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Author(s): Wantuck, Rebecca Kellan

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Assessment of Potential Ergonomic Injury Risk in the Nuclear Material Processing Glovebox Environment

by

Rebecca Wantuck

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Assessment of Potential Ergonomic Injury Risk in the Nuclear Material Processing Glovebox Environment

Abstract

Gloveboxes are isolation barriers that are used within many different industries such as pharmaceuticals, electronic parts fabrication, nuclear, and biological. The research on glovebox ergonomics is currently limited with few ergonomic professionals that focusing exclusively on glovebox working environments. There is existing documentation on occupational injuries, such as musculoskeletal disorders (MSD), sustained as a direct result of working in gloveboxes. The main elements that pose ergonomic risks to glovebox workers are operational repetition, duration, force, vibration, lifting heavy (more than 15lbs with two hands) objects, and awkward postures. This paper examines a small sample of the potential causal or risk factors that lead to the ergonomic injuries. A meta-analysis utilizing a random effect model is used to examine data from several studies which focus on, dexterity and strength changes as result of glove thickness, and robotic assistive technology as a means to improve postural mechanics. With the meta-analysis technique, similar data sets from different research studies can be coalesced into a single weighted, statistically significant result for subsequent consideration. The results from the analysis show that increased glove thickness results in decreased dexterity for operators thus increasing ergonomic risk factors such as task duration. It is also shown that glove thickness decreases grip strength but a similar decrease in pinch strength is not definitively demonstrated. With decreased grip strength, operators will need to exert more force (a known ergonomic risk factor) on processing tools, etc. during operations thus increasing the risk of ergonomic injury. The use of robotic assistive technology as a means to improve operator posture (risk factor) was also examined. Although it may be intuitively assumed that human-robotic collaboration would be beneficial in reducing risk factors, the result from this study's analysis was not statistically significant. It is inferred that with additional directed research on this topic another study/analysis could be statistically significant demonstrating the benefits of the technology.

Keywords: dexterity, robotic assistive technology, ergonomics, meta-analysis, human factors, glovebox, MSD, posture, force

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Chapter I

Introduction

Significance of the Study

Gloveboxes are sealed boxes in which a person can manipulate items that require different atmospheres or specific environments. These boxes are typically designed with windows so the operator may see within the box and with either round or oval ports with attached gloves, that allow an operator to access the interior of the glovebox without breaking containment. Gloveboxes are designed and built in a variety of sizes and configurations to accommodate different process/manufacturing requirements. Gloveboxes are used in many industrial manufacturing environments including nuclear, semiconductor, pharmaceutical, and biochemical. Each of these industries present with different requirements for the box design and environment. Nuclear material processing gloveboxes represent a special class of gloveboxes that are designed to isolate the operator/worker from both the hazardous material being handled and the radiation hazards inherent to the material. Figure 1 depicts a nuclear material glovebox line found at Los Alamos National Laboratory. Nuclear gloveboxes are made from thick radiation blocking, corrosion resistant metal (i.e., stainless steel) and contain a limited number of reduced sized, lead infused windows to provide enhanced radiological protection for the workers utilizing the boxes.

Figure 1

LANL Gloveboxes

Note. Courtesy of Los Alamos National Laboratory

Current literature regarding Human Factors and Ergonomic (HF/E) for nuclear processing glovebox environments is quite limited. The majority of the research occurs at Los Alamos National Laboratory (LANL) as there are a large and growing number of gloveboxes utilized and planned for the site, in response to a significant growth in nuclear material programmatic/processing demands. There are a number of concerns regarding the HF/E aspects of a nuclear material glovebox, which include their lack of adjustability, requirement of the workers to perform gross motor and micro tasks within the boxes, and a potential risk for the development of an occupational injury. The growth in nuclear processing work at LANL has prompted an enhanced recognition of the detrimental impact of ergonomic injuries for the specialized workforce involved in these operations, and the need to better understand the underlying factors associated with such injuries.

Statement of the Problem

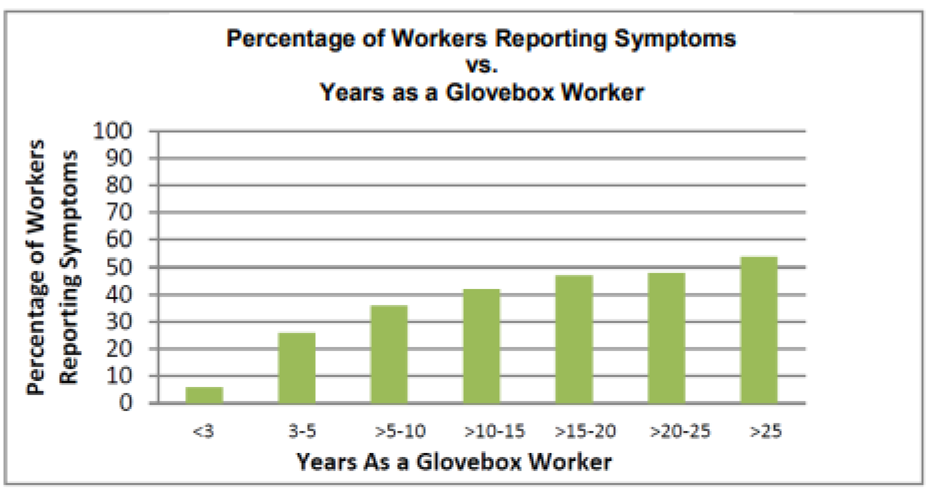
According to the Bureau of Labor Statistics (2020), there were over 300,000 worker compensation cases due to overexertion and bodily reaction, repetitive motions involving microtasks, and other exertions or bodily reactions. This statistic includes injuries that would qualify as musculoskeletal disorders (MSD) which occur over a longer period of time and increase in likelihood with the prevalence of certain risk factors. These risk factors are often separated into seven factors; repetitive tasks, long durations, awkward postures, vibration, force, environment and individual susceptibility, some sources also cite emotional stress as a contributing factor in MSD development (CSU, 2023). The risk factors represent a primary focus element of this research study, specifically, duration, force, and improper postural mechanics. The extent that these risk factors influence potential ergonomic injuries for workers involved in nuclear material processing at LANL (see Figure 2 which illustrates the historical extent of ergonomic symptoms experienced by operators at LANL as a function of years as a glovebox worker) is important to understand as it serves as guidance for possible improvement actions. Such improvements could involve equipment modifications, process revisions, changes in training, and other relevant actions.

At LANL the glovebox glove represents a key component of the manufacturing process as the gloves allow glovebox workers to directly contact the nuclear material and associated processing hardware/systems. To ensure chemical compatibility, structural integrity, and radiation protection, the gloves are usually multi-layer and often lead-lined. The effect of such properties typically results in gloves with reduced dexterity, which can translate to increased task completion time, along with the need to exert increased forces on tools and equipment utilized for material processing in the gloveboxes. It is important to quantify glove dexterity loss on process time and increased force requirements for tool operation to assess the potential risk for ergonomic injuries and MSDs.

