Evaluation of Physical Risk Factors for Musculoskeletal Disorders among Reforestation Workers in the Southeastern United States

by

Robert F. Granzow

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

Auburn, Alabama
December 15, 2018

Keywords: ergonomics, forestry, musculoskeletal disorders, safety, health

Approved by

Mark C. Schall, Jr., Chair, Assistant Professor of Industrial and Systems Engineering
Mathew F. Smidt, Professor of Forestry and Wildlife Sciences
Jerry Davis, Professor of Industrial and Systems Engineering
Richard Sesek, Associate Professor of Industrial and Systems Engineering
Sean Gallagher, Associate Professor of Industrial and Systems Engineering

Abstract

Work-related musculoskeletal disorders (MSDs) are a major concern for society due to their high prevalence and the magnitude of their direct and indirect costs. Exposure to physical risk factors in the work environment such as forceful muscular exertions, non-neutral postures, and repetitious movements have been associated with MSD incidence. Accurate characterizations of worker exposure to these physical risk factors using direct measurement methods provide critical information for researchers interested in developing interventions intended to lessen the impact of work-related MSDs.

Workers in the United States Agriculture, Fisheries, and Forestry (AFF) sector have been identified as having a higher prevalence of work-related MSDs compared to workers in other industries. Reforestation workers, in particular, report high rates of injury and illness. More accurate and comprehensive characterizations of exposure to physical risk factors among reforestation workers are needed to determine the optimal methods for performing reforestation work.

This dissertation will address the gap in the scientific literature regarding exposure to physical risk factors associated with the development of MSDs among reforestation workers in the southeastern United States. Chapter 1 introduces the problem and provides an overview of the goals of this dissertation. Chapter 1 also provides the background and significance of the studies discussed in this dissertation through a thorough review of the literature. Chapter 2 presents the results of a field-based study characterizing exposure to several common physical risk factors among a sample of hand planter forestry workers. Chapter 3 provides the results of a study evaluating the effect of planting tool design on physical risk factors among hand planters. Chapter 4 presents a work measurement study on hand planting production and provides a time standard for hand planting. Chapter 5 is a discussion of the implications of the three studies conducted, while also providing recommendations for future research.

Acknowledgments

Several individuals and organizations must be acknowledged for the important role they played in making this dissertation possible. I would like to express my deepest appreciation to Dr. Mark Schall Jr. for serving as my committee chair, believing in me, and guiding me through the doctoral program. I would also like to thank my committee members, Dr. Mathew Smidt, Dr. Richard Sesek, Dr. Jerry Davis, and Dr. Sean Gallagher for providing their assistance and expertise throughout the completion of this work.

I would like to thank Dr. Jack Ogutu and Dr. Paul Specht for assisting me through the transition from my undergraduate curriculum at Millersville University of Pennsylvania to my graduate work at Auburn University and being supportive mentors for continuing my education.

The work presented in this dissertation was made possible through support from several funding agencies. These include extramural grants from the Southeast Center for Agricultural Health and Injury Prevention and the Southwest Center for Agricultural Health, Injury Prevention and Education. The Southeast Center is supported by Cooperative Agreement No. 5U54-OH007547-15 from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health. The Southwest Center for Agricultural Health, Injury Prevention and Education is supported through Cooperative Agreement No. 2U54-OH007541-16 from the Centers for Disease Control and Prevention/National Institute for Occupational Safety and Health. The work presented in this dissertation would not have been possible without the support of the CDC / NIOSH supported Deep South Center for Occupational Health and Safety at the University of Alabama Birmingham and Auburn University (Grant no. 2T42OH008436-13).

I would like to thank all of my friends and colleagues that I had the pleasure of working with at Auburn University throughout my graduate studies. I would like to specifically thank Dr. Yousif Abulhassan, Dr. Mohamed Badawy, Fehmi Capanoglu, Dr. Howard Chen, Dr. Richard Garnett, Pam Halstead, Dr. Rong Huangfu, Connor Lusk, Jake Montgomery, Behnam Rasoolian, Akash Shettannavar, Sinan Su, and Lynn Tamblyn. This dissertation is a product of the work of many individuals within the 'OSE Family' that volunteered their time and effort.

Finally, I would like to express my deepest appreciation to my family for supporting me throughout my education. Thank you to my parents for instilling in me a dedication to education and lifelong learning. Most importantly thank you to my wife, Margret Granzow, for the endless encouragement while I worked on my graduate studies. Without her support I could not have completed my dissertation work.

Contents

List of Figures

List of Tables

Chapter 1

Introduction and a Review of the Literature

1.1 Work-related musculoskeletal disorders

Musculoskeletal disorders (MSDs) are conditions affecting the muscles, tendons, nerves, ligaments, joints or spinal discs (Punnett, 2014). MSDs include sprains, strains, tears, soreness, pain, hernias, and connective tissue injuries (da Costa et al., 2010). MSDs that develop as a result of occupational exposure to environmental, psychosocial, organizational, and physical risk factors are referred to as work-related MSDs. While many occupational injuries and illnesses can be linked to an exposure of a single cause (i.e. asbestosis development as a result of exposure to respirable asbestos), work-related MSDs are generally the result of multiple factors (van der Beek et al., 1998). The most commonly affected body regions for MSDs are the low back, neck, shoulder, forearm, and the hand (Punnett, 2014). Carpal tunnel syndrome, low back pain, tendinitis, bursitis, and tenosynovitis are a few examples of MSDs (Bernard, 1997).

MSDs are a major societal health concern due to their high prevalence and associated costs. According to the U.S. Bureau of Labor Statistics, MSDs accounted for 31 percent of the over 1.1 million days-away-from-work injury and illness cases in 2015, with an incidence rate of 29.8 cases per 10,000 full-time workers (BLS, 2016). Workers sustaining an MSD required a median of 12 days to recover before returning to work in 2015, compared to 8 days for all types of cases (BLS, 2016). Low back pain, a common work-related MSD, is the leading cause of work absence and limitation of activity throughout the world (Lidgren, 2003). Worldwide, MSDs are the second greatest cause of disability (Horton, 2012). MSDs are expected to have an increasingly dramatic impact on individuals and society as aging, a risk factor for MSD incidence, of the global population markedly increases (Woolf et al., 2003).

Several studies have attempted to estimate the total annual cost of work-related MSDs. OSHA estimates the direct cost of MSDs to be $20 billion in the U.S., with indirect costs associated with training new workers and lost productivity being estimated as up to five times that amount (OSHA, 2014). Other studies have calculated costs substantially higher for all cause MSD cases, with one study estimating costs at $149.4 billion in 1992 (Yelin et al., 1995). While the total cost of occupational MSDs is difficult to measure, studies in Germany, the Netherlands, and Taiwan have identified work-related MSDs as the most expensive form of work disability (Guo et al., 2004; Picavet et al., 2003; Thiehoff, 2002). MSD injuries and illnesses of the back and spine have been identified as the most costly subcategory of MSDs (Coyte et al., 1998). Work-related low back disorders account for 16-19% of all worker compensation claims, yet comprise 33-41% of the total cost of all worker compensation costs (Spengler et al., 1986; Webster et al., 1994).

These statistics illustrate the high prevalence and severe impact of work-related MSDs, and demonstrate the need for exposure studies that can result in interventions to reduce MSD incidence.

1.2 Risk factors for MSDs

Personal characteristics, psychosocial and organizational work factors, and exposure to physical risk factors are some of the factors that are associated with the development of MSDs. MSD causation is frequently multifactorial involving a combination of risk factors (Bernard, 1997; WHO, 1985).

Personal characteristics that have been associated with MSD incidence include a person's age, anthropometry, gender, smoking habits, increased body mass index, and previous history of musculoskeletal conditions (Butterworth et al., 2012; da Costa et al., 2010; Hooper et al., 2006; Kerr et al., 2001; Picavet et al., 2003). An employee's ability to respond to external work factors can be dependent on personal characteristics, thus these factors should be considered when conducting exposure assessments (Bernard, 1997).

Psychosocial risk factors relate to how an employee perceives the occupational environment and job tasks within it. Examples include perceptions of intensified workload, monotonous work, limited job control, low job clarity, low social support, and the employee's environment outside of work. Psychosocial factors are often difficult to objectively quantify and can vary widely between individuals within the workplace (Bernard, 1997). Work organization is the way in which work is organized, supervised, and carried out (Kourinkaetal et al., 1995). Risk factors related to work organization, such as job change, have been linked to negative musculoskeletal health outcomes (Gerr et al., 2014; Punnett et al., 2004). Cross sectional studies indicate that work organization factors combined with physical risk factors increases the probability of MSD incidence (Widanarko et al., 2014; Huang et al., 2003; Devereux et al., 2004).

Comprehensive literature reviews suggest substantial evidence that exposure to certain physical risk factors may lead to the development of MSDs (Bernard, 1997; da Costa et al., 2010). These physical risk factors include awkward (non-neutral or extreme) working postures, forceful muscle exertions, intense physical activity, excessive repetition, and exposure to whole-body vibration. The present dissertation will focus primarily on addressing the development of MSDs as a response to physical risk factor exposure.

1.2.1 Awkward postures

Awkward, or non-neutral postures have been identified as a physical, or biomechanical, risk factor for the development of work-related MSDs. Longitudinal studies of MSD incidence of the neck, low back, elbow/forearm, wrist/hand, and knee have demonstrated reasonable evidence of a causal relationship (da Costa et al., 2010). Other reviews of the literature have suggested a possible association between MSD incidence and non-neutral postures of the shoulder, wrist/hand, and low back (Bernard, 1997).

Awkward posture definitions vary depending on the body region being considered. The shoulder joint is comprised of muscles, tendons, ligaments, protective tissues, as well as three bones: the clavicle, humerus, and scapula. The shoulder is a large and complex joint, allowing the upper arm to rotate, abduct, adduct, and move through 360° in the sagittal plane. The shoulder is prone to musculoskeletal pain and injury. A neutral posture for the upper arm has been defined as one in which the arm hangs straight down by the side of the torso (Bernard, 1997). The angle between the torso and the upper arm increases as the arm is flexed, abducted, or extended. Neutral arm working postures have been described as those in which the upper arms are flexed or abducted in angles less than 20° (Stephen Bao et al., 2009; Kazmierczak et al., 2005; Wahlström et al., 2010), 30° (Hooftman et al., 2009; Juul-Kristensen et al., 2001), and 45° (Keyserling, 1986). Extreme postures have been expressed as those angles of flexion or abduction larger than 45° (Douphrate et al., 2012; Schall Jr. et al., 2016b), 60° (Bernard, 1997; Hansson et al., 2006; Hooftman et al., 2009; Kazmierczak et al., 2005; Wahlström et al., 2010) or 90° (Keyserling, 1986; Svendsen et al., 2004b). Studies indicate that as the angle of shoulder elevation increases, the load on the musculature of the shoulder also increases (Giroux et al., 1992; Jonsson et al., 1973; Sigholm et al., 1983; Sporrong et al., 1999). Although defined non-neutral postures are helpful in characterizing risk and comparing exposures between studies, musculoskeletal damage likely occurs along a continuum of severity, from angles of 30 degrees to a maximally abducted arm (Bernard, 1997).

Defining neutral and extreme postures of the trunk for the purpose of determining the risk of negative health outcomes of the low back are typically concerned with trunk movement in several distinct directions: forward flexion and backward extension about the sagittal plane, lateral bending about the coronal plane, and axial rotation (trunk twisting) about the transverse plane (Bernard, 1997). Trunk flexion angles of less than 20° and 30° have been defined as neutral in recent exposure assessment studies, while extreme postures have been expressed as angles greater than 45° and 60° (Bernard, 1997; Fethke et al., 2011;

Hooftman et al., 2009; Kazmierczak et al., 2005; Schall Jr. et al., 2015; Schall Jr. et al., 2016b). Extreme postures for lateral bending of the trunk have been described as angles greater than 15° (Schall Jr. et al., 2015). As with shoulder MSD development resulting from inclination exposures at all angles, including those less than what has been defined as “extreme”, trunk inclination of near-neutral postures may still result in musculoskeletal conditions, such as low back pain (LBP) (Punnett et al., 1991).

1.2.2 Forceful muscle exertions

High muscular exertions, or heavy physical work, has been identified as a biomechanical risk factor for the development of work-related MSDs. Forceful muscular exertions have been determined as reasonable evidence for the development of work-related MSDs for the low back, shoulder, wrist/hand, and hip (da Costa et al., 2010). Excessive force exposure of the neck and neck/shoulder has also been associated with MSD incidence (Bernard, 1997).

Literature from medical, rehabilitation, ergonomics, and sports science research is typically used to determine the best muscle groups to select for exposure assessment of a given body region. The anterior deltoid has been identified as one muscle group related directly to musculoskeletal shoulder conditions due to it being a prime flexor of the shoulder, and that it is known to contract synchronously with the supraspinatus muscle (Kadefors et al., 1976). Shoulder-neck MSD incidence studies often involve the collection of muscle activity of the upper trapezius muscle, as it is easily accessible for current exposure assessments and is a common site for work-related pain (Anderson, 1984; Mathiassen et al., 1995; Wallace et al., 1987; Waris, 1979). Additionally, the upper trapezius plays an important role in stabilizing the shoulder (De Mey et al., 2009).

1.2.3 Excessive repetition

Studies focused on the elbow/forearm, wrist/hand, and knee have determined that there is reasonable evidence of a causal relationship between repetitive work and MSD incidence (da Costa et al., 2010), and a positive association between highly repetitive work and MSDs of the neck and shoulder, hand/wrist tendinitis, and Carpal Tunnel Syndrome has been established (Bernard, 1997). Due to the literature support associating repetition and MSD incidence, most available ergonomic assessment tools used to characterize MSD risk consider repetition as a component (Drinkhaus et al., 2003; Moore et al., 1995; Waters et al., 1993).

While high muscle force and excessive repetition have been identified as causes of MSDs, a recent systematic literature review concluded that evidence of an interdependence of force and repetition with respect to MSD risk may exist, signifying a possible fatigue failure process in affected tissues (Gallagher et al., 2013). Exposure to combinations of risk factors (force and repetition, force and posture) have been positively associated with epicondylitis and other cumulative injuries and illnesses of the elbow, Carpal Tunnel Syndrome, and hand/wrist tendinitis (Bernard, 1997).

1.2.4 Work load

Physical activity (PA) is body movement produced by skeletal muscles that results in energy expenditure (Caspersen et al., 1985). PA exposure metrics are used to measure energy expenditure. These values can be used to estimate how strenuous the demands of a job task or full-shift work are. Exposure metrics may also be used to compare energy demands between different jobs or occupations. While moderate exposure to PA has been demonstrated as having an association with positive health outcomes, including acting as a protective factor for cardiovascular mortality (Nocon et al., 2008; Sofi et al., 2008), several studies have found that occupational exposure to high levels of PA is associated with chronic health conditions (Harari et al., 2015; Heneweer et al., 2011; A. Holtermann et al., 2012; Holtermann et al., 2010; Sitthipornvorakul et al., 2011). PA exposure metrics can be reported as activity "counts" or "Metabolic Equivalents (METs)" (Freedson et al., 2012; Freedson et al., 1998). PA intensity derived from MET categories (light, <3 METS; moderate, 3-6 METs; vigorous, >6 METs) has been proposed (Pate et al., 1995). Similarly, PA intensity as derived from “counts” has been defined (sedentary, 0-100 counts/min; light, 101-1952; moderate, 1953-5724; vigorous, 5725-9498; very vigorous, >9498) (Freedson et al., 1998). PA intensity categories currently rely on proprietary algorithms, meanwhile new methods of PA estimation have been recommended, such as pattern recognition algorithms that adapt to individual accelerometer data which may provide more accurate energy expenditure estimations (Freedson et al., 2012).

Oxygen uptake has been established as a valid basis for measuring energy expenditure, although it is difficult to directly measure during prolonged field based studies due to the equipment required (i.e. metabolic cart). During the performance of work, physical work load may be assessed through the direct measurement of oxygen uptake or by the indirect estimation of oxygen uptake based on the recorded heart rate of the individual (Astrand et al., 1986). This association between heart rate and energy expenditure, or work load, has made the direct measurement of heart rate common among work physiologists, ergonomists, and injury prevention professionals (Sullman et al., 2000; Vitalis et al., 1994; Vitalis, 1987). Astrand et al. (1986) provides general guidelines for the severity of work associated with the heart rate of average individuals age twenty to thirty (Table 1.1).

Table 1.1: Heart rate severity of work classifications for prolonged physical activity among average individuals twenty to thirty years of age (Astrand et al., 1986).

Severity of Work	**Heart Rate Response**
Light work	up to 90 beats $\cdot$ min^{-1}
Moderate work	90—110 beats $\cdot$ min^{-1}
Heavy work	110—130 beats $\cdot$ min^{-1}
Very heavy work	130—150 beats $\cdot$ min^{-1}
Extremely heavy work	150—170 beats $\cdot$ min^{-1}

While these guidelines are helpful in comparing estimated work loads among occupational groups, as well as providing work-rest recommendations to workers, the vast individual variations including age, gender, environmental conditions, emotional factors, and job stress, limit the injury prevention application of these guidelines (Astrand et al., 1986). In addition to these guidelines, various indices have been developed to apply recorded heart rate measurements against in order to estimate the severity of work. These include the relative heart rate at work index (Saha, 1978; Lewis et al., 1993), the ratio of working heart rate to resting heart rate (Vitalis, 1981; Fordham et al., 1978; Goldsmith et al., 1978), and the 50% level (Lammert, 1972). These indices have been used in previous studies of AFF workers (Kirk et al., 1995; Kirk et al., 1996; Hodges et al., 2011; Roberts, 2002).

1.3 Methods of measuring exposure to physical risk factors

Several methods for measuring exposure to MSD risk factors have been previously developed. These methods can be grouped into three categories: (1) subjective self-reports, (2) observational methods, and (3) direct measurement (Spielholz et al., 2001). Many studies rely on multiple methods from the different method categories to gain a more comprehensive assessment of occupational exposures.

Self-reports are used in most field studies, often to gain additional information regarding worker perceptions for comparisons with more objective exposure assessment methods. Workers can be asked to estimate the prevalence of postures, the frequency of repetitive motions, the duration of force exertions, the magnitude of forces, and about other physical risk factors experienced (Spielholz et al., 2001). Self-reporting, such as through questionnaires, has the advantages of being relatively low cost compared to other methods and research suggests that self-reporting may lead to individual workers reporting symptoms of MSDs such as pain allowing for early intervention (Hansson et al., 2001). However, the validity of self-reports in accurately estimating exposure to physical risk factors has not been determined (Hansson et al., 2001; Spielholz et al., 2001).

Observational methods of exposure assessment may be field-based or video recorded in the field and analyzed in detail (Spielholz et al., 2001). Field-based observational physical risk factor assessments may utilize expert checklists or a researcher logging detailed components and actions of the job. Video-based methods result in more detailed and reproducible evaluations due to the ability to review the data and with the use of assistive software (Spielholz et al., 2001). Time-motion studies, the Ovako Working Posture Analyzing System (OWAS), the Rapid Entire Body Assessment (REBA), and the Rapid Upper Limb Assessment (RULA) are examples of exposure assessment tools using observational methods (Armstrong et al., 1982; Hignett et al., 2000; Mattila et al., 1993; McAtamney et al., 1993; Spielholz et al., 2001). Observational methods have been demonstrated to provide valid and reliable exposure metrics (Dartt et al., 2009; Kazmierczak et al., 2006; Li et al., 1999; Spielholz et al., 2001; Takala et al., 2010).

Direct measurement methods of exposure assessment offer quantitative and objective estimates of exposure to physical risk factors and can be used to appropriately evaluate possible interventions (Hansson et al., 2009). Direct measurement methods provide the most precise exposure estimates compared to self-reporting and observational methods for exposures to forceful exertions, postures, and repetitions (Amasay et al., 2009; van der Beek et al., 1998; Burdorf et al., 1999; Hansson et al., 2001; Schall Jr. et al., 2016a; Winkel et al., 1994).

1.3.1 Posture

Direct measurement of body segment posture can be accomplished using several different techniques. These include optical motion capture, inclinometry, goniometry, and the applied use of inertial measurement units (IMUs). An IMU measures an object's spatial orientation and motion characteristics using multiple electromechanical sensors (accelerometers, gyroscopes and/or magnetometers) (Schall Jr. et al., 2016a; H. Chen et al., 2018). By securing an IMU to the trunk and/or upper arms non-neutral and extreme working postures can be measured (David, 2005; Li et al., 1999; Schall Jr. et al., 2016a; Teschke et al., 2009). IMUs have advantages over accelerometers as the combination of components may address limitations of accelerometers and gyroscopes independently (Liunge et al., 2005; Roetenberg et al., 2007).

1.3.2 Muscle activity

Electromyography (EMG) is a technique used to quantify voluntary muscle activation within postural tasks, functional movements, and work conditions (Basmajian, 1962). EMG uses electrodes to collect electric signals from muscles produced during muscle contraction. The measured signal represents the muscle activity of motor units and can be normalized to represent muscular effort as a risk factor for MSD incidence (Chowdhury et al., 2013). Field-based epidemiologic studies frequently employ the use of surface EMG to measure forceful muscle exertions. Raw surface EMG amplitudes are highly sensitive to factors determined by the electrode configuration, including the electrode/skin impedance and the location of the spacing of electrodes, and differ widely between individuals based on factors such as muscle fiber composition and tissue properties. Thus, normalization of EMG signals is necessary for meaningful research study comparisons and conclusions (Mathiassen et al., 1995).

EMG signals for each muscle group are commonly compared to either a maximum voluntary contraction (MVC) or a submaximal reference voluntary exertion (RVE), and are expressed as a percent MVC or percent RVE. A submaximal RVE has certain advantages compared to an MVC in some field-based settings, including reduced time requirements and minimized risk for discomfort and injury (Shihan Bao et al., 1995; Hägg et al., 1997; Mathiassen et al., 1995; Nieminen et al., 1993; Schall Jr. et al., 2014). Processing of EMG signals for relevant summary measures has been described (Attebrant et al., 1995; Shihan Bao et al., 1995; Fethke et al., 2015; Mathiassen et al., 1995).

1.3.3 Work load

Many PA monitors utilize accelerometers or IMUs and use the collected data to calculate PA summary metrics of the quantity and intensity of movements (Schall Jr. et al., 2016a).

PA monitors are typically worn on the dominant hip, near the upper point of the iliac crest (Berntsen et al., 2010; Hendelman et al., 2000), although it is possible this placement could underestimate PA due to a waist-worn monitor not capturing activity of the upper arms and trunk (Hendelman et al., 2000; Schall Jr. et al., 2016a). Studies indicate that the use of direct measurement methods of measuring PA through the application of tri-axial accelerometers, such as those found in IMUs, can accurately discriminate between PA types, including standing, walking, sitting, walking stairs, running, and cycling (Skotte et al., 2014).

Deriving PA summary metrics from IMUs requires converting raw acceleration to measures of PA such as counts and METs in order to categorize PA and make comparisons with studies of other occupational groups. Detailed processing techniques have been described for the conversion of raw acceleration into counts (Arias et al., 2015; K. Y. Chen et al., 2005; Freedson et al., 1998; Freedson et al., 2012; Schall Jr. et al., 2016a; Umukoro et al., 2013) and to METs (Hildebrand et al., 2014; Schall Jr. et al., 2016a; Van Hees et al., 2013).

The collection of heart rate (HR) data during field-based assessments of physical risk factors can be achieved using different methods. While the ‘gold standard’ for measuring HR is by means of an electrocardiograph (ECG), this method is not feasible for field use. Instead, the use of heart rate monitors (HRMs) is commonly used for field based work physiology studies (Hodges et al., 2011; Sullman et al., 2000; Roberts, 2002; Trites et al., 1993; Kirk et al., 1996). Commercially available HRMs exist that may be worn unobtrusively on the wrist, arm, or chest, and are capable of continuously collecting HR data. The accuracy of these devices has been shown through validation studies comparing their use to that of the standard ECG (Weippert et al., 2010; Laukkanen et al., 1998).

1.4 Forestry industry sector

The southeastern U.S. experienced a massive increase in the volume of timber produced from the 1950s to the beginning of the 21st century. Specifically, southeastern pine productivity as measured by mean annual increment of pine plantations has more than doubled

(Wear et al., 2002). This increase in productivity and pine plantation acreage has resulted in the southeastern U.S. being referred to as the ‘wood basket of the world’. (Schultz, 1997). Through the conversion of some agricultural lands to natural forests and expected productivity gains, industrial wood output is projected to increase by more than 50 percent between 1995 and 2040 (Prestemon et al., 2002)

1.4.1 Hand planters

Reforestation is defined as the intentional restocking of depleted forests, which provides many valuable resources and amenities to our society including clean air and water, healthy habitats for wildlife, and recreational opportunities (USDA-FS, 2016). Reforestation in the southeastern U.S. is completed using a mix of manual hand planters and mechanical planters. Hand planting involves carrying a large bag of seedlings over the shoulder and planting the seedlings one at a time using a planting tool. Commonly used planting tools include a hoedad, which resembles an axe with a long blade, and a dibble bar, which is a narrow spade shovel. Typically, the planter forces the planting tool into the ground using the dominant arm and his or her foot to dig a hole for the seedling. He or she then reaches behind their back into the carried bag to remove a seedling, bends at the waist to place the seedling into the hole, and seals the hole with his or her hand or foot.

Planting crews range in size depending on the size of the acreage to be planted. Despite being physically demanding work (Giguere et al., 1993; Hodges et al., 2011; Roberts, 2002; Robinson et al., 1993; Trites et al., 1993), hand planting has been observed to provide a yield of nearly 95% survival (Stjernberg, 2003). Another benefit of hand planting is the high rate of production that is possible regardless of terrain conditions. Hand planters of containerized seedlings in eastern and central Canada have been observed to average 11.7 s per planting (Stjernberg, 1988). In British Columbia, average production rates were above 1,900 plantings per day or roughly 10 s per seedling (Stjernberg, 2003). Another survey of planters in Canada reported an average productivity of 1,245 plantings per day (Giguere et al., 1993), while Roberts (2002) observed a mean planting of 1,558 trees per day with some workers exceeding 2,400 trees per day. McDonald et al., 2008 observed that hand planting of bareroot seedlings with a dibble bar took 7 s or less for 70% of plantings. Assuming 60% productive time, the planting rate would be about 300 plantings per hour or 2,400 plantings across an 8-h shift. For these reasons, hand planting has been reported on six times more acres than machine planting (Folegatti et al., 2007).

