Exploring the use of the RCRA equation as an MSD risk assessment tool to evaluate electrical harness installation tasks.

by
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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Electrical wire harnessing on an automotive line consists of routing a harness through a car's engine, securing electrical connections, and successfully securing retention clips to keep the harness in place. The wire harnessing task is complex in nature and installation involves many hand forces and repetitive motions. Additionally, wire harnessing is highly repetitive, with workers having to install up to 500 engine harnesses per shift. Anecdotal evidence is emerging that some wiring harnessing work can lead to workplace musculoskeletal disorders of the hand and wrist. Due to the complex nature of the task, and difficultly in measuring internal exposures in-field by using tools such as electromyography, there is a lack of quantification and analysis of biomechanical demands of the task. The Recommended Cumulative Rest Allowance (RCRA) tool, developed by Potvin & Gibson (2016), aims to characterize exposures by assessing isolated subtasks in conjunction with other subtasks to assess the risk of a complete job. The RCRA is informed by percent efforts (%Efforts) that can vary and result in different outcomes based on inputs.

Thus, there is a need to quantify and analyze biomechanical demands of wire harnessing using both high-fidelity in-laboratory equipment and potential lower-fidelity in-field equipment to compare and validate a cumulative tool to be used on the line.

This study aimed to evaluate the usability of the RCRA tool for estimating required rest necessary to prevent undue fatigue during harness installation. Using a mock-engine setup in a controlled laboratory environment, 26 participants completed repeated installations of two harness types while surface electromyography (EMG) and force data were collected for wrist flexors, extensors, and applied hand force. RCRA ratios were calculated across

subtasks and input types including muscle activity as a percent of maximum voluntary contraction of the wrist flexors and extensors and applied force as a percent maximum voluntary force to assess fatigue accumulation.

Findings revealed that input selection significantly influenced RCRA outputs, with applied force and wrist flexor EMG producing consistent and interpretable estimates of required rest allowances. In contrast, peak wrist extensor inputs often resulted in unrealistically high RCRA ratios due to the extensor muscle's sustained activation patterns and the equation's sensitivity to frequency and duration. No significant differences were found between the two harness types, likely due to their similar physical characteristics.

Overall, this study supports that the RCRA tool yields similar outputs when driven with peak force or peak wrist flexor EMG, but not when driven with peak extensor EMG. It also underlines the need for careful input selection and complementary assessment strategies when evaluating different muscles. These insights provide a foundation for developing validated, in-field fatigue assessment protocols to help prevent overuse injuries in automotive manufacturing.

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List of Abbreviations

ECR: Extensor carpi radialis

ECU: Extensor carpi ulnaris

ED: Extensor digitorum

EMG: Electromyography

FCR: Flexor carpi radialis

FCU: Flexor carpi ulnaris

MVC: Maximum voluntary contraction

MVF: Maximum voluntary force

MSDs: Musculoskeletal disorders

RCRA: Recommended cumulative rest allowance

REBA: Rapid entire body assessment

RPE: Rating of perceived exertion

RULA: Rapid upper limb assessment

VAS: Visual analog scale

WMSDs: Work-related musculoskeletal disorders

Chapter 1 Introduction

1.1 Background

A wiring harness is a bundle of wires that have been taped together and organized into a single web that connect the engine's electrical systems. Wire harnesses relay electrical power and control information to outlying components. Harnesses must be manually attached onto a vehicle by an assembly worker to ensure all connections are properly secured. Assembly workers can harness approximately 500 engines per shift, or one every minute. The recent rise of electric vehicles within production along with increased electrical systems is causing assembly workers to install more harness connections and is increasing musculoskeletal disorder (MSD) concerns (Jones, 2024).

Wire harness installation involves a combination of wire harness manipulation and insertion of retention clips and cables. Workers must first route the cable, which involves placing the harness onto the engine in the correct location, securing the harness at retention points and mating any required connections. Wire harness characteristics can vary based on wire thickness, stiffness, etc. for harnesses of different vehicles or even between different harnesses for the same vehicle. Understanding how wire harness characteristics influence the physical demands and subsequent MSD hazards on workers is becoming increasingly important, particularly as wiring harness installation work becomes more prominent on the line.

MSD risk assessment is an important component in MSD prevention. Upper extremity risk assessment tools include postural assessments like RULA (Rapid Upper Limb

Assessment) or REBA (Rapid Entire Body Assessment) (Hignett & McAtamney, 2000), dynamometers to measure force, or other indirect tactics to get force data such as force matching (Lowe et al., 2019) that can be used as inputs into risk assessments. However, one challenge is that many of the current MSD risk assessment approaches focus on single tasks or actions (Veerasammy et al., 2022). Single task strategies work to characterize risk and quantify forces for specific snapshots of the task. Limited to one axis of force application and a single static posture, such single task risk assessment tools are not applicable to an engine harness installation task. Other methods to quantifying the internal exposures associated with wire harness installation may be measuring %effort, which can be done through rating of perceived exertion (RPE), electromyography (EMG) and applied force or moments (Wells & Grieg, 2001). But, interpreting RPE, EMG, or applied force data also poses a challenge, where threshold limit exposure values do not yet exist.

Though limited data exist to characterize how wire harness installations affect internal demands on the body, data does exist about the external forces required. Currently, wire harnessing manipulation requirements are measured using Instron bend testing as informed by industry partners. Additionally, in-field, reliable uniaxial direct force measurements exist for connection portions of the task such as securing electrical connections by thumb pressing (SAE International [US Council for Automotive Research], 2020). The snapshots of maximum force needed to manipulate the wire is useful to ensure workers have the necessary strength to manipulate the wire, but such tests do not account for the decay in human strength capacity that might occur over the course of a shift. Therefore, there is a need to investigate the internal exposure (i.e., demands internal to the human that

might reflect the external force requirements but also the internal capability) of an electrical wiring task. One method that might be useful to aggregate all external demands in the context of internal capacity is the Recommended Cumulative Rest Allowance (RCRA) equation. The RCRA determines the rest needed between repetitions of a task based on the effort required for each subtask, the duration of each subtask, and the frequency of each subtask within a cycle. The RCRA equation then estimates the rest required based on each subtask and adds up all the rest allowance to indicate how much rest time might be necessary within a cycle. The RCRA ratio, the recommended rest expressed relative to the actual rest, may provide insight on rest acceptability for a task with many subtasks, such as wire harness installation. However, an RCRA analysis has not yet been completed for use with an electrical harness installation task. Additionally, RCRA analysis can be generated by using different inputs to represent %effort, such as normalized force, or normalized EMG. No research has investigated how different input data influences outputs from the RCRA.

1.2 Problem Statement

Wiring harness installation requires a series of hand demands. While tools and methods exist to quantify MSD risks associated with individual hand demands, the automotive sector continues to struggle to estimate how risk might accumulate based on the number of individual hand demands required to install a particular harness type. Emerging tools like the RCRA may help to quantify how risk may accumulate, but no evidence is available to understand how RCRA outputs might differ when the %effort input is capture using different measurement approaches used (i.e., high vs. low fidelity measures), or if the

RCRA might be sensitive enough to detect differences that might emerge between different wiring harness types.

1.3 Research Questions

Among a convenience sample of university students:

1) How does the RCRA change when the %effort inputs are determined from normalized EMG, or normalized applied force?
    a. Hypothesis 1: There will be no significant difference on RCRA outcome when either direct or indirect exposure measures are inputted.
2) Does the RCRA differ when calculated based on the requirements of a larger (i.e., larger gauge wire, longer route, more attachment clips) versus smaller wiring harness?
    a. Hypothesis 2: There will be a significant increase in %effort (e.g., Muscular activation, applied force, psychophysical data) with harnesses of increased size.

1.4 Objectives

This research was done with the goal of using normalized force and EMG as measures representative of the construct of percent effort (%effort). RCRA analysis requires %effort as an input to quantify exposures, but different ways of characterizing %effort may influence the interpretation of MSD risk associated with wiring harness installs in the workplace. In addition to understanding the utility of RCRA to evaluate wire harness installation, this study will also describe a range of biomechanical exposures of the hand and

wrist and task information such as frequency and duration of effort for an electrical harness installation task to provide to industry partners.

1.5 Significance

This study provides a more detailed understanding of the muscle activation patterns and hard forces required to install a wiring harness and all its respective subtasks. Additionally, it provides understanding for the perception of effort as captured by an OMNI-res score. Lastly, insight will inform how the RCRA might be used to assess risks with wiring harness installations that can be applicable to both in-field and in-laboratory collections.

Chapter 2 Literature Review

2.1 Work-Related Musculoskeletal Disorders

Musculoskeletal disorders (MSDs) are injuries of the muscles, joints, tendons, cartilage, or discs of the human body. Work-related musculoskeletal disorders, or WMSDs, are conditions in which the work environment or performance of work contribute significantly to the condition, and/or the condition is made worse due to work conditions (Bernard, 1997). Within Ontario, MSDs are the most frequent injury claim and the largest contributor to lost time claims (CRE-MSD, 2023). In 2024 the U.S. industry spent $58.07 billion on the direct costs of worker injuries. NIOSH reports the neck, shoulder, elbow, hands, and wrists, and back to be most at risk for MSDs due to work condition (Bernard, 1997). Additionally, there are other burdens of WMSDs besides lost time and cost, such as emotional, physiological, and financial burden placed upon the worker and their family (Amell & Kumar, 2001; Carson, 1994) and this problem remains (Tee et al., 2017; Garg et al., 2016). These reasons show the need for prevention of MSDs in the workplace.

2.1.1 Common Risk Factors and Injuries of WMSDs

Armell & Kumar in 2001 stated that there are numerous factors within work tasks that may contribute to WMSDs. There are numerous studies that discuss how most risk factors of WMSDs can be narrowed down to three main contributors: high forces, awkward postures, and high repetitions (NIOSH, 1997; Keyserling, 2010; Armstrong et al., 1993). These hazards, when combined with a frequent nature and long duration of a task or shift can put the body at risk. Additionally, contact stress, cold temperatures, vibration as other

environmental factors have been found to relate to WMSD risk (Keyserling, 2000). These injuries can be chronic or acute (Kumar, 2001; Anghel et al., 2007).

2.2 Importance of Ergonomics within the Automotive Industry

Ergonomics and WMSD prevention are especially important in the automotive industry. Automotive manufacturing plants contain workers that fulfill demanding and strenuous physical tasks. In plants, most tasks are tailored to best fit the underlying production process, not the worker themselves (Thun et al., 2011). A major problem of the automotive industry is the repetitive hand work required for many tasks (Fredriksson et al., 2001). Repetitive hand grips are a common demand in industry and are often performed at low intensities for long durations with short breaks (Eksioglu, 2006). These demands are usually coupled with awkward postures and have been found to be associated with disorders. Force gripping and grasping have been associated with high risks of WMSDs such as carpal tunnel syndrome, where work tasks require lots of pinch grips (Dong et al., 2005). Many interventions aim to reduce repetitive hand motions in the workplace (Fredriksson et al., 2001), but this may be unpreventable for some tasks that require human interventions, such as manipulations, insertions, or pinches to install automotive equipment.

2.3 Ergonomic Analyses

Measuring hand demands has been approached in multiple ways. One way is measuring the external exposures, or the forces and torques needed to manipulate a piece of equipment to be used on the line. The other way is to measure the internal exposures, which includes measuring the exposures within the human body (i.e., EMG) (Wells et al., 2004).

This can be measured either directly or indirectly to show the perceived effort, grip strength matching, and muscle activation needed to perform a task on the line.

