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Biomechanical Evaluation of a Jackhammering Task with and Without List Assist

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BIOMECHANICAL EVALUATION OF A JACKHAMMERING TASK WITH AND WITHOUT LIST ASSIST

by

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ABSTRACT
BIOMECHANICAL EVALUATION OF A JACKHAMMERING TASK WITH AND WITHOUT LIST ASSIST

by

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Under the supervision of Professor Naira Campbell-Kyuregyhan

The construction and utility industries have relatively high levels of hazardous tasks that impose high physical demands on a worker. For the past decade these industry sectors had one of highest incident rates for non-fatal injuries (BLS, 2013). The task of operating a jackhammer presents several risk factors that promote the high rates of injuries to this industry sector. Until the introduction of the lift assist, relatively few interventions were available to make the task of operating a jackhammer safer. However, no research has been conducted to support that this device is able to make jackhammering safer. The aim of this study was to evaluate and quantify the changes of operating a jackhammer with and without a lift assist.

Eight experienced jackhammer operators participated in this study. All participants were asked to use a 90lb and 60lb jackhammer once with the lift assist attachment and once without the lift assist attachment while breaking a 3'x3' concrete section. Throughout the trials, grip pressure, bilateral muscle activity, vibration, and task time were recorded. For each variable a general linear model ANOVA was with 95% confidence was performed to determine statistically significance changes. The factors of lift assist, weight, and the

interaction between the two were factors in the ANOVA. The factor of subject was blocked.

Results showed that using the lift assist reduced the grip pressure and muscle activity for the lifting portion of the task. During operation, using the lift assist did not result in a change of vibration amplitude on the jackhammer or dose of the exposure to the operator or affect the grip pressure needed to operate the jackhammer. However, the task time was slightly increased. This is suspected to be due to the inexperience of the operators with using the lift assist. These results support that the lift assist reduces the lifting effort/demands required of the operator, while without altering other risk factors during the jackhammering task. Reduction in the jackhammer lifting effort while using a lift assist device may lead to a reduced risk of overexertion injuries, as well as allow more diverse population of the operators to perform the task.

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Chapter 1: Introduction

Throughout history, the construction and utility industries have been burdened with injuries. In 2004, there were 71% more nonfatal injuries that required days away from work than any other industry (BLS, 2005c). In 2007, construction had the 2nd highest nonfatal injury rate just behind transportation with 174.3 per 10,000 workers. The utility industry cracked the top ten as well, sitting at number 8 (BLS, 2008a).These rates of injuries have continued, with construction being in the top 3 among all private industry in 2011 and 2012 (BLS, 2011; BLS, 2012). Along with being among the industries with the highest rates of injury, the severity of the injuries ranks just as high. In the same year, 2012, the construction industry had the 5th highest median days away from work, just below the utility industry which is tied for 3rd (BLS, 2013). Given the high number of injuries and high level of severity, there are large injury-related costs associated with these trades. In 2002 it was estimated that every injury in construction costs approximately $27,000, which was almost double the overall industry average of $15,000 (Waehrer, 2007), and in 2004 construction was ranked in the top 15 for average cost per injured employee (Leigh, 2004). With injury rates remaining at a high rate, even up to the present day, it can be expected that construction is still ranked high in the average cost per injury.

One of the main contributors to these injuries is overexertion. In the construction industry this type of injury had the 4th highest rate. Researchers have observed a high rate of material handling and manual lifting involved in the construction industry (Burkhart, 1993; Schnieder, 1998; Choi, 2007). In addition, the construction industry had one of the highest rates for performing work in awkward postures such as bending and twisting (Tak, 2011).

Although less data is available overall, the consensus is that there is a high incidence rate of cumulative trauma injuries in the construction trade (BLS, 1998). Types of cumulative trauma injuries common in construction are: trigger finger, carpal tunnel syndrome, arthritis, and hand arm vibration syndrome (HAVS) (Killough, 1996). HAVS can be very serious problem because it is associated with many different symptoms such as decreased vascularization, muscle weakness/ pain in the hands, and loss of sensation/ tingling in the hands (Bovenzi, et. al, 1990; Brammer, et. al, 1987; Deschmukh, et. al, 2012). Not only does exposure to vibration increase the risk of carpal tunnel syndrome, it can also decrease productivity through the debilitation of hand dexterity making manual handling tasks harder to perform (Bovenzi, et. al, 1990; Brammer, et. al, 1987; Deschmukh, et. al, 2012). Thus, HAVS affects the construction industry in two ways; through the direct medical costs associated with the effects, and through reductions in output from the affected workers.

Exposure to vibration has also been linked to overexertion injuries, which is one of the leading sources of injury in construction (Inyang, 2012). Overexertion is believed to be linked to vibration exposure through the tonic vibration reflex (TVR), which is believed to promote muscular fatigue by causing the muscles to voluntarily, involuntarily, and reflexively contract (Bongiovanni, 1990; Park, et. al., 1993). Increased stress and fatigue on the muscles raises the risk of a muscular skeletal injury (Dolan, et. al., 1998).

The operation of a jackhammer is a common task in the construction industry that presents risks that have been associated with costly injuries. The jackhammering task entails an individual holding onto a device that repeatedly provides forceful blows to the ground in order to break the surface. This portion of the task has been linked to a high level of vibration exposure (Burgress, 2012). Since the jackhammer can only break small portions of the surface at a time, the process of operating the jackhammer must be repeated. In order to repeat the breaking process the operator must first lift the jackhammer out of the broken surface and place it on the unbroken surface. This process of lifting the jackhammer can promote overexertion injuries due to the weight being lifted. Jackhammers can vary in weight anywhere between 45-95 lbs. At these weights, only 47% of the male population, and no females, are considered capable of performing this lift without risk of a low-back injury (Snook, 1991). For the most common weight of a jackhammer used in the construction industry (90 lbs), also known as a conventional jackhammer, less than 10% of the male population is capable of performing this task (Snook, 1991). In addition, based on a National Institute of Occupational Health (NIOSH) report it is believed that any weight over 51lbs is considered to be unsafe for all individuals (Waters, 1991). After examining the research done on vibration and manual handling tasks, one cannot help but agree that the jackhammering task poses multiple hazards to the operator.

Even though this task presents clear risks to the operators, little research has been done to try to mitigate these risks. Over 60 articles were reviewed for this study (Table 1). Although many of the articles are not specific to jackhammering, they were selected on the basis of whether they provided relevance to any aspect of the current study. In particular, the articles discuss hand arm vibration measurements or effects, construction or utility injuries, overexertion/ repetitive lifting injuries, muscle activity in dynamic lifting tasks, provide insight on quantifying grip pressure/ contact area, or had any relation to the task of jackhammering. The articles also provided insight that informed the methodology used in this study, including sensor selection and placement.

The literature search identified only eight articles that investigated the task of operating a jackhammer. These articles discussed the vibration exposure and the difficulty of the task, however they provided no insight into addressing the reduction of injury risk associated with this task. Two of the articles researched ways of preventing vibration transmission; however the research technique was either ineffective or not applicable to a jackhammer. One article was found that investigated a lifting aid for manual handling tasks; however it appeared to not be applicable to jackhammering. Only a few articles discussed the overall difficulty and risks associated with the task. Thus, there is a clear lack of knowledge about the risks involved of operating a jackhammer and devices available to reduce these risks.

One device that is designed to reduce the risks involved in jackhammering is the lift assist. The lift assist aims at reducing the stress on the operator during the lifting portion of the task. The lift assist device is a metal rod housed in a cylindrical container that attaches directly to the jackhammer. When triggered, this device uses the existing pneumatic power source of the jackhammer to forcefully push the metal rod out of its housing and onto the ground/surface. Through the downward pushing motion of the device, the jackhammer is removed from the pavement and propelled off the ground in such a way that the operator should no longer need to lift the jackhammer but merely guide it to the new breaking surface. By making the lifting portion of the task easier, it is thought that the lift assist will provide a benefit through reducing the stress on the operator during the lifting portion of the task, as well as provide an overall increase in productivity, and will not negatively affect general operation of the jackhammer. However, no studies have been conducted to quantify these potential benefits..

This study aims at evaluating the effectiveness of the lift assist device at reducing the stress on the operator while lifting and increasing productivity. A biomechanical evaluation of a jackhammering task with and without a lift assist device will be performed to investigate the effects on the operator for two common weights of jackhammers, 60lb and 90lb. Changes in biomechanical markers and user perceptions between lifting the jackhammer and operating the jackhammer with and without the lift assist will be quantified. Five specific aims were developed in order to assess the differences in grip pressure, muscle activity, vibration, and task time. These specific aims are:

1. Quantify the impact of using the lift assist on the operator’s grip pressure during operation and lifting of the jackhammer.

   Hypothesis 1a: Using the lift assist while lifting a jackhammer from the pavement will reduce the grip pressure on the hand of the operator.

   Hypothesis 1b: Using the lift assist while operating a jackhammer will not affect the grip pressure on the hand of the operator.

2. Quantify the impact of using the lift assist on the operator’s muscle activity during operation and lifting of the jackhammer, as well as throughout the entire task.

   Hypothesis 2a: Using the lift assist while lifting a jackhammer from the pavement will reduce the muscle activity of the operator.

   Hypothesis 2b: Using the lift assist while operating a jackhammer will not affect the muscle activity of the operator.

   Hypothesis 2c: Using the jackhammer with the lift assist will reduce the muscle activity of the operator throughout the task overall.

3. Quantify the impact of using the lift assist on the jackhammer and hand-arm vibration parameters, as well as vibration dose during the jackhammering task.

   Hypothesis 3a: Using the lift assist during a jackhammering task will not change the vibration amplitude on the jackhammer.

   Hypothesis 3b: Using the lift assist during a jackhammering task will not change the vibration amplitude transmitted to hand.

Hypothesis 3c: Using the lift assist during a jackhammering task will not affect the total vibration dose.

4. Quantify the impact of using a jackhammer with the lift assist on overall time to complete the task.

   Hypothesis 4: Using the jackhammer with the lift assist will reduce the overall time to complete the task.

5. Investigate the user's perceptions of operating a jackhammer with a lift assist.

To achieve these specific aims certain methodologies will be utilized. To quantify the muscle activity, electromyography will be placed on upper extremity muscles. This will provide numerical data of how much activity the muscle is producing. Data will be separated between lifting and operating to quantify the impact of using the lift assist in these portions of the task. To quantify grip pressure, the operator's will wear a grip pressure measuring glove. Grip pressure data will also be separated similarly to the muscle activity data. To address the issue of vibration, accelerometers will be placed on the jackhammer and the hand to collect acceleration data. Vibration will be quantified with the aid of a vibration specific computer program along with the ISO 5349 standard on hand arm vibration. Productivity will be measured through the overall task time the operator takes to complete the task. Finally, a structured interview will be used to address the operator's perception of the lift assist device.

Table 1: Articles reviewed for the current study with a description of the topics addressed.

