The Effects of a Reduced Force Aerial Bucket Control on Upper Extremity Muscular Demands as Assessed with Surface Electromyography

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by

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Abstract

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A common control for operating aerial bucket trucks for utility companies in North America is called a pistol grip control. Based upon many anecdotal reports of forearm muscle fatigue from workers using this control, Prof. Richard Marklin began an EPRI-sponsored study in 2016 using EMG to determine muscle fatigue of workers while they used the pistol grip. Muscle activity recorded by EMG is a measure of the magnitude of muscle force under controlled conditions. This study confirmed the reports of muscle fatigue in extensor digitorum communis (EDC) muscle in the right forearm. The next phase of the study was to design and build a self-contained, battery-powered replacement for the pistol grip that could reduce the required input force and therefore muscle fatigue in the EDC. This new design is called the reduced-force pistol grip. The reduced-force pistol grip was then tested in a 20-participant laboratory study using EMG to quantify the reduction in muscle fatigue of the right arm.

This laboratory study showed that there was a decrease in muscle activity of the right EDC while using the reduced force (50% reduced force) pistol grip as compared to a conventional force pistol grip currently used on utility trucks. The results of the truck to line full trials, which are the most representative of actual movements of the pistol grip in the field, showed that the reduction of 50% required input force produced a meaningful reduction in muscle activity of 5.6%. EMG results provide evidence that the reduced force pistol grip decreases the risk of muscle fatigue of line workers who operate the pistol grip. EMG results also corroborate reports of muscle fatigue from utility line workers who operate the pistol grip with conventional force levels. This study was the first to quantify muscular loading of an aerial bucket pistol grip control and results of the redesigned pistol grip show promise for improving the occupational health of electric utility line workers.

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1 Background and Rationale

1.1 Background

Aerial bucket trucks are essential vehicles for U.S. and Canadian electric utilities because workers use these trucks to access the overhead lines for maintenance and repair. Aerial trucks have a hydraulically powered boom that moves the worker who stands in a bucket in six directions – up/down, forward/rear, and angled to the right/left. A common control for operating the movement of the bucket is located inside the bucket (**Figure 1).** This aerial bucket control is called a "pistol grip" in the electrical industry. The pistol grip, referred to as original pistol grip in the rest of the thesis connects to the boom's hydraulic system via a plate on the hydraulic manifold's head in the bucket.

The original pistol grip control, which appears to have not changed significantly for at least 25 years by the major manufacturers (Altec and Terex), requires approximately 12 to 15 lbs. of manual force for a worker to move the control in any of the six directions (**Figure 2**), and these forces often have to be exerted for a long duration (60 sec or more). Overhead utility line workers have to operate this control many time per days, often exceeding 15 to 20 exertions per day. The magnitude and long duration of muscle force exertion has been reported by overhead utility workers to cause a significant level of muscle fatigue in the forearm muscles and may increase the risk of a musculoskeletal disorder (MSD) of the upper extremity, such as strains and tendinopathies.

This thesis project was part of a current, ongoing EPRI (Electric Power Research Institute) sponsored project at Marquette University to explore a new design of a pistol grip control with the objective to reduce the forces to operate a pistol grip control by 50% (a decrease to 6 to 8 lbs. external force). In theory, operating the pistol grip that requires less manual force will decrease the risk of muscle fatigue and possibly upper extremity MSDs in overhead electric utility line workers. This new pistol grip design is called a reduced force pistol grip control because it utilizes electrical energy from a portable and rechargeable 18 V battery that is already used to power line workers' tools to cut cables and make crimp connections.

Figure 1. *Aerial bucket truck (left) and common pistol grip control (right).*

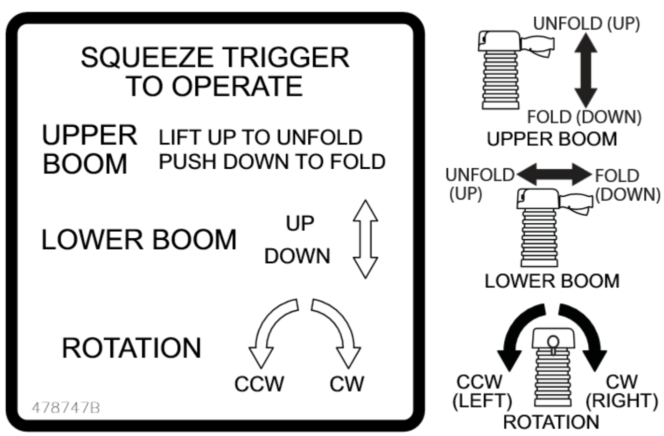


Figure 2. *Movements of the pistol grip control (Figure 1) to maneuver the bucket in six directions. (Terex)*

The objective of this study is to test the reduced force pistol grip control design in a laboratory setting. The new design is a self-contained unit that can be installed on buckets in new trucks or be retrofitted to most existing aerial trucks' hydraulic systems because the new design does not require any changes to common hydraulic systems. The basic truck hydraulic system can be seen in **Figure 3**. The reduced force pistol grip changes only the way that inputs are made to the hydraulic system while operating in the bucket. The electrical system of the reduced force pistol grip control is powered solely by the battery in an isolated system and does not increase the risk of electrical shock to the worker. The safety system for the bucket truck does not change; in addition to the worker in the bucket, another worker at the truck base has a set of valves that can control the bucket in the case of loss of power or loss of control from the operator in the bucket.

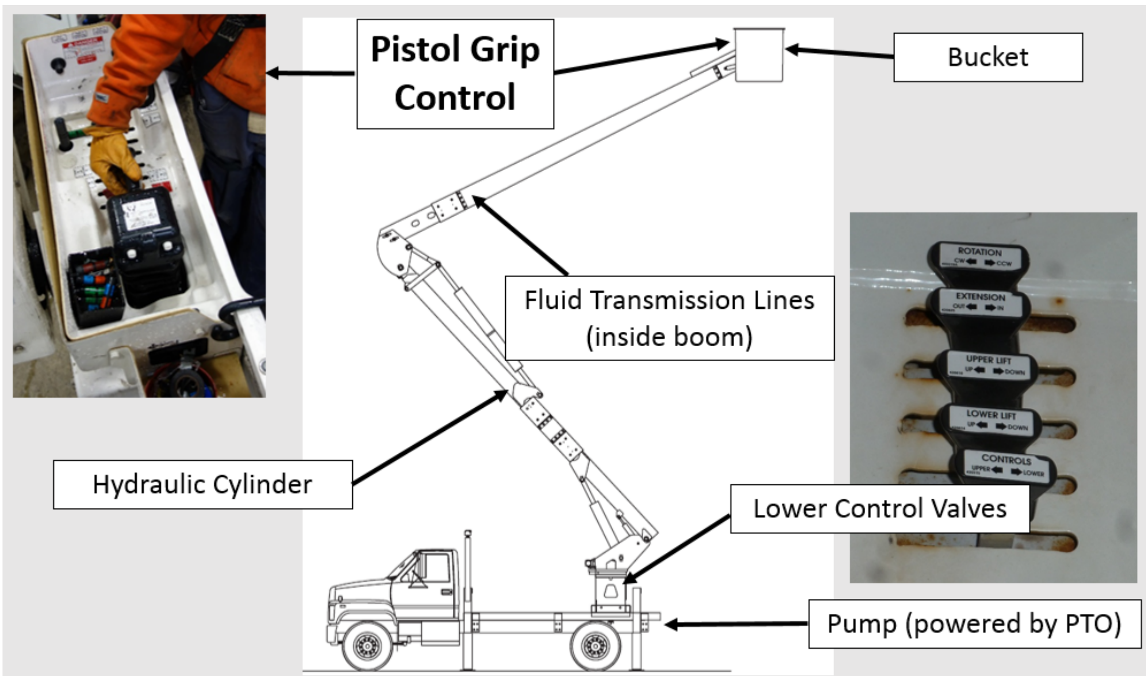


Figure 3. *Overview of complete hydraulic system for aerial bucket trucks.*

This study was broken up into two phases with three objectives.

Phase I:

Objective 1: Design a reduced force pistol grip control that reduces the required manual force substantially (by at least 50%) and uses a portable battery from common battery-powered tools to cut cable and make crimp connections. Results of the new design force requirements can be seen in **Table 1**. The new design should allow for installation on new trucks and as a retrofit to existing buckets with conventional truck hydraulic systems. A prototype of the new design is shown in **Figure 4** Jon Slightam designed and built version 1 of the prototype that this project was based on, version 1 of the prototype was never used in any testing. Version 2 of the prototype was the reduced force pistol grip used for testing in this thesis. Objective 2: In the laboratory, choose a percentage decrease in external force and select springs to achieve this force. Build pistol grip control and test as it maneuvers a 1/15 scale model (**Figure 5**) of a truck boom and bucket in two tasks: a) bucket movement in the six principal directions and b) elevation of the bucket from the truck platform to a 40 ft. overhead line in the scale model.

Phase II:

Objective 3: Quantify EMG signal amplitude of the four major muscles in the right (operating) arm to assess the amount of muscle force that is required to operate the new design of the pistol grip. Complete a 20-participant lab study measuring 50th and 90th percentiles of EMG activity for all four major muscles in right arm. Use these data to estimate the reduction of muscle force, and subsequently fatigue, resulting from workers using the reduced force pistol grip control.

Table 1. *Reduced and conventional pistol grip force data for 2016 field study and the present laboratory studies.*

	Conventional Force (100%)				Reduced Force (50%)			
	Field Results 2016 (lb) n = 14 trucks		Lab Prototype Results (lb) n = 3 trials		Field Results 2016 (lb) exactly 50% of field results*		Lab Prototype Results (lb) n = 3 trials	
Direction	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
UP	14.7	2.3	12.8	0.4	7.4	---	7.5	0.1
Down	13.5	3.5	12.3	0.3	6.8	---	5.7	0.2
Forward	12.7	3.4	13.8	0.1	6.4	---	6.6	0.4
Rearward	12.8	2.9	12.8	0.6	6.4	---	6.7	0.5
Clockwise	15.5	3.4	13.6	0.5	7.7	---	6.3	0.2
Counter Clockwise	13.8	2.1	12.4	0.3	6.9	---	6.4	0.2

*Calculated at 50% of the average force measured in field study (n=14).

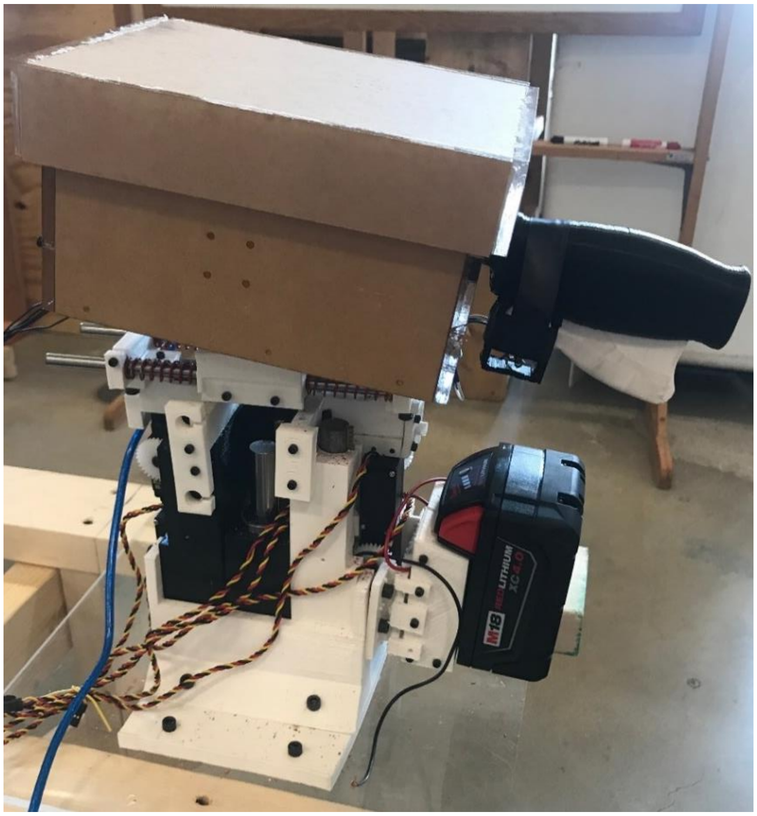


Figure 4. *Prototype of reduced force pistol grip that utilizes a portable 18V battery to reduce required manual force.*

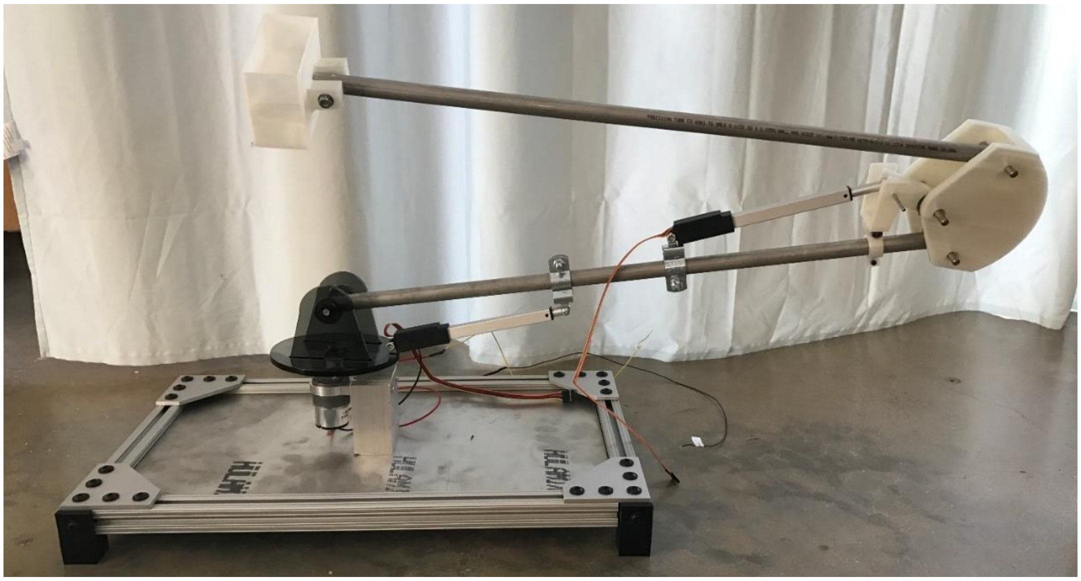


Figure 5. *Scale model (1/15) of a two-segmented boom and bucket. The reduced force pistol grip controls the movement of the boom segments. Both boom arms are 24 in long.*

1.2 Rationale

The current, ongoing EPRI study was motivated by anecdotal reports from overhead line workers that the pistol grip control causes significant muscle fatigue in the forearm muscles. Based on more than 20 site visits to U.S. and Canadian electric utilities from 1998-2010 on EPRI-sponsored ergonomics projects at Marquette University, overhead line workers frequently reported that the pistol grip control should be evaluated and redesigned to reduce the level of required force. When workers requested the redesign of the pistol grip, they often rubbed the extensor side of their forearm vigorously to emphasize the high level of muscle fatigue.

Redesign of the pistol grip control was the third most commonly suggested task for ergonomic evaluation from the line workers during the past 20 years, due to the pistol grip's required high arm force, long duration of exertion, and high frequency of use. The first and second most problematic tasks reported by overhead line workers were i) cutting cables and making wire connections with manual tools and ii) entering and exiting an aerial bucket. The first task was solved by battery-powered cutting and crimping tools and solutions to the second task were not feasible because ANSI standards regarding the design of an aerial bucket do not allow for bucket design changes, such as a door on the bucket.

2 Literature review

2.1 Literature Review of Muscle Fatigue from Hand Grip Exertions.

To date, to our knowledge, no studies in the published literature have evaluated the physical requirements to operate an aerial bucket pistol grip control. A literature review on muscle fatigue and endurance limits for hand grip exertions was done to gain an understanding of the previous work done.

Review of the physiology literature regarding muscle fatigue indicates that forearm muscle force greater than 10% MVC contributes to physiologic fatigue (Bjorksten and Jonsson, 1977), and 10% MVC contractions for the handgrip was considered unacceptable (Bystrom 1994). As muscle force increases, the buildup of physiologic fatigue increases, and exertions at higher levels of muscle force decrease substantially the time that a muscle force can be maintained. In addition to force level, the duration that a muscle exerts force above 10% MVC increases physiologic fatigue. The median EMG findings from the field study in 2016, which ranged from 11 to 42% MVC for the EDC muscle, provided physiologic evidence to support the anecdotal reports by line workers of fatigue in the forearm muscles after using the pistol grip control for repeated, long durations (often exceeding 60 s) to maneuver an aerial bucket.

According to the literature, there is an exponential decrease of time before fatigue based on percent MVC of maximal force (Sato 1984). Although forearm muscles were not tested in Sato's study, the trends in all muscles were similar. The relationship between percent MVC and endurance time as illustrated in **Figure 6** is very sensitive to changes in percent MVC. A small change in percent MVC can lead to a much longer endurance time (Sato, 1984). These figures show that the endurance time for a given percent MVC is larger than the time before pain and time before tiredness referred to as "Itai" and "Darui" in **Figure 6**, respectively. In terms of literature specifically on the forearm and grip strength it is known that muscle force over 10% MVC results in fatigue based on a lack of blood flow that occurs in the forearm above 10% MVC contraction levels (Bystrom, 1994).

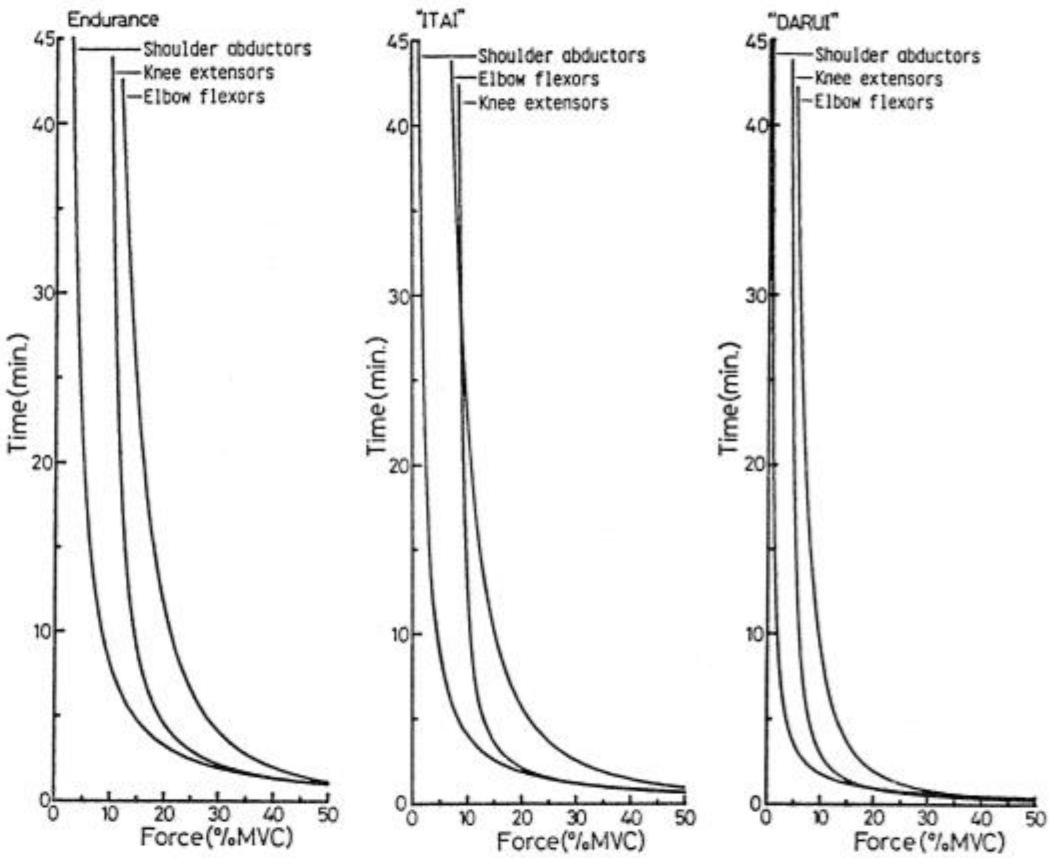


Figure 6. *Relation of time until endurance, pain, and tiredness to percent MVC. (Sato 1984).*

It is unclear how much time is required to reach fatigue based on the percent MVC for the forearm. There was published literature that gave models to predict the maximum endurance time (MET) based on the joint in the upper limb that was being evaluated (El Ahrache, 2006). Based on **Figure 6**, the MET is longer than the time until fatigue, which is the time of interest in this study. The specific model used was published by Manenica (1986) within the paper from Ma Liang (2009) for the hand and can be seen in equations **(1)** and **(2)**. For the subject who had 42% MVC in the field study, the MET would be 2.5 minutes. The pistol grip is used for, on average, 60 seconds to go from the truck to the line, which suggests that the pistol grip was contributing to muscle fatigue in the forearm muscles.

$$MET = 16.6099e^{-4.5fMVC} \quad \textbf{(1)}$$

$$fMVC = \frac{\%MVC}{100} \quad \textbf{(2)}$$

$$MET = 33.55(\%MVC)^{-1.61} \quad \textbf{(3)}$$

$$MET = 808.15e^{(\%MVC(-4.01))} \quad \textbf{(4)}$$

The above equation **(1)** and results are corroborated by Frey Law (2009). Frey Law's study used results from 754 participants that had hand grip EMG data and created two equations, **(3)** and **(4)**, that fit the data collected to predict endurance time for hand grip exertions. Equations **(3)** and **(4)** give results of 2.25 and 2.5 minutes respectively for the 42% MVC from the field study in 2016.

If equations **(1)**, **(3)**, and **(4)** are used to calculate the endurance time for the average of the medians for the field 2016 truck to line trials of 26% MVC, the endurance times are 5.2 min, 4.9 min, and 4.8 min respectively. The reason that percent MVC was chosen to be measured in this experiment was that muscle fatigue can be inferred from the endurance time and percent MVC of a muscle.

