscle activity normalized as %RVE (correlation coefficient = 0.30-0.40).

Posture parameters, both upper arms and back, were positively correlated among one another but were not correlated with other variables such as Borg CR10 or any EMG parameters.

The frequency of muscle activity, i.e. MDF, was not correlated with any other variables (correlation coefficient < 0.20). Muscle activities were not correlated with other variables either. However, static (10th %tile), median (50th %tile) and peak (90th %tile) muscle activities normalized as %RVE were positively correlated among themselves. Similarly, static, median and peak muscle activities normalized to maximal dynamic activity had very high positive correlations among themselves.

Table 12 – Correlation matrix of exposure measures in upper arms / shoulders

	Borg Shoulder	Repetition	Elevate 30	Flex 30	Abduct 30	Elevate 60	Flex 60	Abduct 60	Elevate 90	Flex 90	Abduct 90	Elevate Avg	Flex Avg	Abduct Avg	MDF	10PCT norm Max	50PCT norm Max	90PCT norm Max	10PCT norm Ref	50PCT norm Ref	90PCT norm Ref
Borg Shoulder	1																				
Repetition	0.04	1																			
Elevate 30	-0.11	0.25	1																		
Flex 30	-0.05	0.24	0.74	1																	
Abduct 30	-0.16	0.02	0.34	-0.32	1																
Elevate 60	-0.16	0.33	0.77	0.74	0.08	1															
Flex 60	-0.11	0.33	0.72	0.87	-0.17	0.94	1														
Abduct 60	-0.27	0.11	0.24	-0.20	0.79	0.25	-0.04	1													
Elevate 90	-0.26	0.35	0.56	0.40	0.38	0.60	0.49	0.62	1												
Flex 90	-0.25	0.36	0.58	0.49	0.31	0.60	0.56	0.50	0.97	1											
Abduct90	-0.34	0.26	0.40	0.16	0.55	0.41	0.26	0.81	0.92	0.86	1										
Elevate Avg	-0.13	0.28	0.99	0.77	0.30	0.85	0.80	0.27	0.61	0.63	0.44	1									
Flex Avg	-0.08	0.23	0.62	0.95	-0.34	0.64	0.80	-0.19	0.41	0.53	0.21	0.65	1								
Abduct Avg	-0.07	-0.07	-0.02	-0.55	0.86	-0.30	-0.49	0.66	0.14	0.09	0.41	-0.07	-0.50	1							
MDF	-0.16	0.18	0.15	-0.01	0.19	-0.01	-0.08	0.21	0.03	-0.03	0.13	0.11	-0.11	0.20	1						
10PCT norm Max	-0.01	-0.23	0.22	0.09	0.23	0.12	0.06	0.19	0.15	0.17	0.12	0.22	0.04	0.17	-0.06	1					
50PCT norm Max	0.06	-0.18	0.15	0.03	0.20	0.06	0.01	0.13	0.09	0.11	0.06	0.16	-0.03	0.18	-0.09	0.97	1				
90PCT norm Max	0.16	-0.10	0.14	0.11	0.09	-0.02	0.07	-0.12	-0.02	0.14	-0.07	0.13	0.14	0.15	-0.22	0.68	0.74	1			
10PCT norm Ref	-0.13	0.30	-0.02	-0.08	0.17	-0.06	-0.07	0.14	0.05	0.07	0.14	-0.02	-0.04	0.27	0.17	0.03	0.01	0.06	1		
50PCT norm Ref	-0.13	0.32	-0.04	-0.08	0.15	-0.08	-0.08	0.12	0.04	0.06	0.13	-0.03	-0.05	0.26	0.18	-0.04	-0.04	0.03	1	1	
90PCT norm Ref	-0.14	0.32	-0.04	-0.08	0.13	-0.08	-0.07	0.11	0.04	0.06	0.13	-0.04	-0.04	0.24	0.19	-0.10	-0.10	0	0.99	1	1

* 39 data points, pooled dominant and non-dominant arms, N = 19

Table 13 – Correlation matrix of exposure measures in back

	Borg Lower Back	Back 10	Back 20	Back 30	Back Avg
Borg Lower Back	1				
Back: % time angle > 10^o	-0.14	1			
Back: % time angle > 20^o	-0.25	0.91	1		
Back: % time angle > 30^o	-0.29	0.56	0.84	1	
Back average angle	-0.26	0.77	0.93	0.93	1

* N = 23

7.3 Discussion

7.3.1 Subjective Measures

Borg RPE and Borg CR10 represent how the participants perceived the tiredness and/or fatigue at overall body and local body parts, respectively. All the measures showed that the time of the day significantly affected the perceived tiredness/fatigue. That may be due to the work itself, i.e. Borg scores increased from before work to after work. For the other reason, the time of the day might have affected the scale ratings in terms of heat that increased from morning to afternoon.

The perception of overall tiredness (Borg RPE) and the lower back pain (Borg CR10) were not affected by the harvesting method. This is agreed with the results of back bending exposure in Chapter 4 that there was no significant effect of harvesting method on the exposure time to back bending.

The results of subjective measures for the perceived fatigue at the shoulders were different from the objective measure. The Borg CR10 suggested that platform workers had higher fatigue at shoulders, which is opposite to the results of objective measures in Chapter 4, 5 and 6. However, the low variability in the EMG during the platform work may have contributed to the higher self-reported fatigue in the shoulders. For kinematic measures (Chapter 4-5), the platform workers had the lowest and the ground workers had the second lowest exposures to non-neutral postures and repetitive motions of upper arms. For physiological measures (Chapter 6), the platform-related work resulted in lower muscle fatigue and muscle activity than the ladder work.

In addition, it was of interest to identify if the objective measurement or subjective questionnaires could be complimentary to each other. The correlation coefficients between the measures would show whether it would be necessary to measure many parameters or whether one could be a representative of the other.

7.3.2 Correlations of Exposure Measures and Recommendations

Since all the correlation coefficients between the pairs of a subjective measure and an objective measure were insignificant (less than |0.40|), it can be concluded that the subjective measures did not track or readily parallel the objective measures in this study. That is, in the context of apple harvesting work, the subjective measures like the modified Borg RPE and Borg CR10 used in this study cannot replace the objective measures of physical and physiological exposures. This also suggested there might have been other measurable and unmeasurable factors that affect the subjective results. Therefore, the use of the modified Borg scales needs some cautious interpretation. In addition, more work to improve or validate the translation and/or instruction of these modified Borg scales is recommended.

Moreover, as none of the EMG parameters were significantly correlated with any other objective parameters including postures and repetitions, it can be said that EMG could add more information to exposure measurement. In this case, muscle activity was significantly higher in the dominant shoulder, considering EMG amplitudes normalized to maximal dynamic voluntary activities. Still, the results that EMG parameters were not strongly correlated with the others may be due to the variability of the EMG data. Thus, it is recommended to improve EMG field measurement for greater signal reliability or to redesign the study by increasing sample size or using repeated measures. This may have a tradeoff in terms of its higher equipment and measurement cost. Also, since the EMG results had a similar trend as the repetition rates (ladder > ground > platform), if the purpose of studies is only to compare harvesting equipment, omitting EMG measurement could be an option when there is a constraint on cost.

Chapter 8 Conclusions

This chapter concludes the dissertation with the rationale, contribution and limitation of this research. This conclusion comes with the potential value of how the research outcomes may provide implications for both future technical research and the improvement of work practice regarding agricultural ergonomics.

8.1 Summary of Existing Gaps

The United States tree fruit industry is facing a challenge in global competition. Harvesting is usually labor intensive and, therefore, the shortage of labor is the main issue resulting in high production cost. Harvest-assisted mobile orchard platforms have recently been implemented in some industrialized orchards aiming to increase harvesting productivity; however, they have not been evaluated in the aspect of the potential positive or negative health effects on the workers. From the perspective of fruit growers or orchard owners, the mobile platforms are expected to improve harvesting efficiency because their workers do not have to spend time climbing up and down or moving ladders, neither they have to walk back and forth to fill apple bins. In addition, ladder-related injuries primarily as a result of falling will for the most part not occur on these mobile platforms. In contrast, for the mobile platform workers, they are expected to pick fruit faster and repeatedly in potentially more confined workspaces. This may introduce new types of physical exposures: postural stresses and may increase exposure to repetitive motion.

While technological innovations are helping the economy of industrialized countries like the United States and Canada, the people who may not benefit from the result of these innovations may be the migrant farmworkers of Hispanic or indigenous origin who actually harvest the fruits. They are perceived by the public to be more tolerant to difficult living and working conditions; however, this population is considered vulnerable and just may complain less due to the temporary employment. Pressured to work physically hard and for long workdays without sufficient breaks, these migrant agricultural workers may develop WMSDs, which go unreported.

As the mobile platform might change the pattern of harvesting tasks, i.e. changing their work postures and body movement while working, there is a need to evaluate the exposures to WMSD risk factors and whole body and localized fatigue in these workers. A number of techniques can be used to study the ergonomics, usability and workability of equipment. Still, these techniques are more suitable for evaluating how human interact with machines or man-made built environments rather than with natural environment like farmlands. The exposure to the risk factors of WMSDs in agriculture remains unique due to the diversity of the work activities and the crops themselves, for instance, apples are not at the same height and different types of apples require different picking techniques. The existing and previous ergonomic evaluation methods such as human motion analysis using cameras were primarily laboratory-based and had some restrictions; thus, they are not appropriate for use in field studies in orchards.

8.2 Study Contributions

8.2.1 Intellectual Merits

Migrant agricultural workers are essentially an integral part of the food supply chain in North America as their contribution in harvesting labor helps bringing agricultural produce to market. Therefore, their health and overall well-being should be considered. While the new methods of performing agricultural work like mobile platforms are brought into practice to improve work efficiency, it is important to consider the effect on the workers. The monitoring and evaluation techniques developed in this dissertation may provide metrics that can be used for finding scientific evidence whether new technologies, such as the mobile orchard platform, are helping to reduce or leading to increase health risks for the workers.

The systematic methods developed for this dissertation are based on data collected in actual field settings and are based on how workers actually perform their harvesting tasks. The research approach is unique as its data were collected in the field while workers were doing their actual work during their normal, full workday. The proposed computational program to characterize work repetition attempts to account for the nature of work activity so that it can be also used for evaluating other harvesting equipment as well as future interventions for mitigating WMSDs among orchard workers.

Currently, this is the first study to the author's knowledge that has measured muscle fatigue and muscle activity using surface EMG during an actual work of a full workday in agriculture. Not only could the results potentially help with understanding the link between shoulder pain or fatigue and the physical exposures associated with agricultural work, but also the methodology developed in this research could be an asset for others to overcome challenges in EMG field measurement in future studies.

Above all, developing the techniques to assess ergonomics exposures in field settings is the first step in developing standards and recommendations for evaluating work practice as well as technological interventions. The methods developed in this dissertation provide implications for future studies which attempt to support the healthy work environment of farmworkers. That is, they will ultimately help improving the health equity of the underserved population of migrant farmworkers.

8.2.2 Implications to Industry

This study found meaningful differences in physical exposures – the non-neutral postures and repetitive motions – between traditional harvesting with ladder and using mobile platform. Implementing the mobile platform has a potential to improve the long-term health of farmworkers due to its capability in reducing exposures to the risks of WMSDs. Still, there may be many cases where working with ladders are necessary; for example, when the orchard terrain is not suitable for using the mobile platforms. Job rotation may also help reduce physical exposures in individuals. Job rotation could be done between ladder- and mobile platform-based work as well as between the platform and ground-based work.

Studying muscle fatigue over time may lead to recommendation for shortening or limiting work hours. The results showed that the MDFs during the break (after the 90^{th} up until the 150^{th} minutes of work) dropped ($p < 0.05$), taking more frequent breaks may allow new restart points and help the farmworkers work longer and may reduce the potential for muscle fatigue. Accordingly, adding another break in the afternoon or a more even distribution of breaks may be merited.

Subjective or qualitative information may not necessarily indicate true exposure in this population as the results were different from and for the most part had little to no correlation with objective measures. However, qualitative research could give information that may not be measurable and may meaningfully lead to the ideas for intervention.

8.3 Considerations and Recommendations

8.3.1 Study Limitations

The study has some systematic biases. Videotaping or the presence of the researchers in the field might have altered the way the participants worked as compared to when their work is not monitored. Administering the survey of subjective efforts could have somewhat interrupted their lunch break. It is likely that the workers ended up answering the questions as fast as they could rather than attentively.

The data collection tool, the accelerometer, is limited as it cannot capture different angles in horizontal planes. In other words, internal and external rotation of the shoulders cannot be measured by this accelerometer even though flexion and abduction angles could be measured. All information measured from the accelerometer was relative to the gravity. The lack of the information of the arm posture in horizontal plane limits clinical implications regarding the identification of painful shoulder positions, i.e. internal and external rotations. This can also impact the design or redesign of the platform to improve work postures.

There are several limitations in the EMG measurement in field settings. Firstly, despite the use of anti-sweat adhesive solution and tape to adhere the electrodes to the body, there was still perspiration causing some electrodes to come off the participants' skin during the experiment. This issue greatly affects the quality of the EMG data; that is, the EMG data from several subjects could not be used for the entire workday. Therefore, the analysis of only the first work shift (1.5 hours) was conducted in order to retain an adequate sample size, ladder: N = 5, ground: N = 7 and platform: N = 8. Also, the fact that harvesting activity requires workers to wear bag straps which reside over the EMG electrodes interfering the electrode-skin connection for some participants. This issue was avoided by lowering the placement of the differential electrode pairs on the shoulder. Additionally, from time to time during the experiment, workers in the ladder group tended to carry the ladders on their shoulder, which could shear or rip the electrodes off the shoulder. This could cause interference at the electrode-skin connection, and the worst-case scenario could remove the electrode from being in contact with the skin. This issue was found at the end of the first day of running the experiment on the workers in the ladder group, but was prevented on the days after. The researchers asked the participant not to carry the ladder on their shoulder.

Finally, even though this study was well-controlled, some caution should be made with respect to generalizability. The study was conducted in a trellised orchard, which is a standard type of orchard in Washington State but may not be typical of orchards in other parts of this country or the world. In this study, trees were grown as tree walls with a certain height in a trellised orchard. However, in other orchards, trees are generally taller and the growth of the branches is not constrained, therefore, the trees are typically wider and cover a greater area. Harvesting fruits in these types of orchards where the tree growth is not constrained or controlled may expose workers to more non-neutral postures, i.e. far reaching, than in the more controlled trellised orchard in this study. Moreover, the type of apples harvested and the picking method (e.g. clipping or not clipping stems, strip picking, 1st color picking, 2nd color picking, etc.) should also be taken in to consideration. For example, Red Delicious apples are harvested with strip picking technique; that is, all the apples are picked at once. Gala apples are harvested using a color picking technique; that is, apples with the right color are picked but the other ones are left on the trees until their color is appropriate for picking. Fuji apples, which were harvested in this study, are also harvested using color picking and, since their skins are delicate, their stems have to be clipped to prevent them scratching and damaging the skin of other apples. All things considered, this study provided a very fair and controlled comparison of the harvesting methods (the newly-developed mobile platform and the traditional use of the ladders) but caution may be merited when comparing to other apple harvesting studies.

8.3.2 Future Research

As the mobile orchard platform does not appear to increase the physical exposures associated with apple harvesting, the next study could focus on how to help workers use the mobile platforms more efficiently. How do farm owners and farmworkers understand the benefits in terms of health besides economic advantage? What are the constraints that prevent the extensive use of the mobile platform? Qualitative research may play an important role in figuring out the best way to implement new technology.

There may be ways to improve measures of productivity. The quality of harvested apples, i.e. the amount of apples that passed the quality inspection and could be sent to market as compared to the amount of apples harvested, may or may not be affected by harvesting method. However, this was not taken into account when measuring productivity in this research. The fruits harvested were sent straight to cold storage to be shipped to market later in the year. Hence, it is possible to integrate the quality of fruits into measuring the true productivity using data from warehouse, i.e. the amount of fruits that are good to be sent to market after sorting.

There are several lessons learned from measuring EMG in agricultural field. Although the measurement duration was as long as the full workday, the data used in the statistical analysis for harvesting method comparison were shorter, only the first part of the work session that lasted for 1.5 hours was included in the muscle activity analyses. EMG studies could be beneficial for determining appropriate work duration in a day for specific orchard tasks would benefit farmworkers. Also, more breaks could be added and another study could be conducted to investigate the time effect on muscle fatigue; that is, to prove whether shortening continuous work duration or adding more breaks would reduce muscle fatigue during work and at end of the work day.

From this study, the results from statistical comparison of muscle activities depended on whether they were normalized as %RVE or as %peak(d). One way to find out why this EMG normalization provided different results may be to compare the two different normalization techniques using controlled laboratory experiment with other certain tasks that are similar to tree fruit picking but more controlled in terms of height and how to pick the fruits.

Borg scales might or might not have been ideal measures in this research. Platform workers had higher scores than ladder and ground workers, which was very different from most of the other objectively measured parameters. Additionally, their correlations with the other exposure parameters were in opposite direction from expected. Yet this may be interpreted that Borg scores gave different information that the non-subjective measures could not capture or that Borg were too subjective and did not present the true tiredness in this case. Thus, future studies may try to discover what other factors may affect the Borg scores.

Lastly, a repeated-measure design, i.e. same subjects performing all harvesting tasks, would help reducing the study variability, especially the EMG parameters which depend greatly on individuals. Instead of having 24 participants in the study, it might have been better to have only 8 participants but performing all the three harvesting tasks. In this case, the researchers would have reached out to more experienced workers who had used ladders before. Note that the majority of the workers in the cooperating orchard in this study had only worked either on platforms or was working from the ground prior to the study, thus a repeated measures design was not feasible.

Appendix A Accelerometer Validation

The accelerometers used for obtaining postural exposures in Chapter 4 are validated with the motion analysis system at the Human Motion Analysis Laboratory, Department of Rehabilitation Medicine at the University of Washington.

Instrumentation Setup

The motion analysis system captured human postures using six cameras. Two markers were used to obtain body segment orientation and movement (Figure 68 left). The system collected the Cartesian coordinates of each marker which x, y and z were defined according to Figure 68 right, at the frequency of 30 Hz.

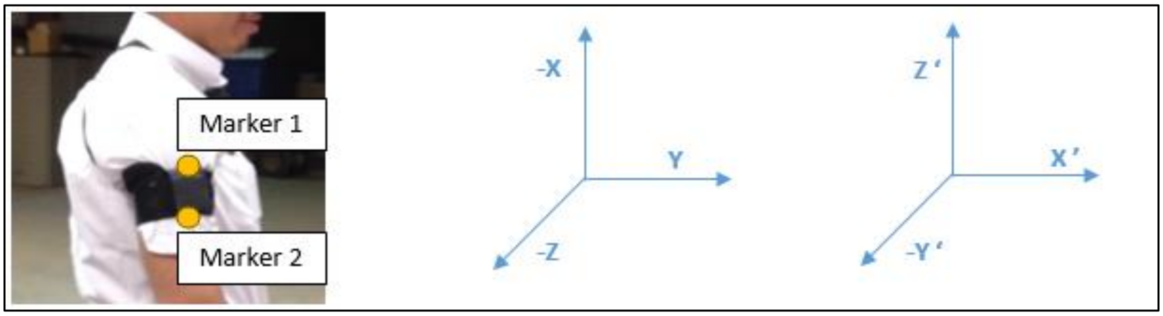


Figure 38 – Motion analysis markers as compared to accelerometer (left), accelerometer coordinate (middle) markers' coordinate (right)

Data Collection

Data from an accelerometer and the motion analysis system were collected simultaneously in order to compare the angles obtain from each instrument. The accelerometer and the two markers were attached to an analog goniometer and the goniometer was rotated to simulate upper arm flexion and abduction (Figure 69 – 70, respectively). The simulating steps for both flexion and abduction angles were conducted as follows.

- Start at 0^{o} (Figure 68 left)

- Move to 30^o then stay for 10 seconds
- Move to 60^o, 90^o, 120^o, 150^o, 180^o, 210^o and -30^o and stay for 10 seconds at each step

Figure 39 – Simulation of right arm flexion

Figure 40 – Simulation of right arm abduction

Data Processing: Calculating Upper Arm Angles

From the data obtained from the Human Motion Analysis Laboratory, postures, i.e. upper arm angles, were calculated from the relative position of the two markers. The equations were shown in Table 14 right column, in parallel with the equations for accelerometer data as shown in the left column. The continuous plots of data both data are shown in Figure 71 – 74.

Table 14 – Calculation of upper arm postures

	Accelerometer Data	Human Motion Analysis Laboratory Data
Flexion	$\tan^{-1}\left(\frac{y}{x}\right)$	$\tan^{-1}\left(\frac{z_1 - z_2}{y_1 - y_2}\right)$
Abduction	$\tan^{-1}\left(\frac{-z}{x}\right)$	
Elevation	$\tan^{-1}\left(\frac{\sqrt{y^2 + z^2}}{x}\right)$	$\tan^{-1}\left(\frac{z_1 - z_2}{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}\right)$

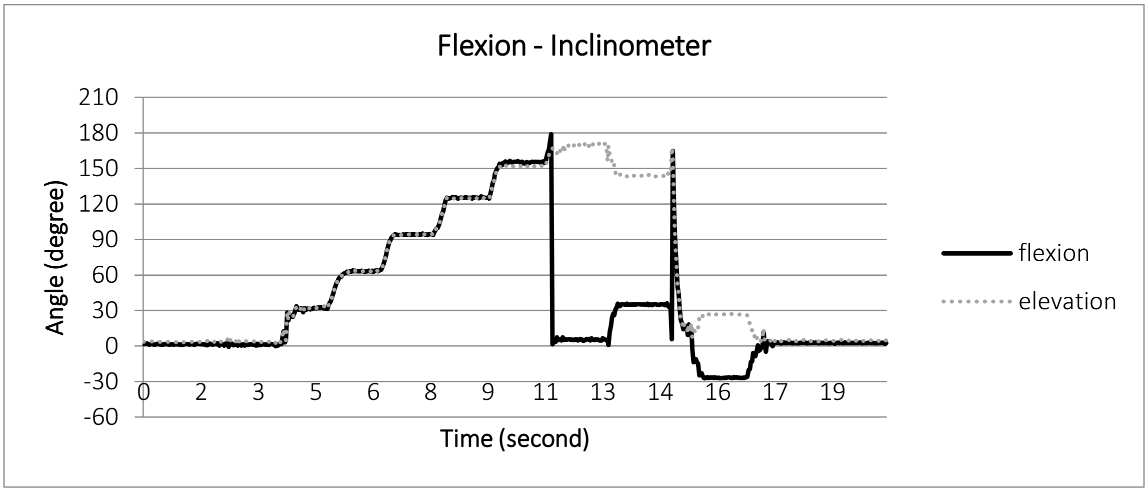


Figure 41 – Flexion angles from accelerometer data

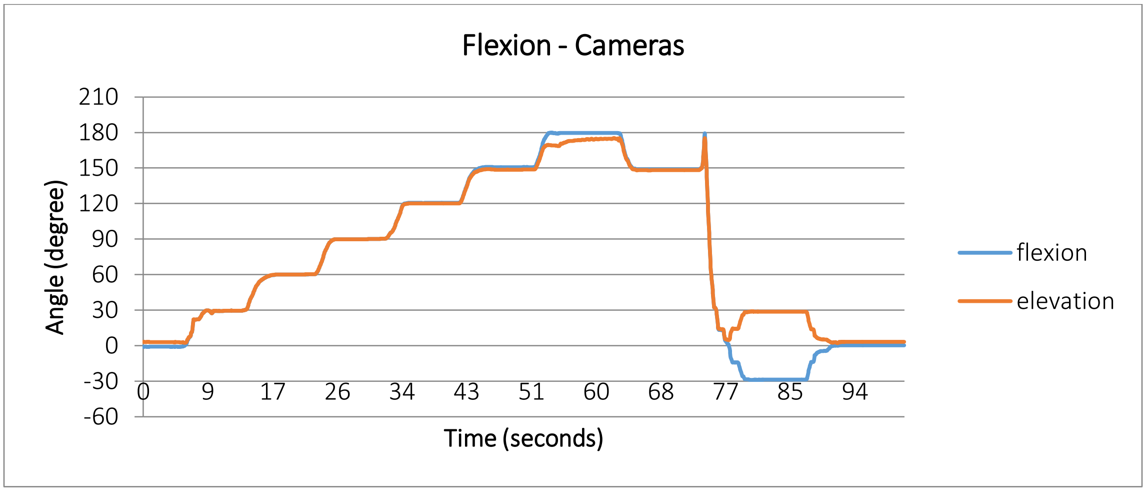


Figure 42 – Flexion angles from human motion analysis laboratory

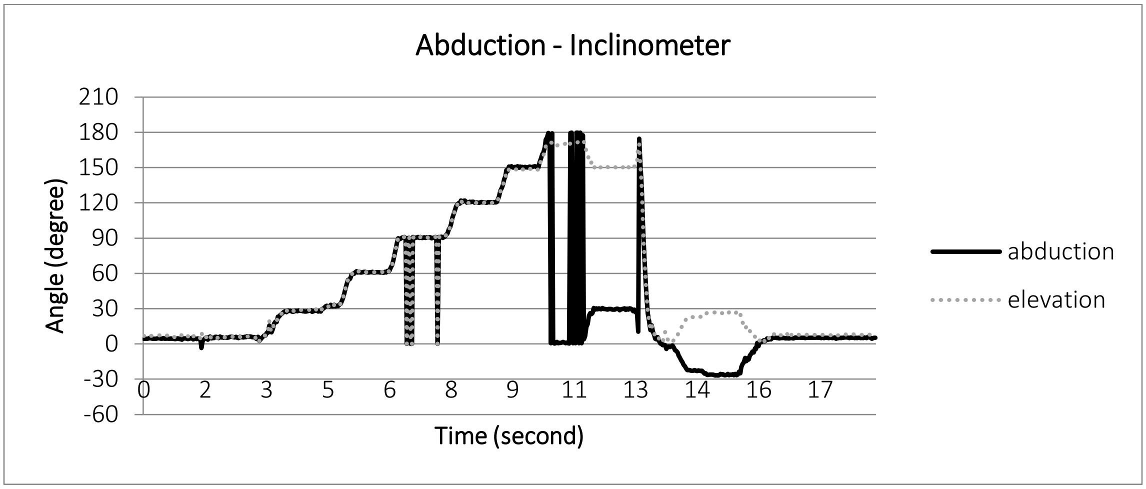


Figure 43 – Abduction angles from accelerometer data

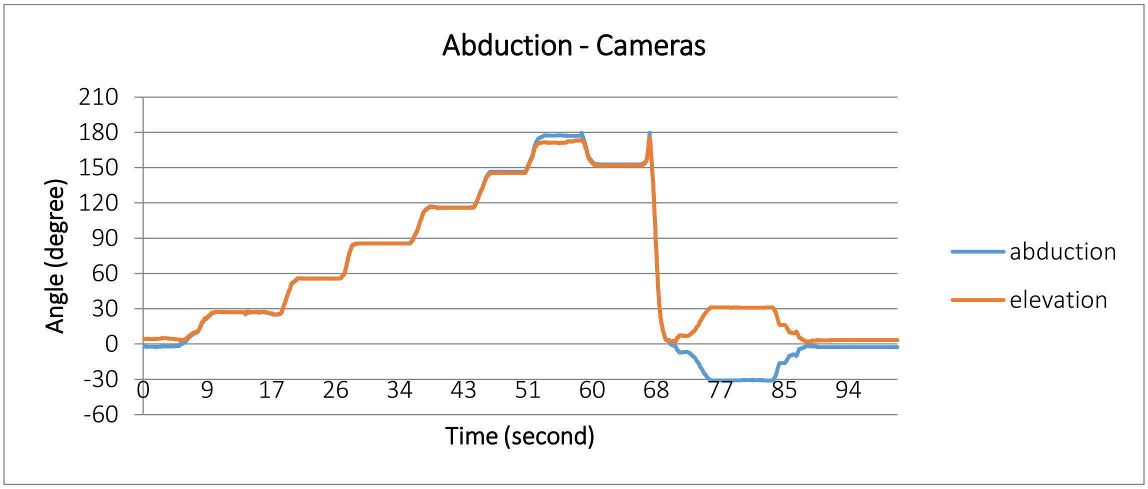


Figure 44 – Abduction angles from human motion analysis laboratory

Statistical Analysis

Resampling for data points at the beginning and the end of each step angle (2 data points for each of -30^o, 0^o, 30^o, 60^o, 90^o, 120^o and 150^o for flexion/abduction), there were the total of 18 points for flexion and 18 data points for abduction. The same process was repeated for the elevation angles of 0^o, 30^o, 60^o, 90^o, 120^o, 150^o and 180^o.

