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RELATIONSHIP BETWEEN THE GROUND REACTION FORCES AND THE FORCES EXERTED BY THE HANDS DURING AUTOMOTIVE TASKS.

By

Mallak Hamatto

A Thesis
Submitted to the Faculty of Graduate Studies through the Faculty of Human Kinetics
In Partial Fulfillment of the Requirements for
The Degree of Master of Human Kinetics
at the University of Windsor

Windsor, Ontario, Canada

2020

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ABSTRACT

The purpose of this study was to determine the strength of the relationship between the ground reaction forces (GRF), forces directly recorded at the feet and the force exerted by the hands as measured at the hands, during simulated work-related tasks, in an effort to understand the validity of GRF measurements as an accurate alternative indirect measurement of physical hand efforts. Thirty healthy participants were recruited between the ages of 18-60 years with no history of pain or injury in their upper and lower extremities for the previous six months. A total of seven manual hand exertion tasks were simulated and their associated force efforts were obtained. Six of the seven task efforts was completed with and without the ability of the participants to brace themselves while the last task was only completed without a brace. The brace is an external object that was placed between the participant and the vertical force plate. Root Mean Squared Error (RMSE) was calculated to find the percentage error between forces recorded at the hands and the forces measured at the feet. Results revealed that without Brace tasks often resulted with a significantly lower RMSE compared to Bracing tasks, the Drilling task was found to have the smallest RMSE while the Electrical Connector task showed the highest RMSE, and an increase in RMSE was evident with tasks repetitive/wiggly movements (Hose and Weather-Strip tasks).
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LIST OF ABBREVIATIONS

ACGIH TLVs: American Conference of Governmental Industrial Hygienists Threshold Limit Values

ACGIH: American Conference of Governmental Industrial Hygienists

ANOVA: Analysis of Variance CTDs: Cumulative Trauma Disorders

CTS: Carpal Tunnel Syndrome

EMG: Electromyography

FPP: Force Peak Power

FID: Force in Intended Direction

GRF: Ground Reaction Forces

HAL: Hand Activity Level

LUBA: Loading on the Upper Body Assessment

NIOSH: National Institute of Occupational Safety and Health

OCRA: Occupational Repetitive Action

PGRF: Peak Ground Reaction Force

QEC: Quick Exposure Check

REBA: Rapid Entire Body Assessment

RULA: Rapid Upper Limb Assessment

SI: Strain Index

RMSE: Root Mean Squared Error
TLV: Threshold Limit Values

WHO: World Health Organization

WMSD: Work-Related Musculoskeletal Disorders
CHAPTER 1 – INTRODUCTION

1.1 Background

One of the most contributing factors to upper extremity work-related musculoskeletal disorders (WMSD) is forceful exertions (National Institute for Occupational Safety and Health (NIOSH, 1997). In order for a worker to perform the job without fatiguing and possible musculoskeletal disorders, the worker’s strength must meet or exceed the force demanded to complete the tasks. Automotive assembly tasks often require operators to use their hands to secure various parts of the vehicle, where individual parts require some degree of human physical force effort. Therefore, ergonomic investigations have been conducted to analyze the association between tasks that include physical loads and the development of musculoskeletal disorders (Winkel and Westgaard, 1992; Kilbom, 1994). Studies that have investigated WMSD revealed that forceful efforts, including lifting, high handgrip forces, and pulling/pushing forces, were considerably correlated with the widespread of rotator cuff syndrome, lateral epicondylitis, and carpal tunnel syndrome (Fan et al., 2007; Silverstein et al., 2008).

Ergonomic studies have been carried out over the years to define the relationship between diverse exposure factors and musculoskeletal disorders (Punnett et al., 2000, Fallentin et al., 2001). The major research topics in these studies were to quantify the numerous exposure parameters and repetitive hand activities. Epidemiologists, ergonomics professionals, and other ergonomics researchers agree that forceful exertions are often difficult to quantify directly in the field by means of instrumentation (Chiang et al., 1993; Silverstein et al., 1987). This is challenging for professionals as most ergonomic exposure assessment tools and methods use force as a primary measure to determine the risk of injury.
The Strain Index (SI) is an exposure assessment tool that is widely used by ergonomists to systematically analyse the physical demands of a job related to upper extremity WMSD. The SI consists of six exposure factors which quantify upper extremity risk factors. In order to calculate a single index, multipliers for the intensity of exertion, duration of exertion (% of cycle), efforts per minutes, hand/wrist posture, speed of work, and duration of task per day (hours) are needed to determine the jobs injury risk. The intensity of exertion, the most influential to the calculation among all six factors, is often estimated using the BORG CR-10 rating scale that allows individuals to subjectively rate their level of exertion due to the difficulty in directly measuring the force exertion (Moore and Garg, 1995; Borg et al., 1990).

The American Conference of Governmental Industrial Hygienists (ACGIH) hand activity level (HAL) threshold limit values (TLV), another method used by ergonomists, uses peak hand force and hand activity level to assess the WSMD risk associated with upper extremity tasks. Furthermore, ergonomist have various options to obtain the forceful exertion magnitudes, however, SI, Borg CR10, and ACGIH HAL TLV are subjective and observational techniques to obtain force estimates (McGorry et al., 2010). Many researchers including Burdorf et al., (1992) have stated that there is a decrease in the level of accuracy and precision, when using subjective based measurements due to their subjectivity to inter- and intra-observer variability, which can lead to low validity and exposure misclassification. Unfortunately, there is a misconception that subjective based force measurement estimations can be used interchangeably with another without a substantial difference in the outcome. Directly measuring force by using a force transducer is one of the techniques and methods that provide reproducible and accurate results, yet, ergonomists are not always able to utilize a traditional force transducer due to the difficulty of obtaining enough space clearance to use them. Consequently, in order to obtain the force
measurement, ergonomists then must use an indirect assessment method that may produce unreliable results.

Different methods that have been used to quantify forceful exertion in ergonomics application and research include direct and indirect measurements of forces. Indirect measurements, such as force-matching, is when the worker estimates the physical exertion force required of a task by simulating the force demand on an instrument such as a hand force gauge or dynamometer (Bao and Silverstein, 2005; Casey et al., 2002). The worker typically performs the force estimation immediately following performance of the actual task to produce the best recall (Lowe, 1995).

While force matching was anticipated to produce accurate estimates, results using this method have been mixed. This may be due, in part, to the lack in the human’s ability to accurately translate their perceived effort to an actual quantifiable value of force. Furthermore, since this method uses a hand dynamometer, the simulated tasks may not perfectly represent reality discrepancies between handle configuration and the tool being evaluated (Kumar and Chouinard, 1997; McGorry et al., 2004; McGorry et al., 2010). King and Finet (2004) stated that this method is subjective and has some level of inaccuracy since it relies on the memory of the subject when applying the force.

Another indirect ergonomic measurement method is Electromyography (EMG) which has been used to estimate physical efforts using muscle activation involved in producing grip force, which is the internal response to forceful exertions (Cook et al., 1998). Koppelaar and Wells, (2005) proposed that measuring muscle activity using EMG is sometimes considered as a more relevant measure of arm/hand force exposure, since tasks that include force may involve, to some extent, other exposure modifiers such as repetitive motions and awkward postures. The study revealed that the EMG method had more variability in hand force measurements than the direct
measurement method. The authors also stated that the variability in EMG between participants is well known due to, among other factors, technical factors such as electrode placement, participant size and strength. Other studies have stated that this method does not provide the direct muscle force quantification and therefore, interpretation of the EMG results can be challenging due to factors such as co-contraction, change in the length of muscle, and movement of skin relative to underlying muscles (Hoozemans and van Dieen, 2005). Furthermore, ergonomic practitioners are unlikely to use this technique largely because it is time consuming and the costly sophisticated equipment needed (Bao et al., 2009).

Observation estimation is an additional indirect method which is completed by trained evaluators to estimate forceful exertions by observing the performances of tasks done by workers, where evaluators use a rating scale to assess the tasks. This method is relatively easy to complete and less intrusive to workers. Bao et al. (2009) found that the observational method was able to detect the lifting and pushing/pulling forces between job categories yet found that the direct measurement of using a force gauge was more sensitive to detect the forces exerted in these tasks. The authors also disclosed that the observation estimation method was more sensitive than the self-reported assessment in detecting force levels of pinch grip between job categories.

The last common indirect method is self-reported ratings of perceived exertions. This method is executed by the workers performing the tasks, who then rate their tasks using a ratio-based scale such as the Borg Scale (1990). Hjelm et al. (1995) concluded that in large population studies, this method is the most cost effective and feasible technique to obtain force data. However, Spielholz et al. (2001) stated that ratings of perceived exertions are extremely imprecise force assessment methods when measuring hand force and concluded that they should
not be used only for any scientific assessment of exposure to physical risk factors such as hand force. Therefore, precision in measuring the hand force is very important since an ideal force assessment method would exhibit minimal variability (Koppelaar and Wells, 2005), suggesting that, in many situations, the most accurate method is not always available to measure the physical effort. Bao et al., (2006) compared the difference between the methods of assessing repetitive hand force exertions. Three different methods were used to measure hand forces: 1) force matching using a force gauge; 2) rating scales completed by ergonomists; 3) self-reports by subjects. The authors also used the ACGIH HAL and Strain Index methods when different repetitiveness quantification methods were used. The results showed that different definitions of repetitive exertion might lead to assessing different physical exposure phenomena and result in contrasting outcomes. Moreover, the correlations between force quantifications using different methods, and the correlations between the measures of repetitiveness estimated by the different methods were very poor. This suggests that it is difficult to find the most accurate method to measure an effort and that parameters measured by different methods might not be interchangeable.