Article Information				Article Topics										
	Authors	Date	Journal	Jackhammers	Construction Injuries	Overexertion	Repetitive Lifting	HAVS	Jackhammer Vibration	Hand Vibration	Grip Pressure	Dynamic Lifting	Lift Assist	Grip Pressure Tolerance
1	Killough	1996	Int. J. of Industrial Ergonomics	x	x		x	x	x					
2	Holmstrum	1992	Spine		x		x							
3	Ringen	1995	Annual Review of Public Health		x	x	x	x		x				
4	Dong	2004	Mechanical Engineering and Physics					x		x	x			
5	Bongiovanni	1990	Journal of Physiology							x				
6	Potvin	1997	J. Appl Physiol									x		
7	Mannion	1997	J. Elec. Kines.									x		
8	Slane	2011	Cinical Biomech.								x			
9	Marcotte	2011	Canadian Acoustics								x			
10	Dong	2006	J. of Biomchanics					x		x	x			
11	Sorensson	1997	Int. Arch. Occup. Environ. Health					x		x	x			
12	Park	1993	Scan. J. Work Environment Health							x		x		
13	Dong	2005	Industrial Health							x	x			
14	Lopez	2013	I. J. of Industrial Ergonomics	x	x			x	x	x				
15	Chand	2013	Int. J. of Mechanical Engineering	x				x	x	x	x			
16	Lotz	2009	J. Elect. Kines.				x					x	x	
17	Ritzmann	2010	Eur. J. of Appl. Physio.											
18	Verschueren	2003	J. Neurophysiology											
19	Radwin	1987	Ergonomics					x		x	x			
20	Wakeling	2002	J. Appl Physiol											

21	Johansson	1999	Ergonomics								x			x
22	Granata	1999	Clinical Biomechanics		x									
23	Murhalidar	2000	Ergonomics								x			x
24	Alonso	2013	Int. Journal of Industrial Ergonomics	x					x					
25	Kim	1987	Int. Journal of Industrial Ergonomics				x					x		
26	Hill	2001	Chronic Disease in Canada					x						
27	Griffin	1997	Occupational and Environmental Medicine	x				x						
28	Schnieder	1994	American Journal of Industrial Hygeine Association	x		x	x	x						
29	Brammer	1987	Scan. J. Work Environment Health					x						
30	Stenlund	1993	Scan. J. Work Environment Health		x	x	x	x						
31	Jacobsson	1993	Safety Science	x				x		x				
32	Carlsoo	1982	Applied Ergonomics					x		x				
33	Rohmert	1989	Eur. J. of Appl. Physio.					x		x				
34	Chris Nelson	2004	10th ICHAV							x				
35	G. Moschioni	2011	Measurement							x				
36	M Gasparetto	2004	10th ICHAV							x				
37	Singh	2014	Applied Ergonomics							x				
38	Burgess	2012	Proceeds of Acoustics							x				
39	Burnette	2004	Injury Prevention		x	x	x							
40	Bovezi	1990	International Journal of Industrial Ergonomics					x		x				
41	Governement	2009	Burearu of Labor Statistics		x									
42	Government	2012	Burearu of Labor Statistics		x									
43	Dolan	1998	Journal of Biomechanics				x					x		
44	Deshmukh	2012	International Journal of Engineering					x		x				
45	Griffin	1990	Handbook of Human Vibration (book)					x		x				
46	Inyang	2012	Journal of construction and Engineering Management		x									

47	Pyykko	1976	Scandinavian Journal of Work Environment Health							x	x			
48	Schneider	1994	American Industrial Hygiene Association	x	x	x	x			x				
49	Waters	1993	Ergonomics			x	x							
50	Pelmear	2000	Applied Occupational and Environmental Hygiene					x		x				
51	Burstrom	1994	Ergonomics					x		x				
52	Tak	2011	American Journal of Industrial Medicine		x									
53	Anderson	2008	Work		x									
54	Burkhart	1993	American Journal of Industrial Medicine		x									
55	Fung	2010	International Journal of Project Management		x									
56	Lataza	2000	Occupational and Environmental Medicine		x									
57	Lataza	2002	Scandenavian Journal of Work Enviroment Health		x									
58	Lemasters	2006	Experimental Aging Research		x									
59	Nelson	2009	International Journal of Industrial Ergonomics		x									
60	O'Connor	2006	Occupational and Environmental Medicine		x									
61	Ray	2012	Advanced Engineering Informatics		x									
62	Schoenfish	2011	American Journal of Industrial Medicine		x									
63	Vedder	2005	Applied Ergonomics		x									
64	McDowell	2013	Ergonomics							x				

Chapter 2: Methods

All study materials and the study protocol were reviewed and approved by the University of Wisconsin-Milwaukee Institutional Review Board. (Protocol # 13.119).

2.1 Experiment Design

The study was designed to simulate the actual tasks performed with a jackhammer. All trials were performed outdoors during normal working hours, 8am to 4pm. Outdoor temperatures were monitored to make sure they remained in a safe working environment and ranged from 4 degrees Celsius to 12 degrees Celsius. Each subject performed four trials that were identical other than using a different jackhammer/lift assist condition: 90lb and 60lb pneumatic jackhammers, with and without the lift assist. Each trial consisted of breaking a 3' X 3' section of 6" thick concrete (Figure 1). All segments had 5 diagonal lines painted within the square to guide the operator's breaking to assist with consistency between trials and operators. No further instructions were given to the operator. The number of breaking and lifting operations during each trial ranged between about 20 and 40. An outline of the experimental design is displayed in Figure 2.

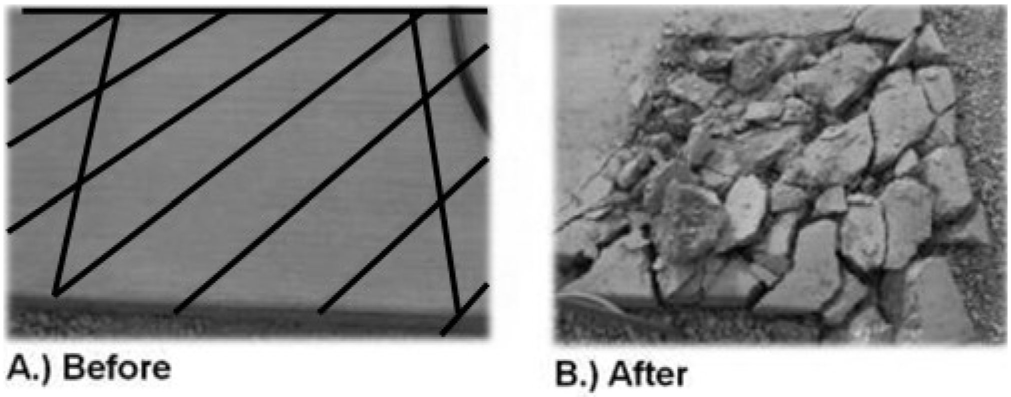

Figure 1: Concrete slab before and after trial.

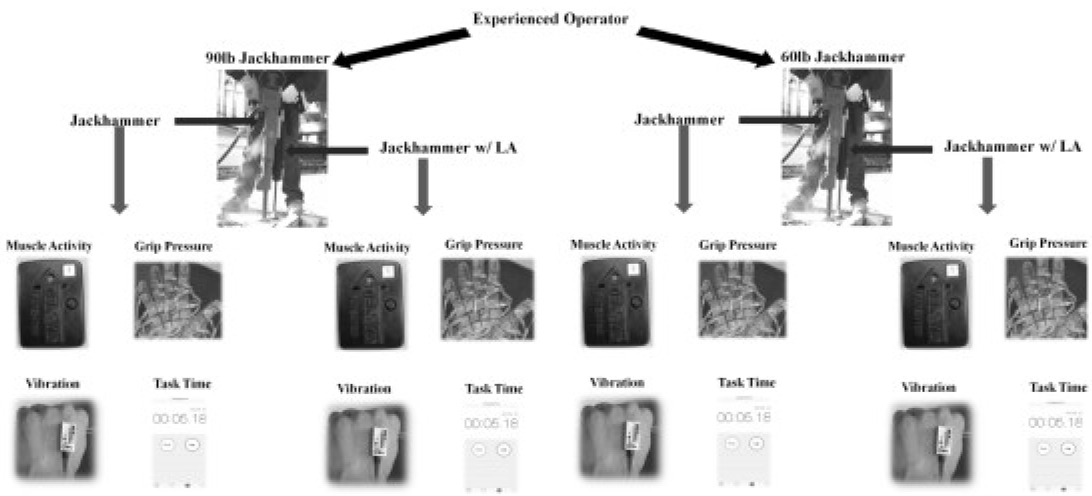

Figure 2: Experimental design.

2.2 Subjects

Subjects were recruited from local utilities by the project sponsor, the Gas Technology Institute. Eight (seven male and one female) experienced jackhammer operators agreed to participate in the study by signing the IRB approved informed consent form. The anthropometric data for the subjects were collected and are presented in Table 2. The subjects had 3 to 20 years of experience in the construction industry operating a jackhammer. However, only one subject had any experience using the lift assist. All subjects were allowed to practice operating a jackhammer with the lift assist device before data collection started.

Table 2: Anthropometric data

Anthropometry	S1	S2	S3	S4	S5	S6	S7	S8
Jackhammer Exp. (yrs)	13	7	3	4	1-3	4	17	20
Gender	Male	Male	Male	Male	Male	Male	Female	Male
Age	30	40	34	39	32	49	46	42
Weight (kg)	90	77	125	63	116	84	52	91
Height (cm)	165	155	172	167	178	165	157	187
BMI	33	32	42	23	37	31	21	26

2.3 Equipment

Accelerations were measured on both the handle of the jackhammer (Figure 3) and the left hand (Figure 4) of the operator using high frequency (up to 5,000 Hz) accelerometers (NexGen Ergonomics, CA). The accelerometer on the left hand was placed to provide a secure attachment to the operator. Prior to processing the axes were digitally switched to conform to the ISO 5349 standard (Figure 4). In order to monitor arm vibration at different locations, eight additional accelerometers (Delsys Trigno, MA) were placed on the subject's right and left forearm, Bicep, Tricep, and Deltoid and the axes were similarly rotated to the ISO 5349 standard directions.

Figure 3: High frequency accelerometer placed on the jackhammer handle.

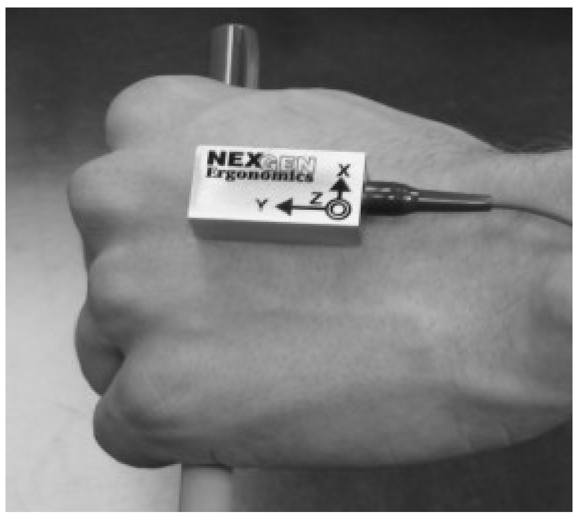

Figure 4: High frequency accelerometer placed on the left hand.

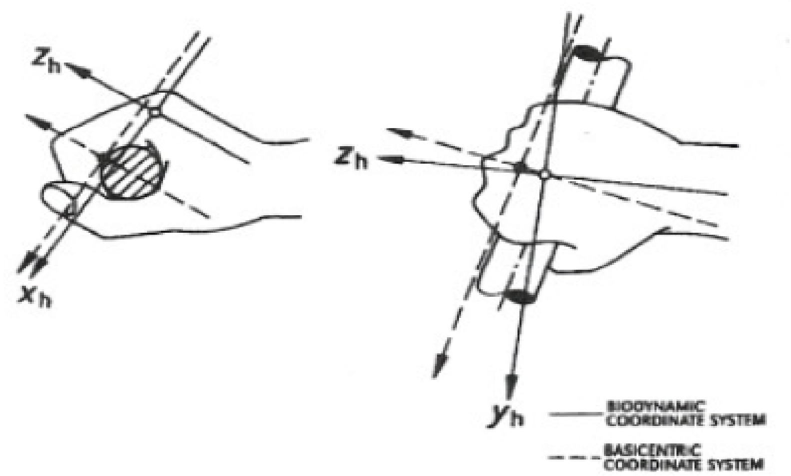

Figure 5: Biodynamic and basicentric coordinate system for the ISO 5349 standard.

Wireless surface electromyography sensors (sEMG),Figure 6, were integrated with the accelerometers (Delsys Trigno, MA) and collected the muscle activity of the right and left Bicep Brachii, Tricep, Deltoid, Erector Spine, Rectus Abdominus, and Latissimus Dorsi (Figure 7 and Figure 8). It was determined that only the Bicep Brachii, Deltoid, and Erector Spinae were the primary muscle contributors in the lifting motion of the jackhammer and thus these are the only muscles presented in the results. Placement areas were shaved and cleaned with rubbing alcohol to decrease any potential artifact resulting from skin interaction. After skin preparation, the electrodes were carefully selected and placed on each muscle belly in accordance with Surface EMG for Non-Invasive Assessment of Muscles standards (Stegeman, 2007). All sensors were additionally secured with hurt free athletic wrap to prevent the SEMG sensors from losing contact with the skin during jackhammer operation.

Figure 6: Delsys Trigino wireless SEMG sensor.

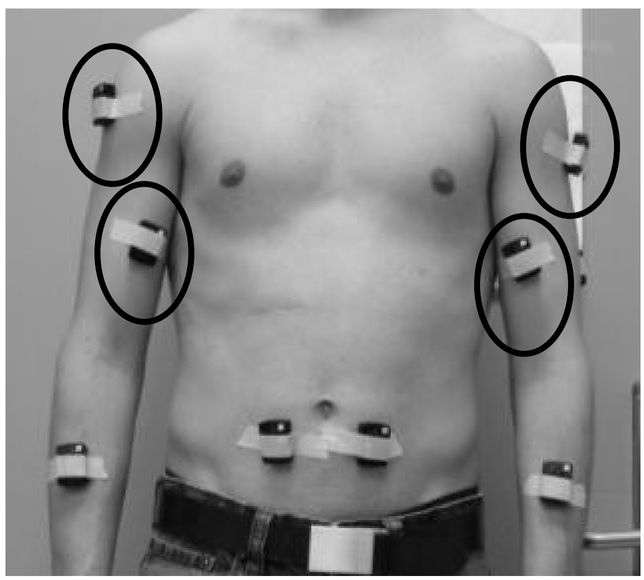

Figure 7: SEMG placement on the anterior side of the body.