The correlation coefficients between upper arm angles obtained from the motion analysis system and accelerometer data were computed for flexion, abduction and elevation. Also, mean square errors were calculated to represent the deviation from analog goniometer. The results are shown in Figure 75 – 77 and Table 15. The data from two sources were highly correlated. Both methods had small mean square errors: less than 5°.

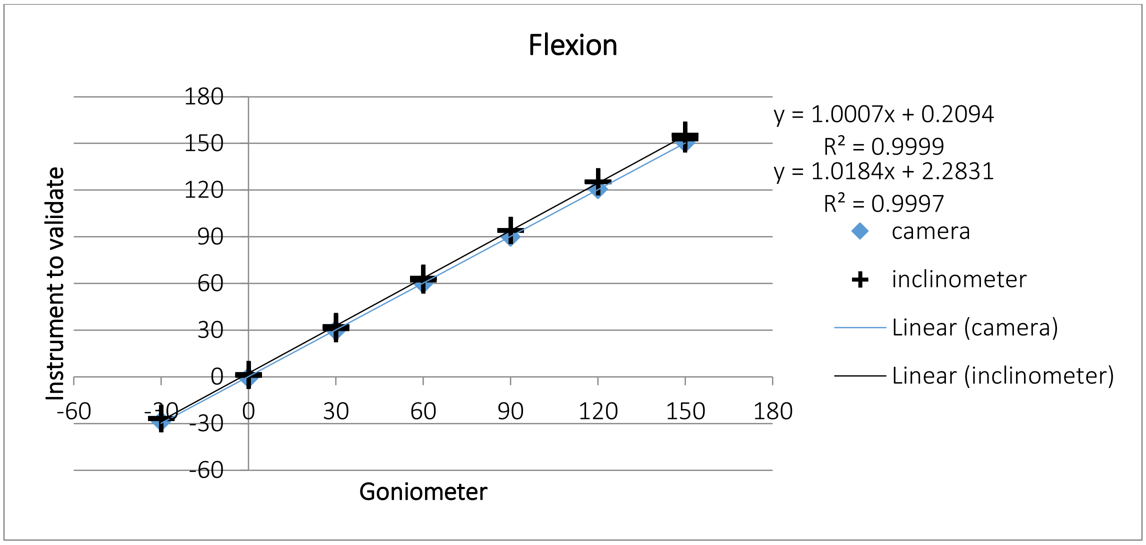


Figure 45 – Flexion angles: correlations between data from human motion analysis laboratory and accelerometer

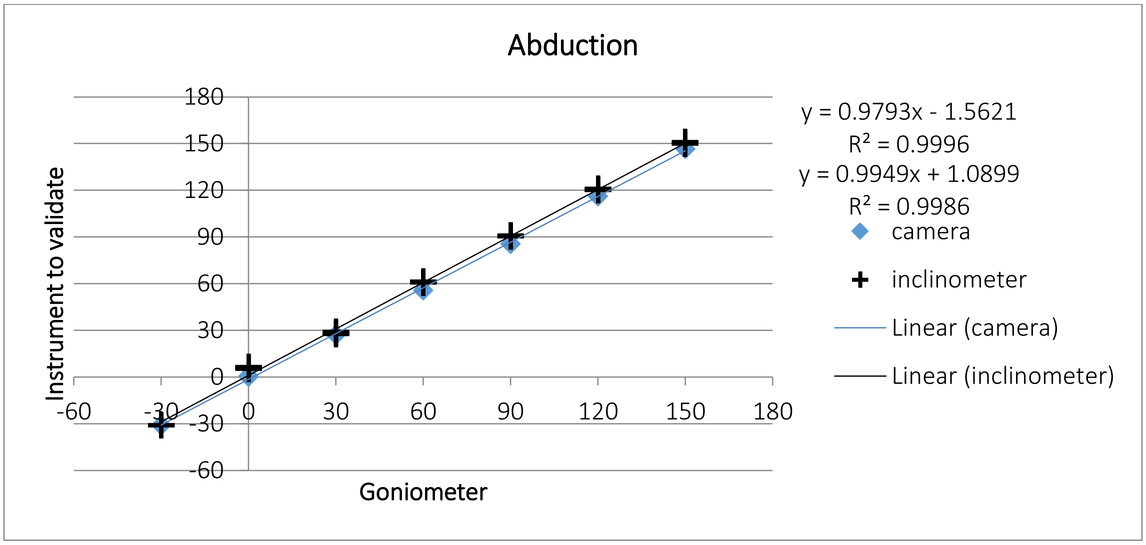


Figure 46 – Abduction angles: correlations between data from human motion analysis laboratory and accelerometer

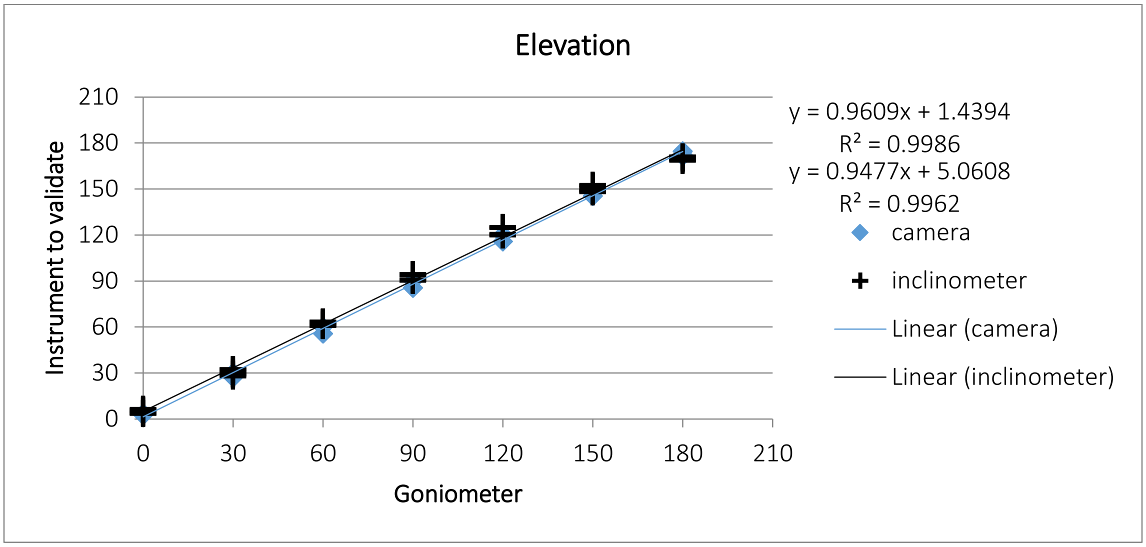


Figure 47 – Elevation angles: correlations between data from human motion analysis laboratory and accelerometer

Table 15 – Root mean square errors of motion analysis data and accelerometer data

	Accelerometer Data	Human Motion Analysis Laboratory Data
Flexion	3.71°	0.65°
Abduction	2.42°	3.27°
Elevation	4.72°	3.82°

Appendix B Work Productivity

The research team member recorded the daily amount of apples picked by the four participants and the number of work hours each day. The raw data is described as below.

Day 1, platform: 4.25 bins/subject/day (7 hours)
Day 2, ground: 3 bins/subject/day (4 hours)
Day 3, ladder: 6, 5, 7, 5 bins/day (7 hours)
Day 4, ladder: 5, 7, 5, 5 bins/day (7 hours)
Day 5, platform: 4.75 bins/subject/day (7 hours)
Day 6, ground: 2.25 bins/subject/day (3 hours)

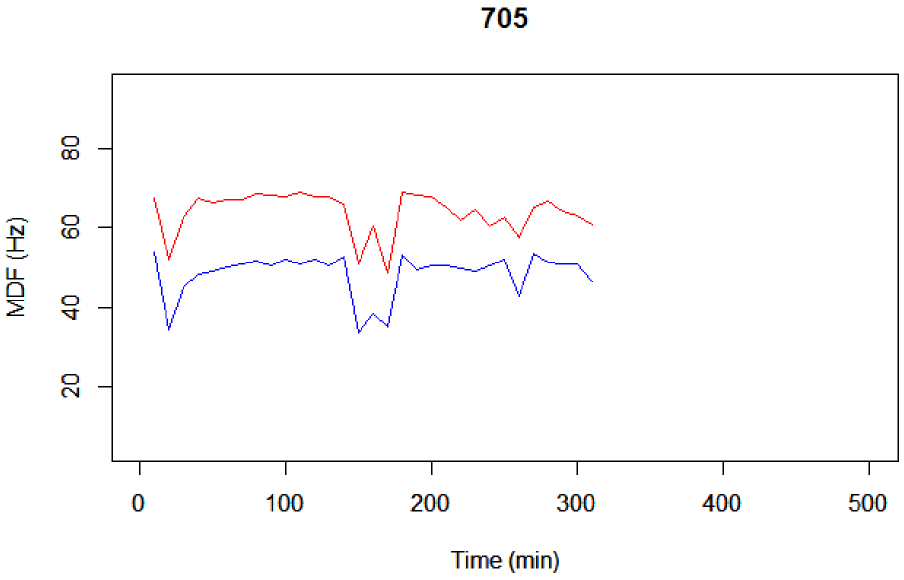
On average, the workers picked apples at the rates below.

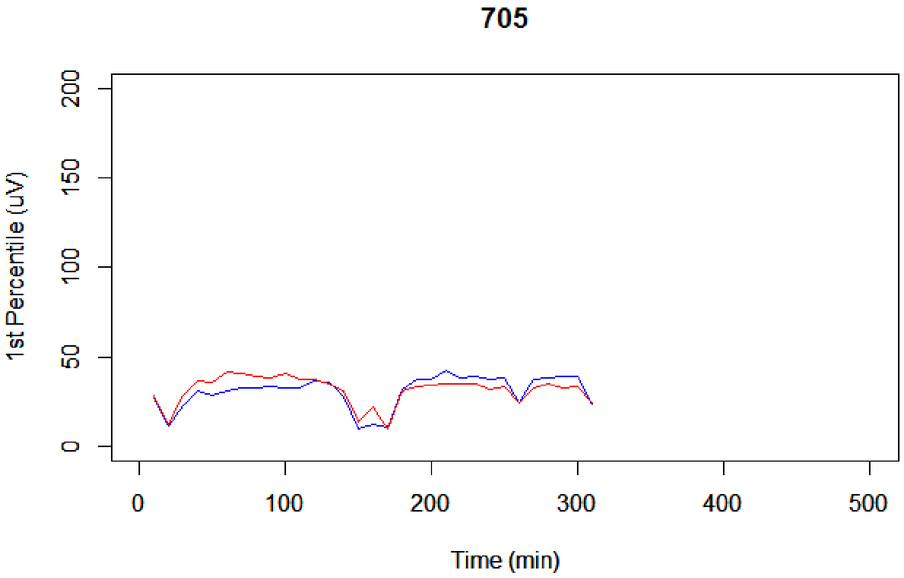
Platform (N=8): 0.64 bins/hour
Ground (N=8): 0.75 bins/hour
Ladder (N=8): 0.80 bins/hour

Appendix C Electromyography Data

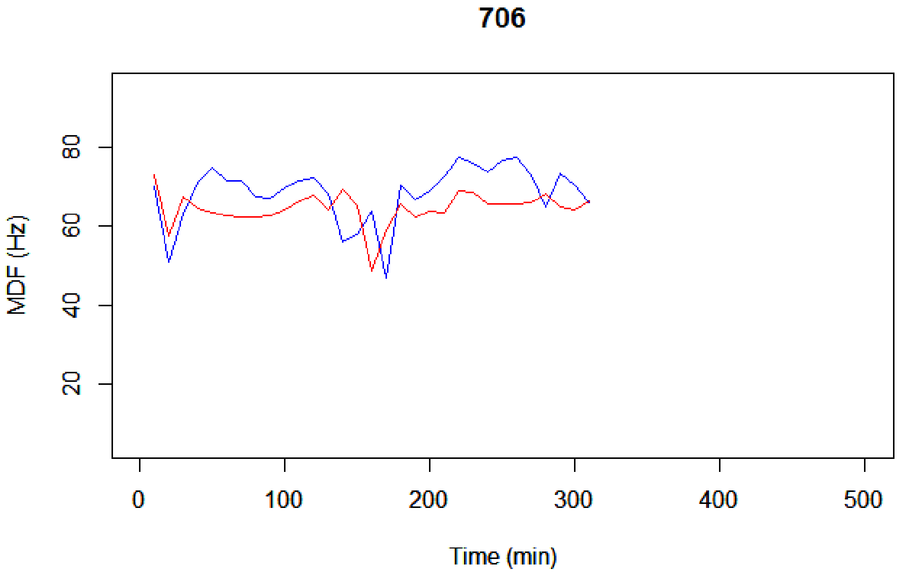
The following figures show the MDF and the 1st percentile of RMS amplitude for each individual participant over the work period in minute, left in blue and right in red.

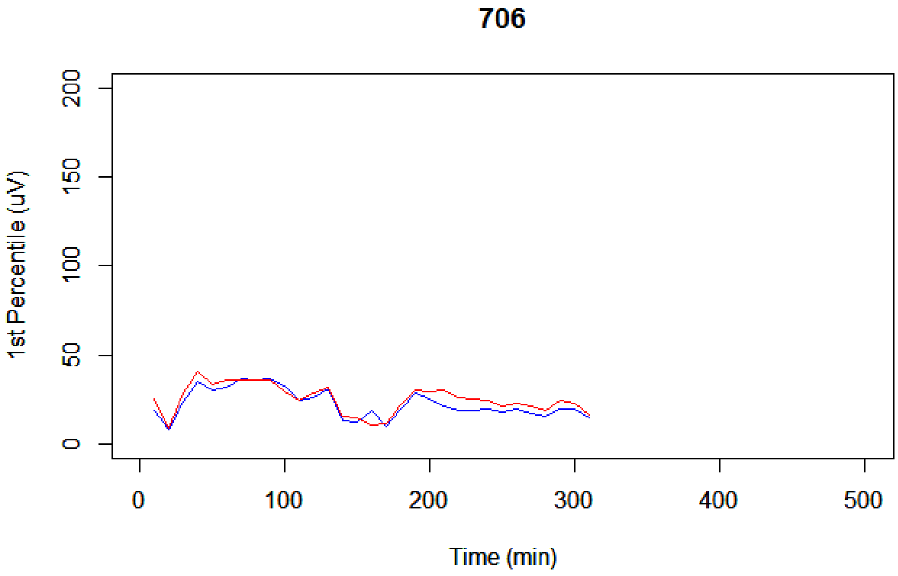
Ground workers



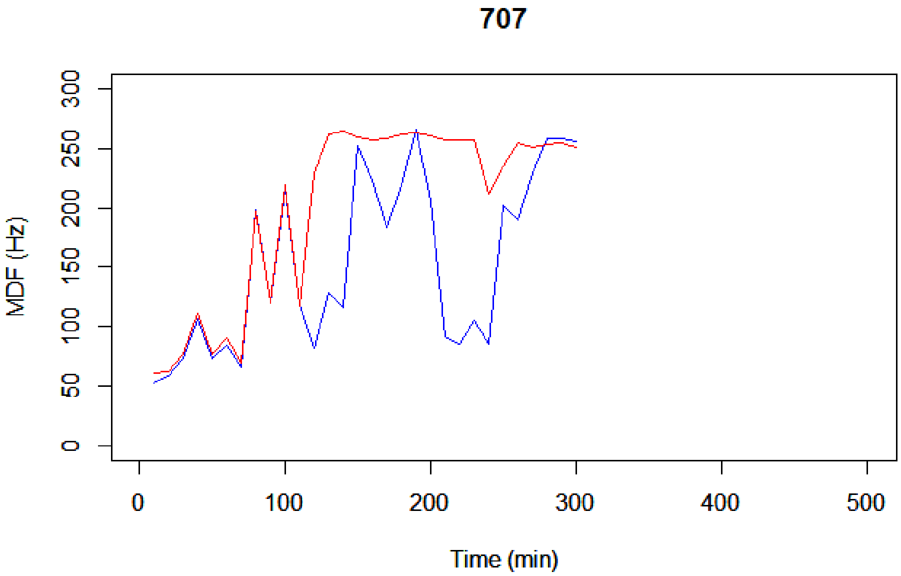


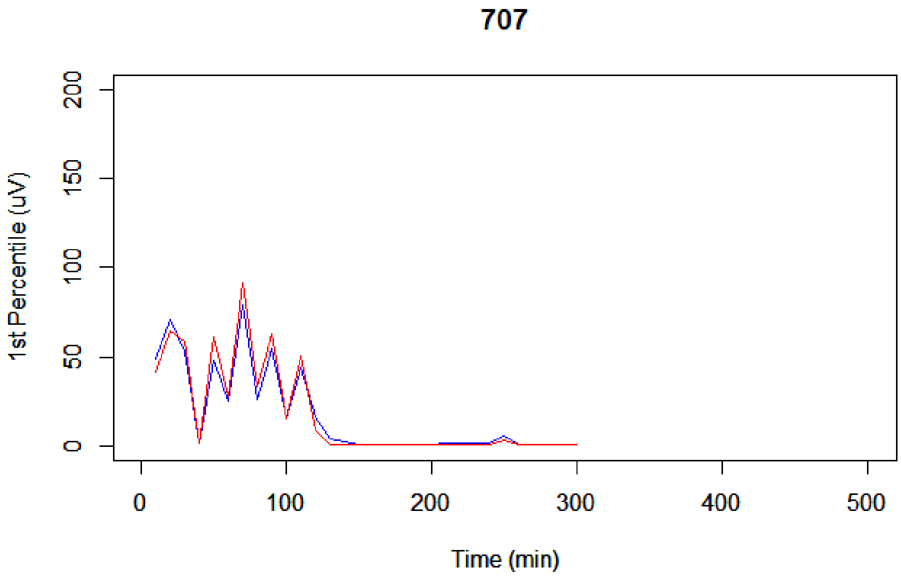
Subject 705



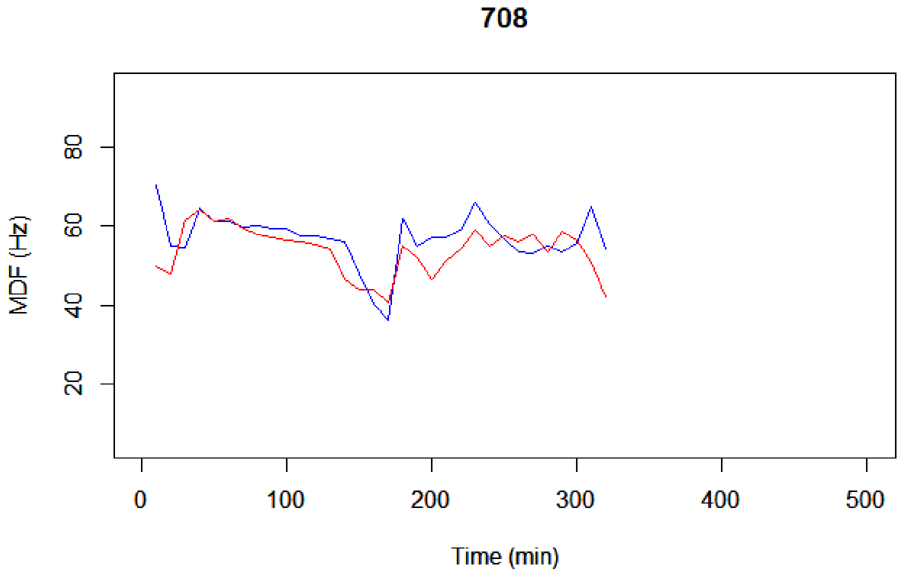


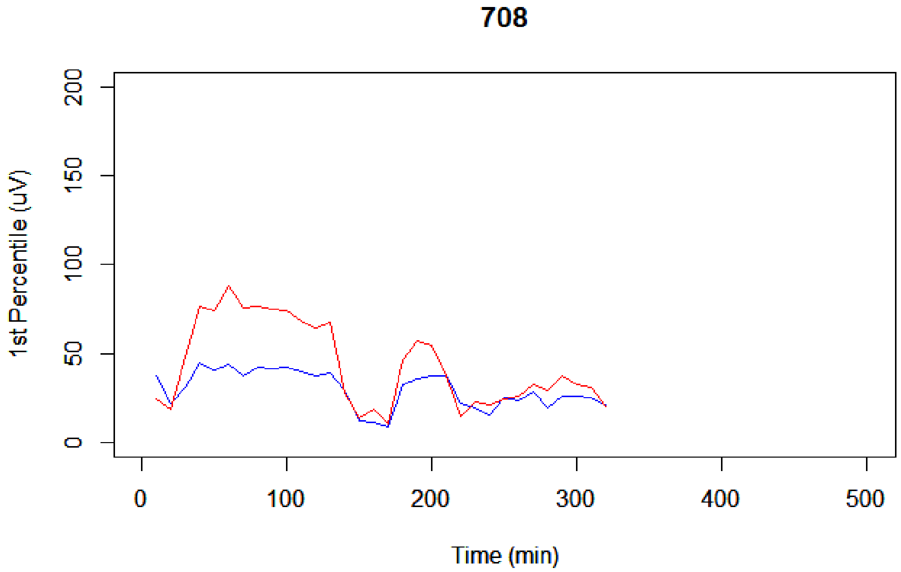
Subject 706 (Dominant body size is left.)



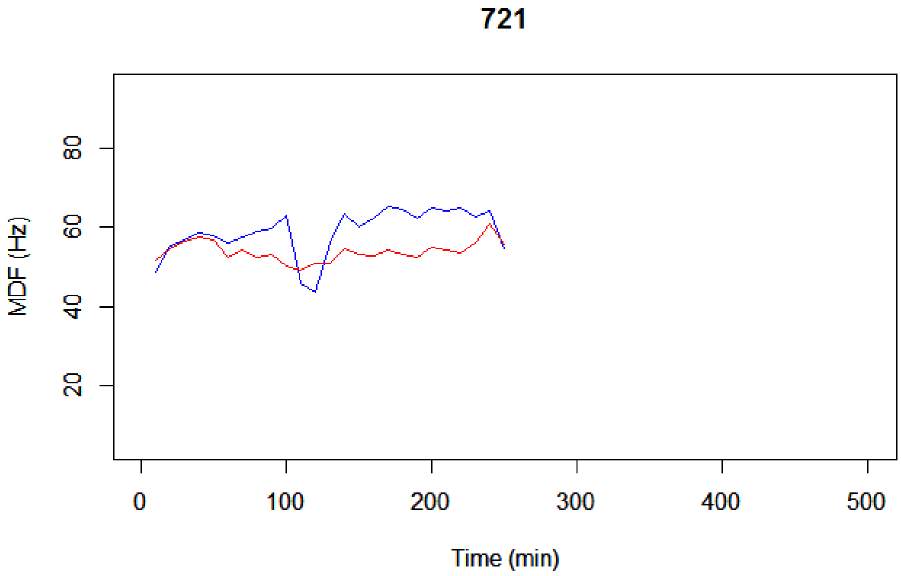


Subject 707 (Clear errors are presented with high median power frequency.)