Direct measurement is the “gold standard” for physical effort assessment and determining grip forces during hand tool use and it can be accomplished using instrumentation to measure forces at the hand-tool interface. These techniques vary from force gauges to assess external forces to simulating work using instrumented handles (McGorry et al., 2004). Ergonomic practitioners agree that direct measurements provide detailed information about force exposure, allow better precision than other ergonomic measurement methods, and produce accurate measurement of the measured force component (Koppelaar and Wells, 2005). Moreover, Van der Beek and Frings-Dresen (1998) argued that it is a valid method to assess grip force and the only
serious option to accurately quantify hand force. A study by Koppelaar and Wells (2005) quantified hand force by using five different assessment methods (force transducer, EMG, observational method, self-report approach, and force matching). The results concluded that the direct measurement method (force transducer) was considered the most precise method to estimate exertion. In another study that investigated grip forces applied during power grip tasks by using instrumented tool handle. Results show that the test handle produced an accurate measure of the forces applied as it senses all the forces applied radially, towards the center of the handle (McGorry et al., 2004).

Some methods that are currently used, and discussed previously, are considered unreliable and subjective yet, the techniques that produce accurate and reproducible results cannot be utilized in every situation (e.g. not enough space clearance to use a force transducer). Measurement of forceful exertion in ergonomic assessments is both necessary and challenging for ergonomists, yet while there are different methods that are used to measure physical effort, they all vary in accuracy and sensitivity (Bao et al., 2009). As all ergonomics assessment tools rely on physical effort measurements it is paramount that they are accurate as if they are not, the ergonomists run the risk of incorrect conclusions based on erroneous ergonomics analyses. Unfortunately, often direct physical efforts measurement cannot be obtained due to lack of space for the conventional hand-held force transducer. Therefore, in order to remove this limitation new force measurement methods are required to be developed that will allow ergonomists the ability to directly measure the physical efforts required to complete work-related tasks.

1.2 Purpose

The purpose of this study is to determine the relationship between the ground reaction forces (GRF), forces directly recorded at the feet, and the force exerted by the hands, measured at the
hands, during simulated work-related tasks, in an effort to understand the validity of GRF measurements as an accurate alternative indirect measurement of physical hand efforts.

1.3 Hypotheses

1) Ground reaction forces measured will highly correlate with the forces produced and recorded at the hand

A study by Sazonov et al. (2011), presented a wearable shoe-device for automatic recognition of six different activities and postures (sitting, standing, walking/jogging, ascending stairs, descending stairs, cycling), and found that footwear sensors can provide excellent recognition accuracy average of 98.1%. Edgar et al. (2012) used a wearable system consisting of SmartShoe sensor and a wrist node containing a tri-axial accelerometer. They were able to accurately classify data in a real-time processing platform while investigating specific activities of daily living. Results show that the wrist accelerometer along with the footwear system were able to accurately classify basic activities (sitting and walking), activities of daily living (ascending and descending stairs, doing the dishes, folding laundry, and vacuuming) and athletic activities (jumping jacks, east coast six count swing dancing, and ice skating).

Sylla et al., (2014) examined the ergonomic performances of exoskeleton, analyzed GRF of right-handed subjects performing a screwing task while standing on a force plate. Results demonstrated that the forces on the right foot were higher than ones applied on the left one for both trials (assisted with exoskeleton and free-screwing). The increase in the right foot value was caused by the additional weight of the tool and side leaning of the subject to maintain balance and posture during screwing. Therefore, the above studies suggest that footwear sensors and force plates are able to accurately measure the GRF of activities of daily living and workstation
tasks, not only those specific to hand movements, but also activities that include movement of other body parts.

2) *Tasks requiring greater force efforts will produce a higher statistical correlation between the ground reaction forces and those recorded at the hands in comparison to tasks requiring lower force efforts.*

Edgar et al. (2012) classified basic activities, house hold activities, and athletic activities by using a wearable SmartShoe sensor and an accelerometer on the wrist. Results show that accuracy of the sensors were higher for the athletic activities (93.1%) compared to the basic/house hold activities (89.62%). This difference could be due to the increased effort needed by the subjects to complete athletic activities that require more movements exceeding the muscles and joints ability to dampen the force. Keller et al, (1996) obtained GRF from male and female subjects during running at speeds between 3.5 and 6.0 s, as well as slow jogging and walking at speeds between 1.5 and 3.0 s on an indoor platform. The results revealed that GRF increased linearly for both males and females during walking and running, while jogging resulted in a greater than 50% higher GRF when compared to walking and running. Additionally, both males and females had similar vertical GRF values at all speeds examined, and linear regression relationship between vertical thrust maximum force and velocity were alike for both genders indicating no difference.

Moreover, as a subject operates a power hand tool or uses a manual tool without any damping material on the handle, muscles and joints of the arm act as dampers to decrease the amount of force vibration being transmitted to the body (Wachter et al., 1996). As tool reaction increases, the forces would exceed the operator’s capacity, resulting in an eccentric contraction of the damping muscle due to the motion in opposition of the muscle contraction (Oh and Radwin,
Therefore, it is hypothesized that tasks requiring low force efforts will be damped throughout the subject’s body by muscles and joints decreasing the GRF at the feet as force can be produced without rigidity.

3) Males and females’ results will not differ; thus, a sex effect will not be found.

A study that examined peak power, GRF, and velocity during squat exercise performed at different loads for both males and females found that peak ground reaction force (PGRF) and force at the time of peak power (FPP) increased as load increased from 20 to 90% of 1 repetition maximum. These results suggest that tasks that require considerable muscle force would generate high resistance between the foot and the ground to meet the demands of the increasing effort regardless of sex (Zink et al., 2006). Therefore, these results suggest that similar vertical GRF norms can be established for male and female subjects.

4) Tasks that include the ability for participants to brace themselves against an external object (hand or body) will result in a lower correlation between the forces at the hands and the reaction forces at the feet in comparison to tasks without a brace.

A one hand lifting style was studied by Ferguson et al. (2002), the study examined subjects when lifting with and without supporting their body weight with the free hand. Shear and lower back spinal compression forces were significantly lower during the supported lifting conditions by 15.7% – 17.4%. A similar study that compared one-handed lifting with and without supporting body weight using the free hand with two-handed lifting, found that about 250N force was applied by the supported hand and the net lumbar moment and L5/S1 joint forces were 30% lower for the one-handed supported tasks versus unsupported (Kingma and van Dieen, 2004). Fewster and Potvin (2015) investigated tasks with constrained reaches by studying hand leaning characteristics and preferred leaning postures. The authors found that there is an association
between higher task hand force and higher leaning hand force with a range of 3.6% to 8.9% of body weight level. Other studies that have used specific tasks that undertake large task hand forces have reported higher body weight association with leaning hand forces (Lardi & Frazer, 2003; Godin et al., 2008). Godin et al. (2008) reported that leaning hand force levels ranged from 5.5% to 12.1% of body weight during four specific occupational tasks studied, while Lardi and Frazer (2003) found that, when completing a one-handed bolt fastening task, 10% to 15% of the body’s weight is associated with leaning hand forces. Therefore, it was hypothesised that leaning and/or bracing would result in supporting the weight of the body which in return decreases the GRF.

CHAPTER 2 – LITERATURE REVIEW

2.1 Occupational Musculoskeletal Disorders

Work-related musculoskeletal disorders have been investigated extensively by researchers to identify the key risk factors associated with workplace injuries. The term disorder is recommended due to the multifactorial nature of this pervasiveness issue, not only to acknowledge the physical factors and limit the definition to injuries and illness, yet to also consider the various psychological, psychosocial, and organizational risk factors that may lead to disorders to musculoskeletal systems (World Health Organization, 1985). All of these terms affect the same basic family of the musculoskeletal system and are usually limited to the upper extremity and low back. Tendons, muscles, ligaments, bones, nerves, and vascular structures are musculoskeletal tissues that can possibly be at risk of developing a disorder if tissues were disposed to risk factors (National Research Council, 1998; World Health Organization, 1985; Putz-Anderson, 1988; Hagberg, 1995).
2.1.1. Common Risk Factors of WMSDs

A study by Amell & Kumar (2001) stated that since each occupational task has its own distinctive characteristics, sufficient risk of disorder development is predictable when numerous factors are combined in varying proportions. Nevertheless, works within the literature dispute over which risk factor contributes the most weight to WMSD. Some tasks may exceed the physical strength capabilities of workers which consequently may result in muscle fatigue and injury. Therefore, the physical demands created by the required actions/tasks of the job are necessary to assess, as these demands can then be compared to the capacity of the workers to accurately assess the risk of injury associated with the job.

Since the dominant risk factor for upper extremity musculoskeletal disorders is defined as the force exerted during task execution, modified by its frequency and duration (Hagberg, 1995, Moore and Garg, 1995; National Research Council, 2001; Mattioli et al., 2015), the quantification and analysis of the physical force demand is vital to the ergonomics analysis. WMSD continue to be prevalent, thus suggesting that specific risk factors may increase the risk of injury as proposed by Silverstein et al. (1986, 1987). Specific factors that have been described as necessary for the development of a WMSD include high exertion forces, awkward postures, and repetitive or prolonged motions. Therefore, the inability to accurately measure such demands may explain why WMSD’s continue within the workplace.

Such factors can contribute to the accumulation of fatigue thereby reducing the overall physical capability of the worker which can put them at greater risk of injury (Silverstein et al., 1986; Armstrong et al., 1993; Fransson-Hall et al., 1995; Moore & Garg, 1995; Hagberg, 1995; de Zwart et al., 2000). The relationship between these three risk factors and WMSD’s can be seen in Figure 1. As mentioned earlier, most WMSDs are most commonly associated with upper
extremities and low back (Jensen, 1988). In the US, more than 60% of low back pain patients claim that overexertion was the leading cause of pain. In a 10-year study, only 45% of all heavy labor workers reported pursuing medical assistance for low back pain (Rowe, 1969). Furthermore, repetitive movements cause continuous muscle contractions which stretch the corresponding tendons, therewith initiating functional damage to the microstructures of the muscle. The third injury risk factor, awkward postures, contributes to tendon inflammation which is attributed to the compression that muscle microstructures are being exposed to and the increase in force requirements of tasks.