1.4.2 Injury and illness data

The incidence rate for nonfatal occupational injuries and illnesses requiring days away from work for employees within the AFF occupation group was 126.8 per 10,000 full-time workers in 2015. This is markedly higher compared to an incidence rate of 104.0 for all occupations (BLS, 2015). Lynch et al. (2014) reported an increasing linear relationship of self-reported neck and back pain with increasing years spent in the logging industry within the southeastern U.S. This study also reported linearly increasing neck and back pain with increases in age and consistently higher neck and back pain reported among full-time loggers compared to part-time loggers.

Injury and illness data among hand planters is limited. A study on Canadian hand planters in British Columbia found that nearly 90% of tree planters surveyed experienced a work-related injury during their lifetime activity as a hand planter. The study found that within any given season, the average worker had a 75% chance of becoming injured (Smith, 1987). A separate survey of 48 male and female manual tree planters in Quebec, Canada found that 50% of workers reported a work-related injury during his or her planting career (Giguere et al., 1993). The Workplace Safety and Insurance Board in Ontario, Canada indicates that MSDs are the most common injuries among Ontario reforestation workers (Workplace Safety and Insurance Board, 2016; Slot et al., 2010a).

1.4.3 Exposure to physical risk factors

Literature examining the exposure of hand planter reforestation workers to physical risk factors is limited in comparison with other occupational industry sectors, such as manufacturing and health care. Few studies have been conducted in the U.S., and only a fraction of these have centered on hand planters in the southeastern U.S.

In Finland, Appelroth et al. (1970) recorded HR on hand planters in order to examine the effect of different tools on physical load. This study characterized the measured HR data as ‘moderate’ to ‘heavy’ work, corresponding with the heart rate severity guidelines outlined by Astrand et al. (1986). In a similar study conducted in Bulgaria, Mincheva et al. (1986) collected HR measurements on 21 female reforestation workers. These workers were involved in manual site preparation and hand planting activities. Results from this study suggest similar HR recordings indicative of comparable work loads to the Appelroth et al. (1970) sample, with higher work loads for site preparation compared to tree planting. Physiologic response to work among hand planters was estimated by Smith (1987). Their findings on maximum aerobic output (60% for long periods) suggested work loads comparable Appelroth et al. (1970) and Mincheva et al. (1986) based on the Astrand et al. (1986) work load severity guidelines. HR data collected in subsequent studies provides further evidence of ‘moderate’ to ‘heavy’ work demands among hand planters that may be a risk factor for injuries (Giguere et al., 1993; Trites et al., 1993; Roberts, 2002; Sullman et al., 2000; Hodges et al., 2011).

In 1988, the Forest Engineering Research Institute of Canada conducted a study on manual hand planting. The results of this observational study suggested that the tools available to hand planters were not adjustable and were designed without consideration for energy absorption during use (Stjernberg, 1988). Tools with a ‘D’-type handle were suggested as needing marked improvements to reduce the stress and strain on the worker. The results of this study further suggests that tree planting can be improved through changes to the organization of work that would reduce inefficiencies related to increased demands on the worker.

Trites et al. (1993) evaluated cardiovascular and muscle strain among 16 hand planters in British Columbia. The research team collected full-shift HR data, a daily diary of each workers' work-rest schedule, repeated blood samples over six sample dates during the first 32 days of the planting season, and the results of a standardized fitness test estimating aerobic fitness. A group mean working HR of 116.5 beats per minute suggests 'heavy' work, corroborated previous findings already discussed. Blood chemistry over the course of the season suggested some adaptation to the work load. Recommendations for this study were to further examine the work-rest cycle among hand planting activities over the course of the work day and planting season to improve worker well-being.

Roberts (2002) provided the most extensive evaluation of physiologic responses to the demands of prolonged hand planting work. HR, oxygen consumption, caloric intake, body mass, and cumulative stress were evaluated on 10 male hand planters over the course of 37 days within a planting season. Among this sample, two occupational injuries occurred (a severe infection and a knee strain injury). A detailed HR analysis showed HR between 60%-70% of maximum for over half of the planting shift. Indicators of heightened cumulative stress were found from increased resting cortisol, norepinephrine, and creatine kinase (CK) levels.

Working postures during hand planting has been investigated, and several studies have noted the cyclic, pronounced trunk flexion suggestive of low back MSDs (Giguere et al., 1993; Appelroth et al., 1970; Upjohn et al., 2008; Denbeigh et al., 2013; Slot et al., 2010b). Slot et al. (2010b) provides the working posture results of a study investigating different loading conditions of seedlings during planting. This study concluded that asymmetrical loading of seedling bags resulted in more neutral working postures, and provides a baseline of results for which future investigations of planting methods and equipment can be evaluated.

1.5 Work measurement

Work measurement methodologies employ a standardized approach to determining the duration of time required to perform work. This information can be used to improve production efficiencies by more accurately estimating labor requirements, predicting production schedules, and measuring individual or production team performance (Zandin, 2002). Vyse (1973) applied these methods to contemporary tree planting methods in British Columbia. This study, however, found the time to plant a bare root seedling to be 24.1 seconds. This rate is significantly slower than what has been observed as average bare root planting rates in subsequent studies (Roberts, 2002; Stjernberg, 1988; Stjernberg, 2003). Giguere et al. (1993) outlined a macro-level of primary elements of the planting cycle, while associating the performance of these elements by the worker with physiologic responses, but did not provide a standard for planting rate based on the elements identified. These included the percent of total shift time spent planting, traveling, restocking seedlings, and resting. While the literature is clear in the benefit of applying work study techniques to the hand planting cycle, the literature remains sparse in this area.

1.6 Limitations of existing research

While literature regarding the characterization of exposures to physical risk factors among hand planters exists, there has not been an extensive study conducted on hand planters in the southeastern U.S. Variability among hand planter tools and equipment provided to workers, environmental conditions, compensation strategies, worker populations, and production rates must be investigated to determine if previous studies are generalizable to this geographic region. Additionally, full-shift physical risk factor direct measurement within many occupational groups is challenging, and is likely the reason for the absence of data regarding full-shift forceful muscle exertions of the neck/shoulder. The added elements of an uncontrolled work environment and intense physical demands associated with hand planting magnify the potential impact of addressing this research gap.

Several studies have identified the potential reduction of injury risk from determining optimal tools for hand planters to employ, however the literature is sparse in the actual evaluation of tools currently available to reforestation employers. By determining if an optimal tool already exists that may reduce injuries, or identifying potential characteristics of tools (i.e. handle design, tool length, tool weight) that affect exposure to physical risk factors, overall injury risk may be reduced. Addressing this research gap may provide parties interested in reforestation injury prevention with crucial information that can lead to better decisions when purchasing tools for workers.

The application of work methods research to hand planter reforestation work is limited and non-existent among hand planters in the southeastern U.S. Previous studies have identified elements of the planting cycle, but a methodical approach to developing a planting standard is not currently available. A work methods standard for manual hand planting may provide more accurate expectations for acreage production to reforestation land owners and contractors, while potentially providing a better management strategy for the overall exposure to physical risk factors among hand planters.

1.6.1 Summary and specific aims

This dissertation was designed to expand upon the current literature regarding the characterization of physical risk factors associated with the incidence of MSDs among reforestation workers within the southeastern U.S. These physical risk factors include awkward and extreme non-neutral postures, forceful muscle exertions, intense physical activity, and excessive repetition. By applying direct measurement methods of assessing these physical risk factors objective estimates of risk can be determined. MSD incidence data and several studies suggest that reforestation workers are at a higher risk for work-related MSDs compared to other occupational groups. The current dissertation seeks to address the risk of reforestation worker MSD incidence through three specific aims that were developed in support of this goal: (1) Characterize physical risk factors for MSDs among hand planter reforestation workers in the southeastern U.S. through the use of direct measurement methods; (2) Compare commonly used planting tools in the southeastern U.S. and evaluate their effect on exposures to physical risk factors; (3) Apply work study techniques to the planting cycle employed by manual planters in order to develop a hand planting work standard.

The dissertation is organized into four additional chapters. Chapter 2 presents the results and conclusions from a field-based study investigating exposure to physical risk factors among fourteen hand planting reforestation workers using direct measurement methods. Chapter 3 presents the results and conclusions from a study evaluating the effect of tool design on physical risk factor exposure to hand planting work. Chapter 4 discusses the development and presentation of a work standard for hand planting reforestation work. Lastly, Chapter 5 will provide suggestions for future research studies and summarizes the major findings of this dissertation.

Chapter 2

A Characterization of Physical Risk Factors among Hand Planter Reforestation Workers

The study described in this chapter was published in an occupational ergonomics journal. The author requests that readers seek the published manuscript for the most relevant information and for citation purposes.

Granzow, R. F., Schall Jr., M. C., Smidt, M. F., Chen, H., Fethke, N. B., and Huangfu, R. (2018). Characterizing exposure to physical risk factors among reforestation hand planters in the Southeastern United States. *Applied Ergonomics*, *66*, 1–8. doi:10.1016/j.apergo.2017.07.013

2.1 Introduction

Reforestation, or the intentional restocking of depleted forests and woodlands, provides many valuable resources and amenities to our society including clean air and water, healthy habitats for wildlife, and recreational opportunities (USDA-FS, 2016). Quality seedlings and plantings are a requirement for successful reforestation (South et al., 1984). Planting quality is typically highest when performed by hand planting crews (Stjernberg, 2003).

Hand planting involves carrying a large bag of seedlings and planting them one at a time at a desired spacing using a planting tool (e.g., spade, hoedad, dibble bar, etc.) (Figure 2.1). Despite being physically demanding work (Giguere et al., 1993; Hodges et al., 2011; Roberts, 2002; Robinson et al., 1993; Trites et al., 1993), hand planting has been observed to provide a yield of nearly 95% (Stjernberg, 2003). Another benefit of hand planting is the high rate of production that is possible regardless of terrain conditions.

Although several studies are available describing the main elements of the planting cycle and the intensive cardiac demands of hand planters (Denbeigh et al., 2013; Giguere

Figure 2.1: A hand planter using a ‘T’ handle dibble bar to plant a seedling

et al., 1993; Hodges et al., 2011; Upjohn et al., 2008), limited information is available characterizing the full shift exposures to physical risk factors associated with the development of adverse musculoskeletal health outcomes. These physical risk factors include sustained and/or non-neutral postures of the low back and shoulder, high movement velocities, and forceful muscular exertions (da Costa et al., 2010). Characterizations of such exposures during a full work shift are needed to design tools and interventions capable of mitigating exposures and preventing the development of musculoskeletal conditions (Quandt et al., 2013). The objective of the present study, therefore, was to (i) characterize the trunk and upper arm postures, movement velocities, and neck and shoulder muscle activation patterns during full-shift work, and (ii) compare these findings with data from other available studies in order to evaluate the exposures to physical risk factors challenging hand planters.

2.2 Background

2.2.1 Hand planting production

Studies examining the planting rates of hand planters have been conducted within the reforestation sector. Stjernberg (1988) observed a planting rate of 11.7 seconds per planting among hand planters of containerized seedlings in eastern and central Canada. McDonald et al. (2008) observed a planting rate of 7 seconds per planting of bareroot seedlings among 70% of plantings. A conservative estimate of 60% of the work shift spent planting extrapolates that rate to 300 plantings per hour or 2,400 plantings across an 8 hour shift. Average daily productivity over the course of a planting season in Canada has been estimated as 1,245 plantings per day (Giguere et al., 1993). Planting rates can vary based on tool selection, the type of seedling planted, and environmental factors such as soil composition, ground temperatures, site preparation, and vegetation (McDonald et al., 2008).

2.2.2 Musculoskeletal disorders among forestry workers

A major cause of disability and lost productivity, work-related musculoskeletal disorders (MSDs) are widespread in the United States. MSDs represent approximately 32% of all non-fatal occupational injuries and illnesses across industry sectors (BLS, 2015). MSDs are the second most common cause of disability worldwide, and have increased 45% since 1990 (Horton, 2012; Vos et al., 2012). Workers in the U.S. Agriculture, Forestry, and Fishing (AFF) industry sector report among the highest rates of work-related MSDs across all industry sectors each year (e.g., second in 2013; BLS, 2014; third in 2014; BLS, 2015). Specifically among hand planters, stresses and strains on the body from repetitive motions and non-neutral working postures resulted in 38% of events resulting in lost-time injuries and illnesses among Ontario tree planters in 2015 (Workplace Safety and Insurance Board, 2016). Reducing injury rates through occupational injury prevention research can lead to increased productivity, higher job satisfaction among workers, and reduced costs that will benefit the AFF sector and reforestation workers in general.

2.3 Methods

2.3.1 Participants and study design

Fourteen male reforestation workers (mean age = 26.9 ± 6.0 years; mean body mass index = 24.8 ± 1.7 kg/m^2) were recruited from a reforestation contractor registered with the Alabama Forestry Commission for hand planting services in the state of Alabama. All of the participants enrolled in the study were seasonal workers employed through the H-2B visa program and were compensated on an hourly basis. Participants self-reported 1) no history of physician-diagnosed MSDs in the neck/shoulder or back regions, 2) no neck/shoulder or back pain two weeks prior to participation in the study, and 3) no history of neurodegenerative disease. All participants were right-hand dominant. Institutional Review Board approval of all study procedures from Auburn University was obtained prior to commencing study activities, and each participant provided written informed consent. Data were collected in the first quarter of the calendar year during the regular planting season.

2.3.2 Data collection procedures

Data were collected as subjects performed hand planting tasks. The work location varied based on the planting schedule, but each participant started and ended the workday in the same general plot of land. Each participant was observed for one full-shift. A research assistant shadowed each worker and recorded the time on a notepad (to the nearest minute) at which specific tasks began and ended. Tasks included 1) unloading boxes of tree seedlings from a cooler trailer, 2) loading seedlings into bag for planting, and 3) the actual hand planting of the seedlings. After the conclusion of the study each day, the research assistant transferred the field notes onto a computer for reference during data analysis.

2.3.3 Surface electromyography and forceful muscle exertions

Continuous surface electromyography (EMG) recordings were acquired from the bilateral upper trapezius and anterior deltoid muscles. Preamplified EMG electrodes (model SX230, Biometrics Ltd, Gwent, UK) were secured to the skin according to published guidelines (Cram et al., 1998). A reference electrode was attached to the skin over the non-dominant clavicle. The electrode cables were connected to a portable data logging system (DataLog, Biometrics Ltd, Gwent, UK). The raw EMG signals were sampled at 1000 Hz and stored on a compact memory card for analysis.

EMG signals were post-processed using custom LabVIEW software (version 2013, National Instruments, Inc., Austin, TX, USA). Unprocessed EMG signals were first visually scanned for transient artifacts which were subsequently removed and replaced with the mean voltage of the recording period. After resolving the transients, the mean voltage value of each unprocessed EMG file was subtracted in order to remove DC offset and the power spectral density of each EMG recording was examined to identify possible sources of interferences with the EMG signals (e.g., 60 Hz or electrocardiogram). If interference was detected, it was attenuated using standard filtering methods (Drake et al., 2006; Redfern et al., 1993). Each raw EMG recording was converted to instantaneous root-mean-square (RMS) amplitude using a 100-sample moving window with a 50-sample overlap.

Submaximal, isometric reference contractions were collected prior to the beginning of each participant's work shift. For the upper trapezius, the participant held a 2 kg weight in each hand with the upper arms abducted 90° in the scapular plane, elbows fully extended and forearms pronated (Fethke et al., 2015; Mathiassen et al., 1995). For the anterior deltoid, participants held a 2 kg weight in each hand with upper arms flexed forward to 90° of elevation and the elbows fully extended (Cook et al., 2004; Fethke et al., 2015; Rota et al., 2013; Yoo et al., 2010). RMS-processed EMG amplitudes during the work shift were expressed as a percentage of the RMS EMG amplitudes observed for the submaximal reference contractions (%RVE). Three repetitions of each reference contraction were performed, with a 1-minute rest between repetitions. Subjects maintained each contraction for roughly 15 seconds and the mean RMS amplitude of the middle 10 seconds was calculated. The average of the mean RMS EMG amplitudes of the three reference contractions was used as the RVE activation level. Baseline noise was defined as the lowest RMS EMG amplitude observed during the full-shift EMG recording and subtracted from all other RMS EMG amplitude values in a power sense (Jackson et al., 2009; Thorn et al., 2007).

The mean amplitude of the RMS signal for each muscle across the entire recording period was calculated as a global index of muscular load. Gaps in muscular activity were defined as any periods in which muscle activity fell below 5% RVE for at least 0.25 s (Hansson et al., 2000). Gap frequency was expressed as the number of gaps/min and muscular rest was defined as the summed duration of all gaps expressed as a percentage of total recording time. For each muscle, static, median, and peak amplitudes of muscle activity were calculated as the normalized RMS EMG amplitudes associated with the 10th, 50th, and 90th percentiles of the amplitude probability distribution function (APDF; (Jonsson, 1982)).

2.3.4 Direct measurement of posture, movement velocity, and rest/recovery

Direct measurements of non-neutral working postures were obtained using Actigraph GT9X Link inertial measurement units (IMUs) (Actigraph, Pensacola, Florida, USA). Specifically, four IMUs were affixed to each study participant on the 1) trunk (secured to the anterior torso at the sternal notch), 2) each upper arm (approximately one-half the distance between the lateral epicondyle and the acromion), and 3) on the dominant hip. Each IMU contained a tri-axial accelerometer, gyroscope, and magnetometer and stored data at a sampling rate of 100 Hz. Similar sensors have been used recently to characterize non-neutral postures and PA among laborers in other industries such as construction and health care (Arias et al., 2015; Schall Jr. et al., 2016a; Umukoro et al., 2013).

The transverse, sagittal, and longitudinal (i.e., vertical) axes were aligned to the x, y, and z-axis, respectively, of each trunk IMU using a rotation matrix. A first-order complementary filter combined the raw acceleration and angular velocity information obtained from each IMU to calculate inclination measurements relative to gravity. The complementary filter had the following generalized structure:

$$\theta_n = (1 - K)\ \Big[\theta_{n-1} + (\dot{\theta}_n \times dt)\Big] + K(\alpha_n) \tag{1}$$

where θ_n represents the complementary inclination angle estimate at the current sample, θ_{n-1} is the complementary inclination angle estimate at the previous sample, $\dot{\theta}$ is the angular velocity at the current sample, α_n is the inclination angle at the current sample based soley on the inclination of the accelerometer with respect to gravity, and dt is the time between samples (H. Chen et al., 2018; Schall Jr. et al., 2016a; Schall Jr. et al., 2014). α_n was calculated as $\tan^{-1}$ $(-Ax/\sqrt{Ay^2 + Az^2})$ for rotations about the sagittal axis and as $\tan^{-1}$ (Ay/Az) for rotations about the transverse axis. $\dot{\theta}_n$ was calculated according to procedures outlined by Von Marcard, 2010. An Euler rotation sequence of trunk lateral bending [right (+), left (−)] followed by trunk inclination [flexion (+), extension (−)] was used to ensure that trunk inclination was not constrained to a range of 180°.

For the upper arms, the local coordinate sensor frame was used. Specifically, the x, y, and z-axis of each upper arm IMU aligned with the sagittal, longitudinal (i.e., vertical), and transverse axis, respectively. Upper arm elevation was calculated as rotation about the sagitall axis with an offset of 90° added to ensure that upper arm elevation was between 0° and 180°. This approach was used to improve the accuracy of the inclination estimates given the high speed motions used by the planters. High speed motions have been observed to negatively affect the accuracy of inclination measurements derived solely from an accelerometer (Amasay et al., 2009; Bernmark et al., 2002; Ligorio et al., 2015). The complementary filter has shown RMS differences of 5.4° for the trunk and 8.5° for the upper arm in comparison to a 'gold-standard' optical motion capture system when used with IMUs similar to those employed in this study (Schall Jr. et al., 2016c). All inclination estimates were down sampled to 20 Hz using linear interpolation to match the effective sampling rate of the EMG data following RMS processing.

The resulting trunk and upper arm elevation waveforms were used to obtain median, peak, and static flexion and elevation levels. The peak flexion and elevation levels were defined as those associated with the 90th percentile of the APDF, while the static flexion and elevation levels were defined as those associated with the 10th percentile of the APDF. Differences between the estimates of the 90th and 10th percentiles (referred to as angular displacement variation) were calculated to estimate the range of motion for each body segment. ‘Extreme’ postures were defined as having the trunk flexed $\geq$45°, the trunk laterally bent $\geq$30°, and/or the upper arms elevated $\geq$60°. ‘Neutral’ postures were defined as having the trunk flexed <20°, the trunk laterally bent <15°, and/or the upper arms elevated <30°.

The angular displacement waveforms of trunk flexion/extension and upper arm elevation were differentiated and full-wave rectified to obtain movement velocities. Consistent with previous studies (Douphrate et al., 2012; Kazmierczak et al., 2005; Schall Jr. et al., 2016b; Wahlström et al., 2010), exposure metrics included the proportion of time working with high ($\geq$90° per second) and low (<5° per second) angular velocities and selected percentiles (10th, 50th, 90th, and the difference between 90th and 10th) of the APDF. ‘Rest’ and ‘recovery’ descriptive variables were computed for contextual purposes. ‘Rest’ was defined as having the trunk or upper arm in a neutral posture (<20° for trunk flexion and <30° for the arms) and moving with an angular velocity of <5° per second. ‘Recovery’ periods were defined as the number of times per minute of substantial periods ($\geq$3 seconds) in a neutral posture.

2.3.5 Occupational physical activity

Full shift occupational physical activity summary measures were obtained from the IMUs using availabe software (ActiLife 6.13, Actigraph, Pensacola, Florida USA). The energy cost of PA was determined by calculating metabolic equivalents (METs) from the acceleration data obtained from the IMU worn on the dominant hip. Physical activity software was used to obtain the METs according to an energy expenditure algorithm described in (Freedson et al., 1998). Categorization of PA intensity were sedentary (1.0 - 1.5 METs), ‘light’ (1.5 -

3 METs), ‘moderate’ (3.0 - 6.0 METs), and ‘intensive/vigorous’ (> 6 METs) per standard definitions (Whaley et al., 2005).

2.3.6 Statistical analysis

Each posture, movement velocity, and rest/recovery exposure metric was described with descriptive statistics (mean, standard deviation [SD]) across all participants. The frequencies and durations of planting and non-planting activities were described using proportions, means and SDs, respectively.

2.4 Results

The average shift length for the 14 hand planters that participated in this study was 433.9 (SD = 88.0) minutes. Planting comprised 75.8% of the shift time. The remaining 24.2% of the shift time was comprised of non-planting activities such as loading seedlings into bags, shaking and striking of seedlings against objects in order to dislodge ice particles, unloading and carrying the boxes of seedlings to staging areas inaccessible by vehicles, and a lunch break. The planters were observed to expend an average of 3.1 METs (SD = 0.7) during the course of a shift.

2.4.1 Full-shift planting muscle activity levels

Descriptive statistics and probabilities for the bilateral upper trapezius and anterior deltoid EMG summary measures are provided in Table 2.1. In general, muscle activity was greater in the dominant (right) arm than the non-dominant (left) arm regardless of summary metric. Additionally, muscular effort associated wtih planting was observed to be greater than non-planting activities such as placing seedlings in bags before engaging in planting.

It should be noted that four participants’ right anterior deltoid, two participants’ left anterior deltoid, one participant’s right trapezius, and two participant’s left trapezius EMG recordings were excluded from the analyses. For these participants, the integrity of the skin-to-electrode interface was compromised by task-related electrode contact resulting in an obvious loss of signal quality. Additionally, the EMG data for two participants was lost due to instrumentation failure. None of the EMG data from these participants was included in the analysis.

Table 2.1: Distributions of full-shift, hand planting, and non-planting occupational tasks EMG summary measures by muscle.