Robotic systems have become an important facet of current manufacturing strategy and process improvement. As a complement to the dexterity and force analysis discussed above, this research effort also seeks to quantify the impact of human-robot collaboration in the nuclear material glovebox environment. The analysis will assess the risk level for ergonomic injuries following incorporation of robotic assistive technology to influence proper technique by glovebox workers, i.e., correct postural mechanics, etc., while performing their tasks.

Figure 2

Percentage of Workers Reporting Symptoms vs. Years as a Glovebox Worker



Note. Glovebox worker survey results indicating the increased prevalence of symptom reporting with years of glovebox work experience (Lawton, 2013)

Purpose Statement

The purpose of this research is to assess the potential risk of ergonomic injuries and MSDs to operators working in the glovebox environment associated with nuclear material processing and manufacturing predominantly at Los Alamos National Laboratory. This paper will focus on examining hand dexterity effects as well as strength requirements associated with the use of specialized glovebox gloves and the use of robotic assist to determine if there is a statistically significant reduction or increase in occupational injury risk. The need to reduce the ergonomic injury risk to the specialized, highly-trained workforce associated with nuclear material processing and manufacturing demonstrates the need for this paper.

Research Questions and Hypothesis

There are two questions that will be answered by this research paper:

1. Will improvements to glove design with considerations for increased dexterity and reduced strength requirements help to lower the risk of ergonomic injuries and MSDs in glovebox workers?
2. Is there a benefit to introducing robotic assistive technology into the nuclear material processing glovebox environment to reduce the risk of ergonomic injuries and/or improving human factors?

This paper will examine two elements of the nuclear material/processing glovebox system. The first element is the weakest part of the system, namely, the glovebox glove. Both dexterity, as it relates to time needed to complete several tasks, and strength (i.e., force) of the hands/fingers needed to execute gripping and pinching actions will be examined with a focus on studies that are specific to nuclear material glovebox gloves. The second element investigated is the utilization of assistive robotic technology as a means to improve the mechanics of worker positioning to reduce the potential risk of ergonomic injury. Studies that utilize robotic assistive technology in a manner applicable to the glovebox environment will be examined. The hypotheses for this research paper are as follows:

Regarding the assessment of glovebox glove strength dexterity and strength impacting the risk of ergonomic injury and MSDs to operators/workers:

H_A: There is a statistically significant difference between occupational injury risk occurring in workers who have improved strength and dexterity and those who do not.

H_0: There is no statistically significant difference between occupational injury risk occurring in workers who have improved strength and dexterity and those who do not.

Regarding the assessment of the utilization of robotic assist technology in a manner applicable to the glovebox environment:

H_A: There is a statistically significant difference between the risk of occupational injuries occurring in workers who do not utilize robotic assistive technologies compared against workers who do.

H_0: There is no statistically significant difference between the risk of occupational injuries occurring in workers who do not utilize robotic assistive technologies compared against workers who do.

This research will examine if the elements examined have an impact on the risk of ergonomic injuries occurring to glovebox system operators and potentially support efforts to improve glovebox components and overall system design. The methodology for this study utilizes a meta-analysis with a random effects model to analyze data obtained from similar studies to generate a statistically significant result.

Delimitations

Although gloveboxes are utilized in several industries, including semiconductor manufacturing, bioscience research applications, and pharmaceutical development, this study focused on the ergonomic issues inherent to gloveboxes and glovebox components (e.g., gloves) associated with nuclear material processing. There are multiple identified risk factors for ergonomic injuries and MSDs. This study limited its analysis to three such factors including dexterity as it relates to glove box gloves, and its impact on time to complete tasks (a risk factor) as well as the influence of gloves on grip strength and pinch strength, both which translate to the force required (another risk factor) to manipulate tools/hardware. In addition, robotic assist was investigated/analyzed as a method to potentially improve the risk factor associated with poor postural and body mechanics. Finally, considering glovebox hardware, only glovebox gloves were examined from an ergonomic perspective (certainly one if not the most critical components) and no other glovebox components, for example windows or glovebox port designs.

Limitations and Assumptions

The field of glovebox ergonomics, particularly for the nuclear material processing realm, is still relatively young and as a result the number of relevant, peer reviewed papers, studies, and research results is relatively few. As a result, an analysis may be based on a small data set which can drive uncertainty and/or the statistical validity of the results. In general, studies that were selected for analysis was based on their shared commonalities and direct connection to gloveboxes. For the robotic assist analysis, however, the studies themselves were similar in nature but a direct connection to gloveboxes was absent. Nevertheless, an assumption was made that for the actual studies chosen for analysis, applicability to glovebox operations was appropriate.

List of Acronyms

AGS	American Glovebox Society
ALARA	As Low as Reasonably Achievable
MSD	Musculoskeletal Disorders
HF/E	Human Factors and Ergonomics
LANL	Los Alamos National Laboratory
CSM	Chlorosulphonated Polyethylene

Chapter II

Review of the Relevant Literature

The American Glovebox Society (AGS) defines a glovebox as "a controlled environment work enclosure providing a primary barrier from the work area. Operations are performed through sealed gloved openings to protect the worker, the ambient environment, and/or the product" (AGS, 2007). Gloveboxes are essential to several industries including the pharmaceutical, nuclear, semi-conductor, and biochemical industries. The gloveboxes are important elements to protect the workers from direct interaction with the substances housed in these boxes, however, working within the boxes also exposes the workers to ergonomic risk factors. The main ergonomic hazards are repetitive motions, duration, force, lifting heavy objects, awkward postures, and vibration. These risk factors increase the likelihood of developing a musculoskeletal disorder.

Human factors and Ergonomics are terms used to describe the utilization of multiple disciplines such as, psychology, sociology, engineering, anthropometry, industrial designs, visual design, user experience, user interface design, and physiology, to influence designs of workspaces, human-machine interfaces, work environments, and tools. HF/E applications seek to improve effectiveness, efficiency, safety, and reduce risk of injury in workplace environments (Nachreiner et al., 2006).

Nuclear Material Processing Environments- Gloveboxes

Gloveboxes are *absolute barriers* and because of this are used in operations involving plutonium and other nuclear materials. Gloveboxes used for work with radioactive material are maintained at a lower pressure than that of the exterior atmosphere to protect against any microscopic leaks and possible contamination of the external surroundings (Castro et al., 2017). In nuclear material processing environments, the gloveboxes are constructed from thick stainless steel and have windows that are lead-infused or utilize transparent lead shielding to protect the workers from the radiation emission. When discussing the structural integrity of gloveboxes, the gloves remain the weakest part of the safety envelope as they are more susceptible to failure, punctures, chemical exposures, etc. (Castro et al., 2017).