![Figure 1](image.png)

*Figure 1. Pictorial representation of the three risk factors that increase the risk of WMSD.*

The combination of high force and high repetitiveness were significantly associated with hand wrist cumulative trauma disorders (CTDs). Moreover, awkward postures were positively correlated with tasks that involved high force and high repetition (Silverstein et al., 1986). Silverstein et al. (1987) found that forceful exertions were a leading cause of reported hand injuries (specifically CTS and tendinitis). Therefore, for the purpose of decreasing and possibly limiting the risk of musculoskeletal disorders, more research should be done in order to explore these inter-related complex factors.
2.1.2 Common Work-related Injuries Reported

According to the World Health Organization (WHO) (1995), approximately 45% of the world’s population and 58% of the population >10 years of age comprises the global workforce. Subsequently, approximately 50% of workers are exposed to physically hazardous working conditions that require unreasonable work demand and exceed the worker’s capabilities. In fact, many individuals are exposed to hazardous working settings for about one-third of their adult life.

In the United States, WMSD that result in days away from work most commonly involve the back alone. Musculoskeletal disorders involving the back accounted for 38.5 percent of all WMSD (134,550 back cases out of 349,050 total cases). Nursing assistants experienced 10,330 back-related musculoskeletal disorder cases in 2016. Laborers and hand material movers experienced another 10,660 cases. These occupations accounted for 15.6 percent of all the back-related cases in 2016. The most common body parts affected by musculoskeletal disorders vary by occupation. Among nursing assistants, more than half of their cases in 2016 affected the back. Compared with other occupations, heavy tractor-trailer truck drivers had a greater proportion of injuries that affected the shoulder (19.2 percent) and leg (16.3 percent). Moreover, musculoskeletal disorders accounted for 32 percent of days-away-from-work cases in 2016 in private industry and occurred at a rate of 29.4 cases per 10,000 full-time equivalent workers (Bureau of Labor Statistics, US Department of Labor, 2017, 2018).

In Canada, during 1998, there were 793,666 reported incidents of WMSDs. Of these, 17% were caused by bodily motions, 26% resulted from overexertion, and 41% were lost-time incidents due to sprains and strains. Similarly, on a smaller scale, according to the Occupational
Health and Safety Council of Ontario, between 1996 and 2004, in Ontario, WMSDs resulted in over 27 million lost-time claims, and direct costs of $3.3 billion reaching $12 billion including indirect costs (Occupational Health and Safety Council of Ontario, 2005). Likewise, the three major American automotive companies compensated works of 11.4 billion for low back injuries and 563 million for upper limb injuries (shoulder, elbow, and hand/wrist injuries) (Punnett, 1999). Furthermore, a total of 264,438 lost-time claims have been accepted in Canada in 2018, of these claims 91,415 were related to the trunk, 54,075 were associated with the upper extremities, and 47,874 were related to the lower extremities (Association of Workers’ Compensation Boards of Canada (AWCBC), 2016-2018).

Since the most common injuries related to WMSDs are connected to the low back and upper extremities, much attention is required in investigating the effects of overexertion, repetitive movements, and awkward postures on these specific body parts (Hoogendoorn et al., 1999, 2000; National Research Council and Institute of Medicine, 2001). Applying appropriate ergonomic principles in workplace design can reduce many life cycle costs (Riley & Dhuyvetter, 2000).

2.2 Importance of Workplace Ergonomics in Automotive Manufacturing

The science of ergonomics aims to minimize and possibly prevent musculoskeletal disorders by improving work design measures and limiting ergonomic risk factors such as high forces, awkward postures and repetitive movements (Pearce, 2003). A survey study initiated by Fuchs (2006) underlined the general importance of ergonomic workplace design. The study revealed that 74% of the survey respondents preferred a workplace environment that promotes heath and preserve working capabilities as important or very important. Moreover, the survey included negative impacts and ergonomic risk factors to be identified by participants. Time pressure, one-
sided monotonous exposures, and hard physical labor were the main negative strains reported by respondents in connection with their working conditions.

At the present time, the ergonomic design of a workplace is becoming an important matter in many companies. Research has identified that consideration and implementation of ergonomic practices in the workplace will result in conserving, augmenting, and enhancing a company’s workforce, and thereby its competitiveness (Duffy and Salvendy, 1999; Karwowski et al., 1994). This is evident in the automotive industry, in which workers are required to complete tasks that involve high physical and strenuous efforts. Therefore, the ergonomic design of a workplace plays a vital role in the way strenuous tasks performed by decreasing possible risk factors, and consequently improving the production process of the company (Black, 1999). Decreasing the exposure to ergonomic risk factors will not only increase efficiency of workers and promote occupational health and safety, but ultimately maintain the workforce employability.

2.2.1 Influence of Ergonomic Practices on Economic and Social Goals

With the help of ergonomics, certain economic and social goals can be accomplished. In terms of economic factors, Eklund (1995) and Breedveld (2005) have revealed that ergonomics can support high quality production, increase productivity, result in fewer downtimes, and decrease in the number of defects and mistakes that occur during the production process. Eklund (1995) stated that approximately 50% of industrial quality errors are attributed to tasks that are deemed as ergonomically problematic. Other research studies have supported the notion of the importance of ergonomics for quality issues in manufacturing (Falck et al., 2010). If a company’s objective is to make effective and efficient usage of its manpower by implementing ergonomic practices, it in turn results in a direct improvement in employee performance (Hendrick, 2003).
The correlation between ergonomic practices and social development goals has been reported in the literature. Eklund (1995) stated that the utilization of ergonomic measures and supporting human performance will thereby result in highly motivated employees and job satisfaction. The aim of ergonomic interventions is the reduction of job stress, workloads, risk of accidents, which will assist in providing a "comfortable" workplace environment and ultimately maintain health and workforce (Dul et al., 2004). Ergonomic processes have the potential to address numerous categories of risk factors that increase the risk of WMSDs simultaneously (Vink and Kompier 1997; St-Vincent et al., 1998).

Other reported outcomes from participatory ergonomics interventions include: enhanced communication between workers (Haims and Carayon, 1998); improvements in worker psychosocial elements (Evanoff et al., 1999); decreased in the number of injury incidence and lower compensation expenses (Halpern and Dawson, 1997; Moore and Garg, 1998; Evanoff et al., 1999); and a reduction in pain reports or musculoskeletal complaints (Vink and Kompier, 1997; Evanoff et al. 1999). Most importantly, a reduction in physical risk factors for WMSDs has been reported by a number of studies that provided information on measurement and evaluation tools (Vink and Kompier, 1997; St-Vincent et al., 1998).

### 2.3 Ergonomic Analysis Methods

Conventional ergonomic analysis methods were the product of statistical data from previously conducted empirical studies. In order to suggest a solution to the task in question, ergonomists were required to interpret ergonomic risk factors, therewith analyze and compare to available data (Thun et al., 2011). Different methods that have been used to quantify forceful exertion in ergonomics application and research include direct and indirect measurements of forces.
2.3.1 Direct Methods

Direct methods vary from the traditional, hand-held force gauges to more complex, advanced devices that quantify the external exertion forces in three dimensions (Van der Beek et al., 1998). Examples of direct measurement methods that have been developed are shown in Table 2.

Electronic goniometry are devices that have been developed to measure finger and wrist angles and forearm rotations by applying lightweight sensors directly across articulating joints. The data from the devices are sent to a corresponding system to be computationally analyzed (Radwin & Lin, 1993; Biometrics, 1997). CyberGlove, is another system that simultaneously measures and records multiple wrist, hand and finger movements along with grip pressure directly to an online laptop (Freivalds et al., 2000). An electronic exoskeleton referred to as the Lumbar Motion Monitor is designed to record continuous data from truck position, velocity, and acceleration in three-dimensional components. This is achieved by applying the exoskeleton to the torso of a participant to collect data that were subsequently analyzed by a computer (Marras, 1992). Inclinometers, another direct method to measure force exertions, are tri-axial accelerometers that in combination with suitable software, are able to monitor ambulatory movements during whole-day of occupational work and provide an assessment of body postures (Hansson et al., 2001; Bernmark & Wiktorin, 2002).

Recording body posture through the usage of techniques that rely on the attachment of sonic, optical or electromagnetic markers placed on specific anatomical points on the subject in combination with a scanning unit to track the angular movement and position of different body segments (Li & Buckle, 1999). Using dedicated computing systems, the three-dimensional coordinates of all body markers can be recorded in real time. A force gauge is able to collect data directly from hand forces that have been applied by a worker. This can be done by mounting a
force gauge in tool handles, or by simulating work using instrumented handles (McGorry et al., 2004). Lastly, force platforms have been developed to measure the required applied forces directly from the subject, in all three axes, while the subject performs the tasks. A vertically mounted force plate can be used to quantity forces applied against them by the hands, while a force plate that is mounted to the ground is able to measure GRF generated by the body standing or moving across them (Heglund, 1981).