2.3.1 External Exposures

External exposures can be estimated by using mechanical tests to measure the bending and torsion required to manipulate and install parts used on the line. However, external exposure is only one component of a task demand. These exposures only represent the demands needed to manipulate an object but do not consider the internal aspects of the exposure or capacity to withstand the exposure, and therefore create a disconnect between external exposure and MSD risk (Wells et al., 2004). Exposure determined using these methods may not predict MSD risk well and may subsequently misrepresent the overall exposure or dosage of a task (Slater, 2009). An example of external exposures being measures is by Drinkaus et al. in 2010, where a three-axis programmable mill was used to insert wires onto spark plugs mounted onto a force transducer.

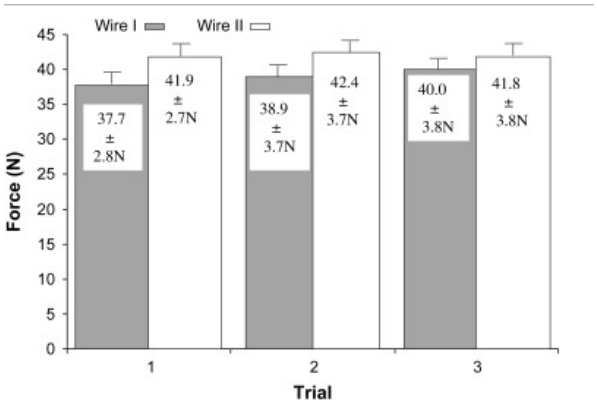


Figure 1: Measured mechanical force needed by a mill to insert a wire onto a spark plug (Drinkaus et al., 2010).

Inflection points and slope of the force-displacement curves were found to correct mechanical events in which the wire and plug were joined. This gave an accurate show of

external exposure of force needed for this insertion; however, this methodology may fall short when considering the internal exposures onto the human body and its associated hazards.

2.3.2 Direct Internal Exposures

Internal exposure measures aim to quantify or estimate direct exposures on tissues of the human body (Wells et al., 2004). In terms of hand exposures, this can include directly measuring EMG to measure muscular activity while the worker is performing the task (Koppelaar, 2005). Keir and Mogk (2005) used the muscle activation of six finger and wrist muscles to model grip strength. They found that muscle activation explained 85% of the variance in grip force in a standardized grip in similar postures. This model can estimate grip force and does not require instrumenting parts but is limited to situations where multiple electromyography (EMG) signals can be recorded and processed and in which external forces and torques are not applied. In industry, it is hard to apply EMG measures as it is not commonly done or feasible in the field, with only about 17% of ergonomists using EMG previously in industry, versus 62% for hand grip goniometers or 91% for psychophysical material handling data which is more common (Lowe et al., 2019). Additionally, Kopelaar & Wells (2005) found good precision and reliability when comparing perceived exertion with effort determined using other methods such as EMG. When internal exposures can be measured directly, there is increased insight of obtaining real-time internal exposures while the subject is performing the task.

2.3.3 Indirect Internal Exposures

Indirect internal exposure measures entail measuring internal exposure of a worker without measuring demands of the body while they perform the task. This is typically done after the task is completed. This can be done by self-reports using a visual analog scale (VAS) such as a Rating of Perceive Exertion (RPE) scale or a force matching protocol. In the literature of measuring hand internal exposures, several studies confirm that hand and grip forces can be reproduced by self-reports with high precision (Hammerskjold et al. 1989; Wiktorin et al. 1996). When the operator is given clear instructions and follows them closely, force matching with a hand dynamometer is a legitimate and dependable way of determining grip and pinch forces, according to Bao and Silverstein (2005). Research on the relationship between force and variability has yielded mixed results. While some studies (Kumar et al., 1997; Lowe, 1995) have found higher variability when force matching is done at low levels, other studies (King and Finet, 2004; Bao and Silverstein, 2005) have found higher variability when force matching is done at high levels. In contrast to short, straightforward instructions, Bao and Silverstein (2005) discovered that with more thorough instructions, accuracy increased, and variability decreased. The force matching approach is often reliable and consistent at the group level, especially if the hand positions, grip contact circumstances, and upper arm positions during the force matching test and real task execution are replicated well. Therefore, it is important to ensure similar hand posture, grip contact conditions and upper arm positions during force matching tests (Bao & Silverstein, 2007).

Since self-reports, such as the force matching and VAS methods, are less time-consuming and easier to use in the field than instrumented measurement methods, they are

usually preferred when estimating hand force in the field. Self-reports do not interfere with the work as instrumented methods do (Koppelaar & Wells, 2005). Within the scope of measuring biomechanical internal exposures on the line, indirect measures can provide a method of measuring exposures while the work and productivity of the line remains uninterrupted and untouched.

2.4 Moment Wrench

In 2004, Grieg and Wells explored the idea of expanding how we interpret hand exposures. Often, when we measure force demands they are measured through only one-axis. This is often not the case when performing a task, especially tasks that require complex movements of hand assembly on the line. Also, most effort estimations are determined from the normalization to grip strength. This is relevant for a task where only a grip is necessary but does not well characterize tasks where both grip and manipulation of an object is needed (Grieg & Wells, 2001). They proposed the idea of an external moment wrench to better characterize strength during a functional task. Moment wrench represents the forces and torques as a 7x1 vector applied at a point. They suggested that moment wrench, when coupled with muscle activation measurements of the forearm and hand, may provide more comprehensive understanding of the task demand.

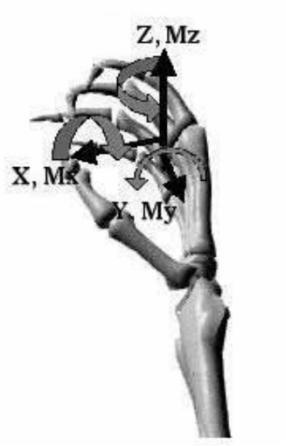


Figure 2: Visual description of a moment wrench vector of the hand, including three axes of force and their respective torques (Greig & Wells, 2004).

2.5 Interpreting Exposures

Psychophysics is a class of MSD tools that is presented to characterize the exponential relationship between sensation and physical stimulus (Stevens, 1957). Utilizing this relationship, Snook (1968) conducted one of the first published ergonomics studies that explored psychophysics, establishing acceptable demands for repetitive jobs. This was done by asking participants the maximum frequencies for lifting exercises with different beginning heights and set load weights to create an acceptability criterion. Potvin in 2011 developed a psychophysical relationship for the upper extremities between Maximum Acceptable Effort (MAE) and duty cycle, by analyzing eight upper extremity psychophysical studies related to ergonomics. MAE is average maximum acceptable effort, where 1.0 represents 100% maximum voluntary effort. The Duty Cycle (DC) represents the working time as a percentage of cycle duration. The result was a non-linear, negative relationship between duty cycle and average MAE (Figure 3). This relationship can also be shown as the equation:

$$MAE = 1 - \left[DC - \frac{1}{28{,}800}\right]^{0.24}$$

Where:

MAE = Maximum acceptable effort (%)

DC = duty cycle (%)

Additionally, this relationship can be compared with literature that suggests fatigue, showing a fatiguing region (Shaded area in Figure 4).

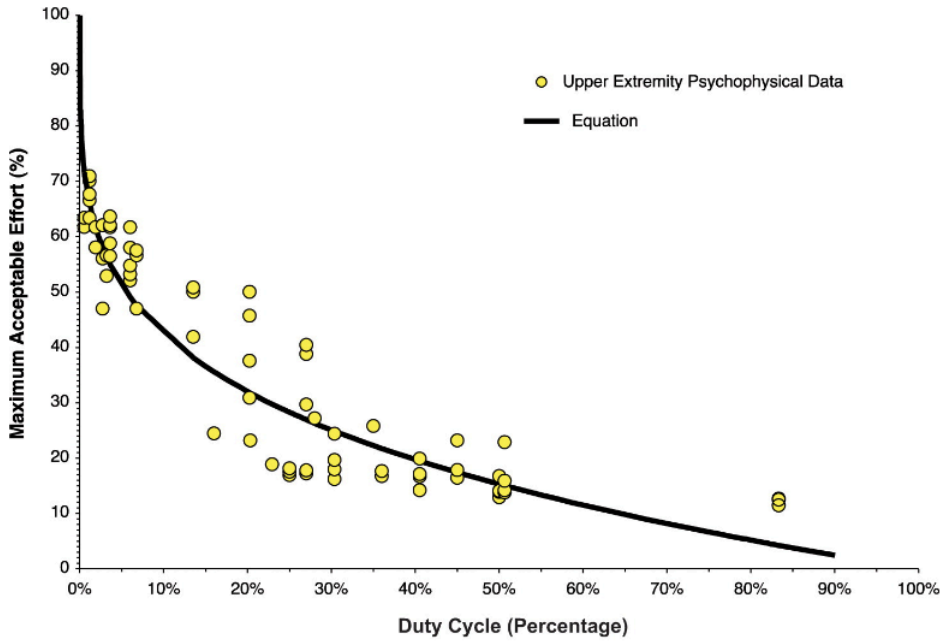


Figure 3: Maximum acceptable effort (as a percentage of maximum voluntary effort (MVE)) versus duty cycle as a percentage of an 8-hr workday. All upper extremity (n = 69) data from Potvin, 2011 are shown along the curve.

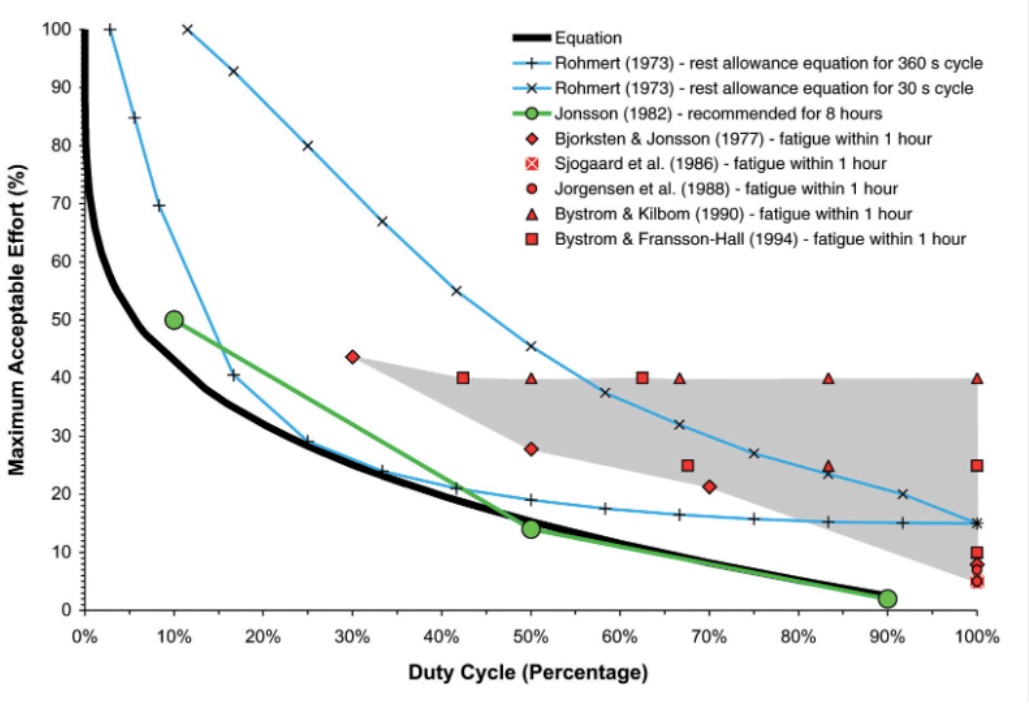


Figure 4: The proposed curve MAE DC curve plotted against physiological data from the literature. The unlined symbols indicate conditions with physiological evidence of fatigue within 1 hr. The shaded area (and above) indicates a fatiguing region (Potvin, 2011).