708
MDF (Hz)
20
40
60
80
0
100
200
300
400
500
Time (min)


708
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

Subject 708


721
MDF (Hz)
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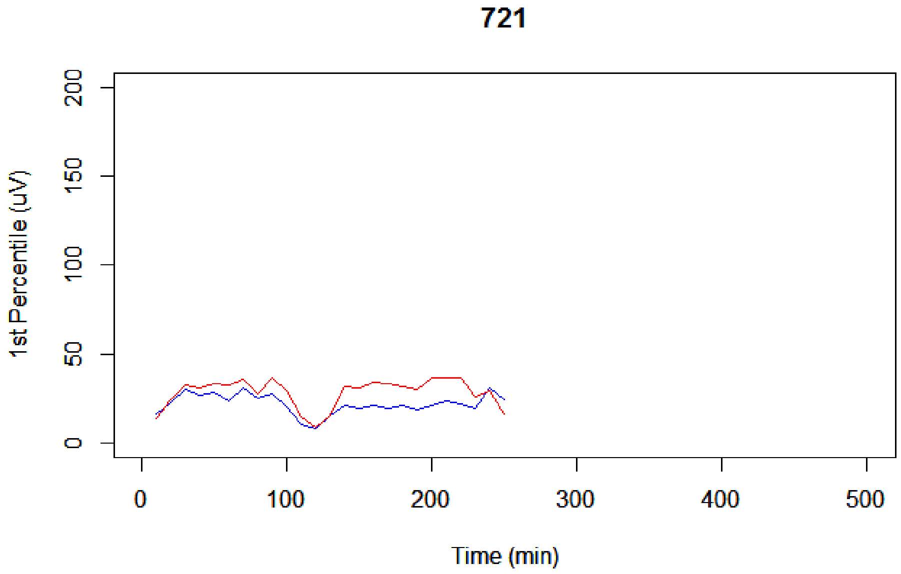
500
Time (min)


721
1st Percentile (uV)
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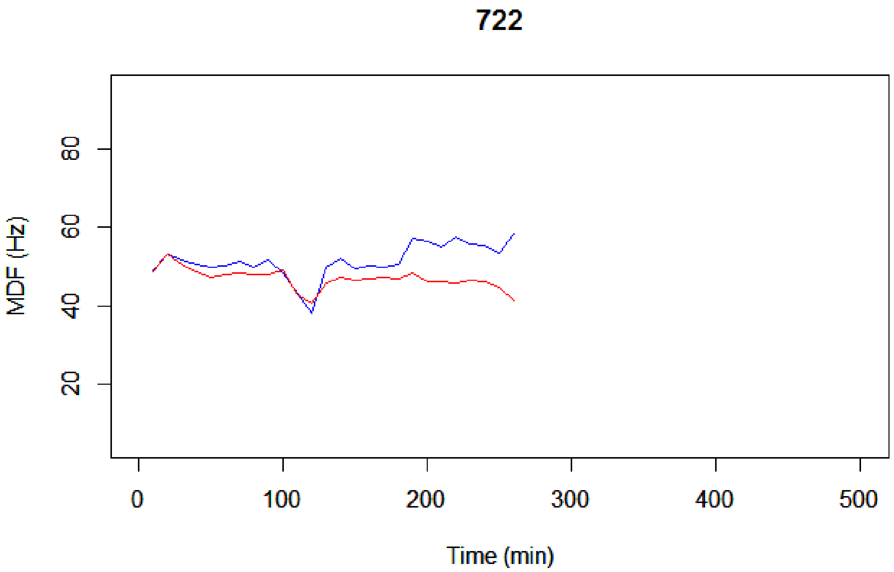
Time (min)

Subject 721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MDF (Hz)
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80
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100
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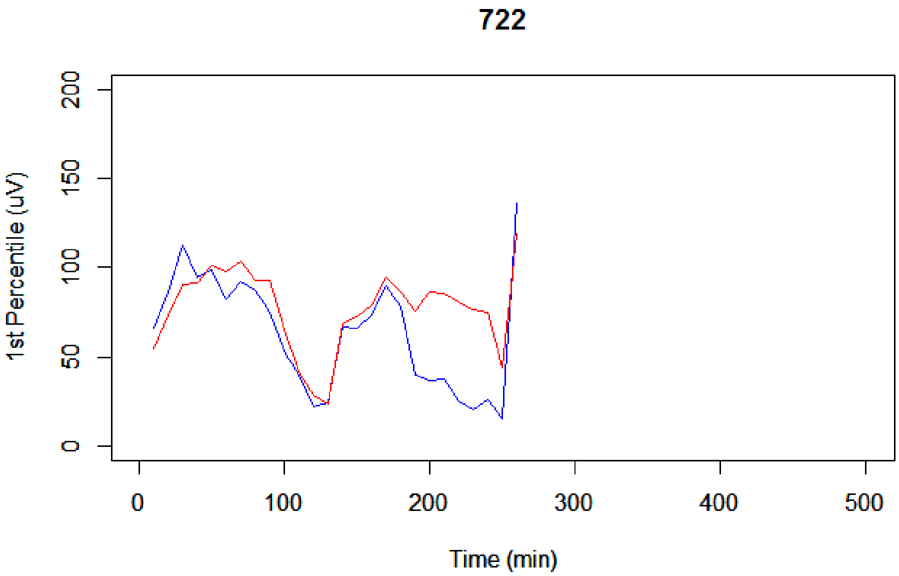
Time (min)


722
1st Percentile (uV)
0
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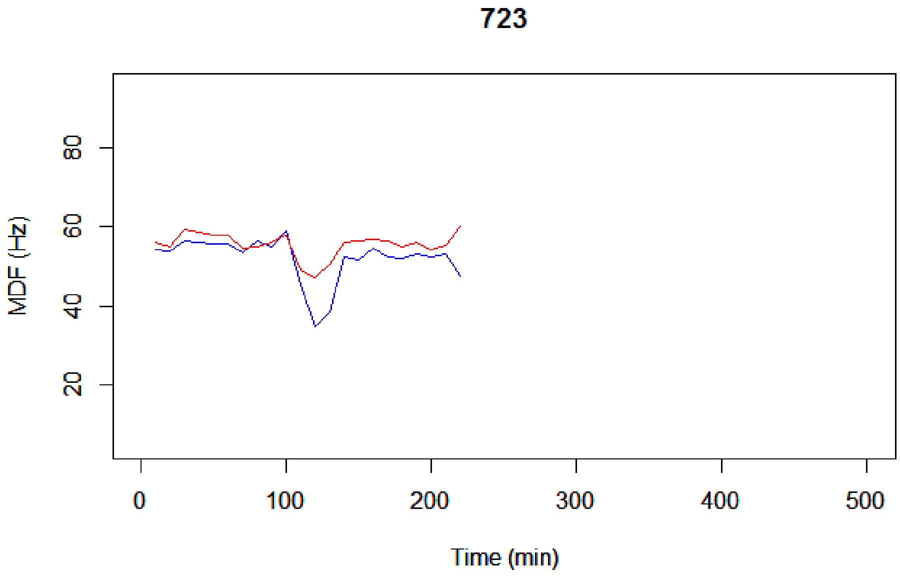
100
150
200
0
100
200
300
400
500
Time (min)

Subject 722


723
MDF (Hz)
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60
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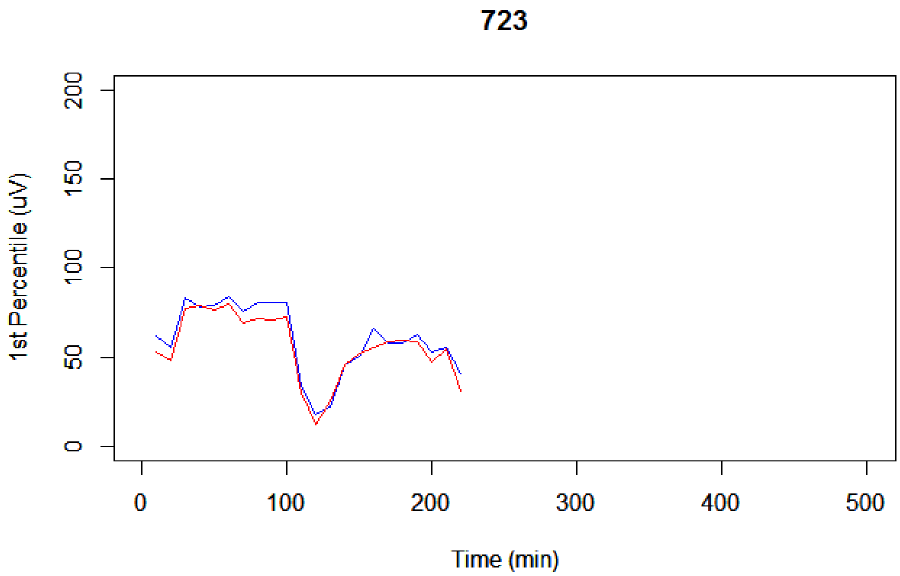
0
100
200
300
400
500
Time (min)


723
1st Percentile (uV)
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0
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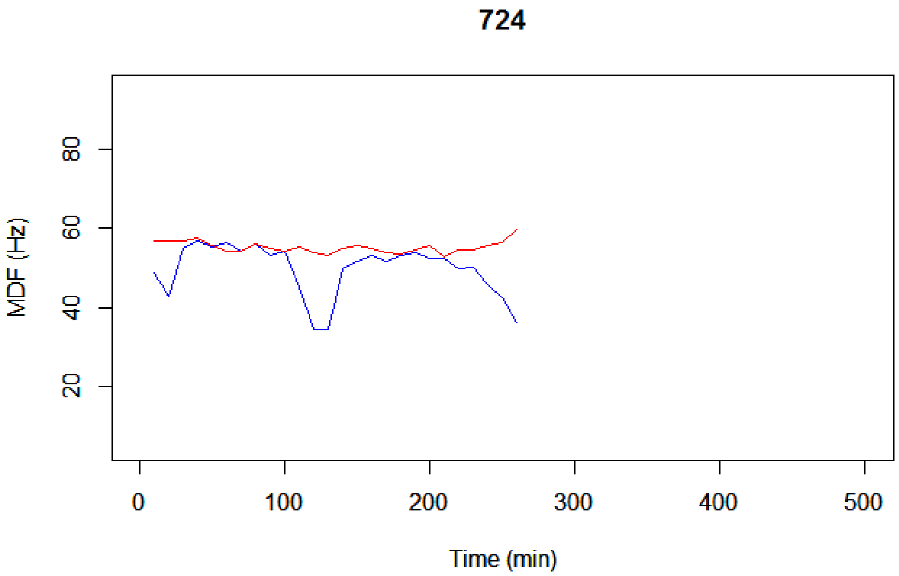
300
400
500
Time (min)

Subject 723


724
MDF (Hz)
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40
60
80
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100
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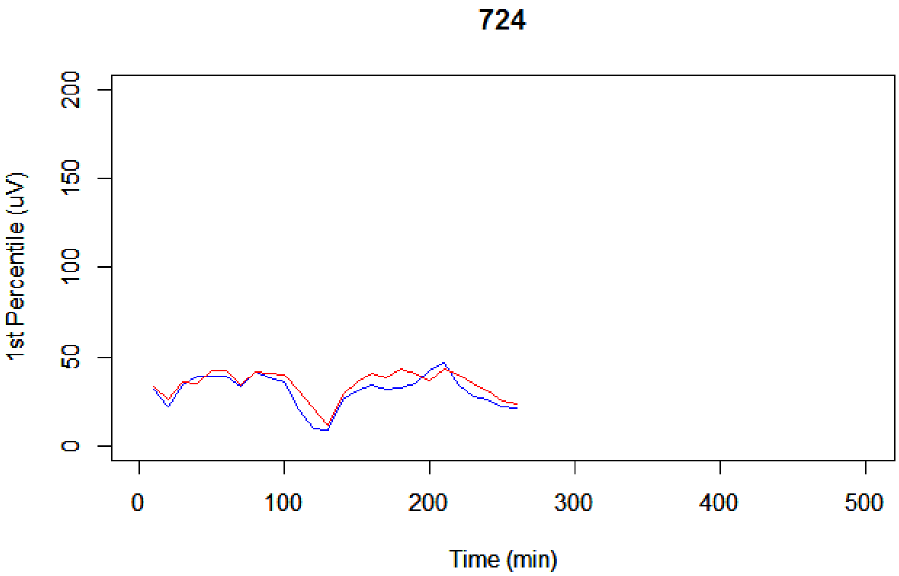
300
400
500
Time (min)

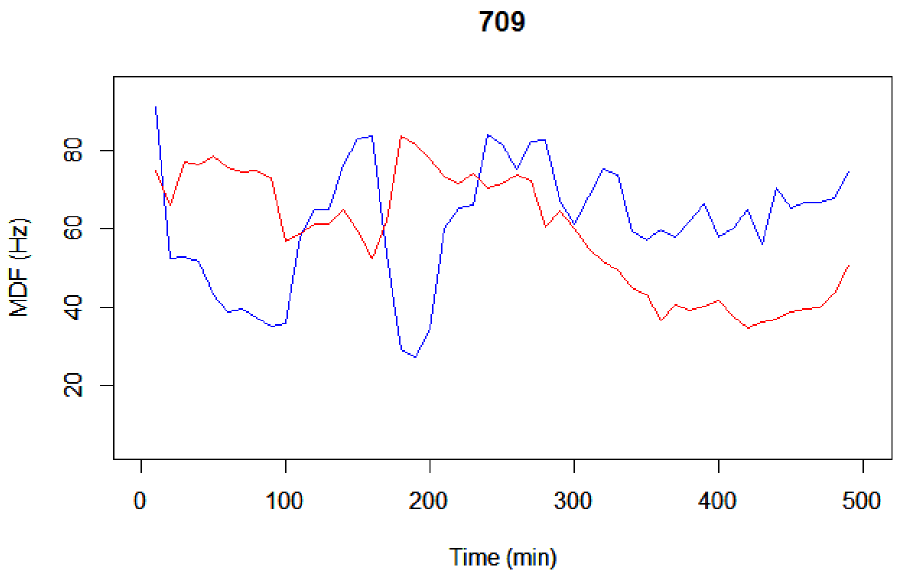

724
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

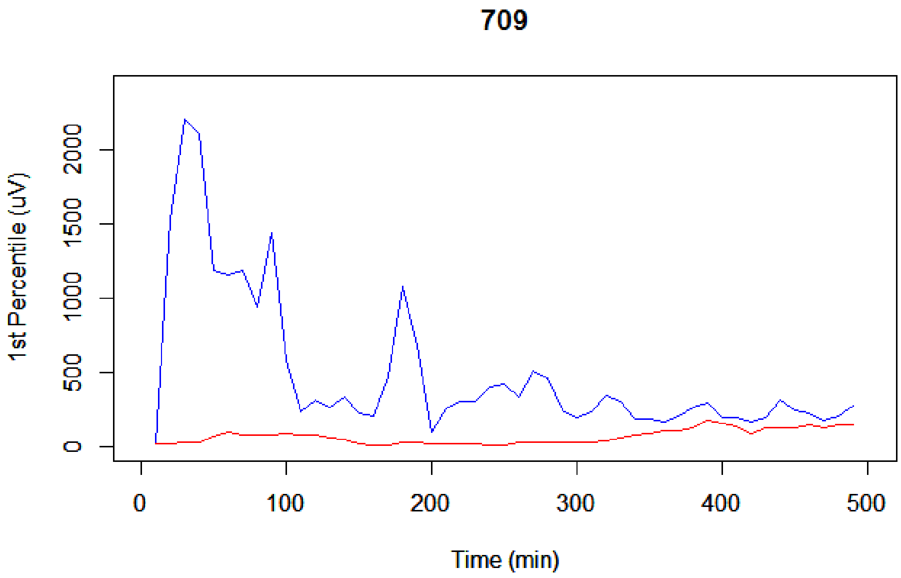
Subject 724

Ladder workers

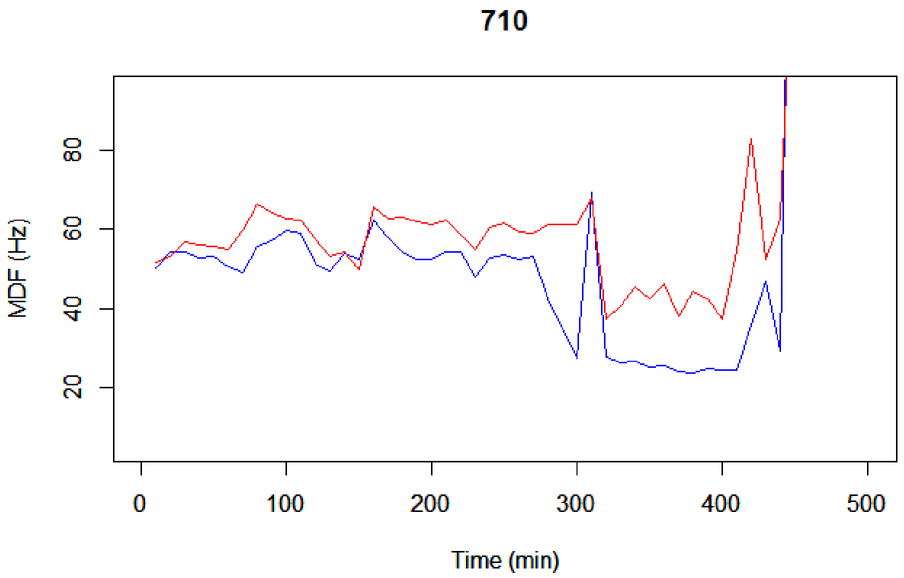
Note that there was a problem in the EMG data recording instrument during the data collection.

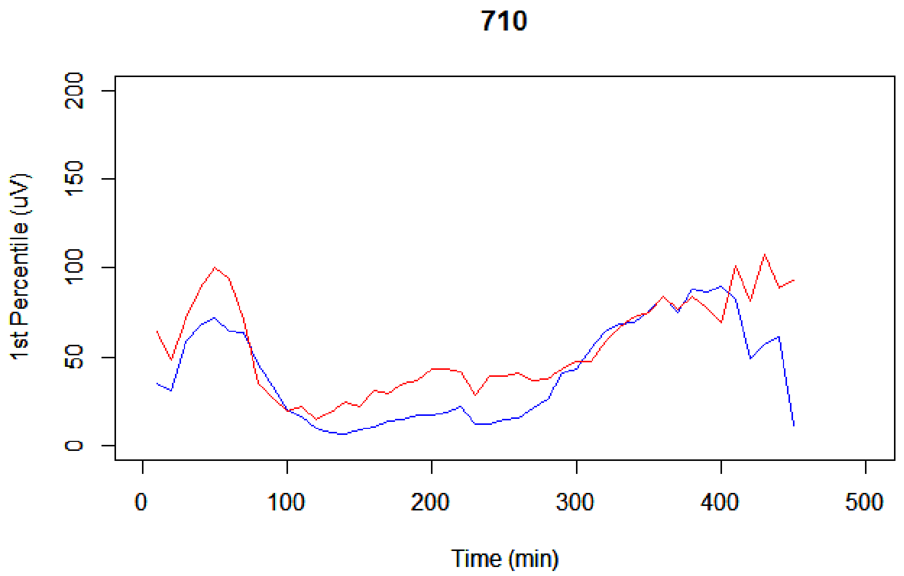
The EMG of Subject 712 was not recorded.



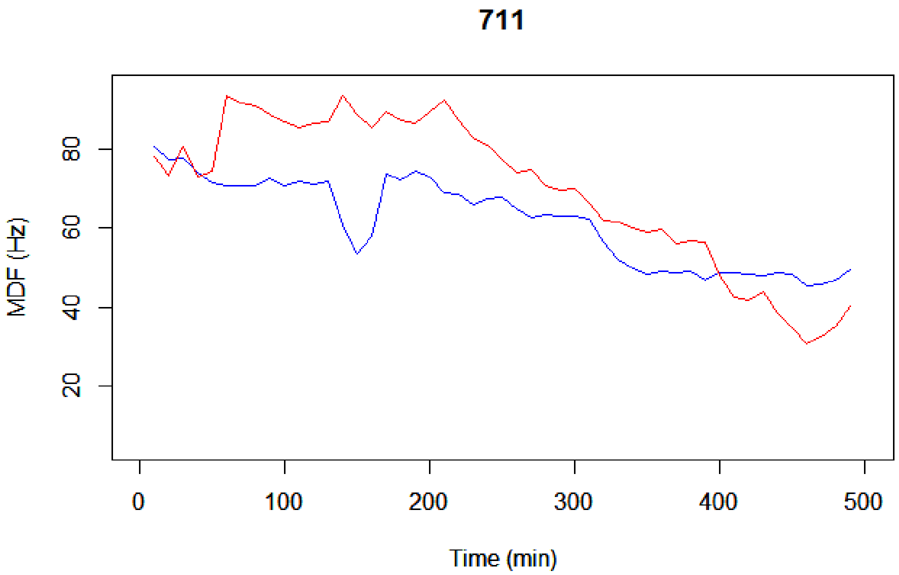


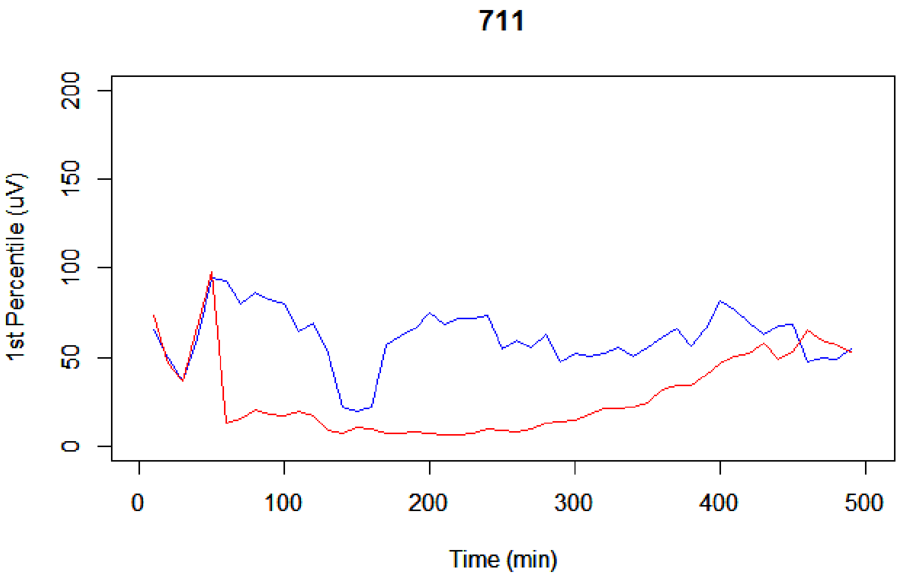
Subject 709 (Error in electrode-skin connection for left trapezius, only right muscle was used.)



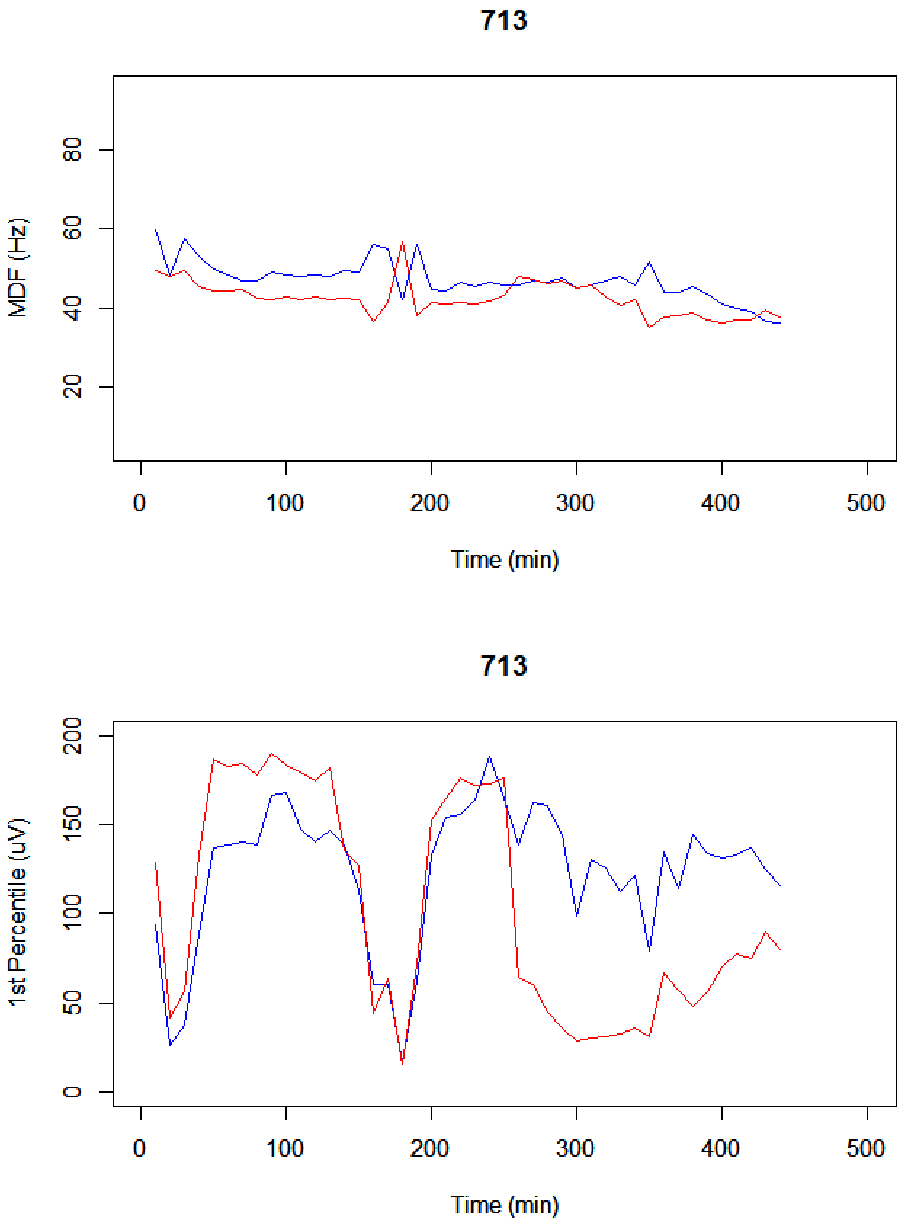


Subject 710 (The muscle activity levels, not shown, had significant outliers; thus, was excluded.)

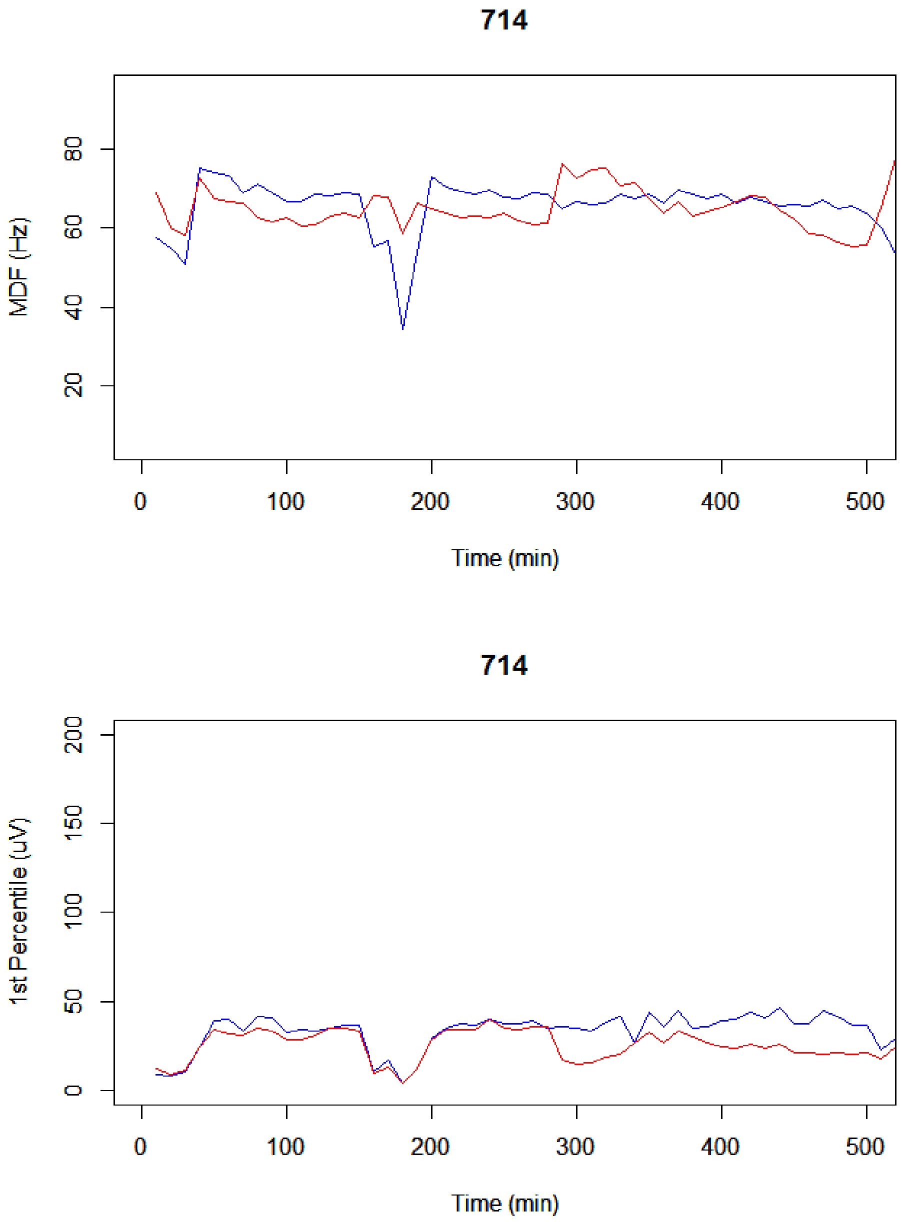




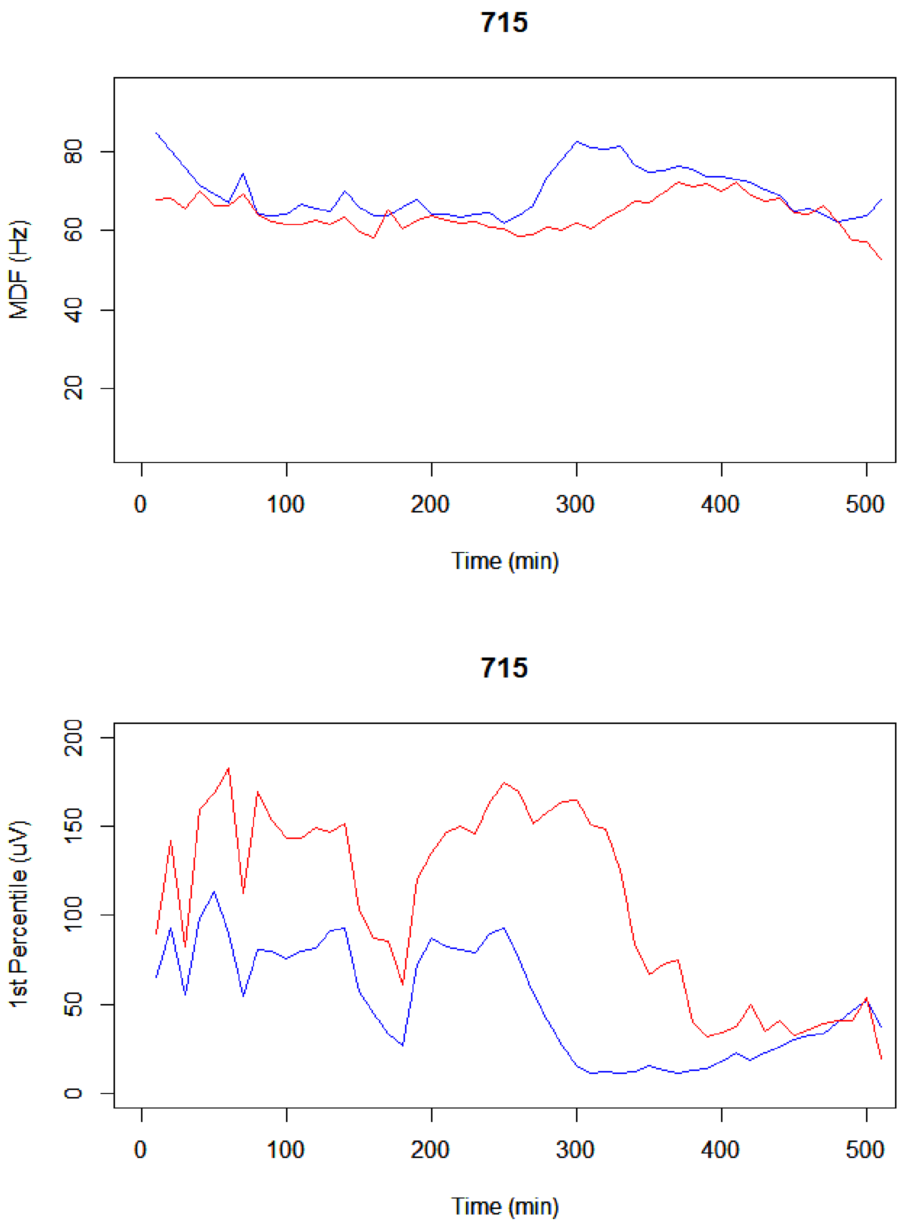
Subject 711 (Error in electrode-skin connection for right trapezius, only left muscle was used. This participant also showed the decreasing trend of MDF after the break until the end of work, suggesting muscle fatigue. The data at the later part of work were not usable.)