Direct measurement methods may result in slight discomfort, some alterations in work behaviour, and are more suited to the investigation of task simulation, rather than investigations at industrial locations. Nonetheless, a study conducted by van der Beek & Frings-Dresen, (1998) critically evaluated the different methods to assess push and pull forces, suggested that direct measurement methods are the only serious option to assess the level of the exerted forces with the accuracy needed to make an ergonomic decision.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Technique</th>
<th>Main feature</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radwin, &amp; Lin, 1993; Biometrics, 1997</td>
<td>Electronic goniometry</td>
<td>Single or dual plane electronic goniometers and torsiometers to record joint posture</td>
<td>Measurement of angular displacement of upper extremity postures</td>
</tr>
<tr>
<td>Freivalds et al., 2000</td>
<td>CyberGlove</td>
<td>Lightweight glove incorporating 22 motion sensors and Uniforce pressure sensors</td>
<td>Measurement of wrist, hand and finger motion with superimposed grip pressure</td>
</tr>
<tr>
<td>Marras, 1992</td>
<td>Lumbar Motion Monitor</td>
<td>Tri-axial electronic goniometer</td>
<td>Assessment of back posture and motion</td>
</tr>
<tr>
<td>Hansson et al., 2001; Bernmark &amp; Wiktorin, 2002</td>
<td>Inclinometers</td>
<td>Tri-axial accelerometers that record movement in two degrees of freedom</td>
<td>Measurement of postures and movement of the head, back and upper limbs</td>
</tr>
<tr>
<td>Method</td>
<td>System Type</td>
<td>Measurement</td>
<td>Reference(s)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-----------------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Body posture scanning systems</td>
<td>Optical, sonic or electromagnetic registration of markers on body segments</td>
<td>Measurements of displacements, velocities and accelerations of a body segment</td>
<td>Li &amp; Buckle, 1999</td>
</tr>
<tr>
<td>Force gauges</td>
<td>Single axis that records tensile and compression applied forces</td>
<td>Measurements of directly applied force</td>
<td>McGorry et al., 2004</td>
</tr>
<tr>
<td>Force platforms</td>
<td>Tri-axial that records applied forces of continuous movements</td>
<td>Measurements of directly applied force</td>
<td>Heglund, 1981</td>
</tr>
</tbody>
</table>

*Table 1. Examples of Direct measurement methods. Table adapted from David, (2005).*

### 2.3.2 Indirect Methods

A number of indirect methods have been developed for systematically recording workplace force exposures to be assessed by an ergonomist observing tasks and recording assessments on pro-forma sheets, as shown in Table 1. Each method manifests a number of exposure factors that can be assessed by different techniques. Some methods only allow postural assessments of various body segments to be completed, while other methods assess multiple factors critical for physical force exposure. The number of exposure factors assessed by different techniques varies. Some permit only postural assessments of various body segments to be made, but the majority assess several critical physical exposure factors. Some of the mentioned methods including Occupational Repetitive Action (OCRA), Quick Exposure Check (QEC), and Borg CR10 Scale provide subjective data from the workers to be considered as part of the assessment of physical demands to make an ergonomic decision (Occhipinti, 1998; Li & Buckle, 2000; Borg et al., 1998).
Other methods mentioned in Table 1, permit the combination of numerous overall exposure factors to be determined such as RULA, NIOSH, SI, LUBA, REBA, and ACGIH TLVs. The aim of these methods is to prescribe acceptable force limits for workers, and establish priorities for intervention across a range of tasks for the purpose of limiting possible musculoskeletal disorders (McAtamney & Corlett, 1993; Waters et al., 1993; Moore & Garg, 1995; Kee & Karwowski, 2001; Hignett & McAtamney, 2000; Monnington et al., 2003).

Generally, indirect methods have the advantage of being practical for use in large studies and less disruptive than other methods when conducted in a wide range of workplaces. However, intra- and inter-observer variability is one of the major disadvantages of indirect methods as the accuracy of the outcome would not be very reliable. Another disadvantage is that indirect methods are more befit to quantify force exposures of static tasks such as fixed postures or repetitive motions such as simple patterns, as appose to simultaneous movements or tasks (van der Beek & Frings-Dresen, 1998).

<table>
<thead>
<tr>
<th>Reference</th>
<th>Technique</th>
<th>Main feature</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occhipinti, (1998)</td>
<td>OCRA</td>
<td>Measures for body posture and force for repetitive tasks</td>
<td>Integrated assessment scores for various types of jobs</td>
</tr>
<tr>
<td>Li &amp; Buckle, (2000)</td>
<td>QEC</td>
<td>Exposure levels for main body regions with worker responses, and scores to guide intervention</td>
<td>Assessment of exposure of upper body and limb for static and dynamic tasks</td>
</tr>
<tr>
<td>Borg et al., (1998)</td>
<td>Borg CR10 scale</td>
<td>Scale anchored at number 10, which represents extreme intensities.</td>
<td>Measure exertion and pain</td>
</tr>
<tr>
<td>McAtamney &amp; Corlett, (1993)</td>
<td>RULA,</td>
<td>Categorization of body postures and force, with</td>
<td>Upper body and limb assessment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Method</td>
<td>Description</td>
<td>Application</td>
</tr>
<tr>
<td>-----------</td>
<td>--------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Kee &amp; Karwowski, (2001)</td>
<td>LUBA</td>
<td>Classification based on joint angular deviation from neutral and perceived discomfort</td>
<td>Assessment of postural loading on the upper body and limbs</td>
</tr>
<tr>
<td>Hignett &amp; McAtamney, (2000)</td>
<td>REBA</td>
<td>Categorization of body postures and force, with action levels for assessment</td>
<td>Entire body assessment for dynamic tasks</td>
</tr>
<tr>
<td>ACGIH Worldwide, 2001.</td>
<td>ACGIH TLVs</td>
<td>Threshold limit values for hand activity and lifting work</td>
<td>Exposure assessment manual work</td>
</tr>
</tbody>
</table>

*Table 2. Examples of Indirect measuring methods. Table adapted from David, (2005).*

### 2.4 Physical Work Demand

By employing direct and indirect measurement tools, it is possible to understand the physical demands of a specific task. Literature has suggested that physical load work that exceeds the workers capabilities can pose a potential risk factor for many reported diseases, including cardiovascular and musculoskeletal systems (Hagberg 1992; Winkel and Westgaard 1992; Karlqvist et al., 2003). Currently, many industrial workplace tasks are created with poor ergonomic design can be highly fatiguing resulting in considerable loads on tendons, tendon attachments, muscles, and joints of the working hand, wrists and arms (Kilbom, 1976).
Additionally, automotive industrial workplace jobs involve strenuous manual handling, such as pushing, lifting, carrying, and pulling of auto parts. Manual handling is identified as an injury risk to workers as it can lead to muscle fatigue, and as fatigue accumulates the force production potential decreases, thus reducing the overall workers’ physical capacity (Potvin, 2014).

Potvin (2014) suggest that the ratio between the actual physical demand of a task and the physical capacity of workers is associated with the injury risk of the work task. Therefore, in order to measure the ratio difference between the two factors, precision in measuring or estimating them is consequential. A study that investigated the relation between occupational work demands and, the assessment of the maximum acceptable forces on the workers, proposes the importance of attributing attention on the definition of the demand, the evaluation of the demand under assessment, and the quality of the method employed to measure the demand (Bos et al., 2002). Therefore, ergonomically designing the workplace plays an important role in keeping the physical demand of a task equivalent or possibly less than the physical capabilities of the workers.

**CHAPTER 3 – METHODS**

The current chapter is dedicated to the methodology that were employed for this study. The study design, involved subjects, instrumentation, data recording, experimental protocols, workstation description and data analysis is described in this section.

**3.1 Study Design**

The applied forces required by automotive assembly operators to complete forceful tasks of various designs were measured through two perpendicular force plates and in a certain task a
linear low friction device was used to simulate the mating of parts. The data collection set involved:

1. A vertically mounted force plate was used to directly measure hand forces of six independent tasks.
2. For the simulated electrical connector task, a simulation device was securely mounted on an adjustable table to directly measure hand forces.
3. During both items 1 and 2, an external object was mounted between the participant and the vertical force plate which was used during the Bracing conditions.
4. In both items 1 and 2, a force plate that was mounted to the floor (horizontal plane) to measure the corresponding GRF at the participants’ feet for all seven exertion tasks.

All task simulations and data recording were completed in a laboratory environment. The tasks chosen were common one- and two-handed manufacturing tasks that have been identified as difficult to obtain direct force measurements. A total of seven manual hand exertion tasks were simulated and their associated force efforts were obtained. Participants were permitted to adopt whole-body postures they deem necessary to complete the task. Six of the seven tasks were completed with an additional variable, bracing, such that the tasks were completed with and without the ability to brace the body against an external object. The remaining task did not require a bracing condition. Three-dimensional force was obtained from the vertical force plate simultaneously.

This work determined the percentage of erroneous between the force exertions measured at the hand to those recorded at the feet for each task. The independent variables in this study were as follows: i) task effort; ii) task type; and iii) sex. An independent variable matrix can be viewed in Figure 2.
Figure 2. Example of the independent variable matrix for the Power Hand Task. A total of seven independent variable matrices were done, one for each task effort.

3.2 Participants

Thirty healthy participants (15 males and 15 females) were recruited between the ages of 18-56 years with no history of pain or injury in their upper and lower extremities for the previous six months. Participant’s anthropometric data (height, weight) were measured and recorded (Table 3 lists the average and standard deviation (SD) of age, weight, and height of all participants). A detailed explanation of the study was provided to the participants upon arrival to the lab. This was followed by participants being asked to fill out a letter of consent, and complete an upper limb questionnaire to determine musculoskeletal injuries that may result in participant exclusion. Those participants that report no pain or upper limb injury (i.e. shoulder, elbow, wrist and hand)
and verified by the questionnaire were permitted to participate in this study. After a detailed explanation of the methodology and the risk associated with the study, subjects were informed that they are free to withdraw without any consequences at any time. All participants were required to attend one session that entailed both the orientation and testing portions of the study.