Gloves used at LANL in the plutonium facility are made from different types of material with the most common being Chlorosulphonated Polyethylene (CSM). Some of the CSM gloves also contain an inner lead oxide layer to help with radiation protection. The gloves come in 15mil (0.4mm) and 30 mil (0.8mm) thicknesses, the lead-lined CSM gloves also come in a thickness of 30mil (Castro et al., 2017). Nuclear processing facilities are designed to account for ALARA which stands for “as low as reasonably achievable”. ALARA is a mitigation technique that is practiced by all workers in radiological environments to take measures to reduce time spent exposed to radiation. In processing environments where gramma and X-ray radiation is significant operators are required to wear lead-lined glovebox gloves as the gamma and X-rays easily penetrates through non-leaded gloves (Castro et al., 2017).

Musculoskeletal Disorders

According to the U.S. Bureau of Labor Statistics, in 2011 there were over 300,000 cases reported involving an MSD (2020). MSDs are a result of cumulative and chronic injuries to the tendons, ligaments, muscles, joints, discs, and nerves that are aggravated and/or caused by human activity and actions within an environment that does not promote HF/E principles. MSD’s are the cause of over 500 million physician visits, over 300 million visits to non-physician health professionals, close to 400 million home health visits, and 21 million hospital visits (Yelin et al., 2016). MSD's are the most common injuries seen in association with poor ergonomics. With intervention, most MSDs are treatable, and workers will recover full bodily function but if they go unchecked, they can easily lead to a diagnosis requiring further intervention including surgery.

In 2013 a symptom survey was conducted of the LANL glovebox workforce. It was found that the frequency of reporting symptoms increased with years working in gloveboxes, see Figure 2 for additional clarity (Lawton). Over 50% of glovebox workers experienced symptoms after 25 years of working (Lawton, 2013). At LANL the time spent in the glovebox varies with task requirements, however, some workers may be working for more than 3 hours a day in gloves (Christman, 2016).

Working in gloveboxes requires both fine and gross motor skills which are made even more rigorous when wearing gloves. Glovebox work requires operators to work with tools such as Allen wrenches, screwdrivers, chisels, pipettes, hammers, etc. All such tools are used while the operator wears glovebox gloves with a range in thickness, the most common being 15mil (0.4mm), 30mil (0.8mm), and 30mil (lead-lined). Castro et al., states that the likelihood of ergonomic injuries increases as the amount of programmatic work being performed increases. In addition, tasks become more difficult to perform with the increase in glove thickness (2017).

Dexterity

Dexterity is the demonstration of agility and skill while performing tasks and is often used in reference to hand movement. Having limited or reduced dexterity due to wearing gloves can lead to increased task time, fatigue, and risk for MSD type injury. In the nuclear material processing environment glove usage is important to the overall safety of the worker, however, it is important to understand if the thickness increase and/or glove type will lead to an increased risk of occupational injuries. Studies conducted by Cournoyer et al (2009), Wantuck (2019), Sung (2014), and Castro et al (2017), all discuss the results of dexterity and/or strength loss as glovebox glove thickness increases.

Robotic Assistive Technology

Robotic assistive technology, otherwise referred to as human-robot collaboration is increasing in prevalence especially in industrial settings. Robotics in industrial settings are often used to increase production rates and have been used to replace humans in tasks that are physically intensive or dangerous (Gihleb et al., 2020). In the context of HF/E, robotic devices are used with the intention to reduce MSD or occupational injury risk to workers. As discussed in Brinkmann's et al. (2022) paper, collaborative robots are utilized to reduce the prevalence of MSD's in the nursing population as manual patient handling is one of the most significant causes of MSD's. Brinkmann et al (2022) looked at two distinct movement patterns exhibited by nurses during patient handling. It was found that highly asymmetric postures had extreme levels of lower spin and limb exertion but with the use of robotic collaborative technology reduced the exertion by 51%. El Makrini et al. (2022) and Xie et al., (2022) both utilized accepted ergonomic assessment techniques to determine optimal postural improvements with the use of assistive robotic technology. These adjustments reduced the assessment scores which indicates an improvement in the operation and reduction of injury risk. Robotics utilization in glovebox environments as a method to reduce ergonomic risk factors and therefore MSDs is still in a largely research phase. A study proposal by Ghosh et al. (2020) cites that robotic enhancement in gloveboxes has the potential to increase safety and reliability. They propose using a robotic manipulator inside of the box which is being remotely controlled by operators outside of the box would increase productivity (Ghosh et al, 2020). A concern with utilizing robots is the increase in cognitive load on operators which increases overall fatigue and possibility of errors occurring. This paper by Ghosh et al. (2020) focus on the development of the system to improve operator perception and decrease fatigue. Ultimately the assumption is that with human-robot collaboration the risk of ergonomic injuries decreases, and the processing becomes easier for operators.

Summary

This review of literature demonstrates the limited amount of published research regarding ergonomic risk factors in the nuclear material processing glovebox environments. The elements examined for this research paper are dexterity and/or strength loss as glove thickness increases and the utilization of robotic assistive technology as a means to improve postures. These elements were chosen to be further examined as they have direct correlation to MSD prevention or development via reduction of the ergonomic risk factors, force, duration, and posture.

Chapter III

Methodology

Research Approach

This study utilizes meta-analysis of quantitative data sets gathered from applicable research literature. This paper examines several studies that focus on one of the two improvement topics, 1) hand/finger dexterity and gloves composition, and 2) assistive robotic technology. These studies were conducted to examine the effects of each focus/improvement topic as it correlates to reduced occupational injuries. To assess the viability of each improvement topic, a meta-analysis of the resulting data is performed for each of the two focus areas to determine if the suggested improvements are significant and feasible. Within each study a key metric, such as grip strength, was combined with other studies with similar methodological approaches. The meta-analysis utilizes a random-effects model which takes into account the heterogeneity of the studies as the studies themselves vary in terms of environment, element, factors of use, etc. Each of the studies are analyzed according to the factors mentioned above, however, studies that do not manifest to potential occupational injuries such as MSD's were not considered.

Design and Procedures

A meta-analysis of each focus area was performed to merge findings from several studies that had similar dependent variables. A Q statistical method was used to determine the total variance and to calculate the "absolute" effect, i.e., the overall effect that allows an assessment of the efficacy of the various study results to answer the improvement questions. This absolute effect was determined by calculating a weighted average of the effect size of the individual studies. Each study was given a weight that is inversely proportional to the variance in the study. As it cannot be assumed that there is only one effect in the studies evaluated (due to the variety and niche elements involved), a random-effects model was used for analysis. The random effects model accounts for differences in the included studies by considering both the variance inherent to the study itself as well as the variance between all the various studies to determine the weights. With a fixed effect model, studies that are larger in size will be given more weight than that of a smaller study. By including an extra weight factor that accounts for the variance between studies, small studies are less likely to be overshadowed by large studies. With this approach, the effect sizes in the studies will represent a random sample of the possible effect sizes.

The objective of the meta-analysis of the selected research studies is to answer the following questions with consideration of the associated alternative (H_A) and null hypothesis (H_0):

1. Will improvements to glove design with considerations for increased dexterity and reduced strength requirements help to lower the risk of ergonomic injuries and MSDs in glovebox workers?

HA: There is a statistically significant difference between occupational injury risk occurring in workers who have improved strength and dexterity and those who do not.