2.5.1 RCRA

The Recommended Cumulative Rest Allowance (RCRA) is a re-expression of the Maximum Acceptable Effort (MAE) equation (Gibson & Potvin, 2016). It was created with the purpose of assessing isolated subtasks in conjunction with other subtasks to assess the risk of a complete job. The RCRA is then determined by adding up all the rest allowances for each individual subtask during the work cycle, which is determined using the duration of each effort and maximum acceptable DC determined by the effort of the subtask needed. The task is considered acceptable if the total cycle time is less than the sum of the effort durations and the RCRA (Potvin, 2012), or the RCRA ratio is calculated to be less than 1 (Figure 5). If the RCRA

ratio is greater than 1, insufficient recovery time would be available, and the cumulative effects of the three subtasks would be considered unacceptable (Potvin & Gibson, 2016).

$$t_{R/C} = \frac{(t_E)\,(f)}{[\,1 - E\,]^{4.167} + DC_{MIN}} - (t_E)\,(f)$$

Equation: RCRA tool (Potvin, 2012).

Where:

$t_{R/C}$ = recovery time per cycle (seconds)
t_E = duration of each effort (seconds)
f = effort frequency
E = known effort (% maximum strength)
DC_{MIN} = 0.000035 representing the assumption that a 100% effort could be held for 1s each 8 hours

In figure 5, an example of the RCRA is shown. Subtask information such as effort, frequency and duration of effort is shaded in yellow. From this, duty cycle can be calculated for each subtask by dividing the subtask's total duration by the total cycle duration, which can be compared with the maximum acceptable duty cycle. Lastly, by adding up all the total rest required for each subtask using the total cycle duration and maximum acceptable duty cycle, we can compare out total rest required, and total rest provided times, represented by shaded blue boxes. A ratio of these rest times creates the RCRA ratio.

Subtask	Effort (%MVC)	Freq (per cycle)	Duration of each effort (s)	Total Duration (s/cycle)	Actual Duty Cycle (DC)	Maximum Acceptable DC	Acceptable in Isolation?	Required Rest (s/cycle)	Total and Effort + Recovery Time (s)
Orientating Harness	10.00%	1.00	5.00	5.00	0.111	0.645	Yes	2.76	7.76
Routing/Rentention Clips	15.00%	5.00	1.00	5.00	0.111	0.508	Yes	4.84	9.84
Electrical Connections	20.00%	7.00	1.00	7.00	0.156	0.395	Yes	10.74	17.74
Total				**17.00**				**18.34**	**35.34**

Total Cycle Duration (s)	45.00	**Total Rest Required (s)**	18.34
Total Effort Duration (s/cycle)	17.00	**Total Rest Provided (s)**	28.00
Total Duty Cycle	0.38	**RCRA Ratio**	0.65

Figure 5: Example of the RCRA tool being used. Fictitious data using durations from the literature and %efforts based on reasonable biological estimates. The RCRA ratio is

determined to be 0.65, meaning the cumulative requirements of the subtasks would be considered acceptable.

2.6 Electrical Harnessing

Electrical wire harnessing is a task which requires an operator to route and connect a wire harness bundle onto an engine. To start the process, an operator will remove the harness from the dunnage, then place the harness onto the engine. They will then begin to install the harness by connecting the retention clips, which keep the harness attached to the engine. Next, from an initial start point, the operation will work their way making all retention clips secure and electrical connections. Often, this task is performed with an operator at either side of the engine, each responsible for harness routing and retention clips/connectors on their respective side. Clipping connections can be anywhere from seven to ten connections per minute, depending on the engine type.

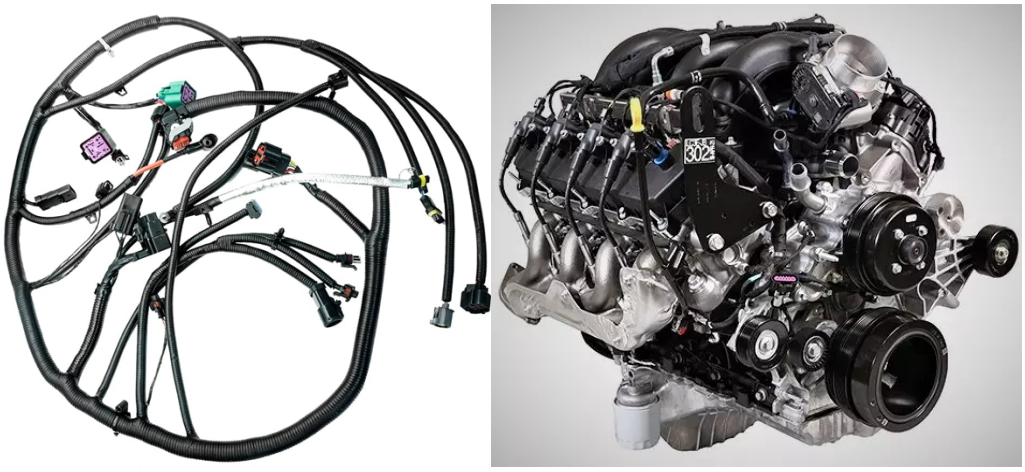


Figure 6 (Right): Example of a wire harness (Left) (Photo from https://www.amazon.ca). Figure 6 (Left): Example of an engine with harness installation at the top of engine (Right) (Photo from https://www.onallcylinders.com).

Operators perform this task for the entirety of their shift, and their job only requires harnessing of one side of the harness, so operators do not switch sides. This task is performed

during an eight-hour shift, with two 15-minute breaks and one 30-minute lunch break during the shift. The number of installations per shift can range anywhere from 300-500, dependent on the cycle time ranges which are usually between 30-90 seconds.

Large variability exists between wire harness bundles in terms of size/diameter, weight, and stiffness. Stiffness is driven by gauge of wiring, bundle thickness, and routing caused by a tight bend radius or retention clip spacing. This variability exists between harness bundles of different engines, but also within harnesses of similar engines. This is due to the process of building the harness, which involves laying out wires over a board and then taping them. Variability in amount of tape, layering of the harnesses, and tension when taping can all cause variability harness to harness.

Chapter 3 Methodology

3.1 Research Design

A cross-sectional, repeated measures design was used to answer the research questions. The study involved participants repeating the installation of an electrical wire harnessing task onto a mock engine (Figure 7). This task included retrieving the harness, routing the harness along the engine, and securing the harness to the mock engine using retention clips. Lastly, electrical connections were made by securing all connectors. Wiring was done with two different harnesses both varying in size (Table 2). Both harness 1 and 2 were for the same size engine, however harness 1 was destined for a pickup truck and harness 2 was destined for a midsized SUV.

3.2 Population and Sample

A sex-balanced convenience sample of 26 university-aged students were recruited to participate in this study. Though a sex-based analysis was not motivated by the hypotheses, a comparative summary of RCRA differences can be found Appendix E. Participants had to meet the inclusion criteria to be able to participate, which entailed having no history of pain or injury in their upper or lower extremities in the last six months. The Nordic Questionnaire (Kuorinka et al., 1987) was used to screen for any history of pain or injury (Appendix B). Upon entering the lab, participants completed a consent and demographics form. The participants had an average age of 24.5 ± 3.6 years; an average height of 173.7 ± 7.7 cm; and an average weight of 71.0 ± 11.4 kg. Only two participants were left-handed. Prior to participation, all individuals provided both verbal and written consent. After a detailed overview of the study and associated risks with participating, participants were informed that

they were free to withdraw at any time. The protocol was reviewed and cleared by the University Research Ethics Board (ORE #46841).

3.3 Data Collection

After filling out consent and demographic forms, participants were instrumented with electromyography electrodes. Noraxon Ultium sEMG sensors (Noraxon USA, Scottsdale, AZ, USA) were applied to the following muscles unilaterally on the right arm along the muscle belly according to SENIAM guidelines: three wrist extensors (extensor digitorum (ED), extensor carpi ulnaris (ECU), extensor carpi radialis (ECR)) and two wrist flexors (flexor carpi radialis (FCR), flexor carpi ulnaris (FCU)). Prior to electrode placement the area of interest was exfoliated, shaven and cleansed with 70% isopropyl alcohol to improve electrical signal and reduce residual moisture/oil. The EMG data were sampled at 2000Hz using the Noraxon Ultium System (Noraxon USA, Scottsdale, AZ, USA) as a digital device in Vicon Nexus 2.6.1 (Vicon Motion Systems, Ltd., Oxford, UK).

The data collection required participants to harness a wire onto a mock-engine block that simulated an engine block on the conveyor belt on the line (Figure 7). The engine block was constructed out of wood as to not deform when force was applied onto the mock engine. Hooks and clips were attached onto the engine in the same locations as in the automotive line according to Ford reach standards (Height between 30-56” and reach between 0-20”), and all clips and connecters were tested with a force transducer to ensure the workspace in-laboratory was simulated to ensure everything would meet the acceptable “green zone” on an automotive line according to SAE USCAR guidelines (<45N) (SAE International [US Council for Automotive Research], 2020). Additionally, industry partners were able to tour

the lab and experience the protocol to ensure the design of subtasks and equipment met in-field fidelity. The engine block was mounted on top of a 6-degrees-of-freedom force plate (Bertec Corporation, Columbus, OH, USA) using a rigid wooden frame to capture real-time applied forces during the trial. Female components of parts were affixed onto the mock engine. Male components of all retention clips and electrical connectors were replaced after each participant to minimize any potential wear and tear. Testing was done during the piloting stage to ensure valid force responses when loaded (Appendix C). Force data from each exertion was sampled at 1000 Hz into Vicon Nexus (Vicon Motion Systems, Ltd., Oxford, UK).



Figure 7: Mock-Engine Block used for trials.



Figure 8: Push pin clips used for orientation and retention subtasks (top) and electrical connector clips used for connection subtask (bottom).

Maximum voluntary contractions (MVCs) were collected for all muscles. A combination of wrist flexion, extension, pronation, supination, adduction, abduction, and elbow flexion was performed and the highest MVC for each muscle was collected, as per Morose et al., 2004. Additionally, task-specific maximum voluntary forces (MVFs) were collected on the mock-engine block to normalize applied forces obtained. MVFs consisted of 5s trials where the participants would assume the posture of the connections for each subtask (i.e., electrical connection, retention clip, etc.) and were instructed to produce the maximum amount of force possible to secure a connection. During MVFs, all connections were already secured before force was applied to ensure no movement of the female or male components of any connections occurred. Participants performed each MVC and MVF a total of two

times, and the maximum value was taken over a five second trial length. Two minutes of rest was given in between MVCs/MVFs to minimize fatigue effects.

Table 1: Hand/forearm muscles, their respective function and MVC (Schreuders et al., 2014; Delagi, 1975).

Muscle	Electrode Landmark	Function	MVC
ED	Grasping the forearm between upper and middle third with thumb and middle finger of radius and ulna. Then use index finger to bisect two points and place electrode	Extends the phalanges, then the wrist, and the elbow	Finger extension/wrist extension
ECU	Palpate the ulna in the middle of the forearm and place just above the shaft of the ulna	Extends the hand at the wrist joint	Wrist extension/adduction
ECR	Two fingerbreadths distal to lateral epicondyle	Produces wrist extension and abduction (radial deviation)	Wrist extension/ abduction
FCR	Three-four fingerbreadths distal to the midpoint of a line connecting the medial epicondyle and biceps tendon.	Provides flexion of the wrist and assisting in abduction of the hand and wrist	Wrist flexion/abduction
FCU	Two fingerbreadths volar to the ulna at the junction of the upper and middle thirds of the forearm	Flexes and adducts the hand	Wrist flexion/adduction

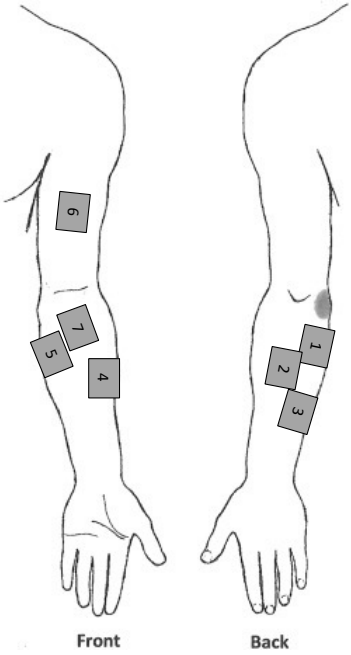


Figure 9: Surface electrode placement for selected muscle sites (1 ECR, 2 ED, 3 ECU, 4 FCR, 5 FCU).