<table>
<thead>
<tr>
<th>Sex</th>
<th>Count</th>
<th>Age Range</th>
<th>Average Age (SD)</th>
<th>Average Height (cm) (SD)</th>
<th>Average Weight (kg) (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>15</td>
<td>18 - 53</td>
<td>27.06 (8.8)</td>
<td>205 (10.9)</td>
<td>81.5 (19.7)</td>
</tr>
<tr>
<td>Female</td>
<td>15</td>
<td>18 - 56</td>
<td>26.33 (12)</td>
<td>178 (6.8)</td>
<td>65.1 (14.1)</td>
</tr>
</tbody>
</table>

*Table 3. Average and standard deviation (SD) of age, weight, and height of all participants.*

### 3.3 Instrumentation and Data Acquisition

Participant’s anthropometric data (i.e. height, weight) were measured and recorded. Weight of subjects was measured by having the subject stand still on a force plate for 3 seconds and recorded in kilograms; height was measured in centimetres (cm) through the use of a conventional measuring tape. To measure exertion forces in six experimental conditions, two independent force plates oriented perpendicularly from each other simultaneously measured the 3 dimensional forces (X, Y, Z coordinates) of each task effort. Both force plates *AMTI-OR6-OP* (Advanced Medical Technologies, Inc, Watertown MA, USA) were synchronized to directly record all forces during all tasks and sampled at a rate of 1000 Hz. The vertical force plate was mounted on a metal stand in the vertical plane to measure hand forces while the ground force plate was mounted on the horizontal plane (floor) to measure the corresponding forces at the participants’ feet (Figure 3).
Figure 3. Example of the vertical and horizontal force plate setup in this study. Illustration of how the 3 dimensional axes were recorded with respect to the two independent force plates.

Force exertion of the remaining experimental condition (Electrical Connector) was measured using a linear, low friction simulated electrical connector device (Figure 4 illustrates the main features of the device). The gripfixture was attached in series with a strain gauge via a frictionless gliding block. A 100 lb linear strain gauge (Sensor Development Incorporated, Southfield, MI) was used to measure force output. All strain gauge signals were collected and processed with custom designed software developed with the LabVIEW software package (National Instruments, Austin, TX). Additionally, signals were analog-to-digital (A/D) converted (AT-MIO, National Instruments, Austin, TX) at a sampling rate of 1000 Hz.
Figure 4. Illustration of the Connector Simulation Device. Turning the dial would move the frictionless gliding blocks forward (shortening the spring and increasing resistance) or backwards (lengthening the spring and decreasing resistance).

### 3.3.1 Tool Description

This research employed tools that have been repeatedly used by the manufacturing automotive industry. Figures 5 illustrate the tools that were used to collect data. The 6 tools were as follows:

- **Tool 1**: Power hand tool (DeWalt DCD771C2 Compact Drill/Driver, maximum non-load speed: 1,500 RPM);
- **Tool 2**: Pistol Grip Nutrunner (Atlas Copco Etp St32-10-10) was deployed to fasten bolts;
- **Tool 3**: Pressure Release Shaft mimicking installation of car bumpers, fenders and tires.
- **Tool 4**: A standard rubber hose (15.5cm in length, 3.8cm diameter) was used for the hose insertion task.
- Tool 5: A Universal Car Door Weather Strip (Door Seal Horizontal Bulb Extrusion 0.62" Bulb Height x 0.039"-0.137" Grip Range x 0.53 U Height); and
- Tool 6: Inserting a simulated electrical connector grip using the Connector Simulation Device. The spring had a stiffness of 5.5 N/cm (1.1 N/revolution of the dial), a resting length of 20 cm and a diameter of 2.3 cm.

![Image of instrumentational tools](image)

**Figure 5.** Illustration of five of the instrumentational tools that were used in this study. (1) Drilling-machine (DeWalt DCD771C2), (2) Pistol Grip Nutrunner (Atlas Copco Etp St32-10-10), (3) Pressure Release Shaft, (4) a standard rubber hose (15.5cm in length, 3.8cm diameter), and (5) A Universal Car Door Weather Strip.

### 3.4 Experimental Procedures and Protocols

On the day of the study, prior to the start of the orientation session, participants were given a thorough explanation of the purpose of the study, the instrumentation, and the set-up.
3.4.1 Orientation Session

As mentioned in section 3.2, after the screening for eligible participants, the detailed explanation of the study was provided in this session. At this point, any questions or concerns regarding participation were answered. Thereby, participants were introduced and given the opportunity to familiarize themselves with all the instruments and experimental conditions. Once participants were acquainted and familiar with the tasks, they were then asked to complete the experimental session. The orientation took approximately 15 minutes to complete.

3.4.2 Experimental Session

As each task was assigned randomly, participants completed five trials per condition (Conditions (7) x Bracing (2) – except pulling task x Trial (5) = 65 trials). Since this study investigated a possible relationship between hand forces and GRF recorded at the feet, six task efforts was completed with and without the ability of the participants to brace themselves. The brace is an external object that was placed between the participant and the vertical force plate. The brace was made adjustable to accommodate anthropometry of different participants. Participants were asked to brace their thighs during the Bracing condition. During the No Brace conditions, participants were given the instructions to stand on the force platform with both feet and freely complete the task without any restrictions (Figure 6). During the Brace conditions, participants stood on the force plate with both feet while bracing their thighs against an adjustable brace located between the participant and the vertical force plate (Figure 7).
Figure 6. Example of the Forward hose Insertion Task without a brace.
3.4.3 Tasks Description

Tasks that were targeted for this research were simulated within a laboratory environment and are described in the following chapter.

- Task 1: Feed force when operating a power hand tool;
Power hand-tool feed force was applied using a drilling-machine (DeWalt DCD771C2 Compact Drill/Driver, approx. weight 1.65 kg, dimension of tool: 35.3 x 25.1 x 10.8 cm). Participants were instructed to drill five times into an aluminum plate that was rigidly affixed to the vertical force plate.

➢ Task 2: Weather stripping car doors;

Participants applied a maximum force of 110 N while inserting a weather strip on a 2mm metal frame that was attached to the vertical force plate (approx. weight 204 g, dimension of tool: 29.2 x 26.2 x 7.1 cm) (Chengalur, S. N., 2004).

➢ Task 3 and 4: Pushing/Pulling Pressure Release Shaft;

Participants pushed and pulled the Pressure Release Shaft mimicking the installation of car tires, bumpers, and fenders with a maximum force of 225 N (Chengalur, S. N., 2004).

➢ Task 5: Fastening bolts while using a Pistol Grip Nutrunner;

As per Potvin et al. (2004), fastening bolts using a powered nutrunner, was completed by applying a maximum force of 70.7 N. Soft joints bolts were fastened five times and set at a 7.5 Nm (Etp St32-10-10, Etp St32, 2.2-8.0 Ft Lbs, and approx. weight: 1.8 kg, tool length: 197 mm, tool height: 179 mm)

➢ Task 6: Inserting a simulated electrical connector grip; and
While using the dominant hand, the maximum acceptable force to insert the simulated grip was 28.2 N as defined by Potvin et al. (2006). The resistance level was set to "low" by the researcher by turning the dial to move a low friction gliding block along a threaded rod (5 threads/inch), thus changing the length of the spring, and subsequently its resistance. During each insertion, the simulated connector interface traveled a distance of 1.3 cm (0.5 in), which was determined to be the average distance of an electrical coupling. To accommodate the differences in height of participants, the device was securely mounted to a standing metal frame with the ability of adjusting height.

- Task 7: Forward hose insertion;

Participants were provided with a hoses to be inserted five times onto a cylindrical handle. The handle was used to mimic a flange that is directly attached to the vertical force plate corresponding to the parasagittal plane of the participant (approximately 20 cm from the median plane) at wrist level.

Finally, Tasks were carried out five times without an external object to brace against and five times with a Brace (at the thighs). One minute was provided as a rest-break between each trial. Data collected from all trials were saved on a computer and analyzed when all participants were completed. The experimental session took approximately 1.5 hr to complete.

3.5 Data Analysis

Both the hand and GRF data was smoothed using a sixth-order Butterworth low-pass filter with a cutoff frequency of 10 Hz in custom LabVIEW software (National Instruments, Austin,
TX). As mentioned earlier, the two independent force plates gauge simultaneously measured the 3D forces (X, Y, and Z axes) of each task effort yet the linear strain gauge only measured forces in the force of intended direction (FID) which was the insertion force of the Electrical Connector (FzHand). The vertical force plate collected FHand value (FxHand, FyHand, and FzHand), while the ground force plate recorded FFoot Value (FxFoot, FyFoot, and FzFoot). FID are the forces that were applied in the direction of force exertion on the vertical force plate. If forces were exerted in the forward direction, FID would be FzHand, where a force exertion downword/upward (e.g., Weather Strip Task) would have an FID in the FxHand coordinate, and a force exertion in the frontal plane (left and right) would have an FID in the FyHand coordinate. For the vertical force plate, the FID would be FzHand and FyHand for the ground force plate. All forces were collected from the 1 sec before the effort initiation to 1 second following the effort and the end of the effort. The resultant force were calculated for each sample point using the equation:

\[ R = \sqrt{(F_x^2) + (F_y^2) + (F_z^2)} \]

where \( R \) is the resultant force, \( F_x, F_y, \) and \( F_z \) are the axes that are orthogonal to each other.

Since the force plates are positioned into two different planes (vertical and horizontal), the axes on one force plate is not equal and opposite to the second force plate. Where \( F_{x\text{Hand}}/F_{z\text{Foot}} = \text{Up/Down}, \ F_{y\text{Hand}}/F_{x\text{Foot}} = \text{Right/Left}, \) and \( F_{z\text{Hand}}/F_{y\text{Foot}} = \text{Push/Pull} \) (Figure 2).

The Root Mean Square Error (RMSE) was used to measure the accuracy based on percentage errors. RMSE measures how much error there is between two data sets. In other words, it compares a predicted value and an actual value. The smaller an RMSE value, the closer predicted and actual values are. RMSE is the squared difference between the predicted and the actual values divided by the sum of values as expressed in the formula:
\[ RMSE = \sqrt{\frac{avg((F_{foot} - F_{Hand})^2)}{avg(F_{Hand}^2)}} \]

where \( F_{foot} \) is the magnitude of force acquired from the force plate at the feet, \( F_{Hand} \) is the magnitude of force acquired from the force plate at the hands.