Exposure Variable	**Full Shift**		**Planting**		**Non-planting**	
Right Upper Trapezius (N=11)	Mean	SD	Mean	SD	Mean	SD
Mean RMS (%RVE)	54.1	24.4	56.7	24.8	44.4	24.2
10th Percentile APDF (%RVE)	7.0	4.1	7.5	4.4	5.1	3.0
50th Percentile APDF (%RVE)	37.5	18.9	39.0	19.8	31.8	18.4
90th Percentile APDF (%RVE)	122.5	54.4	129.1	55.1	97.5	55.3
Muscle Rest (% time)	8.6	9.4	6.8	8.5	14.8	13.7
Gaps / Min	6.7	5.6	6.0	6.1	9.2	5.5
Left Upper Trapezius (N=10)	Mean	SD	Mean	SD	Mean	SD
Mean RMS (%RVE)	42.1	13.5	43.7	14.1	36.5	13.2
10th Percentile APDF (%RVE)	5.6	3.2	5.9	3.5	4.5	2.5
50th Percentile APDF (%RVE)	31.5	15.8	33.7	16.6	23.3	14.7
90th Percentile APDF (%RVE)	94.8	27.4	97.2	27.3	86.3	33.4
Muscle Rest (% time)	14.4	21.5	12.7	22.6	20.8	18.0
Gaps / Min	12.3	7.7	10.3	7.7	20.3	13.5
Right Anterior Deltoid (N=8)	Mean	SD	Mean	SD	Mean	SD
Mean RMS (%RVE)	31.4	16.8	34.8	19.7	20.6	10.3
10th Percentile APDF (%RVE)	4.8	4.3	5.4	4.9	2.5	2.0
50th Percentile APDF (%RVE)	17.2	13.9	19.5	16.2	9.2	6.5
90th Percentile APDF (%RVE)	75.9	33.3	83.1	37.1	52.8	23.9
Muscle Rest (% time)	23.2	20.9	19.5	21.0	34.8	21.1
Gaps / Min	14.3	11.2	13.4	12.7	17.6	7.6
Left Anterior Deltoid (N=10)	Mean	SD	Mean	SD	Mean	SD
Mean RMS (%RVE)	17.0	5.7	18.3	6.7	13.4	4.6
10th Percentile APDF (%RVE)	2.2	0.7	2.4	0.7	1.6	0.7
50th Percentile APDF (%RVE)	7.8	4.0	8.7	4.6	5.4	2.9
90th Percentile APDF (%RVE)	43.6	13.7	47.3	17.0	33.2	11.7
Muscle Rest (% time)	36.6	18.9	33.4	19.9	46.0	16.6
Gaps / Min	22.8	7.2	22.7	5.8	24.7	13.7

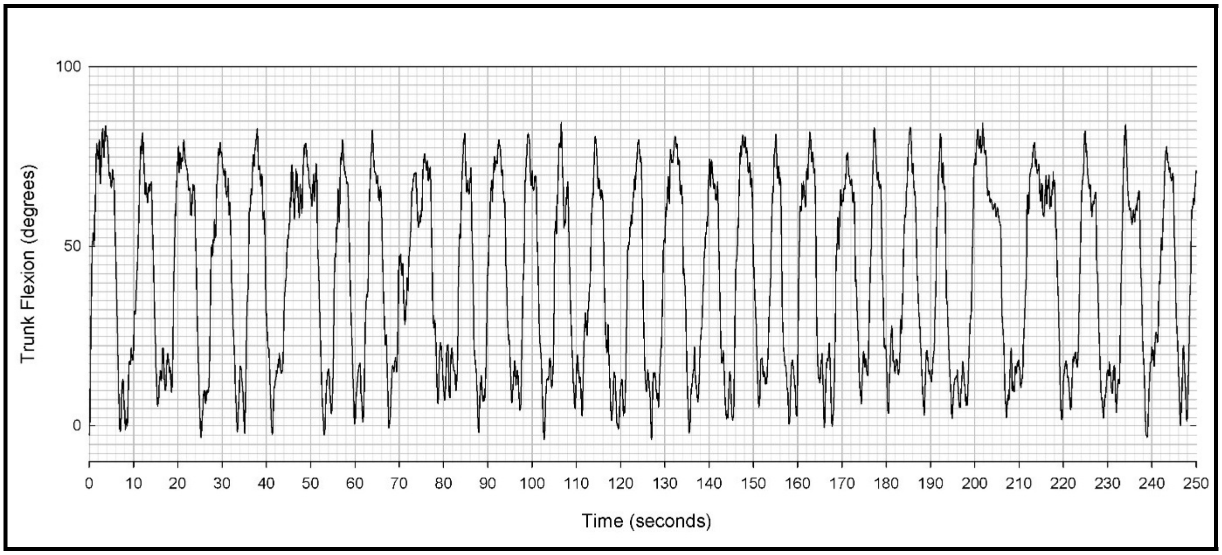


Figure 2.2: Representative 5 min segment of trunk flexion during hand planting for one participant illustrating the repetitive nature of the task.

2.4.2 Full-shift planting non-neutral working postures and movement velocities

Hand planters in this study were observed to spend a large percentage of their work time in extreme postures and moving at high velocities (Tables 2.2 and 2.3). Specifically, 32.5% of the observed work time was spent with the trunk flexed ≥45°, 10.1% of the work time was spent with the left arm elevated ≥60°, and 15.2% of the work time was spent with the right arm elevated ≥60°. On average, roughly 2.5% of work time was spent flexing the trunk at a high velocity (≥90°/s). The left arm was moving at a high velocity for 2.6% of the work shift, while the right arm moved at a high velocity for 11.9% of the work shift.

In addition to the elevated movement velocities and sustained non-neutral working postures, hand planters had few opportunities for rest and recovery. Hand planters spent 12.2% and 11.1% of their work time with the left and right upper arms in a neutral posture (<30°) and moving at a low velocity (<5°/s), respectively. Similarly, hand planters spent only 11.3% of their work time with the trunk flexed in a neutral posture (<20°) and moving at a low velocity (<5°/s). Figure 2.2 illustrates the repetitive nature of hand planting that requires extreme trunk flexion with very few opportunities for rest.

It should be noted that one participant's right arm elevation data was excluded as the participant felt the IMU was obstructive to his natural motion. Two participants' entire posture recordings were excluded from the analyses due to pre-shift battery charging failure.

Table 2.2: Distributions of full-shift, hand planting, and non-planting occupational tasks postural summary measures for the trunk.

Exposure Variable	**Flexion**						**Lateral Bending**					
	Full Shift		Planting		Non-planting		Full Shift		Planting		Non-planting	
Posture[a]	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10th percentile (°)	-1.4	11.7	0.0	11.2	-6.1	16.1	-14.0	7.5	-15.1	8.2	-9.1	6.6
50th percentile (°)	23.2	14.8	24.0	15.3	20.4	21.7	-1.3	6.5	-1.9	4.7	0.0	6.3
90th percentile (°)	75.2	14.6	80.2	14.1	57.0	25.9	9.4	6.3	9.7	4.9	9.2	6.8
Time in neutral posture (<15°)(%)	-	-	-	-	-	-	83.0	7.9	79.6	9.9	90.2	6.0
Time in neutral posture (<20°)(%)	40.3	12.6	38.9	13.4	43.6	16.3	-	-	-	-	-	-
Time in extreme posture (≥30°)(%)	-	-	-	-	-	-	0.2	0.3	0.2	0.3	0.2	0.4
Time in extreme posture (≥45°)(%)	32.5	10.6	34.4	10.9	27.0	17.3	-	-	-	-	-	-
Movement velocity	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10th percentile (°/s)	2.3	0.4	2.8	0.3	0.9	0.3	1.6	0.4	1.8	0.4	0.7	0.3
50th percentile (°/s)	15.9	2.5	18.6	2.4	6.7	1.7	12.3	1.9	14.1	1.8	5.6	2.2
90th percentile (°/s)	53.9	7.3	61.1	7.9	30.1	5.5	38.0	5.2	41.5	5.4	24.3	6.5
Time at low velocities (<5°/s)(%)	23.8	3.5	17.5	2.0	48.0	13.4	29.6	4.4	22.9	3.5	54.0	12.5
Time at high velocities (≥90°/s)(%)	2.5	1.1	3.1	1.4	0.6	0.3	0.4	0.3	0.5	0.3	0.1	0.1
Rest/Recovery	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Time in neutral posture (<15°) for substantial periods (≥3s)(%)	-	-	-	-	-	-	64.1	14.0	58.3	15.5	80.6	10.5
Time in neutral posture (<20°) for substantial periods (≥3s)(%)	36.6	12.5	32.6	14.3	44.5	17.7	-	-	-	-	-	-
Time at low velocities for substantial periods (≥3s)(%)	3.6	1.7	0.5	0.3	13.7	6.5	7.3	2.9	2.7	1.6	22.4	10.1
Time in neutral posture (<15°) and low velocity (%)	-	-	-	-	-	-	25.9	4.6	19.4	3.8	46.5	9.8
Time in neutral posture (<20°) and low velocity (%)	11.3	3.5	8.7	2.4	19.3	8.3	-	-	-	-	-	-

[a] Negative values denote trunk extension or lateral bending to the left; Positive values denote trunk flexion or lateral bending to the right.

Table 2.3: Distributions of full-shift, hand planting, and non-planting occupational tasks postural summary measures for the upper arms.

Exposure Variable	**Left Arm Elevation**						**Right Arm Elevation**					
	Full Shift		Planting		Non-planting		Full Shift		Planting		Non-planting	
Posture	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10th percentile (°)	16.0	3.1	16.5	3.2	14.1	3.7	15.8	3.4	15.8	3.7	15.6	3.5
50th percentile (°)	33.0	3.3	34.1	4.0	29.0	3.1	32.5	5.0	33.3	5.4	29.4	4.7
90th percentile (°)	59.5	10.2	61.2	10.8	53.4	10.3	67.5	7.9	70.9	8.6	55.4	13.3
Time in neutral posture (<30°)(%)	43.1	6.9	39.7	8.4	54.7	10.0	45.6	9.1	43.3	8.9	53.7	12.7
Time in extreme posture (≥60°)(%)	10.1	6.7	10.9	7.6	7.1	4.8	15.2	5.7	16.9	6.5	8.7	5.1
Movement velocity	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10th percentile (°/s)	2.3	0.4	2.6	0.4	1.1	0.5	3.1	0.9	3.7	1.1	1.2	0.5
50th percentile (°/s)	15.5	2.6	17.5	2.1	9.2	3.5	24.1	5.6	27.7	6.0	11.7	3.7
90th percentile (°/s)	52.4	8.9	56.3	8.6	39.9	10.4	97.4	17.9	111.4	19.1	49.7	11.4
Time at low velocities (<5°/s)(%)	22.9	3.7	17.9	2.2	38.2	8.5	18.3	3.5	13.6	2.6	33.9	8.1
Time at high velocities (≥90°/s)(%)	2.6	1.5	3.0	1.6	1.6	1.1	11.9	3.9	14.5	4.4	3.0	1.5
Rest/Recovery	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Time in neutral posture (<30°) for substantial periods (≥3s)(%)	21.0	7.8	15.5	8.7	39.5	10.7	21.3	9.3	17.1	8.8	35.8	13.1
Time at low velocities for substantial periods (≥3s)(%)	4.5	1.8	1.4	1.2	13.9	5.8	4.1	1.6	1.4	1.1	13.0	5.8
Time in neutral posture (<30°) and low velocity (%)	12.2	2.5	8.6	1.9	23.5	7.1	11.1	3.3	8.6	2.6	19.0	6.0

2.5 Discussion

Health and safety outcomes among hand planters and other AFF workers are generally not well understood and are under-studied. Vulnerability due to immigration/seasonal worker status, language difficulties, and adverse working conditions likely contribute to the lack of research (Grzywacz et al., 2013; McDaniel et al., 2005; Sarathy et al., 2008). The few studies that have been performed among hand planters have concluded that strenuous work pace, inadequate rest periods, and poor living conditions may have negative effects on planter safety and health (Giguere et al., 1993; Hodges et al., 2011; Roberts, 2002; Trites et al., 1993). The results of the current study contribute to the scientific literature by providing novel information regarding hand planter exposures to physical risk factors that are associated with work-related MSDs in the Southeastern United States.

2.5.1 Occupational physical activity

In general, hand planters were exposed to high levels of occupational PA. 'Vigorous' and 'very vigorous' was measured to be the predominant PA intensity levels exhibited by the workers for the left and right arms (63.1% and 73.5% of shift duration, respectively). Similarly, 'moderate', 'vigorous', and 'very vigorous' PA comprised 84.1% of the hand planters' work shifts when using data from the IMU secured to the right hip, the most common location for assessing PA Freedson et al., 2012; Welk et al., 2012. This is dramatically higher than what has been measured among registered nurses (7.9%; Schall Jr. et al., 2016b), construction workers (12.0%; Arias et al., 2015), and patient care workers (1.0%; Umukoro et al., 2013). Average METs for the present study indicate comparable summary values with other AFF workers, and higher METs than production health care support occupational groups (Tudor-Locke et al., 2011).

2.5.2 Posture and movement velocities

Results from the present study indicate that hand planters are exposed to higher levels of extreme postures and movement velocities for the upper arms and trunk when compared to several other occupational groups that report a high prevalence of work-related MSDs. Hand planters in the present study were observed to exhibit a mean 90th percentile trunk inclination angle of 75.2°. This was greater than material pickers (26.0°; Christmansson et al., 2002), poultry processing workers (16.0°; Juul-Kristensen et al., 2001), automobile assembly workers (40.2°; Kazmierczak et al., 2005), and registered nurses (35.9°; Schall Jr. et al., 2016b). Trunk flexion ≥45° was measured for 32.5% of the work shift, presumably due to the high frequency of forward bending to plant seedlings at ground level (Figure 2.2). While this result is less than what has been observed among hand planters in Northern Ontario (Slot et al., 2010b; Upjohn et al., 2008), it exceeds values measured among registered nurses (6.1%; Schall Jr. et al., 2016b). Differences with the hand planters from Northern Ontario may be explained by the use of a different planting tool ('D' handle spade), terrain, and factors related to the experience and personal characteristics of the two study samples.

Previous studies suggest that routine exposure to elevated arm positions and high movement velocities may be associated with increased risk of shoulder MSDs (Hanvold et al., 2015; Putz-Anderson et al., 1997; Svendsen et al., 2004a; Svendsen et al., 2004b). Arm elevation results in this study indicate that hand planters are exposed to mean dominant arm elevations of 37.7° for the right arm and 35.7° for the left arm, which is higher than what has been observed for apple orchard workers (22.7° and 19.2° for the right and left arm, respectively; Thamsuwan et al., 2015). Mean 90th percentile arm elevation angles of 67.5° and 59.5° were observed for the right and left arm, respectively. Dairy parlor workers (71.9° right arm and 61.3° left arm) were observed to be exposed to higher levels of exposure (Douphrate et al., 2012), while poultry processing workers (42° right arm and 41° left arm) were observed to exhibit lower levels (Juul-Kristensen et al., 2001). High movement velocities were also measured for the right and left upper arms (mean 90th percentile of 97.4°/s and 52.4°/s, respectively). These movement velocities were greater than those observed in studies of air traffic controllers (37.0°/s and 31.0°/s; Arvidsson et al., 2006) and lower than that observed among dairy parlor workers (148.0°/s and 134.9°/s; Douphrate et al., 2012).

2.5.3 Muscle activity

Studies examining full shift anterior deltoid muscle activity are limited in the scientific literature. A recent study examining muscular effort of faculty ophthalmologists using comparable reference voluntary contraction procedures indicated considerably lower muscle activity exposures of the dominant (right) arm anterior deltoid muscle group among ophthalmologists (mean = 13.5 %RVE and 90th percentile APDF = 35.7 %RVE; Fethke et al., 2015) when compared to the hand planters in the present study (mean = 31.4 %RVE and 90th percentile APDF = 75.9 %RVE). However, it is important to note that ophthalmologists were observed to have greater muscle activity exposures of the non-dominant (left) arm anterior deltoid muscle group (mean = 14.4 %RVE and 90th percentile APDF = 35.8 %RVE; Fethke et al., 2015) in comparison to the hand planters in this study (mean = 17.0 %RVE and 90th percentile APDF = 43.6 %RVE). This result, as well as the documented increased muscle activity required of the dominant (right) arm anterior deltoid muscle group during planting only (mean = 34.8 %RVE and 90th percentile APDF = 83.1 %RVE; Table 2.1), demonstrates the high intensity work required of hand planters while using a dibble bar to plant. The increased anterior deltoid muscle activity among hand planters suggests that hand planters may be at increased risk for developing neck/shoulder discomfort and/or MSDs similar to ophthalmologists, an occupational group that reports a high prevalence of neck/shoulder pain (Kitzmann et al., 2012).

While available research on upper trapezius muscle activity is more widely available, variability in normalization procedures limits comparisons. Dominant upper trapezius 90th percentile mean APDF full shift results suggest hand planters experience markedly higher trapezius muscle activity (122.5 %RVE) when compared to stud welders (54.1%; Fethke et al., 2011), faculty ophthalmologists (37.4%; Fethke et al., 2015), office workers (61.1%), custodians (64.1%), and maintenance workers at a university (77.5%; Fethke et al., 2012).

Although the act of planting with a dibble bar was the most demanding task performed by the hand planters, muscle activity during non-planting work tasks was also observed to be relatively high. Non-planting tasks include rigorous shaking and striking of seedlings against objects in order to dislodge ice particles prior to placing in bags, as well as unloading and carrying the boxes of seedlings to staging areas inaccessible by vehicles. These physically demanding work tasks likely contribute to the high levels of muscle activity observed during the non-planting portion of the work shift and suggest that all aspects of hand planting may benefit from increased research attention. Dominant upper trapezius muscle rest (% of time during shift) results indicate hand planters experience fewer opportunities for rest (average of 8.6%) when compared to the faculty ophthalmologists (31.4%; Fethke et al., 2015), stud welders (39.5%; Fethke et al., 2011), university custodial (19.8%), maintenance (11.9%), and office workers (17.4%; Fethke et al., 2012).

2.5.4 Interventions

Available research regarding interventions for reducing exposure to physical risk factors for MSDs among hand planters is limited. Administrative controls, such as improvements in worker training, may not have substantial potential for reducing planting workload since work pace rather than work efficiency is related to higher productivity (Hodges et al., 2011). However, it is important to note that Hodges and Kennedy studied hand planters in Canada that were compensated via a piece rate strategy in comparison to the hand planters in this study that were compensated at an hourly rate. Planter's choice of tool for efficiency may contribute to injury and ergonomic risks (Robinson et al., 1993). Development of an ambidextrous planting tool or methodology may help to decrease the disparity of muscle activity between dominant and non-dominant muscle groups and potentially help prevent the development of MSDs among hand planters. Ground conditions may also be an important factor when considering physical demands during the planting process. Frozen ground in the morning is an environmental condition that can change the force requirements for the worker to reach planting depth in the soil. Further investigation into environmental and soil variations may provide insight into ideal planting conditions for the reduction of worker physical stress.

2.5.5 Study limitations

Several limitations of this feasibility study should be acknowledged. First, a small sample size of geographically homogenous workers limits the generalizability of the results to the wider field of hand planting reforestation work. This study did however show comparable average planting time (75.8%) to the 71-94% observed in a previous study (Hodges et al., 2011). The participants were not asked their level of experience. Reports from the contractors suggests that experience levels among the planters varied, with some workers being first year planters while others had over 10 years of experience. However, it is unknown which participants had more experience. Second, the hand planters recruited for this study were paid on an hourly compensation scale which differs from the piece rate payment strategy that is often used among hand planters. The exposures to physical risk factors observed in this study therefore, may not be representative of the exposures among hand planters paid via a piece rate payment strategy. Third, time constraints in the field for data collection made it infeasible to collect low back EMG data in the present study. The addition of low back muscle activation data would allow for a more thorough characterization of the physical risk factors associated with hand planting and is recommended for future studies when feasible. Fourth, observation of planting occurred on sites that were typical of planting sites in the Southeastern United States, but do not represent the full range of planting site variability with regard to slope, obstacles, and soil strength and depth.

The intense physical demands of hand planting presents a challenge to future research involving direct measurement of physical risk factors. The location of the seedling bag worn near the EMG sensors on the neck/shoulders may result in a loss of EMG electrode-skin contact when donning and doffing the bag, as well as unintended electrode impact. While water-proof protective sealants and tapes were used to reduce the potential of compromising the skin-electrode interface, loss of some participants' EMG data did still occur in this study. The average length of the analyzed EMG recordings was 329.4 minutes (with 78.7% consisting of planting and 21.3% other activities). The reported findings should, therefore, be interpreted pragmatically until additional data may be collected and more precise estimates of exposure can be developed. Finally, this study did not address certain job stressors, such as psychosocial stress and time pressure, which are commonly associated with MSDs (da Costa et al., 2010; Hagen et al., 1998). Research evaluating the broad spectrum of work demands challenging hand planters is needed. This includes further assessment of the effects of the seedling bag weight and design on muscle activity and posture. More research is also needed to understand the exposures to risk factors of mechanized planting, an alternative to hand planting for reforestation.

2.6 Conclusions

Results of this study indicate that hand planters are exposed to a combination of high effort muscular exertions, non-neutral working postures, generation of high movement speeds, and generally physically intensive labor that place them at increased risk for the development of neck, shoulder, and low back MSDs. The findings indicate a need for continued field-based research among hand planters to identify and/or develop maximally effective intervention strategies and tools.

Chapter 3

Measuring the Effect of Tool Design on Exposure to Physical Risk Factors among Novice Hand Planters

3.1 Introduction

Work-related musculoskeletal disorders (MSDs) accounted for approximately 31 percent of all nonfatal workplace injuries and illnesses across U.S. industries in 2015 (BLS, 2016). The MSD incidence rate among workers within the Agriculture, Fishing, and Forestry (AFF) sector (39.6 per 10,000 full-time workers) exceeded those in all other industry sectors (BLS, 2016). Reforestation hand planters represent an important subset of the AFF sector responsible for replenishing U.S. forests through the planting of seedlings. In the southeastern U.S., the planting season typically runs from December through April and hand planting is almost exclusively performed by seasonal migrant workers (McDaniel et al., 2005). Planting takes place on tracts of land by workers carrying a bag of seedlings and using a 'dibble' or planting bar to dig a hole for the seedling. After a hole has been made in the soil, the worker reaches behind his or her back to remove a seedling from the bag, bends at the waist to place the seedling into the hole, and then seals the hole with his or her foot (Granzow et al., 2018). The task is repeated throughout the work shift, with some studies reporting more than 3,000 seedlings planted per worker per day (Trites et al., 1993).

Physical risk factors associated with the development of MSDs include non-neutral working postures, forceful muscle exertions, and excessive repetition of motions (da Costa et al., 2010). Previous studies have characterized exposures to physical risk factors among reforestation hand planters (Granzow et al., 2018; Giguere et al., 1993; Hodges et al., 2011; Roberts, 2002; Robinson et al., 1993; Trites et al., 1993; Denbeigh et al., 2013). Results of those studies have suggested that the work demands associated with hand planting places

Figure 3.1: Research assistant demonstrating hand planting process.

reforestation hand planters at increased risk for MSDs (Slot et al., 2010a). Among Canadian hand planters 62% of lost time injuries are the result of strains, sprains, and tears (Ontario Forestry Safe Workplace Association (OFSWA), 2006; Slot, 2010).

The design of hand planting tools has been posited by some previous research teams as a means to potentially reduce exposures to physical risk factors among hand planters (Giguere et al., 1993; Denbeigh et al., 2013). However, the available literature lacks comparisons of direct measurement evaluations of exposures to physical risk factors among planters while using different tools. The objective of this study was to evaluate and compare exposures to physical risk factors measured among novice hand planters using four different commercially available tools. It was hypothesized that the design of certain tools (e.g. pointed vs. flat edge) may lead to reductions in exposures to physical risk factors. This information could prove valuable to hand planters and contractors interested in reducing injuries and improving productivity through a reduction in lost time due to MSD symptoms and injuries.

3.2 Methods

3.2.1 Study participants

Fourteen male participants (mean age = 26.9 ± 3.8 years; mean height = 178.4 ± 2.4 cm; mean body mass index [BMI] = 24.8 ± 3.2 kg/m^2) were recruited from the Auburn University community. Participation criteria included a measured BMI of <30 kg/m^2 and self-reporting: 1) no history of physician-diagnosed MSDs in the neck/shoulder or back regions, 2) no neck/shoulder or back pain within two weeks prior to participation in the study, and 3) no history of neurodegenerative disease. All participants were right-hand dominant. The study took place on a tract of cleared land that was prepared for professional reforestation (Figure 3.2). The study was approved by the Auburn University Institutional Review Board and each participant provided informed consent. Each participant received $25.00 compensation for participation in the study.

Figure 3.2: Experiment planting location.

3.2.2 Instrumentation and Data Collection

Heart Rate

Participants were fitted with a chest-worn heart rate (HR) monitor (Polar H10) that wirelessly transmitted data to a data logging watch (Polar M400) worn by a research team member. Resting HR ($\mathrm{HR_{REST}}$) was determined prior to data collection by having the subject sit in a relaxed position for several minutes until the subject's HR reached a constant (±3 $\mathrm{beats_{-1}}$·min) rate for 60 seconds. Working HR ($\mathrm{HR_{WORK}}$) was determined as the arithmetic mean of heart rates measured over the course of each trial (Jankovský et al., 2017). $\mathrm{HR_{WORK}}$ and $\mathrm{HR_{REST}}$ were used to calculate absolute heart rate (AHR):

$$AHR = HR_{WORK} - HR_{REST}$$

which is an indicator of the increment of HR due to work (Jankovský et al., 2017).

Age-predicted maximal HR ($\mathrm{HR_{MAX}}$) was calculated as 208 – 0.7 × age (Tanaka et al., 2001; Gellish et al., 2007). In addition to AHR, HR summary measures were expressed according to:

$$Ratio = \frac{HR_{WORK}}{HR_{REST}}$$

which provides a normalized ratio of working HR to resting HR for each participant (Diament et al., 1968; Kirk et al., 2001).

Posture

A three-dimensional motion capture system was used to collect upper-body kinematic data from each participant during planting (Xsens, Enschede, Netherlands). Specifically, the Xsens system involved securing 11 inertial measurement units (IMUs) to the sternum, pelvis, bilateral upper arms, bilateral forearms, hands, shoulders, and head. The system was calibrated prior to data collection per manufacturer guidelines. Xsens MVN Studio (Version 4.2) software was used for exporting the posture data into Extensible Markup Language (XML) structured files for analysis.

A custom Python (version 3.5) program was used to calculate posture summary measures of the trunk, dominant upper arm, bilateral wrists, and neck. Percentiles of the amplitude probability distribution function (APDF) were determined for each body segment using a custom Python program and the NumPy package (version 1.13). Percent time in neutral and extreme postures were determined for the trunk, with threshold values determined according to previously published research (Granzow et al., 2018; Schall Jr. et al., 2016b; Douphrate et al., 2012).

Muscle Activity

Pre-amplified surface electromyography (EMG) electrodes (Model SC230, Biometrics Ltd, Gwent, UK) connected to a belt-worn data logger (Datalog MWX8, Biometrics Ltd., UK) were used to continuously digitize raw EMG signals of the bilateral upper trapezius and anterior deltoid muscles at a sampling rate of 1,000 Hz. Electrodes were secured using published guidelines (Criswell, 2010). The EMG signals were post-processed using custom LabVIEW (version 2013, National Instruments, Inc., Austin, TX, USA) and Python (version 3.5) software. For each muscle, the mean voltage value of each unprocessed EMG signal was subtracted in order to remove DC offset. The file was visually scanned for the presence of electrocardiogram and/or electromagnetic (i.e., 60 Hz) interference. If interference was detected, it was attenuated using standard filtering methods (Drake et al., 2006; Redfern et al., 1993). Transient artifacts were also removed and replaced with the mean voltage of the recording period. Each raw EMG recording was converted to instantaneous root-mean-square (RMS) amplitude using a 100-sample moving window with a 50-sample overlap.