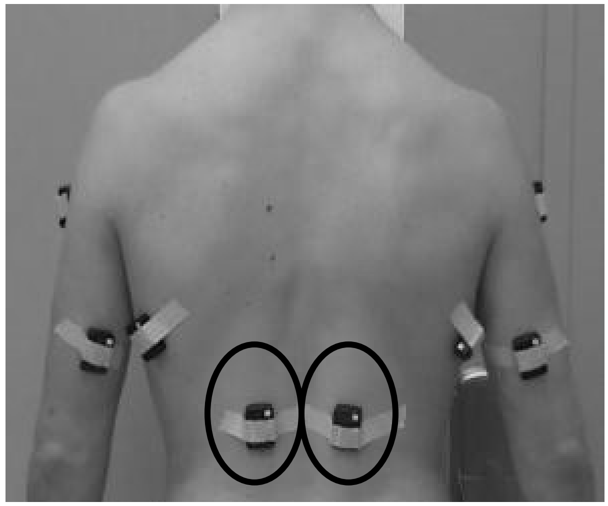

Figure 8: SEMG placement on the posterior side of the body.

Grip Pressure was measured using a pressure mapping glove (Vista Medical, CA) placed on the subject's right hand (Figure 9). The 24 individual sensors were spread in a custom manner amongst the fingers and palm (Figure 10). An identical template for the sensor configuration was used that was consistent between all trials and subjects. The 24 sensor system is believed to be adequate because previous research has identified that only four sensors are needed to adequately measure grip forces (Tornifoglio, 2012).

Figure 9: Grip pressure glove placed on subject's right hand.

Figure 10: Grip pressure sensor placement on the hand.

2.4 Data Collection

2.4.1 *Muscle Activity:* sEMG data were collected with the EMGworks 4.0 Acquisition software (Delsys, MA) at 2,000 Hz and processed in EMGworks 4.0 Analysis software (Delsys, MA) in accordance with the Standards for Reporting EMG data for (Merletti, 1999). The sEMG sensors have an analog bandpass filter of 20Hz to 450Hz. The smoothing technique of calculating the root mean square (RMS) was used on the filtered data. A sliding window of 0.125 seconds and an overlap of 0.0625 seconds were used in the RMS calculation. The RMS data was separated into lifting and operating tasks (Figure 11). The peak muscle activity measured during each lift was found, and the average over all the lifts in a trial was calculated to quantify the muscle activity required to lift the jackhammer. The operating RMS of muscle activity was also averaged to obtain one representative value for the entire trial.

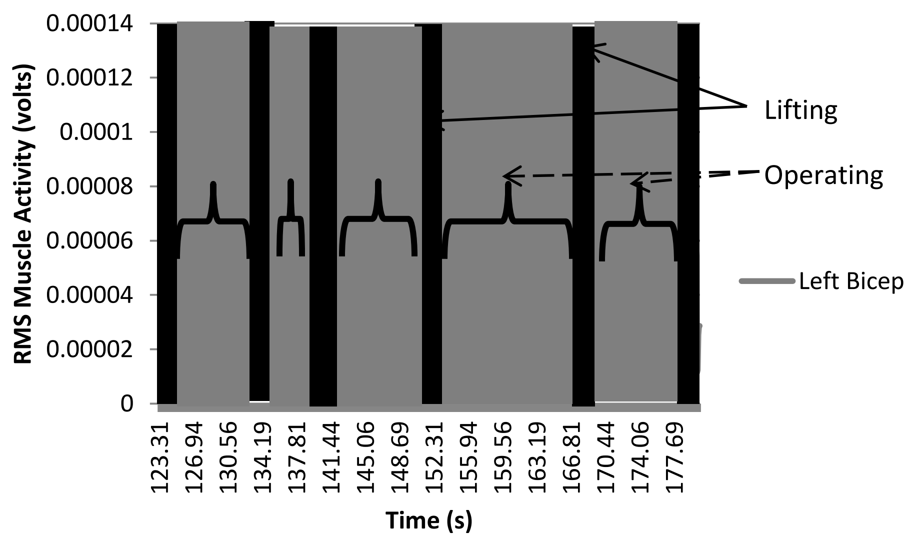

Figure 11: Example of muscle activity data separated between operating and lifting portion of the task.

2.4.2 Grip Pressure: Grip pressure was collected at 5 Hz using the FSA software (Vista Medical, CA). The raw data was extracted and placed in an Excel spreadsheet (Microsoft, WA) for processing. At every time step the data collected at all 24 pressure sensors were summed to obtain the total pressure being applied to the hand. Data was then separated between the operating and lifting phases (Figure 12).

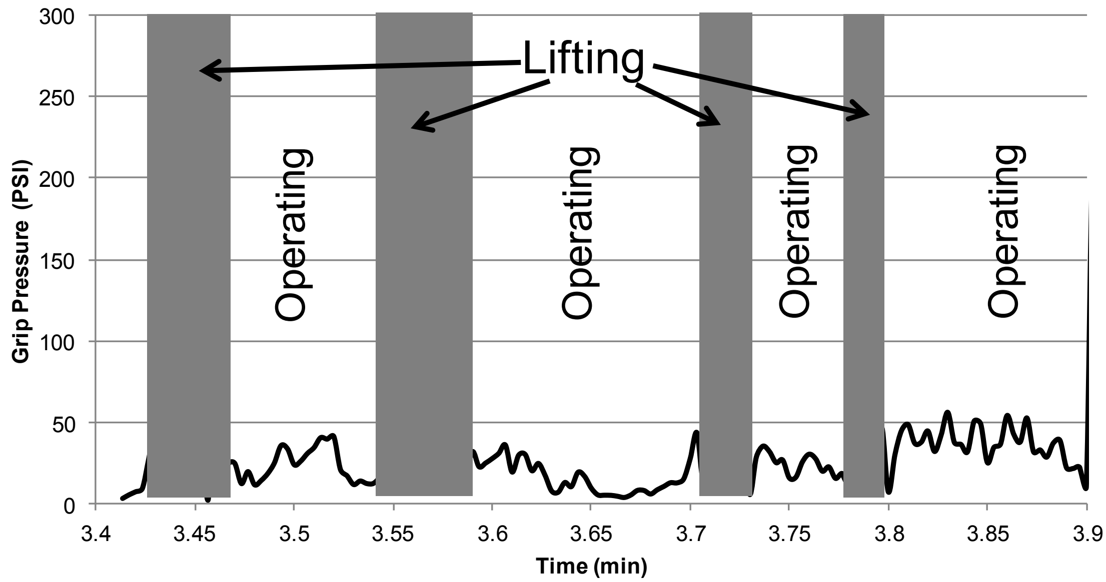

Figure 12: Example of grip pressure data separated between operating and lifting portion of the task.

2.4.3 Vibration: Signal from the high frequency accelerometer were collected at 500 Hz using the Biometrics Data Logger software (Biometrics, VA). The data was then imported to the Vibration Analysis Toolset Software (Biometrics, VA) for processing after rotating the axes to fit the ISO 5349 standard. The raw acceleration data was filtered with a 2^{nd} order bandpass Butterworth filter with corner frequencies at 4 Hz and 250 Hz. For comparison with the ISO 5349 standard a weighted Hanning FFT filter was applied to the raw data.

2.4.4 Task Time: Task time for each trial was collected using a standard stopwatch (Nike, OR) along with 2 digital camcorders (Sony, TKY) The experemental set up is shown in Figure 13.

Time data was imported into an Excel document for analysis. All data was synchronized with the help of video analysis using two standard digital video cameras (Sony, Japan).

Figure 13: Picture of experimental set up.

Each subject was given a number corresponding to the order in which they participated in the study. The jackhammer/lift assist conditions were given a label to allow for easy identification of data files. The 90lb jackhammer was labeled as “A” and the 90lb jackhammer with the lift assist it was labeled “ALA”. The 60lb jackhammer was labeled “B” and the 60lb jackhammer with the lift assist was labeled as “BLA”. Files were labeled with the study information, then subject number, and finally the type of data in the file and version. An example of this is, “Jackhammer_S3_Grip Pressure_v1.” The jackhammer/lift assist conditions were each stored on a separate sheet within the workbook.

2.4.5 Structured Interview: A structured interview (Appendix H) was administered immediately after the completion of each trial to obtain data about user perception. There were five categories to the interview which were focused on the jackhammering experience of the operator, anthropometry of the operators, user's perception of loading/unloading the jackhammers from the truck, user's perception of the weight of the jackhammer, and another section that focused on the user's perception of the lift assist. For the biomechanical evaluation, this study will focus on the user's perceptions of the lift assist. This section asked the operators to provide a rating of agreeability, 1 referring to strongly disagree to 5 referring to strongly agree, after a statement was read to them. A total of seven statements were given to the operator. Of the seven, four main statements were analyzed for this study. The four statements analyzed were, "lift assist relieved muscular effort from removing the tip," "the lift assist improved my performance," "lift assist improves task completion time," and "the lift assist is easy to use." After the operator completed the study, they were asked if they preferred operating a jackhammer with or without a lift assist.

2.5 Data Analysis

2.5.1 *Grip Pressure:* Grip pressure was separated between the operating and lifting portion of the jackhammering task. The peak lifting grip pressure was determined for each lift and then the lift values were averaged to obtain one overall lifting value for each trial. Similarly, the values for the operating sections were averaged to obtain one overall representative value for operating grip pressure. These grip pressure values were used in a general linear model

ANOVA for statistical analysis of lifting and operating grip pressure. Factors of jackhammer weight and lift assist and the interaction between the two were investigated while blocking the subject factor to eliminate subject variability. Confidence was set at 95%. A power of 0.836 was calculated using PS Power and Sample Size Program (Dupont, 1997) for lifting grip pressure. For graphical comparisons the percent change of peak grip pressure (Equation 1) and average operating grip pressure (Equation 2) was calculated between operating a jackhammer using the lift assist versus not using the lift assist.

$$Percent\ Change = \frac{(Peak\ Grip\ Pressure_{With\ lift\ assist} - Peak\ Grip\ Pressure_{Without\ lift\ assist})}{Peak\ Grip\ Pressure_{Without\ lift\ assist}} \quad (1)$$

$$Percent\ Change = \frac{(Average\ Grip\ Pressure_{With\ lift\ assist} - Average\ Grip\ Pressure_{Without\ lift\ assist})}{Average\ Grip\ Pressure_{Without\ lift\ assist}} \quad (2)$$

2.5.2 Muscle Activity: Muscle activity was separated between the operating and lifting portion of the jackhammering task. The peak lifting muscle activity was found for each lift and the values for each lift were averaged to obtain one overall lifting value for each lifting trial. Similarly, the values in the operating sections were averaged to obtain one overall representative value for operating muscle activity for each muscle. These calculated values were used in a general linear model ANOVA statistical analysis of lifting and operating muscle activity. Factors of jackhammer weight and lift assist and the interaction between the two were investigated while blocking the subject factor to eliminate subject variability. Confidence was set at 95%. The lowest statistical power associated with lifting muscle activity was 0.833 in the right Deltoid. For graphical comparisons the percent change was calculated between lifting (Equation 3), operating (Equation 4), and overall (Equation 5) muscle activity for jackhammering using the lift assist versus not using the lift assist.

$$Percent\ Change = \frac{(Peak\ Lifting\ RMS\ EMG_{With\ lift\ assist} - Peak\ Lifting\ RMS\ EMG_{Without\ lift\ assist})}{Peak\ Lifting\ RMS\ EMG_{Without\ lift\ assist}} \text{......(3)}$$

$$Percent\ Change = \frac{(Average\ Operating\ RMS\ EMG_{With\ lift\ assist} - Average\ Operating\ RMS\ EMG_{Without\ lift\ assist})}{Average\ Operating\ RMS\ EMG_{Without\ lift\ assist}} \text{..............(4)}$$

$$Percent\ Change = \frac{(Overall\ Average\ RMS\ EMG_{With\ lift\ assist} - Overall\ Average\ RMS\ EMG_{Without\ lift\ assist})}{Overall\ Average\ RMS\ EMG_{Without\ lift\ assist}} \text{............(5)}$$