The data collection took place over one day in a two-hour session. Following MVC and MVFs, participants were then asked to perform the wiring task. Participants first learned how install the electrical harness from verbal instructions and a live demonstration from the researcher. Participants installed the engine harness a minimum of 10 times during the familiarization period, or until the participants reported that the cognitive load of learning how to install the harness has decreased. After familiarization, participants routed the wire harness from one end to the other, then ensured retention clips and all connections were made. Wiring was done on only one side of the engine to emulate a worker's task on the line. The participants were restricted to working on only one side of the table to represent where a worker is freely able to move around in front of the compounds of the automotive line conveyor. This task was limited to a maximum cycle time of 45 seconds, a common cycle

time in the field as described and confirmed by industry partners. This process was done repetitively for one engine 10 times per harness, for two harnesses. Engine type first presented was randomized.

Table 2: Tested engine types and respective specifications.

Engine Harness Type	Photo	# of Connections	Length (m)	Weight (kg)
Harness 1		34	2.99	2.23
Harness 2		32	3.05	2.23

After each successful harnessing bout, participants were asked to rate their perceived exertion using the OMNI-res scale (Appendix A) for each of the subtasks on a scale from 0-10 with 0 being "resting" and 10 being "extremely hard" for a total of three scores per trial. The OMNI-res scale was chosen to measure the perceived intensity of physical exertions to allow findings to be easily inputted into tools, such as the Distal Upper Extremity Tool.

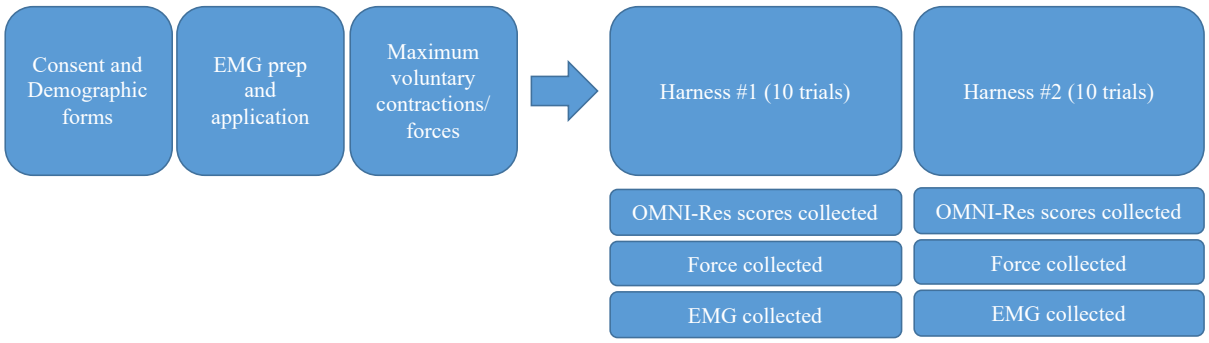


Figure 10: Protocol flowchart.

3.4 Data Analysis

Force and EMG data were first segmented into subtasks (orientation, retention, electrical connections) by using a voltage switch that was triggered by the researcher when each subject moved from one subtask to the next. The voltage switch generated an electric potential when held down, and subtasks were separated when switch electrical potential surpassed 1V. All data processing was done in Matlab R2023b (Mathworks, Inc., Natick, MA).

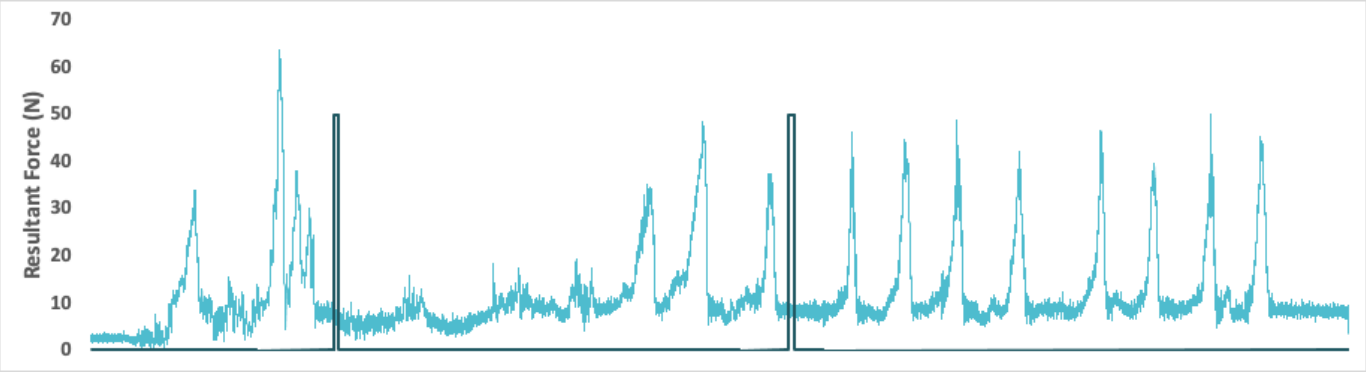


Figure 11: Raw resultant force data (N) (light blue) with overlaid voltage switch data (dark blue) to show segments.

3.4.1 Peak Resultant Force Amplitudes

The force signals were processed using a digital dual-pass 6th order Butterworth filter with a cutoff frequency of 12 Hz. A cutoff frequency was chosen to reduce the vibrations of the table/engine when the plastic clips were inserted. A residual analysis was performed to determine the cutoff frequency (Appendix D). Additionally, a baseline offset correction was made at the beginning of each trial to correct for any force baseline changes due to part of the harness being installed onto the engine. Force was analyzed and exported as peak force in the x, y, and z direction as well as resultant peak force. To analyze peak force data, resultant force calculated as the Euclidean norm of the three force components was used. Resultant force was used for RCRA inputs.

$$Normalized\ Force\ (\%) = \frac{Resultant\ Force}{Resultant\ MVF\ Maximum} \cdot 100\%$$

3.4.2 Force Duration

Forces for each automotive subtask were recorded in all axes (x,y,z) but expressed as the resultant to determine %effort. To calculate effort durations, a 5 N single-threshold on-off

detection algorithm was used (Bonato et al., 1998). The thresholding algorithm assigned a binary value of "1" when the resultant force surpassed 5 N, or a "0" when the force was below the 5 N threshold. Effort durations were calculated as the length, in seconds, of when thresholds of frames surpassed 5N, or "1" in binary values. Frequency inputs of the RCRA were kept consistent with the physical demands description of the job and required number of connections needed to install the harness (orientation, 2 push pins, retention, 3 retention clips, connectors, 8 electrical connections).

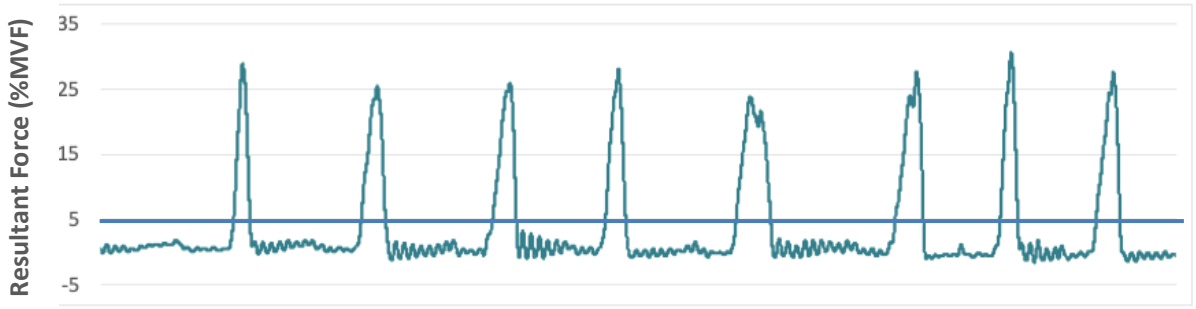


Figure 12: Visual representation of applied force data of a subtask. Events are calculated when force passes the 5N threshold.

3.4.3 Surface Electromyography Amplitudes

To analyze EMG data, EMG data of the maximum voluntary contraction (MVC) and installation trials were imported. For each trial, DC bias was removed. Next, data was full wave rectified, and filtered using a single pass, second order low-pass Butterworth filter with a 3Hz cutoff (Yung & Wells, 2013; Ngo & Wells, 2016). EMG signals were then normalized to the individuals MVCs trials, using maximum activation of the muscle across all MVC trials, creating a percentage of maximum muscle activation.

$$Normalized\ EMG\ (\%) = \frac{EMG}{MVC\ Maximum} \cdot 100\%$$

3.4.4 Surface Electromyography Duration

Once muscle activity data were processed and normalized, EMG effort durations were calculated. EMG for each subtask was segmented into events by determining a single "on-off" threshold of when muscle activity surpassed the mean muscle activity of that subtask as done previously in effort duration calculations for industry partners (Allen, 2024). Effort durations were calculated as the length, in seconds, of when thresholds of frames surpassed mean muscular activation of the subtask, or "1" in binary values.

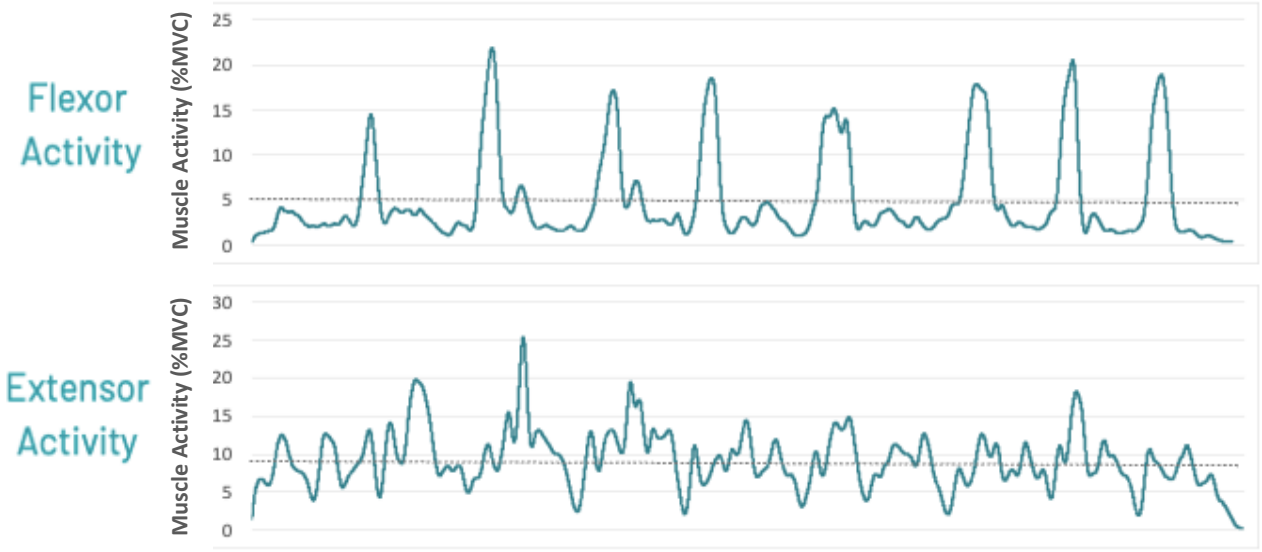


Figure 13: Visual representation of normalized sEMG data of a trial with average muscle activity denoted by blue line. Events denoted as any time sEMG surpasses average muscle activity.