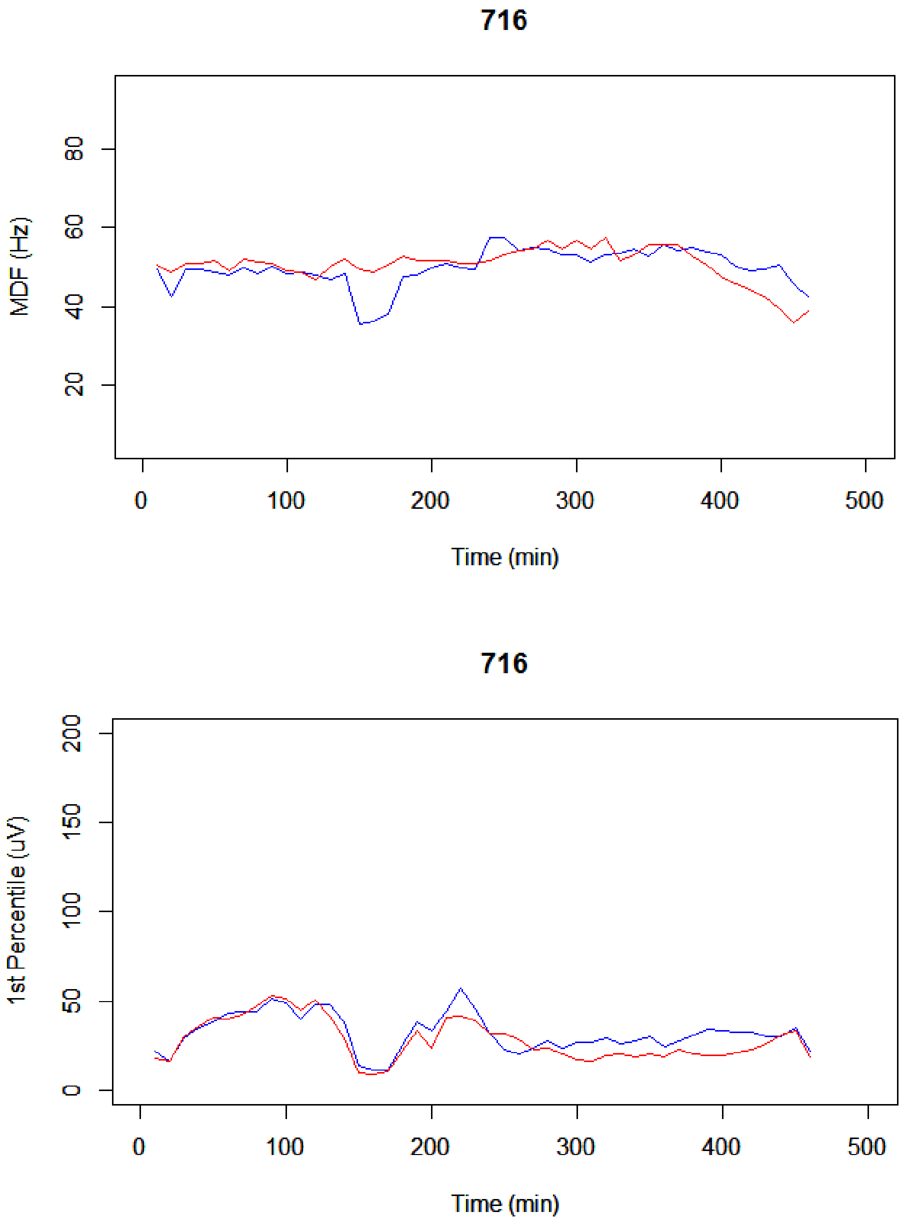
Subject 713 (Data logger was restarted after lunch break, the graphs were from two files.)



Subject 714 (Muscle fatigue in right trapezius in the afternoon)



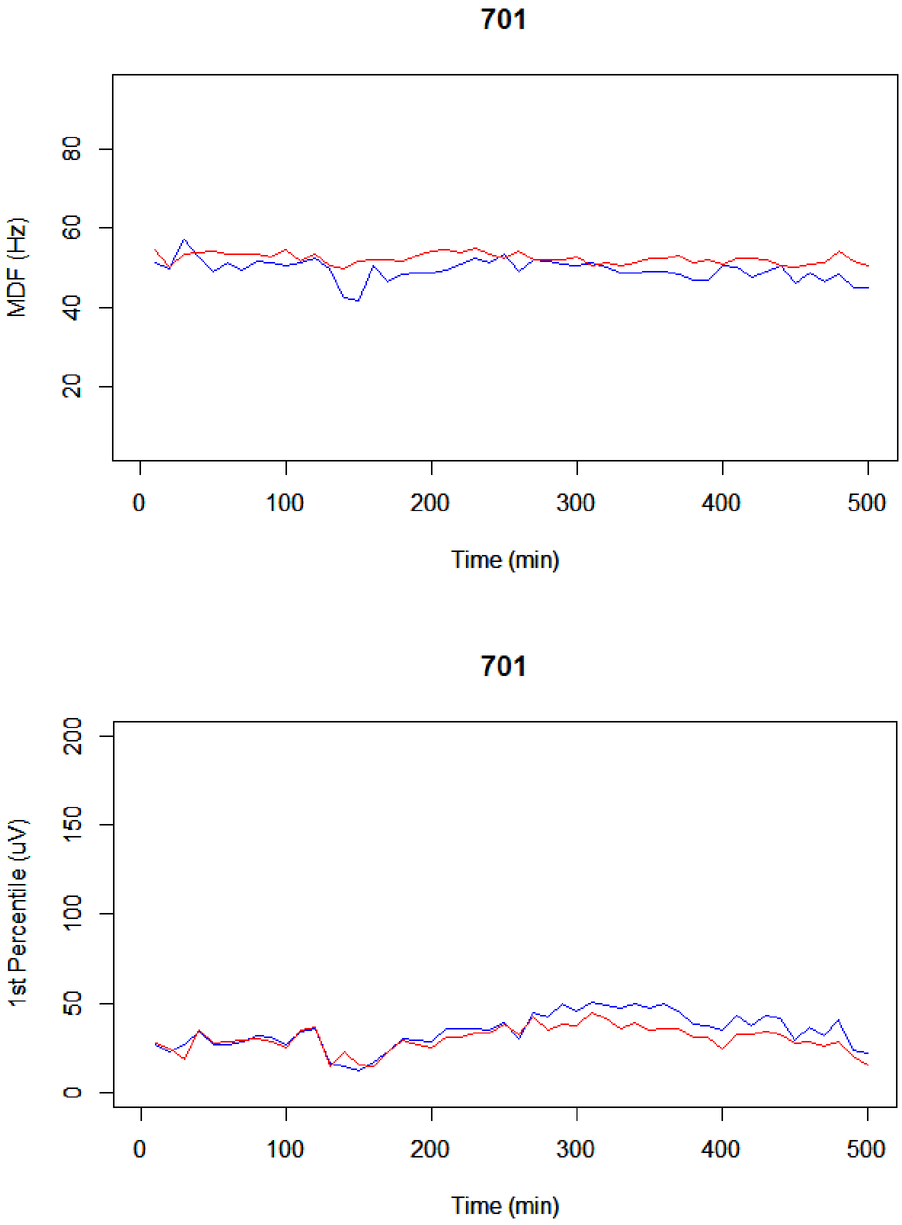
Subject 715 (Muscle fatigue in both left and right trapezius in the afternoon)



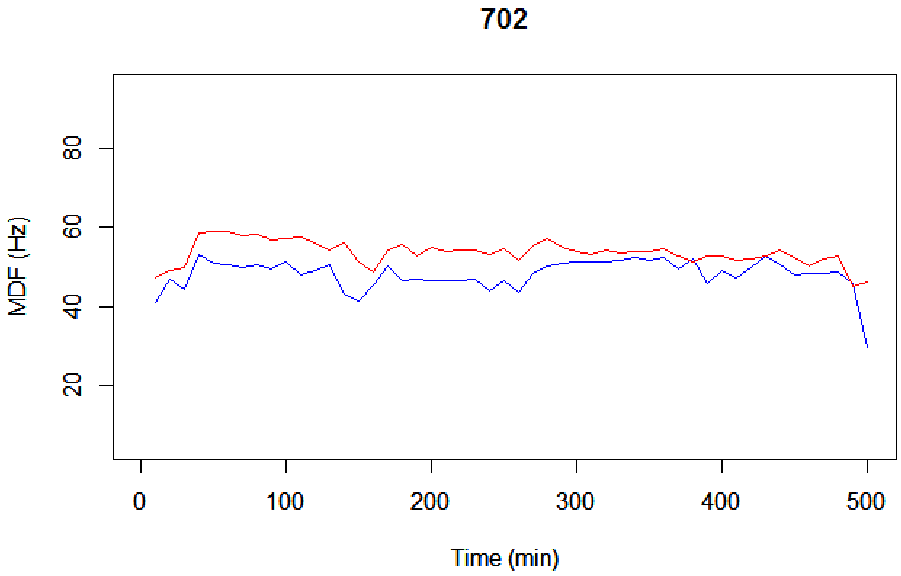
Subject 716 (Reported to the questionnaire that dominant body side was left while carrying clippers with right hand. Still, the body side coded as the dominant was left.)

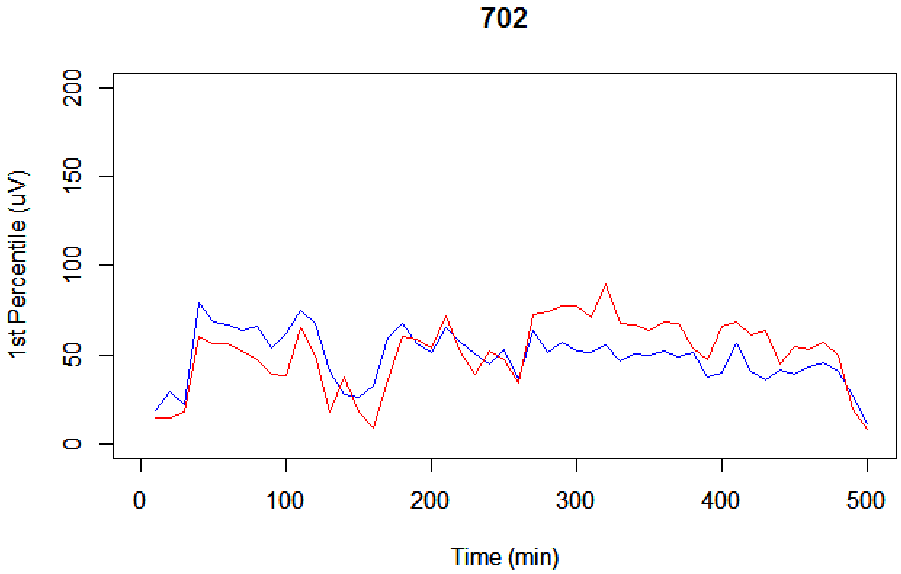
Platform workers

All participants in this group had good data, no errors. However, slight decreases started to show after the lunch break in some participants.