2.5.3 Vibration: Vibration amplitude was determined using a weighted average RMS value for the whole trial calculated from the measured acceleration. Accelerations were measured on the jackhammer handle and hand. The vibration dose value was also calculated from the average weighted RMS acceleration and total task time. These three values were used in a general linear model ANOVA for statistical analysis. Factors of jackhammer weight and lift assist and the interaction between the two were investigated while blocking the subject factor to eliminate subject variability. Confidence was set at 95%. For graphical comparisons the percent change was calculated between operating a jackhammer using the lift assist versus not using the lift assist (Equation 6).

$$Percent\ Change = \frac{(Acceleration_{With\ lift\ assist} - Acceleration_{Without\ lift\ assist})}{Acceleration_{Without\ lift\ assist}} \text{....................(6)}$$

2.5.4 Task Time: Task time was determined by the total amount of time in minutes the operator took to break apart the concrete section. Any delays due to errors in data collection (wires or sensors requiring readjustment mid trial) were eliminated from the data. The overall task time was used in a general linear model ANOVA for statistical analysis. Factors of jackhammer weight and lift assist and the interaction between the two were investigated while blocking the subject factor to eliminate subject variability. Confidence was set at 95%. For task time, the power to determine statistically significant changes was 0.26. To obtain a power of 0.8 a sample size of 56 is suggested. For graphical comparisons the percent change was calculated between operating a jackhammer using the lift assist versus not using the lift assist (Equation 7).

$$Percent\ Change = \frac{(Time_{With\ lift\ assist} - Time_{Without\ lift\ assist})}{Time_{Without\ lift\ assist}} \qquad (7)$$

Chapter 3: Results

3.1 Grip Pressure

3.1.1 Lifting Grip Pressure: A significant reduction in lifting grip pressure was noticed between the operators lifting a jackhammer with versus without a lift assist regardless of weight (p = 0.00) In the case of the 60lb jackhammer, the lift assist reduced grip pressure on average by 31% (±14%) but a maximum of 56% was observed (Figure 14). Similar results, although with smaller magnitude, 16% (±7%) were observed for the lifting grip pressure using the 90lb jackhammer. To ensure that the decrease in peak grip pressure was not due to changing the way the individual gripped the jackhammer, the pressure was broken down into total force and contact area. The contact area was determined through calculating the number of sensors that has a peak pressure exceeding 3 PSI. The total force was calculated by first multiplying the area of one sensor by the total number of "active" sensors to obtain the total contact area. The contact area was then multiplied by the grip pressure measured at that data point to obtain the total force. The lift assist was found to decrease the contact area by about 15% (±11%) (Figure 14) for both weights of the jackhammer (p = 0.005). Every subject saw a reduction in contact area ranging from 9% to 40% for either weight of the jackhammer. The total force was decreased on average by33% (±14%) and 45% (±15%) for the 90lb and 60lb jackhammers respectively, with a range of 2% to 71% (p = 0.001).

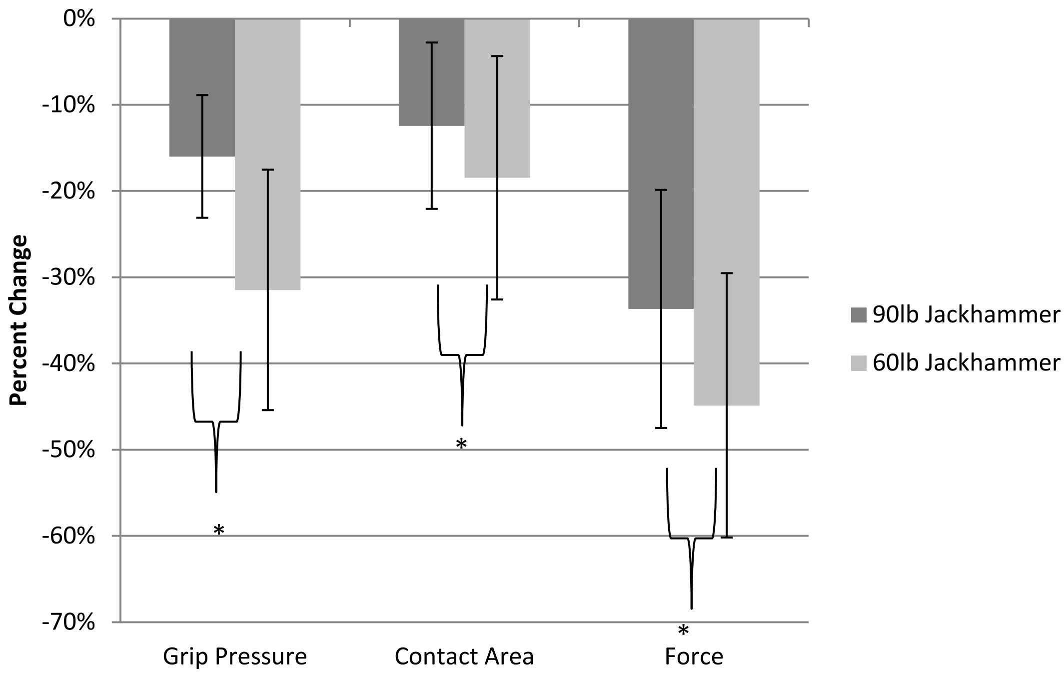

Figure 14: Percent change of contact area, force, and pressure from lifting the jackhammer with and without a lift assist for both weights of the jackhammer. * indicates statistical significance

3.1.2 Operating Grip Pressure: Large variations were observed in the operating grip pressure results. The 60lb jackhammer had a larger range of results varying between a 60% reduction to a 12% increase in grip pressure. For the 90lb jackhammer trials the grip pressure difference varied between 34% reduction to a 1% increase, while using a lift assist (Figure 15). The general linear model ANOVA revealed that only the blocking subject factor, subject, was significant (Appendix G Table 20 and Figures 30 and 31). This means that there are differences between operators that significantly affected the recorded \ grip pressure.

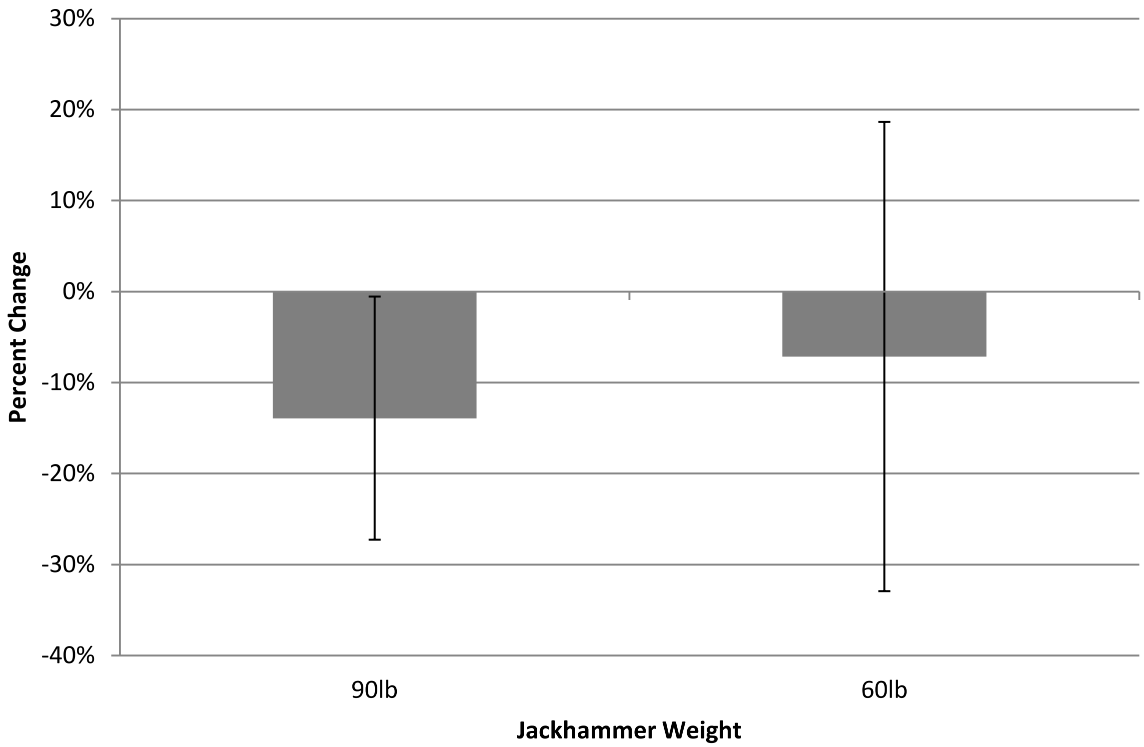

Figure 15: Percent change in grip pressure due to a lift assist during 90lb and 60lb jackhammer operation. * indicates statistical significance

3.2 Muscle Activity

3.2.1 Lifting Muscle Activity: Overall, large reductions were observed in RMS values for all muscles when lifting the jackhammer while using the lift assist. The general linear model ANOVA indicated the factor of using the lift assist was significant for all muscles investigated (Appendix G). The right and left Biceps both observed significant reductions when the operator used the lift assist to lift both weights of jackhammer (p = 0.000 and 0.000). In the case of the 90lb jackhammer there was an average of 55% (±16%) reduction in RMS value for the left Bicep and 50% (±21%) for the right Bicep. Similar results were seen while using the 60lb jackhammer. Using the lift assist with the 60lb jackhammer helped to reduce muscle activity an average of 49% (±23%) and 45% (±28%) in RMS values for the left and right Biceps respectively (Figure 16).

Similar to the Biceps, substantial reductions in RMS values were observed in the right and left Deltoid muscles while using the lift assist for both jackhammer weights (p = 0.001 and 0.016). Reductions ranged between 5% and 83% for the 90lb jackhammer,43% (±23%) reduction on average, and 10% and 66% for the 60lb jackhammer, 39% (±15%) reduction on average (Figure 16).

Significant reductions were observed in the left and right back extensor muscles due to using the lift assist for both jackhammer weights (p = 0.002 and 0.005). The average reductions in RMS values while using the jackhammer with the lift assist were 36% (± 27%) for the 90lb jackhammer and 28% (± 23%) for the 60lb jackhammer for the left Erector Spinae muscle . Similarly, the RMS values for the right Erector Spinae had a reduction of 29% (± 20%) for both the 90lb and 60lb jackhammers.

Weight was also identified as a significant factor for the left and right Bicep (p = 0.04 and 0.013) and left Deltoid (p = 0.02) muscle activity for both jackhammer weights. Using the 60lb jackhammer resulted in average RMS value reduction of 38% (± 20%) ranging between 12% and 66% for the left Bicep. The right Bicep saw reductions from 5% to 66% averaging 39%(±25%). The left deltoid saw reductions from 18% to 55% with an average reduction of 35% (±15%). This was not similar with the right Deltoid. The right deltoid saw large variation in between the weights of jackhammers. There were reductions of 61% up to an increase of 28%. With the large range, there was still an average of

23% (±28%). The interaction between weight and lift assist was not significant for all muscles (Appendix G).

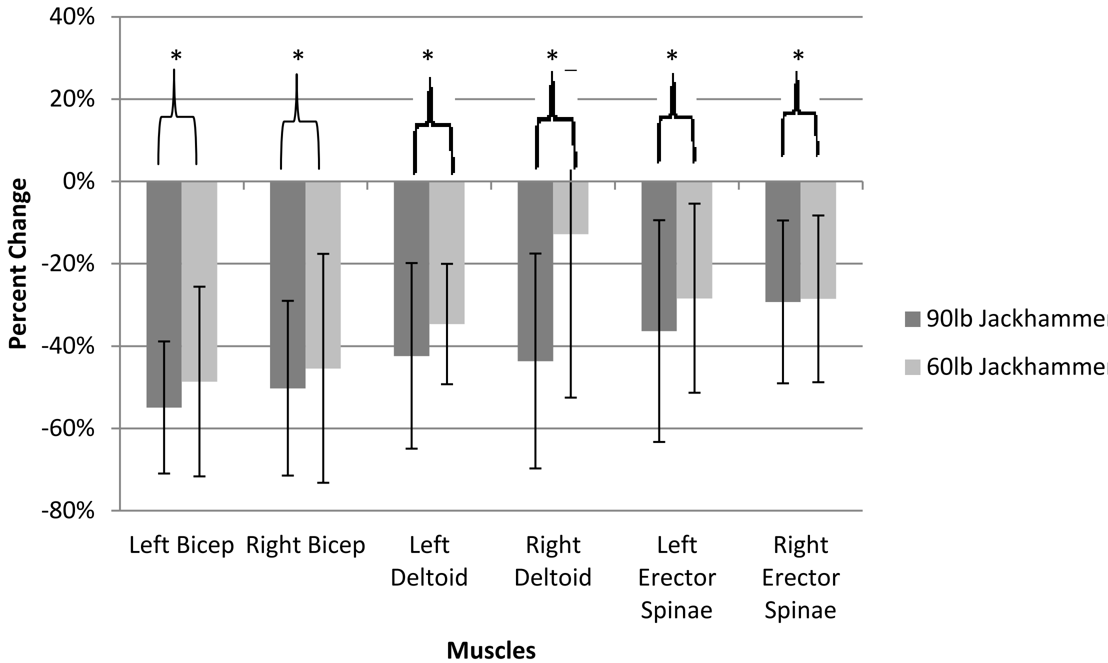

Figure 16: Percent change of arm RMS muscle activity between lifting a 90lb and 60lb jackhammer with and without a lift assist. * indicates statistical significance

To investigate the potential for the lift assist to increase the population capable at performing this task, the percent change from using a jackhammer with the lift assist versus without the lift assist was compared to the operator's percentile in weight. As seen in Figure 17, the subject's whose weight is among the higher percentile had less of a reduction in muscle activity from the lift assist versus operator's whose weight is in the lower percentile.