3 Phase I: Design and Function of Pistol Grip

3.1 Field Study 2016

The required external force and related muscular demands to operate the currently used pistol grip control were measured in 2016 in the initial phase of the current, ongoing EPRI study at Marquette University, and these results are available in the interim project report (Marklin et al., June 30, 2016). All field study results were recorded before this thesis began but were still part of the EPRI study. In that initial phase, in addition to quantifying the external forces required to operate the pistol grip (**Table 1**), electromyographic (EMG) signal amplitude of four major muscles in the arm of eight apprentice line workers was measured to assess the level of muscle force required to move the pistol grip. Specifically, the four muscles were the extensor digitorum communis (EDC) and the flexor digitorum superfiicialis (FDS) based on their prominent role to control wrist flexion and extension, and the biceps and triceps for their role to control elbow flexion and extension. Accordingly, these 4 muscles play a prominent role moving the pistol grip. The apprentice line workers maneuvered the bucket in two primary tasks -- movement of the bucket in six directions (up/down, forward/rearward, right/left) and elevating the bucket from its resting position on the truck bed to an overhead conductor on a 40 ft. tall pole.

EMG signal amplitude is a measure of the relative magnitude of force that a muscle exerts. The 50^{th} and 90^{th} percentiles of EMG signal amplitude during trials were calculated to provide median and peak levels of relative muscle force required to move the pistol grip. Line workers exerted approximately twice as much force in the EDC forearm muscle than the other three muscles in the two bucket tasks. The EDC is a primary muscle that extends the wrist (towards the wrist's back side) and contracts when a person grasps a handle tightly. The line workers exerted 14 to 30% of their maximal EDC force (%MVC – percentage of maximal voluntary contraction) to move the pistol grip in the six directions. Preliminary analysis of EMG data of the truck to overhead line task revealed that the median level of EDC EMG ranged from 11 to 42% MVC.

3.2 Objectives 1 and 2

A prototype of the reduced force pistol grip control was made with a 3-D printer (**Figure 4**). Details about the interior working of the pistol grip are discussed in section 3.3 of the thesis (the design was filed as a patent in Fall 2017). The pistol grip is briefly described here to familiarize the reader with the overall design.

The reduced force pistol grip handle is of the same size and form as the original pistol grip (**Figure 1**) and is operated in the same manner. A Milwaukee Tool 18 v lithium battery powers the control to reduce the manual force to move the bucket in six directions. This design mounts to the connection plate of the hydraulic head in the bucket with 4 bolts in the same manner as the original pistol grip control.

Removable springs are installed inside the housing of the redesigned pistol grip assembly such that the pistol grip can be used with two force settings: the original pistol grip force (12 to 15 lbs.) and a 50% reduced level of force. Less stiff springs will replace the higher force springs to mimic the reduced force. Selected spring force results are shown in **Table 1**. A Chatillon force measuring device was used to measure the forces in the 2016 field study and in the present laboratory study. The Chatillon can be seen in **Figure 7**. The forces were measured by connecting the Chatillon to the pistol grip by clamping it to the hand grip. The forward/rearward and up/down directions were measured by clamping the Chatillon in the same location each time and pushing or pulling the Chatillon in the proper direction to measure the force. The clockwise and counterclockwise direction forces were measured by clamping the Chatillon at a set distance of 2.5 in from the center and then measuring the force required to move it at that set distance.

Figure 7. *Chatillon force measuring setup for field study 2016. Same setup was used to test force for reduced force pistol grip in the laboratory. Measuring force for up/down direction (left). Measuring force for forward/rearward movement (right).*

3.3 Design and Function of Reduced Force Pistol Grip

The reduced force pistol grip's function was to reduce the amount of input force required from the user to actuate the hydraulic system on the aerial bucket truck, which in theory will reduce forearm muscle fatigue in line workers. The user's inputs to the pistol grip, which were mechanically linked to the hydraulic manifold, were separated from the hydraulic system. The hydraulic system was not changed in this design and can be seen in **Figure 8**, which shows no changes below the hydraulic manifold.

The user's inputs were recorded by sensors, off the shelf potentiometers, that were read by a microcontroller (Arduino Mega 2560). The Simulink block diagram used to control the Arduino Mega is shown and described in **Appendix D.** The microcontroller then sent signals to the correct pair of servos which were connected to the hydraulic manifold valves through a rack and pinion gear. The entire system was powered by an onboard battery that is the same type that a utility line worker would have access to while on the job site. The overall shape and function of the reduced force pistol grip was the same as the current pistol grip used in the field.

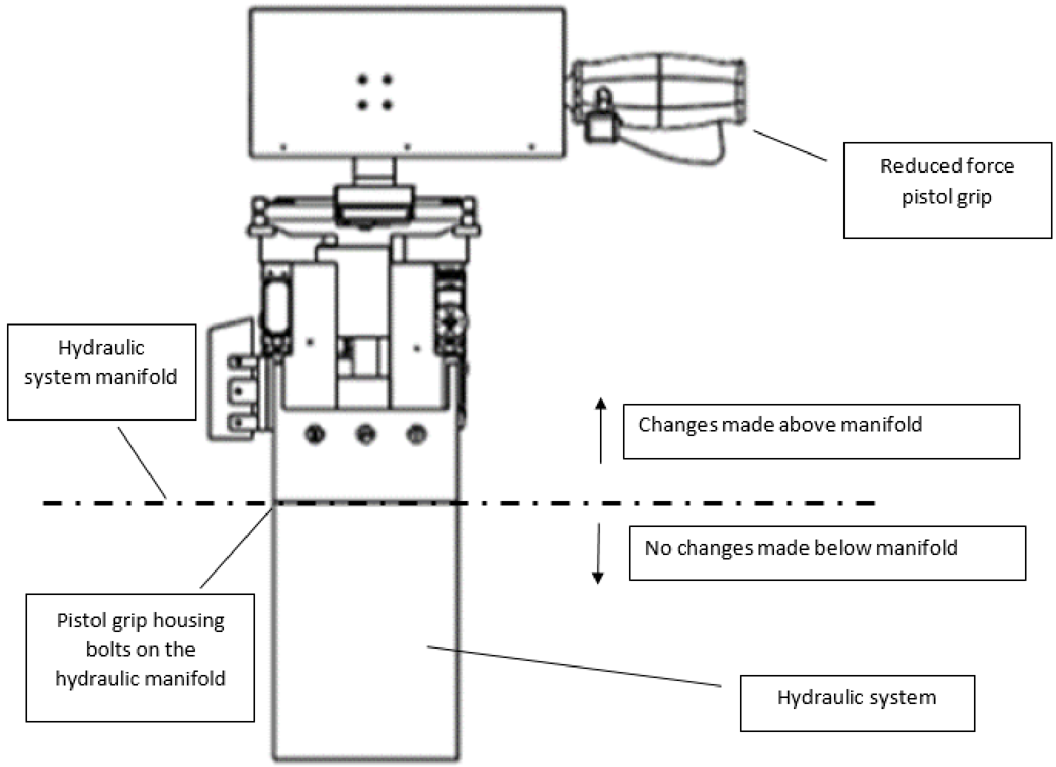


Figure 8*. Reduced force pistol grip schematic showing where changes were made. (Marklin et al., Electrical Power)*

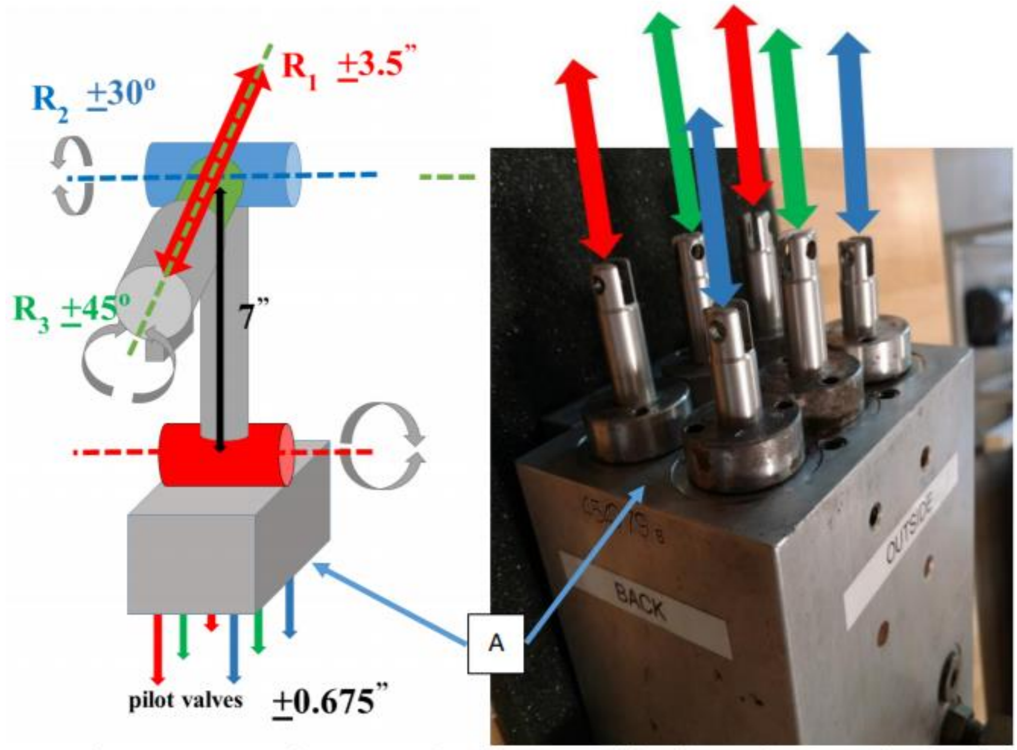


Figure 9. *Directional movements of pistol grip and corresponding valve movements on hydraulic system.*

The directional movements and corresponding valve movements can be seen in **Figure 9**. Each movement has a maximum value for the angle it can move, or in the case of the forward/rearward motion a maximum travel distance. The directional movements were not changed from the pistol grip to the reduced force pistol grip. Each directional movement is attached to two specific hydraulic valves as illustrated in **Figure 9**. The entire system can be seen in **Figure 10**, the reduced force pistol grip has the same bolt holes that mount onto the hydraulic system as the current pistol grip used in the field. This allows for the redesigned pistol grip to be connected to trucks that are currently in the field as well as new trucks. The servo drive system is the output from the reduced force pistol grip that moves the hydraulic valves in the manifold. The servo drive system is revealed in **Figure 11** which shows a closeup of how the rack and pinion shafts connect to each hydraulic valve.

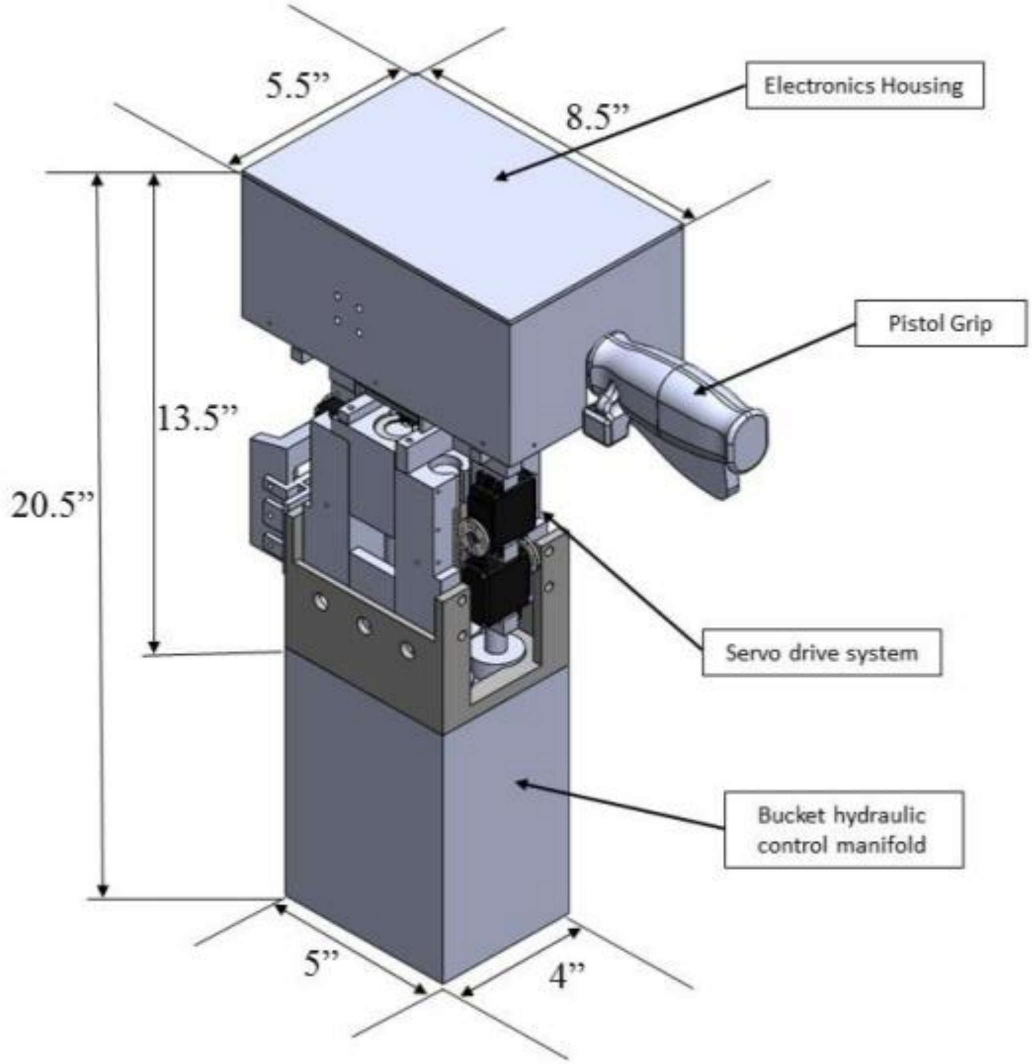


Figure 10. *Pistol grip CAD shown attached to hydraulic system. (Marklin et al., Electrical Power)*

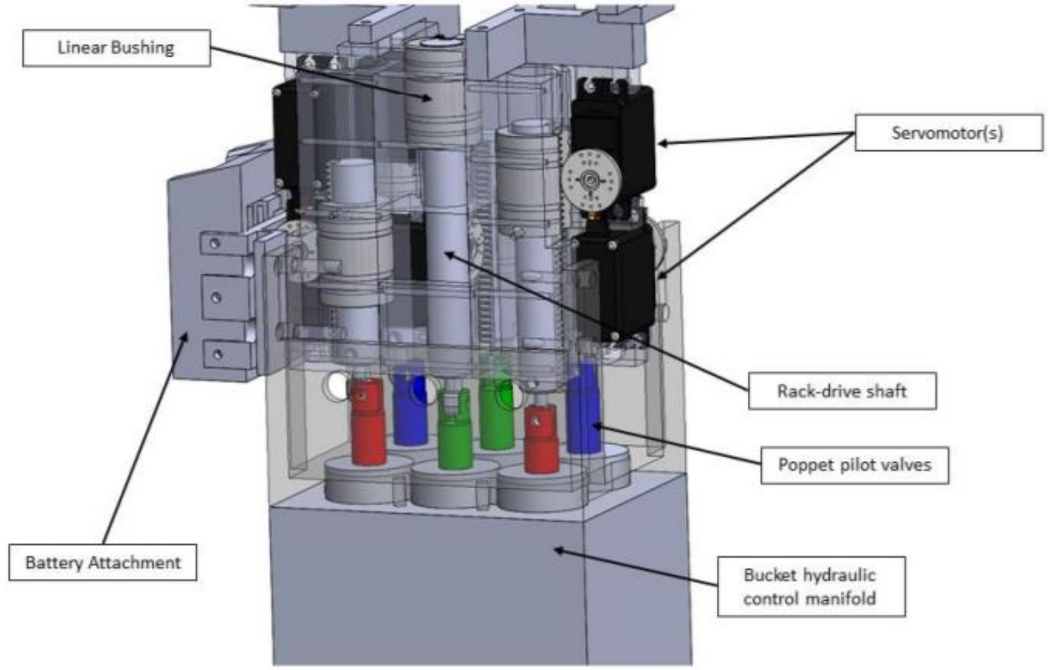


Figure 11. *Expanded view of servo, rack and pinion, and hydraulic valve connections. (Marklin et al., Electrical Power)*

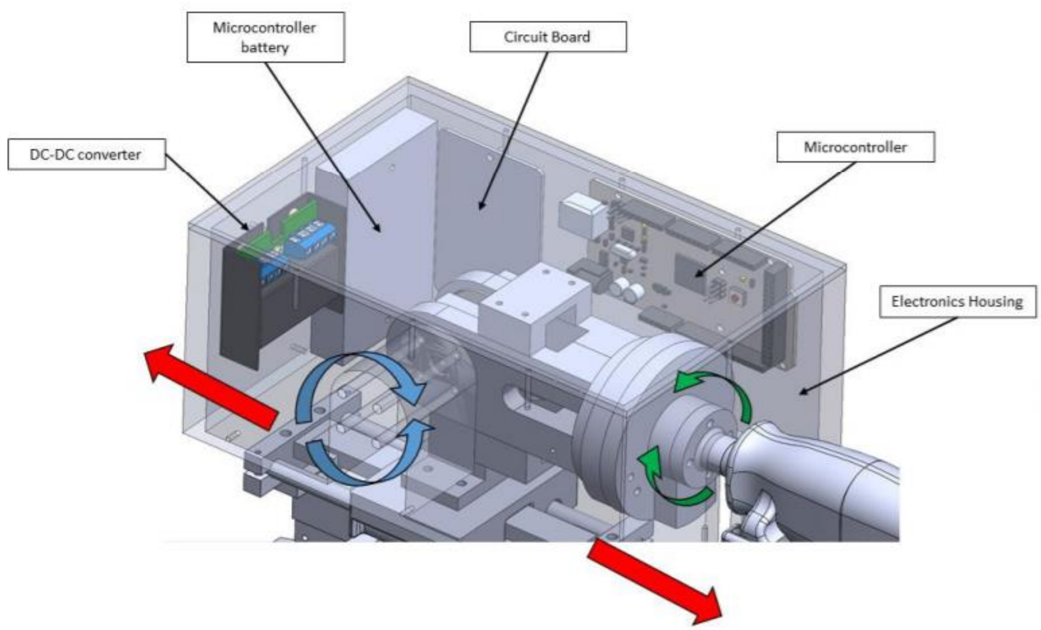


Figure 12. *Expanded view of pistol grip interior mounting of components. (Marklin et al., Electrical Power)*

The electrical and control components can be seen in **Figure 12**. The microcontroller receives signals from the sensors and uses a proportional control to send signals to the servo motors. The sensors that were used were off the shelf potentiometers due to the ease of installation and vast supply of replacement components. There was one sensor for each of the three directional movements and a final sensor in the dead man's switch. The dead man's switch was not only an on/off signal but also contributed to the proportional signal of the servos. The proportional constants could be tuned during field testing to achieve smooth motion of the bucket truck. The DC-DC converter allowed for two voltages to be used for the system, one voltage for powering the microcontroller and one for powering the servo motors. All programming of the Arduino Mega 2560 was done through Simulink in Matlab, these are all shown in **Appendix D**.

The electrical system for the laboratory prototype was powered from a 110V outlet due to the extra power consumption of running the scale model of the bucket truck. A field model could be powered completely through the on-board 18V battery.

The on-board battery life was calculated for the reduced force pistol grip for field use. The standard M18 Milwaukee Tool battery pack, which is an 18V battery pack with 4.0 amp-hours, was used in the battery life calculations. The assumptions used as well as calculations are listed in **Appendix C**. This particular M18 battery will last for 40 eight hour working shifts, or about two months of working one 8-hour shift every work day.

4 Thesis Research Objective

Quantify EMG signal amplitude of the four major muscles in the right (operating) arm to assess the amount of muscle force that is required to operate the new design of the pistol grip. Complete a 20 participant lab study measuring 50^{th} and 90^{th} percentiles of EMG activity for all four major muscles in right arm. Use these data to estimate the reduction of muscle force, and subsequently fatigue, resulting from workers using the reduced force pistol grip control. Calculate the results from a paired t-test and two t-tests shown below.

- Paired t-test: laboratory conventional force vs laboratory reduced force.
- T-test: field study vs laboratory reduced force.
- T-test: field study vs laboratory conventional force.

5 Phase II: Laboratory Study of Reduced Force Pistol Grip

5.1 Experimental Design

A set of paired t-test and two unpaired t-tests was employed to quantify the EMG signal amplitude of four major right (operating) arm muscles that play a prominent role operating the pistol grip. A paired t-test design is one in which all the participants perform all the experimental conditions, as shown in part of **Table 2**. There was one independent variable: pistol grip force (2 levels: conventional force and reduced force). There were two tasks: movement types (movement in six directions and elevation from truck platform to overhead line). The primary dependent variable was EMG normalized to maximum activity (percent MVC) of each of the four right arm muscles the 50^{th} and 90^{th} percentiles of EMG activity will be used in the analysis. The paired t-test will look for significant differences between the two levels of conventional and reduced force for every condition. This will result in 10 paired t-tests for each muscle group, one for each directional movement and four for the truck to line movements (phases 1, 2, 3 of movement and the full trial). The two-unpaired t-tests will look for significant differences between the two levels done in this study (conventional and reduced) and the field study 2016. Each of these unpaired t-test resulted in 10 t-tests for each muscle group just as the paired t-test. Other dependent variables include subjective assessment of ease of use and physical effort of each task.

The truck to line phases were selected based off the apprentice line workers use of the bucket truck in the 2016 field study. The phases are listed below.

Phase 1: vertical ascent only. The bucket was only moving up or forward

Phase 2: vertical ascent and rotation. The bucket was moving up or forward and rotating.

Phase 3: rotation only. The bucket was rotating only.

Phase 4: final positioning (not used as it was not possible to do final positioning corrections on a 1/15 scale model).

Full Trial: The full trial averaged based on time in each phase.