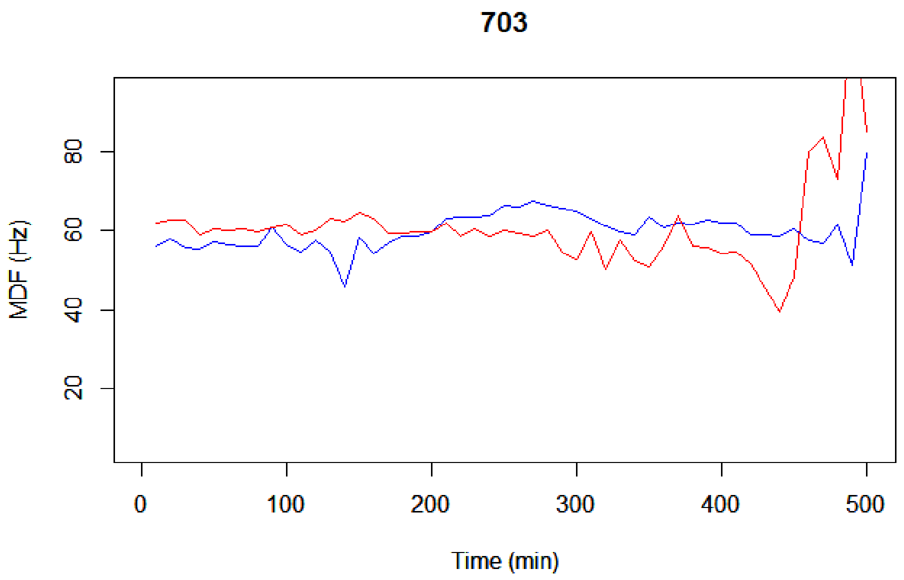


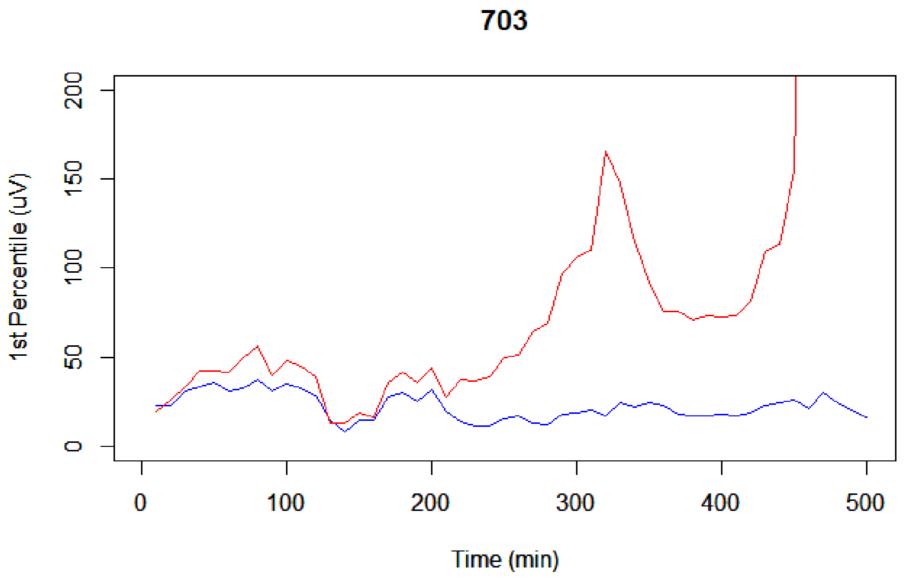
Subject 701


702
MDF (Hz)
20
40
60
80
0
100
200
300
400
500
Time (min)

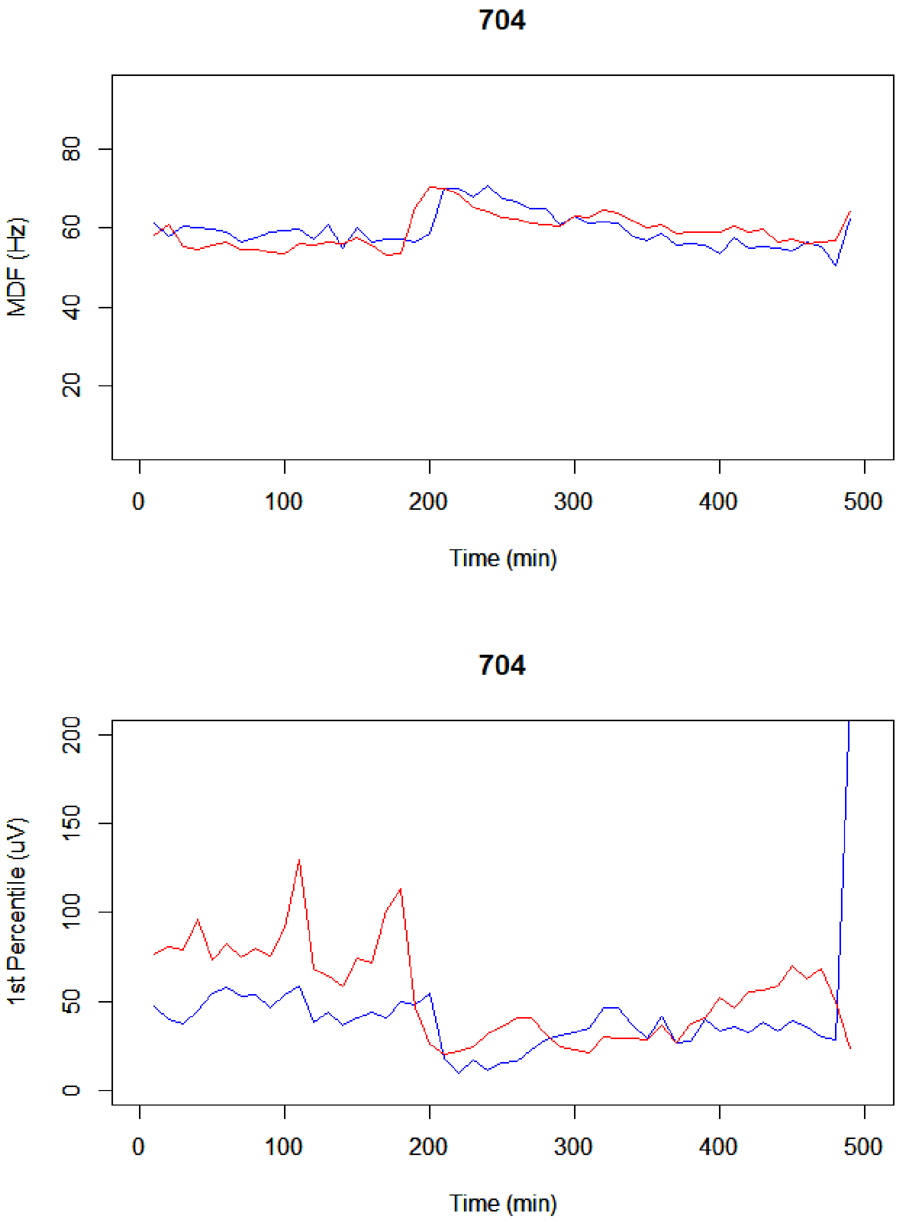

702
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

Subject 702

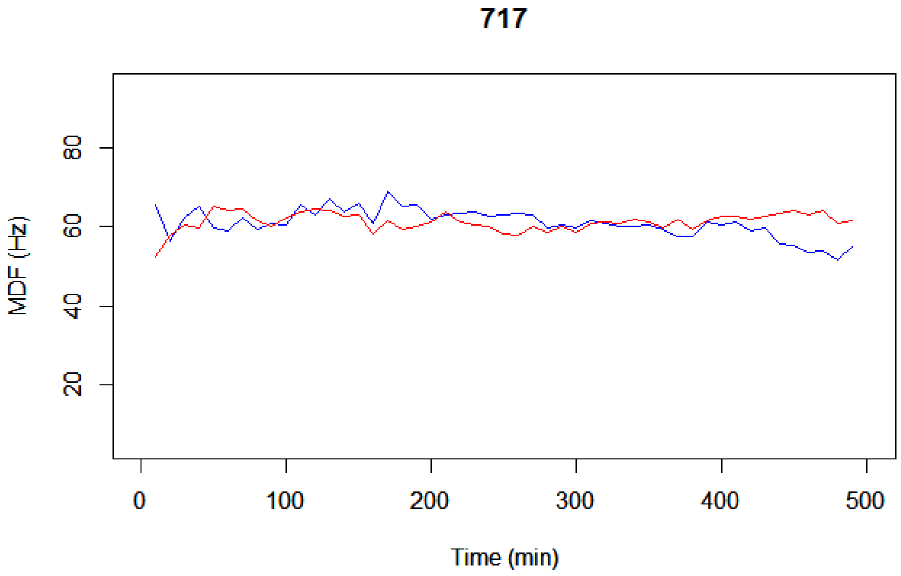

703
MDF (Hz)
20
40
60
80
0
100
200
300
400
500
Time (min)

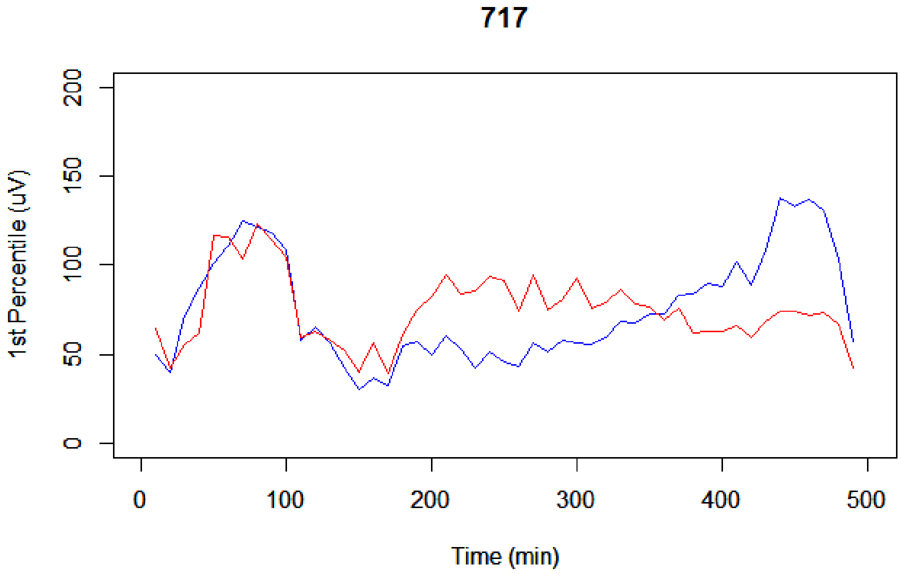

703
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

Subject 703

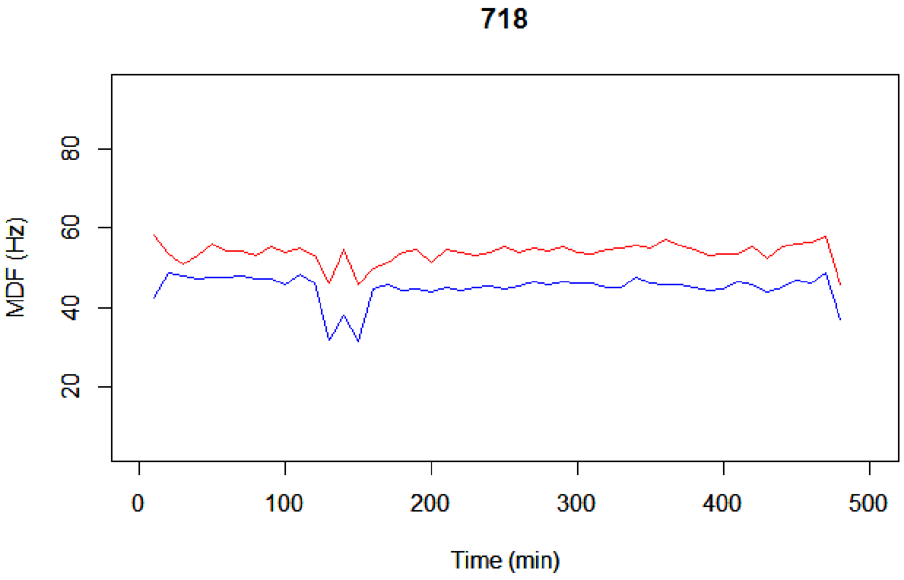

704
MDF (Hz)
20
40
60
80
0
100
200
300
400
500
Time (min)
704
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

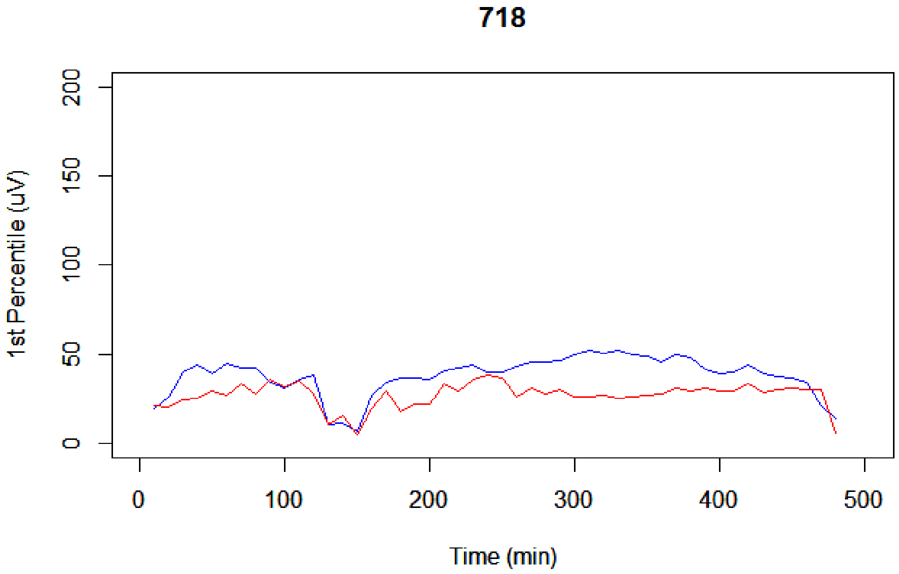
Subject 704


717
MDF (Hz)
20
40
60
80
0
100
200
300
400
500
Time (min)

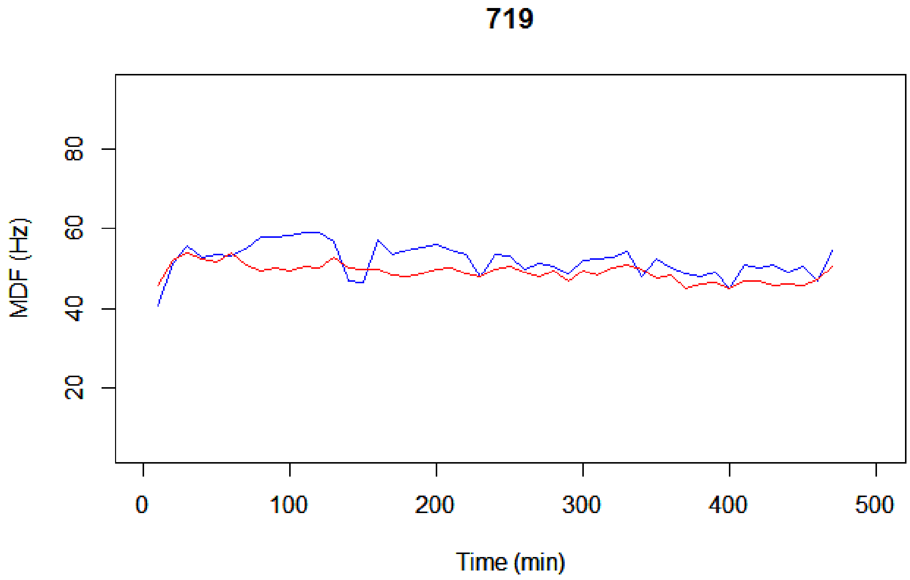

717
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

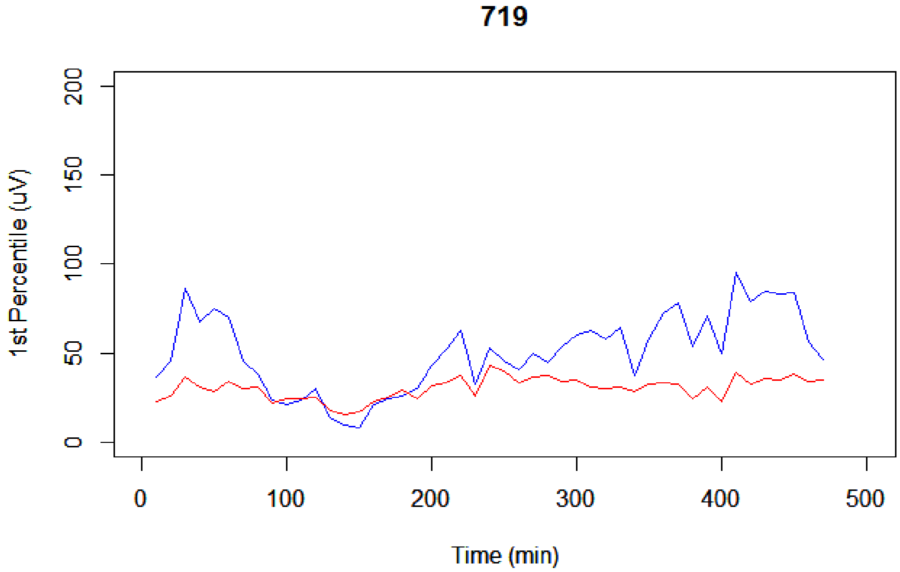
Subject 717


718
MDF (Hz)
20
40
60
80
0
100
200
300
400
500
Time (min)

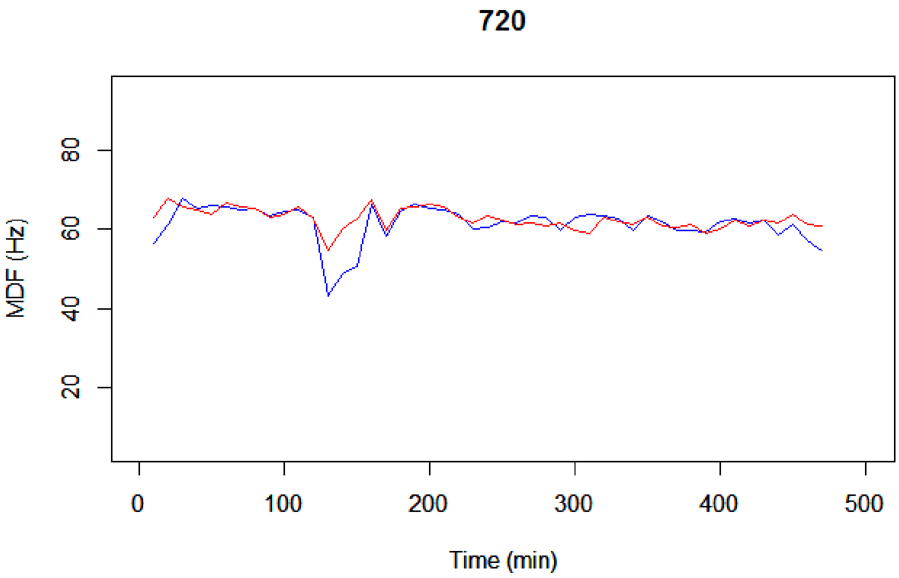

718
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

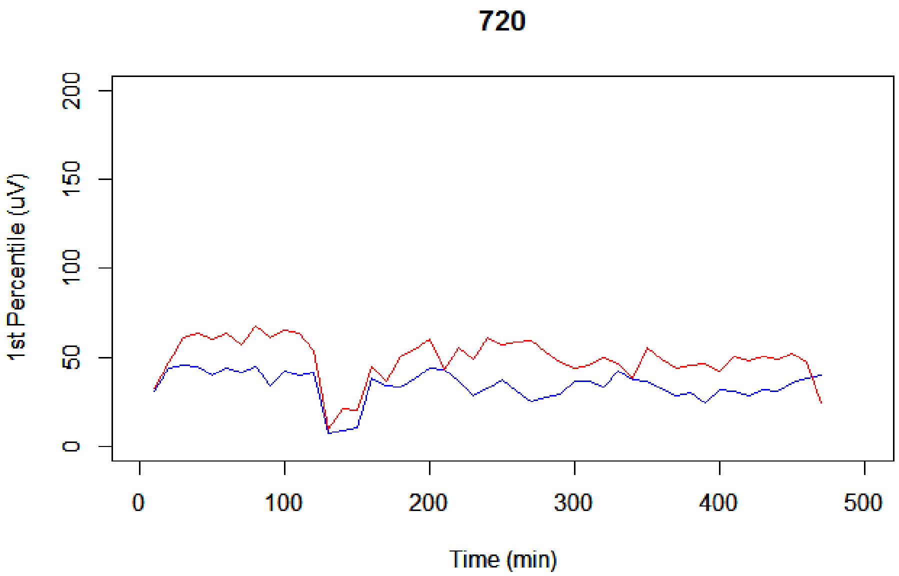
Subject 718


719
MDF (Hz)
20
40
60
80
0
100
200
300
400
500
Time (min)


719
1st Percentile (uV)
0
50
100
150
200
0
100
200
300
400
500
Time (min)

Subject 719





Subject 720

The following Figures 48 – 77 show muscle activity levels of each group (ground, ladder, platform and dominant- and non-dominant hand) by time of the day.

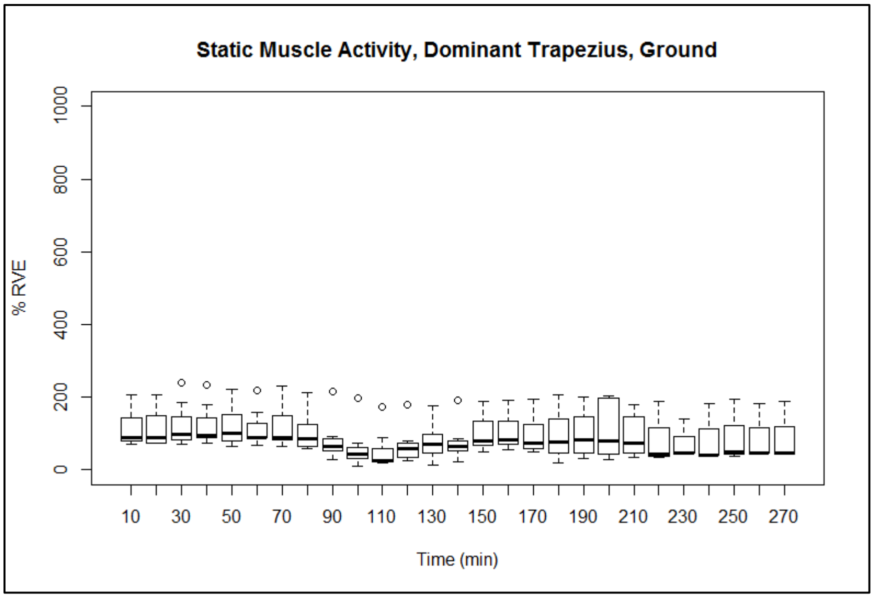


Figure 48 – Boxplot of static muscle activity (%RVE) by time, dominant trapezius, ground (n = 7)

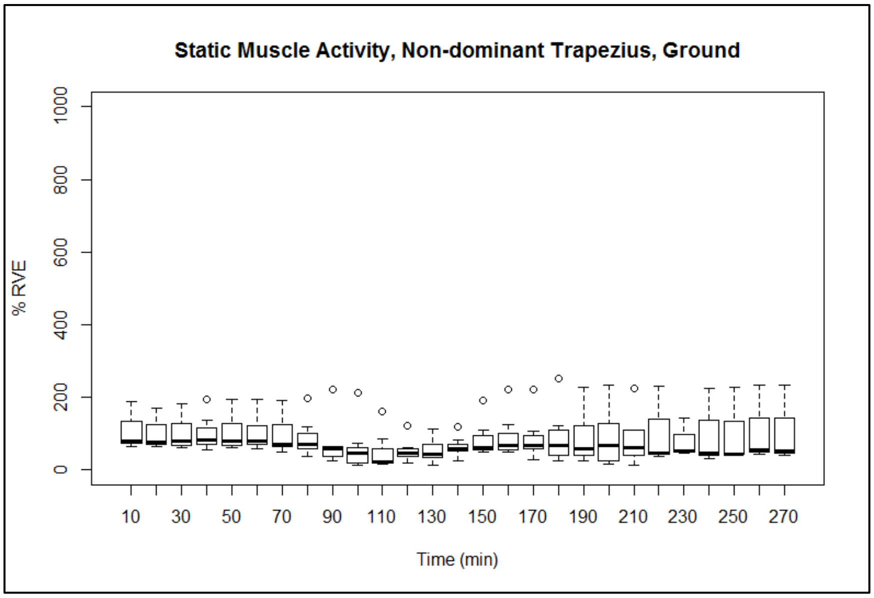


Figure 49 – Boxplot of static muscle activity (%RVE) by time, non-dominant trapezius, ground (n = 7)

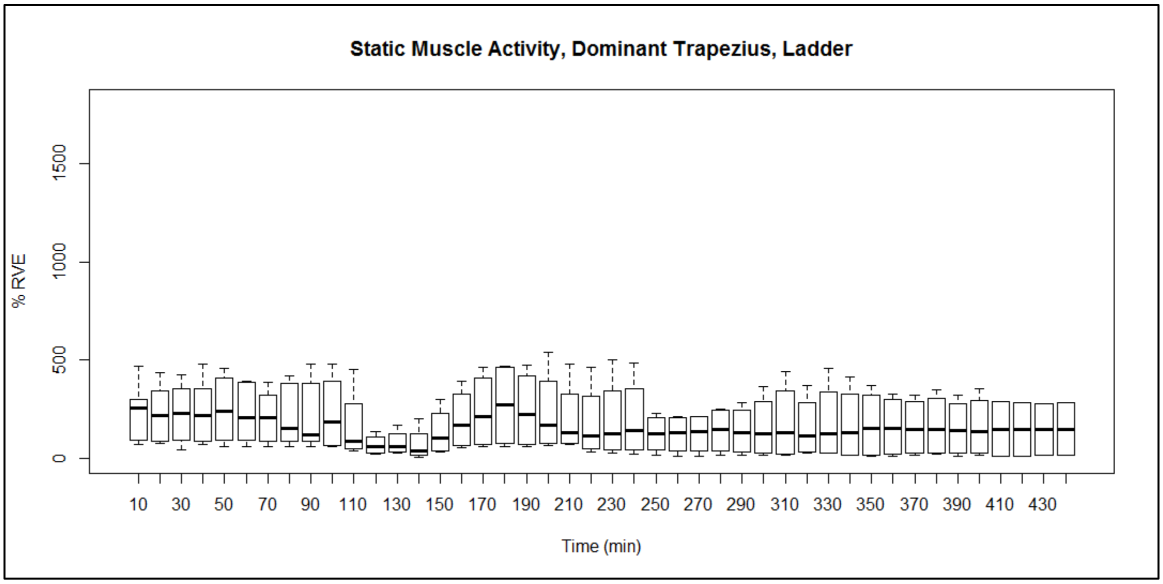


Figure 50 – Boxplot of static muscle activity (%RVE) by time, dominant trapezius, ladder (n = 5)

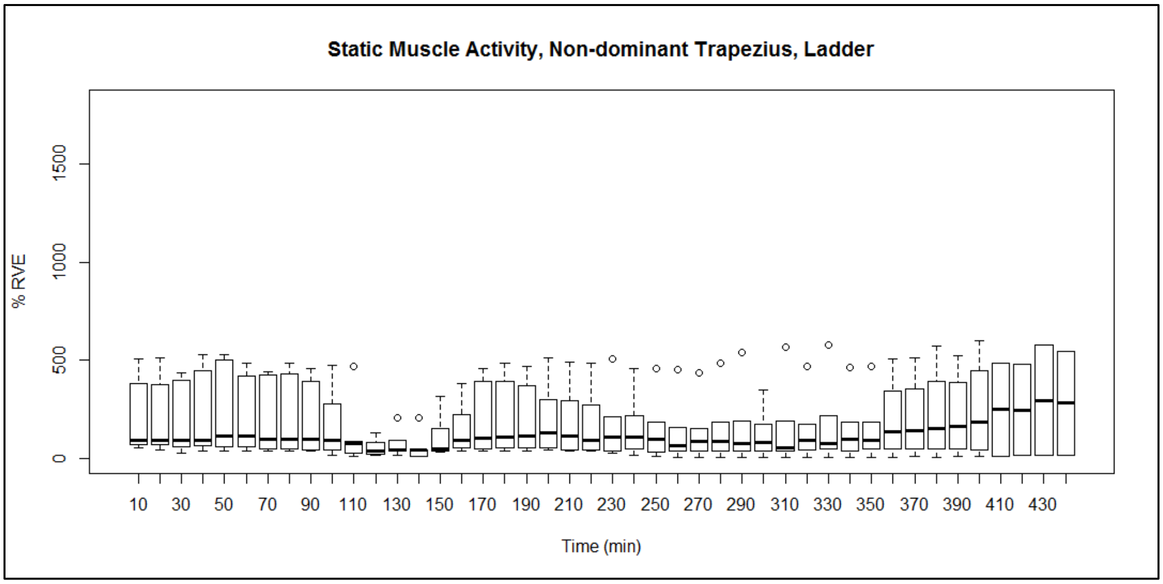


Figure 51 – Boxplot of static muscle activity (%RVE) by time, non-dominant trapezius, ladder (n = 5)

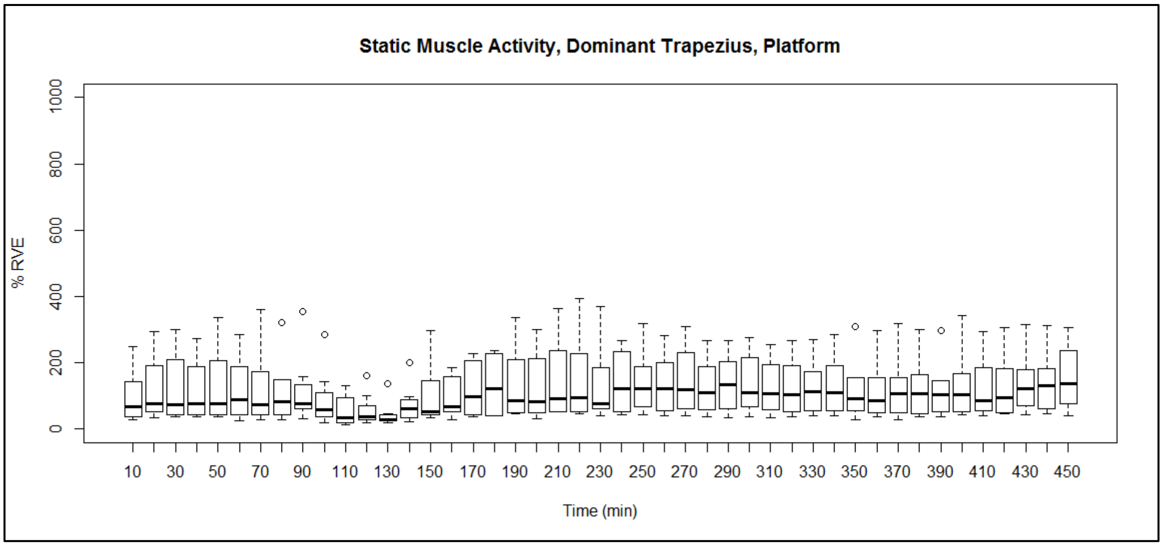


Figure 52 – Boxplot of static muscle activity (%RVE) by time, dominant trapezius, platform (n = 8)

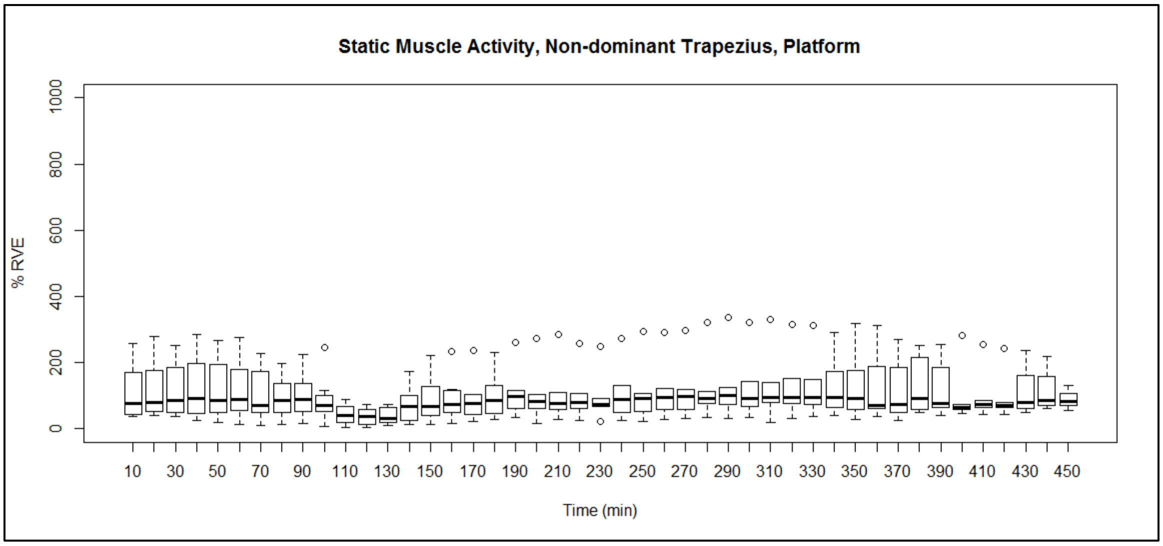


Figure 53 – Boxplot of static muscle activity (%RVE) by time, non-dominant trapezius, platform (n = 8)

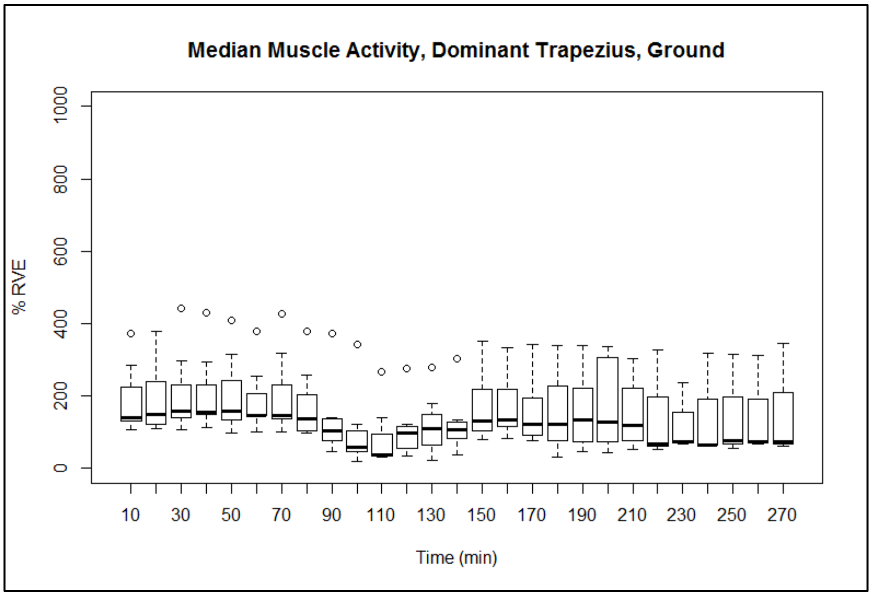


Figure 54 – Boxplot of median muscle activity (%RVE) by time, dominant trapezius, ground (n = 7)

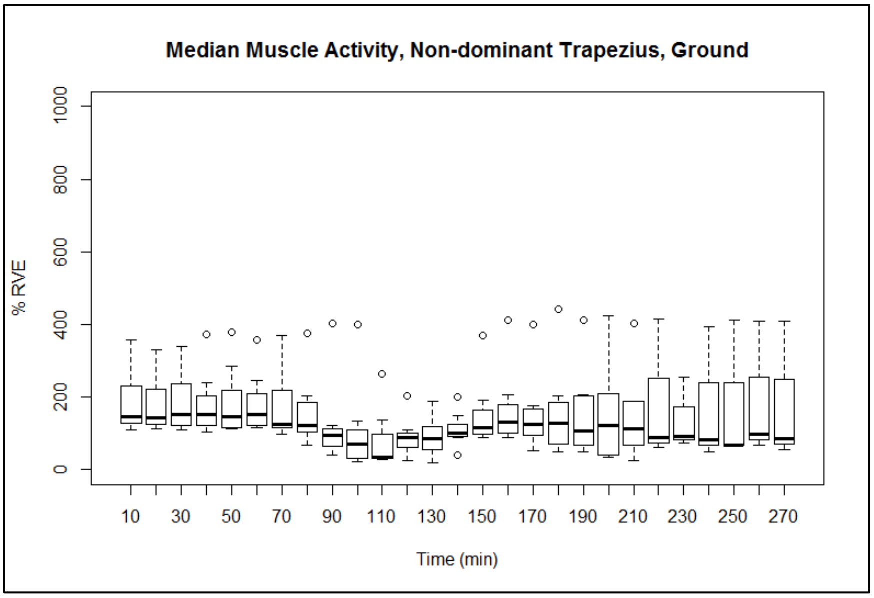


Figure 55 – Boxplot of median muscle activity (%RVE) by time, non-dominant trapezius, ground (n = 7)

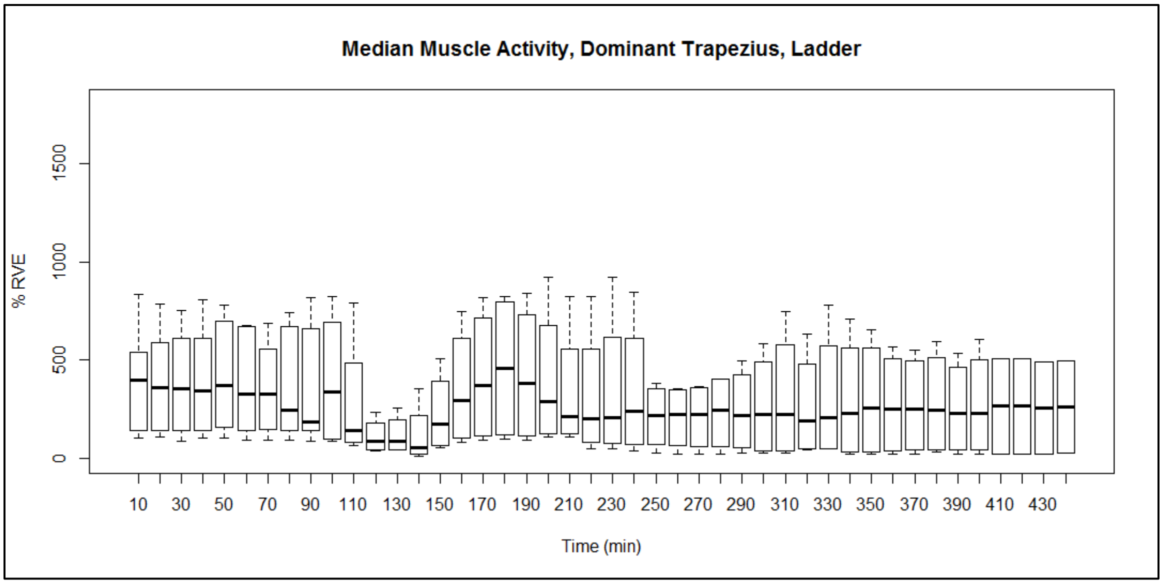


Figure 56 – Boxplot of median muscle activity (%RVE) by time, dominant trapezius, ladder (n = 5)

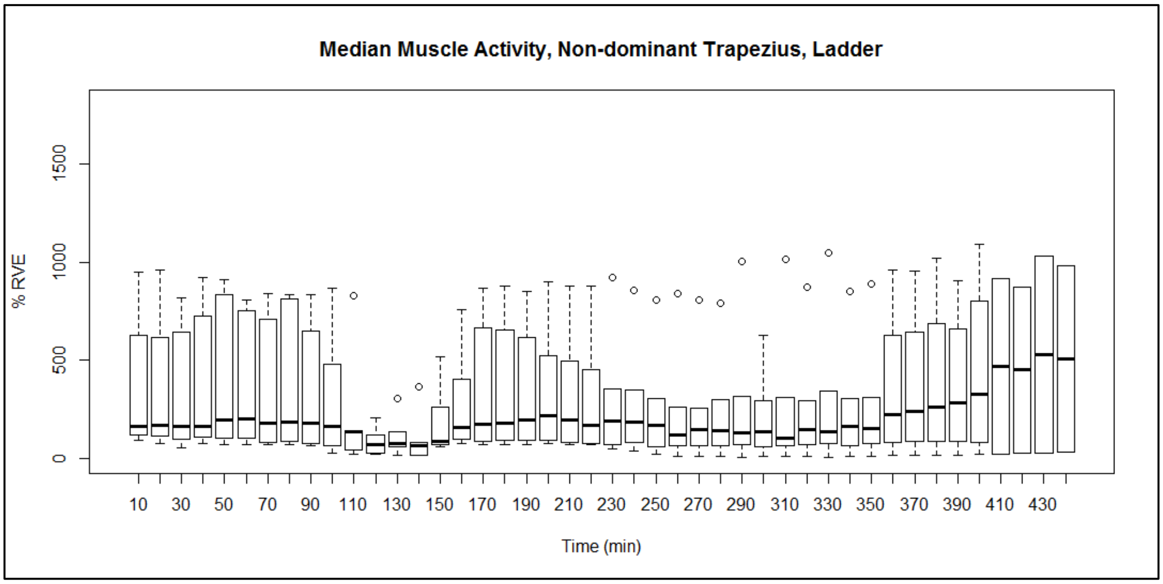


Figure 57 – Boxplot of median muscle activity (%RVE) by time, non-dominant trapezius, ladder (n = 5)