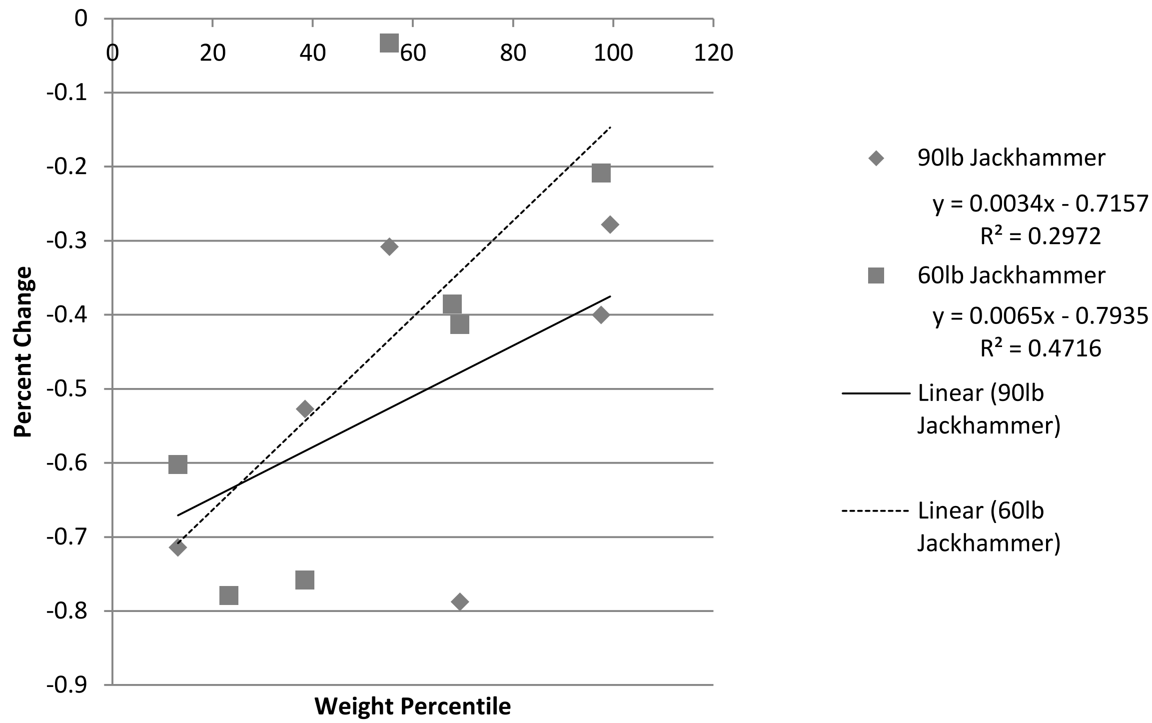

Figure 17: Percent change in right Bicep muscle activity for using a jackhammer with a lift assist versus without a lift assist compared to weight percentile of operator

. 3.2.2 *Operating Muscle Activity:* In all muscle investigated, there were both increases and decreases observed between the operators when using a jackhammer with the lift assist versus without the lift assist, which resulted in large standard deviations (Table 3). The General Linear Model ANOVA revealed that the lift assist had no significant effect on the muscles while operating the jackhammer for either jackhammer weight (Table 4). The right Erector Spinae did see a significant reduction in muscle activity between the two weights of jackhammer, with an average reduction of 19% (±13%). None of the muscles had the interaction between weight and lift assist as a significant factor (Appendix G).

Table 3: Percent change in muscle activity from operating a jackhammer with the lift assist versus without the lift assist

			Left Bicep	Right Bicep	Left Deltoid	Right Deltoid	Left Erector Spinae	Right Erector Spinae
Percent Change	90lb	Average	-7%	-4%	-6%	-11%	-2%	1%
		Standard Deviation	21%	24%	23%	36%	56%	9%
	60lb	Average	30%	31%	-15%	-15%	6%	22%
		Standard Deviation	87%	79%	17%	25%	34%	38%

Table 4: P values from the General Linear Model ANOVA for average RMS operating muscle activity

Factors	Left Bicep	Right Bicep	Left Deltoid	Right Deltoid	Left Erector Spinae	Right Erector Spinae
Subject (Blocked)	0.000	0.015	0.011	0.23	0.001	0.000
Weight	0.117	0.273	0.057	0.153	0.179	0.036
Lift Assist	0.639	0.801	0.528	0.138	0.728	0.263
Weight*Lift Assist	0.714	0.704	0.923	0.684	0.964	0.502

3.2.3 Overall Muscle Activity: There was a wide range of results observed when investigating the effect of using the lift assist on RMS muscle activity over the whole trial including both the lifting and operating tasks. Statistically significant reductions (regardless of weight) were observed in the right Bicep (p = 0.018), with an average reduction of 27% (±20%) and 21% (±16) for the 90lb and 60lb jackhammer respectively. Although not statistically significant, reductions were observed for the 90lb jackhammer (39±16%) and 60lb jackhammer (22±13%) in the left deltoid muscle. All muscles were observed to exhibit reductions in muscle activity due to use of the lift assist for the 90lb jackhammer, while the left Bicep and both Erector Spinea muscles did not show changes in muscle activity for the 60lb jackhammer (Figure 18).

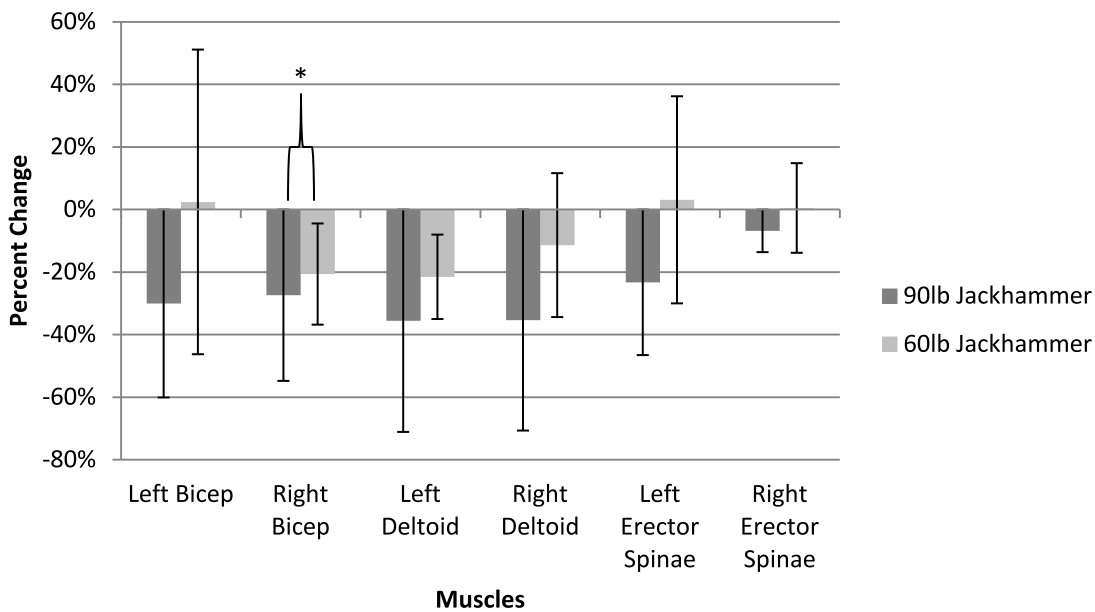

Figure 18: Percent change from using a jackhammer without a lift assist to with a lift assist for overall muscle activity. * indicates statistical significance

3.3 Vibration

3.3.1 Jackhammer Vibration: With or without the lift assist, the average vibration amplitude measured on the handle was approximately 18 m/s^2 (±2.5 m/s^2) for both the 90lb and 60lb jackhammer with our without the lift assist. Consequently the observed changes in vibration amplitude between operating with and without the lift assist conditions there were not statistically significant (p = 0.72), neither for the weight (p = 0.745) .

3.3.2 *Hand-Arm Vibration:* The lift assist reduced vibration amplitude measured on the hand by an average of 12% (± 6%) for the 60lb jackhammer and no change (±14%) for the 90lb jackhammer. The observed changes were statistically significant for the factor of the lift assist regardless of weight (p = 0.038) (Appendix G Table 42). The peak vibration amplitude measured was 25 m/s^2 for both the 90lb and 60lb jackhammer while using the lift assist.

The vibration dose measured with and without the lift assist was 3.5 m/s^2 (±0.8 m/s^2) and 4 m/s^2 (±1.6 m/s^2) on average respectively (Figure 19). These values were just above the ISO action level of 2.5 m/s^2, and under the exposure limit of 5 m/s^2 (ISO 5349, 2001).This standard provides a suggestion based on the measured dose. The action level suggests that anything above a certain measured dose is getting close to a dangerous level and action should be taken to decrease the dosage. The exposure limit suggests that no operator should experience this level of vibration dose due to a high risk of hand arm vibration syndrome. Currently it is recommended that action should be taken to decrease the vibration dose experienced by the operators. The general linear model ANOVA determined that using the lift assist was not a significant factor (p = 0.143) for vibration dose. However, jackhammer weight was determined to be significant (p = 0.001). Using the 90lb jackhammer resulted in a measured vibration dose of 3.3 m/s^2 (±1 m/s^2) while using the 60lb jackhammer resulted in a measured vibration dose of 4.2 m/s^2 (±1.4m/s^2)

The ISO 5349 standard divides the vibration signal into 1/3 octave bands and applies a weighting function to the resulting values. Based on the weighted vibration amplitude at the various frequencies a suggested exposure limit is provided. These various amplitudes that define the exposure limits are defined as zones. The zone provides a range in which a suggested amount of time of exposure for any operator. There were no differences between using the lift assist versus not using the lift assist in relation to the ISO 5349 standard. However, a difference in exposure limit was obtained for the two jackhammer weights, with the 90lb jackhammer exposure limit being less than 0.5 hours (Figure 20), and the 60lb jackhammer exposure limit being less than 2 hours (Figure 21). Using the lift assist did not change the exposure limits for either weight of the jackhammer.