3.4.5 RCRA Calculations

For this study, both muscle activity and applied forces were normalized to obtain %efforts that could be used for the RCRA tool. EMG was normalized to the highest MVC activation for each MVC trial, and force was normalized for the task specific MVF trial.

Once %effort peak amplitudes and effort durations were calculated for each subtask within each trial, each subtask peak was extracted. The maximum peak value for each subtask type was retained as the exemplar exposure for each subtask type. Highest %effort resultant force, highest %effort EMG from a wrist extensor out of three muscles and highest %effort EMG from a wrist flexor out of two muscles was taken. Exemplar exposures were then identified from each wire harness repeat and averaged to yield a representative participant specific peak %effort exposure for each subtask. The result was three averaged %effort input types for each subtask, for a total of nine for each trial (3 %efforts * 3 subtasks) with their corresponding effort duration that was calculated back during the event detection process.

Next, an RCRA score was calculated for each input type using the three subtasks to calculate the total effort duration, duty cycle and required/provided rest times (Figure 14). %Effort and event duration as inputted into the tool, with frequency for the orientation, retention and connection subtask being kept at 2, 3 and 8, respectively. Lastly, an RCRA ratio was calculated. RCRA ratios were calculated using the averaged subtasks peak values, for each harness type, resulting in two RCRA ratio scores per participant. The result was 52 RCRA ratio scores generated from participant's installation averages.

Subtask	Effort (%MVC)	Freq (per cycle)	Duration of each effort (s)	Total Duration (s/cycle)	Actual Duty Cycle (DC)	Maximum Acceptable DC	Acceptable in Isolation?	Required Rest (s/cycle)	Total and Effort + Recovery Time (s)
Orientating Harness	18.80%	2.00	0.30	0.60	0.013	0.420	Yes	0.83	1.43
Routing/Rentention Clips	32.70%	3.00	0.43	1.30	0.029	0.192	Yes	5.45	6.75
Electrical Connections	34.50%	8.00	0.55	4.37	0.097	0.172	Yes	21.10	25.47
Total				**6.26**				**27.38**	**33.65**

Total Cycle Duration (s)	45.00	**Total Rest Required (s)**	27.38
Total Effort Duration (s/cycle)	6.26	**Total Rest Provided (s)**	38.74
Total Duty Cycle	0.14	**RCRA Ratio**	0.71

Figure 14: An example of an RCRA ratio calculation. Effort and duration represent an average of 10 installations for one input type (e.g. Extensor EMG). Frequency was kept constant due to job task demands. The resulting RCRA score was collected to compare between input types and harness types.

3.5 Statistical Analysis

A log-transformed repeated-measures analysis of variance (RMANOVA) was conducted to evaluate the effects of RCRA input type (Flexors, Extensors, Force) on RCRA ratio outputs, addressing research question 1. Violations of normality in the raw data (skewness = 3.64; kurtosis =15.23), were present and sphericity was violated when tested (Mauchly's $p < 0.001$). Pairwise comparisons between input types were performed using Holm-adjusted paired t-tests. A Wilcoxon Signed-Rank test was run to compare average RCRA ratios of flexor and force input types between harness types for research question 2. This test was also chosen due to non-normal data distributions. Extensor inputs were left out due to non-physiological RCRA scores. All analyses were conducted in RStudio (RStudio Team, 2023), with statistical significance set at $\alpha = 0.05$.

Chapter 4 Results

A two-way repeated-measures analysis was conducted to examine the effects of RCRA input type (Flexors, Extensors, Force) on RCRA ratio values. First, RCRA inputs (%effort, duration, and frequency) are reported (Tables 3-6). To better contextualize the figures presented below, Tables 3–6 summarize the average %Effort and event durations across the three subtasks (orientation, retention, and connectors) for both harness types. The tables represent the average %efforts and durations across all participants. In both harnesses, the connectors subtask consistently demonstrated the highest %effort, with the extensor input type showing the highest %MVC values. In contrast, the orientation subtask required the lowest relative effort. Additionally, across both harnesses, extensor and flexor inputs resulted in longer durations of effort across all subtasks when compared to force input methods.

Table 3: %Effort for each subtask for harness #1.

	Flexors		Extensors		Force	
Subtask	Average (%MVC)	SD (+/-)	Average (%MVC)	SD (+/-)	Average (%MVF)	SD (+/-)
Orientation	18.32	9.24	25.95	8.68	25.68	12.60
Retention	20.48	9.19	47.88	17.22	34.87	14.42
Connectors	35.16	12.48	47.65	15.04	41.30	13.57

Table 4: Event Durations for each subtask for harness #1.

	Flexors		Extensors		Force	
Subtask	Average (s)	SD (+/-)	Average (s)	SD (+/-)	Average (s)	SD (+/-)
Orientation	0.96	0.52	0.88	0.25	0.35	0.11
Retention	0.84	0.44	1.05	0.30	0.47	0.33
Connectors	0.85	0.41	0.96	0.24	0.49	0.22

Table 5: %Effort for each subtask for harness #2.

	Flexors		Extensors		Force	
Subtask	Average (%MVC)	SD (+/-)	Average (%MVC)	SD (+/-)	Average (%MVF)	SD (+/-)
Orientation	17.22	8.90	23.83	7.35	24.38	12.17
Retention	22.34	10.79	50.37	19.79	33.12	10.95
Connectors	34.88	13.63	45.14	15.27	41.51	12.60

Table 6: Event Durations for each subtask for harness #2.

	Flexors		Extensors		Force	
Subtask	Average (s)	SD (+/-)	Average (s)	SD (+/-)	Average (s)	SD (+/-)
Orientation	0.87	0.49	0.87	0.28	0.41	0.41
Retention	0.87	0.44	1.10	0.31	0.47	0.41
Connectors	0.73	0.33	0.94	0.18	0.49	0.25

4.3 Effect of RCRA Input Type (RQ1)

The log-transformed repeated-measures ANOVA revealed a significant main effect of input type on RCRA ratios ($F(2, 50) = 24.67$, $p < .001$) generalized eta squared (ges) = 0.35, indicating a large effect size. Post-hoc pairwise comparisons with Holm correction showed significant differences in RCRA ratios between flexors versus extensors and extensors versus force (both $p = <0.01$) however, no significant differences were found between flexors versus force input types ($p = 0.88$). RCRA ratios exceeded recommended thresholds (>1) when using peak flexor EMG (1.97), extensor EMG (37.49) and force (1.77).

Table 7: RCRA Ratios by Input type

Input Type	Mean	SD(+/-)	N	SE	CI_lower	CI_upper
Flexors (Peak)	1.97	2.93	52	0.41	1.16	2.79
Extensors (Peak)	37.49	116.7	52	16.2	5.04	69.9
Force (Peak)	1.77	2.27	52	0.31	1.14	2.40

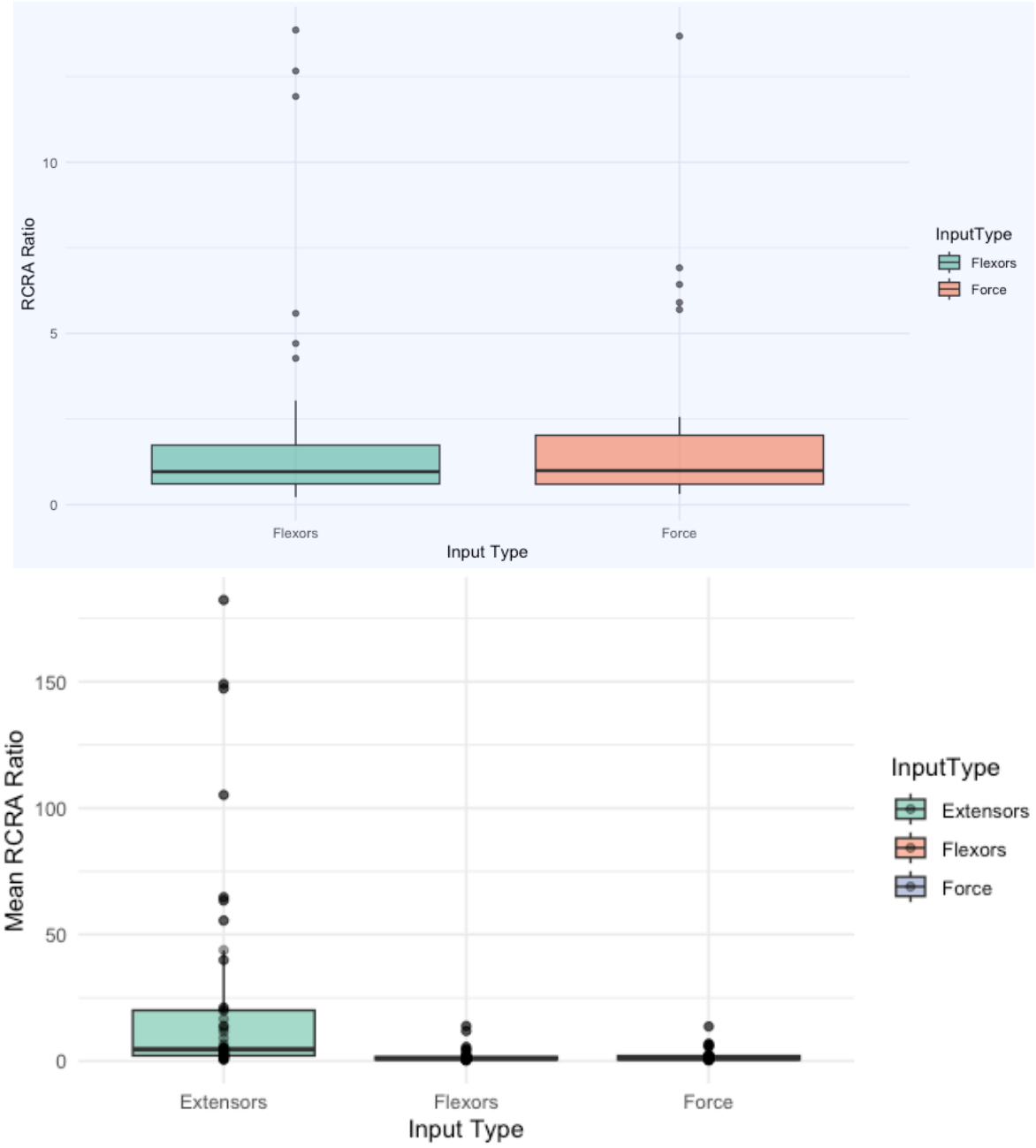


Figure 15: RCRA Ratios by Input Type. Top figure shows expanded flexor and force input types.

4.4 Effect of Harness Type (RQ2)

To assess whether RCRA ratios differed by harness type, a Wilcoxon Signed-Rank test was performed using each participant's mean flexor and force input RCRA ratios. Although the mean RCRA ratio was slightly higher in harness type 1, no significant difference of mean RCRA ratios between harness type was found (p = .12).

Table 8: RCRA Ratios by Harness type

Harness Type	Mean	SD(+/-)	N	p	Effect Size
1	1.98	2.78	26	0.12	-0.31
2	1.76	2.45			

Mean OMNI-res scores were divided by subtask and harness type. Means and standard deviations of OMNI-res scores were calculated. Within-participant OMNI-res score changes were not analyzed due to rest being accounted for in between trials, thus an interaction effect of OMNI-res score and time was not expected. The connectors subtask resulted in the highest OMNI-res scores for the entire task. All mean scores for each harness for each subtask fell under a "3", or "somewhat easy".