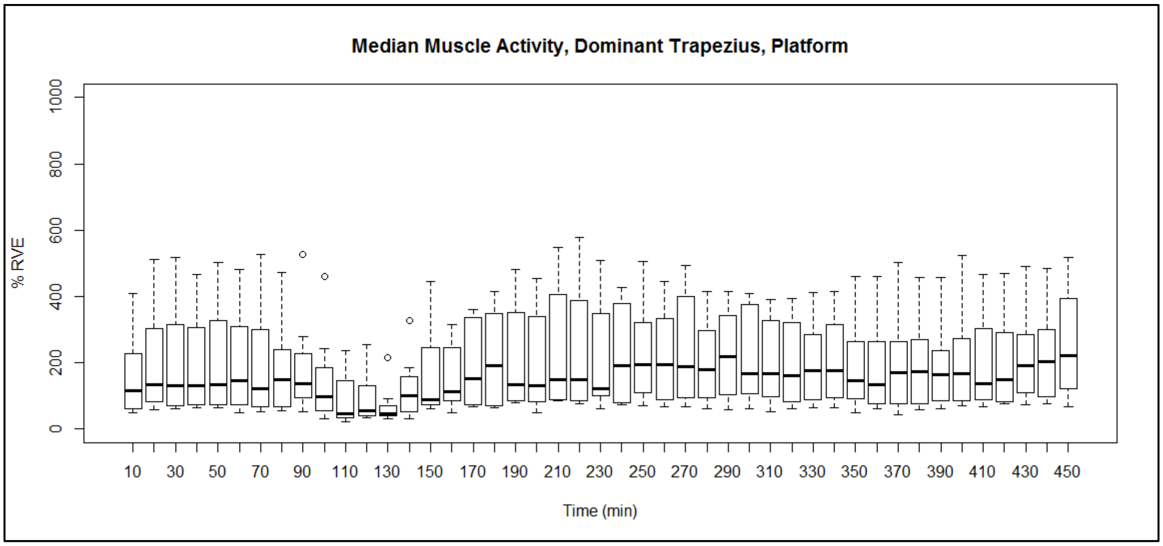


Figure 58 – Boxplot of median muscle activity (%RVE) by time, dominant trapezius, platform (n = 8)

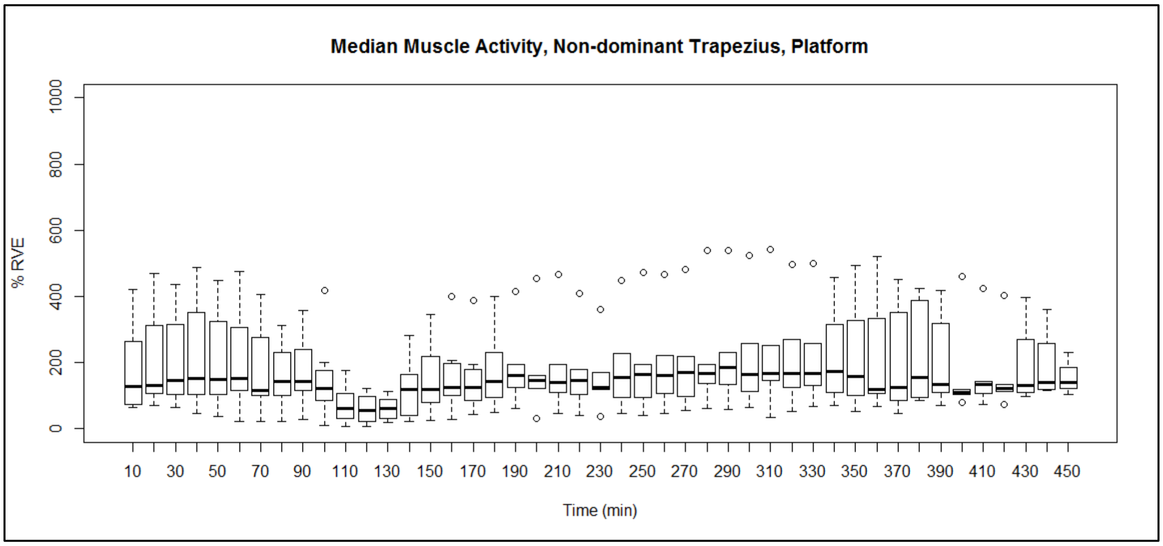


Figure 59 – Boxplot of median muscle activity (%RVE) by time, non-dominant trapezius, platform (n = 8)

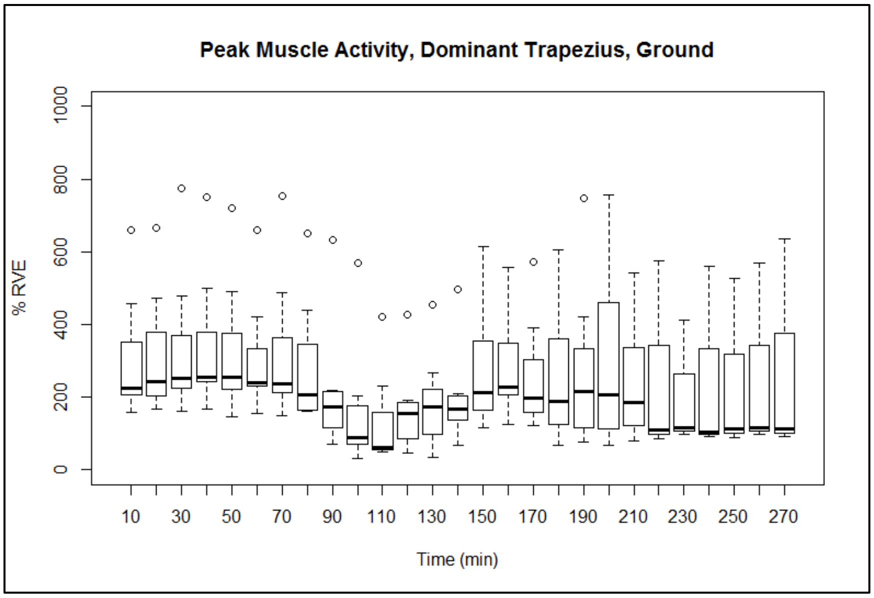


Figure 60 – Boxplot of peak muscle activity (%RVE) by time, dominant trapezius, ground (n = 7)

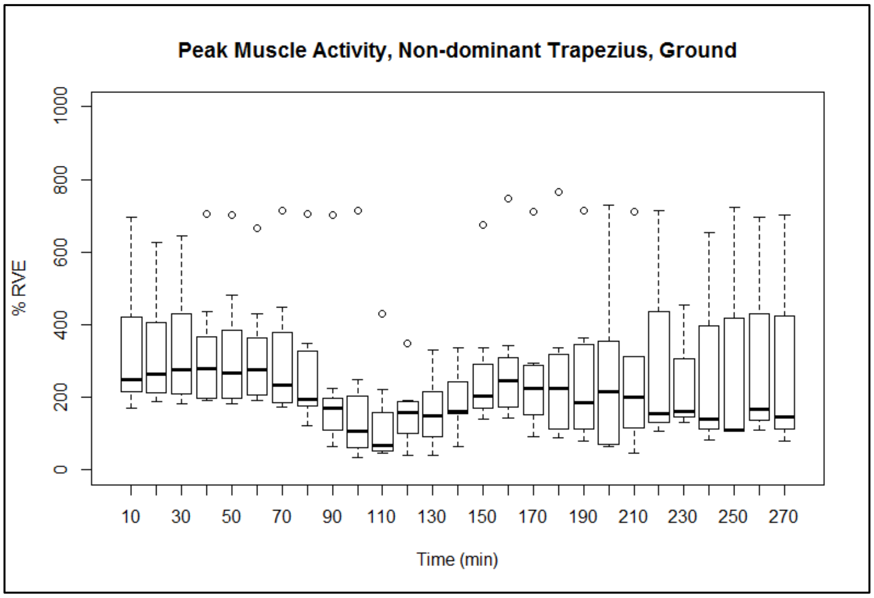


Figure 61 – Boxplot of peak muscle activity (%RVE) by time, non-dominant trapezius, ground (n = 7)

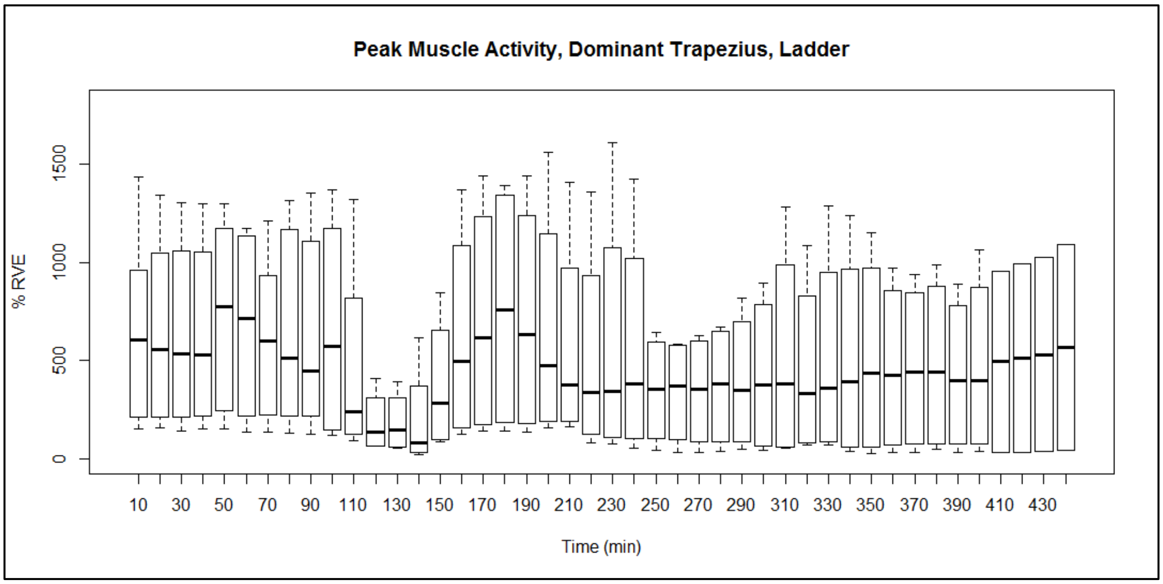


Figure 62 – Boxplot of peak muscle activity (%RVE) by time, dominant trapezius, ladder (n = 5)

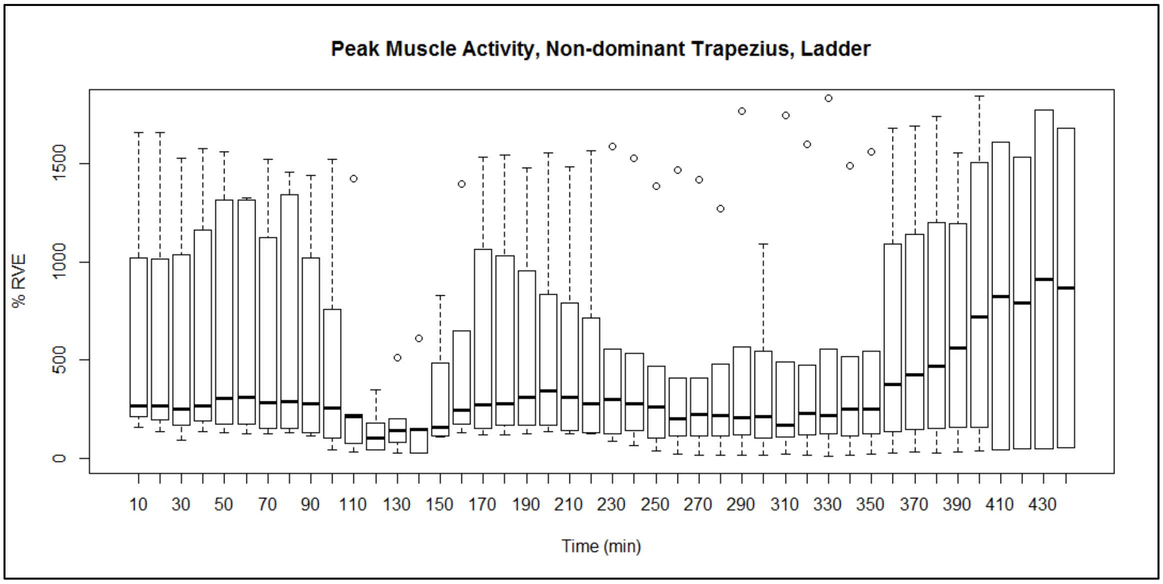


Figure 63 – Boxplot of peak muscle activity (%RVE) by time, non-dominant trapezius, ladder (n = 5)

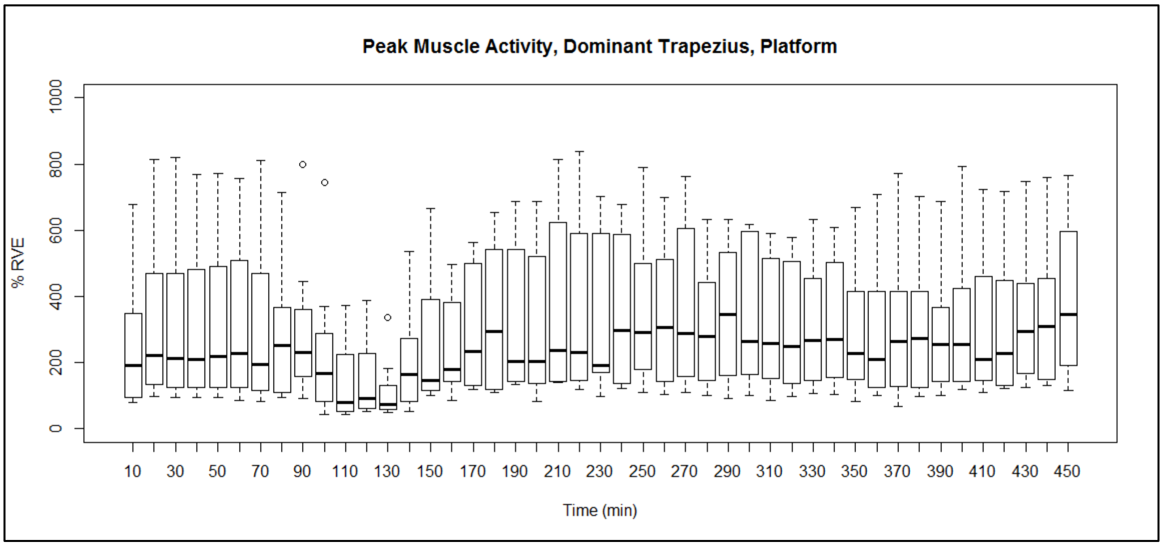


Figure 64 – Boxplot of peak muscle activity (%RVE) by time, dominant trapezius, platform (n = 8)

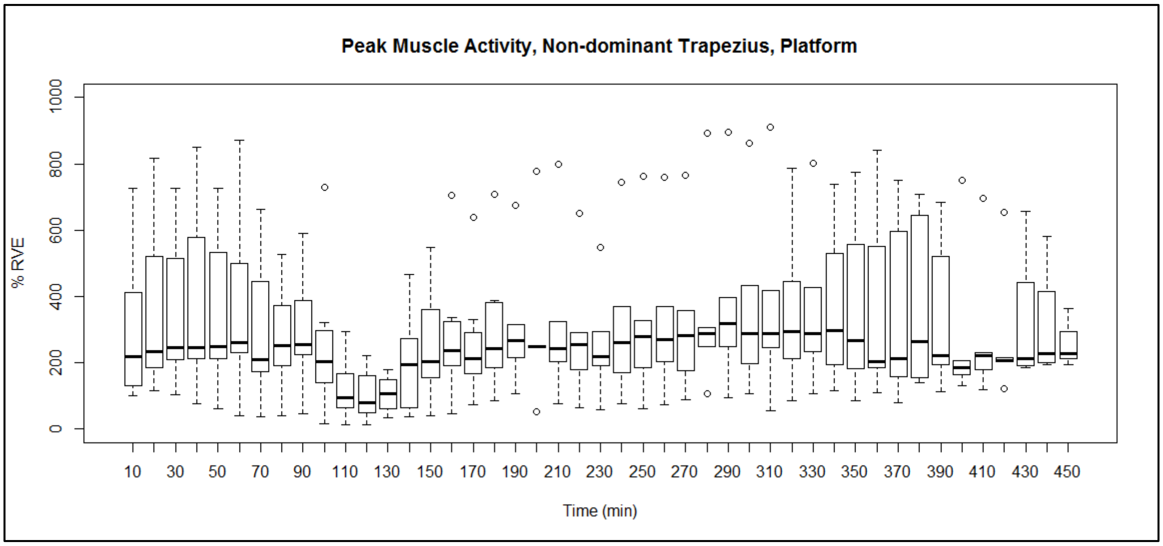


Figure 65 – Boxplot of peak muscle activity (%RVE) by time, non-dominant trapezius, platform (n = 8)

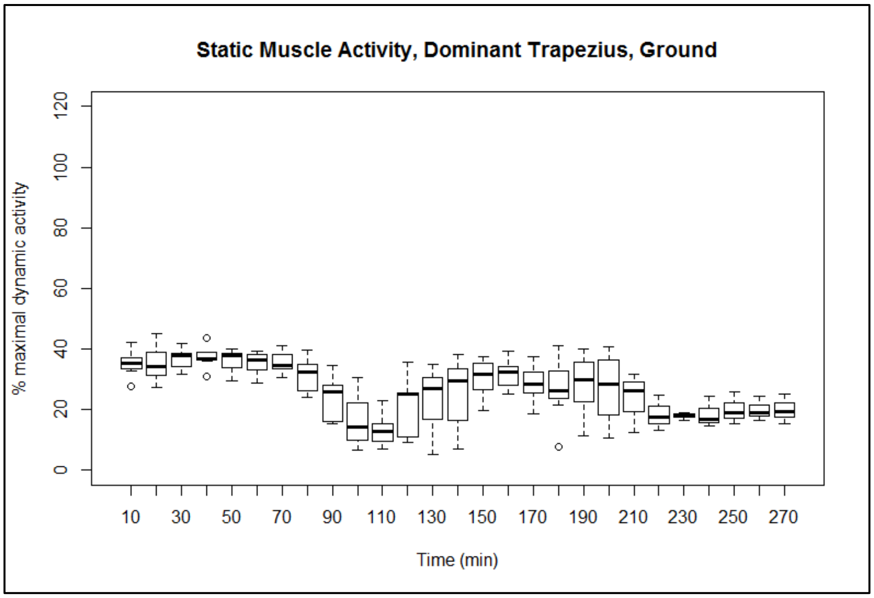


Figure 66 – Boxplot of static muscle activity (% maximal dynamic activity) by time, dominant trapezius, ground (n = 7)

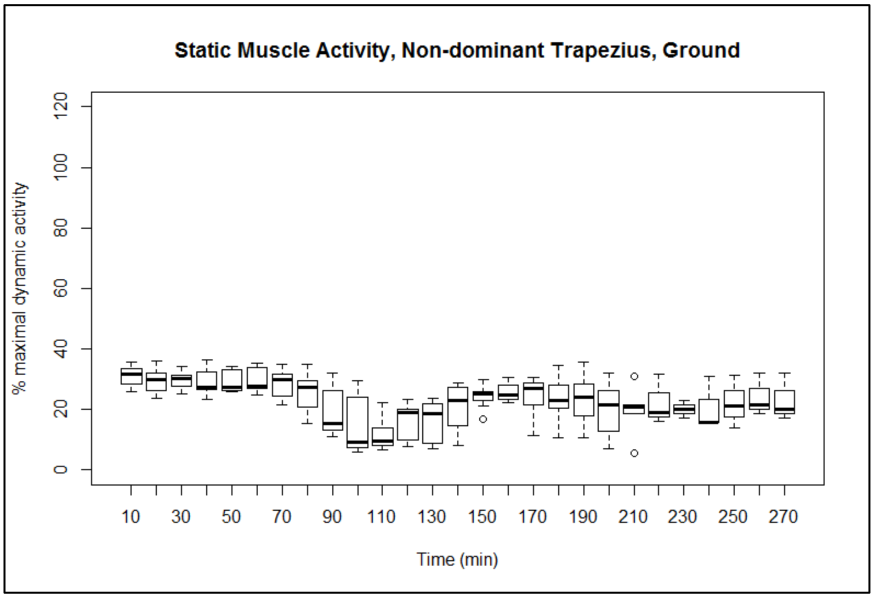


Figure 67 – Boxplot of static muscle activity (% maximal dynamic activity) by time, non-dominant trapezius, ground (n = 7)

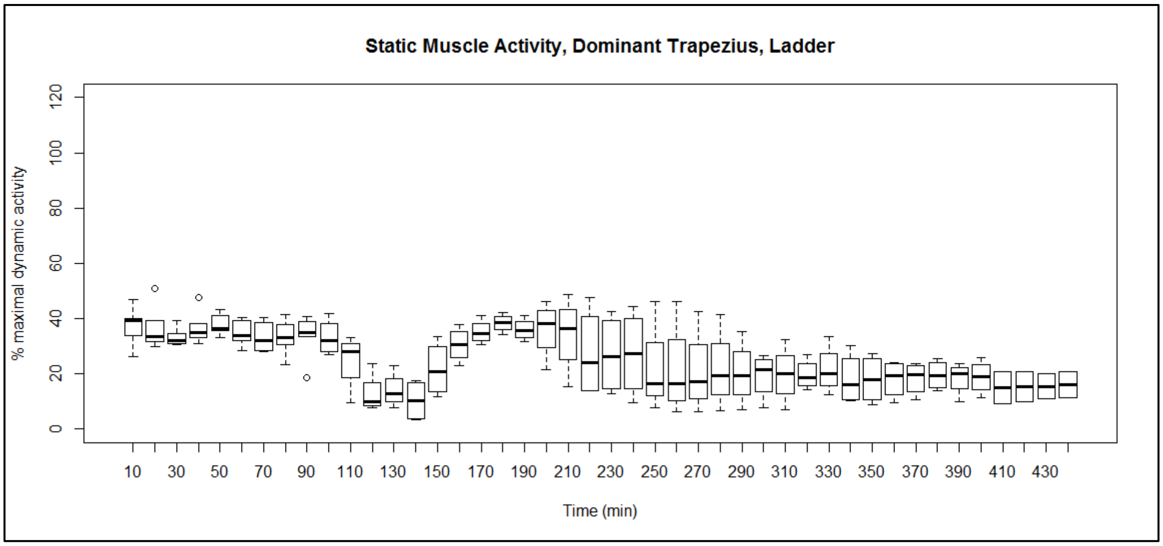


Figure 68 – Boxplot of static muscle activity (% maximal dynamic activity) by time, dominant trapezius, ladder (n = 5)

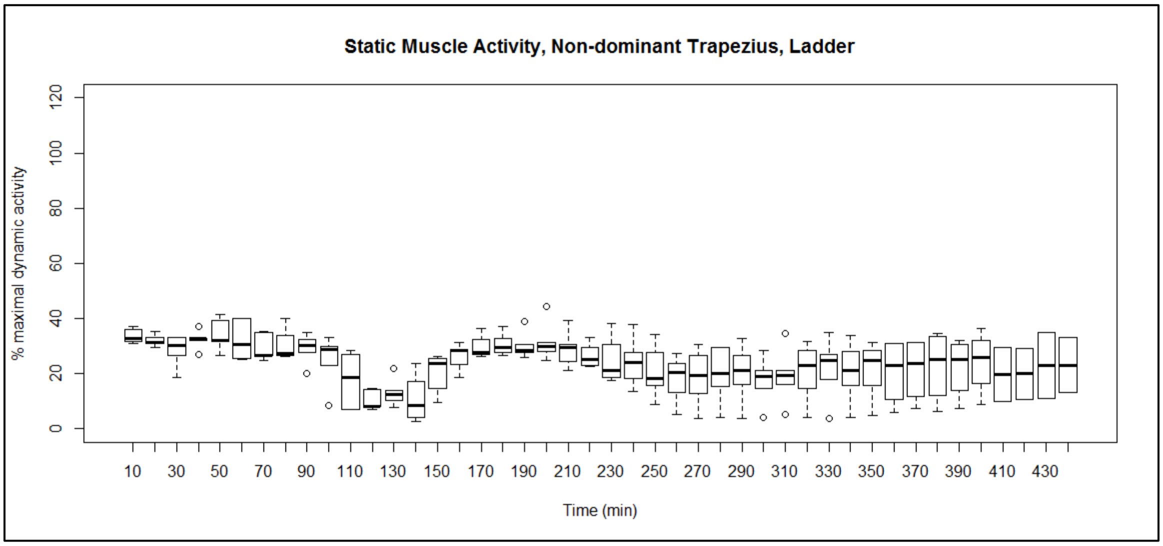


Figure 69 – Boxplot of static muscle activity (% maximal dynamic activity) by time, non-dominant trapezius, ladder (n = 5)

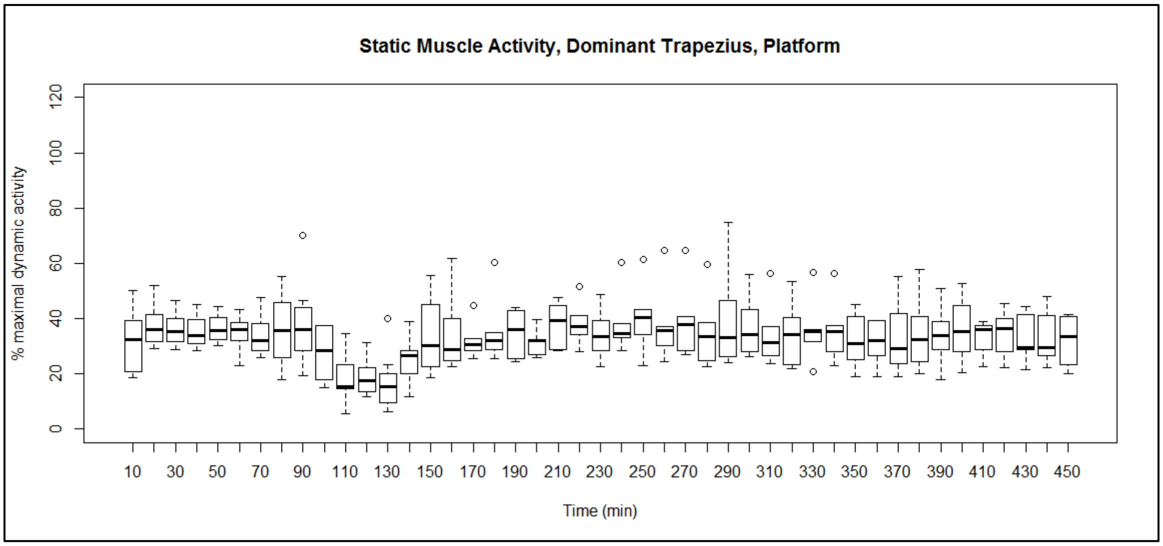


Figure 70 – Boxplot of static muscle activity (% maximal dynamic activity) by time, dominant trapezius, platform (n = 8)