H0: There is no statistically significant difference between occupational injury risk occurring in workers who have improved strength and dexterity and those who do not.

2. Is there a benefit to introducing robotic assistive technology into the nuclear material processing glovebox environment to reduce the risk of ergonomic injuries and/or improve human factors?

H_A: There is a statistically significant difference between the risk of occupational injuries occurring in workers who do not utilize robotic assistive technologies compared against workers who do.

H_0: There is no statistically significant difference between the risk of occupational injuries occurring in workers who do not utilize robotic assistive technologies compared against workers who do.

This effort synthesized the findings of peer-reviewed studies to demonstrate if there is statistically significant correlation between occupational injury reduction and the implementation of robotic assistive technology and, improved dexterity and strength as applied to glovebox gloves.

Sources of the Data (Selection Criteria)/ Materials

The data sources for this research paper are a collection of peer-reviewed scientific literature articles and conference proceedings that focus on one of the two improved topics. The studies were selected if they demonstrate quantitative correlation with the implementation of assistive robotic technology and/or with improved dexterity to reduced musculoskeletal disorders. Xie et al. used proven ergonomic assessment tools such as the Rapid Upper Limb Assessment (RULA) to demonstrate the need for accounting for human postures when utilizing robots to decrease MSD risks (2022). El Makrini, et al, proposed a novel framework for posture optimization during human-robot collaborative tasks that seeks to avoid poor postural positioning thereby reducing MSD risk (2022). A Rapid Entire Body Assessment method (REBA) scoring was employed to provide postural analysis (similar to the RULA methodology employed by Xie et al).

Methods to improve dexterity are provided in three relevant studies. Sung examined the effects of utilizing glovebox gloves on grip and key pinch strength while utilizing a variety of tools (2014). This study demonstrates how a reduction in strength leads to increased ergonomic risk factors which can lead to MSD development. Cournoyer et al, demonstrated how dexterity and strength decreased with increased thickness of glovebox gloves which in turn leads to increased ergonomic risk factors and thus MSD development (2009). Wantuck, looked at the usage of overgloves in conjunction with different thicknesses of glovebox gloves demonstrating a decrease in dexterity and grip and key pinch strength (2019). The studies chosen for the meta-analysis were intended to be as homogenous as possible (and show a direct correlation to the improvement path for decreasing MSDs and occupational injuries), however, using the random-effect model accounted for any remaining heterogeneity.

Validity

Validation of the meta-analysis results is determined by examining the studies and using the "leave one out cross validation" technique. The leave one out cross validation technique is designed to take the studies that are part of the statistical tests, remove one study at a time, and then re-run the test with the remaining study data to see if the outcome changes.

Treatment of the Data

The data for the meta-analyses is pulled directly from the peer reviewed studies and conference proceedings, including variance metrics. The paper by Borenstein, et al, provides a thorough description of the meta-analysis technique with its the underlying statistical processes, including a description of the random effects model (2007). Utilizing a Microsoft Excel program, the effect size, variance, standard error, 95% confidence intervals, Z-value, and P-values are calculated for the chosen data sets. The observed effect size (T) is determined from the true effect (θ) and the within-study error (ε). The true effect is equal to the mean of all true effects (μ) and the between-study error (ζ). Equation 1 shows how the total observed effect size is calculated.

$$T = \theta + \varepsilon = (\mu + \zeta) + \varepsilon \qquad (1)$$

To use the random effects model, it is necessary to differentiate the variance due to within-study error and variance from the between-study error. Starting with the Total Variance (Q), it is possible to break the variance into its two parts. Equation 2 shows how Q is calculated.

$$Q = \sum_{i=1}^{k} w_i (T_i - \bar{T})^2 \qquad (2)$$

In equation 2, w_i represents the inverse of each study's variance, T_i represents the sum of squared deviations from each study, and $\bar{T}$ represents the combined mean of the studies. Knowing Q, the between-studies variance (τ^2) is calculated via equations 3-5, which includes the degrees of freedom for the meta-analysis (df), and a scaling factor C.

$$\tau^2 = \begin{cases} \frac{Q-df}{C} \; if \; Q > df \\ 0 \; if \; Q \leq df \end{cases} \qquad (3)$$

$$df = \#\, of\ Studies - 1 \qquad (4)$$

$$C = \sum w_i - \frac{\sum w_i^2}{\sum w_i} \qquad (5)$$

The previous equations only consider within-studies variance when calculating the weight factors W_i. To determine a weighted mean that considers both sources of variance (within and between), similar notation will be used, however a star (*) will be added to denote the random effects version of the metrics. Equations 6 and 7 shows how the random effects version of the inverse variance is calculated.

$$w_i^* = \frac{1}{v_i^*} \quad (6)$$

$$v_i^* = v_i + \tau^2 \quad (7)$$

The weighted mean is then calculated using Equation 8.

$$\bar{T}^* = \frac{\sum w_i^* T_i}{\sum w_i^*} \quad (8)$$

Chapter IV

Results and Discussion of Results

Results

The data analyzed for this research study was broken into four separate categories, namely, dexterity, grip strength, pinch strength, and robotics collaboration/assist. The subsequent evaluation of these data sets was performed using a meta-analysis approach, which represents an accepted and well-suited statistical technique for combining and analyzing data from several distinct studies. The dexterity section examined the amount of time required to complete specific tasks as a function of increasing glove thickness. More specifically, the data utilized was gathered from two studies, Cournoyer et al (2009) and Wantuck (2019). Both of these studies utilized the well accepted Minnesota Dexterity Test (which measures gross motor dexterity) and the Bennett Board Dexterity Test (which measures proficiency using ordinary mechanical tools) to generate their data sets. The grip strength studies assessed the decrease amount of force that needs to be applied in response to increased thickness of glovebox gloves. Grip strength data points were divided by different types of glovebox glove materials and were taken from three studies, Sung (2014), Cournoyer et al (2009), and Wantuck (2019). The pinch strength studies examined the same effects as the grip strength investigation as a function of glove thickness but with an altered grip style and different instrumentation. For this analysis, the three aforementioned studies (Sung, 2014, Cournoyer et al., 2009, and Wantuck, 2019) provided the data sets. The robotics analysis utilized data from two studies, namely, (Xie et al. (2022) and El Makrini et al. (2022). Xie et al, generated scoring results from a Rapid Upper Limb Assessment (RULA) ergonomic assessment technique while El Markini et al., used the Rapid Entire Body Assessment (REBA) ergonomic assessment technique to ascertain the effects of the implementation of robotic assistive technology. In general, for both ergonomic assessment techniques, lower scores represent a favorable outcome as they translate to reduced MSD occurrences.