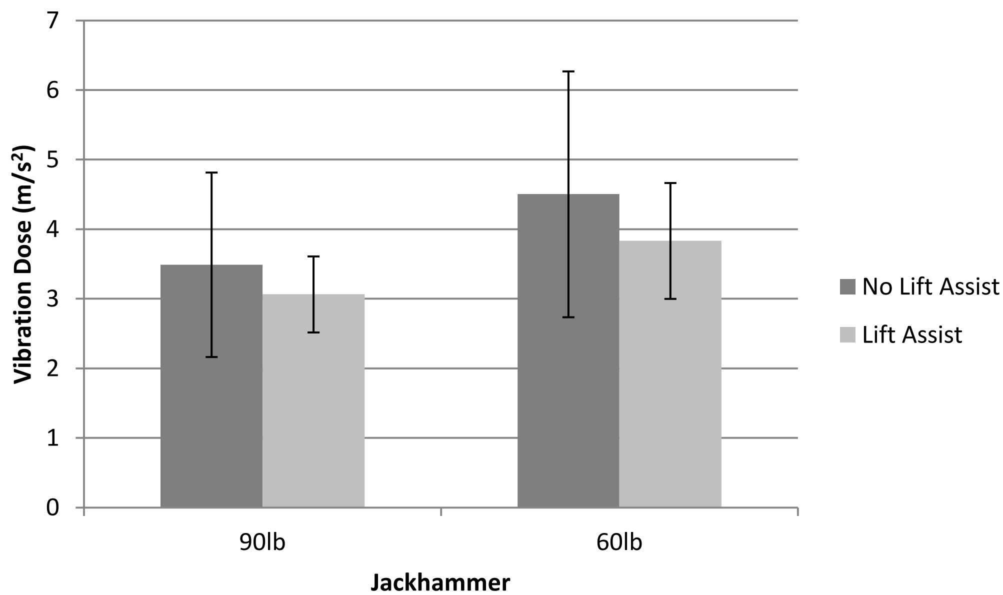

Figure 19: Vibration dose for the 90lb and 60lb jackhammer with and without the lift assist. * indicates statistical significance

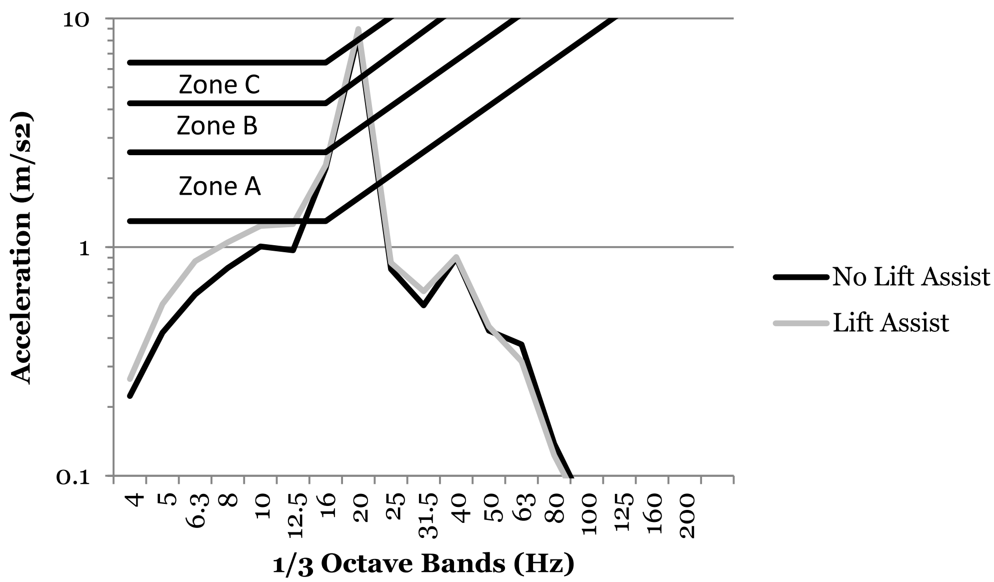

Figure 20: Average weighted accelerations in the Z axis compared to the ISO 5349 standard for the pneumatic 90lb jackhammer with and without lift assist. Zone A: 4-8hrs, Zone B: 2-4hrs, Zone C: 0.5-2hrs

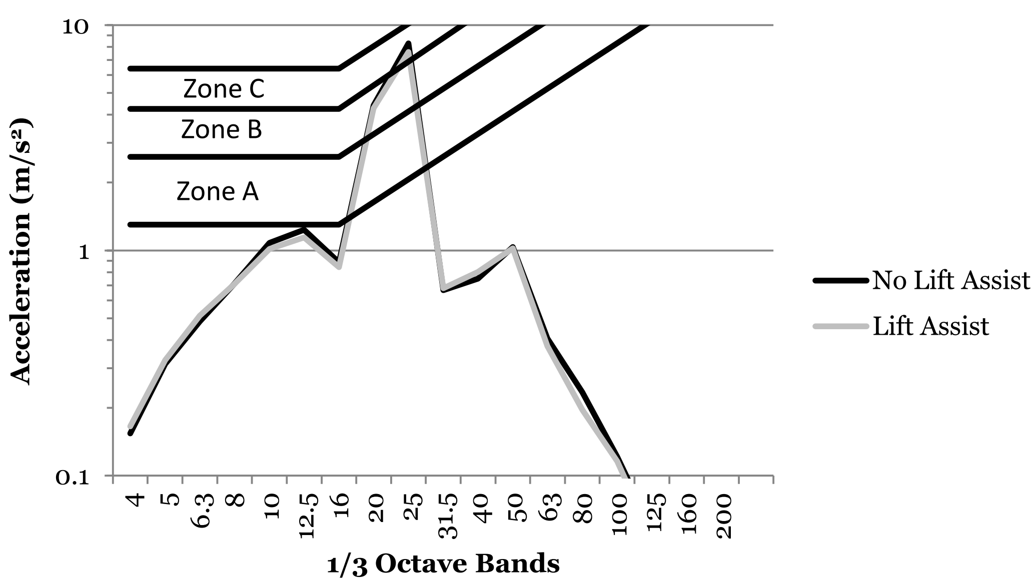

Figure 21: Average weighted accelerations in the Z axis compared to the ISO 5349 standard for the 60lb pneumatic jackhammer with and without lift assist. Zone A: 4-8hrs, Zone B: 2-4hrs, Zone C: 0.5-2hrs.

3.4 Task Time

There was large variation in the observed task time between subjects for both the 90lb and 60lb jackhammer when using the lift assist (Figure 22). The task time ranged between 5 minutes and 25 minutes for the 90lb jackhammer and 7 minutes to 35 minutes with the 60lb jackhammer. The general linear model ANOVA in Appendix G, Table 44 revealed that the lift assist was not a significant factor ($p = 0.502$) with respect to time to complete the task. Changes in task time resulting from the operator using the lift assist ranged from a 45% decrease to an increase of 47%. Five of eight operators had a reduction in task time with the 60lb jackhammer using the lift assist, and only 3 operators completed the task faster with the lift assist in case of 90lb jackhammer.

Overall, the lift assist did not seem to affect productivity at first glance. However, in case of one operator, for example, the repeated trials while using the lift assist resulted in a decrease in task time. This subject took approximately two minutes longer to complete the task using the lift assist for their first trial as compared to not using the lift assist. However, by the end of the trials this subject completed the task 8 minutes (50%) faster with the lift assist than without the lift assist (Figure 23).

The results suggest that there could be a learning curve for the operators. This means that subjects could need more experience to fully learn how to operate a jackhammer efficiently and effectively with the lift assist. To verify that the operator's did not decrease task time due to increased overall exposure to the task, an ANOVA test was used to test trial order. Task time was determined to be significantly reduced (p = 0.001) due to the trial order. However, the Tukey's post hoc test revealed that only the 6th trial (some operators had repeated trials due to issues in data collection) was statistically significantly faster than the other five trials. The result suggests that after 5 trials, the operators were able to reduce task time by becoming more familiar with the task. On average the 6th trial was 39% (±27%) faster than the trial before. The rest of the trials were inconsistently faster and slower than the previous trials, with a standard deviation of 55%.

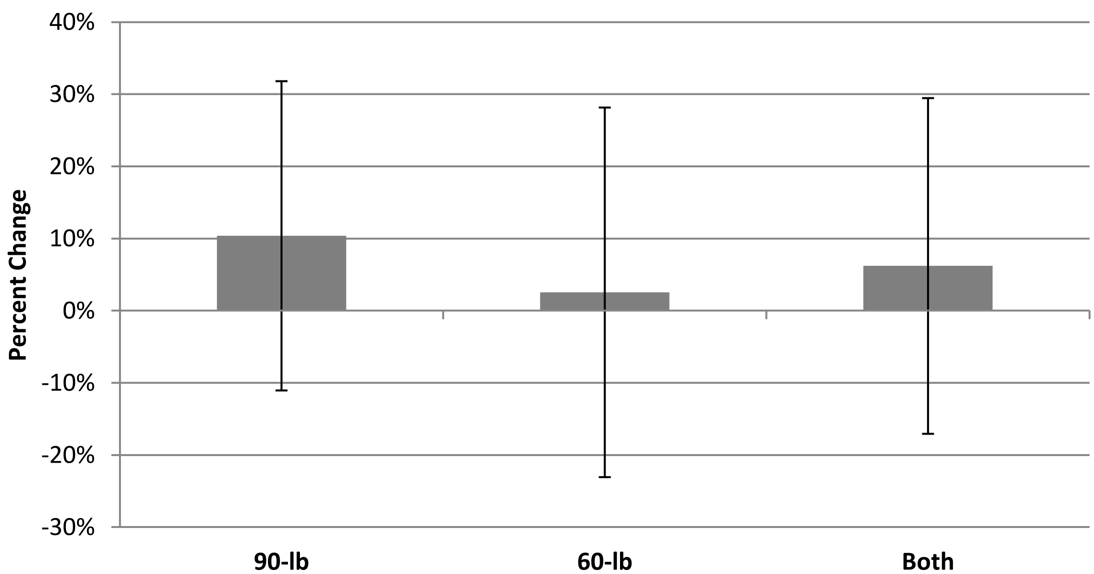

Figure 22: Average percent change of using the lift assist in task time with 90-lb, 60-lb, and combined weights. * indicates statistical significance

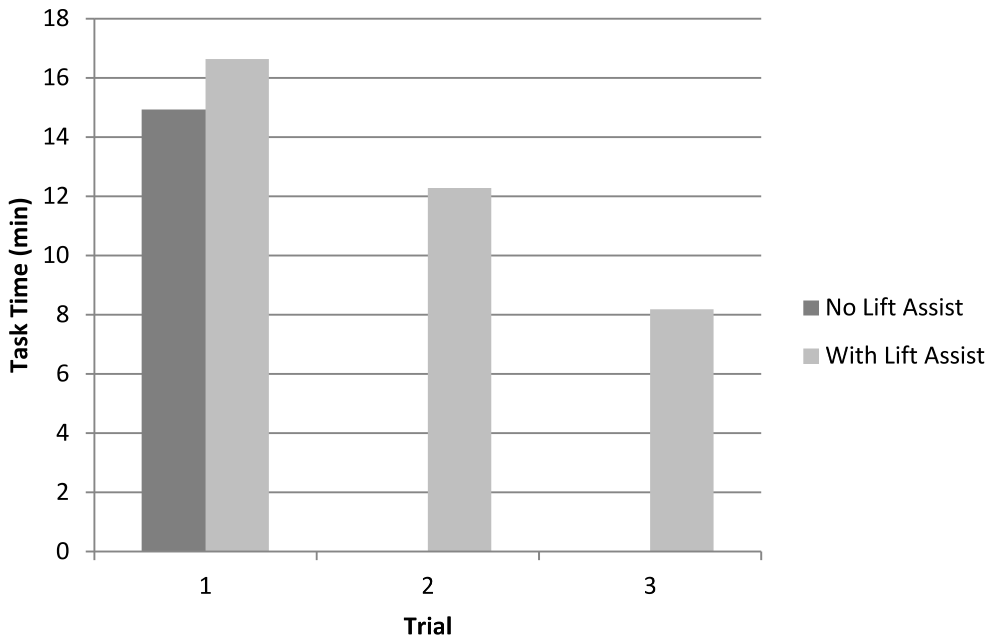

Figure 23: Task Time for Subject 2 using the 60-lb jackhammer.

In terms of the weight of the jackhammer, in case of the 60lb jackhammer it took 63% (±34%) more time to complete the task than in case of the the 90lb jackhammer (p = 0.00) without the lift assist. None of the subjects were more efficient with the lighter weight jackhammer and increases in task time ranged from 9% to 100% (Figure 24).

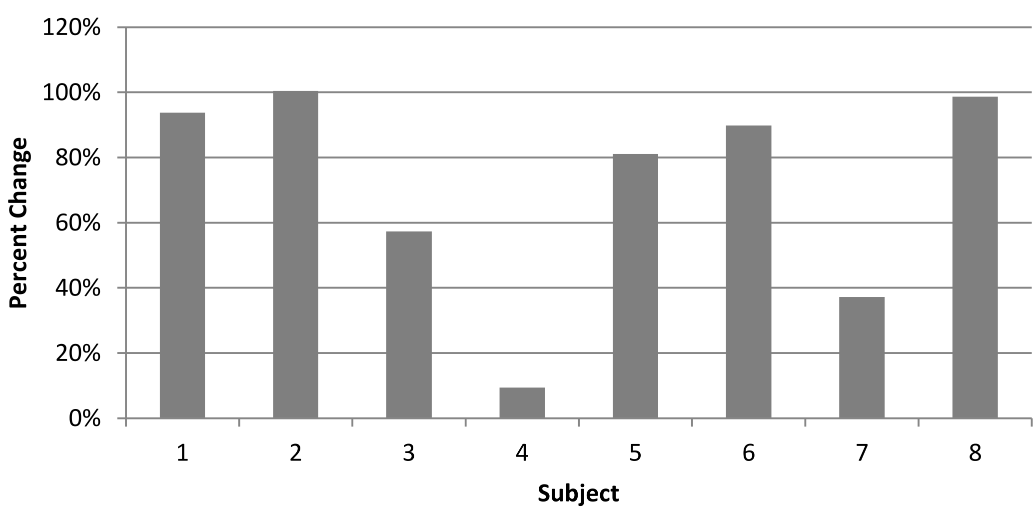

Figure 24: Percent change in task time for each operator while using 60lb jackhammer compared to 90lb jackhammer

The task time had a linear affect on the measured vibration dose. As an operator had a longer task time, the vibration dose calculated was increased (Figure 11). The highest vibration dose (7.9 m/s^2) was with the longest task time (35 mins) and the shortest task time (4.3 mins) was among one of the smallest vibration dose (2.5 m/s^2). The calculated R^2 was 0.52. This relationship makes sense since time is a factor of vibration dose.