Table 9: OMNI-res scores (0-10) by subtask type and harness type.

Harness Type	Subtask	Mean	SD(+/-)
1	Orientation	1.40	0.059
	Retention	2.03	0.068
	Connectors	2.95	0.140
2	Orientation	1.43	0.038
	Retention	2.01	0.149
	Connectors	2.88	0.125

Chapter 5 Discussion

The objective of this thesis was to use different types of %efforts obtained from an automotive wire harnessing task to inform the RCRA tool and assess how different inputs influence ratio outputs. It was hypothesized that:

1) There will be no significant difference on RCRA outcome when either direct or indirect exposure measures are inputted, and;
2) There will be a significant increase in %effort (e.g., muscular activation, force) with harnesses of increased size.

The main findings were that 1) mean RCRA ratios exceeded recommended thresholds (>1) when using peak flexor, extensor and force %effort inputs, 2) There was a significant main effect of RCRA input type on RCRA output ratio, and 3) Pairwise comparisons revealed that RCRA ratios calculated from wrist extensor muscle activation are significantly different from those calculated using wrist flexor muscle activation, and applied force as inputs, and 4) Different harness types tested did not significantly differ the resulting RCRA ratio outputs when comparing the same %effort input type. The first hypothesis was partially supported, with flexor muscles and force inputs not being statistically different, however extensor muscles as an input was different. The second hypothesis was not supported, where different harness types did not result in significant differences.

The primary objective of this study was to determine whether valid and meaningful RCRA ratios could be generated using biomechanical input data derived from wrist flexor and extensor muscle activity and applied force during a wire harness installation task. Findings suggest that RCRA analysis of wiring harness work may yield similar insights when

informed with peak flexor EMG or peak force, supported by the lack of significant differences in RCRA output ratio between the two input types. However, using peak wrist extensor EMG as a RCRA tool input resulted very high RCRA ratios with the average being 37.49, suggesting that the rest required from the task is ~37x the rest provided based on the cycle time and effort duration.

Differences in RCRA outputs based on flexor or extensor EMG are likely related to their underlying EMG patterns. Flexor activation was characterized by a distinct "on-off" pattern of muscle activity (Figure 14), with bursts of high activation during gripping and insertions, separated with periods of rest or reduced activity. In contrast, the extensor muscles displayed a more sustained activation pattern, with frequent smaller bursts and relatively constant engagement (Figure 14). This likely reflects their stabilizing role during manipulation, where consistent posture and wrist control are required, even without strong force generation (Caumes et al., 2019). Differences in flexor and extensor muscles activation patterns during the task aligns with findings in literature and further suggests that wrist flexors will behave in a more task-dependant way, but extensor activity is likely not task dependent.

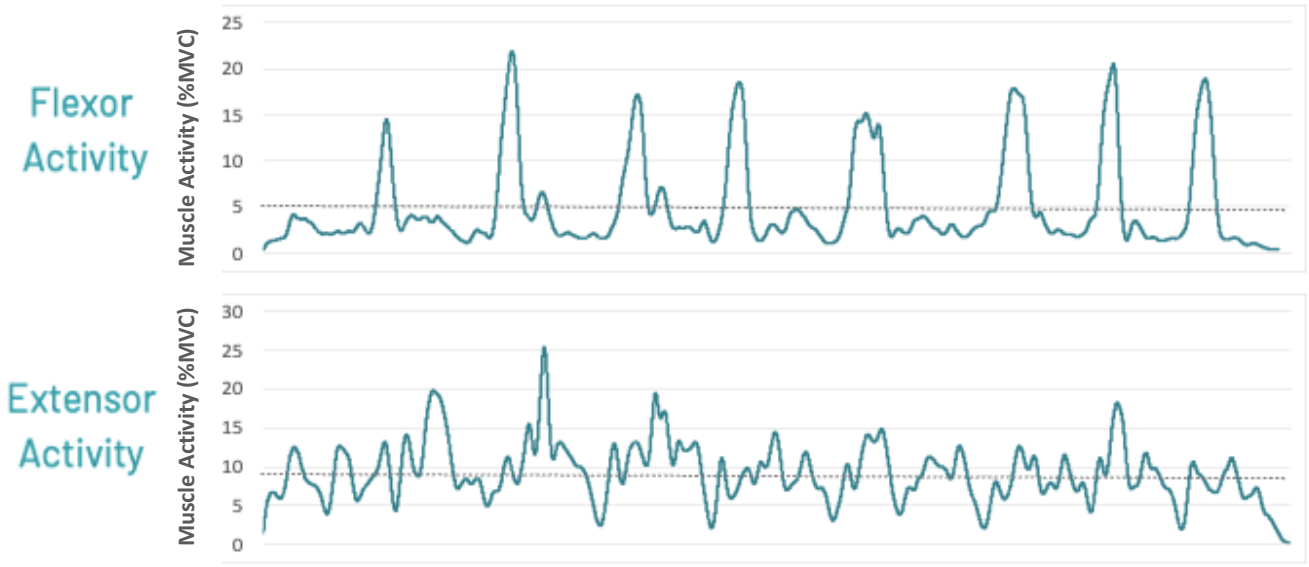


Figure 16: An exemplar time-series illustration of flexor (flexor capri radialis) and extensor (extensor carpi ulnaris) activity of the wrist during a wire harness installation. Mean activation is denotes with the dotted line. Flexor activity (top) shows an "on-off" pattern of activation with a lower average activity and extensor activity (bottom) shows more of a sustained activation type.

In literature, wrist extensors have been characterized to be exhibiting the highest activation when collecting wrist flexors and extensors. In typing tasks which also require a high amount of wrist movement, extensors have been found to be prone to fatigue (Lin et al., 2004). Although not identical, gaming and typing tasks exhibit a similar repetitive nature of constant hand and finger movement to a wire harness installation task, which has not yet been looked at in literature in terms of hand demands. Forman et al (2025) found significant fatigue of the extensors in a repetitive aiming/gaming task through changes in mean power frequency and median frequency. Additionally, they also found no performance metrics being caused by the fatiguing extensors. The harnessing task was performed by all

participants with an OMNI-res score with a mean of "somewhat easy" and less, suggesting that fatigue still may be accumulating even though performance or perceived effort is not changing. Specifically, extensor carpi ulnaris has also been shown to display the greatest muscle activity during repetitive wrist tasks such as aiming compared to other muscles of the upper extremity (Forman et al., 2024). This is not just characterizable to aiming tasks, handgrip and wrist force tasks have also shown that flexors highly behave task-dependant between conditions, but extensor activity is consistently high throughout the experiment to assist with co-contraction (Forman et al., 2021). Forman et al. in 2021 found moderate-to-high levels of constant muscle activity across nearly all conditions varying in handgrip force (0-60%) and wrist flexion or extension (0-60%) flexion/extension.

Wrist extensors have also been shown to become injured more frequently than wrist flexors, supported by the prevalence of a greater proportion of lateral epicondylitis versus medial epicondylitis (Shiri et al. 2006, 2007). Noting that extensor EMG activity was higher than flexor EMG activity (Tables 3&5), like in previous studies of hand intensive efforts, and the pattern of activity did not align well with subtask efforts, extensor EMG may not be a suitable way to characterize %effort in the context of using the RCRA.

Although the RCRA tool offers valuable insight into muscle fatigue risk by quantifying rest-to-work ratios, it may not be an ideal tool for assessing wrist extensor muscle demands. Despite this limitation, it is important not to dismiss the potential injury risk associated with sustained extensor activation. High extensor workloads when present across all participants and subtasks still may pose a chronic fatigue and overuse risk, particularly if recovery periods are inadequate. Therefore, alternative muscular fatigue assessments such as a gap

analysis (Hansson et al., 2000; Veiersted et al., 1990), mean power frequency analysis (Kwatny et al., 1970; Viitasalo & Komi, 1977) or ADPF analysis (Jonsson, 1978) may be used in future work to give more context into if the high extensor activity because of this task may be causing an accumulation of muscular fatigue.

Another relevant point of note is the introduction of outlier trials due to installation or connection errors. As seen in figure 15, outliers were present in participant data even with the averaging of trials to obtain final %efforts and effort durations and the use of familiarization trials. RCRA ratios exceeding recommended thresholds may be due to the equation requiring the maximum normalized muscle activity or force for each subtask (Potvin & Gibson, 2016). This practice of using the highest %effort required to complete a task to inform a ratio of rest required to rest provided suggests a "worse-case scenario" when calculating RCRA ratios and can inherently overestimate risk. It is important to note that the RCRA ratio uses duration and frequency of each effort multiplied by each other, and when either is increased slightly it can substantially increase the RCRA ratio (Equation 1).

$$t_{R/C} = \frac{(t_E)\,(f)}{[\,1 - E\,]^{4.167} + DC_{MIN}} - (t_E)\,(f)$$

Equation 1: RCRA tool (Potvin, 2012).33

Where:

$t_{R/C}$ = recovery time per cycle (seconds)
t_E = duration of each effort (seconds)
f = effort frequency
E = known effort (% maximum strength)
DC_{MIN} = 0.000035 representing the assumption that a 100% effort could be held for 1s each 8 hours

The introduction of potential outliers that can increase %effort or effort duration indicates that while some extreme task moments may demand more recovery than provided, the typical workload may be sustainable. For example, a prolonged insertion caused by a misaligned or stuck connector could significantly inflate the effort duration, thus inflating the RCRA ratio beyond typical values. Thus, it is important to capture multiple trials to better represent ongoing, real-world exposure as done in this thesis.

Despite discussions of feasibility of each %effort being used as an RCRA tool input, all inputs resulted in an RCRA ratio output greater than one. Exceeding an RCRA ratio of one suggests an accumulation of fatigue since the rest provided (total cycle duration minus total effort duration) is less than rest required (total effort duration combined with maximum acceptable duty cycle). Even though fatigue accumulation does not always result in injury or WMSD risk, links exist in literature (Kumar, 2001; Iridiastadi and Nussbaum, 2006). For instance, Kumar (2001) noted that cumulative physical fatigue is a contributing factor to overuse injuries, particularly in repetitive work environments. Similarly, Silverstein and Clark (2004) propose that managing fatigue could be an effective strategy for reducing MSD risk. Repetitive movements and insufficient rest are risk factors for musculoskeletal disorders (MSDs) and can cause muscle fatigue (Iridiastadi and Nussbaum, 2006). Based on the results from all input types, it is suggested that ergonomic intervention be required to reduce the RCRA ratios to below one.

The analysis done in this thesis found no statistically significant differences in RCRA outputs between both harness types. This lack of observed difference may be explained by the similar physical characteristics of the two harnesses. Both harnesses were within

approximately 6 cm in length and the same weight. Additionally, industry partners have confirmed that both harnesses are designed for use with the same engine model, although for different vehicle platforms, suggesting that functional handling and manipulation requirements during installation may not differ substantially. However, this finding should not be interpreted as evidence that harness design has no impact on biomechanical load. Rather, it focuses the need for larger variability in harness design to observe measurable differences. In real-world automotive assembly, significant harness variation can occur between engine configurations, for example, between smaller (1.0L-2.0L) and larger (3.0+L) engines, or between hybrid and combustion-only vehicles. These harnesses have larger differences in terms of wire density, bundle stiffness, and routing complexity, all which can influence the torque and force required by the operator to bend, route, and secure the harness in confined engine compartments (Trommnau et al., 2019). Thicker or denser harnesses may require more pronounced wrist deviation, firmer grip strength, and higher resistance during manipulation which can in turn increase muscle effort and fatigue risk based on work done on hand grip and manual tasks (Domizio & Kier, 2010; Keir & Mogk, 2005; Finneran & O'Sullivan, 2013), however there is a lack of research done on wire harness manipulation. As such, future research should explore larger harness variation in terms of size, material type and installation requirements.