Forceful muscle exertions were expressed as percentages of maximal isometric contractions (%MVC), which were collected prior to the beginning of the participants' planting trials. The contractions were performed against manual resistance applied at the wrist by a research assistant while the arms were forward flexed to 120° with the elbows in full extension. The participant was instructed to maintain the maximal contraction for 5 seconds. Three repetitions of MVCs were performed, with a 2.5-minute rest between each contraction. The maximum RMS amplitude of the middle 3 seconds of each contraction was used for both the upper trapezius and anterior deltoid muscle groups (Douphrate et al., 2017; Boettcher et al., 2008). The maximum RMS EMG amplitude across all three MVCs was identified as the absolute maximum (Douphrate et al., 2017; Mathiassen et al., 1995). An EMG recording while the subject was resting was collected prior to the MVCs. The minimum RMS EMG amplitude among all of the recordings, including the resting recording, was determined to be the baseline noise and was subtracted from all other RMS EMG amplitude values in a power sense (Thorn et al., 2007; Jackson et al., 2009). In addition to MVCs, submaximal reference voluntary exertions (RVEs) were collected following the methods described in Chapter 2 and working forceful exertions were normalized.

The mean amplitude of the normalized RMS signal for each muscle across the entire recording period was calculated as an index of overall muscular load. Static (10th percentile), median (50th percentile), and peak (90th percentile) amplitudes of muscle activity were also calculated for each muscle using the APDF (Jonsson, 1982).

3.2.3 Experimental Procedures

After the participant was fitted with the HR, EMG, and Xsens systems and the resting HR, reference muscle exertions, and motion capture calibrations were completed, the participant was trained in the hand planting process. The participant was trained using a standard video produced by a professional forestry sector educator (Texas A&M Forest Service, 2012). After watching the training video, each participant practiced planting until they passed a qualitative assessment of planting quality assessed by a research team member. The assessment evaluated proper depth of planting and soil compaction around the seedling.

Figure 3.3: (a) KBC ‘Short’. (B) ‘OST’ Dibble Bar (Jim-Gem MPN 69042). (c) ‘Speedy’ Dibble Bar (Jim-Gem MPN 69048). (d) KBC ‘Long’

Once trained, each participant was provided a tool in a random sequence. The four tools are shown in Figure 3.3 and the weight and height of each tool is shown in Table 3.1.

Table 3.1: Tool characteristics

Tool	Weight (kg)	Length (cm)
Jim-Gem® KBC 'Short'	4.7	96.8
Jim-Gem® OST dibble bar	3.3	96.5
Jim-Gem® Speedy dibble bar	3.0	92.0
Jim-Gem® KBC 'Long'	4.3	105.4

Planting locations were established prior to the trials by marking a typical planting route for 30 trees with flags. The direct measurement systems were started by the research assistant and the participant began planting seedlings. The trial ended after 30 seedlings were planted. After each trial, the participant rested until their HR_{REST} returned to within ± 5 beats^{-1}·min of the previously established HR_{REST}. The participant was provided the next randomly assigned tool and the next trial began. This was repeated for each of the 4 tools.

3.2.4 Data Reduction and Statistical Analysis

HR, EMG, and Xsens data files were synchronized and data quality checks were performed before any statistical analysis was performed. Substantial loss of signal due to wireless transmission failure or data file corruption resulted in three HR trials and three posture trials being lost. Four participants' posture data (all trials) were not measured due to signal interference in the testing location. Four left deltoid muscle group recordings were removed from analysis due to interruption of electrode-skin contact. This resulted in a total of 53 HR, 37 posture, and 56 EMG trials included in the final analysis.

The exposure summary metrics were described across all participants using means and standard deviations. Standard tests for normality (i.e. Anderson-Darling test) and other tests of assumptions (i.e. Grubb's test for outliers, evaluations of homogeneity) for using analysis of variance (ANOVA) were performed. Differences between summary measures were examined using one-way analysis of variance and an alpha value of 0.05. Two-sample t-tests were used to determine differences among dominant and non-dominant muscle groups and joints. All statistical analyses were conducted using Minitab 18.0 (Minitab, Inc., State College, PA, USA).

3.3 Results

The average planting time per trial (30 trees) across study participants was 11.5 minutes (SD = 4.1 min). This pace of planting is comparable to what has been previously reported (Giguere et al., 1993; McDonald et al., 2008).

3.3.1 Heart rate

HR summary measures by tool are presented in Table 3.3. No statistically significant differences among tools were observed for any of the HR summary measures.

Table 3.2: Analysis of variance table for the HR_{WORK} - HR_{Rest} summary measure.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Tool	3	52.0	17.34	0.04	0.989
Error	49	20871.7	425.95		
Total	52	20923.7			

Table 3.3: Heart rate summary measure by tool.

	Tool							
	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=14)	
HR Measure	Mean	SD	Mean	SD	Mean	SD	Mean	SD
HR_{WORK}	114.6	18.1	111.8	21.9	113.8	22.0	112.9	20.6
Absolute HR (AHR)	36.9	18.4	34.2	22.1	36.1	21.9	35.1	20.0
HR_{WORK}/HR_{REST}	1.5	0.2	1.4	0.3	1.5	0.3	1.5	0.3

3.3.2 Working postures

Posture results were determined from the Xsens motion capture system for the trunk (flexion/extension and lateral bending), upper arms (shoulder flexion/extension), and wrist (flexion/extension, pronation/supination and ulnar/radial deviation). Summary metrics by body segment are shown in Tables 3.4, 3.5, 3.6, and 3.7.

Mean trunk posture for the subjects did not differ significantly between tools, $F(3, 29) = 0.87$, $p = 0.47$. Figures 3.4 and 3.5 illustrate the magnitude and repetitive nature of trunk flexion exposures during planting, with each cycle resulting in $\geq 45°$ trunk flexion while reaching to the ground to plant the seedling.

Across all tools, wrist pronation/supination was more pronounced, $t(72) = -2.70$, $p = 0.009$, in the dominant wrist (mean = -15.2°; SD = 31.1°) than the non-dominant wrist (mean = 4.4°; SD = 31.3°). Similarly, wrist flexion/extension was greater, $t(70) = -2.75$,

Table 3.4: Trunk posture summary measures.

	Tool							
	KBC Long (N=8)		KBC Short (N=8)		OST (N=9)		Speedy (N=8)	
Flexion(+)/Extension(-)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	14.6	4.9	16.9	9.2	18.0	7.2	20.7	8.8
10th Percentile (°)	-4.4	5.8	-3.5	8.2	-2.0	5.1	-1.5	7.7
50th Percentile (°)	8.6	5.5	10.8	8.9	11.7	7.2	15.4	9.9
90th Percentile (°)	45.5	15.2	49.4	19.0	50.1	16.4	53.4	14.1
Time in Extreme Posture ($\geq$45°) (%)	10.3	3.6	11.6	7.0	11.9	5.3	13.6	8.3
Lateral Bending[a]	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	-0.3	1.8	1.4	3.1	0.8	2.8	1.8	3.1
10th Percentile (°)	-4.8	2.7	-3.0	3.8	-3.4	3.7	-2.6	3.6
50th Percentile (°)	-0.1	1.6	1.7	3.1	1.1	2.9	1.9	3.0
90th Percentile (°)	3.8	2.0	5.3	3.0	4.4	2.5	5.6	3.4

[a]Positive values denote lateral bending to the right; Negative values denote lateral bending to the left.

Table 3.5: Dominant upper arm posture summary measures.

	Tool							
	KBC Long (N=9)		KBC Short (N=9)		OST (N=10)		Speedy (N=9)	
Flexion(+)/Extension(-)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	21.4	8.6	21.4	8.9	19.9	9.1	19.8	9.1
10th Percentile (°)	6.2	11.6	6.8	10.0	4.5	12.8	4.7	10.4
50th Percentile (°)	20.0	8.1	20.0	7.9	17.8	8.8	17.8	8.6
90th Percentile (°)	38.7	10.2	37.9	10.5	38.1	8.7	37.4	10.2

$p = 0.008$, for the dominant wrist (mean = -23.4°; SD = 13.4°) than for the non-dominant wrist (mean = -13.4°; SD = 17.1°). Mean and 50th percentile wrist rotation suggests more time spent by planters across all tools in supination (-) compared to pronation (+). Positive mean and 50th percentile values for wrist deviation indicate that, on average, participants are exposed to ulnar rather than radial deviation. Figure 3.6 shows ulnar(+)/radial(-) deviation, pronation(+)/supination(-), and flexion(+)/extension(-) for the dominant wrist for one participant over a planting cycle.

Table 3.6: Dominant wrist posture summary measures.

	Tool							
	KBC Long (N=9)		KBC Short (N=9)		OST (N=10)		Speedy (N=9)	
Flexion(+)/Extension(-)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	-26.1	19.5	-22.3	6.6	-22.5	14.3	-22.6	11.9
10th Percentile (°)	-65.1	27.8	-53.2	17.8	-53.8	22.7	-53.9	23.7
50th Percentile (°)	-30.4	22.1	-26.3	6.4	-27.2	15.9	-26.1	16.5
90th Percentile (°)	16.3	37.4	13.5	26.3	14.8	30.3	12.8	20.3
Pronation (+)/Supination(-)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	-3.5	28.2	-26.1	33.9	-13.0	22.6	-18.4	39.1
10th Percentile (°)	-40.5	33.8	-57.2	48.3	-41.5	35.9	-50.8	61.7
50th Percentile (°)	-6.2	29.5	-28.2	39.7	-14.9	23.0	-25.5	54.3
90th Percentile (°)	36.6	39.0	4.9	23.9	17.4	29.3	34.0	48.6
Ulnar(+)/Radial(-) Deviation	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	5.5	18.9	2.8	20.4	9.5	15.4	8.1	13.9
10th Percentile (°)	-21.8	14.4	-26.3	26.8	-16.9	19.7	-20.2	23.6
50th Percentile (°)	6.5	20.8	4.3	22.2	10.8	16.2	8.1	16.0
90th Percentile (°)	31.8	26.6	29.7	14.8	33.8	18.2	36.1	17.1

Table 3.7: Posture summary measures for the neck.

	Tool							
	KBC Long (N=9)		KBC Short (N=9)		OST (N=10)		Speedy (N=9)	
Flexion(+)/Extension(-)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	5.3	8.7	3.8	14.9	5.7	10.9	6.2	15.7
10th Percentile (°)	-12.1	9.2	-12.9	16.0	-11.3	11.3	-9.3	15.8
50th Percentile (°)	7.6	9.3	5.3	15.1	7.7	11.6	7.5	16.0
90th Percentile (°)	18.0	7.0	16.5	13.7	18.0	9.0	18.2	15.1
Lateral Bending[a]	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean (°)	0.7	3.2	-0.6	5.3	-1.0	5.4	-0.1	5.1
10th Percentile (°)	-6.6	2.6	-8.4	5.7	-8.0	6.0	-7.2	6.2
50th Percentile (°)	0.5	3.5	-0.7	5.8	-1.2	6.0	-0.4	5.6
90th Percentile (°)	8.3	3.7	7.1	4.8	6.6	4.9	7.4	4.0
Axial Rotation[a]	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean(°)	-2.1	6.5	-2.0	4.8	-4.7	4.1	-3.8	4.9
10th Percentile (°)	-17.2	7.8	-16.1	6.3	-18.4	5.0	-17.2	7.0
50th Percentile (°)	-1.0	6.4	-1.8	4.9	-3.7	4.2	-2.5	4.3
90th Percentile (°)	10.7	8.4	11.1	7.1	6.4	4.9	6.6	6.1

[a] Positive values denote lateral bending or rotation to the right; Negative values denote lateral bending or rotation to the left.

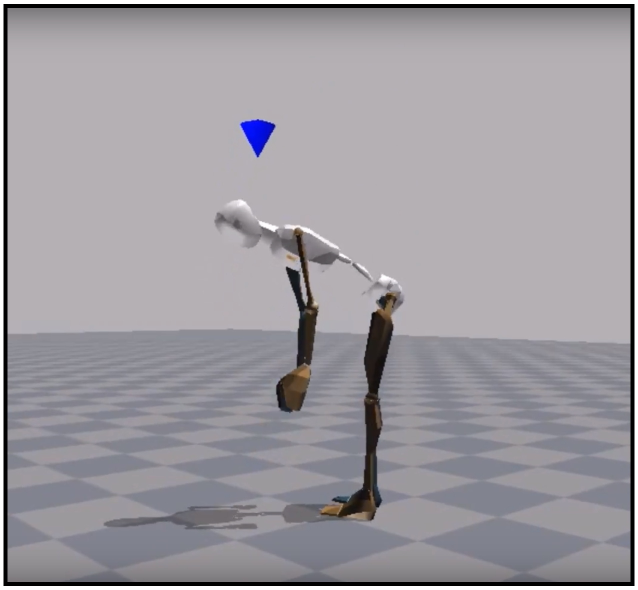


Figure 3.4: Xsens (MVN Analyze 2018) biomechanical model during planting trial.

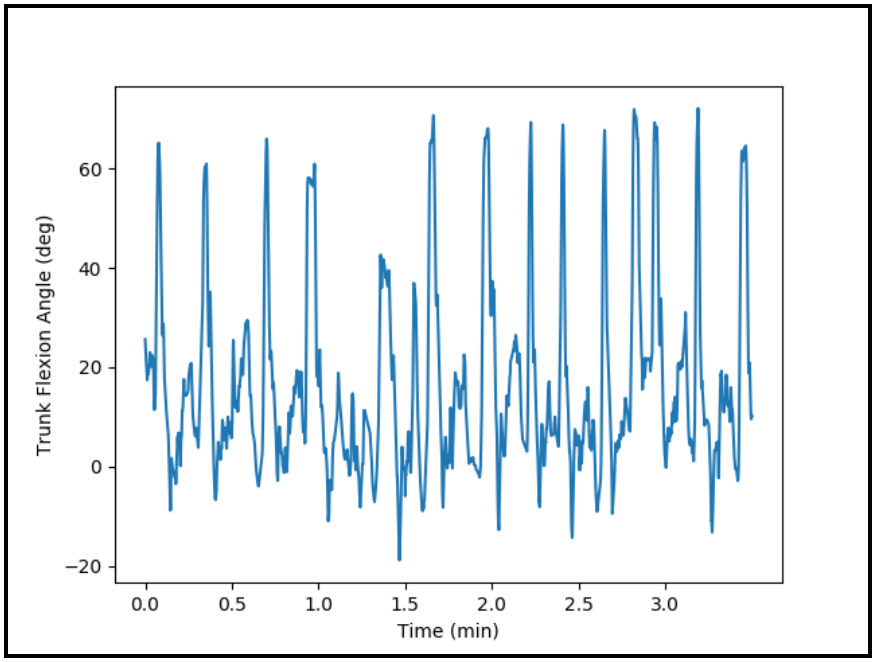


Figure 3.5: Representative 3.5 min segment of trunk flexion for one participant.

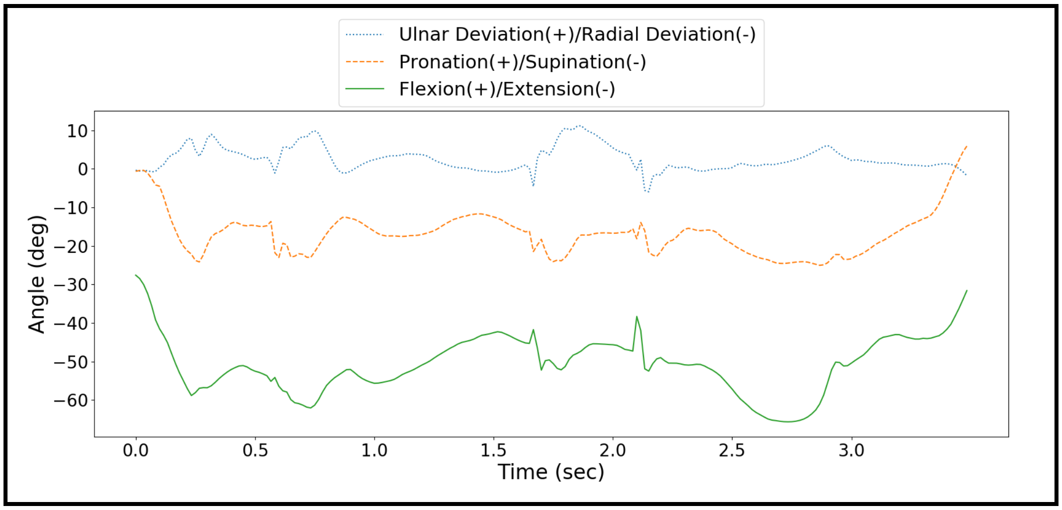


Figure 3.6: Wrist postures during a planting cycle for one participant, showing wrist extension >45°.

3.3.3 Forceful muscle exertions

Descriptive statistics for the dominant upper trapezius and anterior deltoid EMG summary measures are provided in Tables 3.8 and 3.9. No statistically significant differences among tools were determined. Mean muscle activity was greater in the dominant arm (anterior deltoid and upper trapezius groups) than the non-dominant arm.

Table 3.8: Muscle activity summary measures by tool for the dominant upper trapezius muscle group.

	Tool							
Muscle Activity (% MVC)	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=13)	
Dominant Upper Trapezius	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	16.8	11.3	15.9	10.0	15.8	10.4	14.9	10.5
10th Percentile	1.9	1.6	1.8	1.4	1.7	1.4	1.5	1.2
50th Percentile	12.4	9.8	11.1	8.3	10.8	7.6	9.5	7.0
90th Percentile	37.5	23.8	36.4	21.2	36.4	23.8	35.8	25.5
Muscle Activity (% MVC)	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=13)	
Nondominant Upper Trapezius	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	14.6	7.0	13.4	6.1	13.5	6.7	12.1	6.1
10th Percentile	2.2	1.0	1.9	1.2	1.9	0.9	1.8	1.3
50th Percentile	11.6	5.8	10.1	5.2	10.3	5.4	8.5	4.7
90th Percentile	30.8	14.9	29.6	12.4	28.9	14.8	27.8	14.5
	Tool							
Muscle Activity (% RVE)	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=13)	
Dominant Upper Trapezius	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	62.4	26.1	62.2	28.8	59.4	27.4	56.6	28.6
10th Percentile	7.0	3.7	6.8	4.3	6.4	3.6	5.8	3.1
50th Percentile	44.4	22.9	42.7	23.8	41.0	21.3	36.5	20.5
90th Percentile	140.9	58.4	143.8	63.8	138.3	64.2	135.3	69.5
Muscle Activity (% RVE)	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=13)	
Nondominant Upper Trapezius	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	66.2	31.6	64.5	34.9	61.6	34.5	56.1	29.3
10th Percentile	10.3	5.7	9.3	5.9	9.1	6.0	8.5	5.6
50th Percentile	51.5	25.7	48.5	28.2	47.7	30.4	39.8	22.4
90th Percentile	140.8	67.5	141.4	73.3	131.1	68.4	127.6	64.9

Table 3.9: Muscle activity summary measures by tool for the dominant anterior deltoid muscle group.

	Tool							
Muscle Activity (% MVC)	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=13)	
Dominant Anterior Deltoid	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	5.5	2.5	6.2	2.8	6.0	3.0	6.3	3.3
10th Percentile	0.9	0.7	1.0	0.7	1.0	0.7	0.9	0.7
50th Percentile	3.2	1.8	3.5	2.0	3.4	2.2	3.6	2.3
90th Percentile	12.6	5.2	13.6	5.2	13.3	5.5	14.0	6.2
Muscle Activity (% MVC)	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=13)	
Nondominant Anterior Deltoid	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	8.1	12.9	4.8	2.3	5.7	6.0	5.8	6.6
10th Percentile	0.8	0.7	0.8	0.6	1.1	1.4	0.9	1.5
50th Percentile	2.7	2.7	2.5	1.6	2.7	2.2	2.5	2.3
90th Percentile	12.0	5.6	11.9	5.7	12.6	10.9	13.7	13.4
	Tool							
Muscle Activity (% RVE)	KBC Long (N=13)		KBC Short (N=13)		OST (N=13)		Speedy (N=13)	
Dominant Anterior Deltoid	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	26.8	12.2	29.8	13.6	29.1	13.4	29.6	13.5
10th Percentile	4.1	2.2	4.4	2.5	4.5	2.6	4.1	2.6
50th Percentile	15.1	7.6	16.7	8.5	16.1	8.5	16.5	9.1
90th Percentile	61.7	26.6	66.2	26.0	64.9	26.9	67.7	29.8
Muscle Activity (% RVE)	KBC Long (N=12)		KBC Short (N=12)		OST (N=12)		Speedy (N=12)	
Nondominant Anterior Deltoid	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Mean	17.1	6.0	16.7	5.2	15.1	4.3	15.0	5.6
10th Percentile	2.4	1.1	2.2	0.8	2.4	1.2	1.9	0.6
50th Percentile	8.7	4.1	8.4	3.6	7.7	3.5	7.1	3.1
90th Percentile	42.2	14.4	40.9	13.4	37.2	12.1	38.7	14.6

3.4 Discussion

No statistically significant differences were observed among tools, suggesting that selecting between the four tools considered in this study may not have a significant effect on exposure to physical risk factors among novice hand planters. The results of the present study contribute to the scientific literature on the occupational health and safety of hand planters by providing a detailed characterization of novice hand planter exposures to physical risk factors. The work is particularly valuable as it considers southeastern U.S. hand planting practices, which can differ substantially from other geographic regions and has been less commonly studied. For example, Denbeigh et al., 2013 examined wrist postures and forces during different seedling unloading conditions. However, the study was conducted using the most common type of planting instrument in Canada, a 'D'-Handle planting shovel, which has several distinct design features (weight, length, handle material, spade shape) that differentiate it from the 'T'-Handle 'dibble' bars commonly used in the southeastern U.S.

The results of the present study provide additional evidence of the stresses hand planters are exposed to while planting. Across all tools, the measured working HR to resting HR ratios were lower than forestry choker setters (1.84; Kirk et al., 2001), but higher than those reported among steel workers (1.24; Vitalis et al., 1994), cane cutting workers (1.38; Vitalis, 1981), nurses (1.45; Fordham et al., 1978), and car assemblers (1.45; Minard et al., 1971).

Trunk flexion of greater than 45° has been identified as a risk factor for fatigue, pain, or injury (Andersson, 1981; Keyserling et al., 1992; Punnett et al., 1991; Sato et al., 1973). Dibble bars as a tool do not eliminate or reduce the potentially severe non-neutral trunk posture required to reach the ground. Similarly, hand planters are exposed to non-neutral wrist postures exceeding recommended levels for injury prevention. Study participants were exposed to mean wrist extension between -26.1° and -22.3° across the tools. Exposures to wrist extension of greater than 15° may result in a marked reduction in grip strength (O'Driscoll et al., 1992). Wrist postures measured during the present study are comparable to those previously studied (Denbeigh et al., 2013). In addition to non-neutral working postures of the wrist, Denbeigh et al. (2013) observed high wrist loading during the planting cycle suggesting a potential high force-high repetition loading cycle associated with elevated risk of MSD incidence (Silverstein et al., 1987; Gallagher et al., 2013). Previous research into wrist postures during varied seedling unloading strategies (symmetric or asymmetric) suggested workers maintained more neutral postures during asymmetric unloading (Slot et al., 2010b). This finding may suggest that factors other than tool design may have more significant effects on exposures.

Results of the study suggest that limited data collection (30 seedlings) among novice hand planters can provide comparable results to full-shift measurements on professional planters. Planting rates, working HR measures, wrist postures, and submaximally normalized muscle activity were all comparable to what has been reported in previous studies of hand planters (Vyse, 1973; McDonald et al., 2008; Granzow et al., 2018; Roberts, 2002; Denbeigh et al., 2013; Giguere et al., 1993; Stjernberg, 1988; Stjernberg, 2003; Appelroth et al., 1970; Trites et al., 1993; Slot et al., 2010b). This may suggest that the repetitive nature of the work can allow for the increased use of simulation studies similar to the present study that are generalizable to professional hand planters.

Several limitations of this study should be addressed. Study participants were selected from members of a university campus and were not professional hand planters. Demographic differences among the sample of study participants and the typical southeastern U.S. hand planter limit direct comparisons and applicability of study results to the planting community. While the planting site used in the study was prepared for professional hand planting it was not representative of the variability encountered by hand planting crews. This variability includes the degree of plot preparation, grade of the terrain, soil composition, and ground moisture. The site was not a controlled environment so fluctuations in ambient temperature may have affected HR response to work. Each subject planted 120 trees over the course of the study, a small quantity compared to the daily planting rates of professional hand planters. The effect of fatigue on HR, working postures, and muscle exertions over the course of a full-shift was not analyzed in the present study. Finally, ratings of perceived exertions were not collected for each tool. Borg CR-10 scale self-reporting has been used to relative exertion levels of the elbow, shoulder, and total task (Freivalds et al., 1993; Lloyd et al., 1991; Spielholz, 2006).

While the present study did not suggest substantive differences among tools as they relate to physical risk factors, future research has the potential to identify effective means for mitigating exposures. Mechanized planting, while not as prevalent as manual planting in the southeastern U.S., may require lower physical demands. Engineering new hand planting tools that require less force to penetrate the soil may reduce forces, such as ‘bullet’ planting previously studied for productivity (Vyse, 1973). Extreme trunk flexion is a primary risk factor identified through the characterization of working postures, which could be alleviated through the development of a planting device that transports the seedling into the ground without bending. In addition to engineering controls, research into certain administrative controls, such as determining effective work-rest cycles, could potentially reduce MSD symptom development.

3.5 Conclusions

Results of the present study indicate that working heart rate, exposure to non-neutral postures, and forceful muscle exertions of the upper arm and back did not significantly differ among the evaluated tools. However, characterization of novice hand planter risk factor exposures may provide insight for future researchers interested in implementing interventions intended to reduce exposures to physical risk factors associated with work-related MSDs. The findings indicate a need for additional research among novice and professional hand planters to determine optimal interventions that will result in the reduction of risk factor exposures and, consequently, musculoskeletal symptoms.