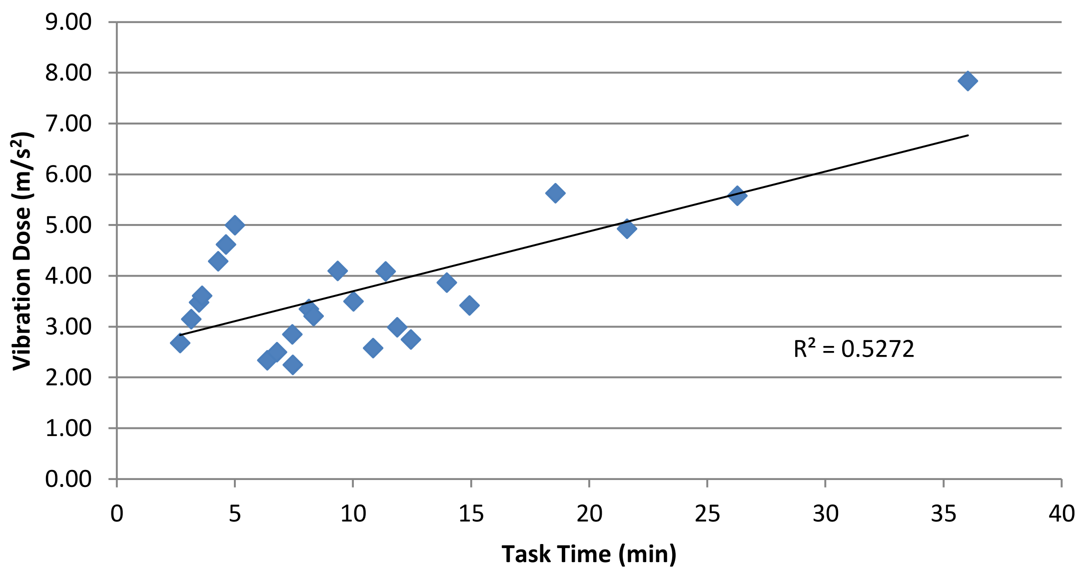

Figure 25: Task time in comparison to the vibration dose

The task time was also correlated with the measured operating grip pressure. A negative relation appeared to be present between these two variables (Figure 26. As grip pressure was reduced during operation, the time to complete the task was increased and vice versa. The largest measured grip pressure (119 PSI) was associated with one of the fastest task times (6 mins) while one of the lowest measured grip pressure (30 PSI) was associated with the slowest time of the experiment (36 min).

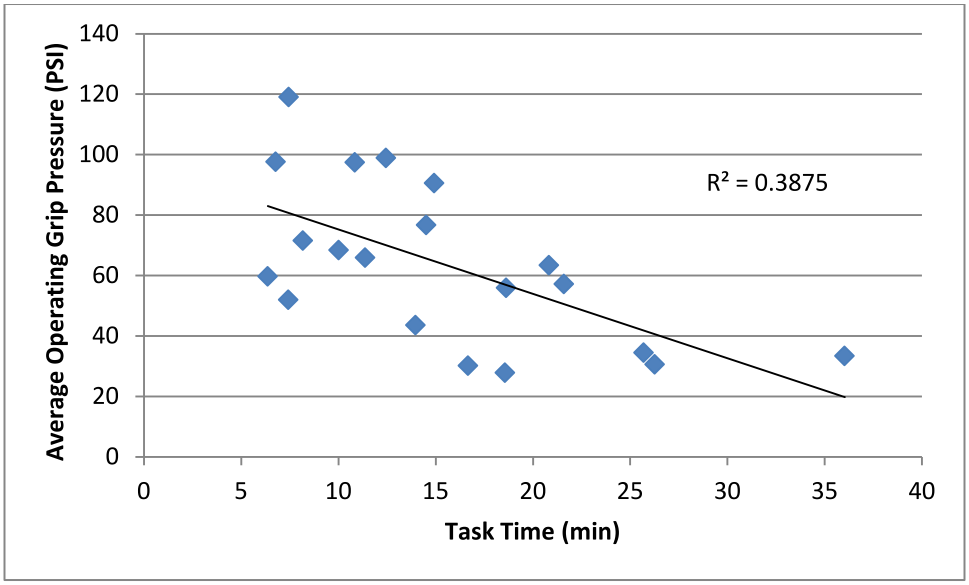

Figure 26: Measured task time in relation to the average operating grip pressure for both the 90lb and 60lb jackhammer with and without the lift assist

3.5 Structured Interview

The feedback questionnaire resulted in overall positive responses in regards to using the jackhammer with the lift assist from the operator's point of view. Operators were asked to respond with the level at which they either agreed or disagreed with several statements. Four main statements were analyzed when investigating the user perception of the lift assist were:

1. The lift assist relieves muscular effort when removing the tip from the concrete.
2. The lift assist improves my performance.
3. Lift assist improves my task completion time.
4. The lift assist is easy to use.

All but one of the operator's who responded agreed with statement 1 (Figure 24). Only one operator was neutral to this statement. Only one operator disagreed and one was neutral with the statement, "The lift assist improved my performance." All other operators were in agreement with 3 of them strongly agreeing. Less positive responses were received for statement 3. Only half of the operators were under the impression that the lift assist improved their task time. The most positive responses were with the statement, "The lift assist was easy to use." Over 85% of the responses were either agree or strongly agree.

With all of the positive feedback, when asked whether or not they preferred using the lift assist, the responses were split. Some of the comments that were associated with the negative views were: the operator didn't like having to use two triggers, the lift assist was hard to control during the lift, the operator got confused having two different triggers, and the lift assist wouldn't be ideal for residential areas.

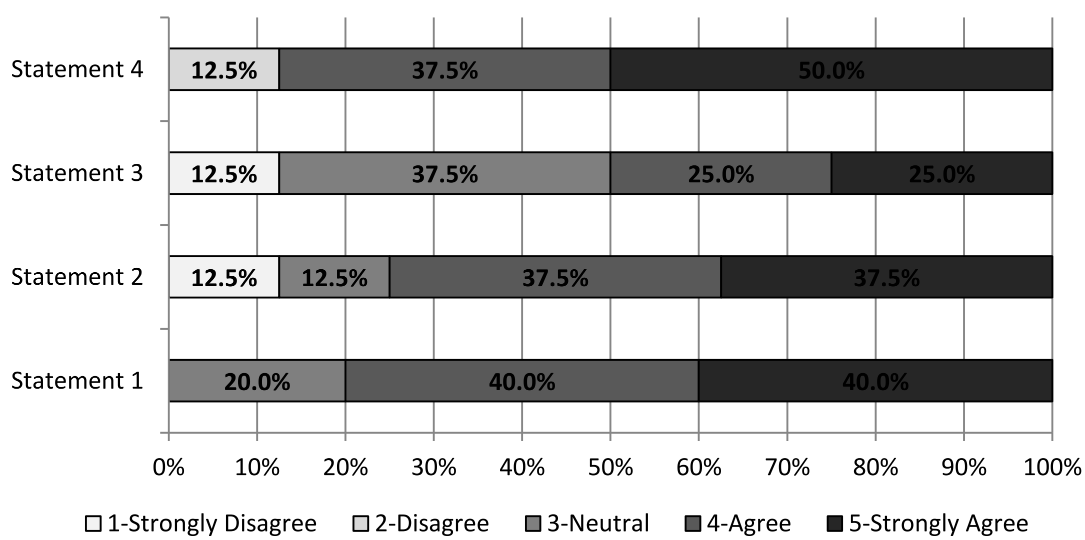

Figure 27: Responses from the operator from the four main lift assist statements

The responses to the interview were compared to a few of the measured variables. The percent change from using a jackhammer with the lift assist versus without the lift assist was compared to the response to the statement, "Using the lift assist improved my performance." Only one operator had a negative response to this question and consequently had the least amount of reduction in the left and right Biceps lifting muscle activity (-28%). Generally the more positive responses were associated with large reductions from using the lift assist in muscle activity of the left and right Biceps during the lifting portion of the task.

The average reduction in task time was also correlated with the operator's response to the statement, "Using the lift assist improved my task completion time." All but one operator who provided a positive response to this statement also observed a measured reduction in task time from using the jackhammer with the lift assist (Table 5).

Table 5: User rating of agreement of improvement task time from using lift assist with calculated affect of using lift assist on task time

Measurement and User Rating of Improved Task Time from Using Lift Assist								
Subject	1	2	3	4	5	6	7	8
User Rating	1	5	4	3	5	3	4	3
Percent Change	16%	-27%	31%	24%	-9%	10%	-29%	-12%

Chapter 4: Discussion

The overall goal of this project was to evaluate the effectiveness of the lift assist device at reducing the stress on the operator while lifting and increasing productivity. Changes in biomechanical markers and user perceptions between lifting the jackhammer and operating the jackhammer with and without the lift assist were collected. The results indicate that overall the lift assist appeared to have some positive impact on the operator, especially during the lifting portion of the jackhammering task, while not affecting the operation portion. Analysis of the results of this study provides evidence to support the concept that the lift assist is beneficial to the operator and each discussed in the next sections.

4.1 Grip Pressure

It was hypothesized that the lift assist would decrease the lifting grip pressure on the operator's hand, and this was supported by the results. A decrease up to 56% was observed between lifting the jackhammer with versus without the lift assist, regardless the weight. These results support the idea that the lift assist can make it easier for the operator to lift the jackhammer. Lower pressure on the operator’s hand during the lift implies that there is less load that the operator must overcome to lift the jackhammer to the new breaking surface (Johansson, 1988). A lower force on the operator’s hands also implies a lower level of required muscle activity. This result indicates that the lift assist could benefit the operator through making the process of removing the tip from the concrete easier.

Larger reductions (15%±7%) in grip pressure were observed while using the lift assist on the 60lb jackhammer versus the 90lb jackhammer. This could be due to the element of control and guidance that is needed throughout the lifting portion of the task. The lift assist propels the device up in the air to eliminate lifting; however it is still up to the operator to guide the jackhammer to the new section of concrete to break. A heavier jackhammer requires more force to move the jackhammer while it is in the air, which could result in smaller grip pressure reductions from using the lift assist for the 90lb jackhammer.

Through video analysis it was observed that some of the operators changed their grip style when lifting with the lift assist versus without the lift assist. To investigate whether the decrease in grip pressure was due to a reduction of force on the hands and not due to a change in contact area, lifting grip pressure was broken down into contact area and force using Equation 8. Both contact area and force were reduced while using the lift assist. Reducing the contact area would provide an increase in grip pressure if the total force remained constant. Since a reduction in contact area was observed along with a reduction in grip pressure, a larger reduction in force should be observed than what is predicted using the pressure alone. This is seen in the force results, where larger reductions in force (up to 71%) were observed compared to grip pressure (up to 56%)

$$Pressure = \frac{Force}{Contact\ Area} \quad (8)$$

Grip pressure can also provide insight into the force requirements for the operator to maintain control of the jackhammer during operation. It was hypothesized that the lift assist would have no effect on grip pressure during operation because the lift assist device is focused on affecting the task of lifting the jackhammer, while not intended to affect the general operation of the jackhammer. The results from this study showed a small, not statistically significant reduction in operating grip pressure. There was some variation in the results that resulted in a range of 12% increase to a 60% reduction in operating grip pressure. Operators that observed an increase in operating grip pressure could have been affected by other factors during operation, like pushing on the jackhammer or prying the concrete away from the pavement.

4.2 Muscle Activity

It was hypothesized that using the lift assist would reduce the muscle activity while lifting the jackhammer. According to the findings of this study, using the lift assist device led to a reduction in muscle activity in all muscles. The RMS values provide an estimate of how much force each muscle is exerting to complete the lifting portion of the task. This study suggests that the operators were required to produce less muscular force, consequently reducing the amount of stress being placed on the body, and therefore the lift assist can potentially reduce overexertion injury risk.