Table 2. *Experimental design of the study to measure EMG activity required to operate the pistol grip control under two force levels and in two tasks.*

Tasks	**Lab Conventional Force: 12 to 15 lb**	**Lab Reduced Force: 6 to 8 lb.**	**Field Study 2016***
Task 1: Move scale model of bucket in 6 directions	Set 1 (20) subjects (M & F)	Set 1 (20) subjects (M & F)	Set 2 (8) Subjects (M)
Task 2: Elevate scale model of bucket from truck platform to height of overhead line	Set 1 (20) subjects (M & F)	Set 1 (20) subjects (M & F)	Set 2 (8) Subjects (M)

* Study completed previously to the start of this thesis research.

5.2 Equipment and Experimental Setup

The same muscles that were monitored with EMG surface electrodes on the eight apprentice line workers in the 2016 field study were monitored in this study. The four right arm muscles are shown in **Figure 13** and are the following:

1) Flexor digitorum superficialis (FDS) – this muscle is on the palm side of the forearm and has the ability to flex (bend) the proximal interphalangeal joints, the metacarpophalangeal joints, and the wrist.
2) Extensor digitorum communis (EDC) – this muscle is on the dorsal side of the forearm and has the ability to extend (straighten) the fingers at the metacarpophalangeal joints and extend the wrist.
3) Biceps – this muscle flexes the elbow joint (moves the hand to the shoulder).
4) Triceps – this muscle extends the elbow joint (moves the hand away from the shoulder).

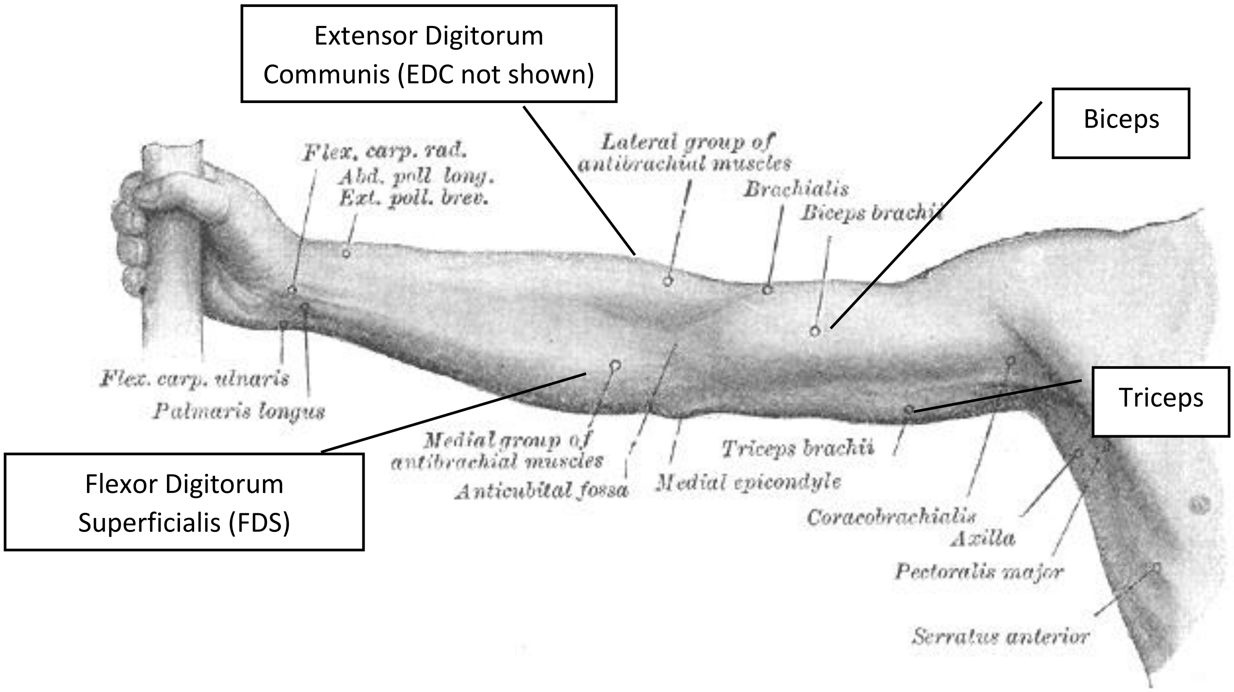


Figure 13. *Upper extremity muscle locations used for EMG data for laboratory and field study. (Marklin et al., Aerial Bucket)*

These four muscles were selected because the FDS and EDC are the principal muscles to exert a power grip force on the pistol grip control and the biceps and triceps move the wrist holding the pistol grip handle up/down and forward/rearward.

The pistol grip was tested with the subject operating the control to move the scale model of the boom and bucket at a proportional rate as an actual boom. Specifically, the time that it takes to move an actual bucket from the truck bed to the height of a 40 ft. overhead line, approximately 60 sec or longer, was the same with the scale model as an actual truck boom and bucket. The laboratory setup can be seen in **Figure 14**. The test stand was built to mount the pistol grip control at the same height as the pistol grip height measured in the bucket truck (36 in).

Figure 14. *Laboratory setup of the 1/15th scale model bucket truck with power line and pistol grip mounted to laboratory test stand.*

EMG signals of four right arm muscles was measured with Biometrics Ltd. (Gwent, UK) integral differential surface EMG sensors (model SX230) (**Figure 15**). The EMG sensors were connected to a Biometrics Ltd. Data Logger, which was strapped to the subject's belt and transmitted EMG data wirelessly to a computer via Bluetooth. Biometrics Ltd. data management software recorded and processed the signals and stored the data for subsequent analysis. Specifications of the EMG sensors and data acquisition system are the following:

- Inter-electrode distance is 20 mm on each surface bipolar unit (**Figure 15,** left).
- The EMG surface electrode's gain is 1000 with a bandwidth from 20 to 450 Hz. Input impedance is greater than 10^{15} ohms, and the common mode rejection ratio at 60 Hz is greater than 96 DB.
- The reference electrode is attached at the ulnar styloid process of the right elbow.

Raw EMG signals in volts was collected at a sampling rate of 1000 Hz and converted to RMS voltage with software. The time window used to compute RMS of raw EMG signals at each time point was 200 ms, which smoothed the RMS EMG trace over time but maintained the responsiveness of the signal.

Figure 15. *Biometrics Ltd. surface EMG sensor (left) and data log unit (right). The EMG sensors are connected to the data log unit, which transmits EMG data wirelessly to a computer via bluetooth.*

The other equipment used in this study was the reduced force pistol grip, which was described in section 3.3, and the scale model of the bucket truck and power line (**Figure 14**).

5.3 Experimental Procedure

Testing took place in the east side of Ergonomics Laboratory, room 369 of Engineering Hall, where curtains were drawn to protect the privacy of the subject. The Subject grasped the pistol grip with the right hand. The scale model of the truck boom and bucket was placed directly in front of the subject. An overhead line was placed above the truck and boom at a height that is proportional to an actual 40 ft. tall line. The truck and boom was positioned such that the bucket faces away from the rear of the truck to replicate the view of a worker standing in the bucket. The entire laboratory setup can be seen in **Figure 14**.

The procedure for subject testing was as follows:

1 Subject signed the Human Consent Form and completed other forms with questions about general health, demographics, and occupation.

2 EMG electrodes were attached to the skin overlying the four muscles on the right arm. Maximal exertions for each muscle were recorded to establish a maximum level of EMG signal amplitude and for subsequent normalization to percent MVC.

3 The presentation order of levels of the independent variables was counterbalanced to control for order, fatigue, and learning effects. For example, the pistol grip force level alternated between subjects such that the first subject started with all the tasks for the 12 to 15 lbs. force and then proceeded to the reduced force tasks. The second subject operated the pistol grip in reverse order of force. Within each pistol grip force, the presentation order of the six tasks was counterbalanced.

4 Subject practiced operating the pistol grip to move the scaled boom in all the directions of the two tasks, namely up/down, forward/rear, and right/left for the first task, and from the truck platform to an overhead line in the second task.

5 Subject performed the experimental conditions shown in **Table 2** according to his/her assigned presentation order. Directional conditions were done two times and truck to line trials were done three times each. The subject could rest as needed between trials and was given as many practice attempts as needed to understand how the pistol grip moved the bucket.

6 After all testing was complete, subject filled out forms that assess subjective assessment of ease of use and physical effort.

7 EMG electrodes were removed, and skin was cleaned.

8 Subject anthropometry data and grip strength were measured and recorded.

5.4 Subjects

The number of human subjects in this study was 20, which was calculated by a priori statistical power analysis for the paired t-test as the minimum number of subjects to minimize the type I error (probability of a false positive) to 0.05 and type II error (false negative) to 0.20 (which results in at least 80% statistical power) (Montgomery, 1991). Statistical power is the probability that a correct conclusion is made, i.e. a false null hypothesis is rejected, thereby concluding that the alternate hypothesis is true. A minimum of 80% statistical power is accepted by the human factors and ergonomics profession.

(Null Hypothesis) $H_o: \mu_1 = \mu_2$

(Alternate Hypothesis) $H_A: \mu_1 \neq \mu_2$

In this study, if the means of the conventional force and the reduced force conditions (μ_1 and μ_2) are different then the null hypothesis should be rejected; if it is not rejected that would be an example of type II error. If the means of the conventional force and reduced force conditions are the same, then the null hypothesis should be accepted; if it is rejected then that would be an example of type I error.

Volunteer male and female subjects were recruited from the Marquette University student body and staff. Eighteen males and two females participated in the experiment. Each volunteer subject was paid $50 for participation. Requirements of subjects for participation in the study were the following:

- Sign a Human Consent Form, approved by the Marquette University Institutional Review Board (IRB)
- Age range from 18 to 65 years old
- No existing or pre-existing injuries or physical ailments that could be exacerbated by participation in the study
- Overall good musculoskeletal health and mobility of upper extremities
- At least 20/20 aided vision

5.5 Presentation Order of Experimental Conditions

The testing order was a Latin Square design for an experiment, which eliminates carry-over and order effects. The presentation order is shown in **Table 10** in **Appendix A**, and this pattern repeated every 3 subjects. Test 1 denotes the reduced force condition while test 2 denotes the conventional force condition (D'Amato 1970). The directional trials were done two times each while the truck to line trials were done three times each. The participants practiced using the pistol grip as needed to understand how it works. The participants were also allowed to rest as needed between trials.

5.6 Data Conditioning and Statistical Analysis

All the EMG voltage data, both 50th and 90th percentiles, were conditioned and then normalized to percent MVC using the protocol in NIOSH (1992). This was done using the Datalink and Datalog software packages from Biometrics. The data were then normalized for each subject to percent MVC using equation **(5)**. The resting voltage was close to zero for every subject and therefore the equation was simplified to exclude that term. The data for the trials for each participant was averaged to give one value per condition for 50th and 90th percentiles. Then the data were analyzed with Minitab using paired and unpaired t-tests because the data are continuous and ratio scale. T-tests determine if is a statistical difference between two conditions. The statistical power was then calculated for every test using the G*Power program.

$$\%MVC = \frac{V_{task} - V_{rest}}{V_{max} - V_{rest}} = \frac{V_{task}}{V_{max}} \quad \textbf{(5)}$$

The subjective assessment data were analyzed with the nonparametric Friedman's test because these data were ordinal and as such should not be analyzed with ANOVA. In this study, it was assumed that the subjective assessment was not a ratio scale because it cannot be assumed that the Borg scale or Likert scale had a constant distance between successive pairs (Borg 1998).

6 Results

6.1 Subject Anthropometry

The subject anthropometry data can be seen in **Table 12** in **Appendix A**, and the field study 2016 subject anthropometry data can be seen in **Table 11** in **Appendix A**. Basic anthropometric measures between the laboratory and field study subjects are summarized below:

- The average height of the laboratory study (±SD) was 182.1 (±8.3) cm while the field study in 2016 had an average of 182.4 (±5.0) cm. The heights of subjects in the laboratory study ranged from 167.7 to 200.6 cm and the range for the 2016 field study was 176.6 to 190.0 cm.
- The average weight of the laboratory study (±SD) was 184.6 (±28.6) lb. while the field study in 2016 had an average of 195 (±46.0) lb. The laboratory study subjects' weight ranged from 130 to 245.0 lb. and ranged from 150 to 300 lb. for the field study.
- The average grip strength of the laboratory study (±SD) is 98.4 (±22.9) lb. while the field study in 2016 had an average of 132.05 (±12.1) lb. The grip strength in the laboratory study ranged from 57.5 to 135.0 lb., and in the field study the range was 116.3 to 147.1 lb.
- The remainder of the rest of the anthropometric variables measured had similar values between the laboratory and field studies.

6.2 Statistical Tests of EMG Muscle Activity

Hypothesis testing was conducted to determine if there were statistically significant differences in means of EMG activity of the four muscles between pairs of the three experimental conditions. A p-level of 0.05 was selected as the maximum allowable Type I error (false positive). Three t-tests were conducted:

- Paired t-test: laboratory conventional force vs laboratory reduced force.
- T-test: field study vs laboratory reduced force.
- T-test: field study vs laboratory conventional force.

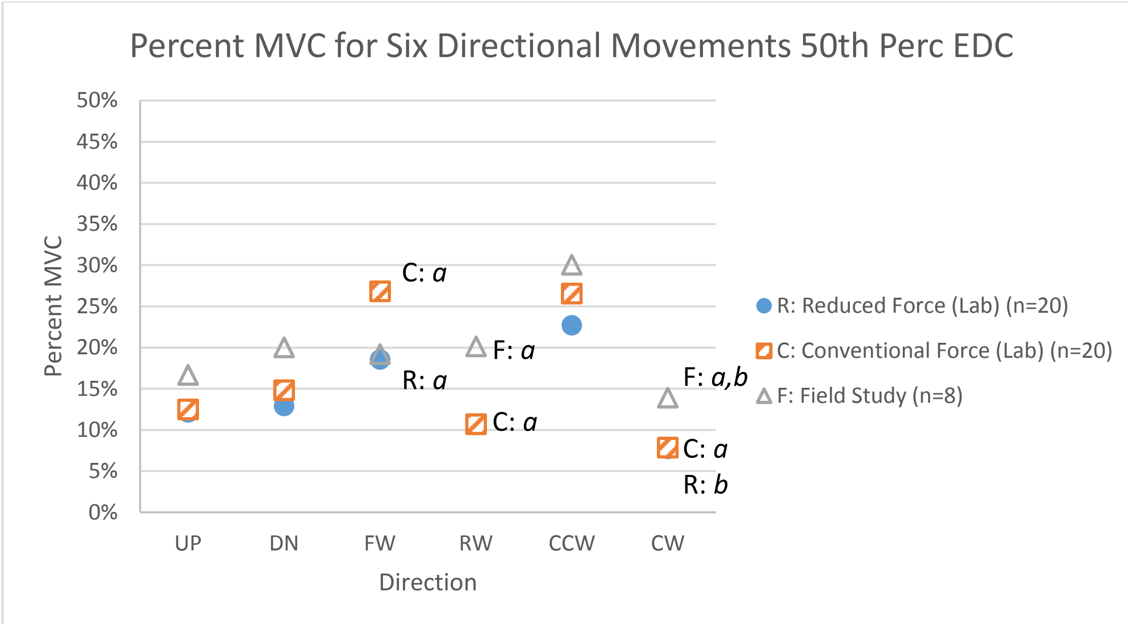
A paired t-test was conducted for the two laboratory pistol force levels (conventional and reduced) because the same 20 subjects performed these two conditions. A regular t-test (unpaired) was conducted to see if there were differences between a laboratory force condition and the field test because the subjects were different people (20 college students in laboratory study vs. eight apprentice line workers in field study).

6.3 T-Tests of EMG Muscle Activity from Six Directional Movements

All figures and tables use the following acronyms for the six directions of movement of the pistol grip: down (DN), up (UP), forward (FW), rearward (RW), counter clockwise (CCW), clockwise (CW). In the figures showing the plotted means of the experimental conditions, significant differences are indicated with letters next to the plotted means. Means with the same letter indicate that there is a significant difference between the two means.

The EMG activity for the EDC muscle will be reported in this section because these results generally showed the greatest difference among the two laboratory force conditions and the 2016 field study. As such, **Figure 16** reveals the 50^{th} and 90^{th} percentile of the EDC muscle in this section while the results of EMG activity for the other three muscles (FDS, biceps, and triceps) are shown in figures and tables in **Appendix A**. Summary statistics of EMG results for the laboratory study are shown in **Table 3** while the EMG results for the field study are shown in **Table 4**.

As indicated in **Figure 16** the mean 50^{th} percentile of the EDC muscle activity for the forward direction was approximately 27% MVC for the conventional force, which was about 10% greater than the reduced force condition. For rearward and clockwise movements, the percent MVC of the EDC in the field study was about 7% MVC greater than the conventional force and reduced force conditions (means of 14% vs. 7%, respectively). There were no other differences between pairs of mean EMG activity for the 50^{th} percentile EDC muscle activity. There were more significant differences among pairs of means for 90^{th} percentile EDC EMG (**Figure 16**), with the field study showing greater EMG activity than the other two conditions for the up, down, and rearward movements.



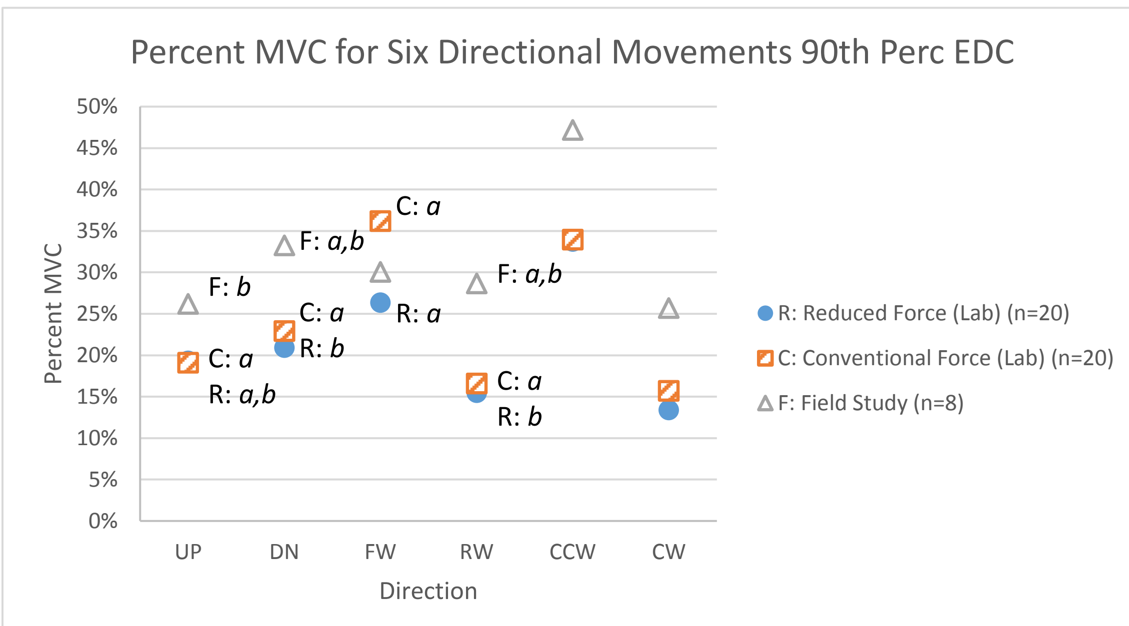


Figure 16. *Percent MVC for six directional movements for 50th and 90th percentile for EDC muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05.*

Table 3. *Percent MVC for six directional movements summary statistics for laboratory reduced force and laboratory conventional force conditions.*