Dexterity Meta Analysis

The Minnesota Dexterity Test is a validated test utilized in many industry settings to measure gross motor dexterity and simple rapid eye-hand-finger movements (Cournoyer et al, 2019). The apparatus associated with the Minnesota Dexterity Test is shown in Figure 4 (Note the discs and board with disc slots). The complete Minnesota Dexterity Test consists of five different tests. however, for commonality with the research papers of Cournoyer et al. (2009) and Wantuck (2019), only the turning (both hands) and one-handed turning tests were utilized. The turning test requires the discs to be pre-set in the board slots. The study participant is then is instructed to pick up the disc with their left hand, turn the disc while passing to their right hand and then replace it in the original slot. This test is timed from the moment they touch the first disc to when they place the last disc. The single hand-turning test requires the participant to pick up the disc with their dominant hand, turn it in that hand, and then replace it in the original slot.

In addition to the Minnesota Dexterity Tests, Wantuck (2019) utilized the Bennett Board Dexterity Test to assess dexterity degradation when using different thicknesses of gloves. The apparatus associated with this test is shown in Figure 5. The Bennett Board measures gross motor dexterity by examining proficiency using ordinary mechanical tools such as an adjustable wrench and Phillip's or flathead screwdrivers. The Bennett board measures the time taken to transfer a screw or bolt, washer and nut from one side of the board to the other. The full Bennett Board Test utilizes several sets of a screw or bolt, washer and nut all preset on one side of the board. Wantuck modified this test to use one size of each set (2019). The Bennett board test was conducted with participants using the 0.8mm lead lined glovebox glove alone and with the overglove. The average effect is the difference between the 0.8mm lead lined glove and the addition of the overglove.

Cournoyer et al, (2009) and Wantuck (2019) measured the turning and one-handed turning tests in seconds to determine the time necessary to complete the specific motion associated tasks as a function of increasing glove thickness. The Dexterity Meta-Analysis examined the effect on task time with increase in glove thickness during specific dexterity tasks across the various applicable studies to generate a synthesized result. Cournoyer et al. (2009) had participants execute the one-hand turning test with three different Hypalon glovebox glove thicknesses, 0.4mm, 0.8mm, and 0.8mm lead lined. The data point defined for the *one-handed turning tests* average effect size is the difference of the mean for the 0.4mm to 0.8mm lead lined gloves data set. This same method was utilized to define the effect size for the *turning* test conducted by Cournoyer et al. for the 0.4mm to 0.8mm lead lined gloves (2009). Wantuck (2019) had participants execute the *one-hand turning test* and the *turning test* with 0.8mm lead lined CSM/Hypalon glovebox gloves alone and paired with Westchester leather cut, puncture resistant overgloves. The average effect for both the one-hand turning and the turning tests is the difference of the 0.8mm lead lined glove alone and with the addition of the overgloves. Table 1 shows the average effect size and variance associated with these studies as well as the results of the meta-analysis utilizing the statistics formality presented in the Methodology section and as described by Borenstein et al. (2007). Figure 3 shows the graphical representation of the effect size and within-study standard error of each study.

This Dexterity results meta-analysis exhibited large within-study variances relative to the between-study variances. The Q statistic metric described by Equation 2 was not larger than the degrees of freedom (df), therefore utilizing Equation 3, the between-studies variance, τ^2 is 0. The final weighted mean, calculated using Equation 8, shows that with an increase in glove thickness there was an average increase of 40.42 seconds to complete the dexterity tasks. The p-value indicated that the dexterity meta-analysis is statistically significant at the 5% significance level. While it is shown with high probability that glove thickness increases task time, the calculated confidence intervals for this analysis also show that the total variance is high; there is a 95% probability that the average task time improvement is between 11.85 and 69.06 seconds. The null hypothesis stated that there is no statistically significant difference between occupational injuries occurring in workers who have improved strength and dexterity and those who do not. The Dexterity meta-analysis shows that with decreased thickness the workers will spend less time completing a task and exhibit increased dexterity. These conditions decreases the HF/E risk factors of duration and force thus in turn decreasing the risk of developing an occupational injury or other MSDs. As a means of assessing validity of these results a “leave one out” cross validation was performed. This exercise shows overall average effect sizes ranging from 37.93 to 47.13 and p-values from 0.005 to 0.015 which substantiate the validity of the process and the accompanying results, confirming the hypothesis as well for all cases.

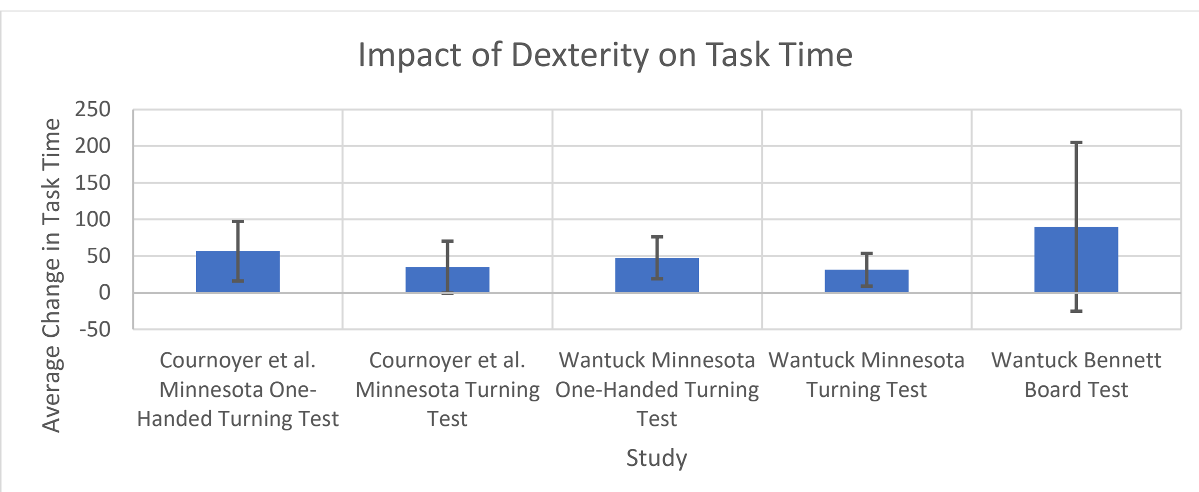
Table 1

Dexterity Meta-Analysis - Effect on Task Time

Dexterity Meta-Analysis – Effect on Task Time		
Study	**Effect Size (Seconds)**	**Variance**
Cournoyer et al. Minnesota One-Handed Turning Test	56.7	1653.6
Cournoyer et al. Minnesota Turning Test	35.0	1256.3
Wantuck Minnesota One-Handed Turning Test	47.7	820.5
Wantuck Minnesota Turning Test	31.5	500.1
Wantuck Bennett Board Test	90.0	13250.9
Q	1.24	
τ^2	0	
Weighted Average	40.45 seconds	
p-value	0.006	