RMSE was used to measure the difference between the forces collected at the hands and the forces recorded at the feet as GRFs.

### 3.6 Statistical Analysis

Only the data from the testing sessions was used in the statistical analyses. Six independent two-way Factorial ANOVAs were completed for two independent variables; 1) task type (brace and no brace), and 2) sex (males and females). The dependent variable in this study is RMSE to determine the percentage error between the forces at the hands and feet. Also, a Univariate ANOVA was conducted for the pulling task with sex as the independent variable and RMSE as the dependent variable. The significance level for each ANOVA was set at \( p < 0.05 \). Partial eta squared was recorded for each significant interaction to determine if the effect’s explained variance meets the threshold of > 1% to be considered functionally relevant as 1% is deliberated as the smallest effect size that is considered merely statistical (Cohen, 1988).

### CHAPTER 4 – RESULTS

The following section will reveal the results for the Resultant Force (\( F_R \)) and the single force axis vector that depicts the force in intended direction (FID). To clarify, the following FID’s relate to the push/pull efforts required to complete the following tasks where the \( F_{z\,Hand} \) and \( F_{y\,Feet} \) forces were the primary forces to complete the tasks: FID_{EC} (electrical connector task), FID_{D} (drilling task), FID_{FS} (fastener task), FID_{HI} (hose install task), FID_{Pull} (pull task) and FID_{Push} (push
task). For these tasks, the two additional forces in the non-FID (Fx_{Hand} - Fz_{Feet} and Fy_{Hand} - Fx_{Feet}) axes will not be discussed as they on average only contributed 20.9% (17.22% for Fx_{Hand} - Fz_{Feet} and 3.7% for Fy_{Hand} - Fx_{Feet}) to the calculated F_R, whereas the FID for these tasks contributed on average 79.1% to the resultant. For the Weather-Strip task, since there are two FID (FID_{WSD} (Weather-Strip – Push Down) and FID_{WSS} (Weather-Strip – Pull to Side)) which contributed 76.4% to the F_R, the forces from all axes, as well as the resultant will be shown. Mean force and standard deviation values for each task is presented in Table 4.

<table>
<thead>
<tr>
<th>Task</th>
<th>Measure</th>
<th>Hand Force Mean</th>
<th>Hand Force Stdev (N)</th>
<th>Feet Force Mean</th>
<th>Feet Force Stdev (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(N)</td>
<td>Brace</td>
<td>(N)</td>
<td>Brace</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No Brace</td>
<td>No Brace</td>
<td>No Brace</td>
<td>No Brace</td>
</tr>
<tr>
<td>Connector</td>
<td>FID</td>
<td>15.89</td>
<td>16.71</td>
<td>6.67</td>
<td>7.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fresultant</td>
<td>27.67</td>
<td>28.97</td>
<td>11.38</td>
<td>12.79</td>
</tr>
<tr>
<td>Drill</td>
<td>FID</td>
<td>102.90</td>
<td>97.38</td>
<td>26.94</td>
<td>27.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fresultant</td>
<td>107.50</td>
<td>102.76</td>
<td>28.68</td>
<td>29.80</td>
</tr>
<tr>
<td>Hose</td>
<td>FID</td>
<td>91.20</td>
<td>84.22</td>
<td>29.90</td>
<td>30.10</td>
</tr>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fresultant</td>
<td>94.87</td>
<td>88.09</td>
<td>29.52</td>
<td>30.39</td>
</tr>
<tr>
<td>Pull</td>
<td>FID</td>
<td>78.90</td>
<td>-</td>
<td>28.78</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fresultant</td>
<td>82.90</td>
<td>-</td>
<td>28.57</td>
<td>-</td>
</tr>
<tr>
<td>Push</td>
<td>FID</td>
<td>82.88</td>
<td>73.37</td>
<td>20.98</td>
<td>23.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fresultant</td>
<td>89.32</td>
<td>87.52</td>
<td>22.56</td>
<td>29.54</td>
</tr>
<tr>
<td>Fastener</td>
<td>FID</td>
<td>37.74</td>
<td>38.02</td>
<td>27.13</td>
<td>23.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fresultant</td>
<td>39.35</td>
<td>39.40</td>
<td>28.20</td>
<td>24.41</td>
</tr>
</tbody>
</table>

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Table 4. Mean forces (N) and Standard deviations (N) for the hands and the feet for all tasks during the Brace and No Brace conditions.

<table>
<thead>
<tr>
<th>Weather-Strip</th>
<th>Fresultant</th>
<th>40.25</th>
<th>41.51</th>
<th>10.45</th>
<th>11.09</th>
<th>42.56</th>
<th>129.71</th>
<th>10.85</th>
<th>39.55</th>
</tr>
</thead>
</table>

4.1 Electrical Connector Task RMSE

4.1.1 Electrical Connector Force Comparison - $F_{\text{IDEC}}$

The analysis revealed a significant main effect of Task Type ($F(1, 28) = 112.5, p < .001, \eta_p^2 = .80, \text{Figure 8}$). The RMSE was 87.2% greater for the Brace condition than in the No Brace condition.

4.1.2 Electrical Connector Force – $F_R$

The analysis revealed significant main effect of Task Type ($F(1, 28) = 112.8, p < .001, \eta_p^2 = .80, \text{Figure 8}$). The RMSE was 87.5% greater for the Brace condition than in the No Brace condition.
4.2 Drilling Task RMSE

4.2.1 Drilling Force Comparison - $F_{IDC}$

The analysis revealed significant main effect of Task Type ($F(1, 28) = 244.23, p < .001, \eta^2_p = .90$, Figure 9). The RMSE was 88.97% greater for the Brace condition than in the No Brace condition.

4.2.2 Drilling Force – $F_R$

The analysis revealed significant main effect of Task Type ($F(1, 28) = 219.68, p < .001, \eta^2_p = .89$, Figure 9). The RMSE was 84.46% greater for the Brace condition than in the No Brace condition.
4.3 **Pistol Grip Nutrunner (Fastener) Task RMSE**

### 4.3.1 Fastener Force Comparison - $F_{IDFS}$

The analysis revealed significant main effect of Task Type ($F(1, 28) = 71.64, p < .001, \eta^2_p = .72$, Figure 10). The RMSE was 96.36% greater for the Brace condition than in the No Brace condition.

### 4.3.2 Fastener Force - $F_{R}$

The analysis revealed significant main effect of Task Type ($F(1, 28) = 60.20, p < .001, \eta^2_p = .69$, Figure 10). The RMSE was 93.02% greater for the Brace condition than in the No Brace condition.
4.4 Hose Insertion Task RMSE

4.4.1 Hose Force Comparison - $F_{ID_{HI}}$

The analysis revealed significant main effect of Task Type ($F(1, 28) = 137.06, p < .001, \eta^2_p = .83$, Figure 11). The RMSE was 67.78% greater for the Brace condition than in the No Brace condition.

4.4.2 Hose Force – $F_R$

The analysis revealed significant main effect of Task Type ($F(1, 28) = 151.59, p < .001, \eta^2_p = .84$, Figure 11). The RMSE was 67.68% greater for the Brace condition than in the No Brace condition.
Figure 11. The effect of Task Type (H (Hose) and HB (Hose with Brace)) on the percentage of RMSE for the FID_{Hh} and F_R. Means and standard deviations bars are shown.

4.5 Pulling Task RMSE

No significant effects were found at a significance level of .05.

4.6 Pushing Task RMSE

4.6.1 Pushing Force Comparison – FID_{Pushing}

The analysis revealed significant main effect of Task Type ($F(1, 28) = 124.35, p < .001, \eta^2_p = .82$, Figure 12). The RMSE was 79.87% greater for the Brace condition than in the No Brace condition.

4.6.2 Pushing Force – $F_R$
The analysis revealed significant main effect of Task Type \( (F(1, 28) = 98.78, p < .001, \eta^2_p = .78, \text{Figure 12}) \). The RMSE was 76.24% greater for the Brace condition than in the No Brace condition.

![Figure 12](image)

*Figure 12. The effect of Task Type (H (Hose) and HB (Hose with Brace)) on the percentage of RMSE for the FID_{Pushing} and F_R. Means and standard deviations bars are shown.*

### 4.7 Weather-strip Task RMSE

Figure 16 demonstrates the difference in RMSE (%) for FID_{WSD}, Non-FID_{WS}, and F_R.

#### 4.7.1 Weather-strip Force Comparison – FID_{WSD}

The analysis revealed significant main effect of Task Type \( (F(1, 28) = 91.00, p < .001, \eta^2_p = .77, \text{Figure 13}) \) The RMSE was 63.72% greater for the Brace condition than in the No Brace condition.

#### 4.7.2 Weather-strip Force Comparison – Non-FID_{WS}
The analysis revealed significant main effect of Task Type ($F(1, 28) = 217.23, p < .001, \eta_p^2 = .89$, Figure 14). The RMSE was 92.43% greater for the Brace condition than in the No Brace condition.

### 4.7.3 Weather-strip Force – $F_R$

The analysis revealed a significant main effect of Task Type ($F(1, 28) = 317.61, p < .001, \eta_p^2 = .92$, Figure 15). The RMSE was 86.64% greater for the Brace condition than in the No Brace condition.

### 4.7.4 Weather-strip Force Comparison – $FID_{WS}$

No significant effects were found at a significance level of .05.