			Lab Reduced Force Condition						Lab Conventional Force Condition					
			UP	DN	FW	RW	CCW	CW	UP	DN	FW	RW	CCW	CW
FDS	50th Percentile	Mean	**10.69%**	**5.89%**	**9.16%**	**8.65%**	**13.89%**	**13.83%**	**12.40%**	**6.23%**	**11.82%**	**10.78%**	**16.28%**	**15.58%**
		SD	8.94%	3.43%	6.76%	5.08%	9.40%	10.47%	12.42%	3.21%	7.56%	6.46%	8.66%	9.76%
		Min	3.27%	2.10%	2.64%	2.60%	2.99%	3.90%	2.77%	2.54%	3.25%	3.16%	3.60%	3.87%
		Max	35.56%	15.34%	30.35%	20.82%	33.20%	46.85%	59.00%	12.75%	30.21%	24.49%	30.04%	33.48%
	90th Percentile	Mean	**17.39%**	**10.18%**	**13.71%**	**12.86%**	**21.85%**	**20.95%**	**14.80%**	**10.52%**	**16.39%**	**15.81%**	**25.20%**	**24.21%**
		SD	13.16%	7.00%	11.90%	8.61%	15.98%	16.34%	9.55%	6.23%	11.31%	11.62%	14.36%	17.50%
		Min	4.07%	3.06%	3.11%	2.99%	3.65%	3.84%	3.54%	3.06%	4.33%	3.50%	5.06%	4.64%
		Max	51.23%	27.94%	54.68%	33.11%	60.48%	62.09%	32.65%	21.15%	43.72%	44.70%	47.68%	61.81%
EDC	50th Percentile	Mean	**12.12%**	**12.90%**	**18.56%**	**10.60%**	**22.70%**	**7.70%**	**12.47%**	**14.81%**	**26.85%**	**10.69%**	**26.55%**	**7.87%**
		SD	8.25%	9.47%	11.61%	11.72%	14.08%	4.02%	9.03%	8.63%	16.12%	8.63%	18.49%	4.20%
		Min	2.78%	2.27%	5.01%	0.96%	8.67%	2.27%	2.28%	3.42%	7.51%	1.13%	6.64%	2.05%
		Max	37.92%	45.36%	43.89%	56.15%	65.81%	17.37%	38.60%	41.84%	74.23%	32.00%	72.60%	17.07%
	90th Percentile	Mean	**19.32%**	**20.90%**	**26.35%**	**15.47%**	**33.73%**	**13.39%**	**19.09%**	**22.91%**	**36.19%**	**16.59%**	**33.94%**	**15.71%**
		SD	17.26%	13.09%	16.83%	15.79%	19.75%	7.56%	14.79%	11.26%	20.71%	11.87%	21.06%	10.59%
		Min	3.78%	5.63%	6.30%	3.33%	16.09%	3.36%	4.56%	10.64%	9.91%	6.80%	5.99%	4.58%
		Max	78.90%	63.22%	63.81%	77.86%	86.56%	32.65%	69.30%	59.84%	93.53%	43.84%	89.69%	47.71%
Tricep	50th Percentile	Mean	**2.70%**	**6.67%**	**2.66%**	**7.21%**	**4.67%**	**4.07%**	**2.64%**	**6.60%**	**5.57%**	**12.12%**	**4.86%**	**7.78%**
		SD	2.54%	6.47%	1.86%	6.04%	6.24%	7.22%	1.93%	5.69%	8.38%	8.25%	3.73%	14.58%
		Min	0.55%	0.66%	0.49%	1.41%	0.59%	0.54%	0.71%	0.87%	0.82%	3.37%	1.07%	0.55%
		Max	12.46%	22.96%	8.20%	26.49%	24.80%	33.80%	7.72%	22.83%	39.26%	29.86%	13.89%	64.19%
	90th Percentile	Mean	**3.80%**	**9.49%**	**3.76%**	**11.47%**	**8.27%**	**5.94%**	**3.45%**	**10.01%**	**5.21%**	**18.78%**	**8.30%**	**6.92%**
		SD	4.82%	9.25%	2.86%	10.02%	11.18%	10.14%	2.51%	7.81%	3.60%	12.37%	7.31%	7.27%
		Min	0.63%	0.99%	0.63%	1.71%	0.84%	0.63%	0.86%	1.35%	1.18%	4.26%	1.43%	0.65%
		Max	23.44%	35.53%	12.60%	42.34%	39.49%	46.37%	10.43%	32.30%	16.73%	43.88%	30.63%	34.68%
Bicep	50th Percentile	Mean	**13.91%**	**2.02%**	**12.09%**	**3.12%**	**2.24%**	**14.54%**	**15.18%**	**1.78%**	**16.85%**	**3.96%**	**1.97%**	**19.45%**
		SD	7.82%	1.82%	5.22%	3.29%	1.80%	11.61%	7.07%	1.59%	7.06%	4.39%	1.54%	15.41%
		Min	5.09%	0.42%	2.61%	0.23%	0.34%	2.54%	7.56%	0.28%	6.25%	0.53%	0.49%	5.00%
		Max	43.44%	7.13%	24.29%	9.28%	5.80%	49.71%	38.93%	5.57%	39.26%	15.52%	6.37%	64.19%
	90th Percentile	Mean	**19.21%**	**3.99%**	**16.17%**	**5.21%**	**4.25%**	**19.96%**	**20.43%**	**3.83%**	**22.73%**	**6.04%**	**4.09%**	**26.25%**
		SD	10.10%	2.46%	7.93%	4.35%	2.57%	18.08%	9.51%	2.35%	9.44%	5.32%	2.21%	21.73%
		Min	6.69%	0.51%	3.25%	0.74%	0.67%	3.21%	9.36%	0.79%	7.96%	0.69%	0.95%	6.02%
		Max	51.48%	9.87%	39.26%	14.79%	10.22%	75.94%	49.55%	10.53%	48.91%	19.67%	9.04%	95.57%

Table 4. *Percent MVC for field study 2016 six directional movements summary statistics.*

			Field Study 2016 Force Condition					
			UP	DN	FW	RW	CCW	CW
FDS	50th Percentile	Mean	**7.28%**	**3.24%**	**4.49%**	**4.52%**	**3.64%**	**8.24%**
		SD	6.13%	2.45%	3.07%	3.06%	1.62%	4.39%
		Min	2.59%	1.43%	2.10%	2.08%	0.87%	3.82%
		Max	21.48%	8.61%	11.64%	11.68%	6.50%	17.80%
	90th Percentile	Mean	**11.66%**	**5.53%**	**7.59%**	**6.99%**	**5.91%**	**13.97%**
		SD	8.79%	2.93%	4.50%	3.22%	2.22%	8.48%
		Min	4.12%	2.85%	3.32%	3.69%	2.21%	6.25%
		Max	32.18%	11.52%	15.74%	14.12%	9.32%	32.81%
EDC	50th Percentile	Mean	**16.66%**	**20.03%**	**19.21%**	**20.13%**	**30.04%**	**13.92%**
		SD	8.57%	6.80%	7.23%	11.51%	11.73%	7.60%
		Min	3.10%	8.54%	8.45%	4.44%	11.08%	2.36%
		Max	30.56%	29.31%	28.59%	44.19%	53.11%	25.83%
	90th Percentile	Mean	**26.21%**	**33.26%**	**30.04%**	**28.66%**	**47.20%**	**25.70%**
		SD	15.94%	13.19%	11.86%	15.88%	19.73%	14.12%
		Min	7.35%	16.01%	13.71%	8.29%	19.82%	6.30%
		Max	57.43%	49.01%	47.46%	59.90%	87.78%	53.37%
Tricep	50th Percentile	Mean	**2.60%**	**3.77%**	**3.36%**	**8.81%**	**1.76%**	**2.61%**
		SD	1.73%	3.09%	6.09%	6.00%	1.60%	1.79%
		Min	1.02%	0.62%	0.67%	1.17%	0.29%	0.75%
		Max	6.61%	9.81%	18.39%	22.41%	4.60%	5.96%
	90th Percentile	Mean	**4.35%**	**6.24%**	**5.49%**	**13.76%**	**3.73%**	**4.60%**
		SD	4.10%	4.68%	8.95%	8.63%	2.46%	2.43%
		Min	1.54%	1.85%	1.31%	2.71%	0.90%	1.62%
		Max	14.31%	14.00%	27.54%	32.89%	7.55%	8.54%
Bicep	50th Percentile	Mean	**8.14%**	**0.37%**	**10.16%**	**3.15%**	**1.00%**	**6.09%**
		SD	4.49%	0.31%	6.60%	2.16%	1.23%	6.30%
		Min	2.08%	0.08%	2.68%	1.12%	0.15%	0.14%
		Max	15.75%	0.96%	22.46%	7.07%	3.87%	19.36%
	90th Percentile	Mean	**11.01%**	**1.50%**	**14.28%**	**4.92%**	**3.43%**	**9.55%**
		SD	5.64%	1.23%	9.76%	3.07%	3.55%	10.13%
		Min	3.48%	0.28%	3.69%	1.61%	0.84%	1.35%
		Max	19.29%	3.56%	31.70%	10.50%	9.84%	27.45%

6.4 T-Tests of EMG Muscle Activity for Truck to Line Trials

The percent MVC muscle activity for the truck to line trials for the EDC muscle is shown in **Figure 17** and includes the field study data from 2016. The number of subjects for each plotted mean is not shown in **Figure 17** because it changed between subjects for each phase of the truck to line movements. Not all subjects in the field study or the laboratory study used the same process to get from the truck bed to the power line. The exact number of subjects for the plotted means in **Figure 17** is shown in **Table 5**, as well as the summary statistics for all conditions and phases. Results of mean EMG activity for the other three muscles are shown in the **Appendix A**.

As indicated in **Figure 17** and **Table 5**, the conventional pistol grip force required 22.7% MVC mean 50^{th} percentile EDC EMG activity for the *entire trial* of truck to line movement, which was 5.6% MVC greater than the reduced force pistol grip mean (17.1% MVC). The 90^{th} percentile EDC EMG means for conventional and reduced force conditions revealed the same pattern with a difference of approximately 9% MVC (36.1% vs. 26.9% MVC for the conventional and reduced force conditions, respectively).

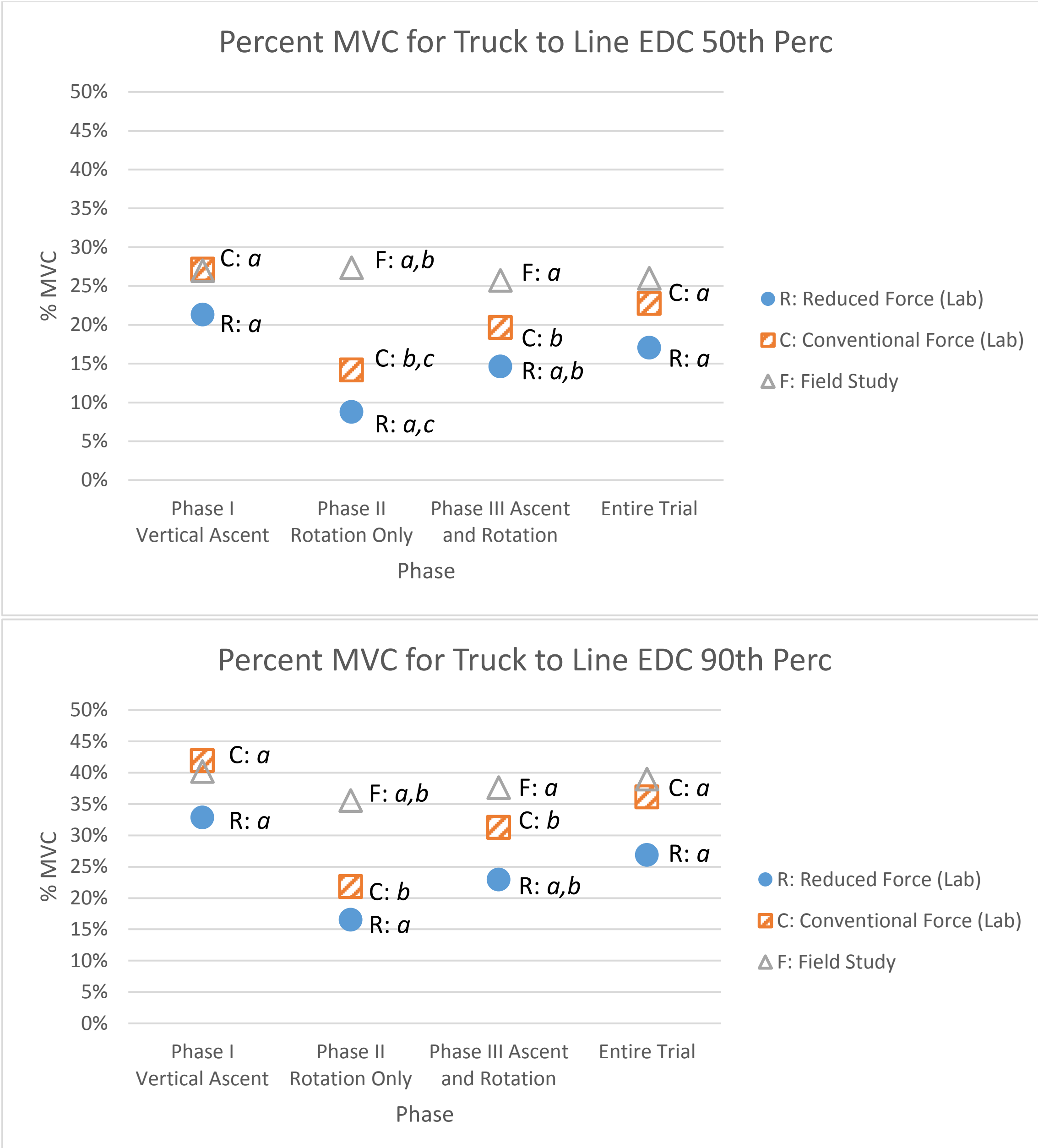


Figure 17. *Percent MVC for truck to Line 50th and 90th percentile for EDC muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05.*

Table 5. *Percent MVC for truck to line summary statistics for laboratory reduced force, laboratory conventional force, and field study 2016.*

			Lab Reduced Force Condition				Lab Conventional Force Condition				Data from Field Study 2016			
			Phase I Vertical Ascent	Phase II Rotation Only	Phase III Ascent and Rotation	Entire Trial	Phase I Vertical Ascent	Phase II Rotation Only	Phase III Ascent and Rotation	Entire Trial	Phase I Vertical Ascent	Phase II Rotation Only	Phase III Vertical Ascent and Rotation	Entire Trial
		Subjects	20	14	20	20	20	18	19	20	7	3	7	7
FDS	50th Percent MVC	Mean	**11.45%**	**12.61%**	**11.67%**	**11.42%**	**12.42%**	**14.08%**	**13.36%**	**12.70%**	**12.55%**	**8.35%**	**10.03%**	**10.16%**
		SD	7.46%	6.22%	7.56%	6.45%	8.46%	7.54%	8.12%	7.76%	13.52%	9.29%	5.91%	6.17%
		Min	2.91%	2.97%	2.86%	2.93%	3.21%	2.48%	3.04%	3.12%	2.64%	5.25%	4.20%	3.84%
		Max	32.37%	27.97%	29.90%	24.17%	35.04%	39.72%	30.72%	29.09%	42.11%	22.33%	21.17%	22.45%
	90th Percent MVC	Mean	**17.28%**	**18.15%**	**16.41%**	**16.56%**	**18.52%**	**22.29%**	**20.15%**	**19.19%**	**19.27%**	**11.67%**	**17.63%**	**17.60%**
		SD	10.59%	8.90%	10.73%	9.20%	12.46%	11.80%	13.05%	11.71%	15.32%	9.29%	10.15%	10.29%
		Min	4.44%	3.77%	3.84%	3.81%	4.15%	4.19%	5.06%	4.23%	5.27%	5.25%	6.07%	6.78%
		Max	43.03%	40.47%	41.61%	33.03%	46.70%	51.58%	50.06%	47.62%	51.28%	22.33%	36.86%	38.78%
EDC	50th Percent MVC	Mean	**21.33%**	**8.77%**	**14.63%**	**17.05%**	**27.15%**	**14.19%**	**19.64%**	**22.74%**	**26.97%**	**27.36%**	**25.71%**	**26.00%**
		SD	14.45%	4.78%	8.88%	10.75%	13.50%	10.95%	10.95%	11.81%	8.13%	13.96%	8.96%	8.37%
		Min	5.56%	2.76%	3.24%	4.79%	9.19%	1.70%	5.41%	8.37%	12.30%	11.61%	12.42%	13.52%
		Max	60.85%	20.45%	41.20%	51.54%	65.11%	60.87%	46.49%	63.94%	39.73%	38.22%	38.54%	40.00%
	90th Percent MVC	Mean	**32.84%**	**16.51%**	**22.93%**	**26.87%**	**41.92%**	**21.82%**	**31.25%**	**36.13%**	**40.19%**	**35.57%**	**37.59%**	**38.96%**
		SD	21.94%	10.72%	12.26%	16.36%	20.45%	15.46%	16.15%	17.87%	10.11%	17.22%	12.16%	10.94%
		Min	7.52%	3.83%	7.04%	8.02%	13.08%	4.73%	11.39%	12.59%	26.00%	15.87%	20.03%	22.85%
		Max	89.55%	55.14%	53.24%	74.09%	96.79%	79.47%	70.38%	91.98%	57.71%	47.73%	54.94%	56.29%
Tricep	50th Percent MVC	Mean	**4.21%**	**2.30%**	**4.08%**	**3.96%**	**4.61%**	**4.47%**	**5.49%**	**4.77%**	**2.67%**	**1.25%**	**2.38%**	**2.59%**
		SD	3.29%	1.30%	2.62%	2.76%	2.98%	3.03%	2.66%	2.47%	1.95%	0.94%	0.92%	1.08%
		Min	1.24%	0.71%	0.84%	1.00%	0.89%	0.99%	1.05%	1.13%	0.37%	0.62%	0.98%	0.84%
		Max	15.77%	4.97%	14.36%	14.88%	11.90%	12.01%	11.52%	10.68%	6.71%	2.33%	3.39%	4.21%
	90th Percent MVC	Mean	**6.96%**	**3.65%**	**6.27%**	**6.08%**	**8.41%**	**7.39%**	**9.37%**	**8.53%**	**4.65%**	**2.12%**	**5.12%**	**5.22%**
		SD	6.10%	2.17%	5.13%	5.44%	6.46%	5.23%	7.55%	5.94%	2.85%	1.40%	4.18%	2.70%
		Min	2.05%	0.92%	1.36%	1.68%	2.01%	1.38%	1.43%	1.77%	1.01%	1.15%	1.51%	1.72%
		Max	31.03%	9.42%	28.45%	29.45%	32.90%	20.09%	46.20%	33.09%	10.12%	3.73%	14.28%	10.53%
Bicep	50th Percent MVC	Mean	**17.13%**	**16.65%**	**28.15%**	**24.76%**	**19.63%**	**27.54%**	**37.66%**	**31.16%**	**16.54%**	**16.09%**	**16.34%**	**14.73%**
		SD	9.94%	5.71%	18.02%	13.28%	11.36%	20.36%	17.37%	16.97%	7.23%	11.26%	7.85%	5.62%
		Min	5.70%	8.54%	8.10%	6.98%	8.39%	9.06%	12.56%	9.54%	8.92%	6.45%	7.37%	8.90%
		Max	55.24%	28.84%	100.00%	72.36%	59.49%	100.00%	74.04%	79.23%	31.26%	28.46%	28.90%	24.53%
	90th Percent MVC	Mean	**27.35%**	**22.78%**	**41.89%**	**31.53%**	**30.22%**	**39.89%**	**56.85%**	**38.09%**	**24.25%**	**22.90%**	**23.48%**	**21.48%**
		SD	17.87%	8.26%	22.98%	19.13%	16.26%	24.33%	24.70%	17.40%	10.44%	19.11%	10.99%	8.52%
		Min	9.00%	11.15%	12.60%	11.24%	12.45%	12.96%	17.42%	14.02%	14.44%	8.24%	11.27%	11.85%
		Max	94.69%	41.65%	100.00%	96.73%	94.65%	100.00%	100.00%	96.37%	45.94%	44.51%	42.14%	35.14%

6.5 Statistical Power of Hypothesis Tests

The p-values and statistical power were calculated for all t-tests and are displayed in **Table 6** and **Table 7** and also in **Table 13** and **Table 14** in **Appendix A**. The t-tests that resulted in a P-value <0.05 or a statistical power >50% are highlighted in grey in the tables. In addition, the magnitudes of differences between the means in each test are shown.

P-value is the probability of a Type I error (false positive conclusion from a hypothesis test) and statistical power is equal to one minus the probability of a Type II error (false negative conclusion). The human factors and ergonomics profession has traditionally used cutoff values of a 0.05 p-value and a 0.20 Type II error; a 0.20 Type II error results in at least 80% statistical power.

The conventional force in the lab study required 5.7% MVC and 9.3% MVC more EDC muscle activity for the 50^{th} and 90^{th} percentiles, respectively, for the *entire trial* of truck to line movement, as shown in **Table 7.** The p-values were < 0.0001 and with statistical power of 60% or greater. There were no other significant differences in means of EDC muscle activity for the tests between conditions for the entire trial of truck to line movement.