Figure 3

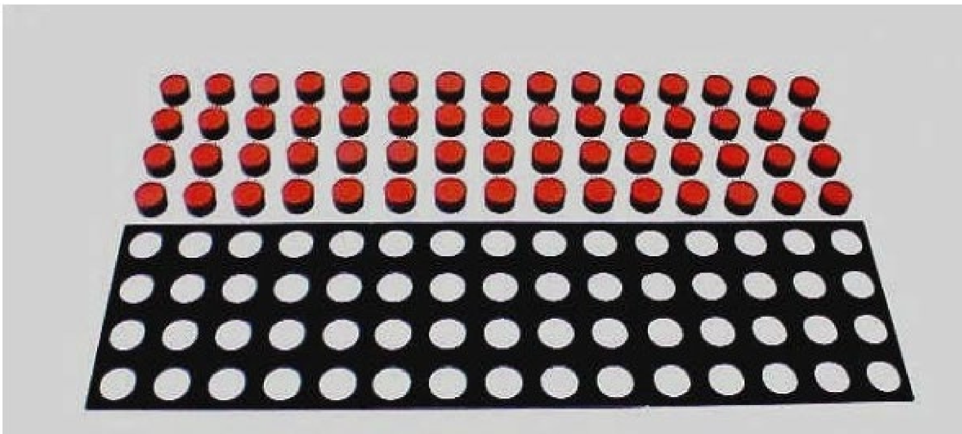
Impact of Dexterity on Task Time Meta-Analysis



Note. The in average change in task time for each study element. The error bars shown represent the standard error.

Figure 4

Minnesota Dexterity Test board



Note. Minnesota Dexterity Test Board set up with discs and board with slots (Lafayette Instrument, 1998)

Figure 5

Bennett Board Dexterity Test

Note. Bennett Board Dexterity Test with tools and bolts, nuts and washers (Wantuck, 2019)

Grip Strength Meta Analysis

The effect of increasing glove thickness on grip strength was studied by several researchers and their results serve as the data source for the next meta-analysis treatment. Sung (2014) examined grip strength variation using gloves fabricated from Butyl, Neoprene, and CSM/Hypalon in two different thicknesses, 15mil (0.4mm) and 30mil (0.8mm). Sung performed his study using these aforementioned glove types in a single (glove only), double (0.040 mm thick natural rubber glove as the inner glove), and triple (natural rubber glove plus 0.020 mm thick cotton glove serving as inner gloves) configuration (2014). The study participant's grip strength for gloved and bare hands, was then measured using a Jamar hydraulic hand dynamometer. The average effect size for Sung's study is the mean force (in kg) difference between the 15mil (0.4mm) single layer results and the 30mil (0.8mm) triple layer gloves (2014). Cournoyer et al. (2009) used a Jamar hydraulic hand dynamometer to collect the grip strength measurements for study participants wearing 0.4mm, 0.8mm, and 0.8mm lead lined gloves. The effect size is the average (mean) force difference (in kg) measured between the 0.4mm and 0.8mm lead lined gloves. Wantuck (2019) also used the Jamar dynamometer to collect the grip strength. The effect size for this study is the average (mean) force difference (in kg) between the 30mil lead-lined glovebox glove and the 30mil lead-lined glove plus the overglove. Table 2 shows the average effect and variance of these studies as well as the results of the meta-analysis. Figure 6 shows a graphical representation of the individual study results with error bars representing the standard error.

This meta-analysis results exhibited large within-study variances relative to the between-study variances. The Q statistic metric (Eq. 2) was not larger than the degrees of freedom, therefore the between studies variance, τ^2, was set to 0 (see Eq.3). The overall weighted mean shows that an increase in glove thickness results in a 6.4 kg decrease in grip strength, i.e., force. The p-value indicated that this Grip Strength meta-analysis is statistically significant at the 5% significance level. The confidence intervals for this analysis shows that there is a 95% probability that the average decrease in grip strength is between 4.39 and 8.36 kgs. The null hypothesis stated that there is no statistically significant difference between occupational injuries occurring in workers who have improved strength and dexterity and those who do not. The meta-analysis shows that with increased glove thickness the workers will experience a decrease in their grip strength which likely causes them to spend more time completing a task. In addition, the workers may attempt to compensate for the force reduction by applying additional force to the object, thus increasing their fatigue levels. The decrease in force and concomitant increase in time spent completing a task increases the HF/E risk factors of duration and force, thus increasing risk of occupational injuries or MSD development. As a means of assessing the validity of the results a "leave one out" cross validation calculation was performed. This calculated generate overall average effect sizes ranging from 5.92 to 6.91 and p-values from $1.19E^{-06}$ to $5.77E^{-10}$. This result confirms the hypothesis in all cases attests to the validity of the Grip Strength results.

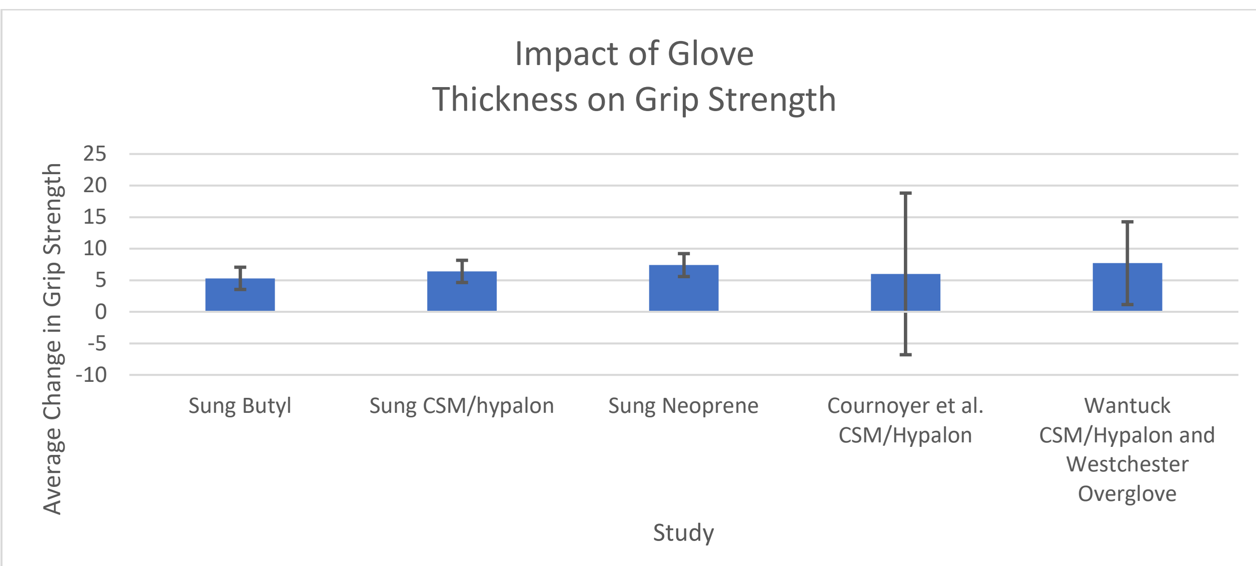
Table 2

Grip Strength Meta-Analysis- Effect on Force

Grip Strength Meta-Analysis – Effect on Force		
Study	**Effect Size (Kg)**	**Variance**
Sung Butyl	5.3	3.1
Sung CSM/Hypalon	6.4	3.1
Sung Neoprene	7.4	3.3
Cournoyer et al. CSM/Hypalon	6	164
Wantuck CSM/Hypalon and Westchester Overglove	7.7	43
Q	0.8	
τ^2	0	
Weighted Average	6.4 kg	
p-value	$3x10^{-10}$	

Figure 6

Impact of Glove Thickness on Grip Strength Meta-Analysis



Note. The average change in grip strength force for each study element (each using varied glove thicknesses). The error bars shown represent the standard error associated with the study.