Chapter 4

Applying Work Measurement Methods to Hand Planter Reforestation Work

4.1 Introduction

In many industries, work measurement is used as a tool to accomplish planning, determine performance, and establish costs (Zandin, 2002). Work measurement provides organizations vital information for evaluating work processes and modifying them with the intent to increase productivity, drive down costs, and increase profits (Niebel et al., 2003). Traditionally, work measurement has been used on industrial practices for setting work pace standards, employee salaries, and balancing production system outputs (Wells et al., 2007).

Practitioners and researchers interested in reducing exposures to physical risk factors associated with musculoskeletal disorders (MSDs) have previously used work measurement techniques (Feyen et al., 2000; Karkowski et al., 1990; Porter et al., 1995). The central premise of work measurement is that job tasks can be divided into sequences of actions, from which standard durations can be developed (Meyers, 1992). By integrating biomechanical stress evaluations into the breakdown of job tasks, each sub-operation of a job can be assigned a risk score and improvements can be prioritized to potentially reduce overall MSD risk. In addition to injury prevention, ergonomic improvements resulting from the application of work measurement methods have been associated with increases in quality and operator productivity improvements (Drury, 2000; Jörgen A. Eklund, 1995; Jörgen A Eklund, 1997; Battini et al., 2011).

In the southeastern United States, hand planting is the primary method for reforestation of pine stands (McDonald et al., 2008). Hand planting has been observed to provide a nearly 95% yield (Stjernberg, 2003). In addition to the quality of planted seedlings, hand planting is an ideal method for hilly terrain or rough, cut-over sites, in contrast to machine planting that typically requires more preparation work (Kushla et al., 2017). Hand planting work involves planting seedlings one at a time from a large bag of seedlings carried on the worker's back. The seedlings are planted at the desired spacing in holes created by the hand planter through the use of a planting tool, such as a spade, hoedad, or dibble bar. Research suggests that hand planting is physically demanding and exposes workers to numerous physical risk factors for MSDs (Giguere et al., 1993; Hodges et al., 2011; Roberts, 2002; Robinson et al., 1993; Trites et al., 1993).

Available literature regarding the application of work measurement methodologies on hand planting work is limited. Vyse (1973) divided the planting task into six sub-operations and assigned durations to each of these according to field observations. Results suggested that 24.1 seconds are required to plant one seedling; however the elemental time study employed in the study was not an industry standard methodology. Previous observational studies have suggested planting rates of 7 seconds (McDonald et al., 2008), 10 seconds (Stjernberg, 2003), and 11.7 seconds (Stjernberg, 1988) per bareroot seedling. A study of hand planters observed 75.8% of the work shift was spent planting and that an average shift lasted 433.9 (SD = 88.0) minutes, although planting rates were not described (Granzow et al., 2018).

The objective of the present study was to develop a time standard for the hand planting of bareroot seedlings using a dibble bar. This method of planting is typical of hand planting contractors in the southeastern U.S. Such a time standard could be used by industry groups, hand planter contractors, and land owners to identify elements of the planting cycle that require the longest durations. By examining these elements, interested parties could make adjustments to the planting process to increase productivity, provide appropriate rest allowances, and more accurately forecast required labor resources.

4.2 Methods

Maynard Operation Sequence Technique (MOST) is an accurate predetermined time system commonly used by industrial engineers (Niebel et al., 2003). Several variations of MOST have been developed for application in nuanced manners for different job tasks, including MiniMOST, BasicMOST, MaxiMOST, and AdminMOST. BasicMOST is the most frequently used variation of MOST, and is applied to job tasks that are performed for intermediate frequencies (between 150 and 1,500 repetitions per week) or relatively large action distances (>2 steps) (Zandin, 2002). Based on the large action distances observed in hand planting work, BasicMOST was applied in the present study.

BasicMOST provides three sequence models to define work elements. The general move sequence model (1) identifies the spatial free movement of an object through the air (Zandin, 2002) and is comprised of three phases and a subset of parameters:

$$\begin{array}{|c|c|c} \text{A B G} & \text{A B P} & \text{A} \\ \text{Get Object} & \text{Put Object Aside} & \text{Return} \end{array} \qquad (1)$$

where A = action distance, B = body motion, G = gain control, and P = placement.

The controlled move sequence model (2) describes the movement of an object when it remains in contact with a surface or remains attached to another object during the movement (Zandin, 2002) and is comprised of the phases and parameters:

$$\begin{array}{|c|c|c} \text{A B G} & \text{M X I} & \text{A} \\ \text{Get Object} & \text{Move or Actuate Object} & \text{Return} \end{array} \qquad (2)$$

where M = move controlled, X = process time, and I = alignment. The 'Move or Actuate Object' phase is related to the movement or actuation of a machine, if it is applicable.

The tool use sequence model (3) is applied for the use of common hand tools (Zandin, 2002) and is comprised of the phases and parameters:

$$\begin{array}{c|c|c|c|c} \text{A B G} & \text{A B P} & & \text{A B P} & \text{A} \\ \text{Get tool} & \text{Put tool or} & \text{Tool} & \text{Put tool or} & \text{Return} \\ \text{or object} & \text{object in place} & \text{action} & \text{object aside} & \end{array} \qquad (3)$$

where A = action distance, B = body motion, G = gain control, and P = placement. The 'Tool action' parameters can be applied based on the specific tool being used, and include 'fasten', 'loosen', 'cut', 'surface treat', 'measure', 'record', and 'think'. BasicMOST provides the practitioner the autonomy to create new tool actions based on the process.

Each parameter is assigned an index value from a list of prescribed guidelines based on the complexity and/or difficulty of the activity. Frequency multipliers are applied to each sequence based on the repetitions of the sequence. For each activity the parameter indices are summed, multiplied based on the assigned frequency, and finally multiplied by 10, which provides the time measurement unit (TMU) for that sequence. Once the TMU is calculated for each sequence model, the sequence models are summed to provide the total TMUs for the job. One TMU is equal to 1/100,000 of an hour, or 0.036 seconds.

For the present study, each sub-operation of the planting process was defined through the use of a professional hand planting training video (Texas A&M Forest Service, 2012). The training video demonstrates each sub-operation of the productive planting process for bareroot pine seedlings. A video observing hand planters loading seedling bags was used to define sub-operations of the preparation phase (Timber Industry, 2016). To complete the BasicMOST analysis, assumptions were made based on descriptions of the hand planting process published in several hand planter studies to present a standard time work measurement model that represents average planting processes and conditions for dibble bar hand planting in the southeastern U.S.

4.2.1 Allowances

In order to make adjustments to the time standard to account for 'legitimate lost time' throughout the planting cycle, certain allowances need to be applied. Allowances are grouped as constant allowances (personal needs and basic fatigue), variable fatigue, or special allowances (unavoidable delays, extra allowances, and policy allowances) (Kanawaty, 1992).

These allowances are summed to calculate the total allowances that are added to the determined normal time, resulting in a standard time measure that accounts for factors outside of the BasicMOST sub-opeartions. The most commonly used fatigue allowances come from the International Labour Organization (ILO) recommendations (1992), Cornman (1970), and Williams (1973). Each of these sources use physiological, psychological, and environmental categories of rest allowances. In addition to categorical recommended allowances, models have been published for determining allowances. Published allowances for fatigue are based on physiologic responses to work, such as heart rate and energy expenditure. A common rest allowance model uses the formula (Kanawaty, 1992):

$$\text{RA} = (\Delta HR/40 - 1)X100 \quad (4)$$

where RA = rest allowance, as a percentage added to work time and ΔHR = difference between HR_{WORK} and HR_{REST}. A 40 bpm increase in HR from resting to working is considered an acceptable increase (Grandjean, 1988). Therefore, any HR increases less than 40 bpm would result in no variable fatigue allowance, while HR increases greater than 40 bpm would result in positive variable fatigue allowances. Rest allowances can also be based on energy expenditure, such as the model developed by Murrell (1965):

$$\text{R} = (\text{W - 5.33})/(\text{W - 1.33}) \quad (5)$$

where R = time required for rest as a percent of total time and W = average energy expenditure during work (kcal/min). A kcal/min rate of 5.33 is suggested as acceptable energy expenditure for an 8-hour work day (Bink, 1962). A 5.33 kcal/min increase in energy expenditure has been shown to correspond to a 40 bpm increase in heart rate, resulting in Formula (4) and (5) being closely correlated for purposes of assigning fatigue allowances (Niebel et al., 2003). Energy expenditure can be expressed as metabolic equivalents (METs), with one MET equaling to 1 kcal/kg/hour. Variable fatigue allowances were added according to the physical demands of the hand planting process.

4.3 Results

Sub-operations of the planting process were defined by BasicMOST instructions outlined in Zandin (2002) per the professional hand planting training video. Field observations of hand planting by a southeastern U.S. contractor on pine stands described in this dissertation within the chapter titled "A Characterization of Physical Risk Factors among Hand Planter Reforestation Workers" were used to define sub-operations related to loading the seedling bags. The BasicMOST analysis only included sub-operations logically contained within a broadly defined productive planting cycle. The analysis begins when the worker has a closed box of seedlings in front of him, with a dibble bar and a seedling bag on the ground at his side. From there, the planting process consists of three main phases of sub-operations: seedling bag loading, planting preparation and walking to the planting location, and the productive planting phase. Work typically completed at the beginning and the end of the work shift was excluded from analysis in order to limit the sub-operations to the repetitive planting cycle. Examples of tasks excluded from analysis but typically completed by hand planters include loading boxes of seedlings onto trucks at the seedling nursery, travel to the planting location, unloading of seedling boxes from trucks, and the removal of securing bands from boxes.

4.3.1 BasicMOST analysis

BasicMOST analysis of the planting process is shown in Figure 4.1. Each of the three basic sequence models for manual work were applied to elements of the planting cycle: general, controlled, and tool use sequence models. Twenty-six sub-operations were identified among three main phases of the work cycle: seedling bag loading (6 sub-operations), planting preparation and walking to the planting location (9 sub-operations), and the productive planting phase (11 sub-operations).

4.3.2 Hand planting sub-operations

The seedling bag loading sub-operations are as follows:

A-01 Bend and remove (lay aside) lid from seedling box
A-02 Within reach, blind grasp handful of seedlings from box (approximately 20 seedlings)
A-03 Strike the roots of the seedlings against the box to dislodge ice
A-04 Place the seedlings in the seedling bag (low effort)
A-05 Place the seedlings in the seedling bag (moderate effort)
A-06 Place the seedlings in the seedling bag (high effort)

In the seedling bag loading phase, the hand planter removes the lid from the box and grasps a handful of seedlings. The worker strikes the roots of the seedlings against the box to dislodge ice particles and water. The worker then loads the handful into the seedling bag and repeats the process until the bag is full. As the worker starts loading the bag the effort to place the seedlings is generally low. However, as the bag begins to fill it becomes more difficult, with the last few handfuls requiring the most force to fit (push-in) the seedlings. Elements A-02 to A-06 are repeated approximately 25 times until the seedling bag is full of about 500 seedlings. The hand planter will then:

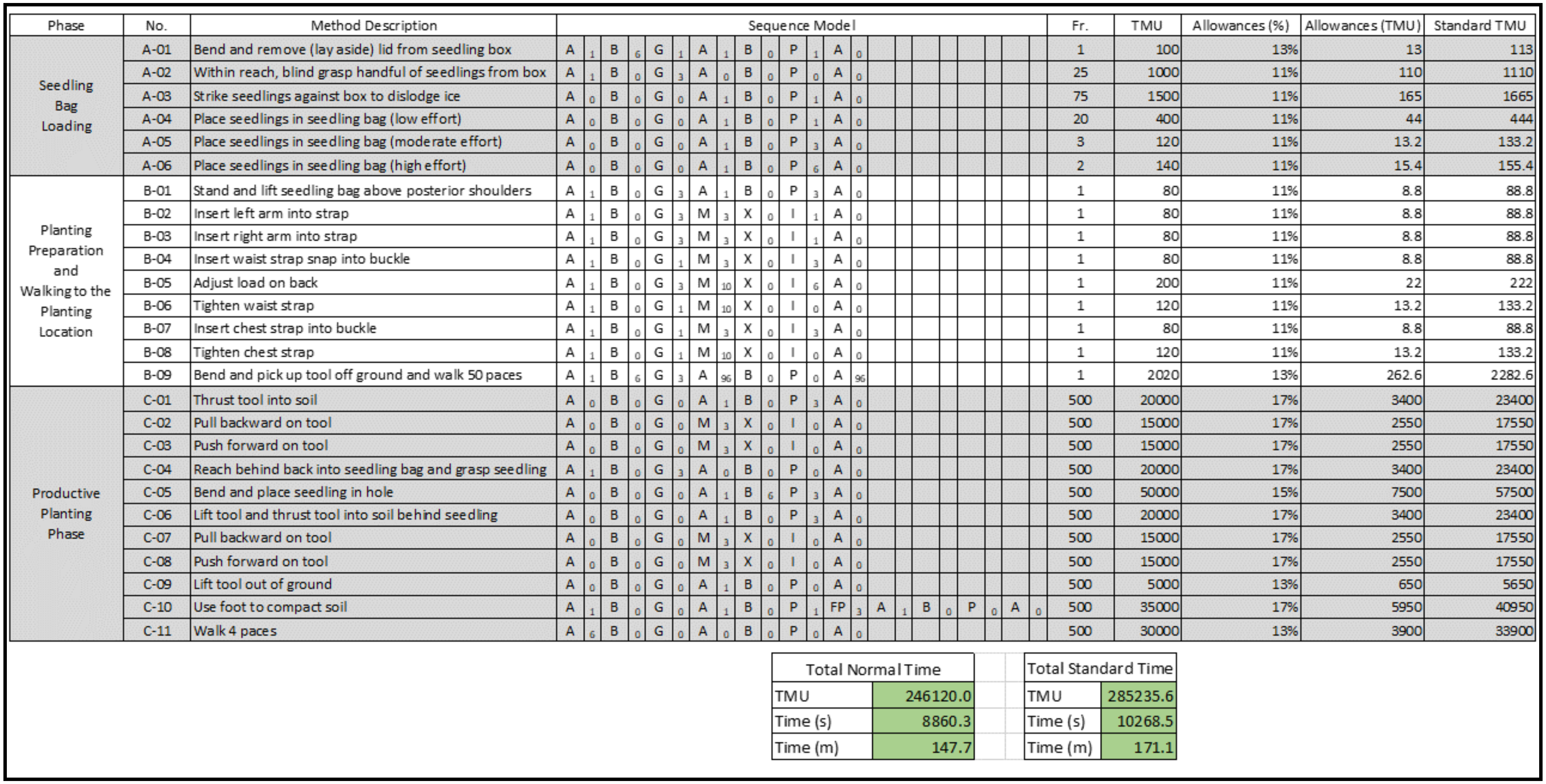
B-01 Stand and lift seedling bag above posterior shoulders
B-02 Insert left arm into strap
B-03 Insert right arm into strap
B-04 Insert waist strap snap into buckle
B-05 Adjust load on back
B-06 Tighten waste strap
B-07 Insert chest strap into buckle
B-08 Tighten chest strap
B-09 Bend and pick up tool off ground and walk 50 paces

The planting preparation and locomotion phase begins with the worker lifting the loaded seedling bag and securing it to his body in a manner similar to a typical backpack. This involves adjusting a waist strap, a chest strap, and the load within the seedling bag in order for the bag to be secure and comfortable as possible. The final sub-operation is for the worker to pick the dibble bar up from the ground and walk to the planting location for the first seedling.

After arriving at the planting location for the first seedling, the hand planter then begins the productive planting phase of the planting cycle.

C-01 Stand and lift seedling bag above posterior shoulders
C-02 Pull backward on tool
C-03 Push forward on tool
C-04 Reach behind back into seedling bag and grasp seedling
C-05 Bend and place seedling in holek
C-06 Lift tool and thrust tool into soil behind seedling
C-07 Pull backward on tool
C-08 Push forward on tool
C-09 Lift tool out of ground
C-10 Use foot to compact soil
C-11 Walk 4 paces

The productive cycle phase of the planting involves using the dibble bar to dig a ‘V’ shaped hole for the seedling to be planted into. The length of the dibble bar blade determines the depth of the hole. The planting of the seedling requires a level of precision to ensure the roots are deep enough to avoid dehydration, yet not too deep resulting in ‘J’ hooking of the roots. ‘J’ hooking results when the roots are bent upwards in the hole in the shape of a capital letter ‘J’, resulting in decreased health of the plant (Murphy et al., 2004). Once the productive planting phase of the work cycle is complete for each of the 500 seedlings, the hand planter walks back to the seedling staging area to refill his bag, starting a new work cycle.



Phase	No.	Method Description	Sequence Model	Fr.	TMU	Allowances (%)	Allowances (TMU)	Standard TMU
Seedling Bag Loading	A-01	Bend and remove (lay aside) lid from seedling box	$A_1 B_6 G_1 A_1 B_0 P_1 A_0$	1	100	13%	13	113
	A-02	Within reach, blind grasp handful of seedlings from box	$A_1 B_0 G_3 A_0 B_0 P_0 A_0$	25	1000	11%	110	1110
	A-03	Strike seedlings against box to dislodge ice	$A_0 B_0 G_0 A_1 B_0 P_1 A_0$	75	1500	11%	165	1665
	A-04	Place seedlings in seedling bag (low effort)	$A_0 B_0 G_0 A_1 B_0 P_1 A_0$	20	400	11%	44	444
	A-05	Place seedlings in seedling bag (moderate effort)	$A_0 B_0 G_0 A_1 B_0 P_3 A_0$	3	120	11%	13.2	133.2
	A-06	Place seedlings in seedling bag (high effort)	$A_0 B_0 G_0 A_1 B_0 P_6 A_0$	2	140	11%	15.4	155.4
Planting Preparation and Walking to the Planting Location	B-01	Stand and lift seedling bag above posterior shoulders	$A_1 B_0 G_3 A_1 B_0 P_3 A_0$	1	80	11%	8.8	88.8
	B-02	Insert left arm into strap	$A_1 B_0 G_3 M_3 X_0 I_1 A_0$	1	80	11%	8.8	88.8
	B-03	Insert right arm into strap	$A_1 B_0 G_3 M_3 X_0 I_1 A_0$	1	80	11%	8.8	88.8
	B-04	Insert waist strap snap into buckle	$A_1 B_0 G_1 M_3 X_0 I_3 A_0$	1	80	11%	8.8	88.8
	B-05	Adjust load on back	$A_1 B_0 G_3 M_{10} X_0 I_6 A_0$	1	200	11%	22	222
	B-06	Tighten waist strap	$A_1 B_0 G_1 M_{10} X_0 I_0 A_0$	1	120	11%	13.2	133.2
	B-07	Insert chest strap into buckle	$A_1 B_0 G_1 M_3 X_0 I_3 A_0$	1	80	11%	8.8	88.8
	B-08	Tighten chest strap	$A_1 B_0 G_1 M_{10} X_0 I_0 A_0$	1	120	11%	13.2	133.2
	B-09	Bend and pick up tool off ground and walk 50 paces	$A_1 B_6 G_3 A_{96} B_0 P_0 A_{96}$	1	2020	13%	262.6	2282.6
Productive Planting Phase	C-01	Thrust tool into soil	$A_0 B_0 G_0 A_1 B_0 P_3 A_0$	500	20000	17%	3400	23400
	C-02	Pull backward on tool	$A_0 B_0 G_0 M_3 X_0 I_0 A_0$	500	15000	17%	2550	17550
	C-03	Push forward on tool	$A_0 B_0 G_0 M_3 X_0 I_0 A_0$	500	15000	17%	2550	17550
	C-04	Reach behind back into seedling bag and grasp seedling	$A_1 B_0 G_3 A_0 B_0 P_0 A_0$	500	20000	17%	3400	23400
	C-05	Bend and place seedling in hole	$A_0 B_0 G_0 A_1 B_6 P_3 A_0$	500	50000	15%	7500	57500
	C-06	Lift tool and thrust tool into soil behind seedling	$A_0 B_0 G_0 A_1 B_0 P_3 A_0$	500	20000	17%	3400	23400
	C-07	Pull backward on tool	$A_0 B_0 G_0 M_3 X_0 I_0 A_0$	500	15000	17%	2550	17550
	C-08	Push forward on tool	$A_0 B_0 G_0 M_3 X_0 I_0 A_0$	500	15000	17%	2550	17550
	C-09	Lift tool out of ground	$A_0 B_0 G_0 A_1 B_0 P_0 A_0$	500	5000	13%	650	5650
	C-10	Use foot to compact soil	$A_1 B_0 G_0 A_1 B_0 P_1 FP_3 A_1 B_0 P_0 A_0$	500	35000	17%	5950	40950
	C-11	Walk 4 paces	$A_6 B_0 G_0 A_0 B_0 P_0 A_0$	500	30000	13%	3900	33900

Total Normal Time	
TMU	246120.0
Time (s)	8860.3
Time (m)	147.7

Total Standard Time	
TMU	285235.6
Time (s)	10268.5
Time (m)	171.1

Figure 4.1: BasicMOST analysis of hand planting process.

4.3.3 Assumptions

Several necessary assumptions were made based on the available literature. The number of bareroot seedlings that are typically loaded into a seedling bag, which affects how many trees are planted before the worker has to return for more seedlings, was determined from Sullman et al. (2000) who suggested that 200-600 seedlings can be carried in a bag. Based on this range, as well as feedback from a professional reforester researcher (M.F. Smidt, personal communication, June 21, 2018), the number of seedlings per cycle was set at 500. Observations from hand planter research previously reported in Granzow et al. (2018) estimated that 20 seedlings were picked up in each handful from the seedling box to be loaded into the seedling bag at a time. Twenty seedlings per handful being transferred into a seedling bag containing 500 seedlings results in 25 repetitions of moving seedlings from box to bag. Observation data from field based hand planting described in Granzow et al. (2018) estimated that 50 steps were taken from the seedling staging site to the location of planting and 4 paces were taken between each tree planted.

4.3.4 Allowances

The ILO recommends a 5% personal needs allowance be applied to account for water and restroom breaks. A 4% basic fatigue allowance was applied to account for energy expenditure. Based on ILO recommended variable allowances, three fatigue allowances were applied. A 2% 'standing' allowance was applied for all sub-operations. A 2% 'bending' allowance was applied to three of the operations that involved bending, A-01, B-09, and C-05. The relatively short cycle time and repetitive nature of these elements were determined to be classified as 'very tedious' per ILO guidelines, therefore a 2% 'very tedious' allowance was applied to all of the sub-operations in the productive cycle (C-01 through C-11). Based on planting logs from previous research (Granzow et al., 2018), a 4% 'repeated tries' allowance was applied to sub-operations of the productive planting cycle that require additional repetitions when variations in normal soil conditions affect the planting process. A sum of these applied allowances determined that an additional 32,915.60 TMU should be applied to the normal time. Table 4.1 summarizes the applied allowances per ILO guidelines.

Table 4.1: BasicMOST Allowances (ILO Guidelines (Kanawaty, 1992))

Category	Type	Sub-Operations	Allowance (%)
Constant	Personal needs	All	5
Constant	Basic fatigue	All	4
Variable fatigue	Standing	All	2
Variable fatigue	Bending	A-01, B-09, C-05	2
Variable fatigue	Very tedious	C-01 thru C-11	2
Variable fatigue	Repeated tries	C-01 thru C-04, C-05 thru C-08, C-10	4

4.3.5 Standard time

The summed TMU for the sub-operations of the hand planting cycle was 246,120. This equates to 8,860 seconds, or 148 minutes of Normal Time work. The sub-operations assigned the highest TMU values are shown in Table 4.2. Appendix A describes each sub-operation, parameters, and assigned index values in detail. One cycle of the productive planting phase, consisting of sub-operations C-01 thru C-11, was assigned 480.0 TMU Normal Time and 556.8 TMU Standard Time, equating to 17.3 and 20.0 seconds, respectively.

Table 4.2: Highest TMU sub-operations

No.	Method Description	TMU	Percent Normal Time (%)
C-05	Bend and place seedling in hole	50,000	20.3
C-10	Use foot to compact soil	35,000	14.2
C-11	Walk 4 paces	30,000	12.2

4.4 Discussion

The results of the hand planter BasicMOST analysis suggest that a hand planting cycle, defined as all of the work sub-operations beginning with loading the seedling bag through planting the last of 500 trees and returning to the seedling staging area, is allocated 285,236 TMU. This equates to 171.1 minutes, or 2.85 hours of work. A planting cycle of 2.85 hours of work corresponds to planting rates of 1,402 trees per day for an 8 hour shift, or 1,753 trees per day for a 10 hour shift. These BasicMOST planting rates and per day planting volumes are within a range of previously reported hand planting rates and volumes. Giguere et al. (1993) reported planting rates of 1,245 seedlings per day in Quebec, Canada, and Stjernberg (2003) reported daily planting rates of 1,900 trees per day in British Columbia, Canada.

Comparisons with reported per seedling rates suggest the BasicMOST analysis results of 20.0 seconds are also within a range of previously reported results. McDonald et al. (2008) reported planting rates of 7 seconds or less for 70% of bare root plantings and Stjernberg 1988 reported observed rates of 11.7 seconds per containerized seedling. Vyse (1973) reported time study results for bare root seedlings of 24.1 seconds per seedling.

The sub-operations requiring the largest durations of the planting cycle include bending to place the seedling into the hole (115.0 TMU/4.1 seconds per tree), using the worker's foot to compact the soil (81.9 TMU/2.9 seconds per tree), and walking between planting locations (67.8 TMU/2.4 seconds per tree). While Vyse (1973) split the planting process into only 6 sub-operations, some comparisons can still be made. The 'Plant' process from Vyse was assigned 4.5 seconds, and corresponds to steps C-05 thru C-09 from the BasicMOST analysis. Summing the TMU for these sub-operations results in a Standard time of 8.8 seconds, a significant increase from the Vyse (1973) study. While the 'Plant' sub-operations between the BasicMOST presented in this study and Vyse (1973) differ by 96%, the BasicMOST overall productive planting phase was faster than Vyse (1973). Vyse (1973) reported 3.8 seconds were required to 'Tamp' the soil, corresponding to the BasicMOST 2.9 seconds for sub-operation C-10 (use foot to compact soil). Similarly, Vyse (1973) assigned walking between planting locations 8.8 seconds, compared to 2.4 seconds for the BasicMOST analysis. The smallest difference between the two studies is for the sub-operation of selecting a tree from the seedling bag (Vyse (1973) 2.0 seconds, BasicMOST 1.7 seconds). Generalizing these results, the BasicMOST analysis assigned more time to planting the bare root seedling compared to Vyse (1973), whereas Vyse (1973) assigned more time to compacting the soil and walking. Both studies show similar time requirements for selecting a tree from the seedling bag.