Table 6. *Six directional movements EMG muscle activity ANOVA results for laboratory conventional minus laboratory reduced. Highlighted cells denote a P-Value lower than 0.05 or statistical power higher than 50%.*

			Lab Conventional minus Reduced					
			UP	DN	FW	RW	CCW	CW
		# of Subjects	20-20	20-20	20-20	20-20	20-20	20-20
FDS	50th Percentile	Mean Difference	**1.71%**	**0.33%**	**2.66%**	**2.13%**	**2.39%**	**1.75%**
		SD_Pooled	10.82%	3.32%	7.17%	5.81%	9.04%	10.12%
		P Value	0.550	0.558	0.002	0.011	0.085	0.237
		Stat Power	10.30%	7.07%	35.05%	34.37%	20.24%	11.38%
	90th Percentile	Mean Difference	**-2.59%**	**0.35%**	**2.68%**	**2.95%**	**3.36%**	**3.27%**
		SD_Pooled	16.93%	6.62%	11.61%	10.23%	15.19%	16.93%
		P Value	0.100	0.720	0.075	0.009	0.062	0.100
		Stat Power	9.97%	5.58%	16.53%	23.19%	15.57%	13.00%
EDC	50th Percentile	Mean Difference	**0.35%**	**1.91%**	**8.28%**	**0.09%**	**3.85%**	**0.17%**
		SD_Pooled	8.65%	9.06%	14.04%	10.29%	16.44%	4.11%
		P Value	0.768	0.084	0.0001	0.973	0.073	0.759
		Stat Power	5.34%	14.58%	70.62%	5.01%	16.88%	5.35%
	90th Percentile	Mean Difference	**-0.23%**	**2.01%**	**9.84%**	**1.12%**	**0.21%**	**2.32%**
		SD_Pooled	9.47%	12.21%	18.87%	13.97%	20.42%	14.82%
		P Value	0.010	0.144	0.0001	0.707	0.959	0.131
		Stat Power	5.12%	10.77%	60.00%	6.39%	5.02%	10.20%
Bicep	50th Percentile	Mean Difference	**-0.06%**	**-0.07%**	**2.91%**	**4.92%**	**0.18%**	**3.71%**
		SD_Pooled	7.46%	1.71%	6.21%	3.88%	1.67%	13.64%
		P Value	0.094	0.449	0.0001	0.159	0.335	0.012
		Stat Power	5.01%	5.35%	51.17%	99.97%	7.44%	21.15%
	90th Percentile	Mean Difference	**-0.35%**	**0.52%**	**1.45%**	**7.31%**	**0.04%**	**0.98%**
		SD_Pooled	19.99%	2.41%	8.72%	4.86%	2.40%	19.99%
		P Value	0.017	0.763	0.0001	0.179	0.719	0.017
		Stat Power	5.06%	15.04%	10.89%	99.99%	5.06%	5.50%
Tricep	50th Percentile	Mean Difference	**1.27%**	**-0.24%**	**4.76%**	**0.84%**	**-0.27%**	**4.91%**
		SD_Pooled	2.25%	6.10%	6.07%	7.23%	5.14%	11.51%
		P Value	0.837	0.946	0.113	0.001	0.845	0.211
		Stat Power	66.83%	5.32%	91.39%	7.84%	5.57%	44.10%
	90th Percentile	Mean Difference	**-8.20%**	**-2.49%**	**-1.89%**	**-0.28%**	**-0.82%**	**-10.41%**
		SD_Pooled	8.82%	8.56%	3.25%	11.26%	9.45%	8.82%
		P Value	0.221	0.727	0.0001	0.001	0.986	0.221
		Stat Power	97.61%	23.51%	69.42%	5.13%	6.57%	99.88%

Table 7. *Truck to line movements EMG muscle activity ANOVA results. Highlighted cells denote a P-value lower than 0.05 or statistical power higher than 50%.*

			Phase I			Phase II			Phase III			Full Trial		
			Conv. minus Red.	Field minus Red.	Field minus Conv.	Conv. minus Red.	Field minus Red.	Field minus Conv.	Conv. minus Red.	Field minus Red.	Field minus Conv.	Conv. minus Red.	Field minus Red.	Field minus Conv.
		# of Subjects	20-20	7-20	7-20	14-14	3-14	3-18	19-19	7-20	7-19	20-20	7-20	7-20
FDS	50th Percent MVC	Mean Difference	0.97%	1.11%	0.13%	1.47%	-4.26%	-5.73%	1.70%	-1.63%	-3.33%	1.29%	-1.26%	-2.55%
		SD_Pooled	7.88%	9.22%	9.86%	6.66%	5.73%	7.69%	7.69%	7.05%	7.54%	7.11%	6.33%	7.42%
		P Value	0.111	0.787	0.976	0.057	0.261	0.401	0.213	0.602	0.369	0.051	0.654	0.442
		Stat Power	8.19%	8.41%	5.30%	11.95%	19.46%	20.57%	14.96%	7.99%	16.03%	12.03%	7.21%	11.70%
	90th Percent MVC	Mean Difference	1.24%	1.99%	0.75%	4.14%	-6.48%	-10.62%	3.74%	1.22%	-2.52%	2.64%	1.04%	-1.59%
		SD_Pooled	11.51%	11.81%	13.21%	10.28%	8.23%	12.45%	11.39%	10.31%	11.86%	10.48%	9.40%	11.38%
		P Value	0.113	0.658	0.898	0.007	0.381	0.434	0.083	0.789	0.697	0.007	0.802	0.748
		Stat Power	7.44%	6.58%	5.18%	28.69%	21.24%	25.50%	27.32%	5.77%	7.45%	18.81%	5.68%	6.08%
EDC	50th Percent MVC	Mean Difference	5.83%	5.65%	-0.18%	5.42%	18.59%	13.17%	5.01%	11.09%	6.07%	5.69%	8.95%	3.25%
		SD_Pooled	13.58%	13.15%	11.80%	6.68%	5.13%	8.23%	9.61%	8.77%	10.11%	10.93%	10.25%	10.49%
		P Value	0.001	0.307	0.972	0.017	0.0001	0.001	0.001	0.008	0.152	0.0001	0.058	0.487
		Stat Power	44.55%	24.42%	5.36%	80.12%	99.95%	68.26%	57.55%	79.03%	25.64%	59.62%	48.08%	10.42%
	90th Percent MVC	Mean Difference	9.08%	7.35%	-1.73%	5.32%	19.07%	13.75%	8.32%	14.66%	6.34%	9.26%	12.08%	2.82%
		SD_Pooled	20.62%	19.75%	17.47%	12.52%	8.78%	14.88%	13.20%	11.76%	14.09%	16.74%	15.22%	15.87%
		P Value	0.001	0.373	0.823	0.480	0.001	0.030	0.0001	0.009	0.261	0.0001	0.083	0.689
		Stat Power	46.40%	12.89%	5.54%	31.35%	89.04%	29.07%	73.85%	77.88%	16.46%	65.07%	41.29%	6.75%
Tricep	50th Percent MVC	Mean Difference	0.40%	-1.53%	-1.93%	2.17%	-1.05%	-3.22%	1.41%	-1.69%	-3.11%	0.81%	-1.37%	-2.18%
		SD_Pooled	3.11%	3.03%	2.70%	2.45%	1.61%	2.94%	2.60%	2.28%	2.33%	2.58%	2.46%	2.15%
		P Value	0.313	0.289	0.116	0.041	0.339	0.149	0.003	0.103	0.008	0.049	0.218	0.030
		Stat Power	8.49%	29.94%	47.55%	88.57%	16.05%	38.52%	60.90%	36.83%	82.54%	26.60%	23.03%	60.24%
	90th Percent MVC	Mean Difference	1.44%	-2.31%	-3.76%	3.74%	-1.53%	-5.27%	3.10%	-1.15%	-4.25%	2.45%	-0.85%	-3.31%
		SD_Pooled	6.22%	5.44%	5.75%	4.43%	1.97%	5.56%	5.50%	4.90%	5.51%	5.64%	4.92%	5.25%
		P Value	0.008	0.368	0.149	0.013	0.421	0.208	0.0001	0.597	0.119	0.0001	0.592	0.164
		Stat Power	16.61%	15.35%	29.91%	83.12%	20.80%	30.31%	64.22%	8.09%	38.79%	43.44%	6.66%	28.17%
Bicep	50th Percent MVC	Mean Difference	2.50%	-0.60%	-3.09%	10.89%	-0.55%	-11.45%	9.51%	-11.80%	-21.31%	6.40%	-10.03%	-16.43%
		SD_Pooled	10.04%	9.16%	9.72%	15.64%	5.79%	20.24%	17.04%	15.91%	14.66%	14.64%	11.65%	14.33%
		P Value	0.111	0.895	0.476	0.026	0.671	0.564	0.001	0.104	0.005	0.029	0.061	0.015
		Stat Power	18.59%	6.68%	17.35%	67.36%	5.22%	13.85%	63.37%	36.86%	88.37%	45.87%	47.02%	70.87%
	90th Percent MVC	Mean Difference	2.86%	-3.10%	-5.96%	17.10%	0.12%	-16.99%	14.96%	-18.41%	-33.37%	6.56%	-10.05%	-16.61%
		SD_Pooled	15.90%	15.66%	13.83%	20.32%	9.07%	27.16%	23.14%	20.39%	21.28%	17.92%	17.13%	15.16%
		P Value	0.215	0.669	0.336	0.003	0.608	0.456	0.001	0.050	0.003	0.023	0.194	0.020
		Stat Power	11.92%	7.18%	15.71%	82.88%	5.00%	15.88%	75.97%	50.67%	92.53%	34.28%	25.04%	66.95%

6.6 Subjective Assessment Analysis

Questions assessing the physical effort, ease of use, and like/dislike of each experimental condition and preference of pistol grip force can be seen in **Appendix B** under **FORM 3,** which had a front and back side. The results of the subjective assessment can be seen in **Table 15** in **Appendix A**. These questions were asked directly after each condition of truck to line trials were completed to ensure the subjects retained their psychophysical impressions of the condition. All data were analyzed with the Friedman test for non-parametric data because the subjective assessment questions have answers that are ordinal in nature, rather than the ratio scale percent MVC of EMG activity.

The results of the test show that there were significant differences between the conventional and reduced force means for all four questions with a P-value <0.01 (Glantz, 1992.). Results are summarized below:

- Physical Effort: The mean of the reduced force condition was 2.9 (±1.2SD) and conventional force condition was 4.3 (±1.4), this indicating that the physical effort was rated lower for the reduced force condition.
- Ease of Use: The mean of question reduced force condition was 4.8 (±1.3SD) and conventional force condition was 4.0 (±1.4), which indicates that the reduced force condition was rated easier to use.
- Like/Dislike: The mean of reduced force condition (±SD) was 4.8 (±1.3) and conventional force condition was 3.7 (±1.3), which indicates that the reduced force condition was more liked.
- Preference: Seventeen subjects preferred the reduced force condition while three preferred the conventional force.

The average grip strength of the three subjects who preferred the conventional force was 99.2 lb., which was very similar to the average 98.2 lb. grip strength of the other 17 subjects who preferred the reduced force pistil grip. All grip force data are shown in **Table 8**.

Table 8. *Grip strength for subjects who preferred conventional force condition compared to the other 17 subjects.*

Subject	Gender	Grip Strength (lb)
S08	Male	95.0
S13	Male	72.5
S15	Male	130.0
n=17 other subjects	Male and Female	98.2

7 Discussion

7.1 Motivation for Project

This project was chosen because it was the third task that utility line workers had requested to be addressed for ergonomic evaluation by the Marquette research team. During the last 20 years many line workers had reported to Dr. Richard Marklin and team members that using the pistol grip control to operate the aerial bucket caused forearm fatigue. Results of EMG signal intensity from forearm muscles in the 2016 field study of eight apprentice line workers corroborated line workers' reports of muscle fatigue, and that field study provided the first physiological evidence of forearm muscle fatigue, specifically in the EDC muscle of the forearm, from operating the pistol grip control. That finding was the motivation to redesign the pistol grip to reduce the amount of applied force, which would reduce the risk of muscle fatigue.

After the pistol grip was redesigned, which is described in this thesis, it needed to be tested to determine if a reduced level of applied force would result in a lower risk of muscle fatigue. Ideally, this testing would have been done in the field on an actual bucket truck with professional line workers. However, it was not safe to conduct a field test of the redesigned pistol grip because the prototype was not robust enough for field use in a truck and mounting the redesigned pistol grip on the hydraulic system of a truck may violate manufacturers' warranties of truck and boom equipment. Therefore, testing of the redesigned pistol grip was conducted in the laboratory using a scale model of the bucket truck with college students. Professional line workers were not available to participate in the laboratory study because of budget and time constraints.

7.2 Anthropometry of Subject Populations

Anthropometry data for the student population in laboratory study were generally not different from the 2016 field study subjects. For this comparison, the two female subjects were not included so only male subjects from the laboratory and field studies were compared. Excluding the two female subjects for this analysis is justified because all the eight apprentice line workers in the field study were male. The average height and weight between the two groups were well within one standard deviation of each other, and there was no significant difference between the groups in terms of their height and weight. There was a difference between the groups in grip strength, which was an indicator of overall upper body strength. The subjects in the laboratory study had an average grip strength of 102.4 lb. while the field study had an average of 132.0 lb. This difference showed that field workers had, on average, stronger forearm muscles, which are the muscles that are primary contributors to grip strength. These differences in strength should be taken into consideration comparing results of the laboratory and field studies.

7.3 Pistol Grip Mechatronics System

The mechanism that reduces the applied force to move the pistol grip decouples the force input of the user from the force applied to the poppet valves on the manifold of the hydraulic system. In order to achieve this reduction in applied force, a mechatronics system was designed and integrated into the pistol grip assembly to record the position of the pistol grip and then output the required force to the hydraulic system through a system of racks and pinions. Racks and pinions move the poppet valves on the manifold up and down to move the bucket in the desired direction(s). The mechatronics system, which is powered by the same portable lithium battery used to power cutting and crimping tools on the truck, allows for a reduction of applied force to the pistol grip up to 95% of the applied force required for existing manual systems.

A 50% reduction of applied force to move the pistol grip was chosen for testing in the laboratory study to reduce risk of muscle fatigue, ensure safety of the worker, and maintain reliability of the boom equipment. A 50% reduction was hypothesized to produce a meaningful decrease in muscle exertion, as measured by EMG muscle activity, and a 50% reduction would also provide enough tactile feedback to the user to operate the pistol grip safely. Investigators were concerned that a reduction of more than 50% may result in a worker moving the pistol grip too quickly. Rapid movements of the pistol grip in the field may produce jerky movements (large accelerations) of the aerial bucket that may surprise or disorient the worker in the bucket and may stress the hydraulic and mechanical systems of the boom and truck. Jerky movements of the aerial bucket would also decrease the electrical safety of the worker in situations where the bucket is close to energized conductors. In such situations, the worker applies a controlled force to the pistol grip, often in multiple directions simultaneously, to move the bucket smoothly to the conductor. (In the trade, this is called "feathering" the pistol grip.) Abrupt movements of the bucket would make it difficult for a worker to "feather" the pistol grip to move the bucket at a safe velocity to the recommended location near a conductor. Future work is required to determine the magnitude of reduction of applied force to the pistol grip to minimize muscle fatigue while maintaining worker safety.

7.4 EMG Muscle Activity – Directional Movements

It is not presently possible to directly measure muscle fatigue noninvasively. Instead, EMG muscle activity was measured because it is possible to infer muscle fatigue from EMG muscle activity after the data have been converted into percentage of the muscle's maximum isometric strength (percent MVC). A lower percent MVC of muscle activity would decrease risk of muscle fatigue based on physiological studies of muscles. There is a negative exponential relationship between level of muscle force (percentage of maximum muscle force or MVC) and the endurance time to maintain that level of muscle force (**Figure 6**). That is, as the level of muscle force increases, endurance time decreases rapidly.

Reduction of pistol grip force from the redesign of the pistol grip generally decreased percent MVC of the EDC muscle more than the other three muscles (FDS, biceps, and triceps). As such, EDC EMG muscle activity results were the focus of the analysis.

EMG results revealed that 50th percentile EMG activity of the EDC muscle was lower in the conventional laboratory condition than the field study for the CW and rearward movements. A similar trend occurred for 90th percentile EDC EMG activity for the up, down, and rearward movements (**Figure 16**). This difference may be attributed to multiple factors. In the laboratory studies, the college student subjects did not wear the required PPE (personal protective equipment) for the hand and arm, which consists of a long rubber arm sleeve, a rubber glove, and a leather outer glove, because various sizes of gloves that fit the hand sizes of the subjects were not available. In the field study all eight apprentice line workers wore the required PPE. The stiffness and weight of the gloves and sleeve would require more muscle force to move the pistol grip and therefore would cause a higher percent MVC than the laboratory trials. A second factor is the difference between subject populations. The laboratory study relied on untrained subjects (college students) who appear to have used a different neuromuscular strategy to move the pistol grip than the line workers – the students exerted more biceps muscle activity than the apprentices (**Figure 23**). The students exerted 24.8% and 31.1% MVC 50th percentile biceps activity for the reduced and conventional forces, respectively, compared to apprentices' exertion level of 14.7% MVC for the truck to line trials.

For the orthogonal movements, the reduced pistol grip force did not decrease EDC EMG activity compared to conventional force except for the forward movement (**Figure 16**). The lack of differences may be due to the orthogonal movements being simple and not requiring any extra "feathering" to move the pistol grip in only one direction, compared to the more complex manipulation of the pistol grip to move the bucket from the truck to overhead line.

7.5 EMG Muscle Activity – Truck to Line Movements

Unlike the orthogonal movements, the truck to line trials for the EDC muscle present a different pattern of results than the six directional movements. In the truck to line trials, the field study and conventional force laboratory study had similar averages values for 50^{th} percent MVC (26.0% and 22.7%, respectively) (**Figure 17** and **Table 5**). These similar averages were expected as the forces required to move the pistol grip in the laboratory study (conventional force) was calibrated to the actual forces applied to the pistol grip in the field (**Table 1**). However, the college students in the laboratory study did not wear rubber and leather gloves as contrasted to the apprentice line workers in the field study. One would expect that subjects not wearing gloves would exert less forearm muscle force than those wearing gloves, unless there was a difference in muscle strength. In fact, there was a difference in forearm muscle strength between the two groups, as evidenced by grip strength data. The apprentices had an average grip strength of 132 lb., which is approximately 30% higher than the average 102 lb. grip strength of the college students. Whether rubber and leather gloves require a user to exert 30% more muscle activity in the EDC to manipulate the pistol grip is not known specifically, although it is reasonable to conclude that gloves would require more muscle force to overcome the stiffness of the gloves.

The reduced force pistol grip, which was set at 50% of the field force, resulted in a 50^{th} percentile MVC of the EDC muscle of 17.1% MVC, which was significantly lower (5.6% MVC) than the conventional force in the laboratory (22.7% MVC – p-value <0.0001) but not significantly lower than the 26.0% MVC in the field at the level of 0.05 (p-value =0.058) (**Table 7**). The likely reason for this disparity in statistical results is that the statistical test for detecting a difference between the mean %MVC of the two laboratory conditions (conventional and reduced) was a paired t-test, which is a more powerful test than a regular t-test (which was used to test the difference between conventional force in the lab and the field). The paired t-test was appropriate for testing the difference between the two force conditions in the laboratory because the subjects in both laboratory conditions were the same subjects. It was not possible to use a paired t-test for the difference between the reduced force in the lab and the field study because the subjects were not the same (20 college students vs eight apprentices). However, the p-value for the t-test (0.058) is close to the a priori maximum allowable p-value (0.05), which indicates that additional testing with more subjects would likely decrease the p-value below the threshold, and thus result in a statistically significant difference (**Table 7**).

Compared to the conventional force condition, a decrease of 5.6% MVC in the EDC muscle from the reduced force pistol grip (difference between means of 17.17% and 22.7% MVC) is meaningful and suggests that the pistol grip decreases the risk of muscle fatigue in the EDC muscle. While there is no direct method to measure muscle fatigue noninvasively, one can use calculations of maximum endurance time from past studies to infer risk of muscle fatigue (Manenica, 1986; Frey Law, 2009). Using equations **(1)**, **(3)**, and **(4)** from Section 2.1 – Literature Review, the average maximum endurance time for 17.1% MVC is 8.05 min, whereas the average maximum endurance time for 22.7% MVC is 5.82 min (**Table 9**). Maximum endurance time is the time at which a muscle can no longer exert the level of muscle force, as expressed in percentage of maximum force.

The increase of 2.23 min of endurance time (5.82 to 8.05 min) for the reduced force pistol grip results in a 38% increase of endurance time. In addition, the mean EDC EMG muscle activity levels of 17% and 23% for the two pistol grip force levels were substantially greater than 10% MVC, which is considered the level over which muscle fatigue starts (refer to Section 2.2 –

Literature Review). Thus, the increase in endurance time along with EMG levels greater than the fatigue threshold suggest that the reduced force pistol grip would decrease the level of muscle fatigue compared to the conventional force pistol grip.

If the reduced pistol grip EDC EMG levels were compared to the field study, the increase in endurance time would be even greater. With a mean 50th percentile EDC EMG level of 26.0% MVC, the average maximum endurance time is 4.93 min (**Table 9**), which results in a 63% increase of endurance time for the reduced force pistol grip compared to the field study pistol grip. This relative increase in endurance time is stronger evidence of the benefit of the reduced force pistol grip with respect to muscle fatigue.

The maximum endurance times for operating the pistol grip at the reduced force, conventional force, and field study conditions (**Table 9**) are longer than typical durations of muscle exertions that workers apply to the pistol grip in the field. Line workers typically operate the pistol grip for approximately 60 sec to move the bucket from the truck to a 40 ft. tall overhead line. The cumulative effect of approximately one minute or longer grip exertions, performed repeatedly during a shift, can lead to buildup of muscle fatigue. As muscle force applied to the pistol grip increases, the buildup of physiologic fatigue rises, resulting in a lower endurance time until fatigue. The time until muscles get tired is less than the endurance limit. There is no way to directly calculate the time until a muscle gets tired so the maximum endurance time is calculated.

Table 9. *Maximum endurance time (MET) in minutes for level of percent MVC EMG according to equations (1), (2), and (3) in Section 2.2 – Literature Review.*

	Maximum Endurance Time (MET)		
	17.1% MVC	**22.7% MVC**	**26.0% MVC**
Equation (1)	7.71 min	5.97	5.16
Equation (2)	9.65	6.07	4.89
Equation (3)	6.8	5.41	4.75
Average	**8.05**	**5.82**	**4.93**

8 Conclusion

This laboratory study showed that there was a decrease in percent MVC of the forearm muscles that extend the wrist (EDC) while using the redesigned (50% reduced force) pistol grip as compared to a conventional force pistol grip currently used on utility trucks. The results of the truck to line full trials, which are the most representative of actual movements of the pistol grip in the field, showed that the reduction of 50% required input force produced a meaningful reduction in muscle activity. Muscle activity recorded by EMG is a measure of the magnitude of muscle force under controlled conditions. EMG results provide evidence that the reduced force pistol grip decreases the risk of muscle fatigue of line workers who operate the pistol grip. EMG results also corroborate reports of muscle fatigue from utility line workers who operate the pistol grip with conventional force levels. This study was the first to quantify muscular loading of an aerial bucket pistol grip control and results of the redesigned pistol grip show promise for improving the occupational health of electric utility line workers.

9 Limitations

The limitations on this study are listed below.

- Untrained students were used as subjects.
- Personal protective equipment was not used, i.e. rubber glove, rubber arm sleeve, leather glove.
- Reduced force of the redesigned pistol grip was tested at a single 50% reduction level.
- A 1/15th scale model of the truck was used, subject was not in the same conditions as a field worker.

10 Future Work

The future work on this project will follow directly from this study. Some of these projects listed are already being planned. The future work is listed below.

- Testing of multiple percent reductions in force to optimize for minimum muscle fatigue and maximum safety for worker and equipment.
- Redesign of bucket truck control scheme so that instead of the operator moving individual joints they will instead move the location of the bucket.
- Field testing of reduced force pistol grip with bucket truck and professional workers using PPE such as the rubber and leather gloves.

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Terex. *Hi-Ranger TC Series.* Operator's Manual. Terex Telect, Inc. 500 Oakwood Road, Watertown, SD 57201.