Pinch Strength Meta Analysis

Pinch strength loss while wearing gloves of different thicknesses was analyzed using data obtained from the studies of Sung (2014), Cournoyer et al. (2009) and Wantuck (2019). The pinch strength for each of the three studies is measured using the Jamar hydraulic pinch gauge. The average effect and variance of these studies as well as the results of the meta-analysis are provided in Table 3. Figure 7 shows the graphical representation of the individual study results and standard error. The pinch strength study's effect sizes, determined in a manner similar to the grip strength analysis, are relatively small and close in value which suggests a non-contribution of glove thickness to pinch strength loss. The Q statistic metric (Eq. 2) was not larger than the degrees of freedom, therefore the between studies variance, τ^2, was set to 0 (see Eq. 3). The overall weighted mean shows that an increase in glove thickness results in a 0.2 kg decrease in pinch strength loss. The high p-value ($p=0.5$) indicates that the pinch strength meta-analysis is NOT statistically significant. The null hypothesis stated that there is no statistically significant difference between occupational injuries occurring in workers who have improved strength and dexterity and those who do not. As the meta-analysis is not statistically definitive, this hypothesis cannot be proven. A "leave one out" cross validation study affirms the uncertain nature of the analysis and the null hypothesis.

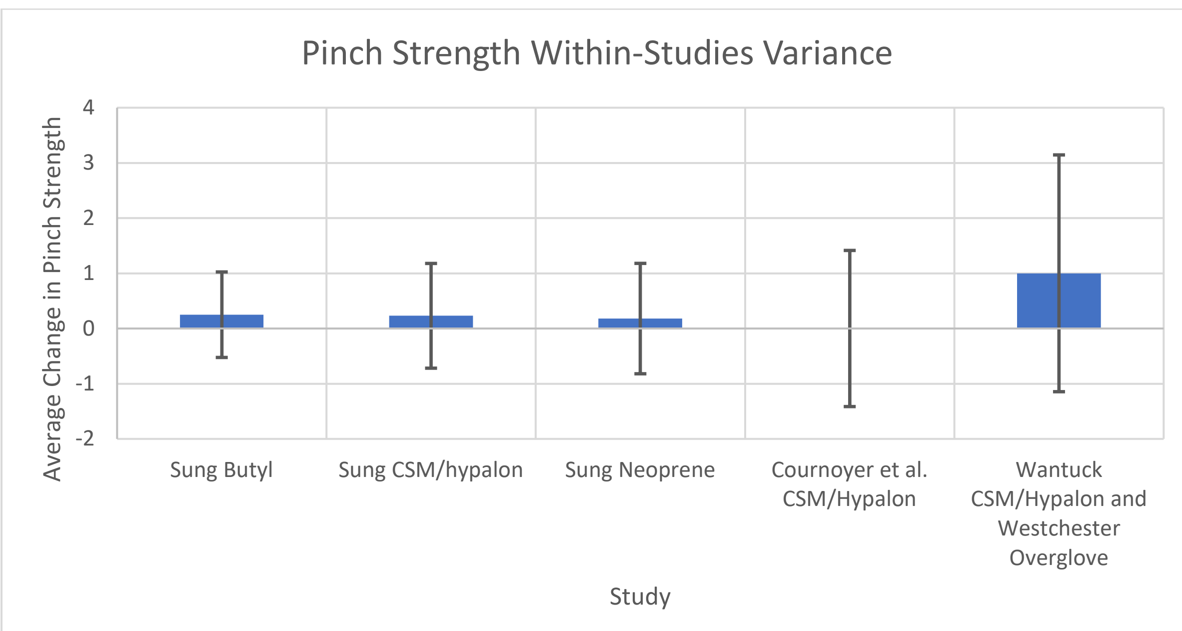
Table 3

Pinch Strength Meta-Analysis- Effect on Force

Pinch Strength Meta-Analysis – Effect on Force		
Study	**Effect Size (Kg)**	**Variance**
Sung Butyl	0.25	0.6
Sung CSM/Hypalon	0.23	0.9
Sung Neoprene	0.18	1
Cournoyer et al. CSM/Hypalon	0	2
Wantuck CSM/Hypalon and Westchester Overglove	1	4.6
Q	0.2	
τ^2	0	
Weighted Average	0.24 kg	
p-value	0.5	

Figure 7

Pinch Strength Within-Studies Variance Meta-Analysis



Note. The average change in Pinch Strength force for each study element. The error bars shown represent the standard error.

Robotic Assistive Technology Meta-Analysis

The robotic assistive technology meta-analysis looked at collaborative robots from a postural analysis and motion perspective to determine how human-robot collaboration can be effective in reducing the risk factors that lead to MSD development. Two recent publications (Xie et al, 2022 and El Makrini et al, 2022) were selected for this study based on their relevance to the research topic and their utilization of documented ergonomic assessment techniques, the Rapid Entire Body Assessment (REBA) and the Rapid Upper Limb Assessment (RULA). These tools are utilized by ergonomists to measure workers' postures and limb movements during work tasks. The REBA allows for a joint analysis of postures of the upper limbs, trunk, neck and lower extremities, consideration is also given to grip type and muscle activity (Hita-Gutiérrez et al., 2020). A score is then given to each body part depending on positioning. These scores are added to determine the ergonomic risk posed to the worker from negligible to very high. The RULA is a very similar assessment but only considers the movements of the upper limbs (wrist, hands, forearm, shoulders), neck, and trunk. Consideration is also given to muscle activation and stability of legs. The RULA scores also determine the ergonomic risks posed to workers. In both cases, a higher score indicates a higher risk factor. Xie et al, examined the risks of MSD development in human-robot collaboration environments (2022). Robots that are pre-programed to operate at a fixed height force workers of varying heights to work in higher ergonomic risk postures. Xie et al, used the RULA to measure the workers postures and then applied the information to a computer vision tool that assesses a worker's posture and adjusts the robot working height to accommodate. The average effect size was taken from the difference in RULA scores with and without the computer vision adjustments. El Makrini et al utilized the REBA during four tasks: "pick up blade", "screw plate", "stack blades", and "hub handover" (2022).

These tasks were completed by the human utilizing a robot in a fixed position. The positions were analyzed using the REBA assessment tool to then generate the fixed position results. The tasks were also completed using human-robot collaboration where the position of the robot adapted to ensure an ergonomic posture for the human. The REBA was used to measure this change in posture for each task. The effect size for each task is the difference between the fixed position and the adapted position scores.