5.1 RCRA Recommendations

Based on the findings and limitations identified in this study, several recommendations can be made to improve the future application of the RCRA tool in complex, multi-effort industrial tasks such as harness installation.

1) Use Task-Appropriate Input Types

This study demonstrated that RCRA outputs vary significantly depending on the selected input variable (e.g., force, flexor EMG, extensor EMG). Therefore, the input type must be carefully selected to best reflect the true biomechanical effort required by the task. For example, while peak force and peak flexor EMG may result in similar ratio outputs and interpretations on fatigue accumulation risk, extensor EMG does not. In tasks with mixed demand profiles (both forceful and postural), combining or comparing multiple inputs may offer a more balanced risk profile.

2) Consider Alternative Tools for Stabilizing Muscles

As discussed in above, the RCRA tool may not be well-suited to assessing muscles like the wrist extensors, whose sustained activity plays a critical stabilizing role during manipulation tasks. In such cases, using RCRA may overestimate risk due to inflated duration and frequency interactions, or underestimate it by missing fatigue accumulation from low-level sustained effort.

3) Use Multiple Trials to Obtain an Average of Task Demands

The multiplicative nature of the RCRA equation can magnify even small increases in task duration or repetition. As a result, task variants that include error recovery, misaligned components, or tool slips may yield disproportionately high RCRA values. Therefore, it is important to capture multiple trials of the task being done to ensure your inputs represent a pattern of behaviour. This will reduce any potential opportunities of one misalignment, etc. causing a non-physiological RCRA ratio result.

5.2 Limitations

Several limitations should be considered when interpreting the results of this study. Firstly, the RCRA tool relies heavily on accurate input values to calculate rest required (e.g., effort duration, %MVC or MVF), which can be sensitive to sensor placement, signal noise and participant behaviour. To attempt to reduce these variables as much as possible, care was taken to ensure electrode placement was done by the same principal investigator across all participants, and participants were given a maximum of ten familiarization trials to reduce any errors in harness installation caused by lack of task familiarity. Secondly, the task was done in a laboratory setting on a mock-engine compared to in in-field setting. Continuous discussions with industry partners took place to ensure all specifications of the engine and task requirements were done to ensure external validity, such as replacing male components of all clips and connectors after each participant, however it cannot be identical to the task on the line. Thus, it is important to note that this thesis looks at the utility of using the RCRA tool, not focusing on giving exact RCRA inputs or scores to industry partners to determine task acceptability. Finally, while multiple trials were collected, not all non-typical task conditions (e.g., misalignments, slips, or a connector getting stuck) could be fully standardized or excluded, meaning that occasional outlier events may have inflated some RCRA ratios, however averaging was done to minimize this. Again, familiarization trials were done to ensure these non-typical task conditions did not occur frequently, and multiple trials (10) were completed per harness type per participant to ensure consistency.

Chapter 6 Conclusion

This thesis set out to quantify the internal biomechanical demands of automotive electrical wire harness installation, a complex, repetitive task associated with emerging reports of hand and wrist musculoskeletal disorders (MSDs) among workers. Historically, this task has only been evaluated through external exposure measurements. To address this gap, the RCRA tool was applied using high-fidelity in-laboratory data such as electromyography and more practical in-field data such as applied force to assess exposure across subtasks.

The results demonstrated that RCRA ratios are highly sensitive to the input type, task duration, and frequency of muscular effort. Wrist flexors and applied force inputs produced similar estimates of required rest, while wrist extensor results were sometimes unreliable due to their unique activation patterns—characterized by sustained, stabilizing contractions that challenge the RCRA framework. Furthermore, while no significant differences were found between the two harness types used in this study, this may reflect similarities in design and handling requirements, rather than the broader influence of harness design on physical demand. Future work with more diverse harness configurations is warranted.

Despite limitations in applying RCRA to certain muscle groups, the tool showed similarities in informing the tool using wrist flexor inputs compared to usual %strength force inputs. This thesis also reinforces the need to supplement RCRA with alternate tools to interpret results, especially for stabilizing muscles. Future work should be done to assess risk of this task using a multimethod approach of ergonomics assessment tools to determine if all tools capture a similar “intervention required” result as the RCRA. Additionally, moment

wrench (Grieg & Wells, 2001) could also be used in the future to characterize functional strength of this task to expand on demands such as grip strength, etc.

In conclusion, this research offers practical recommendations and guidance for selecting appropriate input types when using the RCRA tool in complex automotive tasks.

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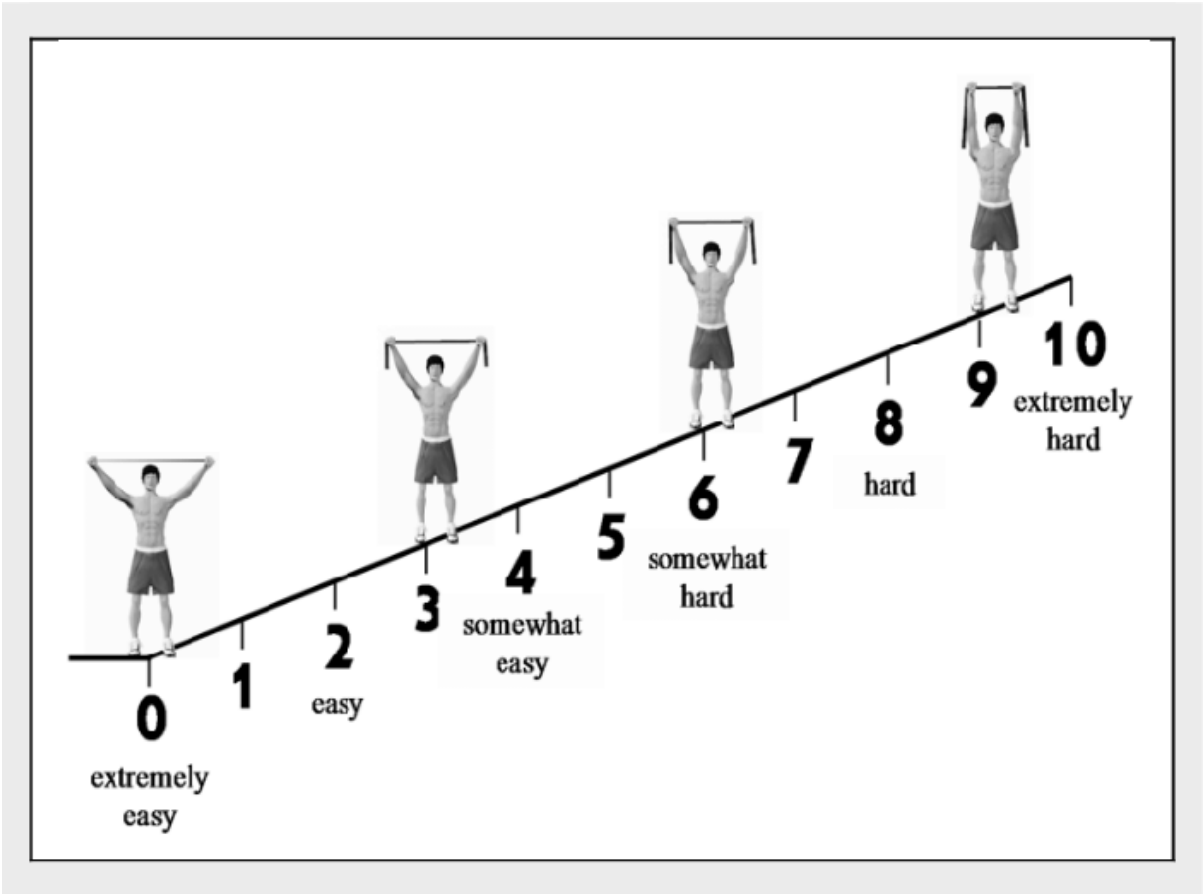
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Appendices

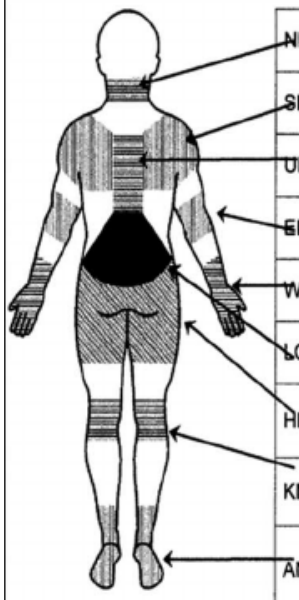
Appendix A

OMNI-Res Scale



Appendix B

Nordic Questionnaire



	Have you at any time during the last 12 months had trouble (such as ache, pain, discomfort, numbness) in:	During the last 12 months have you been prevented from carrying out normal activities (e.g. job, housework, hobbies) because of this trouble in:	During the last 12 months have you seen a physician for this condition:	During the last 7 days have you had trouble in:
NECK	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
SHOULDERS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
UPPER BACK	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
ELBOWS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
WRISTS/ HANDS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
LOWER BACK	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
HIPS/ THIGHS	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
KNEES	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes
ANKLES/ FEET	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes	☐ No ☐ Yes

Appendix C

Validation of a Force Plate Mould

This paper entails the validation of a rigid shape of an engine block to be attached onto a force plate on a table to show the forces applied.

A piece of equipment, hereby referred to as a “force plate mould”, can be used to mount the mock-engine block onto a 60cmx40cm force plate. If snug and rigid, all force applied to the engine block should translate into the force plate with the same direction and magnitude.

Validation: In laboratory, repeated bouts of force was applied with a dynamometer at around 50-60N to the top and sides of the engine block diagonally to determine force was not lost. Additionally, a 5lb weighted plate was applied and left to sit on the top of the engine block to validate magnitude of the force.

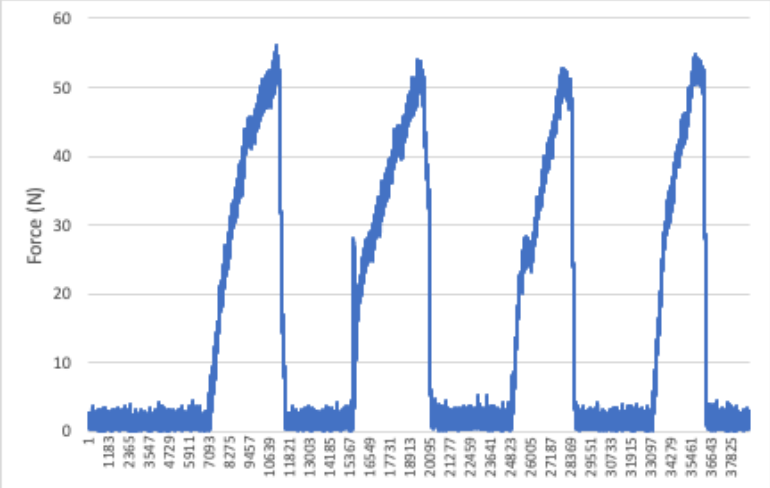


Figure 17: Approximately 50-60N applied at different points of the engine block (Each axis of force can be found in Appendix A).