12 **Appendix A**: Laboratory Study Results

Table 10. *Latin square design for presentation order of experimental conditions.*

Subject	Test order	1	2	3	4	5	6	7
	Test 1	Up	Down	CCW	Forward	CW	Rear	Truck to Line
S1	Test 2	Down	Forward	Up	Rear	CCW	CW	Truck to Line
	Test 2	Forward	Rear	Down	CW	Up	CCW	Truck to Line
S2	Test 1	Rear	CW	Forward	CCW	Down	Up	Truck to Line
	Test 1	CW	CCW	Rear	Up	Forward	Down	Truck to Line
S3	Test 2	CCW	Forward	CW	Down	Rear	Forward	Truck to Line
	Test 2	Up	Down	CCW	Forward	CW	Rear	Truck to Line
S4	Test 1	Down	Forward	Up	Rear	CCW	CW	Truck to Line
	Test 1	Forward	Rear	Down	CW	Up	CCW	Truck to Line
S5	Test 2	Rear	CW	Forward	CCW	Down	Up	Truck to Line
	Test 2	CW	CCW	Rear	Up	Forward	Down	Truck to Line
S6	Test 1	CCW	Forward	CW	Down	Rear	Forward	Truck to Line
	Test 1	Up	Down	CCW	Forward	CW	Rear	Truck to Line
S7	Test 2	Down	Forward	Up	Rear	CCW	CW	Truck to Line
	Test 2	Forward	Rear	Down	CW	Up	CCW	Truck to Line
S8	Test 1	Rear	CW	Forward	CCW	Down	Up	Truck to Line
	Test 1	CW	CCW	Rear	Up	Forward	Down	Truck to Line
S9	Test 2	CCW	Forward	CW	Down	Rear	Forward	Truck to Line
	Test 2	Up	Down	CCW	Forward	CW	Rear	Truck to Line
S10	Test 1	Down	Forward	Up	Rear	CCW	CW	Truck to Line
	Test 1	Forward	Rear	Down	CW	Up	CCW	Truck to Line
S11	Test 2	Rear	CW	Forward	CCW	Down	Up	Truck to Line
	Test 2	CW	CCW	Rear	Up	Forward	Down	Truck to Line
S12	Test 1	CCW	Forward	CW	Down	Rear	Forward	Truck to Line
	Test 1	Up	Down	CCW	Forward	CW	Rear	Truck to Line
S13	Test 2	Down	Forward	Up	Rear	CCW	CW	Truck to Line
	Test 2	Forward	Rear	Down	CW	Up	CCW	Truck to Line
S14	Test 1	Rear	CW	Forward	CCW	Down	Up	Truck to Line
	Test 1	CW	CCW	Rear	Up	Forward	Down	Truck to Line
S15	Test 2	CCW	Forward	CW	Down	Rear	Forward	Truck to Line
	Test 2	Up	Down	CCW	Forward	CW	Rear	Truck to Line
S16	Test 1	Down	Forward	Up	Rear	CCW	CW	Truck to Line
	Test 1	Forward	Rear	Down	CW	Up	CCW	Truck to Line
S17	Test 2	Rear	CW	Forward	CCW	Down	Up	Truck to Line
	Test 2	CW	CCW	Rear	Up	Forward	Down	Truck to Line
S18	Test 1	CCW	Forward	CW	Down	Rear	Forward	Truck to Line
	Test 1	Up	Down	CCW	Forward	CW	Rear	Truck to Line
S19	Test 2	Down	Forward	Up	Rear	CCW	CW	Truck to Line
	Test 2	Forward	Rear	Down	CW	Up	CCW	Truck to Line
S20	Test 1	Rear	CW	Forward	CCW	Down	Up	Truck to Line

Table 11. *Field study 2016 subject anthropometry data.*

Subject	Hand	Stature	Weight	Arm Length	Hand Length	Hand Width	Palm Length	Forearm Girth	Grip Strength
1	Right	190	205	85.7	20.1	9.5	11.4	31.1	146.05
2	Both	177.6	165	79	17.6	8.3	10.1	29.2	116.29
3	Right	187.9	190	90	18.8	8.6	10.6	30.4	123.45
4	Right	179.9	195	89.3	18.6	8.6	10.9	30.5	122.9
5	Right	186.2	300	85.3	19	8.7	10.7	32	137.78
6	Right	181.7	170	87	19.3	9.2	11.2	29	147.15
7	Right	176.6	150	85.2	18.3	8.7	11.1	27	122.35
8	Right	179.6	185	77	18.2	9.4	10.7	31	141.09
	Mean	182.4	195	84.8	18.7	8.9	10.8	30	132.05
	SD	5.0	46	4.6	0.8	0.4	0.4	1.6	12.12
	Min	176.6	150	77	17.6	8.3	10.1	27	116.29
	Max	190	300	90	20.1	9.5	11.4	32	147.15

Table 12. *Laboratory study subject anthropometry data.*

Subject	Gender	Occupation	Hand Dominance	Age	Height(cm)	Weight(lb)	Arm Length(cm)	Hand Length(cm)	Hand Width(cm)	Palm Length(cm)	Forarm Girth(cm)	Grip Strength(lb)
S01	Male	Student	Right	22	186.8	205	85.7	19.6	8.7	11.3	28	122
S02	Male	Student	Left	22	181	245	74.6	18.2	8.9	11.2	31.5	107.5
S03	Male	Student	Right	22	181.7	187	81.6	19.6	8.1	11.6	29.5	119.5
S04	Male	Student	Right	22	186.2	200	82.5	20.7	9.5	12.4	31.8	119
S05	Female	Student	Right	23	167.7	130	75	17.1	7.7	9.5	22.1	57.5
S06	Male	Student	Right	22	188.4	200	83.6	19.4	8.7	11.3	27.4	97.5
S07	Female	Student	Right	20	176.4	170	75.4	17.9	7.8	10.6	25.5	66.5
S08	Male	Student	Right	22	185	170	86.2	19	9	10.4	27.1	95
S09	Male	Student	Right	21	187.1	185	83.9	19.7	9.2	11.9	29.6	80
S10	Male	Student	Right	21	193.6	207	87.9	21.5	9.6	12.2	30.4	112.5
S11	Male	Accountant	Right	24	181.8	220	79.4	18.2	8.6	10.5	30.7	85
S12	Male	Student	Right	22	200.6	220	85.5	20.6	8.8	11.6	30.5	135
S13	Male	Student	Right	21	193	200	86.5	19.4	9.1	11.1	28.7	72.5
S14	Male	Student	Right	25	175.3	155	79.5	18.1	8.3	9.9	26.1	85
S15	Male	Student	Right	21	182.9	170	78.1	18.6	9.1	11	28	130
S16	Male	Student	Right	23	172.7	155	75.2	17.4	8.1	10.6	25.7	97.5
S17	Male	Student	Left	23	180.4	185	80.4	19	8.5	10.1	29.5	117.5
S18	Male	Engineer	Left	24	177.8	142	78	18.1	7.9	10.9	24	75
S19	Male	Student	Right	23	172.2	160	76.4	17.8	8.5	10.7	30	117.5
S20	Male	Student	Right	24	172.2	185	76	16.9	8.4	10.1	28.5	75
Mean				22.4	182.1	184.6	80.6	18.8	8.6	10.9	28.2	98.4
SD				1.3	8.3	28.6	4.4	1.2	0.5	0.8	2.6	22.9
Min				20.0	167.7	130.0	74.6	16.9	7.7	9.5	22.1	57.5
Max				25.0	200.6	245.0	87.9	21.5	9.6	12.4	31.8	135.0

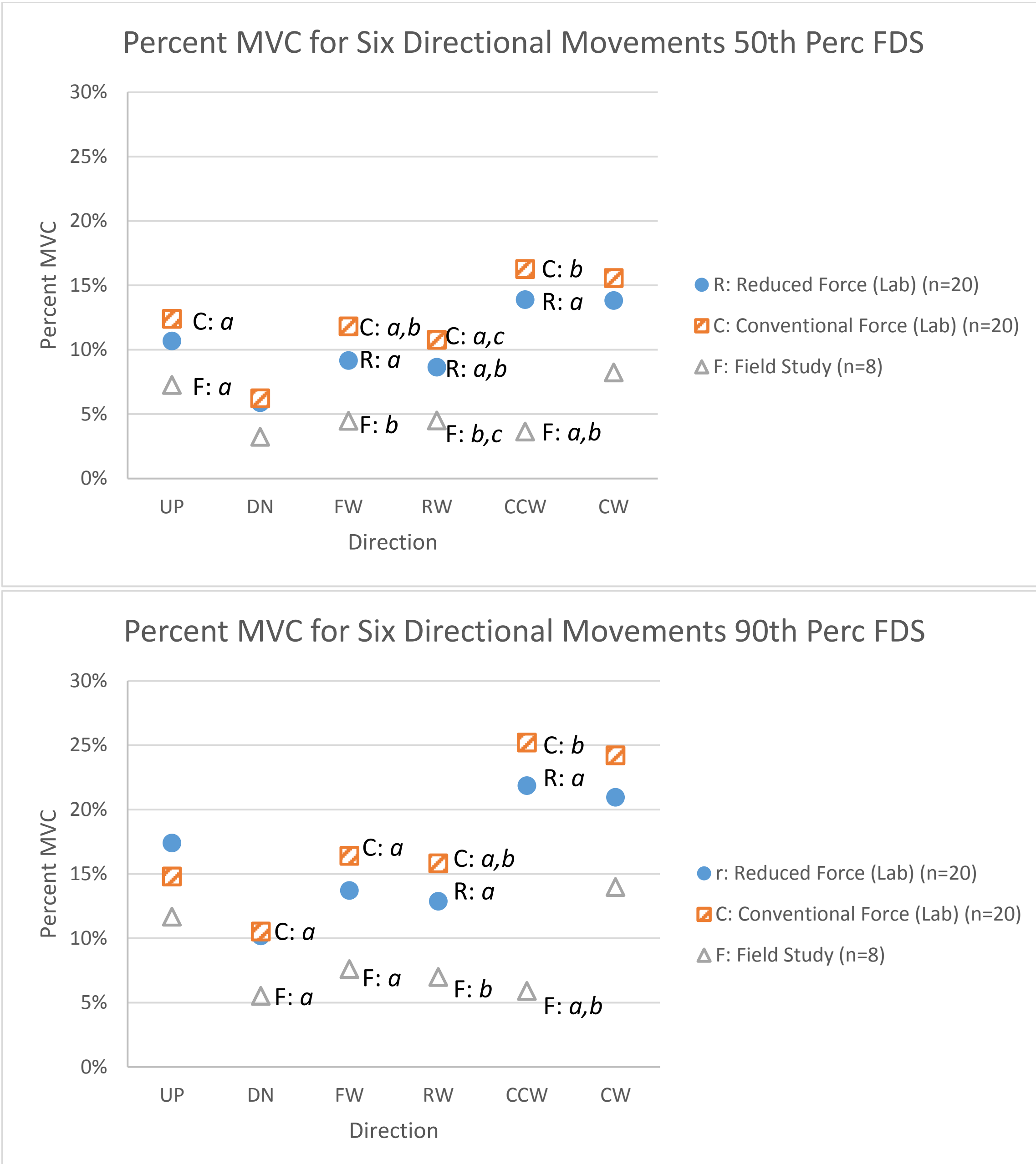


Figure 18. *Percent MVC for six directional movements 50th and 90th percentile for FDS muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05.*

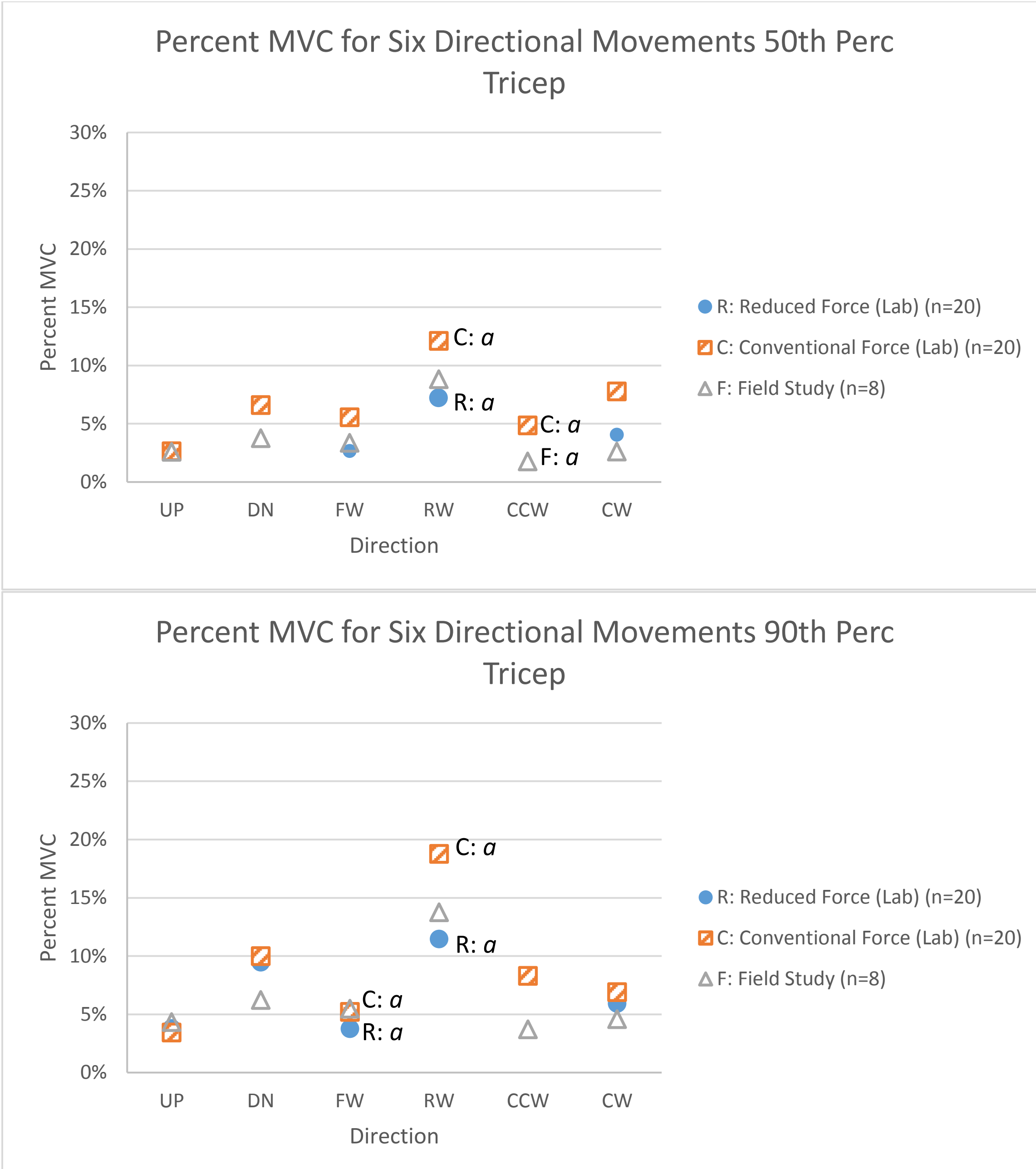


Figure 19. *Percent MVC for six directional movements 50th and 90th percentile for tricep muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05.*

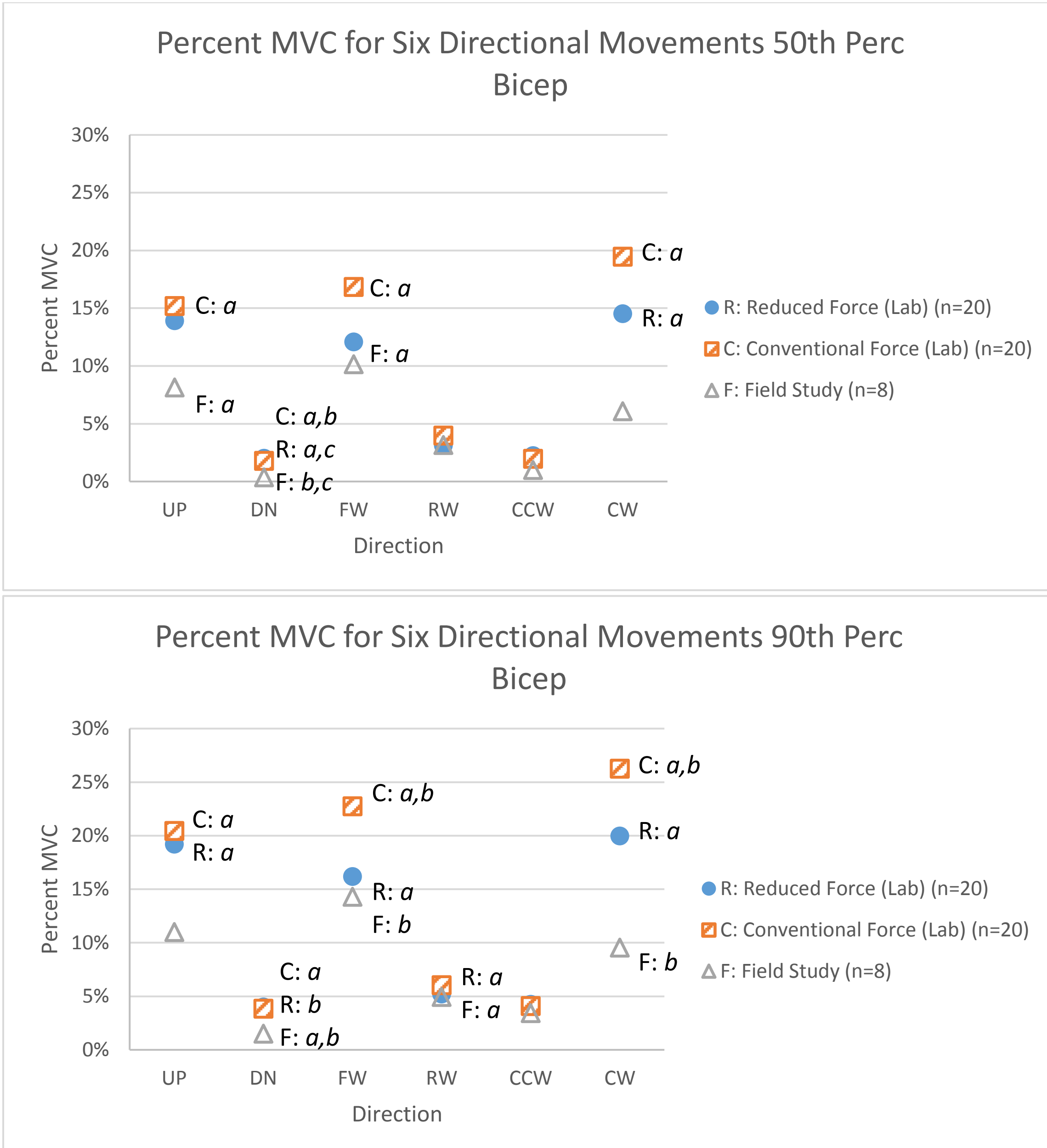
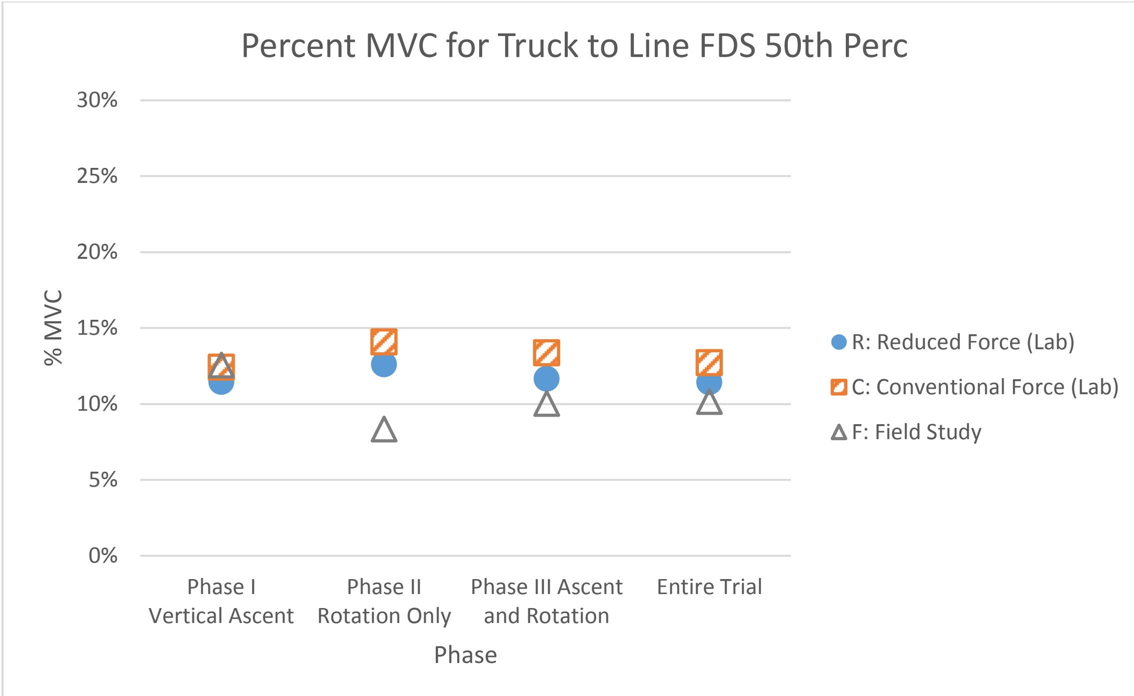


Figure 20. *Percent MVC for six directional movements 50th and 90th percentile for bicep muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05..*