The determination of allowances were based on ILO recommendations. Constant allowances included 5% personal needs and 4% basic fatigue allowances. These are standard allowances typically provided to employees. However, a scientific consensus has not been reached (Niebel et al., 2003). While these allowances are likely acceptable for a majority of workers, the literature is unclear on whether hand planting work would warrant greater allowance consideration. For the purposes of the BasicMOST analysis completed in this study the recommended values of 5% personal needs and 4% basic fatigue were applied to provide a conservative time value that did not overestimate assigned sub-operation durations.

ILO recommendations for variable fatigue allowances may not be the most accurate for considering fatigue effects on workers. Mital et al. (1991) suggests that the additive method of determining allowances may lead to unrealistic allowances if the work is physiologically, psychologically, and environmentally demanding. While HR and energy expenditure data from previously published literature is scarce, there is some data that can applied to determine allowances based on the models shown in Formulas 4 and 5. Average full shift energy expenditure measurements determined using actigraphy among hand planters was reported in Granzow et al. (2018) as 3.1 METs, equating to 4.01 kCal/min. Per the Murrell (1965) energy expenditure allowance formula, this would provide no additional allowances. It should be noted that the Granzow et al. (2018) study included break time in the METs measurement. This likely resulted in an underestimation of energy expenditure during the working portion of the planting process.

Changes throughout the planting cycle and work day may have an impact that was not captured in the BasicMOST analysis. Fluctuations in the weight of the seedling bag and the physiologic responses to the steadily decreasing weight of the bag were not considered. This is a limitation of the study and is due to the researchers not having data regarding the weight of the seedling bag throughout the planting cycle. Subjective responses to increased body temperature, from physiologic response to work and/or from environmental heat conditions changes were noted in Granzow et al. (2018) in the form of the removal of layered clothing by several hand planters. Historic weather data shows average high temperatures for a known planting location in the southeastern U.S. as 54°F (12.2°C) on January 15th and 66°F (18.9°C) on March 15th (NOAA, 2018). Both dates are well within the typical planting season with variation that could affect physiologic responses and contribute to additional fatigue warranting further allowances.

Future research in developing a more accurate time standard should focus on understanding the effects of fatigue on hand planters. ILO recommendations for fatigue allowances were determined by agreements made among management and employees within several industries and have not been verified through scientific research as providing adequate rest for workers (Niebel et al., 2003; Mital et al., 1991). Allowance models based on physiologic responses to work (i.e. HR and energy expenditure) do not capture cumulative trauma of the soft tissues of the musculoskeletal system, a factor associated with MSD incidence. Forceful muscle exertion data used in allowance models rely on isometric maximum voluntary contractions (MVCs), and in practice, do not translate well to dynamic job tasks including hand planting. Production rates among southeastern U.S. hand planters are not well defined in the literature, and an allowance model based on gradual reductions of productivity throughout the work shift from fatigue may provide a better understanding of physical capabilities of hand planter workers.

4.5 Conclusions

Hand planting reforestation work is physically demanding work that can be accurately described using work measurement techniques. The application of work measurement methodology to hand planting provides workers, industry groups, land owners, and hand planting contractors/business owners with vital information for the planning of planting processes. With varying shift lengths, planting rates between 1,402 and 1,753 trees per day can reasonably be expected assuming typical work environments and conditions. Additional allowances for fatigue may be necessary to be applied based on the physiologic responses described in previous studies of hand planting workers. Efforts to reduce the repetitive bending required of the work to reach the seedling holes would reduce the time required to complete a work cycle, increasing overall productivity while reducing stress on the musculoskeletal system of hand planting reforestation workers.

Chapter 5

Conclusions

5.1 Summary of results

Musculoskeletal disorder (MSD) incidence rates and previous studies on physical risk factor exposures suggest hand planting reforestation workers are at heightened risk for MSD development compared to workers in other sectors. The research presented in this dissertation addesses gaps in the scientific literature related to the characterization of physical risk factors among hand planting reforestation workers, risk factor exposures using different hand planting instruments, and the application of work measurement to hand planting work. Interested parties for the results of this dissertation include occupational health researchers, ergonomists, professional reforestation businesses and interest groups, and land owners of commercial southeastern U.S. pine stands. The results provide valuable insight for these parties that can be applied in further occupational injury prevention research, tool design, and can readily be applied in esimating reforestation costs and production schedules.

The results of the study titled "A Characterization of Physical Risk Factors among Hand Planter Reforestation Workers" suggest that hand planters are exposed to increased physical risk factors for MSDs compared to workers in other occupational groups. The study presented characterizations of forceful muscle exertions of the bilateral upper trapezius and anterior deltoid muscle groups, occupational physical activity, and working postures among a sample of 14 full-shift professional hand planters in the southeastern U.S. These characterizations can be used by future researchers to compare process changes to a baseline of risk factor exposures. Process changes include those focused on occupational health outcomes, such as the introduction of work-rest cycles or the development of new tools, to interventions to increase productivity. Like many ergonomic improvements, these interventions may have positive outcomes in reducing risk factor exposures and increasing productivity.

The study titled "Measuring the Effect of Tool Design on Exposure to Physical Risk Factors among Novice Hand Planters" suggests a lack of significant differences among exposures to the risk factors of elevated heart rate, forceful muscle exertions, and non-neutral working postures among four different dibble bars. The study evaluated these effects on fourteen male novice planters. The study also characterized previously unreported working postures of the neck and wrists during the hand planting process. The results can be used by interested parties as baselines for novice hand planter tool development or testing research. Reported wrist postures can be compared to hand planters using tools with various handle designs, as handle shape ('T' shape) was controlled across all tools.

The study titled "Applying Work Measurement Methods to Hand Planter Reforestation Work" provides a Maynard Operation Sequence Technique (MOST) predetermined motion time system time standard for hand planter reforestation work. The presented time standard suggests previously reported hand planting reforestation rates are within reason of standard work measurement results. The results also suggests that MOST analysis may not adequately account for the highly repetive and physically demanding work previously characterized of hand planting. The study suggests that further research into accurate fatigue allowances would provide greater insight into the physical capabilities and expectations of hand planter workers. The results of this study can be used by hand planter contractors and land owners to more accurately estimate costs and schedule production, while providing a framework for applying additional allowances for pine stand variations in terrain and environmental conditions.

The results of these studies address the specific aims of this dissertation by characterizing physical risk factor exposures among southeastern U.S. hand planters, evaluating the effect of tool design on risk factor exposures, and applying work measurement techniques to the planting cycle employed by hand planters.

5.2 Limitations

The results of the present dissertation have several limitations that reduce their universal applicability to reforestation injury prevention and work measurement. First, the study titled “A Characterization of Physical Risk Factors among Hand Planter Reforestation Workers” included a geographically limited and homogeneous sample of participants. Difficulties in the collection of full-shift exposures limited the data sample size further. Two bilateral muscle groups were studied, while forceful muscle exertions of other, potentially important, muscle groups were not sampled. Non-neutral working postures of the low back related to the repetitive bending of the torso to reach the seedling hole were not captured. Ratings of perceived exertions (Borg-10 scale) were not collected among the study participants. Certain parameters, including the weight of the seedling bag and the tenure of experience among each hand planter, were not captured.

The study titled “Measuring the Effect of Tool Design on Exposure to Physical Risk Factors among Novice Hand Planters” did not use professional hand planters that may have developed nuanced biomechanic planting methods from experience that may affect how they use tools. Ratings of perceived exertions were not collected among the study participants. While four styles of dibble bars were evaluated, other planting tools, such as the ‘hoe-dad’, were not evaluated. The study exclusively used bareroot pine seedlings, while not evaluating the planting of containerized seedling, another popular type of seedling that has different weight and rate of planting characterizations. The weight of the seedling bag prior to each trial was not precisely collected or controlled.

The study titled “Applying Work Measurement Methods to Hand Planter Reforestation Work” only used one method of standardized work measurement to evaluate hand planting work. While predetermined motion time systems are widely used, other observational work measurement techniques may provide more insight into the capabilities of workers on planting rates. The weight of a full seedling bag was an unknown factor, as well as the weight of an empty seedling bag, which could have provided additional resolution to the analysis as changes in the weight of the seedling bag may reduce fatigue.

5.3 Recommendations for further research

Further research is needed to fully understand the effects of hand planting work on health outcomes among reforestation workers. Suggested future research includes:

- Characterization of forceful exertions for muscle groups of the low back.
- Comparative evaluation of physical risk factor exposures among mechanized and hand planter reforestation workers.
- Assessment of occupational activities by hand planter population during non-planting months of the year.
- Evaluation of hand planter tools using professional hand planters.
- Development and assessment of innovative planting bar designs that minimize physical risk factors exposures.
- Comparative evaluation of physical risk factor exposures among ‘dibble-bars’, ‘hoe-dads’, and other planting bars in use by southern U.S. reforestation contractors.
- Longitudinal cohort study of health outcomes on southern U.S. hand planters.

In addition, the determination of work measurement allowances for physically demanding and repetitive work is not well understood. Fatigue allowance models that account for physiologic responses to work have not been updated to reflect advances in fatigue research. The development of more accurate models may provide researchers with better tools capable of more accurately estimating the time that is allotted for the completion of work. Work measurement systems that account for ergonomic considerations of the work are not currently available for use.

In conclusion, the research presented in this dissertation was designed to provide more information regarding hand planting work, with the goal of further understanding the risk factors associated with hand planting, the effects of tool variability on those risk factors, and the expectations of planting rates based on the hand planting cycle. The research provides ample opportunities for further scientific inquiry, while presenting valuable results readily applicable to interested parties.

References

Amasay, T., Zodrow, K., Kincl, L., Hess, J., & Karduna, A. (2009). Validation of tri-axial accelerometer for the calculation of elevation angles. *International Journal of Industrial Ergonomics*, *39*(5), 783–789.

Anderson, J. (1984). Shoulder pain and tension neck and their relation to work. *Scandinavian Journal of Work, Environment & Health*, 435–442.

Andersson, G. B. (1981). Epidemiologic aspects on low-back pain in industry. *Spine*, *6*(1).

Appelroth, S. E. & Harstela, P. (1970). The use of the semi-circular hoe, the field spade, plant basket, plant bag and the heger and lmd-1 tree planters in planting spruce in fields. *Folia Forestalia*, *85*(32).

Arias, O. E., Caban-Martinez, A. J., Umukoro, P. E., Okechukwu, C. A., & Dennerlein, J. T. (2015). Physical activity levels at work and outside of work among commercial construction workers: *Journal of Occupational and Environmental Medicine*, *57*(1), 73–78.

Armstrong, T. J., Foulke, J. A., Joseph, B. S., & Goldstein, S. A. (1982). Investigation of cumulative trauma disorders in a poultry processing plant. *American Industrial Hygiene Association Journal*, *43*(2), 103–116.

Arvidsson, I., Arvidsson, M., Axmon, A., Hansson, G. Å., Johansson, C. R., & Skerfving, S. (2006). Musculoskeletal disorders among female and male air traffic controllers performing identical and demanding computer work. *Ergonomics*, *49*(11), 1052–1067.

Astrand, P. O. & Rodahl, K. (1986). *Applied work physiology*: *Textbook of work physiology.* New York: McGraw-Hill.

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), 245–250.

Bao, S. [Shihan], Mathiassen, S. E., & Winkel, J. (1995). Normalizing upper trapezius emg amplitude: Comparison of different procedures. *Journal of Electromyography and Kinesiology*, *5*(4), 251–257.

Bao, S. [Stephen], Howard, N., Spielholz, P., Silverstein, B., & Polissar, N. (2009). Interrater reliability of posture observations. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *51*(3), 292–309.

Basmajian, J. V. (1962). Muscles Alive. Their Functions Revealed by Electromyography. *Academic Medicine*, *37*(8), 802.

Battini, D., Faccio, M., Persona, A., & Sgarbossa, F. (2011). New methodoligical framework to improve productivity and ergonomics in assembly system design. *International Journal of Industrial Ergonomics*, *41*, 30–42. doi:10.1016/j.ergon.2010.12.001

Bernard, B. P. (1997). Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related disorders of the neck, upper extremity, and low back. *DHHS (NIOSH) Publication No. 97-141.*

Bernmark, E. & Wiktorin, C. (2002). A triaxial accelerometer for measuring arm movements. *Applied Ergonomics*, *33*(6), 541–547.

Berntsen, S., Hageberg, R., Aandstad, A., Mowinckel, P., Anderssen, S. A., Carlsen, K. H., & Andersen, L. B. (2010). Validity of physical activity monitors in adults participating in free-living activities. *British Journal of Sports Medicine*, *44*, 657–664.

Bink, B. (1962). The Physical Working Capacity in Relation to Working Time and Age. *Ergonomics*, *5*(1), 25–28.

BLS. (2014). Nonfatal occupational injuries and illnesses requiring days away from work, 2013. *U.S. Department of Labor Publication No. 14-2183.* Retrieved from https://www.bls.gov/news.release/archives/osh_12042014.pdf

BLS. (2015). Nonfatal occupational injuries and illnesses requiring days away from work, 2014. *U.S. Department of Labor Publication No. 15-2205*. Retrieved from http://www.bls.gov/news.release/pdf/osh2.pdf

BLS. (2016). Nonfatal occupational injuries and illnesses requiring days away from work, 2015. *U.S. Department of Labor Publication No. 16-2130*. Retrieved from https://www.bls.gov/news.release/pdf/osh2.pdf

Boettcher, C. E., Ginn, K. A., & Cathers, A. (2008). Standard Maximum Isometric Voluntary Contraction Tests for Normalizing Shoulder Muscle EMG. *Journal of Orthopaedic Research*, *26*(12), 1591–1597.

Burdorf, A. & van der Beek, A. J. (1999). Exposure assessment strategies for work-related risk factors for musculoskeletal disorders. *Scandinavian Journal of Work, Environment & Health*, *25*, 25–30.

Butterworth, P. A., Landorf, K. B., Smith, S. E., & Menz, H. B. (2012). The association between body mass index and musculoskeletal foot disorders: A systematic review. *Obesity Reviews*, *13*(7), 630–642.

Caspersen, C. J., Powell, K. E., & Christenson, G. M. (1985). Physical Activity, Exercise, and Physical Fitness: Definitions and Distinctions for Health-Related Research. *Public Health Reports*, *100*(2), 126.

Chen, H., Schall Jr., M. C., & Fethke, N. B. (2018). Accuracy of angular displacements and velocities from inertial-based inclinometers. *Applied Ergonomics*, *67*, 151–161.

Chen, K. Y. & Bassett, D. R. (2005). The Technology of Accelerometry-Based Activity Monitors: Current and Future. *Medicine & Science in Sports & Exercise*, *37*(11), S490.

Chowdhury, R. H., Reaz, M. B. I., Ali, M. A. B. M., Bakar, A. A. A., Chellappan, K., & Change, T. G. (2013). Surface electromyography signal processing and classification techniques. *Sensors*, *13*(9), 12431–12466.

Christmansson, M., Medbo, L., Hansson, G. Å., Ohlsson, K., Unge Byström, J., Möller, T., & Forsman, M. (2002). A case study of a principally new way of materials kitting—an evaluation of time consumption and physical workload. *International Journal of Industrial Ergonomics*, *30*(1), 49–65.

Cook, C., Burgess-Limerick, R., & Papalia, S. (2004). The effect of upper extremity support on upper extremity posture and muscle activity during keyboard use. *Applied Ergonomics*, *35*(3), 285–292.

Cornman, G. (1970). Fatigue allowances - a systematic method. *Industrial Engineering*, *2*, 10–16.

Coyte, P. C., Asche, C. V., Croxford, R., & Chan, B. (1998). The economic cost of musculoskeletal disorders in canada. *Arthritis & Rheumatism*, *11*(5), 315–325.

Cram, J. R., Kasman, G. S., & Holtz, J. (1998). *Introduction to surface electromyography.* Gaithersburg, MD: Aspen Publishers.

Criswell, E. (2010). *Cram's Introduction to Surface Electromyography* (2nd ed.). Burlington, MA: Jones & Bartlett Publishers.

da Costa, B. R. & Vieira, E. R. (2010). Risk factors for work-related musculoskeletal disorders: A systematic review of recent longitudinal studies. *American Journal of Industrial Medicine*, *53*(3), 285–323.

Dartt, A., Rosecrance, J., Gerr, F., Chen, P., Anton, D., & Merlino, L. (2009). Reliability of assessing upper limb postures among workers performing manufacturing tasks. *Applied Ergonomics*, *40*(3), 371–378.

David, G. C. (2005). Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. *Occupational Medicine*, *55*, 190–199.

De Mey, K., Cagnie, B., Van De Velde, A., Danneels, L., & Cools, A. M. (2009). Trapezius Muscle Timing During Selected Shoulder Rehabilitation Exercises. *Journal of Orthopaedic & Sports Physical Therapy*, *39*(10), 743–752.

Denbeigh, K., Slot, T. R., & Duman, G. A. (2013). Wrist postures and forces in tree planters during three tree unloading conditions. *Ergonomics*, *56*(10), 1599–1607.

Devereux, J., Rydstedt, L., Kelly, V., Weston, P., & Buckle, P. (2004). *The role of work stress and psychological factors in the development of musculoskeletal disorders: The stress and msd study (rr 273).* Health and Safety Executive. Retrieved from http://www.hse.gov.uk/research/rrhtm/rr273.htm%EF%BF%BD

Diament, M. L., Goldsmith, R., Hale, T., & R, K. G. (1968). An assessment of habitual physical activity. *Journal of Physiology*, *200*, 44–45.

Douphrate, D. I., Fethke, N. B., Nonnenmann, M. W., Rosecrance, J. C., & Reynolds, S. J. (2012). Full shift arm inclinometry among dairy parlor workers: A feasibility study in a challenging work environment. *Applied Ergonomics*, *43*(3), 604–613.

Douphrate, D. I., Gimeno Ruiz de Porras, D., Nonnenmann, M. W., Hagevoort, R., Reynolds, S. J., Rodriguez, A., & Fethke, N. B. (2017). Effects of milking unit design on upper extremity muscle activity during attachment among u.s. large-herd parlor workers. *Applied Ergonomics*, *58*, 482–490.

Drake, J. D. M. & Callaghan, J. P. (2006). Elimination of electrocardiogram contamination from electromyogram signals: An evaluation of currently used removal techniques. *Journal of Electromyography and Kinesiology*, *16*(2), 175–187.

Drinkhaus, P., Sesek, R., Bloswick, D., Bernard, T., Walton, B., Reeve, G., & Counts, J. H. (2003). Comparison of ergonomic risk assessment outputs from Rapid Upper Limb Assessment and the Strain Index for tasks in automotive assembly plants. *Work*, *21*(2), 165–172.

Drury, C. G. (2000). Global quality: Linking ergonomics and production. *International Journal of Production Research*, *38*(17), 4007–4018. doi:10.1080/00207540050204876

Eklund, J. A. [Jörgen A.]. (1995). Relationships between ergonomics and quality in assembly work. *Applied Ergonomics*, *26*(1), 15–20. doi:10.1016/0003-6870(95)95747-N

Eklund, J. A. [Jörgen A]. (1997). Ergonomics, quality and continuous improvement conceptual and empirical relationships in an industrial context. *Ergonomics*, *40*(10), 982–1001. doi:10.1080/001401397187559

Fethke, N. B., Gant, L. C., & Gerr, F. (2011). Comparison of biomechanical loading during use of conventional stud welding equipment and an alternate system. *Applied Ergonomics*, *42*(5), 725–734.

Fethke, N. B., Gerr, F., Anton, D., Cavanaugh, J. E., & Quickel, M. T. (2012). Variability in muscle activity and wrist motion measurements among workers performing non-cyclic work. *Journal of Occupational and Environmental Hygiene*, *9*(1), 25–35.

Fethke, N. B., Schall Jr., M. C., Determan, E. M., & Kitzmann, A. S. (2015). Neck and shoulder muscle activity among ophthalmologists during routine clinical examinations. *International Journal of Industrial Ergonomics*, *49*, 53–59.

Feyen, R., Liu, Y., Chaffin, D., Jimmerson, G., & Joseph, B. (2000). Computer-aided ergonomics: A case study of incorporating ergonomics analyses into workplace design. *Applied Ergonomics*, *31*(3), 291–300. doi:10.1016/S0003-6870(99)00053-8

Folegatti, B. S., Smidt, M. F., & Dubois, M. R. (2007). Costs and cost trends for forestry practices in the South. *Forest Landowner*, *66*(5), 11–16. Retrieved from https://www.scopus.com/record/display.uri?eid=2-s2.0-43549098053&origin=inward&txGid=d32b858b7c7ee0611ce94abcde1c2cb7

Fordham, M., Appenteng, K., & Goldsmith, R. (1978). The cost of work in medical nursing. *Ergonomics*, *21*, 331–342.

Freedson, P., Bowles, H. R., Troiano, R., & Haskell, W. (2012). Assessment of physical activity using wearable monitors: Recommendations for monitor calibration and use in the field. *Medicine and science in sports and exercise*, *44*(1 Suppl 1), S1–S4.

Freedson, P., Melanson, E., & Sirard, J. (1998). Calibration of the Computer Science and Applications, Inc. accelerometer. *Medicine & Science in Sports & Exercise*, *30*(5), 777–781. Retrieved from http://journals.lww.com/acsm-msse/Fulltext/1998/05000/Calibration_of_the_Computer_Science_and.21.aspx

Freivalds, A. & Eklund, J. (1993). Reaction torques and operator stress while using powered nutrunners. *Applied Ergonomics*, *24*(3), 158–164. doi:10.1016/0003-6870(93)90003-R

Gallagher, S. & Heberger, J. R. (2013). Examining the interaction of force and repetition on musculoskeletal disorder risk a systematic literature review. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *55*(1), 108–124.

Gellish, R., Goslin, B., Olson, R., McDonald, A., Russi, G., & Moudgil, V. (2007). Longitudinal modeling of the relationship between age and maximal heart rate. *Medicine & Science in Sports & Exercise*, *39*(5), 822–829. doi:10.1097/mss.0b013e31803349c6

Gerr, F., Fethke, N. B., Anton, D., Merlino, L., Rosecrance, J., Marcus, M., & Jones, M. P. (2014). A prospective study of musculoskeletal outcomes among manufacturing workers ii. effects of psychosocial stress and work organization factors. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *56*(1), 178–190.

Giguere, D., Belanger, R., Gauthier, J. M., & Larue, C. (1993). Ergonomics aspects of tree-planting using 'multipot' technology. *Ergonomics*, *36*(8), 963–972.

Giroux, B. & Lamontagne, M. (1992). Net shoulder joint moment and muscular activity during light-weight handling at different heights and frequencies. *Ergonomics*, *35*(4), 385–403.

Goldsmith, R., O'Brian, C., Tan, G. L. E., Smith, W. S., & Dixon, M. (1978). The cost of work on a vehicle assembly line. *Ergonomics*, *21*, 315–323.

Grandjean, E. (1988). *Fitting the Task to the Man* (4th ed.). New York: Taylor & Francis.

Granzow, R. F., Schall Jr., M. C., Smidt, M. F., Chen, H., Fethke, N. B., & Huangfu, R. (2018). Characterizing exposure to physical risk factors among reforestation hand planters in the Southeastern United States. *Applied Ergonomics*, *66*, 1–8. doi:10.1016/j.apergo.2017.07.013

Grzywacz, J. G., Lipsomb, H. J., Casanova, V., Neis, B., Fraser, C., Monaghan, P., & Vallejos, Q. M. (2013). Organization of work in the agricultural, forestry, and fishing sector in the us southeast: Implications for immigrant workers' occupational safety and health. *American Journal of Industrial Medicine*, *56*(8), 925–939.

Guo, H. R., Chang, Y. C., Yeh, W. Y., Chen, C. W., & Guo, Y. L. (2004). Prevalence of musculoskeletal disorder among workers in taiwan: A nationwide study. *Journal of Occupational Health*, *46*(1), 26–36.

Hagen, K. B., Magnus, P., & Vetlesen, K. (1998). Neck/shoulder and low-back disorders in the forestry industry relationship to work tasks and perceived psychosocial job stress. *Ergonomics*, *41*(10), 1510–1518.

Hägg, G. M., Öster, J., & Byström, S. (1997). Forearm muscular load and wrist angle among automobile assembly line workers in relation to symptoms. *Applied Ergonomics*, *28*(1), 41–47.

Hansson, G.-Å., Arvidsson, I., Ohlsson, K., Nordander, C., Mathiassen, S. E., Skerfving, S., & Balogh, I. (2006). Precision of measurements of physical workload during standardised manual handling. Part II: Inclinometry of head, upper back, neck and upper arms. *Journal of Electromyography and Kinesiology*, *16*(2), 125–136.

Hansson, G.-Å., Balogh, I., Byström, J. U., Ohlsson, K., Nordander, C., Asterland, P., ... Skerfving, S. (2001). Questionnarie versus direct technical measurements in assessing postures and movements of the head, upper back, arms and hands. *Scandinavian Journal of Work, Environment & Health*, *27*(1), 30–40.

Hansson, G.-Å., Balogh, I., Ohlsson, K., Granqvist, L., Nordander, C., Arvidsson, I., ... Skerfving, S. (2009). Physical workload in various types of work: Part I. Wrist and forearm. *International Journal of Industrial Ergonomics*, *39*(1), 221–233.

Hansson, G.-Å., Nordander, C., Asterland, P., Ohlsson, K., Strömberg, U., Skerfving, S., & Rempel, D. (2000). Sensitivity of trapezius electromyography to differences between work tasks — influence of gap definition and normalisation methods. *Journal of Electromyography and Kinesiology*, *10*(2), 103–115.