*Figure 13. The effect of Task Type (WS (Weather strip) and WSB (Weather strip with Brace)) on the percentage of RMSE for the $FID_{WS}$. Means and standard deviations bars are shown.*
**Figure 14.** The effect of Task Type (WS (Weather strip) and WSB (Weather strip with Brace)) on the percentage of RMSE for the Non-FID\textsubscript{WS}. Means and standard deviations bars are shown.

**Figure 15.** The effect of Task Type (WS (Weather strip) and WSB (Weather strip with Brace)) on the percentage of RMSE for the Fr. Means and standard deviations bars are shown.
CHAPTER 5 – DISCUSSION

The purpose of this study was to determine the relationship between the GRF, forces directly recorded at the feet, and the force exerted by the hands, measured at the hands, during simulated work-related tasks, in an effort to understand the validity of GRF measurements as an accurate alternative indirect measurement of physical hand efforts.

For all 7 task exertions studied, tasks that were completed without a Brace often resulted with a significantly lower RMSE percentage compared to tasks that were completed with a Brace.

The increase in percentage error (RMSE) that ranged from 55% to 495% during the Bracing tasks can be attributed to bracing the body against an external object at the thighs which in return provided an increase in the FID on the ground force plate caused by the counter-reaction of bracing. Although not measured or recorded, participants were exerting a forward force in the same direction as the hand completing a task (Fz – FID) while bracing their thighs. When
participants completed a No Brace task, the body weight resultant force vector is directed mostly in the vertical axis towards the ground and therefore, the reaction forces at the feet due to the forces exerted at the hands is independent of body weight, thus resulting in low RMSE. In contrast, during the Bracing task, independent of the body part providing the bracing, participants will shift some their body weight towards the bracing point, resulting in a multi-axial force vector. This multi-axial force vector which includes forces in the same direction as the FID exerted by the effort hand, while not recorded, will create reaction forces as captured by the force plate. Therefore, the reaction forces at the feet will include both the exerted force by the effort hand and the bracing force, yet only the effort hand forces were captured and thus, the bracing force appeared at the feet as an added force measurement to those recorded at the hand. The forces exerted by the hand will not significantly change between task type (Brace or No Brace), yet a difference between the GRFs will appear between task type since the bracing is occurring at the thighs. This is because the hand force plate was recording the hand exertion forces only while the ground force plate was recording the forces transferred from the effort hand as well as the forward bracing forces at the thighs. The addition of both force resulted in a high force measurement that was significantly larger than that recorded at the hands, which explains the increased RMSE on an average of 82.22% for the Bracing task compared to the No Brace task. Previous studies support this finding as bracing with the thighs significantly increased force exertion and provided additional compensatory forces and moments at the feet (Fewster and Potvin, 2015). A recent study by Cappelletto and Potvin, 2019, reported that lower body bracing resulted in an increase in bracing force. The researchers investigated when participants would brace and quantify the amount of force used for bracing. They found that average lower body brace forces contributed 117 N for upward and pulling exertions, and 67 N for downward
exertions. This would explain how lower body bracing can increase the bracing force and ultimately be captured on a ground force plate. Therefore, the increased error when bracing provides valuable information and a warning for those who may employ GRF as a technique to capture hand forces for ergonomics purposes. If bracing is evident during a task, the GRF technique will yield very high error and should not be used.

Additionally, our results have revealed that participants’ body weight decreased while bracing during 4 of the 6 tasks that were completed with and without a brace. Some of the forces that are recorded at the feet during a No Bracing task would be transferred to the bracing limbs during a Bracing condition. This is explained as a percentage of body weight is transferred to the bracing object which is supporting the participants’ body weight at the thighs rather than the feet. Therefore, this would result in a decreased body weight being recorded at the ground force plate. This finding was supported by previous studies that examined bracing and body weight association (Fewster and Potvin, 2015; Godin et al., 2008; Lardi and Frazer, 2003). A study that investigated hand leaning characteristics and preferred leaning postures, reported an association between higher task hand force and higher leaning hand force with a range of 3.6% to 8.9% of body weight level (Fewster and Potvin, 2015). Another study that researched four specific hand occupational tasks, revealed that leaning hand force levels ranged from 5.5% to 12.1% of body weight (Godin et al., 2008) while Lardi and Frazer (2003) determined that the magnitude of force exerted while bracing, ranged from 10% to 15% of body weight when completing a one-handed bolt fastening task.

Considering all No Bracing tasks, the Drilling task resulted in the lowest RMSE of all tasks. An error percentage of 20 or under was considered low or modest, whereas > 20% was considered high level of percentage error (McDowell et al., 2006; Dale et al., 2011). On average,
the RMSE was 5.93% for the FIDD and 7.71% for FR. The Drilling task was completed with an average of 102.91N, which was the highest physical hand effort of all tasks performed, while the average GRF in FIDD appeared to be 101.76N. Previous research support this finding. Wing et al., (1997) examined the relationship between grip force and ground reaction torques when subjects made horizontal parasagittal hand movements, reported that ground reaction torques traces depart from baseline at the same time hand load forces begin to increase. The authors observed that initial changes in GRT are tightly coupled to the direction of the load force (i.e. push compared to pull). These results provide us with valuable information about how the body transfers the forces from the hands to the feet, which can be attributed to the high physical hand force requirement of this task. Industrial work can lead to eccentric exertions (muscle lengthening contractions), specifically with power hand tools when tool-generated forces are rapidly rising to exceed the operator’s capability to react against them (Armstrong et al., 1999; Oh et al., 1997; and Oh and Radwin, 1998). Initially, torque-producing power hand tool operators overcome the reaction force of the tool with concentric (muscle shortening) and isometric exertion, yet as the tool force promptly increases, the operator may be overcome by the tool force, resulting in upper limb motion in opposition to muscle contraction (Sesto et al., 2006). Prior research has reported that the severity of injury is greatest following eccentric exertions than isometric or concentric exertions (Lieber et al., 1991; Faulkner et al., 1993). These studies can explain how rapidly increasing forces are transferred from the operating tool to the operator’s hand and eventually to the body. Since it is evident that forceful exertions can put the worker at a higher risk of musculoskeletal disorders (Silverstein et al., 1987), the GRF technique is important to ergonomists and can be employed as it is able to provide accurate hand force
measurement of tasks that require high force exertions. Compared to high-force tasks, tasks that required lower force exertions did not provide accurate results.

The No Brace condition of the Electrical Connector task resulted in the highest RMSE of all tasks. On average, the RMSE was 63.20% for the FIDEC and 61.78% for FR. This can be attributed to the fact that the Electrical connector task was completed with an average hand FIDEC of 15.90N, which is the lowest physical hand effort of all tasks. Since a small effort was needed to complete this task, the body was able to dampen some of the forces resulting in a GRF in FIDEC of only 7.56N. Force is transferred through direct physical contact with tools and other objects in multiple directions. A variety of factors including grip forces of the palm and fingers and feed forces that push through the arm and palm combine to produce force on a tool or object (Welcome et al., 2004). When force is transferred through the body, muscles and joints act as dampers to decrease the amount of force being transmitted to the body (Wachter et al., 1996). Previous studies have found a similar trend where tasks requiring less force resulted in a decrease in the accuracy of force measurement and an increased force measurement error caused by the decrease in force effort needed (McGorry et al., 2004; Edgar et al., 2012). Though the findings cannot be directly compared, a study that investigated grip force levels to understand the accuracy of force measurement using a hand dynamometer reported that as force level increased error level of force measurement decreased. The study evaluated four force levels (44.5 N, 89 N, 133.5 N, 178 N), where a dramatic error decrease from 80.8% for the lowest force level (44.5 N) to 23.4% for the second level (89 N) was evident, and the force measurement accuracy continued to improve as force level increased (McGorry et al., 2004). Therefore, due to the dampening of lower forces, a decreased measurement was captured at the ground force plate as a GRF. This marked improvement of force measurement accuracy as force exertion increases and increased
measurement error as force exertion decreases suggests a possible minimal physical hand force requirement in order to use or validate the GRF measurement method.

It has been documented that women report higher musculoskeletal pain or WMSD, especially pronounced for the upper extremity (Mehlum et al., 2013; Wijnhoven et al., 2006; Bingefors et al., 2004; Dahlberg et al., 2004; Hoofman et al., 2004; De Zwart et al., 2000; Nordander et al., 2009; Nordander et al., 2008). Knowing that female sex is a well-established risk for WMSD, sex should be at least included as a confounder. In recent years, it has been suggested to include sex stratification in the analyses of exposure response relationship instead of only adjusting for sex (Silverstein et al., 2009; Messing et al., 2003; Messing et al., 2009). Locke et al. (2014) suggested that uncontrolled sex differences in task distribution may result in exposure misclassification, leading to erroneous risk estimates, thus recommending subject specific exposure assessments on task level. Kennedy et al. (2003) concluded that when assessing physical exposure, accounting for sex is important to minimize inaccurate estimations. The current study included sex as an independent variable to understand its effects on the percentage error between the recorded hand forces and the corresponding GRF. Since this study investigated the relationship between hand and GRF, no significant differences were found between the sexes in percentage error. The average percentage of RMSE in the FID for all tasks was 98.86% for females and 99.13% for males. These results suggest that this force measurement technique can be used by ergonomists regardless of the workers sex, consequently minimizing possible imprecise measurements caused by sex.