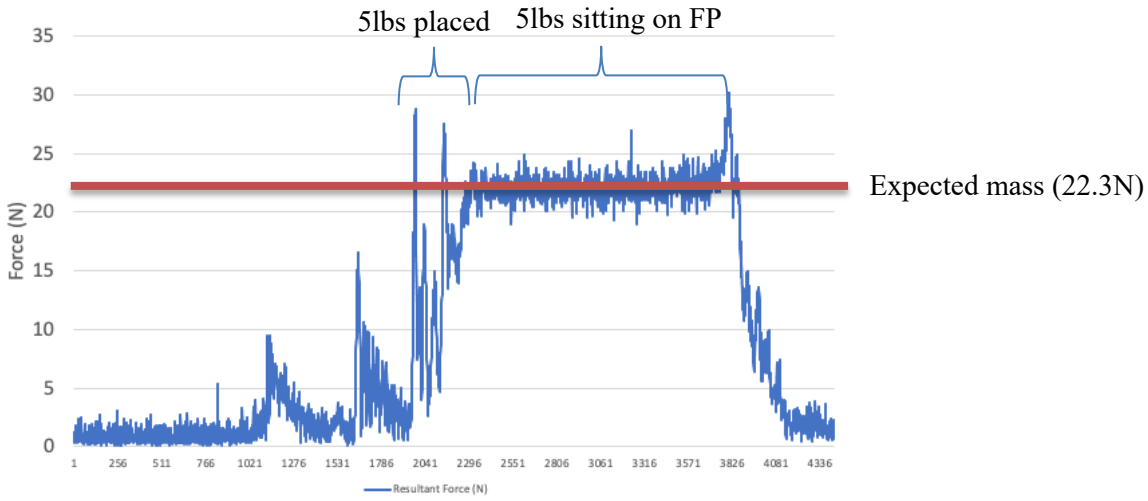
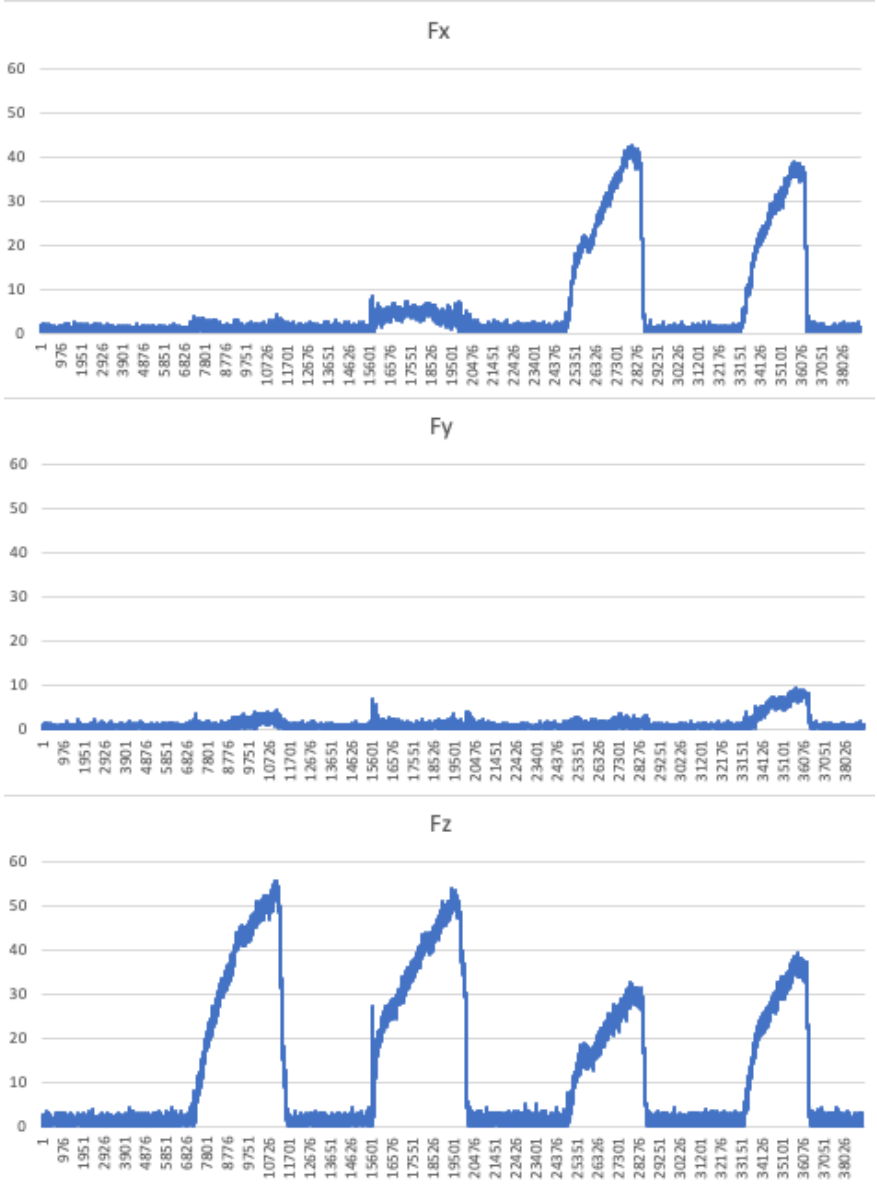


Figure 18: 5lbs (~22.3N) applied directly on top of the engine block.

Results from the validation testing showed resultant forces from the trials were accurate to what was done onto the mock-engine block. Forces obtained from force plate measurements reflect what was applied using a dynamometer or weighted plate. It is important to note that a mock force plate mould was used, so some shakiness of the data may be due to some shifting/flexion of materials.

Limitations: Not proper/rigid fitting (no padding/extra space allowed), properties of materials that force is being dissipated into (100% rigid), force plate adapter edges around force plate must never touch the table/ground.

50N of push force onto the rigid engine block in all directions. Note: First two pushes were straight down, second two were at ~45 degrees diagonal.



Appendix D

Residual Analysis (Winter, 2009)

A residual analysis was done on the force data after discovering presence of noise in raw force data due to vibrations of the force plate on the table and plastic on plastic vibrations when making a connection. A residual analysis was done on multiple resultant force trials during piloting using steps from Winter, 2009.

Steps:

1) Filter the raw data at each frequency over the test range. I tested every frequency between 1 and 50 Hz at 1 Hz intervals
2) After filtering at each frequency, calculate root mean squared error between data points
3) Create a plot with RMS error on y axis and frequency on x - axis
4) Based on multiple plots, determine cut-off frequency – 12Hz

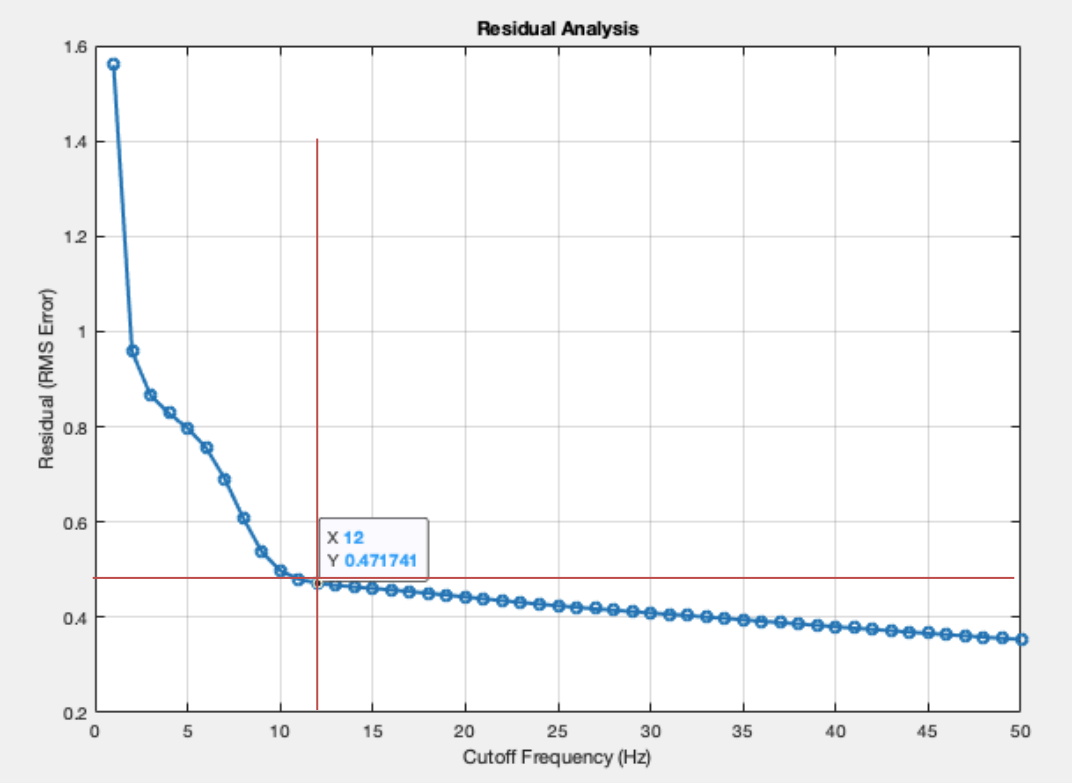


Figure 19:Example of residual analysis for one trial of pilot data.

Appendix E

Sex-Based Differences

Although sex differences were not a primary focus of this thesis, an exploratory analysis showed that females exhibited consistently higher RCRA ratios than males across all input types, suggesting greater fatigue accumulation.

Table 10: RCRA Ratio outputs based on input type and sex differences.

	RCRA Input Type		
Sex	**Flexors**	**Extensors**	**Force**
Females	3.13	60.83	2.33
Males	0.82	14.15	1.22

Specifically, female subjects were present in the highest 25th percent of RCRA ratios for: 85% of flexor inputs, 62% of extensor inputs and 69% of force inputs, showing that female participants made up the majority of high RCRA ratios and outliers.

Several factors may contribute to these findings, including lower absolute strength in females (resulting in higher relative effort), workstation height and posture differences and potential installation strategy differences that could have led to higher outlier inputs. Additionally, a small analysis of participant height on extensor activation was done to assess influence of height on extensor activation and a small trend on decreased activation on taller individuals was present, however a statistical analysis was not completed (Figure 19). Future work should be done on sex-based differences to suggest if differences in findings may be due to postural changes such as table height, or strength differences.

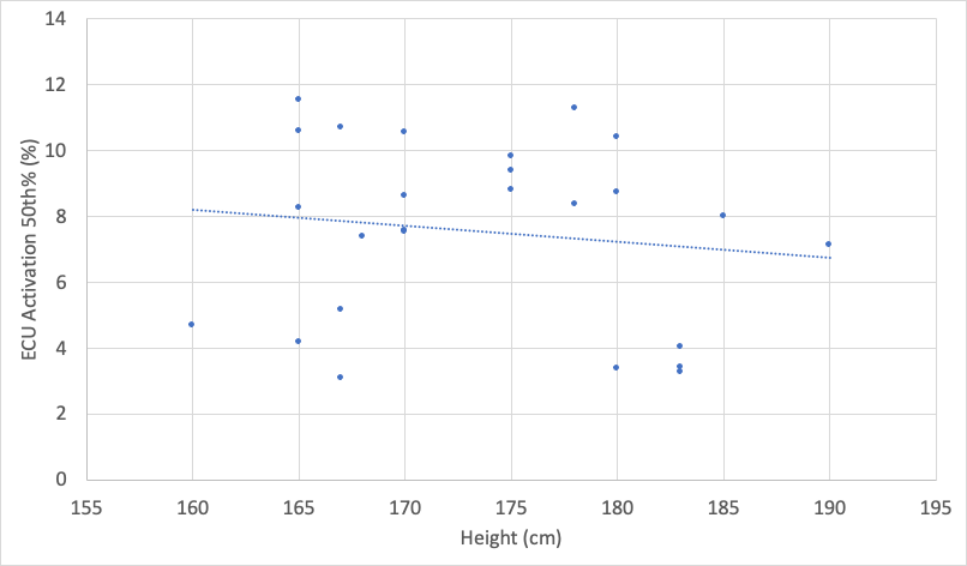


Figure 20: Height of participants on 50th percentile extensor carpi ulnaris muscle activation.