Hanvold, T. N., Wærsteda, M., Mengshoel, A. M., Bjertness, E., & Veiersted, K. B. (2015). Work with prolonged arm elevation as a risk factor for shoulder pain: A longitudinal study among young adults. *Applied ergonomics*, *47*, 43–51.

Harari, G., Green, M. S., & Zelber-Sagi, S. (2015). Combined association of occupational and leisure-time physical activity with all-cause and coronary heart disease mortality among a cohort of men followed-up for 22 years. *Occupational and Environmental Medicine*.

Hendelman, D., Miller, K., Baggett, C., Debold, E., & Freedson, P. (2000). Validity of accelerometry for the assessment of moderate intensity physical activity in the field. *Medicine & Science in Sports & Exercise*, *32*, S442–S449.

Heneweer, H., Staes, F., Aufdemkampe, G., van Rijn, M., & Vanhees, L. (2011). Physical activity and low back pain: A systematic review of recent literature. *European Spine Journal*, *20*(6), 826–845.

Hignett, S. & McAtamney, L. (2000). Rapid Entire Body Assessment (REBA). *Applied Ergonomics*, *31*(2), 201–205.

Hildebrand, M., Van Hees, V. T., Hansen, B. H., & Ekelund, U. (2014). Age Group Comparability of Raw Accelerometer Output from Wrist- and Hip-Worn Monitors. *Medicine and Science in Sports and Exercise*, *46*(9), 1816–1824.

Hodges, A. N. H. & Kennedy, M. D. (2011). Physical exertion and working efficiency of reforestation workers. *Journal of Occupational Medicine and Toxicology*.

Holtermann, A. [A.], Hansen, J. V., Burr, H., Søgaard, K., & Sjøgaard, G. (2012). The health paradox of occupational and leisure-time physical activity. *British Journal of Sports Medicine*, *46*(4), 291–295.

Holtermann, A., Mortensen, O. S., Burr, H., Søgaard, K., Gyntelberg, F., & Suadicani, P. (2010). Physical work demands, hypertension status, and risk of ischemie heart disease and all-cause mortality in the Copenhagen Male Study. *Scandinavian Journal of Work, Environment & Health*, *36*(6), 466–472.

Hooftman, W. E., van der Beek, A. J., van de Wal, B. G., Knol, D. L., Bongers, P. M., Burdorf, A., & van Mechelen, W. (2009). Equal task, equal exposure? Are men and women with the same tasks equally exposed to awkward working postures? *Ergonomics*, *52*(9), 1079–1086.

Hooper, M. M., Stellato, T. A., Hallowell, P. T., Seitz, B. A., & Moskowitz, R. W. (2006). Musculoskeletal findings in obese subjects before and after weight loss following bariatric surgery. *International Journal of Obesity*, *31*(1), 114–120.

Horton, R. (2012). GBD 2010: understanding disease, injury, and risk. *The Lancet*, *380*, 2053–2054.

Huang, G. D., Feuerstein, M., Kop, W. J., Schor, K., & Arroyo, F. (2003). Individual and Combined Impacts of Biomechanical and Work Organization Factors in Work-Related Musculoskeletal Symptoms. *American Journal of Industrial Medicine*, *43*(5), 495–506. doi:10.1002/ajim.10212

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), 416–427.

Jankovský, M., Merganič, J., Allman, M., Ferenčík, M., & Messingerová, V. (2017). The cumulative effects of work-related factors increase the heart rate of cabin field machine operators. *International Journal of Industrial Ergonomics*. doi:10.1016/j.ergon.2017.08.003

Jonsson, B. (1982). Measurement and evaluation of local muscular strain in the shoulder during constrained work. *Journal of Human Ergology*, *11*(1), 73–88.

Jonsson, B. & Hagberg, M. (1973). The effect of different working heights on the deltoid muscle. A preliminary methodological study. *Scandinavian Journal of Rehabilitation Medicine*, *Supplement 3*(26), 26–32.

Juul-Kristensen, B., Hansson, G. Å., Fallentin, N., Andersen, J. H., & Ekdahl, C. (2001). Assessment of work postures and movements using a video-based observation method and direct technical measurements. *Applied Ergonomics*, *32*(5), 517–524.

Kadefors, R., Petersen, I., & Herberts, P. (1976). Muscular reaction to welding work: An electromyographic investigation. *Ergonomics*, *19*(5), 543–558.

Kanawaty, G. (1992). *Introduction to Work Study.* International Labour Office.

Karkowski, W., Genaidy, A. M., & Asfour, S. S. (1990). *Computer-aided ergonomics.* London: Taylor & Francis.

Kazmierczak, K., Mathiassen, S. E., Forsman, M., & Winkel, J. (2005). An integrated analysis of ergonomics and time consumption in swedish 'craft-type' car disassembly. *Applied Ergonomics*, *36*(3), 263–273.

Kazmierczak, K., Mathiassen, S. E., Neumann, P., & Winkel, J. (2006). Observer reliability of industrial activity analysis based on video recordings. *International Journal of Industrial Ergonomics*, *36*(3), 275–282.

Kerr, M. S., Frank, J. W., Shannon, H. S., Norman, R. W., Wells, R. P., Neumann, W. P., & Bombardier, C. (2001). Biomechanical and psychosocial risk factors for low back pain at work. *American Journal of Public Health*, *91*(7), 1069–1075.

Keyserling, W. M. (1986). Postural analysis of the trunk and shoulders in simulated real time. *Ergonomics*, *29*(4), 569–583.

Keyserling, W. M., Brower, M., & A, S. B. (1992). A checklist for evaluating ergonomic risk factors resulting from awkward postures of the legs, trunk and neck. *International Journal of Industrial Ergonomics*, *9*(4), 283–301. doi:10.1016/0169-8141(92)90062-5

Kirk, P. M. & Parker, R. J. (1996). An ergonomic evaluation of douglas fir manual pruning in new zealand. *Journal of Forest Engineering*, *7*(2), 51–58.

Kirk, P. M. & Sullman, M. (1995). *An ergonomic investigation of hauler breaker-outs.* LIRO.

Kirk, P. M. & Sullman, M. J. M. (2001). Heart rate strain in cable hauler choker settlers in New Zealand. *Applied Ergonomics*, *32*(4), 389–398. doi:10.1016/S0003-6870(01)00003-5

Kitzmann, A. S., Fethke, N. B., Baratz, K. H., Zimmerman, M. B., Hackbarth, D. J., & Gehrs, K. M. (2012). A survey study of musculoskeletal disorders among eye care physicians compared with family medicine physicians. *Ophthalmology*, *119*(2), 213–220.

Kourinkaetal, I. & Forcier, L. (1995). *Work related musculoskeletal disorders (wmsds): A reference book for prevention*. Taylor & Francis.

Kushla, J. D. & Ezell, A. W. (2017). *Tree Planting is Easy*. Extension Service of Mississippi State University. Retrieved from https://extension.msstate.edu/sites/default/files/publications/publications/p0160.pdf

Lammert, O. (1972). Maximal aerobic power and energy expenditure of eskimo hunters in greenland. *Journal of Applied Physiology*, *33*, 184–188.

Laukkanen, R. & Virtanen, P. (1998). Heart rate monitors - state of the art. *Journal of Sports Sciences*, *16*, S3–S7.

Lewis, G. L. & Narayan, C. V. (1993). Design and sizing of ergonomic handles for hand tools. *Applied Ergonomics*, *24*(5), 351–356.

Li, G. & Buckle, P. (1999). Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. *Ergonomics*, *42*(5), 674–695.

Lidgren, L. (2003). The bone and joint decade 2000-2010. *Bulletin of the World Health Organization*, *81*(9).

Ligorio, G. & Sabatini, A. M. (2015). A novel kalman filter for human motion tracking with an inertial-based dynamic inclinometer. *IEEE Transactions on Biomedical Engineering*, *62*(8), 2033–2043.

Liunge, H. J. & Veltnik, P. H. (2005). Measuring orientation of human body segments using miniature gyroscopes and accelerometers. *Medical and Biological Engineering and Computing*.

Lloyd, A., Gandevia, S., & Hales, J. (1991). Muscle performance, voluntary activation, twitch properties and perceived effort in normal sujects and patients with the chronic fatigue syndrome. *Brain*, *114*(1), 85–98. doi:10.1093/oxfordjournals.brain.a101869

Lynch, S. M., Smidt, M. F., Merrill, P. D., & Sesek, R. F. (2014). Incidence of MSDs and Neck and Back Pain among Logging Machine Operators in the Southern U.S. *Journal of Agricultural Safety and Health*.

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), 197–226. doi:10.1016/1050-6411(94)00014-X

Mattila, M., Karwowski, W., & Vilkki, M. (1993). Analysis of working postures in hammering tasks on building construction sites using the computerized OWAS method. *Applied Ergonomics*, *24*(6), 405–412.

McAtamney, L. & Corlett, E. N. (1993). RULA: a survey method for the investigation of work-related upper limb disorders. *Applied Ergonomics*, *24*(2), 91–99.

McDaniel, J. & Casanova, V. (2005). Forest management and the h2b guest worker program in the southeastern united states: An assessment of contractors and their crews. *Journal of Forestry*.

McDonald, T. P., Fulton, J. P., Darr, M. J., & Gallagher, T. V. (2008). Evaluation of a system to spatially monitor hand planting of pine seedlings. *Computers and Electronics in Agriculture*, *64*(2), 173–182. doi:10.1016/j.compag.2008.04.011

Meyers, F. E. (1992). *Motion and Time Study - Improving Work Methods and Management*. Prentice-Hall.

Minard, D., Goldsmith, R., Farrier, P. H., & Lambiotte, B. J. (1971). Physiological evaluation of industrial heat stress. *American Industrial Hygiene Association Journal*, *32*, 17–28. doi:10.1080/0002889718506402

Mincheva, L., Khadziolova, I., Dunev, S., & Polianska, L. (1986). Work difficulty and the the physical work capacity of female afforestation workers in forestry. *Problemi na Khigienata*, *11*, 47–54. Retrieved from http://europepmc.org/abstract/med/3823039

Mital, A., Bishu, R. R., & Manjunath, S. G. (1991). Review and evaluation of techniques for determining fatigue allowance. *International Journal of Industrial Ergonomics*, *8*(2), 165–178.

Moore, S. J. & Garg, A. (1995). The Strain Index: a proposed method to analyze jobs for risk of distal upper extremity disorders. *American Industrial Hygiene Association*, *56*(5), 443–458.

Murphy, M. S. & Harrington, T. B. (2004). *Stem sinuosity of loblolly pine seedlings as influenced by taproot shape: General Technical Report SRS-71.* US Department of Agriculture, Forest Service, Southern Research Station. Asheville, NC.

Murrell, K. F. H. (1965). *Human Performance in Industry.* New York: Reinhold Publishing.

Niebel, B. & Freivalds, A. (2003). *Methods, Standards and Work Design* (11th ed.). McGraw-Hill.

Nieminen, H., Takala, E. P., & Viikari-Juntura, E. (1993). Normalization of electromyogram in the neck-shoulder region. *European Journal of Applied Physiology and Occupational Physiology*, *67*(2), 199–207.

NOAA. (2018). Climate Data Online. Retrieved from https://www.ncdc.noaa.gov/cdo-web/

Nocon, M., Hiemann, T., Müller-Riemenschneider, F., Thalau, F., Roll, S., & Willich, S. N. (2008). Association of physical activity with all-cause and cardiovascular mortality: A systematic review and meta-analysis. *European Journal of Cardiovascular Prevention & Rehabilitation*, *15*(3), 239–246.

O'Driscoll, S. W., Horii, E., Ness, R., Cahalan, T. D., Richards, R. R., & An, K. N. (1992). The relationship between wrist position, grasp size, and grip strength. *The Journal of Hand Surgery*, *17*(1), 169–177. doi:10.1016/0363-5023(92)90136-D

Ontario Forestry Safe Workplace Association (OFSWA). (2006). OFSWA's Annual Analysis of Forestry WSIB Rate Groups. Retrieved from www.ofswa.ca

Pate, R. R., Pratt, M., Blair, S. N., Haskell, W. L., Macera, C. A., Bouchard, C., & Buchner, D. (1995). Physical Activity and Public Health: a Recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. *Journal of the American Medical Association*, *273*(5), 402–407.

Picavet, H. S. J. & Schouten, J. S. A. G. (2003). Musculoskeletal pain in the Netherlands: prevalences, consequences and risk groups, the DMC 3-study. *Pain*, *102*(1), 167–178.

Porter, J. M., Freer, M., Case, K., & Bonney, M. C. (1995). *Evaluation of Human Work: A Practical Ergonomics Methodology* (2nd ed.) (J. R. Wilson & E. N. Corlett, Eds.). London: Taylor and Francis.

Prestemon, J. P. & Abt, R. C. (2002). Southern forest resource assessment highlights: the Southern timber market to 2040. *Journal of Forestry*, *100*(7), 16–22.

Punnett, L. (2014). Musculoskeletal Disorders and Occupational Exposures: How Should we Judge the Evidence Concerning the Causal Association? *Scandinavian Journal of Public Health*, *42*(13 suppl), 49–58.

Punnett, L., Fine, L. J., Keyserling, M. W., Herrin, G. D., & Chaffin, D. B. (1991). Back disorders and nonneutral trunk postures of automobile assembly workers. *Scandinavian Journal of Work, Environment & Health*, *17*(5), 337–346.

Punnett, L., Gold, L., Katz, J. N., Gore, R., & Wegman, D. H. (2004, August 1). Ergonomic stressors and upper extremity musculoskeletal disorders in automobile manufacturing: A one year follow up study. *Occupational and Environmental Medicine*, *61*(8), 668–674.

Putz-Anderson, V., Bernard, B. P., Burt, S. E., Cole, L. L., Fairfield-Estill, C., Fine, L. J., ... Nelson, N. (1997). Musculoskeletal disorders and workplace factors. *National Institute for Occupational Safety and Health*, 104.

Quandt, S. A., Kucera, K. L., Haynes, C., Klein, B. G., Langley, R., Agnew, M., ... Nussbaum, M. A. (2013). Occupational health outcomes for workers in the agriculture, forestry and fishing sector: Implications for immigrant workers in the southeastern us. *American Journal of Industrial Medicine*, *56*(8), 940–959.

Redfern, M. S., Hughes, R. E., & Chaffin, D. B. (1993). High-pass filtering to remove electrocardiographic interference from torso emg recordings. *Clinical Biomechanics*, *8*(1), 44–48.

Roberts, D. (2002). In-season physiological and biochemical status of reforestation workers. *Journal of Occupational & Environmental Medicine*, *44*(6), 559–567.

Robinson, D. G., Trites, D. G., & Banister, E. W. (1993). Physiological effects of work stress and pesticide exposure in tree planting by british columbia silviculture workers. *Ergonomics*, *36*(8), 951–961.

Roetenberg, D., Slycke, P. J., & Veltink, P. H. (2007). Ambulatory Position and Orientation Tracking Fusing Magnetic and Inertial Sensing. *IEEE Transactions on Biomedical Engineering*, *54*(5), 883–890.

Rota, S., Rogowski, I., Champely, S., & Hautier, C. (2013). Reliability of EMG normalisation methods for upper-limb muscles. *Journal of Sports Sciences*, *31*(15), 1696–1704.

Saha, P. N. (1978). Aerobic capacity of steel workers in india. *Ergonomics*, *21*, 1021–1025.

Sarathy, B. & Casanova, V. (2008). Guest workers or unauthorized immigrants? the case of forest workers in the united states. *Policy Sciences*, *41*(2), 95–114.

Sato, M. & Tanaka, S. (1973). Postural effect on the relation between oxygen consumption and heart rate. *Journal of Human Ergology*, *2*(1), 21–30.

Schall Jr., M. C., Chen, H., & Fethke, N. B. (2015). Comparing fatigue, physical activity, and posture among nurses in two staffing models. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 59, *1*, pp. 1269–1273).

Schall Jr., M. C., Fehtke, N. B., Chen, H., & Kitzmann, A. S. (2014). A comparison of examination equipment used during common clinical ophthalmologic tasks. *IIE Transactions on Occupational Ergonomics and Human Factors*, *2*(2). doi:10.1080/21577323.2014.964812

Schall Jr., M. C., Fethke, N. B., & Chen, H. (2016a). Evaluation of four sensor locations for physical activity assessment. *Applied Ergonomics*, *53*.

Schall Jr., M. C., Fethke, N. B., & Chen, H. (2016b). Working postures and physical activity among registered nurses. *Applied Ergonomics*, *54*, 243–250.

Schall Jr., M. C., Fethke, N. B., Chen, H., Oyama, S., & Douphrate, D. I. (2016c). Accuracy and repeatability of an inertial measurement unit system for field-based occupational studies. *Ergonomics*, *59*(4).

Schultz, R. P. (1997). *Agricultural Handbook 713: Loblolly pine. the ecology and culture of loblolly pine (pinus taeda l.)*

Sigholm, G., Herberts, P., Almström, C., & Kadefores, R. (1983). Electromyographic analysis of shoulder muscle load. *Journal of Orthopaedic Research*, *1*(4), 379–386.

Silverstein, B. A., Fine, L. J., & Armstrong, T. J. (1987). Occupational factors and carpal tunnel syndrome. *American Journal of Industrial Medicine*, *11*(3), 343–358. doi:10.1002/ajim.4700110310

Sitthipornvorakul, E., Janwantanakul, P., Purepong, N., Pensri, P., & van der Beek, A. J. (2011). The association between physical activity and neck and low back pain: A systematic review. *European Spine Journal*, *20*(5), 677–689.

Skotte, J., Korshøj, M., Kristiansen, J., Hanisch, C., & Holtermann, A. (2014). Detection of physical activity types using triaxial accelerometers. *Journal of Physical Activity and Health*, *11*, 76–84.

Slot, T. R. (2010). *A Study of Musculoskeletal Symtoms, Posture, and Joint Reaction Forces in Ontario Tree-Planters* (Doctoral dissertation, Queen's University).

Slot, T. R. & Dumas, G. A. (2010a). Musculoskeletal symptoms in tree planters in ontario, canada. *Work*, *36*(1), 67–75. doi:10.3233/WOR-2010-1008

Slot, T. R., Shackles, E., & Dumas, G. A. (2010b). Upper limb and trunk kinematics in tree planters during three load carriage conditions. *Occupational Ergonomics*, *9*(3,4), 169–182. doi:10.3233/OER-2010-0187

Smith, T. J. (1987). Occupational characteristics of tree-planting work. *Silviculture Magazine*, *2*, 12–17.

Sofi, F., Capalbo, A., Cesari, F., Abbate, R., & Gensini, G. F. (2008). Physical activity during leisure time and primary prevention of coronary heart disease: An updated meta-analysis of cohort studies. *European Journal of Cardiovascular Prevention & Rehabilitation*, *15*(3), 247–257.

South, D. & Mexal, J. G. (1984). Growing the "best" seedling for reforestation success. In *Auburn university forestry departmental series* (Vol. 12). Alabama Agricultural Experiment Station.

Spengler, D. M., Bigos, S. J., Martin, N. A., Zeh, J., Fisher, L., & Nachemson, A. (1986). Back Injuries in Industry: A Retrospective Study: I. Overview and Cost Analysis. *Spine*, *11*(3).

Spielholz, P. (2006). Calibrating borg scale ratings of hand force exertion. *Applied Ergonomics*, *37*, 615–618. doi:10.1016/j.apergo.2005.10.001

Spielholz, P., Silverstein, B., Morgan, M., Checkoway, H., & Kaufman, J. (2001). Comparison of self-report, video observation and direct measurement methods for upper extremity musculoskeletal disorder physical risk factors. *Ergonomics*, *44*(6), 588–613.

Sporrong, H. & Styf, J. (1999). Effects of isokinetic muscle activity on pressure in the supraspinatus muscle and shoulder torque. *Journal of Orthopaedic Research*, *17*(4), 546.

Stjernberg, E. I. (1988). A Study of Manual Tree Planting Operations in Central and Eastern Canada. *Point Claire, Canada: Forest Engineering Research Institute of Canada.*

Stjernberg, E. I. (2003). Injury reduction and performance enhancements in tree planters: Productivity and quality analysis. *Advantage*, *4*(11).

Sullman, M. J. M. & Byers, J. (2000). An Ergonomic Assessment of Manual Planting Pinus Radiata seedlings. *Journal of Forest Engineering*, *11*(1), 53–62.

Svendsen, S. W., Bonde, J. P., Mathiassen, S. E., Stengaard-Petersen, K., & Frich, L. H. (2004a). Work related shoulder disorders: Quantitative exposure-response relations with reference to arm posture. *Occupational and Environmental Medicine*, *61*(10), 844–853.

Svendsen, S. W., Gelineck, J., Mathiassen, S. E., Bonde, J. P., Frich, L. H., Stengaard-Petersen, K., & Egund, N. (2004b). Work above shoulder level and degenerative alterations of the rotator cuff tendons: A magnetic resonance imaging study. *Arthritis & Rheumatism*, *50*(10).

Takala, E.-P., Pehkonen, I., Forsman, M., Hansson, G.-Å., Mathiassen, S. E., Neumann, W. P., . . . Winkel, J. (2010). Systematic evaluation of observational methods assessing biomechanical exposures at work. *Scandinavian Journal of Work, Environment & Health*, *36*(1), 3–24.

Tanaka, H., Monahan, K. D., & Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *Journal of the American College of Cardiology*, *37*(1), 153–156. doi:10.1016/S0735-1097(00)01054-8

Teschke, K., Trask, C., Johnson, P., Chow, Y., Village, J., & Koehooorn, M. (2009). Measuring posture for epidemiology: Comparing inclinometry, observations and self-reports. *Ergonomics*, *52*(9), 1067–1078.

Texas A&M Forest Service. (2012). How to Plant a Seedling. Retrieved from https://www.youtube.com/watch?v=4xqeKRsaa0E

Thamsuwan, O. & Johnson, P. (2015). Comparing upper arm and back postural exposures between apple harvesting with ladders and mobile platform. In *Proceedings of the human factors and ergonomics society annual meeting.*

Thiehoff, R. (2002). Economic significance of work disability caused by musculoskeletal disorders. *Der Orthopade*, *31*(10), 949–956.

Thorn, S., Søgaard, K., Kallenberg, L. A. C., Sandsjö, L., Sjøgaard, G., Hermens, H. J., … Forsman, M. (2007). Trapezius muscle rest time during standardised computer work – a comparison of female computer users with and without self-reported neck/shoulder complaints. *Journal of Electromyography and Kinesiology*, *17*(4), 420–427.

Timber Industry. (2016). Planting trees in bulk — reforesting with white pine. Retrieved from https://www.youtube.com/watch?v=eg186sbSYBg

Trites, D. G., Robinson, D. G., & Banister, E. W. (1993). Cardiovascular and muscular strain during a tree planting season among british columbia silviculture workers. *Ergonomics*, *36*(8), 935–949. doi:10.1080/00140139308967958

Tudor-Locke, C., Ainsworth, B., Washington, T. L., & Troiano, R. (2011). Assigning metabolic equivalent values to the 2002 census occupational classification system. *Journal of Physical Activity and Health*, *8*(4), 581–586.

Umukoro, P., Arias, O. E., Stoffel, S. D., Hopcia, K., Sorensen, G., & Dennerlein, J. T. (2013). Physical activity at work contributes little to patient care workers' weekly totals. *Journal of Occupational and Environmental Medicine*, *55*(Supplement 125), S63–S68.

Upjohn, T., Keir, P., & Dumas, G. (2008). Upper body posture during tree planting work. In *Proceedings nacob.*

USDA-FS. (2016). Reforestation overview. Retrieved November 10, 2017, from https://www.fs.fed.us/restoration/reforestation/overview.shtml

van der Beek, A. J. & Frings-Dresen, M. H. W. (1998). Assessment of mechanical exposure in ergonomic epidemiology. *Occupational and Environmental Medicine*, *55*(5), 291–299.

Van Hees, V. T., Gorzelniak, L., Leon, E. C. D., Eder, M., Pias, M., Taherian, S., … Horsch, A. (2013). Separating movement and gravity components in an acceleration signal and implications for the assessment of human daily physical activity. *Public Library of Science ONE*, *8*(4), e61691.

Vitalis, A. (1981). *An investigation of the relationship between pulse rate, environmental heat and work output of cane cutters in fiji* (Doctoral dissertation, London University).

Vitalis, A. (1987). The use of heart rate as the main predictor of the cost of work. In *Inaugural conference of the new zealand ergonomics society*. Auckland, New Zealand.

Vitalis, A., Pournaras, N. D., Jeffrey, G. B., Tsagarakis, G., Monastitiotis, G., & Kvvadiast, S. (1994). Heart strain in greek steelworkers. *Ergonomics*, *21*(5), 845–850.

Von Marcard, T. (2010). *Design and implementation of an attitude estimation system to control orthopedic components* (Master's Thesis, Chalmers University of Technology).

Vos, T., Flaxman, A. D., Naghavi, M., Lozano, R., Michaud, C., Ezzati, M., … Aboyans, V. (2012). Years lived with disability (ylds) for 1160 sequelae of 289 diseases and injuries 1990–2010: A systematic analysis for the global burden of disease study 2010. *The Lancet*, *380*(9859), 2163–2196.

Vyse, A. H. (1973). Work Study Techniques to Tree Planting: Tree Planter's Note. *Pacific Forest Research - Canadian Forestry Service*, *24*, 19–23.

Wahlström, J., Mathiassen, S. E., Liv, P., Hedlund, P., Ahlgren, C., & Forsman, M. (2010). Upper arm postures and movements in female hairdressers across four full working days. *Annals of Occupational Hygiene*, *54*(5), 584–594.

Wallace, M. & Buckle, P. (1987). Ergonomic aspects of neck and upper limb disorders. *International Review of Ergonomics*, *1*, 173–200.

Waris, P. (1979). Occupational Cervicobrachial Syndromes: a Review. *Scandinavian Journal of Work, Environment & Health*, *5*(Supplement 3), 3–14.

Waters, T. R., Putz-Anderson, Garg, A., & Fine, L. J. (1993). Revised NIOSH equation for the design and evaluation of manual lifting tasks. *Ergonomics*, *36*(7), 749–776.