Moreover, it was interesting to note that tasks requiring less force in different axes (e.g., fastening bolts or drilling tasks) resulted in a decreased RMSE when compared to task that required more “wiggly” movements and thus forces were distributed in multiple axes (e.g., hose
insertion and weather strip tasks). The Fastener task was completed with an average of 37.75N in the FID\textsubscript{F} and revealed a RMSE of 11.01\% for the FID\textsubscript{F}, yet, the Hose insertion task was completed with an average of 91.20N in the FID\textsubscript{H} and showed a RMSE of 27.53\% for the FID\textsubscript{H}, while the WS task required an average of 49.27N in the FID\textsubscript{WS} and yielded a RMSE of 30.09\% for the FID\textsubscript{WS}. A reasonable explanation for the larger error with the Hose and WS tasks may be due to muscle tuning which is the alteration in muscle activation to minimize the transmission of force after impact (Boyer & Nigg, 2004; Nigg & Liu, 1999; Wakeling & Nigg, 2001a, 2001b; Wakeling et al., 2001, 2003). It is presumed that, due to the wiggling movement needed for the Hose task and repetitive forces needed to complete the WS task, participants decreased muscle activation which reduces the stiffening of the muscles being employed. As muscles become less stiff through decreased activation state, it will be better equipped to attenuate impact forces (Pain & Challis, 2002) due to the dynamics of the wobbling mass (e.g., muscles and soft tissues) (Flynn et al., 2004; Holmes & Andrews, 2006). Impact forces can generate a shock wave that travels through the musculoskeletal system from the source of impact to other parts of the body (Lafortune et al., 1996). Therefore, during the Hose and WS tasks, much like what occurs in impact related forces, the wobbling mass could dampen the forces exerted resulting in an increased error between the recorded hand forces and GRFs. Holmes & Andrews (2006) examined the effects of voluntarily manipulating muscle activation and localized muscle fatigue on tibial response parameters, including peak tibial acceleration, time to peak tibial acceleration, and the acceleration slope, measured at the knee during unshod heel impacts. The authors found a steady decrease in time to peak acceleration from the baseline state to 60\% of the maximum activation state. As leg muscles became stiffer through increased activation state, the tibialis anterior muscle was less capable of attenuating the impact shock, resulting in the decreased time
to peak acceleration. It was also noted that increasing the stiffness of a muscle may create a disadvantage when trying to dampen forces.

5.1. **Limitations and Assumptions**

It was assumed that the force-time histories resulting from the 7 physical hand efforts completed in this study represented those that occurring in the workplace. However, there was a functional difference between the actual forceful exertion tasks performed in manufacturing and the action of the simulated automotive physical hand efforts performed in the laboratory. The current laboratory study simulated the hand forceful exertions in a static application of force to a rigidly fixed vertical force plate. In manufacturing, automobile parts are installed/fastened with the part moving dynamically relative to the fixture.

Furthermore, although participants were given the instructions to stand on the force platform with both feet and freely complete the task without any restrictions to eliminate any limitations, participants were given their time to complete the tasks without constraining the duration to complete each task. In reality, automotive parts are installed/fastened on a dynamic vehicle being assembled, which restricts the workers with a cycle time for each task.

5.2. **Hypotheses Revisited**

1. *Ground reaction forces measured will highly correlate with the forces produced and recorded at the hand.*

This statement was made prior to adjustments in the methodology and since then it was decided that an error (RMSE) analysis will be done rather than a correlation analysis. Some tasks resulted in high RSME between the GRFs and the forces recorded at the hands which can be attributed to either the low force requirement needed to complete the task, bracing against an
external object, or wiggling and repetitive movement while performing the task. Other tasks revealed low RSME between the recorded hand forces and the resultant GRFs. The decreased error can be attributed to either the high force requirement needed to complete the task or performing the task without a brace. These results led us to believe that a low RMSE would represent a correlation between the recorded and reaction forces.

2. **Tasks requiring greater force efforts will produce a higher statistical correlation between the ground reaction forces and those recorded at the hands in comparison to tasks requiring lower force efforts.**

This statement was made prior to adjustments in the methodology and since then it was decided that an error (RMSE) analysis will be done rather than a correlation analysis. The results suggested that lower force efforts were associated with higher RMSE. As mentioned in the discussion section, the Electrical connector task, which required the least physical force effort of all tasks, demanded a low average force in the FID\textsubscript{EC} and resulted in a high RMSE in the FID\textsubscript{EC}. Contrarily, the Drilling task, which was the highest in physical force demand of all tasks, required a high average force in the FID\textsubscript{D} and resulted in the lowest RMSE in the FID\textsubscript{D} of all tasks. The results show that lower force efforts are dampened through the body, therefore the GRFs would represent a different measurement than those recorded at the hands, resulting in greater RMSE. These results led us to believe that a high RMSE would represent no correlation between the recorded and reaction forces.

Some tasks that required high physical force effort resulted in a high RMSE such as the Hose insertion and the Weather Strip tasks. This can be due to the nature of the movement needed to complete the Hose insertion and weather-stripping tasks where force attenuation is increased while completing these tasks.
3. *Males and females’ results will not differ; thus, a sex effect will not be found.*

The study allowed the investigators to accept the null hypothesis, as sex did not show any significant main effect (p < .05) on RMSE, as well as the interaction between sex and task type were not statistically significant (p < .05) for any of the tasks.

4. *Tasks that include the ability for participants to brace themselves against an external object will result in a lower correlation between the forces at the hands and the reaction forces at the feet in comparison to tasks without a brace.*

This statement was made prior to adjustments in the methodology and since then it was decided that an error (RMSE) analysis will be done rather than a correlation analysis and that participants will only brace their upper legs for the all Bracing tasks. This study showed a significant main effect for Task Type (Brace and No Brace) for each of the six physical hand efforts studied. When comparing tasks that were completed without a brace to tasks that were done while bracing, Bracing tasks showed a significantly higher RMSE percentage. These results led us to believe that a high RMSE would represent no correlation between the recorded and reaction forces. The ground force plate was able to pick up the counter-reaction force of bracing in the FID as well as the forces transferred from the hands, while the hand force plate only picked up the physical hand effort which was relatively similar between both Task Types.

**CHAPTER 6 – CONCLUSION**

Forceful exertions are considered one of the most contributing factors to upper extremity WMSD (National Institute for Occupational Safety and Health (NIOSH), 1997). Therefore, this study investigated a new force measurement method that included a direct measurement of hand force while recording an indirect measurement that provided the recorded GRFs. The data collected in the current study showed that, tasks that were performed with a Brace often resulted
with a significantly higher percentage of RMSE compared to tasks that were carried out without a Brace. Based on these results, tasks that were completed with a brace unveiled an average increase in the percentage of RMSE of 82.22% than those executed without a brace.

Furthermore, tasks the required greater force effort were related to lower RMSE percentage between the forces recorded at the hands and the GRF when compared to tasks that necessitated lower force effort. The current results revealed that, the Drilling task resulted in a lower RMSE percentage caused by the greater physical force effort needed (RMSE for the FID\textsubscript{D} was 5.93% and 7.71% for F\textsubscript{R}), while the highest RMSE percentage caused by the lower requirement of physical force effort occurring in the Electrical Connector task (RMSE for the FID\textsubscript{EC} was 63.20% and 61.78% for F\textsubscript{R}).

In addition, the analyses performed on the collected data revealed no statistical significance of sex on the percentage of RMSE or Task Type (Brace or no Brace). Finally, an interesting finding in the current data showed that tasks requiring less “wiggly” and repetitive movements (e.g., fastening bolts) resulted in a decreased RMSE when compared to tasks that required more movement in different axes (e.g., hose insertion).

Since it is evident that forceful exertions can put the worker at a higher risk of musculoskeletal disorders (Silverstein et al., 1987), the GRF technique is important to ergonomists and can be employed as it is able to provide accurate hand force measurement of tasks that require high force exertions. Contrarily, tasks that required lower force exertions did not provide accurate results and should not be measured using this force measurement method. Moreover, the increased error when bracing provides valuable information and a warning for those who may employ GRF as a technique to capture hand forces for ergonomics purposes. If
bracing is evident during a task, the GRF technique will yield very high error and should not be used.

Measurement of forceful exertion in ergonomic assessments is both necessary and challenging for ergonomists, yet while there are different methods that are used to measure physical effort, they all vary in accuracy and sensitivity. This study is an addition to the numerous ergonomic studies that have been carried out over the years to quantify forceful exertions. Compared to other indirect exposure measurement methods, this technique is more comparable to direct force measurement methods for certain No Brace conditions. This force measurement method is appropriate for tasks that do not incorporate bracing body parts and will provide the ergonomist with an objective force estimate, accurate measurements for certain tasks such as the Drilling, Pushing, and Fastener Tasks, and provide detailed information about the force exposure (e.g., direction of force exertion) compared to tasks that include Bracing, low force requirement (Electrical Connector Task), or repetitive movements (Hose and Weather-strip Tasks). Brudorf et al (1992) stated that the level of accuracy and precision decreases when using subjective based measurements. Furthermore, this force measurement method is unique to other indirect methods as it can provide the ergonomist with an estimate of the forces being damped by muscles, soft tissues, and joints throughout the body, which can offer valuable information regarding the association between forceful exertions and musculoskeletal disorders that can be further studied using this technique.

6.1 Recommendations for Future Work

Future research could concentrate on investigating a minimum acceptable force requirement to for this method to be used. This could allow ergonomists to directly measure physical hand efforts for tasks that require high forceful exertions. Such a study could be able to
provide an accurate hand force cut-off that would lead investigators to research more advanced and feasible methods of comparing forces at the hands and GRF. An example could be a smart wearable shoe that is able to track the forces being transferred to the feet from the hands, which would ultimately benefit the ergonomist working at a dynamic manufacturing industry where force plates can be considered a hurdle to implement.

Another future study can investigate more into tasks that required wiggly motions and repetitive movements along with an EMG system. The EMG sensors can be placed on certain muscles of the arms and lower back expected to dampen the forces transferred through the body. This study will give us an understanding of which muscles carry more force load and is at a higher risk of fatiguing and possible injury. Additionally, as mentioned in the discussion section, tasks that needed movement in different axes resulted in a higher RMSE than those completed steadily, which can be investigated through the usage of EMG. This could clarify how the forces taken into the body are dispersed into different muscle groups and explain the difference between wiggly tasks and tasks that are completed in a steady motion.
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