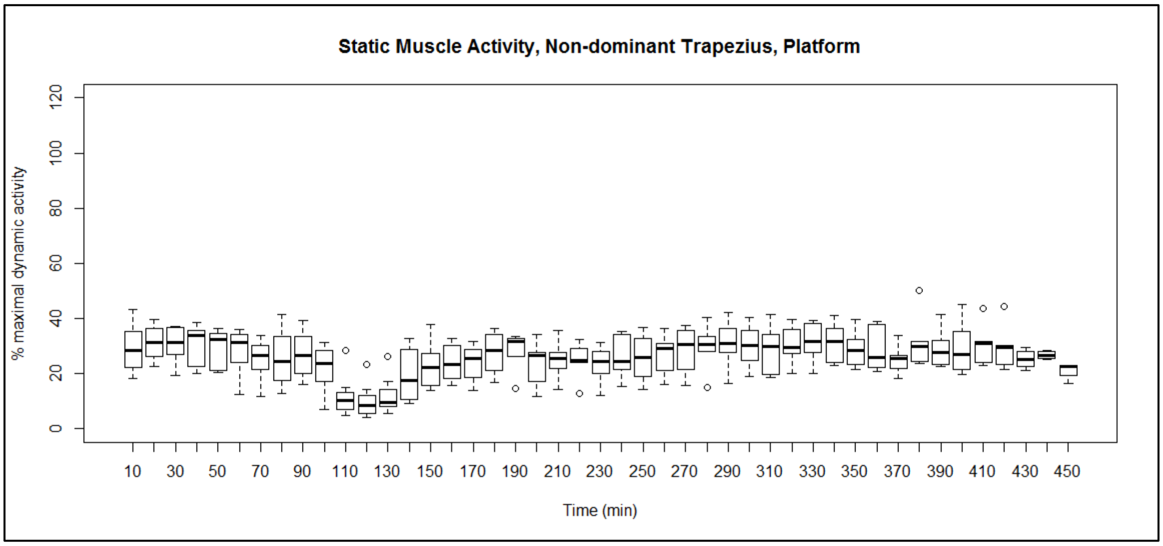


Figure 71 – Boxplot of static muscle activity (% maximal dynamic activity) by time, non-dominant trapezius, platform (n = 8)

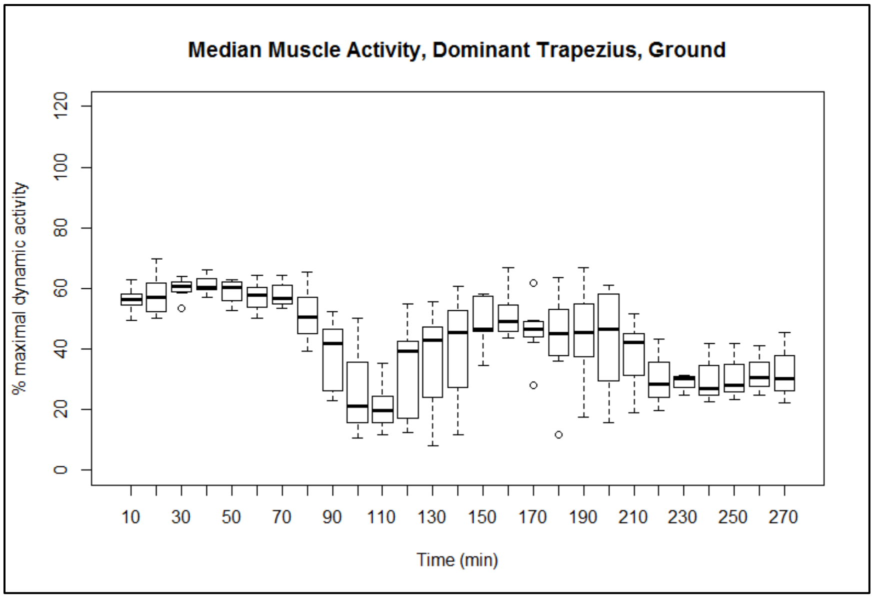


Figure 72 – Boxplot of median muscle activity (% maximal dynamic activity) by time, dominant trapezius, ground (n = 7)

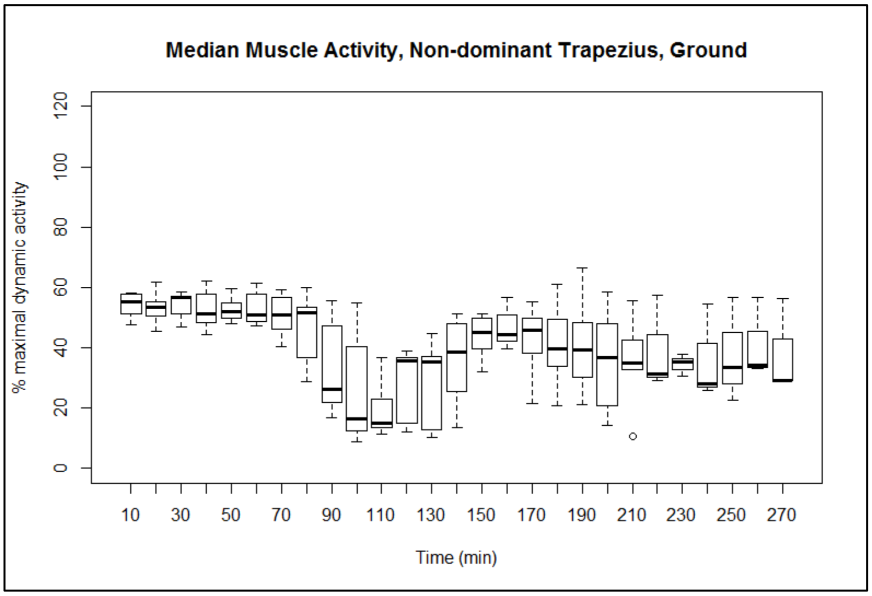


Figure 73 – Boxplot of median muscle activity (% maximal dynamic activity) by time, non-dominant trapezius, ground (n = 7)

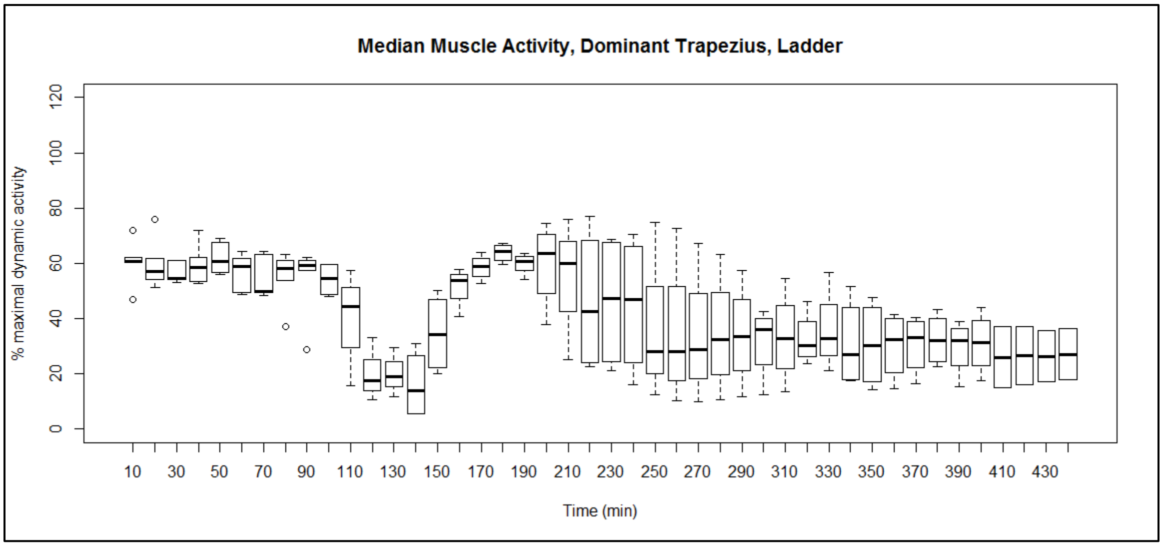


Figure 74 – Boxplot of median muscle activity (% maximal dynamic activity) by time, dominant trapezius, ladder (n = 5)

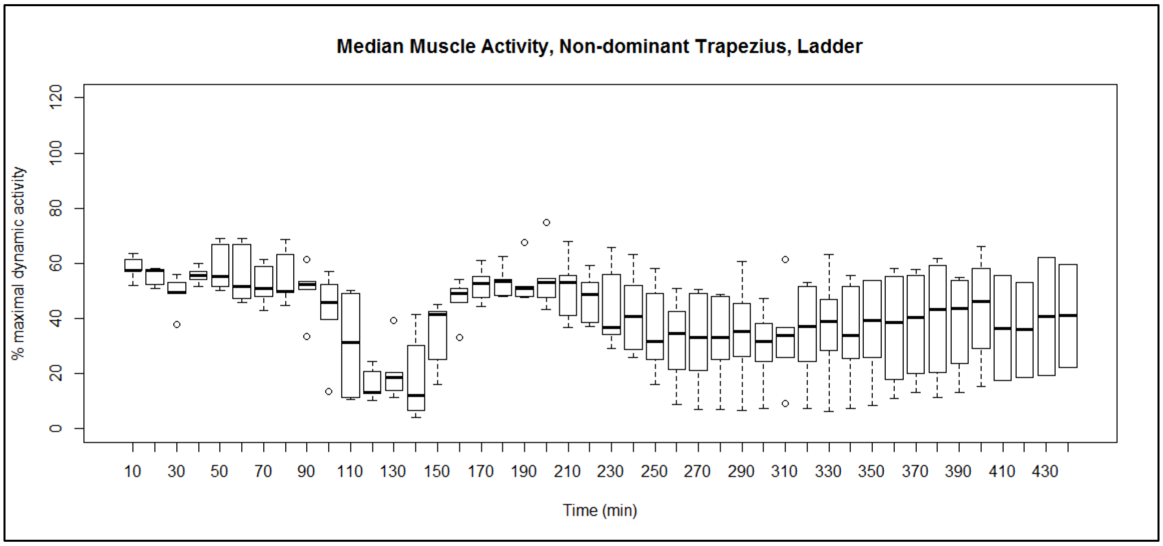


Figure 75 – Boxplot of median muscle activity (% maximal dynamic activity) by time, non-dominant trapezius, ladder (n = 5)

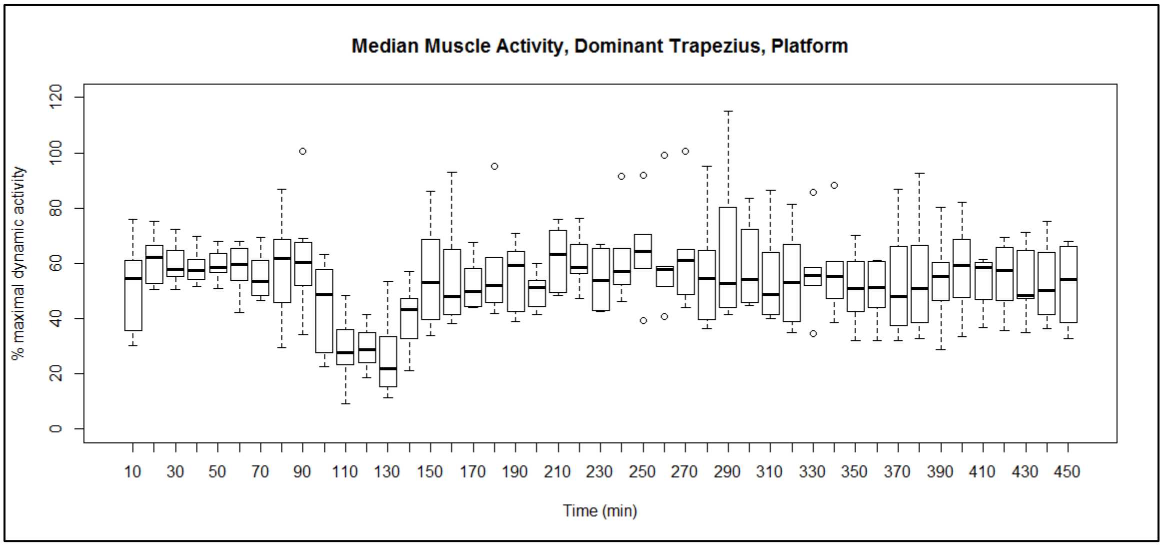


Figure 76 – Boxplot of median muscle activity (% maximal dynamic activity) by time, dominant trapezius, platform (n = 8)

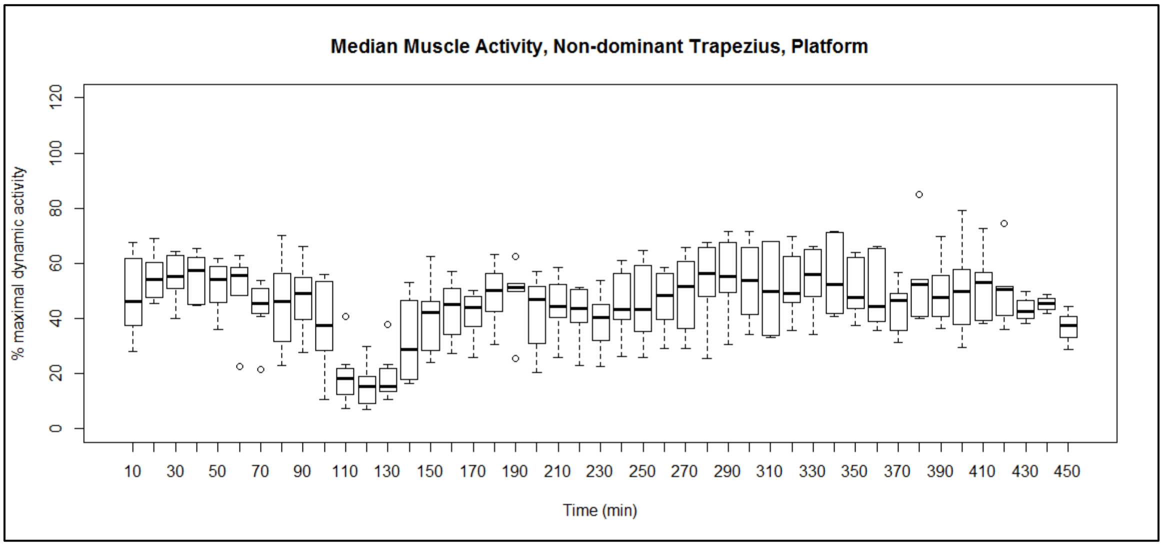
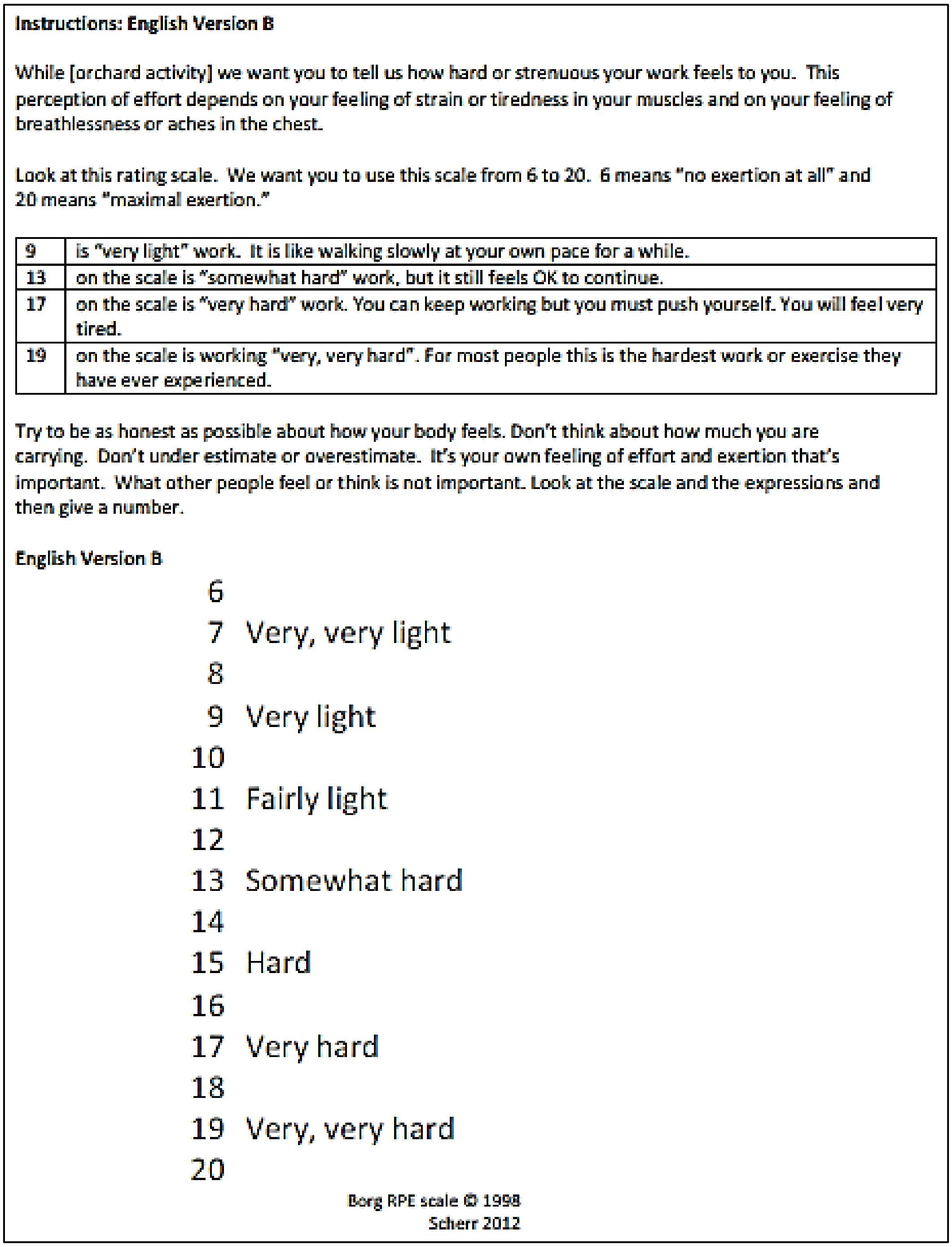


Figure 77 – Boxplot of median muscle activity (% maximal dynamic activity) by time, non-dominant trapezius, platform (n = 8)

Appendix D Modified Borg Scales as Subjective Questionnaires



Instructions: English Version B

While [orchard activity] we want you to tell us how hard or strenuous your work feels to you. This perception of effort depends on your feeling of strain or tiredness in your muscles and on your feeling of breathlessness or aches in the chest.

Look at this rating scale. We want you to use this scale from 6 to 20. 6 means "no exertion at all" and 20 means "maximal exertion."

9	is "very light" work. It is like walking slowly at your own pace for a while.
13	on the scale is "somewhat hard" work, but it still feels OK to continue.
17	on the scale is "very hard" work. You can keep working but you must push yourself. You will feel very tired.
19	on the scale is working "very, very hard". For most people this is the hardest work or exercise they have ever experienced.

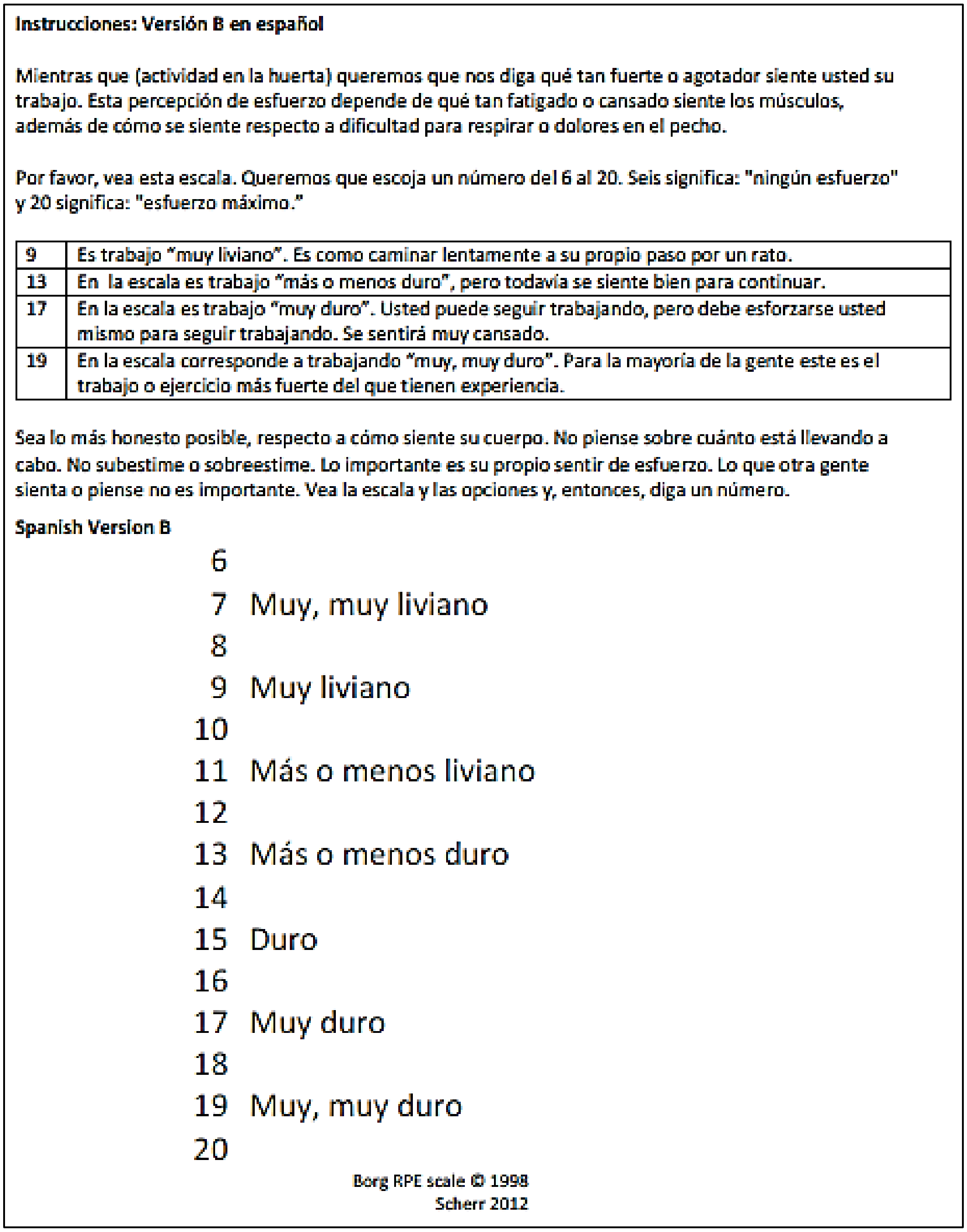
Try to be as honest as possible about how your body feels. Don't think about how much you are carrying. Don't under estimate or overestimate. It's your own feeling of effort and exertion that's important. What other people feel or think is not important. Look at the scale and the expressions and then give a number.

English Version B

6	
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

Borg RPE scale © 1998
Scherr 2012

Figure 78 – Borg RPE English



Instrucciones: Versión B en español

Mientras que (actividad en la huerta) queremos que nos diga qué tan fuerte o agotador siente usted su trabajo. Esta percepción de esfuerzo depende de qué tan fatigado o cansado siente los músculos, además de cómo se siente respecto a dificultad para respirar o dolores en el pecho.

Por favor, vea esta escala. Queremos que escoja un número del 6 al 20. Seis significa: "ningún esfuerzo" y 20 significa: "esfuerzo máximo."

9	Es trabajo "muy liviano". Es como caminar lentamente a su propio paso por un rato.
13	En la escala es trabajo "más o menos duro", pero todavía se siente bien para continuar.
17	En la escala es trabajo "muy duro". Usted puede seguir trabajando, pero debe esforzarse usted mismo para seguir trabajando. Se sentirá muy cansado.
19	En la escala corresponde a trabajando "muy, muy duro". Para la mayoría de la gente este es el trabajo o ejercicio más fuerte del que tienen experiencia.

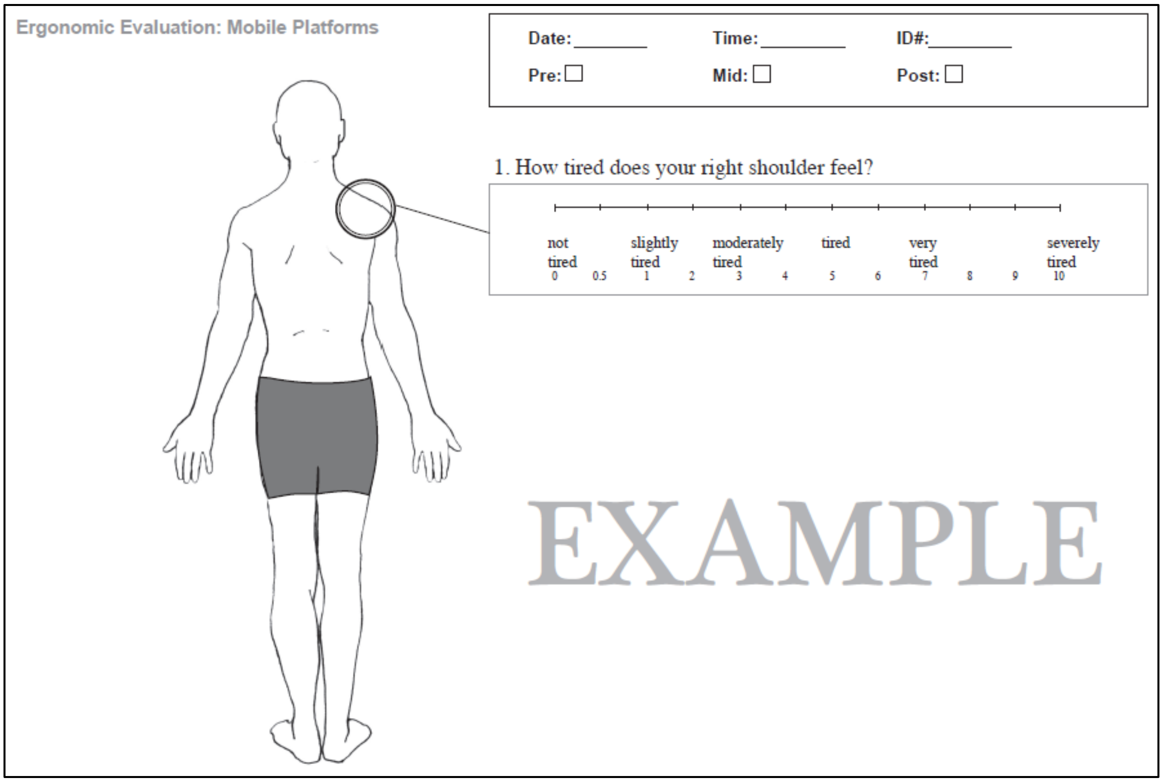
Sea lo más honesto posible, respecto a cómo siente su cuerpo. No piense sobre cuánto está llevando a cabo. No subestime o sobreestime. Lo importante es su propio sentir de esfuerzo. Lo que otra gente sienta o piense no es importante. Vea la escala y las opciones y, entonces, diga un número.