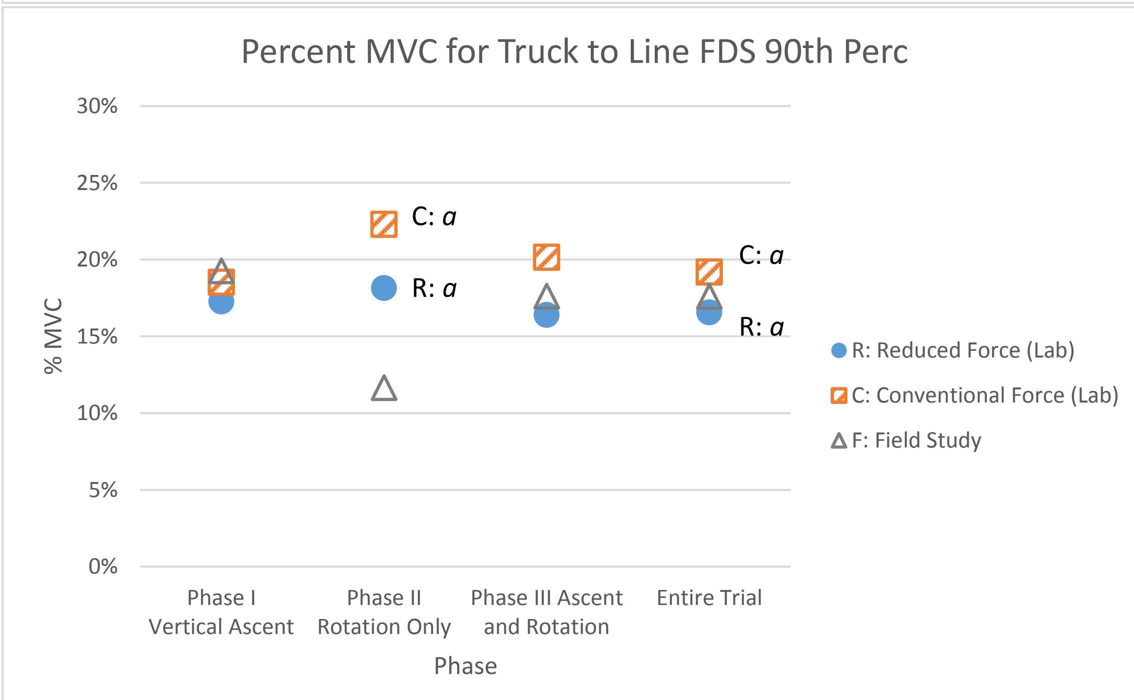
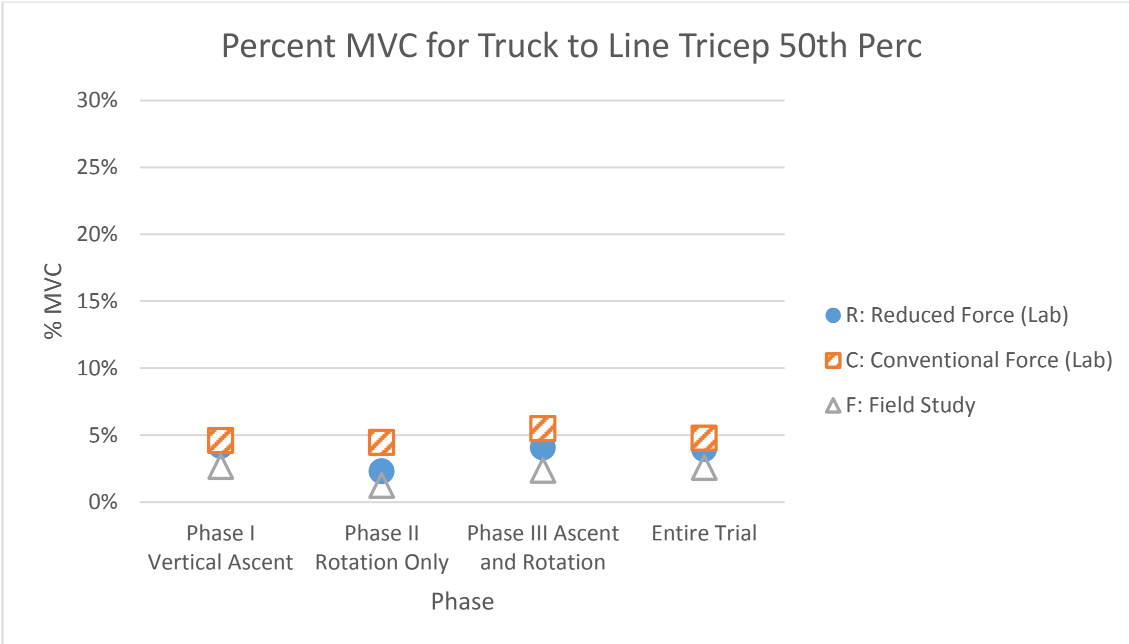


Figure 21. *Percent MVC for truck to line 50th and 90th percentile for FDS muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05.*



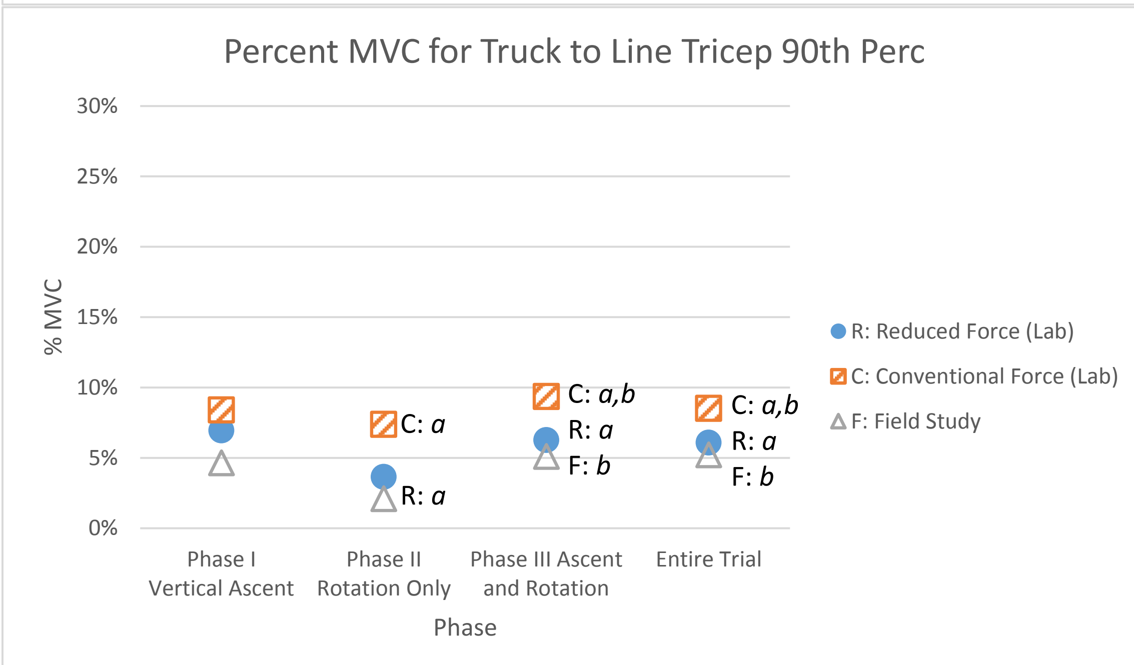
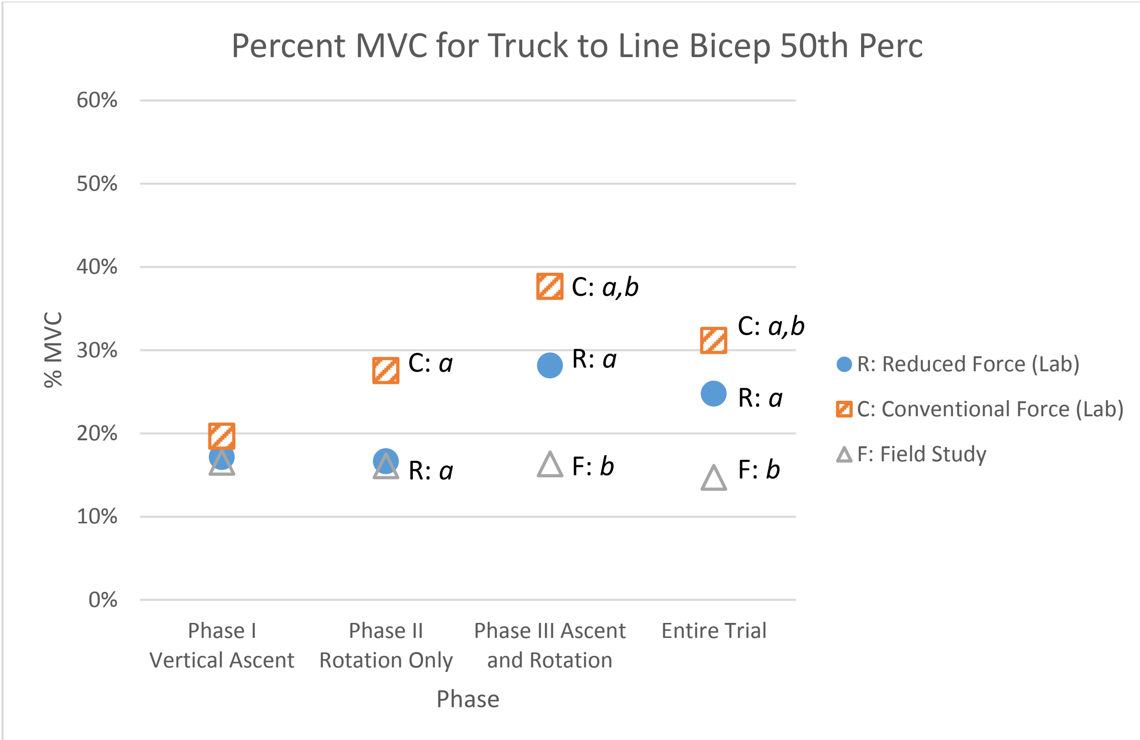


Figure 22*. Percent MVC for truck to line 50th and 90th percentile for tricep muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05.*



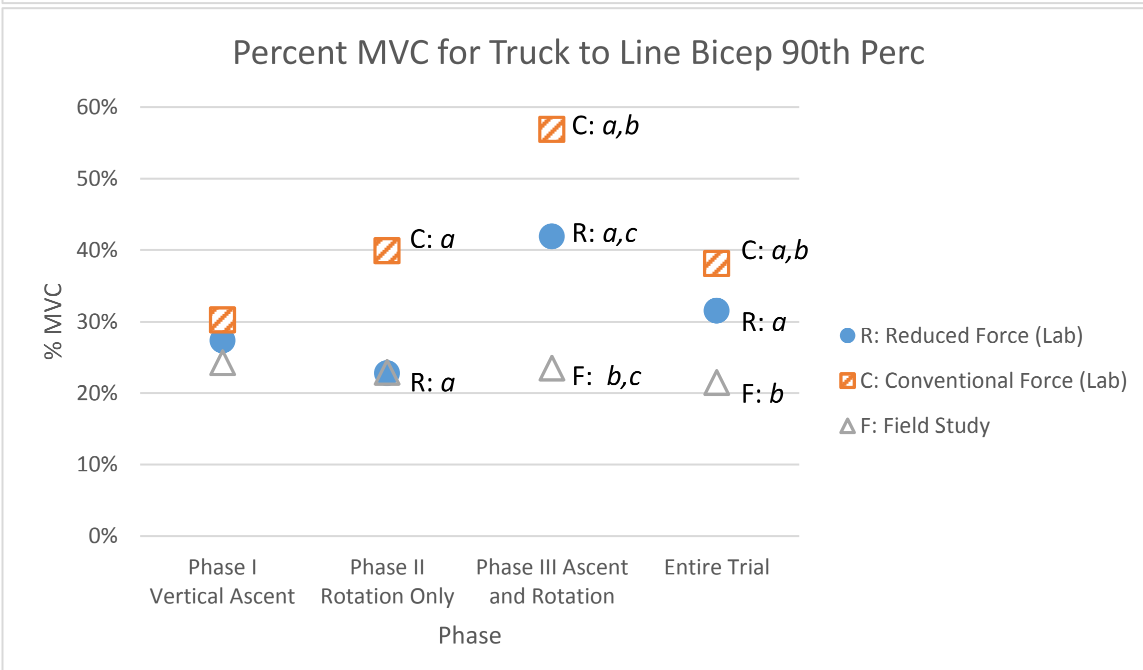


Figure 23. *Percent MVC for truck to line 50th and 90th percentile for bicep muscle. Conditions that have matching letters for a given direction denote a difference in means with a P-value <0.05.*

Table 13. *Six directional movements EMG muscle activity ANOVA results for laboratory conventional minus field 2016. Highlighted cells denote a P-Value lower than 0.05 or statistical power higher than 50%.*

			Lab Conventional minus Field					
			UP	DN	FW	RW	CCW	CW
		# of Subjects	20-8	20-8	20-8	20-8	20-8	20-8
FDS	50th Percentile	Mean Difference	**5.12%**	**2.99%**	**7.33%**	**6.26%**	**12.63%**	**7.34%**
		SD_Pooled	11.08%	3.03%	6.65%	5.74%	7.45%	8.65%
		P Value	0.280	0.026	0.014	0.015	0.0001	0.053
		Stat Power	18.64%	62.21%	71.79%	70.87%	97.37%	49.74%
	90th Percentile	Mean Difference	**3.14%**	**5.00%**	**8.80%**	**8.82%**	**19.29%**	**10.24%**
		SD_Pooled	15.64%	5.54%	9.95%	10.07%	12.33%	15.60%
		P Value	0.066	0.04	0.044	0.046	0.001	0.129
		Stat Power	7.48%	54.68%	53.02%	52.23%	94.93%	32.71%
EDC	50th Percentile	Mean Difference	**-4.20%**	**-5.22%**	**7.64%**	**-9.44%**	**-3.49%**	**-6.05%**
		SD_Pooled	8.91%	8.18%	14.28%	9.49%	16.94%	5.33%
		P Value	0.270	0.139	0.212	0.025	0.627	0.012
		Stat Power	19.21%	31.21%	23.40%	62.90%	7.62%	74.28%
	90th Percentile	Mean Difference	**-7.12%**	**-10.35%**	**6.15%**	**-12.06%**	**-13.26%**	**-9.98%**
		SD_Pooled	12.38%	11.81%	18.74%	13.86%	20.71%	11.65%
		P Value	0.070	0.046	0.440	0.027	0.138	0.051
		Stat Power	26.30%	52.29%	11.75%	51.72%	31.39%	50.48%
Bicep	50th Percentile	Mean Difference	**7.04%**	**1.41%**	**6.69%**	**0.81%**	**0.54%**	**9.33%**
		SD_Pooled	6.48%	1.37%	6.94%	3.91%	1.46%	13.57%
		P Value	0.015	0.021	0.029	0.623	0.125	0.026
		Stat Power	70.75%	65.86%	60.21%	7.65%	13.64%	35.33%
	90th Percentile	Mean Difference	**9.42%**	**2.32%**	**8.45%**	**1.12%**	**0.66%**	**16.70%**
		SD_Pooled	18.81%	2.11%	9.53%	4.82%	2.64%	19.31%
		P Value	0.064	0.014	0.044	0.585	0.554	0.049
		Stat Power	21.08%	71.57%	53.23%	8.34%	8.88%	51.23%
Tricep	50th Percentile	Mean Difference	**0.04%**	**2.83%**	**2.21%**	**3.31%**	**3.10%**	**5.18%**
		SD_Pooled	1.87%	5.12%	7.83%	10.59%	3.30%	12.50%
		P Value	0.959	0.198	0.506	0.505	0.033	0.331
		Stat Power	5.02%	24.65%	9.96%	11.11%	58.01%	15.91%
	90th Percentile	Mean Difference	**-0.90%**	**3.77%**	**-0.27%**	**5.01%**	**4.58%**	**2.32%**
		SD_Pooled	6.57%	7.11%	5.57%	11.48%	6.38%	6.34%
		P Value	0.359	0.216	0.908	0.306	0.098	0.390
		Stat Power	6.15%	23.07%	5.14%	17.13%	37.94%	13.45%

Table 14. *Six directional movements EMG muscle activity ANOVA results for laboratory reduced minus field 2016. Highlighted cells denote a P-Value lower than 0.05 or statistical power higher than 50%.*

			Lab Reduced minus Field					
			UP	DN	FW	RW	CCW	CW
		# of Subjects	20-8	20-8	20-8	20-8	20-8	20-8
FDS	50th Percentile	Mean Difference	**3.41%**	**2.65%**	**4.67%**	**4.13%**	**10.25%**	**5.59%**
		SD_Pooled	8.28%	3.19%	6.00%	4.62%	8.08%	9.24%
		P Value	0.334	0.058	0.074	0.042	0.005	0.16
		Stat Power	15.77%	48.10%	43.33%	53.89%	83.12%	28.58%
	90th Percentile	Mean Difference	**5.72%**	**4.65%**	**6.12%**	**5.87%**	**15.94%**	**6.97%**
		SD_Pooled	14.69%	6.17%	10.44%	7.55%	13.71%	14.64%
		P Value	0.143	0.083	0.173	0.074	0.010	0.265
		Stat Power	14.60%	41.11%	27.13%	43.25%	76.28%	19.50%
EDC	50th Percentile	Mean Difference	**-4.55%**	**-7.13%**	**-0.64%**	**-9.53%**	**-7.34%**	**-6.22%**
		SD_Pooled	8.34%	8.83%	10.61%	11.66%	13.49%	5.23%
		P Value	0.204	0.065	0.886	0.062	0.205	0.009
		Stat Power	24.15%	45.98%	5.22%	46.88%	24.04%	78.13%
	90th Percentile	Mean Difference	**-6.89%**	**-12.36%**	**-3.68%**	**-13.18%**	**-13.47%**	**-12.31%**
		SD_Pooled	10.70%	13.12%	15.65%	16.47%	19.75%	17.10%
		P Value	0.007	0.033	0.578	0.043	0.115	0.43
		Stat Power	31.68%	58.25%	8.42%	45.32%	34.86%	38.12%
Bicep	50th Percentile	Mean Difference	**5.77%**	**1.65%**	**1.93%**	**-0.03%**	**1.24%**	**8.45%**
		SD_Pooled	7.08%	1.56%	5.63%	3.02%	1.66%	10.45%
		P Value	0.063	0.018	0.419	0.984	0.086	0.064
		Stat Power	46.67%	68.23%	12.39%	5.01%	40.52%	46.08%
	90th Percentile	Mean Difference	**8.20%**	**2.49%**	**1.89%**	**0.28%**	**0.82%**	**10.41%**
		SD_Pooled	15.73%	2.20%	8.46%	4.05%	2.86%	16.32%
		P Value	0.185	0.012	0.597	0.869	0.5	0.139
		Stat Power	22.45%	74.04%	8.08%	52.90%	10.13%	31.19%
Tricep	50th Percentile	Mean Difference	**0.10%**	**2.90%**	**-0.70%**	**-1.61%**	**2.91%**	**1.47%**
		SD_Pooled	2.35%	5.76%	3.54%	6.03%	5.40%	6.25%
		P Value	0.918	0.24	0.642	0.53	0.209	0.58
		Stat Power	5.11%	21.26%	7.41%	9.42%	23.67%	8.42%
	90th Percentile	Mean Difference	**-0.55%**	**3.25%**	**-1.72%**	**-2.29%**	**4.54%**	**1.34%**
		SD_Pooled	8.92%	8.27%	5.25%	9.67%	9.64%	8.76%
		P Value	0.673	0.357	0.44	0.576	0.271	0.717
		Stat Power	5.23%	14.78%	11.73%	8.47%	19.18%	6.43%

Table 15. *Subjective assessment results for laboratory study.*

	Reduced Force Condition			Conventional Force Condition				
Subject	Physical Effort	Ease of Use	Like/Dislike	Physical Effort	Ease of Use	Like/Dislike	What was prefered?	1=N, 0=S
S01	1	6	6	4	3	3	N	1
S02	3	5	4	5	3	3	N	1
S03	3	6	6	3	6	6	N	1
S04	3	5	5	3	4	4	N	1
S05	5	3	4	5	2	3	N	1
S06	5	4	3	6	3	3	N	1
S07	3	5	6	5	3	5	N	1
S08	4	2	3	3	3	3	S	0
S09	2	6	6	3	5	5	N	1
S10	2	6	6	3	5	5	N	1
S11	3	6	4	5	5	3	N	1
S12	1	6	6	2.5	5	4.5	N	1
S13	1	6	6	3	7	3	S	1
S14	2	5	6	4	5	5	N	1
S15	3	3	3	4	4	4	S	0
S16	3	5	5	6	5	3	N	1
S17	4	3	3	7	2	2	N	1
S18	3	4	4	4	3	2	N	1
S19	4	3	3	7	2	2	N	1
S20	2	6	6	3	5	6	N	1
Mean	2.9	4.8	4.8	4.3	4.0	3.7		0.9
Median	3.0	5.0	5.0	4.0	4.0	3.0		1.0
SD	1.2	1.3	1.3	1.4	1.4	1.3		0.3
Min	1.0	2.0	3.0	2.5	2.0	2.0		0.0
Max	5.0	6.0	6.0	7.0	7.0	6.0		1.0

13 **Appendix B**: Laboratory Study Forms

MARQUETTE UNIVERSITY
Office of Research Compliance

INSTITUTIONAL REVIEW BOARD
Informed Consent for Research
Protocol Number: HR-3283
IRB Approved 01/26/2017
Consent Form

FORM 1: MARQUETTE UNIVERSITY
AGREEMENT OF CONSENT FOR RESEARCH PARTICIPANTS

Aerial Bucket Control – Laboratory Evaluation of New Pistol Grip Control with Reduced External Force

Richard W. Marklin, Jr., Ph.D., Dept. of Mechanical Engineering

You have been invited to participate in this research study. Before you agree to participate, it is important that you read and understand the following information. Participation is completely voluntary. Your employment and relationship with Marquette University will not be negatively impacted if you do not volunteer to participate in this study. Please ask questions about anything you do not understand before deciding whether or not to participate.

PURPOSE: *The objective of this research study is to measure how much muscle force is exerted to operate the aerial bucket control with two force levels, 15 and 8 lbs. The long term goal of this project is to use these force data to design an improved pistol grip control to reduce muscle fatigue of line workers, who use this control on a daily basis.*

PROCEDURES:
You will practice using the pistol grip control to move the scale model bucket up/down and to the right and left sides. **The overhead line on the scale model is NOT energized, and there is no risk of electrical shock.**

Then you will have EMG sensors taped to 4 muscles on your right arm. After the sensors are calibrated to your body, you will be asked to exert maximum force for each muscle for only 3 sec. A student will hold your arm in a certain posture while you exert a maximal force.