Wear, D. N. & Greis, J. G. (2002). *Southern forest resource assessment* (tech. rep. No. 653). US Department of Agriculture, Forest Service, Southern Research Station. Asheville, NC.

Webster, B. S. & Snook, S. H. (1994). The cost of 1989 workers' compensation low back pain claims. *Spine*, *19*(10), 1111–1115.

Weippert, M., Kumar, M., Kreuzfeld, S., Arndt, D., Rieger, A., & Stoll, R. (2010). Comparison of three mobile devices for measuring r-r intervals and heart rate variability: Polar s810i, suunto t6 and an ambulatory ecg system. *European Journal of Applied Physiology*, *109*(4), 779–786. doi:10.1007/s00421-010-1415-9

Welk, G. J., McClain, J., & Ainsworth, B. E. (2012). Protocols for evaluating equivalency of accelerometry-based activity monitors. *Medicine and Science in Sports and Exercise*, *44*(1 Suppl 1), S39–49.

Wells, R., Mathiassen, S. E., Medbo, L., & Winkel, J. (2007). Time - A key issue for musculoskeletal health and manufacturing. *Applied Ergonomics*. 38th ser., 733–744. doi:10.1016/j.apergo.2006.12.003

Whaley, M. H., Brubaker, P. H., Otto, R. M., & Armstrong, L. E. (2005). ACSM's Guidelines for Exercise Testing and Prescription. *Lippincott Williams & Wilkins, US.*

WHO. (1985). *Identification and control of work-related diseases.* World Health Organization.

Widanarko, B., Legg, S., Devereaux, J., & Stevenson, M. (2014). The combined effect of physical, psychosocial/organisational and/or environmental risk factors on the presence of work-related musculoskeletal symptoms and its consequences. *Applied Ergonomics*, *45*(6), 1610–1621.

Williams, H. (1973). Developing a table of relaxation allowances. *Industrial Engineering*, *5*, 18–22.

Winkel, J. & Mathiassen, S. E. (1994). Assessment of physical work load in epidemiologic studies: Concepts, issues and operational considerations. *Ergonomics*, *37*(6), 979–988.

Woolf, A. D. & Pfleger, B. (2003). Burden of major musculoskeletal conditions. *Bulletin of the World Health Organization*, *81*(9), 646–656.

Workplace Safety and Insurance Board. (2016). Enterprise Information Warehouse: Reforestation classification units 0511001, 0511002. Retrieved from https://www.workplacesafetynorth.ca/sites/default/files/Forest_Products_033A_Tree_Planting_Safety_Infographic_Package-2016.pdf

Yelin, E. & Callahan, L. F. (1995). The economic cost and social and psychological impact of musculoskeletal disorders. *Arthritis & Rheumatism*, *38*(10), 1351–1362.

Yoo, I.-G., Jung, M.-Y., Jeon, H.-S., & Lee, J. (2010). Effects of wrist-extension orthosis on shoulder and scapular muscle activities during simulated assembly tasks. *Industrial Health*, *48*(1), 108–114.

Zandin, K. B. (2002). *MOST Work Measurement Systems* (3rd ed.). CRC Press.

Appendices

Appendix A

MOST Detailed Method Descriptions

Phase	No.	Method Description	Detailed Description
Seedling Bag Loading	A-01	Bend and remove (lay aside) lid from seedling box General Move	The work cycle begins with a box of seedlings on the ground in front of the worker. The worker bends down, grabs the lid of the box, lifts it off the box, and lays it aside for future disposition by the crew foreman (typically burned, along with the seedlings boxes). ‘Get’ Phase Action Distance (A) = 1: lid is within reach of the worker Body Motion (B) = 6: to account for a bend and arise movement Gain Control (G) = 1: grasp of the lid, classified as a light object ‘Put’ Phase Action Distance (A) = 1: as the lid is moved within reach Body Motion (B) = 0: worker does not move vertically Placement (P) = 1: lid is laid aside on the ground for later disposal ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_1 B_6 G_1 A_1 B_0 P_1 A_0 [(1+6+1+1+1)] × 10=100 TMU
Seedling Bag Loading	A-02	Within reach, collect handful of seedlings from box General Move	While still in a crouched/bent posture, the worker reaches into the box of seedlings and grabs a handful of seedlings. The quantity of seedlings will vary based on the size of the seedlings. For a box of 500 seedlings, the estimated quantity of seedlings per grasp is 20. This step will be conducted 25 times over the course of loading the seedling bag, for a total frequency of 25. ‘Get’ Phase Action Distance (A) = 1: seedlings are within reach of worker Body Motion (B) = 0: worker is already in a bent posture from A-01 Gain Control (G) = 3: collect handful of seedlings ‘Put’ Phase Action Distance (A) = 0: no further movement is needed for the duration of the A-02 step Body Motion (B) = 0: no further movement is needed for the duration of the A-02 step Placement (P) = 0: no placement is needed for the duration of the A-02 step ‘Return’ Phase Action Distance (A) = 0: no further movement is needed for the duration of the A-02 step A_1 B_0 G_3 A_0 B_0 P_0 A_0 [(1+3) × 25]×10 = 1,000 TMU

Phase	No.	Method Description	Detailed Description
Seedling Bag Loading	A-03	Strike seedlings against box to dislodge ice General Move	With a handful of seedlings (20) in hand, the worker strikes the seedlings against the box repetitively to dislodge ice particles. Based on field observations, an assumption is made that 3 strikes are required for each handful. 3 strikes per handful and a total of 25 handfuls results in a total frequency count of 75. 'Get' Phase Action Distance (A) = 0: handful of seedlings in hand from A-02 Body Motion (B) = 0: vertical position of worker unchanged from A-02 Gain Control (G) = 0: handful of seedlings in hand from A-02 'Put' Phase Action Distance (A) = 1: box is within reach to strike seedlings against Body Motion (B) = 0: worker does not move vertically Placement (P) = 1: repeated placement against box requiring low control by senses 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_1\ B_0\ G_0\ A_1\ B_0\ P_1\ A_0$ $[(1+1+1)\times125]\times10 = 1{,}500$ TMU
Seedling Bag Loading	A-04	Place seedlings in seedling bag (low effort) General Move	With the ice dislodged from the seedling roots, the handfuls of seedlings are placed in the seedling bag. At the start of the bag loading there is low effort required to fit the seedlings. As the bag gets more full, it becomes harder. The last handfuls are the most difficult to load into the seedling bag as it is reaching maximum capacity. The first 20/25 handfuls loaded are classified as low effort (80%). 'Get' Phase Action Distance (A) = 0: the seedlings are already in the hand of the worker Body Motion (B) = 0: the worker is in the same posture (crouched/bent) Gain Control (G) = 0: the worker has already grasped the handful of seedlings 'Put' Phase Action Distance (A) = 1: seedlings bag is within reach Body Motion (B) = 0: worker does not move vertically Placement (P) = 1: moderate amount of visual/muscular control necessary to place seedlings 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_0\ B_0\ G_0\ A_1\ B_0\ P_1\ A_0$ $[(1+1)\times20]\times10 = 400$ TMU

Phase	No.	Method Description	Detailed Description
Seedling Bag Loading	A-05	Place seedlings in seedling bag (moderate effort) General Move	With the ice dislodged from the seedling roots, the handfuls of seedlings are placed in the seedling bag. At the start of the bag loading there is low effort required to fit the seedlings. As the bag gets more full, it becomes harder. The last handfuls are the most difficult to load into the seedling bag as it is reaching maximum capacity. 3/25 (12%) of the handfuls loaded are classified as moderate effort (80%). ‘Get’ Phase Action Distance (A) = 0: the seedlings are already in the hand of the worker Body Motion (B) = 0: the worker is in the same posture (crouched/bent) Gain Control (G) = 0: the worker has already grasped the handful of seedlings ‘Put’ Phase Action Distance (A) = 1: seedlings bag is within reach Body Motion (B) = 0: worker does not move vertically Placement (P) = 3: close tolerances result in the need for light pressure to seat the seedlings ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_0 B_0 G_0 A_1 B_0 P_3 A_0 [(1+3)×3]×10 = 120 TMU
Seedling Bag Loading	A-06	Place seedlings in seedling bag (high effort) General Move	With the ice dislodged from the seedling roots, the handfuls of seedlings are placed in the seedling bag. At the start of the bag loading there is low effort required to fit the seedlings. As the bag gets more full, it becomes harder. The last handfuls are the most difficult to load into the seedling bag as it is reaching maximum capacity. 2/25 (12%) of the handfuls loaded are classified as moderate effort (80%). ‘Get’ Phase Action Distance (A) = 0: the seedlings are already in the hand of the worker Body Motion (B) = 0: the worker is in the same posture (crouched/bent) Gain Control (G) = 0: the worker has already grasped the handful of seedlings ‘Put’ Phase Action Distance (A) = 1: seedlings bag is within reach Body Motion (B) = 0: worker does not move vertically Placement (P) = 6: very tight tolerances result in the need for heavy pressure to seat the seedlings ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_0 B_0 G_0 A_1 B_0 P_6 A_0 [(1+6)×2]×10 = 140 TMU

Phase	No.	Method Description	Detailed Description
Planting Prep and Locomotion	B-01	Stand and lift seedling bag above posterior shoulders General Move	Once the worker has loaded the seedling bag the worker will stand (captured in as a 'B' bend and arise in A-01. The worker will then begin the process of putting the seedling bag onto his or her back and fastening the seedling bag straps. The first step is to lift the seedling bag above the posterior shoulders, similar to the first step in putting on a backpack. 'Get' Phase Action Distance (A) = 1: the seedling bag is within reach Body Motion (B) = 0: the worker standing is captured in step A-01 Gain Control (G) = 3: the seedling bag is heavy and bulky and must be lifted 'Put' Phase Action Distance (A) = 1: seedlings bag is within reach Body Motion (B) = 0: worker does not move vertically Placement (P) = 3: placement of the bag behind the bag is a blind movement 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_0\ B_0\ G_3\ A_1\ B_0\ P_3\ A_0$ [(1+3+1+3)×1]×10 = 80 TMU
Planting Prep and Locomotion	B-02	Insert left arm into strap Controlled Move	After the seedling bag is behind the back of the worker, the worker will insert his/her left arm into the strap to bring the seedling bag strap onto the left shoulder. This is a controlled move sequence model, as the object (seedling bag strap) is restricted in movement by attachment to the seedling bag. 'Get' Phase Action Distance (A) = 1: the seedling bag strap is within reach Body Motion (B) = 0: the worker does not change vertical position Gain Control (G) = 3: the seedling bag strap is attached to the seedling bag which is in the workers hand 'Move' Phase Move Controlled (M) = 3: the bag strap is moved along a controlled path > 12 inches as the hand passes through the strap and it slides up to rest on the left shoulder Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 1: the strap is aligned to the point of the shoulder where it will rest 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_1\ B_0\ G_3\ M_3\ X_0\ I_1\ A_0$ [(1+3+3+1)×1]×10 = 80 TMU

Phase	No.	Method Description	Detailed Description
Planting Prep and Locomotion	B-03	Insert right arm into strap Controlled Move	After the worker's left arm is inserted through the seedling bag strap and resting on the worker's left shoulder, the worker inserts his/her right arm through the other strap to bring the strap onto the right shoulder. This is a controlled move sequence model, as the object (seedling bag strap) is restricted in movement by attachment to the seedling bag. 'Get' Phase Action Distance (A) = 1: the seedling bag strap is within reach Body Motion (B) = 0: the worker does not change vertical position Gain Control (G) = 3: the seedling bag strap is attached to the seedling bag which is in the workers hand 'Move' Phase Move Controlled (M) = 3: the bag strap is moved along a controlled path > 12 inches as the hand passes through the strap and it slides up to rest on the right shoulder Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 1: the strap is aligned to the point of the shoulder where it will rest 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_1 B_0 G_3 M_3 X_0 I_1 A_0$ [(1+3+3+1)×1]×10 = 80 TMU
Planting Prep and Locomotion	B-04	Insert waist strap snap into buckle Controlled Move	With the seedling bag on the shoulders of the worker, the worker will insert the waist strap into the waist strap buckle, further securing the seedling bag around the worker's torso. This is a controlled move sequence model as the waist strap is attached to the seedling bag on the worker's back. 'Get' Phase Action Distance (A) = 1: the seedling bag waist straps are within reach Body Motion (B) = 0: the worker does not change vertical position Gain Control (G) = 1: the seedling bag waist straps are 'light objects simo' actions 'Move' Phase Move Controlled (M) = 3: the waist straps are seated Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 3: the waist strap buckles need both ends aligned ≤ 4 inches apart 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_1 B_0 G_1 M_3 X_0 I_3 A_0$ [(1+1+3+3)×1]×10 = 80 TMU

Phase	No.	Method Description	Detailed Description
Planting Prep and Locomotion	B-05	Adjust load on back Controlled Move	With the seedling bag on the worker's shoulder and the waist strap fastened the worker will adjust the load on the worker's back by moving the arm straps to ensure that the load is evenly distributed prior to tightening the waist strap and fastening/tightening the chest strap. This is a controlled move sequence model as the seedling bag is affixed to the worker's body at this point, restricting the movement of the straps directionally. ‘Get’ Phase Action Distance (A) = 1: the seedling bag straps are within reach Body Motion (B) = 0: the worker does not change vertical position Gain Control (G) = 3: the adjustment of the straps on the heavy bag require muscle tension for Gain Control ‘Move’ Phase Move Controlled (M) = 10: Three to Four stages of adjustment required to adjust the load Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 6: the straps are aligned for the bag as a Non-typical object ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_1 B_0 G_3 M_{10} X_0 I_6 A_0 [(1+3+10+6)×1]×10 = 200 TMU
Planting Prep and Locomotion	B-06	Tighten waist strap Controlled Move	With the seedling bag on the worker's shoulders and the waist strap fed through the waist strap buckle, the worker will tighten the waist strap. This is a controlled move as the waist strap has been fed through the buckle resulting in movement being directionally restricted. ‘Get’ Phase Action Distance (A) = 1: the seedling bag waist strap is within reach Body Motion (B) = 0: the worker does not change vertical position Gain Control (G) = 1: the strap is a light object that is grasped ‘Move’ Phase Move Controlled (M) = 10: Three to Four stages of tightening adjustment are required Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 0: no alignment required ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_1 B_0 G_3 M_{10} X_0 I_6 A_0 [(1+1+10)×1]×10 = 120 TMU

Phase	No.	Method Description	Detailed Description
Planting Prep and Locomotion	B-07	Insert chest strap into buckle Controlled Move	With the seedling bag on the shoulders of the worker and the waist strap tightened, the worker will grasp both sides of the chest straps and fasten them together. This is a controlled move sequence model as the chest strap is attached to the seedling bag on the worker's back. 'Get' Phase Action Distance (A) = 1: the seedling bag chest straps are within reach Body Motion (B) = 0: the worker does not change vertical position Gain Control (G) = 1: the seedling bag chest straps are 'light objects simo' actions 'Move' Phase Move Controlled (M) = 3: the chest straps are seated Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 3: the chest strap buckles need both ends aligned ≤ 4 inches apart 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_1 B_0 G_1 M_3 X_0 I_3 A_0 $[(1+1+3+3)\times1]\times10 = 80$ TMU
Planting Prep and Locomotion	B-08	Tighten chest strap Controlled Move	With the seedling bag chest straps fastened, the worker will grasp the chest strap and pull the strap to tighten the test strap. This is a controlled move as the fastened chest strap is restricted directionally. 'Get' Phase Action Distance (A) = 1: the seedling bag chest strap is within reach Body Motion (B) = 0: the worker does not change vertical position Gain Control (G) = 1: the seedling bag chest strap is a light object grasped 'Move' Phase Move Controlled (M) = 10: the chest strap is pulled and adjusted in Three to Four Stages Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 0: the chest strap does not need aligned as it was aligned in step B-07 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_1 B_0 G_1 M_{10} X_0 I_0 A_0 $[(1+1+10)\times1]\times10 = 120$ TMU

Phase	No.	Method Description	Detailed Description
Planting Prep and Locomotion	B-09	Bend and pick up tool off ground and walk 50 steps General Move	With the seedling bag on the back of the worker, the worker bends and picks the hand planting tool off of the ground. With the tool in the worker's hands, the worker begins walking from the planting preparation area to the planting location. This is a General Move Sequence Model. 'Get' Phase Action Distance (A) = 1: the planting tool is within reach Body Motion (B) = 6: the worker must bend and arise to pick up the tool Gain Control (G) = 3: the tool is Heavy/Bulky and is laying on the ground requiring effort to lift 'Put' Phase Action Distance (A) = 96: 50-57 steps taken to reach the planting area Body Motion (B) = 0: no vertical body motion during Put phase Placement (P) = 0; tool is not placed in this step 'Return' Phase Action Distance (A) = 96: captures the return walking of 50-57 steps after cycle is complete $A_1 B_0 G_1 A_3 B_0 P_3 A_0$ [(1+6+3+96+96)×1]×10 = 2020 TMU
Productive Cycle	C-01	Thrust tool into soil General Move	At the location where planting for the work cycle will begin, the worker thrusts his planting tool into the soil. The tool moving through the air unrestricted is a General Move Sequence Model. Each of the Productive Cycle (C-01 thru C-11) steps are repeated for each seedling planting, or a frequency of 500 for the planting of one seedling bag (planting cycle or 'bag-up'). 'Get' Phase Action Distance (A) = 0: the tool is in the worker's hand Body Motion (B) = 0: the worker does not change vertical posture Gain Control (G) = 0: the tool is in the worker's hand 'Put' Phase Action Distance (A) = 1: the movement of the arm holding the tool is within reach Body Motion (B) = 0: worker does not move vertically Placement (P) = 3: the placement of the tool requires light pressure (varies with soil composition) 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_0 B_0 G_0 A_1 B_0 P_3 A_0$ [(1+3)×500]×10 = 20000 TMU

Phase	No.	Method Description	Detailed Description
Productive Cycle	C-02	Pull backward on tool Controlled Move	With the tool blade in the soil, the worker pulls backward on the handle of the tool to create the first half of a 'V' shaped depression in the soil. The tool in the soil has restricted movement, resulting in this step being classified as a Controlled Move Sequence Model. 'Get' Phase Action Distance (A) = 0: the tool is in the hand of the worker Body Motion (B) = 0: the worker does not change posture Gain Control (G) = 0: the worker has already grasped the tool 'Move' Phase Move Controlled (M) = 3: the tool requires resistance be overcome during the Controlled Move Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 0: alignment of tool not necessary 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_0 B_0 G_0 M_3 X_0 I_0 A_0 [(3)×500]×10 = 15000 TMU
Productive Cycle	C-03	Push forward on tool Controlled Move	With the tool blade in the soil, the worker pushes forward on the handle of the tool to create the second half of a 'V' shaped depression in the soil. The tool in the soil has restricted movement, resulting in this step being classified as a Controlled Move Sequence Model. 'Get' Phase Action Distance (A) = 0: the tool is in the hand of the worker Body Motion (B) = 0: the worker does not change posture Gain Control (G) = 0: the worker has already grasped the tool 'Move' Phase Move Controlled (M) = 3: the tool requires resistance be overcome during the Controlled Move Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 0: alignment of tool not necessary 'Return' Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_0 B_0 G_0 M_3 X_0 I_0 A_0 [(3)×500]×10 = 15000 TMU

Phase	No.	Method Description	Detailed Description
Productive Cycle	C-04	Reach behind back into seedling bag and grasp seedling General Move	With the 'V' in the soil formed, the worker reaches behind his/her back to grab a seedling to be planted. This is a General Move Sequence Model. ‘Get’ Phase Action Distance (A) = 1: the seedlings are within reach Body Motion (B) = 0: the worker remains standing Gain Control (G) = 3: the worker blindly grasps a seedling ‘Put’ Phase Action Distance (A) = 0: the seedling remains in the workers hand Body Motion (B) = 0: the worker remains standing Placement (P) = 0: the worker does not place the seedling until the following step ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_1\ B_0\ G_3\ A_0\ B_0\ P_0\ A_0$ [(1+3)×500]×10 = 20000 TMU
Productive Cycle	C-05	Bend and place seedling in hole General Move	With the seedling in hand, the worker bends at the waist and places the seedling into the hole in the ground created in steps C-01 thru C-03. This is a General Move Sequence Model. ‘Get’ Phase Action Distance (A) = 0: the seedling is already in the hand of the worker Body Motion (B) = 0: the seedling is already in the hand of the worker Gain Control (G) = 0: the seedling is already in the hand of the worker ‘Put’ Phase Action Distance (A) = 1: the seedling hole is within reach of the worker Body Motion (B) = 6: the worker bends to lower the trunk of the body to reach the hole, later arising after placement of seedling has occurred Placement (P) = 3: the seedling is placed with adjustments to ensure root structures are seated to proper depth - not too shallow and not deep (resulting in "J" hooking of root structure) ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_0\ B_0\ G_0\ A_1\ B_6\ P_3\ A_0$ [(1+6+3)×500]×10 = 50000 TMU

Phase	No.	Method Description	Detailed Description
Productive Cycle	C-06	Lift tool and thrust tool into soil behind seedling General Move	With the seedling placed in the hole, the worker begins a 5 step process (C-06 thru C-10) of sealing the hole. The worker begins this process by lifting the tool and thrusting it into the soil behind the seedling. This is a General Move Sequence Model. ‘Get’ Phase Action Distance (A) = 0: tool is in the worker's hand Body Motion (B) = 0: worker does not change vertical posture Gain Control (G) = 0: tool is in the worker's hand ‘Put’ Phase Action Distance (A) = 1: movement of the tool is within reach Body Motion (B) = 0: worker does not move vertically Placement (P) = 3: the placement of the tool requires light pressure and modest accuracy of placement ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_0 B_0 G_0 A_1 B_0 P_3 A_0 [(1+3)×500]×10 = 20000 TMU
Productive Cycle	C-07	Pull backward on tool Controlled Move	With the tool blade in the soil, the worker pulls backward on the handle of the tool to seal the bottom of the seedling hole and compact the soil around the root structure. The tool in the soil has restricted movement, resulting in this step being classified as a Controlled Move Sequence Model. ‘Get’ Phase Action Distance (A) = 0: the tool is in the hand of the worker Body Motion (B) = 0: the worker does not change posture Gain Control (G) = 0: the worker has already grasped the tool ‘Move’ Phase Move Controlled (M) = 3: the tool requires resistance be overcome during the Controlled Move Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 0: alignment of tool not necessary ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking A_0 B_0 G_0 M_3 X_0 I_0 A_0 [(3)×500]×10 = 15000 TMU

Phase	No.	Method Description	Detailed Description
Productive Cycle	C-08	Push forward on tool Controlled Move	With the tool blade in the soil, the worker pushes forward on the handle of the tool to seal the top of the seedling hole and compact the soil around the root structure. The tool in the soil has restricted movement, resulting in this step being classified as a Controlled Move Sequence Model. ‘Get’ Phase Action Distance (A) = 0: the tool is in the hand of the worker Body Motion (B) = 0: the worker does not change posture Gain Control (G) = 0: the worker has already grasped the tool ‘Move’ Phase Move Controlled (M) = 3: the tool requires resistance be overcome during the Controlled Move Process Time (X) = 0: no work is controlled by electronic or mechanical devices Alignment (I) = 0: alignment of tool not necessary ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_0\ B_0\ G_0\ M_3\ X_0\ I_0\ A_0$ [(3)×500]×10 = 15000 TMU
Productive Cycle	C-09	Lift tool out of ground General Move	With the hole sealed the worker removes the tool from the ground. This is a General Move Sequence Model. ‘Get’ Phase Action Distance (A) = 0: the tool is in the worker's hand Body Motion (B) = 0: the worker does not change vertical posture Gain Control (G) = 0: the tool is in the worker's hand ‘Put’ Phase Action Distance (A) = 1: the movement of the tool out of the ground is within reach of the worker Body Motion (B) = 0: worker does not move vertically Placement (P) = 0: the tool is lifted vertically with no resistance ('pickup') ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_0\ B_0\ G_0\ A_1\ B_0\ P_0\ A_0$ [(1)×500]×10 = 5000 TMU

Phase	**No.**	**Method Description**	**Detailed Description**
Productive Cycle	C-10	Use foot to compact soil Tool Use	With the seedling placed in the soil cavity and the cavity sealed with the tool, the worker uses his/her foot to vertically compact the soil. The worker using his/her foot is a Tool Use Sequence Model. The 'Foot Press (FP)' Tool Action has been created and defined as a foot depression of < 4 inches. ‘Get Tool’ Phase Action Distance (A) = 1: worker lifts dominant foot 'within reach' Body Motion (B) = 0: the worker is in the same posture (crouched/bent) Gain Control (G) = 0: the worker does not need to gain control of a tool ‘Put Tool in Place’ Phase Action Distance (A) = 1: worker moves dominant foot within reach to touch surface of soil behind seedling Body Motion (B) = 0: worker does not move vertically Placement (P) = 1: placement of foot requires very modest amount of control ('Loose Fit') ‘Tool Action’ Phase Foot Press (FP) = 3: worker uses his/her foot to depress the soil <4 inches ‘Aside Tool’ Phase Action Distance (A) = 1: worker moves foot back onto ground for support of standing posture Body Motion (B) = 0: worker does not move vertically Placement (P) = 0: foot placement not necessary to be specified ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_1 B_0 G_0 A_1 B_0 P_1 FP_3 A_1 B_0 G_0 A_0 B_0 P_0 A_0$ $[(1+1+1+3+1)\times500]\times10 = 35000$ TMU
Productive Cycle	C-11	Walk 4 paces General Move	Once the seedling has been planted, the worker walks to the next location where he/she will plant the next seedling. This is a General Move Sequence Model. ‘Get’ Phase Action Distance (A) = 6: the worker walks 4 paces to get to the next location Body Motion (B) = 0: the worker is in the same vertical posture Gain Control (G) = 0: the worker does not gain control of any object ‘Put’ Phase Action Distance (A) = 0: no further movement Body Motion (B) = 0: no vertical movement Placement (P) = 0: no placement ‘Return’ Phase Action Distance (A) = 0: worker does not return to the starting position by walking $A_6 B_0 G_0 A_0 B_0 P_0 A_0$ $[(6)\times500]\times10 = 30000$ TMU