Spanish Version B

6	
7	Muy, muy liviano
8	
9	Muy liviano
10	
11	Más o menos liviano
12	
13	Más o menos duro
14	
15	Duro
16	
17	Muy duro
18	
19	Muy, muy duro
20	

Borg RPE scale © 1998
Scherr 2012

Figure 79 – Borg RPE Spanish



Ergonomic Evaluation: Mobile Platforms

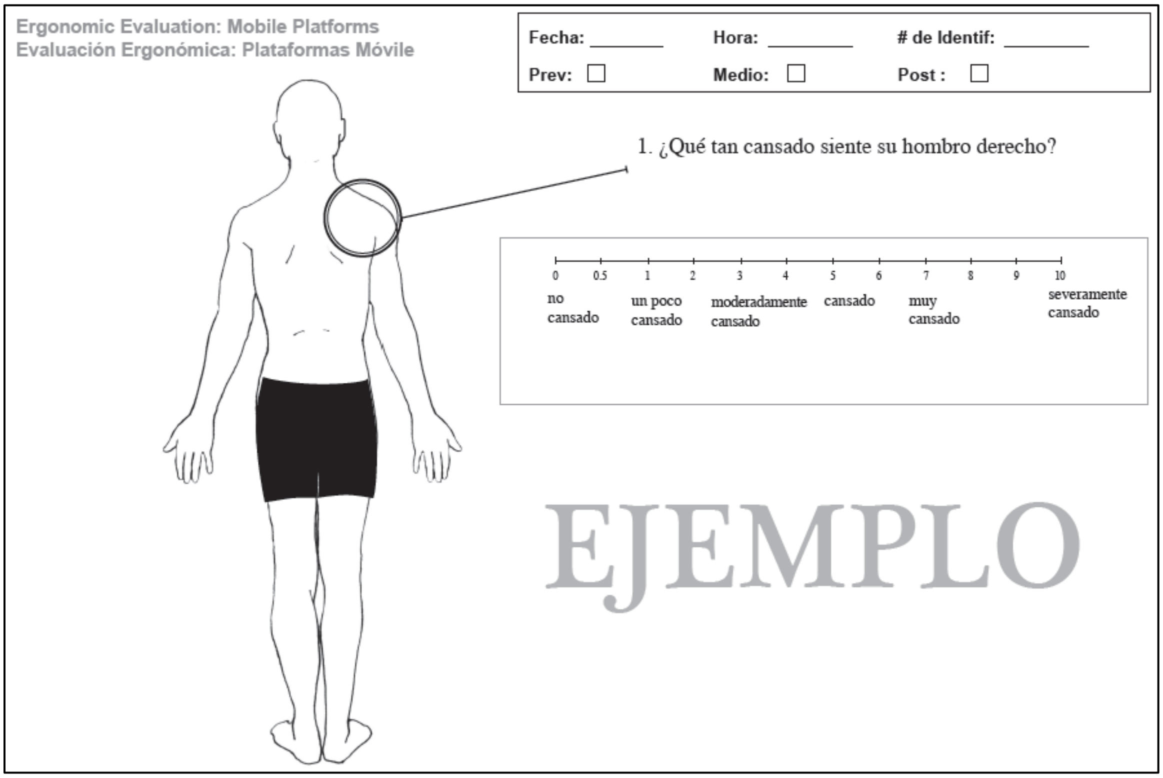
Date:_______ Time:_________ ID#:_________

Pre: ☐ Mid: ☐ Post: ☐

1. How tired does your right shoulder feel?

not tired		slightly tired		moderately tired		tired		very tired			severely tired
0	0.5	1	2	3	4	5	6	7	8	9	10

Figure 80 – Borg CR10 English



Ergonomic Evaluation: Mobile Platforms
Evaluación Ergonómica: Plataformas Móvile

Fecha: _______ Hora: _________ # de Identif: _________

Prev: ☐ Medio: ☐ Post : ☐

1. ¿Qué tan cansado siente su hombro derecho?

0	0.5	1	2	3	4	5	6	7	8	9	10
no cansado		un poco cansado		moderadamente cansado		cansado		muy cansado			severamente cansado

Figure 81 – Borg CR10 Spanish

Appendix E Statistical Power

In order to determine whether the sample sizes for the analyses for aim 1-3 were sufficient, a post hoc analysis for statistical power was calculated using G*Power 3.1.9.2 (Erdfelder et al. 1996) and is shown in Table 16 – 20. The powers to detect differences in the exposures to non-neutral postures and repetitive motion were based on one-way ANOVA methods. The powers to detect differences in the muscle fatigue, muscle activity and subjective measures were based on ANCOVA with fixed effects and interaction. For postures, relatively strong statistical powers were obtained for the percentage of time when upper arm > 90° and back bending > 30°. Strong statistical power (1-β > 0.80) for repetition rates were also yield when using accelerometers (average both arms) and separately for each arm when using video data. Supporting the results from statistical analysis in Chapter 6, the differences between two harvesting methods were able to be detected with high statistical power when normalizing to %RVE whereas the differences between the two sides of trapezius muscles could be detected with high statistical power if data were normalized to maximal dynamic activity. For subjective measures, statistical power were high for detecting the effect of the time of the day but not very high for the other factors.

Table 16 – Post hoc statistical powers (1-β) given α = 0.05 for postural exposure

	Non-dominant upper arm			Dominant arm upper arm			Back bending
	Flex	**Abduct**	**Elevate**	**Flex**	Abduct	Elevate	
% time angle > 30°	0.57	0.08	0.15	0.06	0.25	0.12	0.72
% time angle > 60°	0.60	0.36	0.63	0.10	0.21	0.26	-
% time angle > 90°	0.71	0.88	1.00	0.99	0.98	1.00	-

Table 17 – Post hoc statistical powers (1-β) given α = 0.05 for repetition rates

	Non-dominant arm	Dominant arm	Average arms
Repetition from video recordings	0.94	0.83	0.59
Repetition from accelerometers	-	-	0.95

Table 18 – Post hoc statistical powers (1-β) given α = 0.05 for EMG parameters

	Muscle Fatigue: MDF	Muscle Activity					
		%RVE			%maximal-dynamic		
		Static	Median	Peak	Static	Median	Peak
Dominant side	0.07	0.06	0.05	0.05	0.98	0.95	0.69
Harvesting Method	0.15	0.82	0.80	0.97	0.10	0.07	0.23
Interaction	0.19	0.05	0.05	0.05	0.08	0.08	0.13

Table 19 – Post hoc statistical powers (1-β) given α = 0.05 for subjective measures

	Borg RPE	Borg CR10		
		Non-dominant shoulder	Dominant shoulder	Lower back
Harvesting Method	0.05	0.44	0.53	0.26
Time of Day	1.00	0.99	0.77	1.00
Interaction	0.55	0.67	0.55	0.38

Bibliography

El Ahrache, K., Imbeau, D. & Farbos, B., 2006. Percentile values for determining maximum endurance times for static muscular work. *International Journal of Industrial Ergonomics*, 36(2), pp.99–108.

Antony, N.T. & Keir, P.J., 2010. Effects of posture, movement and hand load on shoulder muscle activity. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*, 20(2), pp.191–8. Available at: http://www.sciencedirect.com/science/article/pii/S1050641109000674 [Accessed August 10, 2014].

Attebrant, M., Mathiassen, S.E. & Winkel, J., 1995. Normalizing upper trapezius EMG amplitude: Comparison of ramp and constant force procedures. *Journal of Electromyography and Kinesiology*, 5(4), pp.245–250. Available at: http://www.sciencedirect.com/science/article/pii/1050641195000054 [Accessed September 5, 2014].

Bao, S., Mathiassen, S.E. & Winkel, J., 1995. Normalizing upper trapezius EMG amplitude: Comparison of different procedures. *Journal of Electromyography and Kinesiology*, 5(4), pp.251–257. Available at: http://www.sciencedirect.com/science/article/pii/1050641195000119 [Accessed September 5, 2014].

Blank, S.C., 1998. *The end of agriculture in American portfolio*, Quorum Books, Westport, CT.

Borg, G., 1970. Perceived exertion as an indicator of somatic stress. *Scandinavian journal of rehabilitation medicine*, 2, pp.92–98.

Borg, G.A., 1982. Psychophysical bases of perceived exertion. *Medicine and science in sports and exercise*, 14, pp.377–381.

Buchholz, B. et al., 1996. PATH: A work sampling-based approach to ergonomic job analysis for construction and other non-repetitive work. *Applied Ergonomics*, 27(3), pp.177–187. Available at: http://www.sciencedirect.com/science/article/pii/000368709500078X [Accessed November 15, 2014].

Burden, A. & Bartlett, R., 1999. Normalisation of EMG amplitude: An evaluation and comparison of old and new methods. *Medical Engineering and Physics*, 21(4), pp.247–257.

Capodaglio, E.M., 2001. *Comparison between the CR10 Borg's scale and the VAS (visual analogue scale) during an arm-cranking exercise.*,

Chapman, A.R. et al., 2010. Intramuscular fine-wire electromyography during cycling: Repeatability, normalisation and a comparison to surface electromyography. *Journal of Electromyography and Kinesiology*, 20(1), pp.108–117.

Chesler, N.C. & Durfee, W.K., 1997. Surface EMG as a fatigue indicator during FES-induced isometric muscle contractions. *Journal of Electromyography and Kinesiology*, 7(1), pp.27–37. Available at: http://www.sciencedirect.com/science/article/pii/S1050641196000168 [Accessed January 21, 2016].

DAUBE, J.R., 1981. Muscles Alive: Their Functions Revealed by Electromyography, Ed. 4. *Neurology*, 31, pp.369–369.

Davis, K.G. & Kotowski, S.E., 2007. Understanding the ergonomic risk for musculoskeletal disorders in the United States Agricultural Sector. *American Journal of Industrial Medicine*, 50, pp.501–511.

Earle-Richardson, G. et al., 2005. An ergonomic intervention to reduce back strain among apple harvest workers in New York State. *Applied Ergonomics*, 36, pp.327–334.

Earle-Richardson, G. et al., 2006. Development and initial assessment of objective fatigue measures for apple harvest work. *Applied ergonomics*, 37(6), pp.719–27. Available at: http://www.sciencedirect.com/science/article/pii/S0003687006000020 [Accessed September 5, 2014].

Earle-Richardson, G. et al., 2004. Ergonomic analysis of New York apple harvest work using a Posture-Activities-Tools-Handling (PATH) work sampling approach. *Journal of Agricultural Safety and Health*, 10, pp.163–176.

Ebaugh, D.D., McClure, P.W. & Karduna, A.R., 2006. Effects of shoulder muscle fatigue caused by repetitive overhead activities on scapulothoracic and glenohumeral kinematics. *Journal of Electromyography and Kinesiology*, 16, pp.224–235.

English, C.J. et al., 1995. Relations between upper limb soft tissue disorders and repetitive movements at work. *American journal of industrial medicine*, 27, pp.75–90.

Erdfelder, E., Faul, F. & Buchner, A., 1996. GPOWER: A general power analysis program. *Behavior Research Methods, Instruments & Computers*, 28, pp.1–11. Available at: http://www.gpower.hhu.de/.

Escobar, C.P., 2006. *Sensitivity analysis of subjective ergonomic assessment tools: impact of input information accuracy and output (final scores) generation*. Auburn University.

Farina, D. et al., 2002. Standardising surface electromyogram recordings for assessment of activity and fatigue in the human upper trapezius muscle. *European Journal of Applied Physiology*, 86, pp.469–478.

Fathallah, F.A., 2010. Musculoskeletal disorders in labor-intensive agriculture. *Applied ergonomics*, 41(6), pp.738–43. Available at: http://www.sciencedirect.com/science/article/pii/S0003687010000487 [Accessed September 5, 2014].

Ferguson, S.A. et al., 2013. Shoulder Muscle Fatigue During Repetitive Tasks as Measured by Electromyography and Near-Infrared Spectroscopy. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 55, pp.1077–1087.

Fernández-Peña, E., Lucertini, F. & Ditroilo, M., 2009. A maximal isokinetic pedalling exercise for EMG normalization in cycling. *Journal of Electromyography and Kinesiology*, 19(3).

Freivalds, A. et al., 2006. Effect of belt/bucket interface in apple harvesting. *International Journal of Industrial Ergonomics*, 36(11), pp.1005–1010. Available at: http://www.sciencedirect.com/science/article/pii/S0169814106001685 [Accessed September 5, 2014].

Fuller, J.R. et al., 2009. Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of electromyography and kinesiology : official journal of the International Society of Electrophysiological Kinesiology*, 19(6), pp.1043–52. Available at: http://www.sciencedirect.com/science/article/pii/S1050641108001570 [Accessed August 10, 2014].

Fulmer, S. et al., 2002. Ergonomic exposures in apple harvesting: Preliminary observations. In *American Journal of Industrial Medicine*. pp. 3–9.

Green, S. et al., 1998. *A standardized protocol for measurement of range of movement of the shoulder using the Plurimeter-V inclinometer and assessment of its intrarater and interrater reliability.*,

Halaki, M. & Ginn, K. a, 2012. Normalization of EMG Signals: To Normalize or Not to Normalize and What to Normalize to? *Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges*, pp.175–194. Available at: http://www.intechopen.com/books/export/citation/EndNote/computational-intelligence-in-electromyography-analysis-a-perspective-on-current-applications-and-future-challenges/normalization-of-emg-signals-to-normalize-or-not-to-normalize-and-what-to-normalize.

Hignett, S. & McAtamney, L., 2000. Rapid Entire Body Assessment (REBA). *Applied Ergonomics*, 31(2), pp.201–205. Available at: http://www.sciencedirect.com/science/article/pii/S0003687099000393 [Accessed September 5, 2014].

Holmes, S.M., 2013. *Fresh fruits, broken bodies : migrant farmworkers in the United States*, Berkeley : University of California Press.

Holtermann, A. & Roeleveld, K., 2006. EMG amplitude distribution changes over the upper trapezius muscle are similar in sustained and ramp contractions. *Acta Physiologica*, 186, pp.159–168.

Huckabee, W.E. & Judson, W.E., 1958. The role of anaerobic metabolism in the performance of mild muscular work. I. Relationship to oxygen consumption and cardiac output, and the effect of congestive heart failure. *Journal of Clinical Investigation*, 37(11), p.1577.

Hummel, A. et al., 2005. Relationship between perceived exertion and mean power frequency of the EMG signal from the upper trapezius muscle during isometric shoulder elevation. *European Journal of Applied Physiology*, 95(4), pp.321–326.

Iridiastadi, H., Nussbaum, M.A. & van Die??n, J.H., 2008. Muscular load characterization during isometric shoulder abductions with varying force. *Journal of Electromyography and Kinesiology*, 18(4), pp.695–703.

Jackson, J.A., Mathiassen, S.E. & Dempsey, P.G., 2009. Methodological variance associated with normalization of occupational upper trapezius EMG using sub-maximal reference contractions. *Journal of Electromyography and Kinesiology*, 19(3), pp.416–427.

Jakobsen, M.D. et al., 2014. Is Borg's perceived exertion scale a useful indicator of muscular and cardiovascular load in blue-collar workers with lifting tasks? A cross-sectional workplace study. *European Journal of Applied Physiology*, 114, pp.425–434.

Jensen, C., Vasseljen, O. & Westgaard, R.H., 1993. The influence of electrode position on bipolar surface electromyogram recordings of the upper trapezius muscle. *European Journal of Applied Physiology and Occupational Physiology*, 67(3), pp.266–273.

Jin, S., McCulloch, R. & Mirka, G.A., 2009. Biomechanical evaluation of postures assumed when harvesting from bush crops. *International Journal of Industrial Ergonomics*, 39(2), pp.347–352. Available at: http://www.sciencedirect.com/science/article/pii/S0169814108001248 [Accessed September 5, 2014].

Johnson, M.P., McClure, P.W. & Karduna, A.R., 2001. *New method to assess scapular upward rotation in subjects with shoulder pathology.*,

Karhu, O., Kansi, P. & Kuorinka, I., 1977. Correcting working postures in industry: A practical method for analysis. *Applied ergonomics*, 8, pp.199–201.

Keyserling, W.M. et al., 1993. A checklist for evaluating ergonomic risk factors associated with upper extremity cumulative trauma disorders. *Ergonomics*, 36, pp.807–831.

Keyserling, W.M., 1986. Postural analysis of the trunk and shoulders in simulated real time. *Ergonomics*, 29, pp.569–583.

Knutson, L.M. et al., 1994. A study of various normalization procedures for within day electromyographic data. *Journal of Electromyography and Kinesiology*, 4(1), pp.47–59.

Kolber, M.J. & Hanney, W.J., 2012. The reliability and concurrent validity of shoulder mobility measurements using a digital inclinometer and goniometer: a technical report. *International journal of sports physical therapy*, 7(3), pp.306–13. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3362980&tool=pmcentrez&rendertype=abstract.

Krissman, F., 1999. Agribusiness strategies to divide the workforce by class, ethnicity, and leval status in California and Washington. In P. Wong, ed. *Race, Ethnicity, and Nationality in the United States: toward the twenty-first century*. Boulder: Westview Press.

Leclerc, A. et al., 2004. Incidence of shoulder pain in repetitive work. *Occupational and environmental medicine*, 61, pp.39–44.

Leigh, J.P., Du, J. & McCurdy, S. a, 2014. An estimate of the U.S. government’s undercount of nonfatal occupational injuries and illnesses in agriculture. *Annals of epidemiology*, 24(4), pp.254–9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24507952.

Linnamo, V., Bottas, R. & Komi, P. V., 2000. Force and EMG power spectrum during and after eccentric and concentric fatigue. *Journal of Electromyography and Kinesiology*, 10(5), pp.293–300.

Lowe, B.D., 2004. Accuracy and validity of observational estimates of shoulder and elbow posture. *Applied ergonomics*, 35(2), pp.159–71. Available at: http://www.sciencedirect.com/science/article/pii/S0003687004000183 [Accessed September 5, 2014].

De Luca, C.J. et al., 2010. Filtering the surface EMG signal: Movement artifact and baseline noise contamination. *Journal of Biomechanics*, 43, pp.1573–1579.

de Luca, C.J., 1997. The use of surface electromyography in biomechanics. *Journal of Applied Biomechanics*, 13, pp.135–163.

Mathiassen, S.E. & Winkel, J., 1990. Electromyographic activity in the shoulder-neck region according to arm position and glenohumeral torque. *European Journal of Applied Physiology and Occupational Physiology*, 61, pp.370–379.

Mathiassen, S.E., Winkel, J. & Hägg, G.M., 1995. Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies — A review. *Journal of Electromyography and Kinesiology*, 5(4), pp.197–226. Available at: http://www.sciencedirect.com/science/article/pii/105064119400014X [Accessed September 5, 2014].

McAtamney, L. & Nigel Corlett, E., 1993. RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, 24(2), pp.91–99. Available at: http://www.sciencedirect.com/science/article/pii/000368709390080S [Accessed September 5, 2014].

McCurdy, S.A. et al., 2003. Agricultural injury in California migrant Hispanic farm workers. *American Journal of Industrial Medicine*, 44, pp.225–235.

Miles, M.P. & Clarkson, P.M., 1994. Exercise-induced muscle pain, soreness, and cramps. *Journal of Sports Medicine and Physical Fitness*, 34, pp.203–216.

National Institutue for Occupational Safety and Health, 1992. *Selected topics in surface electromyography for use in occupational settings: expert perspectives*, DHHS (NIOSH) Publication No. 91-100.

Nishijima, Y. et al., 2010. Application of the segment weight dynamic movement method to the normalization of gait EMG amplitude. *Journal of Electromyography and Kinesiology*, 20(3), pp.550–557.

Öberg, T., 1995. Muscle fatigue and calibration of EMG measurements. *Journal of Electromyography and Kinesiology*, 5(4), pp.239–243. Available at: http://www.sciencedirect.com/science/article/pii/1050641196855829 [Accessed September 5, 2014].

Occhipinti, E., 1998. OCRA: a concise index for the assessment of exposure to repetitive movements of the upper limbs. *Ergonomics*, 41, pp.1290–1311.

Occhipinti, E. & Colombini, D., 2007. Updating reference values and predictive models of the OCRA method in the risk assessment of work-related musculoskeletal disorders of the upper limbs. *Ergonomics*, 50, pp.1727–1739.

Ohlsson, K. et al., 1995. Repetitive industrial work and neck and upper limb disorders in females. *American journal of industrial medicine*, 27, pp.731–747.

Osborne, A. et al., 2012. Prevalence of musculoskeletal disorders among farmers: A systematic review. *American Journal of Industrial Medicine*, 55, pp.143–158.

Paquet, V.L., Punnett, L. & Buchholz, B., 2001. Validity of fixed-interval observations for postural assessment in construction work. *Applied Ergonomics*, 32, pp.215–224.

Potvin, J.R. & Bent, L.R., 1997. A validation of techniques using surface EMG signals from dynamic contractions to quantify muscle fatigue during repetitive tasks. *Journal of Electromyography and Kinesiology*, 7(2), pp.131–139.

Radwin, R.G. & Lin, M.L., 1993. An analytical method for characterizing repetitive motion and postural stress using spectral analysis. *Ergonomics*, 36, pp.379–389.

Rash, G.S., 2008. Electromyography fundamentals. *Available at: TUhttp://www. gcmas. org/EMGfundamentals. pdfUT. Accessed July*. Available at: papers3://publication/uuid/F8E3A390-2C75-42E6-9F0C-768A97087B38.

Sakakibara, H. et al., 1995. Overhead work and shoulder-neck pain in orchard farmers harvesting pears and apples. *Ergonomics*, 38, pp.700–706.

Scherr, J. et al., 2013. Associations between Borg's rating of perceived exertion and physiological measures of exercise intensity. *European Journal of Applied Physiology*, 113(1), pp.147–155.

Scibek, J.S., 2012. Assessment of scapulohumeral rhythm for scapular plane shoulder elevation using a modified digital inclinometer. *World Journal of Orthopedics*, 3(6), p.87.

Seavert, C.F., 2005. Remaining globally competitive in the U.S. tree fruit industry with the national tree fruit technology roadmap. *Acta Horticulturae*, 671, pp.407–411.

Spielholz, P. et al., 2001. Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors. *Ergonomics*, 44, pp.588–613.

Sundelin, B.G. & Hagberg, M., 1992. Electromyographic signs of shoulder muscle fatigue in repetitive arm work paced by the Methods Time Measurement system. *Scandinavian Journal of Work, Environment and Health*, 18(4), pp.262–268.

Triffitt, P.D., Wildin, C. & Hajioff, D., 1999. The reproducibility of measurement of shoulder movement. *Acta orthopaedica Scandinavica*, 70(4), pp.322–324.

Troiano, A. et al., 2008. Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale. *Gait & posture*, 28(2), pp.179–86. Available at: http://www.sciencedirect.com/science/article/pii/S0966636208000994 [Accessed August 10, 2014].

US-BLS, 2015a. *Employer-Reported Workplace Injuries and Illnesses--2014, Table 1. Incidence rates of nonfatal occupational injuries and illnesses by case type and ownership, selected industries, 2014*, Available at: http://www.bls.gov/news.release/osh.t01.htm.

US-BLS, 2015b. *Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work, 2014, Table 16. Number, incidence rate, and median days away from work for nonfatal occupational injuries and illnesses involving days away from work and musculoskeletal disorders*, Available at: http://www.bls.gov/news.release/osh2.t16.htm.

Vasseljen, O. & Westgaard, R., 1997. Arm and trunk posture during work in relation to shoulder and neck pain and trapezius activity. *Clinical Biomechanics*, 12(1), pp.22–31. Available at: http://www.sciencedirect.com/science/article/pii/S026800339700048X [Accessed September 11, 2014].

Veiersted, K.B., Westgaard, R.H. & Andersen, P., 1990. Pattern of muscle activity during stereotyped work and its relation to muscle pain. *International Archives of Occupational and Environmental Health*, 61, pp.31–41.

Walker-Bone, K. & Palmer, K.T., 2002. Musculoskeletal disorders in farmers and farm workers. *Occupational Medicine*, 52, pp.441–450.

Westgaard, R.H., 1988. Measurement and evaluation of postural load in occupational work situations. *European journal of applied physiology and occupational physiology*, 57, pp.291–304.

Wickham, J. et al., 2010. Quantifying "normal" shoulder muscle activity during abduction. *Journal of Electromyography and Kinesiology*, 20, pp.212–222.

van der Windt, D.A.W.M. et al., 2000. Occupational risk factors for shoulder pain: a systematic review. *Occupational and Environmental Medicine*, 57, pp.433–442. Available at: ISI:000087830700001.

Xiao, H. et al., 2013. Agricultural work and chronic musculoskeletal pain among latino farm workers: The MICASA study. *American Journal of Industrial Medicine*, 56, pp.216–225.

Yang, J. & Winter, D., 1984. EMG amplitude normalization methods. *Archives of Physical Medicine and Rehabilitation*, 65, pp.517–521.

Yassierli & Nussbaum, M. a, 2007. Muscle fatigue during intermittent isokinetic shoulder abduction: age effects and utility of electromyographic measures. *Ergonomics*, 50(7), pp.1110–26. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17510825.

Yen, T.Y. & Radwin, R.G., 2002. A comparison between analysis time and inter-analyst reliability using spectral analysis of kinematic data and posture classification. *Applied Ergonomics*, 33, pp.85–93.

Yen, T.Y. & Radwin, R.G., 2000. Comparison between using spectral analysis of electrogoniometer data and observational analysis to quantify repetitive motion and ergonomic changes in cyclical industrial work. *Ergonomics*, 43, pp.106–132.

USDA. (2012). Ranking of Market Value of Ag Product Sold. National Agricultural Statistics Service. [Accessed 5 Sep 2014] http://www.agcensus.usda.gov/Publications/2012/Online_Resources/Rankings_of_Market_Value/Washington/

USDA. (2014). Noncitrus Fruits and Nuts 2013 Summary (July 2014). National Agricultural Statistics Service. [Accessed 5 Sep 2014] http://usda.mannlib.cornell.edu/usda/current/NoncFruiNu/NoncFruiNu-07-17-2014_revision.pdf

WTFRC. (2002). Technology Roadmap for Tree Fruit Production 2010. Version 9.3 (2 Mar 2002) Washington Tree Fruit Research Commission (WTFRC). [Accessed 3 Sep 2014] http://treefruitresearch.com/resources-a-downloads/technology-roadmap

WTRFC. (2006). Developing efficient work platform, Final Project Report. Washington Tree Fruit Research Commission (WTFRC). [Accessed 3 Sep 2014] http://jenny.tfrec.wsu.edu/wtfrc/core.php?rout=displtxt&start=120&cid=344

WTRFC. (2011). Economic analysis of technology adoption by Washington apple growers, Final Project Report. Washington Tree Fruit Research Commission (WTFRC). [Accessed 3 Sep 2014] http://jenny.tfrec.wsu.edu/wtfrc/core.php?rout=displtxt&start=120&cid=552

WTRFC. (2014). Design and development of apple harvesting techniques, Final Project Report. Washington Tree Fruit Research Commission (WTFRC). [Accessed 3 Sep 2014] http://jenny.tfrec.wsu.edu/wtfrc/core.php?rout=displtxt&start=120&cid=676