A trained experimenter from Marquette U. will lead the study and tell you what to do. You will make the following exertions on the pistol grip control (not necessarily in this order):

- Push in then pull out
- Pull up and push down
- Rotate to the right (clockwise) and rotate to the left (counter-clockwise)
- Operate the control to move the bucket from the truck platform (floor of scale model) to the overhead line

Then you will repeat all of the above movements (2 trials each) while electromyographic (EMG) data from sensors on your arms are transmitted wirelessly to a computer.

The experimenter will record video data of the pistol grip movements. If the video recordings are used in any public setting, your identity will be protected by blurring your face in the video. The video recordings will be destroyed 5 years after the completion of the study. After completing all of the trials, up to 10 anthropometric dimensions of your body will be measured.

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After EMG testing is finished, then you will be asked to answer several questions about your occupation and assessment of operating the aerial bucket pistol grip. These questions include the following:

- Age, gender, occupation, # of years in your occupation
- Height, weight, right arm measurements (arm length, hand length, hand width, forearm girth), and right grip strength
- History of physical injuries from occupation(s)
- Perceived physical effort and ease of use from operating the pistol grip and whether you like or dislike the pistol grip

RISKS: There are small risks associated with participation in this study: 1) your skin could become irritated from the tape used to attach non-invasive sensors to your skin, and 2) possible discomfort from not being able to use the restroom for 2-3 hours and 3) Possible muscle soreness after completing tasks.

We will minimize these risks by 1) using high quality hypoallergenic 3M tape, 2) making the testing as short as possible (2-3 hours total testing time), and 3) making sure the exertions will be intermittent and with at least 2 min of rest between successive movements of the pistol grip.

BENEFITS: There are no direct benefits associated with participation in this study. However, the correct application of the results of this study will help us design an improved pistol grip that will reduce the required force and muscle fatigue from electric line workers operating a pistol grip control.

CONFIDENTIALITY:

- All information you reveal in this study will be kept confidential. All your data will be assigned an arbitrary code number rather than using your name or other information that could identify you as an individual. When the results of the study are published, you will not be identified by name.
- The data will be destroyed by shredding paper documents and deleting electronic files 5 years after the completion of the study. The data from this study will be stored in locked cabinet and password-protected computers. Five years after the completion of the study all of your paper forms will be shredded and your electronic files will be permanently deleted.
- Your name will not be used in any reports and will only be recorded on this sheet. All other sheets will only have a subject code number. Your identity will be protected in all video files used outside of the research team by blurring your face.
- Your research records may be inspected by the Marquette University Institutional Review Board or its designees, the Electric Power Research Institute (EPRI), and (as allowable by law) state and federal agencies.

COMPENSATION: You will be compensated $50 for participating in this study. You will sign a form at the end to the study that confirms that you participated in the study, and a check will be

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mailed to you within 2 weeks from Marquette U. If you decide to leave the study early, you will still be paid $50.

INJURY OR ILLNESS: Marquette University will not provide medical treatment or financial compensation if you are injured or become ill as a result of participating in this research project. This does not waive any of your legal rights nor release any claim you might have based on negligence.

VOLUNTARY NATURE OF PARTICIPATION: Participating in this study is completely voluntary and you may withdraw from the study and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled. If you withdraw from the study during testing, then the data collected up to the point of withdrawal will be used by researchers if the amount of data collected is sizeable for comparison with other subjects. If the amount is not sizeable, then the data will not be used and destroyed.

CONTACT INFORMATION: If you have any questions about this research project, you can contact Richard Marklin, PhD, the principal investigator at (414) 288-3622 or (414) 399-3622 (cell) before, during, or after the course of testing and ask any questions. If you have questions or concerns about your rights as a research participant, you can contact Marquette's Office of Research Compliance at (414) 288-7570.

I HAVE HAD THE OPPORTUNITY TO READ THIS CONSENT FORM, ASK QUESTIONS ABOUT THE RESEARCH PROJECT AND AM PREPARED TO PARTICIPATE IN THIS PROJECT.

________________________________ __________________
Participant's Signature — Date

____
Participant's Name (please print)

________________________________ __________________
Experimenter's Signature — Date

____
Experimenter's Name (please print)

Protocol Number: __________

FORM 2: BACKGROUND AND MUSCULOSKELETAL SURVEY

Aerial Bucket Control – Laboratory Evaluation of New Pistol Grip Control with Reduced External Force

Subject ID (e.g. S01, etc.) : ________________ Date:_______________
Occupation: __________________________

Gender: Male Female Age: ________________ yrs
Height: ________________ ft / inches Weight: ______________ lbs

Name of employer: ____

Number of years with employer: ____

Title of current job: ____

Number of years at current job: ____

Have you ever had a physical injury that you believe is caused by your work? Yes No

If yes, when? ____
Please describe: ____

Have you had more than one injury? Yes No
If yes, when? ____
Please describe: ____

Protocol Number: __________

FORM 3: SUBJECTIVE ASSESSMENT SURVEY

Aerial Bucket Control – Laboratory Evaluation of
New Pistol Grip Control with Reduced External Force

Subjective Assessment of S Condition Pistol Grip Control

Subject ID: (e.g. S01, etc.) ________________ Date: ____________________

1. **Borg Perceived Exertion Scale - Please rate the perceived PHYSICAL EFFORT when you use the aerial bucket S Condition PISTOL GRIP control.**

0	Nothing at all
0.5	Very, very weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	-
7	Very Strong
8	-
9	-
10	Maximal

2. **Please rate the EASE OF USE of the S Condition PISTOL GRIP control.**

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

3. **Please rate how much you like/dislike the S Condition PISTOL GRIP control**

1	2	3	4	5	6	7
Very Strongly Disliked	Strongly Disliked	Disliked	Neutral	Liked	Strongly Liked	Very Strongly Liked

4. Please write COMMENTS about the S Condition PISTOL GRIP control

____

____

Initials: __________

Date: __________

Protocol Number: ___________

Subjective Assessment of N Condition Pistol Grip Control

Subject ID: (e.g. 801, etc.) ________________ Date: ____________________

1. **Borg Perceived Exertion Scale - Please rate the perceived PHYSICAL EFFORT when you use the aerial bucket N Condition PISTOL GRIP control.**

0	Nothing at all
0.5	Very, very weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	-
7	Very Strong
8	-
9	-
10	Maximal

2. **Please rate the EASE OF USE of the N Condition PISTOL GRIP control.**

1	2	3	4	5	6	7
Very Difficult	Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Easy	Very Easy

3. **Please rate how much you like/dislike N Condition PISTOL GRIP control**

1	2	3	4	5	6	7
Very Strongly Disliked	Strongly Disliked	Disliked	Neutral	Liked	Strongly Liked	Very Strongly Liked

4. Please write COMMENTS about the N Condition PISTOL GRIP control

____

____

5. Which control would you prefer to use to maneuver an aerial bucket? (circle one)

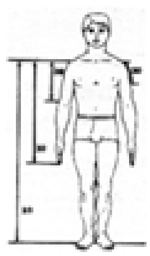
S Condition N Condition

Protocol Number: ___________

FORM 4: ANTHROPOMETRY FORM

Aerial Bucket Control – Laboratory Evaluation of New Pistol Grip Control with Reduced External Force

Subject ID #: ______________________________ Date: ___________________



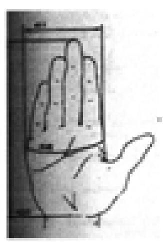
Hand Dominance (circle one): Left Right

Stature __________ (in) (ask worker)

Weight __________ (lb) (ask worker)

Right arm length __________ (cm) (long tape measure)

(NASA 1024 dim #32)

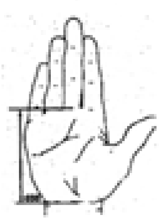


Right hand length __________ (cm) (hand caliper)

(NASA 1024 dim #420)

Right hand width (metacarpals) __________ (cm) (hand caliper)

(NASA 1024 dim #411)



Right hand palm length ___________(cm) (hand caliper)

(NASA 1024 dim #656)

Right forearm girth (relaxed) __________ (cm) (small tape measure)

Right Hand Grip Strength (Jamar grip dynamometer)

Trial 1: ______________________ (lbf)

Trial 2: ______________________ (lbf)

Initials: ___________

Date: ___________

FORM 5: Aerial Bucket Control - Laboratory Evaluation of New Pistol Grip Control

Reimbursement Acknowledgement

I, ____________________ have completed my participation in the laboratory study of New Pistol Grip Control. By signing this form I am acknowledging that I understand that I will receive $50 from Marquette University for my participation in the form of a check mailed to the address that I provided on the completed W-9 form.

____________________________________ _______________

Participant Signature Date

____________________________________ ________________

Investigator Signature Date

This form will be stored along with your consent form in a locked file cabinet separate from all other forms and data collected in this experiment.

14 **Appendix C**: Battery Life Calculation of Reduced Force Pistol Grip

Calculating the number of Truck to Line runs for the reduced force pistol grip battery based on the amount of energy required to move the valves on the bucket truck. Assumptions are listed below, and all calculations and units are shown.

Assumptions:

1. There is only energy required to move a valve but there is no energy required to hold a valve in place because the servo selected will have a high holding torque.
2. An average run from the truck to line requires about 25 separate movements of the joystick resulting in the movement of 50 valves.
3. Energy loss due to gears/motor efficiency is only 10%
4. 40% of the battery energy is lost during battery sitting unused
5. A crew takes the bucket up to the line and back 1 time per hour for an 8 hour shift.

Step 1: Amount of energy to move one valve is based on the amount of energy to move the springs in the manifold and the energy to overcome hydraulic pressure in the poppet valve. k is the spring constant, x is the distance required to move the valve P is hydraulic pressure and A is the effective area in the poppet valve.

$$Energy = \frac{1}{2}kx^2 + PAx \qquad \text{(C-1)}$$

$$Energy = \left(\frac{1}{2}\right)\left(\frac{18.15lb}{in}\right)\left(\frac{7}{8}in\right)^2 + \left(\frac{350lb}{in^2}\right)(0.0996in^2)\left(\frac{7}{8}in\right) = 37.44\ lb\ in \qquad \text{(C-1.1)}$$

Step 2: Converting that to joules with 1lb in equal to 0.1129 joules.

$$Energy = (37.44\ lb\ in)\left(0.1129\frac{J}{lb*in}\right) = 4.23\ J \qquad \text{(C-2)}$$

Step 3: Therefore 4.23 Joules are required to move (and hold) one valve fully. The efficiency of the mechanism is 90%. When this is taken to account the final amount of energy required for one activation is below.

$$Energy\ Required = \frac{4.23J}{0.9} = 4.70\ J \qquad \text{(C-3)}$$

Step 4: The amount of energy in the battery is needed next and there are (2) types of batteries being considered from Milwaukee Tool. Battery A which is an 18V 2.4amp-hour battery and battery B which is an 18V 4.0amp-hour battery. Sample calculations will be done with battery A but the results for battery B will be shown as well.

$$Energy\ in\ Battery\ A = 2.4(amp - hour)(18v)\left(3600\frac{Sec}{hr}\right) = 155{,}520\ J \qquad \text{(C-4)}$$

$$Energy\ in\ Battery\ B = 259{,}200\ J \qquad \text{(C-4.a)}$$

Step 5: Predicting the number of activations per run of Truck to Line. This was done using video of the experiments run at WE Energies in 2016. This number is difficult to get because the direct movement of the boom does not show how many times that the pistol grip is moved. 50 activations is the number used in this calculation. Finally, the number of truck to line uses per battery can be calculated.

$$Battery\ A\ Truck\ To\ Line\ Uses = \left[\frac{Energy\ in\ Battery A[J]}{Energy\ Required\ [J]}\right]\left[\frac{1}{50\ Activations\ per\ Truck\ to\ Line}\right] \quad \text{(C-5)}$$

$$Battery\ A\ Truck\ To\ Line\ Uses = \left(\frac{155{,}520 J}{4.7 J}\right)\left(\frac{1}{50}\right) = 662\ Truck\ To\ Line\ Movements \quad \text{(C-5.a)}$$

$$Battery\ B\ Truck\ To\ Line\ Uses = 1{,}103\ Truck\ To\ Line\ Movements \quad \text{(C-5.b)}$$

Step 6: Now the active time period is calculated assuming that the battery loses 40% of its power due to sitting un-used for most of the time and that a crew goes up to the line and back one time per hour for an 8 hour shift and works 5 days a week. This leads to 16 uses per day.

$$Duration\ of\ one\ charge\ of\ Battery\ A\ (2.4\ amp - hrs)\ Lasts = \frac{Truck\ To\ Line\ Movements(0.6^*)}{16\ Uses\ per\ Shift} \quad \text{(C-6)}$$

$$Duration\ of\ one\ charge\ of\ Battery\ A\ \frac{662\ Truck\ to\ Line\ Uses(0.6^*)}{16\ Uses\ per\ Shift} = 24\ eight\ hr\ work\ shifts \quad \text{(C-6.a)}$$

$$Duration\ of\ one\ charge\ of\ Battery\ B\ (4.0\ amp - hrs) Lasts = 41\ eight\ hr\ work\ shifts \quad \text{(C-6.b)}$$

*Assumes battery will lose 40% of its energy over the duration of one charge.

15 **Appendix D**: Simulink Block Diagrams

The control scheme for the Arduino Mega 2560 is revealed in **Figure 24** and **Figure 25**. The first block diagram, shown in **Figure 24,** is the control that was used during the laboratory trials and does not include the output blocks for the servomotors that would control the hydraulic valves. Both block diagrams have a section that is called "Read Sensors", this section takes the analog reading from all four potentiometers and turns it into a 10 bit (0-1023) digital signal. The next section then creates a dead band for the potentiometers meaning that there is a small section where the pistol grip will move where it will not actuate the scale model of the bucket truck. The next section of the code then takes the signal from the three main potentiometers and scales them based off the dead man's switch potentiometer. Once that has been done the signal then goes into a directional decision which will decide which direction the potentiometer was moving and will send the signal to the appropriate of the six output blocks. The final section then scales the outputs to a 8 bit (0-255) PWM signal and then sends the signals to the three actuators on the scale model of the bucket truck and it moves at the appropriate speed and direction. **Figure 25** shows a very similar block diagram with the additional section that outputs a digital signal to the six servomotors controlling the hydraulic valves.

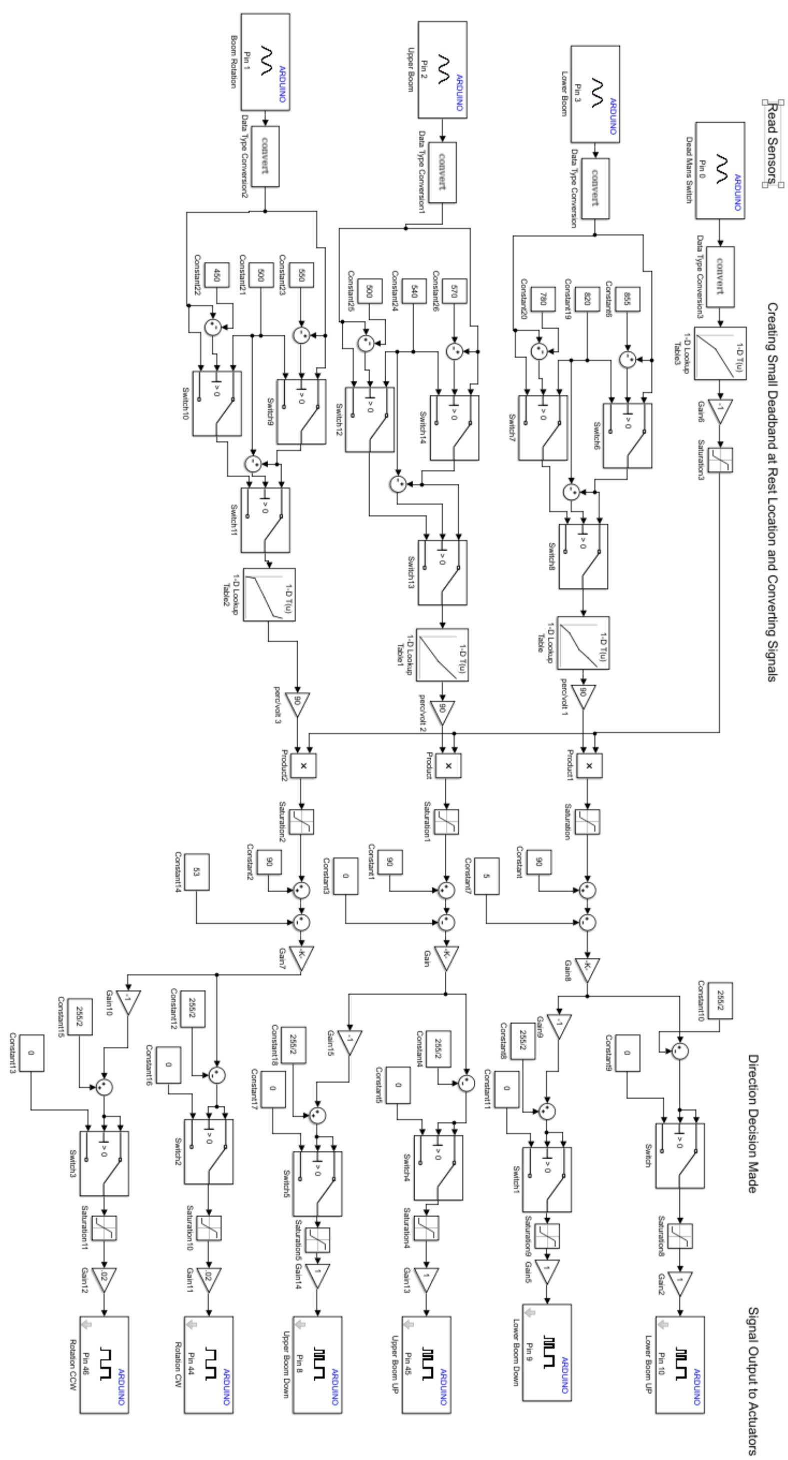


Figure 24. *Condensed Controls in Simulink for Reading Sensors and Controlling the 1/15th Scale Model of Bucket Truck.*

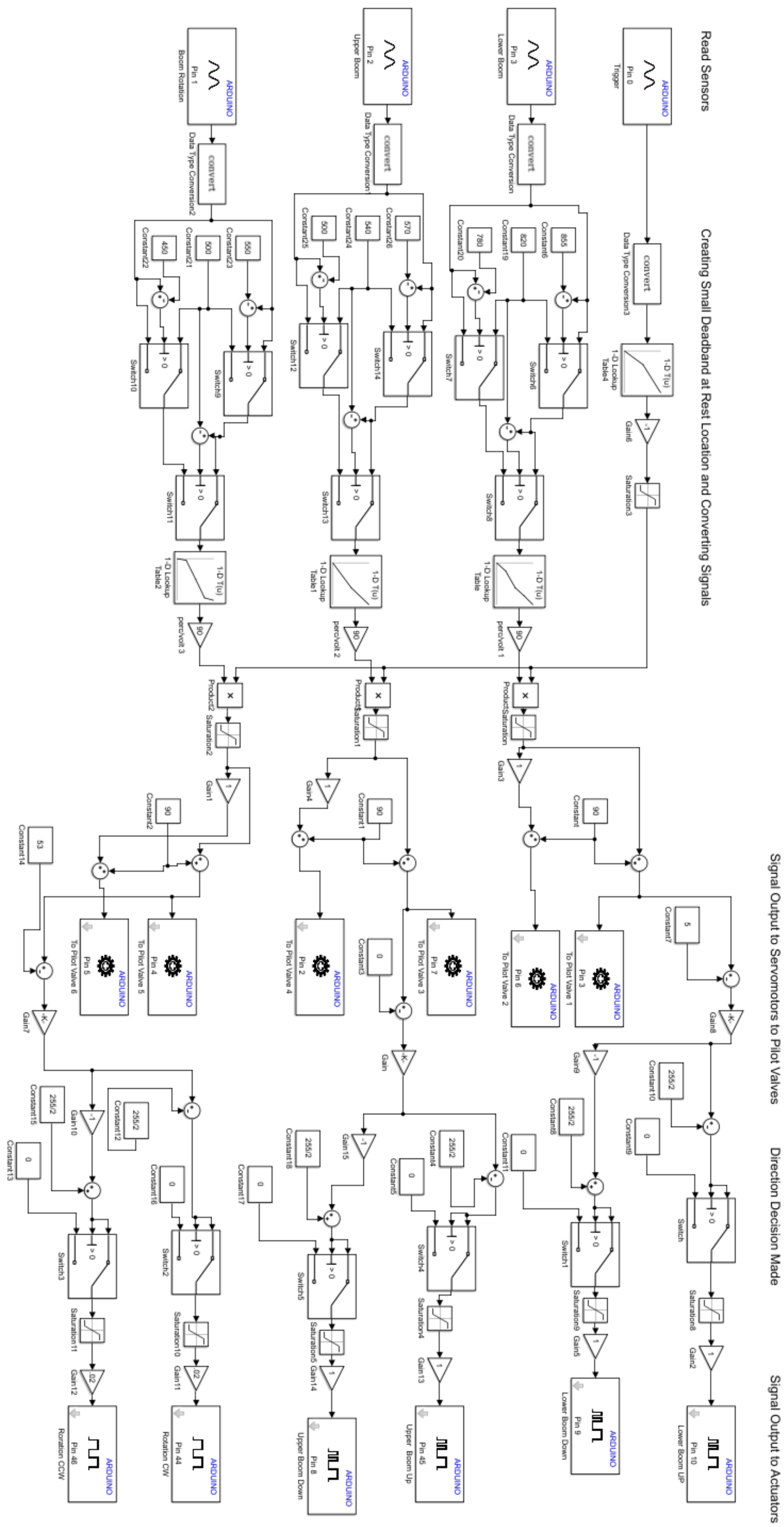


Figure 25. *Combined Controls in Simulink for Reading Sensors, Controlling the 1/15th Scale Model of Bucket Truck and Controlling the Servomotors that Connect to Pilot Valves in Hydraulic System of the Bucket Truck.*