The meta-analysis of the available Human-Robot collaboration studies revealed large between-study variances relative to the within-study variances. Figure 8 shows the graphical representation of the individual study results and standard error. The between studies variance, τ^2, was calculated to be 1.84. The weighted average (1.3) indicates an improvement in the Ergonomic Assessment tool scores. The p-value for this meta-analysis (0.06) is slightly above the 5% significance level (equaling 6%). The null hypothesis for robotic assistive technologies states that there is no statistically significant difference between the number of occupational injuries occurring in workers who do not utilize robotic assistive technologies compared against workers who do. Due to the 6% significance, this meta-analysis cannot reject the null hypothesis. However, the cross-validation results show a large dependence on study selection. When removing either of the two studies that showed no change in score, the weighted average increases to 1.7 with a statistically significant p-value of 0.03. Conversely, the “worst case” cross-validation result showed that the weighted average could be as low as 0.9 with a p-value of 0.24. It is reasonable to state the with additional and appropriate studies the significance level could readily decrease below 5% with an acceptable cross-validation result thereby rejecting the null hypothesis.

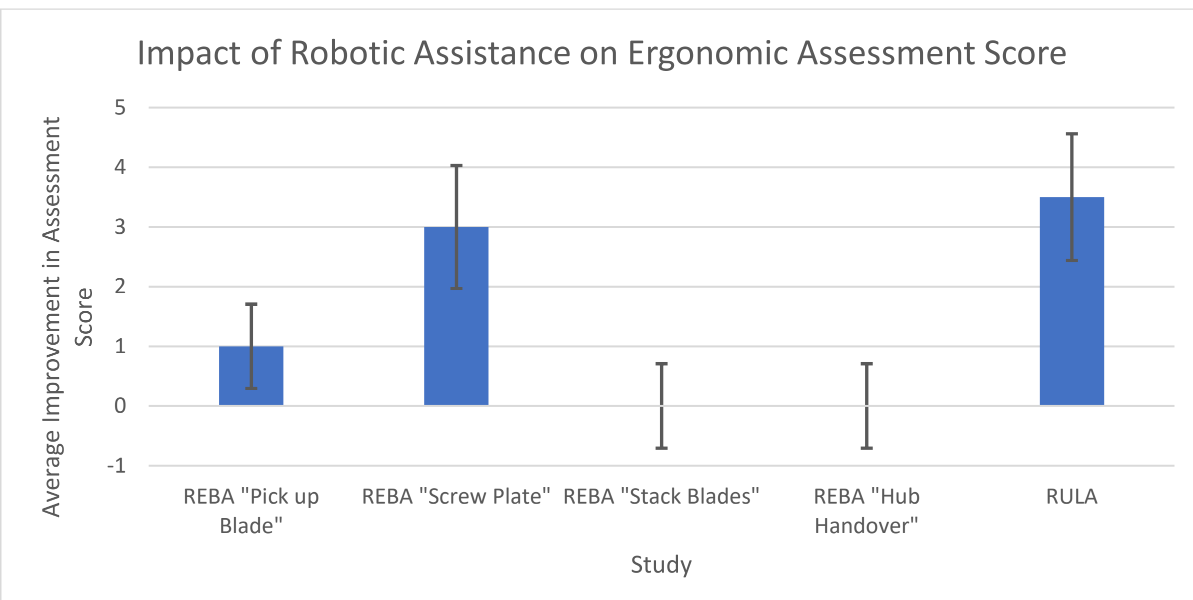
Table 4

Robotics Meta-Analysis- Effect on Position Score

Robotics Meta-analysis – Effect on Positioning Score		
Study	**Effect Size (Score)**	**Variance**
REBA "Pick up Blade"	1	0.5
REBA "Screw Plate"	3	1.1
REBA "Stack Blades"	0	0.5
REBA "Hub Handover"	0	0.5
RULA	3.5	1.1
Q	15.2	
τ^2	1.84	
Weighted Average	1.3	
p-value	0.06	

Figure 8

Impact of Robotic Assistance on Ergonomic Assessment Score



Note. Average improvement of the Ergonomic Assessment score with Robotic Assistance. The error bars shown represent the standard error.

Discussion of the Results

This research study analyzed data from four ergonomic-injury influencing categories, specifically, dexterity, grip strength, pinch strength, and robotic collaboration/assist using meta-analysis to ascertain the magnitude of their impact and possible mitigation strategies. The meta-analyses of increasing glove thicknesses has a statistically significant, *negative* effect on dexterity and grip strength, thereby rejecting the null hypothesis for these cases. The exact amount of effect, however, lies within a large range so although increasing glove thicknesses could likely result in increased ergonomic-related injuries and MSDs, it is not possible to quantify the magnitude of the effect. Glove thickness could not be conclusively shown, however, to have a significant effect on pinch strength loss as the meta-analysis of the studies investigated proved to *not* be statistically significant. For this case the null hypothesis could not be disproven. The robotics meta-analysis produced inconclusive results. It is apparent that the choice of studies to include as a part of the analysis will have a large influence on its significance. Certainly, the results of such an analysis with more and better refined studies, would be of further interest to better quantify the human-robotic collaboration impact on ergonomic injury rates.

Chapter V

Conclusion and Recommendations

Conclusion

Nuclear material processing gloveboxes present human factors and ergonomic concerns to the operators due to the nature of their structural design and processing requirements. This paper substantiated potential causal/risk factors that could increase ergonomic injury risk leading to the development of MSDs. It was shown that dexterity and grip force decrease with an increase in the thickness of glovebox gloves. Dexterity loss is associated with the increase in time spent performing a task which aligns with the ergonomic risk factor of duration. Loss of grip force due to thickness of gloves may result in operators increasing the force put upon objects, an identified risk factor, in an attempt to compensate. Pinch force as a result of glove thickness was also analyzed but the results were **not** statistically significant. A clear correlation between a loss in pinch strength and increased risk for ergonomic injury is not conclusive. Postures, specifically those that deviate from neutral, are considered an ergonomic risk factor as prolonged or repetitive improper positioning can result in MSD development. Robotic assistive technology was examined to determine if utilization of the robots to reduce awkward postures would also reduce the risk of injury. The results showed that there was an improvement in the postural score of workers when using robotic assistive technology. However, due to a slightly higher significance value (p score) and increased inter-study error, the results are judged to be inconclusive.

Recommendations

Nuclear material processing environments such as the one at LANL have come to understand the importance of practicing correct ergonomics in processes and designs of new gloveboxes to prevent injuries to their specialized workforce. The field of glovebox ergonomics is still developing and research in this area is ongoing. Implementation of robotic assistive technology in glovebox environments as a method to reduce operator injuries has not been adequately explored. Further research on the topic may improve the statistical significance of future studies/analysis to definitely show that such technology will reduce ergonomic injury risk to operators. The results of this paper showed that maintaining as much dexterity and reduced strength requirements for glovebox gloves as achievable is an important component of operator safety and health. Further research should be conducted to determine if there is an alternative glove material composition that maintains the protection needed from a radiological standpoint but also addresses the dexterity and strength concerns.

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