In the lifting portion of the task, the primary muscles in this movement are the Biceps and Erector Spinae. The Deltoid muscles are important for guiding the jackhammer and helping to stabilize the jackhammer during the lifting. While operating the jackhammer, the main muscles used for control are the Deltoid muscles. The Biceps and Erector Spinae only offer support when needed. This mainly occurs when the operator is trying to pry the broken concrete away from the intact concrete section.

Larger reductions, about 10%, in muscle activity were observed for the right and left Biceps and the left Deltoid muscles for using the 90lb jackhammer with a lift assist versus a 60lb jackhammer without a list assist. This could be due to the jackhammer weight also being a significant factor for these muscles (Appendix F). The increased weight of the jackhammer has been previously found to increase the amount of muscle activity in the muscles investigated (Campbell-Kyureghyan, 2012). The observed larger reductions in the 90lb jackhammer for the left Deltoid were not similar for the right Deltoid however. Weight could have been less of a factor for the right Deltoid because the operator still needs to guide the jackhammer to the new breaking site, regardless of the weight of the jackhammer, with or without the lift assist. The motion of guiding the jackhammer to a new breaking site is generally done with the right arm of the operator since the lift assist is on the left side. Requiring the operator to pull the jackhammer sideways will at least partially mitigate the possible reduction in muscle activity from using the lift assist for either jackhammer weight. However, larger reductions (about 10% larger) were observed with the 90lb jackhammer as compared to the 60lb jackhammer, suggesting that the lift assist could provide more of a benefit to the operator in terms of lifting muscle activity for heavier jackhammers.

Reducing the muscle activity involved could possibly increase the population capable of performing this task. To investigate this, the operator's percentiles in weight (generally stronger subjects are heavier) were compared with the reductions observed from using the lift assist in the right Bicep (primary lifting muscle). As the operator's weight was towards the lower percentile, the reductions in muscle activity were larger. Larger reductions from using the lift assist provides evidence that the original task could have been more physically demanding for this subject and thus providing an aid for the lifting portion of the task will help more than a subject that was more capable of performing the task without the lift assist.

As hypothesized, none of the muscles were affected by the lift assist during operation of the jackhammer. There were operators who experienced increases and operators who experienced decreases in muscle activity, showing a varied influence on operation from the lift assist. This could be explained by comparing the muscle activity to operating grip pressure. Operators who were observed to have a large increase in the right Bicep muscle activity (above 50%) were also observed to have increase or no change in operating grip pressure. Increases in grip pressure suggest that the operator was pushing or maneuvering the jackhammer while operating which will influence the operating muscle activity. Other changes in jackhammering style could be whether or not they used the tip to pry apart the concrete or the way the operating griped the handle of the jackhammer. Changes in jackhammering style affected the Biceps the most in the lift assist condition especially for the 60lb jackhammer. The operating Bicep muscle activity had a range of 200%. Some operators would push on the jackhammer and even use the jackhammer to pry concrete away from the concrete slab. These actions, which were not consistent between trials, can influence the muscle activity observed during operation. With the muscle activity being unaffected during operation by the lift assist, there is no detriment to the operator in terms of muscle activity during operation.

The muscle activity for the entire trial will provide insight into the potential benefits of the lift assist for the whole task. Since the muscles investigated are most activated during the lifting portion of the task, it was hypothesized that using the lift assist would result in a reduction of muscle activity for the overall task. Although not statistically significant, reductions in overall muscle activity were observed in the right Bicep and right and left Deltoid. A larger sample size might be required to obtain enough statistical power. A sample size of about 15 subjects was calculated to achieve a power of 0.8. The variation in the data could also be due to uncontrollable factors during the jackhammering trials. Some operators will push on the jackhammer or pry the concrete away from the slab with the jackhammer which will influence the muscle activity measurement for the overall trial, but are not a function of whether or not the lift assist is used.

The lift assist offered a benefit to the operator in terms of muscle activity. Substantial reductions in muscle activity across all muscles were observed. With less muscle activity required to perform the lift, the muscles produce less force to perform the same lift. With less force required to lift the jackhammer when using the lift assist, there is the potential of reducing the risk of overexertion injury.

4.3 Vibration

It was hypothesized that using the lift assist would have no effect on the vibration amplitude on either the jackhammer or the hand. This study determined that there was no difference on jackhammer vibration amplitude due to the lift assist device for either jackhammer weight. It was apparent that the added 10lbs on the jackhammer from the lift assist was not enough to affect the amplitude of jackhammer vibration. However, it was found that operating a jackhammer with the lift assist resulted in a reduction of vibration amplitude measured on the hand. This result could be due to the operators loosening their grip on the jackhammer to prepare to activate the lift assist. Although not significant, the study found a reduction in operating grip pressure when using a jackhammer with the lift assist. Video analysis showed that operators would use an open grip instead of a closed grip when using a jackhammer with the lift assist. Previous research has determined that the amount of contact force is related to the amplitude of vibration that is transmitted to the hand (Pyykko, 1976). This means that reduction in the grip pressure will lead to a reduction of vibration amplitude measured on the hand.

Although amplitude of the vector sum of all three axes of vibration measured at the hand was reduced due to the lift assist, the suggested exposure limit for either weight of the jackhammer when separated into 1/3 frequency octave bands did not change. According to the ISO 5349 standard, based on the measured amplitude of vibration in the case of the 90 lb jackhammer the operator exposure should be limited to 0.5 hours and in the case of the 60lb jackhammer the exposure is limited to 2 hours. The vibration dose values measured were also above the action level and below the exposure level for this task for both jackhammer weights with the lift assist (ISO, 5349). It was noticed that the 90lb jackhammer exhibited slightly higher vibration amplitudes than the 60lb jackhammer. This result was concurrent with previous research that also measured a slight reduction in vibration dose (Campbell-Kyureghyan, 2012) with the 60lb jackhammer.

Although this study did not find a benefit to the operator in terms of vibration exposure, specifically vibration dose, the study also found that using the lift assist didn’t increase the exposure and thereby posing potentially an additional harm to the operator. With the lift assist weighing only 10lbs, or approximately 10% to 15% of the weight of the jackhammer, it was expected that there was not enough added weight to influence the vibration amplitude during operation. However, vibration amplitude is not the only component of vibration dose, which also depends on exposure time; thus, reduced task time while using the lift assist could reduce the vibration dose indirectly. This study observed an increase in task time when operators used a jackhammer with the lift assist. This caused the measured vibration dose to increase. Generally the longer the operator took to complete the task, the larger vibration dose was recorded.

4.4 Task Time

It was hypothesized that the lift assist would reduce the overall task time. However, the study did not support this hypothesis. The lift assist had no affect on task time for either of the jackhammer weights. This could be due to the limited experience the jackhammer operators had with the lift assist. Only one operator had previously used the lift assist. The subjects were able to practice with the lift assist before data collection began in order to minimize errors in operation due to unfamiliarity with the device. However, the practice time allowed may not have been sufficient. Through video observation it can be seen that some of the subject had difficulty with the lift assist and would often unknowingly just lift the jackhammer without the lift assist and had to be verbally reminded to use the lift assist.

It is, however, believed that continued use of the lift assist will eventually lead to reductions in task time. Evidence of this was seen when one operator had to recomplete various trial (Figure 23). After the first trial with the lift assist, this subject completed the task 2 minutes slower than without the lift assist. After the second trial with the lift assist the subject completed the task over two minutes faster. Finally, after the third trial the subject was almost twice as fast with the lift assist as without the lift assist. If similar results were found in the field, many potential benefits would accrue with this decrease in task time.

Although the trials were randomized, there was the potential for a learning curve leading to trial order being a significant factor in the results. However, upon investigating the general effect of trial order, only the 6^{th} trial (for operators who had 6 trials) saw a statistically significant reduction in task time. There was not a consistent pattern of reduction or increase in time for the other 5 trials in relation to each other. The larger reduction observed with subject two re-using the lift assist could be due to either the subject having more experience with the task in general, or due to increasing familiarity with the lift assist. To support or deny that a learning curve is present further research is needed. Studying the task time after operators gain more experience with the lift assist will provide a better understanding of the potential improvement in productivity.

To provide more insight to the task time, the results were correlated with the operating grip pressure. It was observed that as operating grip pressure was increased, the task completion time was reduced. Less reductions and increases in operating grip pressure were associated with faster completion times. Operators who pushed the jackhammer while operator could reduce task time and if the operator did not push equally with and without the lift assist, the pushing could influence the task time results.

4.5 Structured Interview

Overall, the operators gave positive feedback when asked about the lift assist. The majority of the operators thought that the lift assist reduced muscular effort. This was consistent with the muscle activity data that was found in this study. Reductions in muscle activity while lifting suggests that the operator needed to produce less force while using the lift assist. The operator exerting less force while using a jackhammer with lift assist could make the operator think the task is easier and thus agree with the statement, "the lift assist reduces muscular effort when removing the tip."

Results from the structured interview were also compared to the results observed for the other variables. The muscle activity of the Bicep muscles were compared to the responses to the statement, "The lift assist improved my performance." Only one operator had a negative response to this statement and consequently had the smallest reduction in muscle activity. With a small reduction in muscle activity, this operator might not have consciously felt the benefit of the lift assist, and thus thought that the lift assist did not improve their performance.

Measured task time was also correlated with the user's perception of improved task time through using the lift assist. Almost all of the user's response followed the measured task time change from using the lift assist where a negative response was given from an operator who experienced an increase in task time and a positive response was given from operators who experienced reductions in task time. There was only one outlier who believed that using the lift assist improved their task time when in fact it did not. However, this operator also had some of the largest reductions in lifting muscle activity across all muscles. It could be possible that making the lifting portion of the task easier put less stress on the operator and thus the operator was under the impression that their task time was reduced.

There seemed to be a discrepancy between the overall positive feedback regarding the lift assist and the fact that only half of the operators would prefer using a lift assist. This is likely due to inexperience with the lift assist. The few negative comments confused sense of confusion by the presence of two triggers. If the operators had more time to adjust to using the lift assist, these operators could be more inclined to use the lift assist.

4.6 Study Limitations:

In this study one of the limitations that could restrict the larger application of the outcomes was the relatively small sample size. The lack of subjects could have affected the statistical significance of the use of lift assists. For example, changes in overall muscle activity were statistically not significant, and a sample size calculation determined that 15 subjects would be required to provide sufficient power for this portion of the study. Another limitation in this study is the experience of the jackhammer operators with the lift assist device. The lack of experience led to operators not being able to fluidly operate the lift assist, which could have affected the task time results. More experienced operators could better represent the changes in task time that would result if the lift assist was incorporated into the construction field.

Another limitation to this study is only having grip pressure measurements from one hand. With only measurements from one hand, this study assumes that the results from grip pressure are symmetrical for both sides of the body. However, it is acknowledged that operators could potentially favor a different hand to be measured, which could potentially alter the results. Using two grip pressure gloves in future studies would allow for a total picture of what the operator is experiencing during the jackhammering trial.

Overall, using the lift assist did result in reductions for all lifting variables. The results of this study provide quantifiable evidence that the lift assist does aid in reducing the stress from lifting the jackhammer on the operator. Reducing the stress on the operator could potentially reduce the overexertion injury risk in the jackhammering task. In terms of general operation, the lift assist did not offer any detriment to the operator. Slight reductions in operating grip pressure and muscle activity were observed. However more power might have been needed to provide statistical evidence. The variable of task time needs further investigation to provide conclusive evidence for using the lift assist to improve productivity.

Chapter 5: Conclusion

This study was aimed at determining the effects of using a jackhammer lift assist on the operator during a jackhammering task. The impact of the lift assist was evaluated through biomechanical analysis of a jackhammering task with and without a lift assist and a structured interview. The biomechanical evaluation results revealed that:

- Using the lift assist reduced the grip pressure required to lift the jackhammer while having no effect on operating grip pressure.
- Using the lift assist reduced muscle activity in the Biceps, Deltoids, and Erector Spinae while lifting the jackhammer.
- No changes were apparent in vibration exposure due to using the lift assist.
- A potential reduction in task time is possible while using the lift assist.
- Overall positive feedback about using the lift assist were provided from the operators.

The lift assist resulted in less muscular exertion required to lift the jackhammer. This could result in a reduction of risk for overexertion and repetitive lifting injuries in this task. Along with reductions in muscle activity, operators generally had positive feedback about using the lift assist. Most operators believed that the lift assist improved their performance and was easy to use. Although the operators thought that there was an increase in productivity, the measured results were inconclusive. Further investigation is required to study the potential learning curve effect. If a learning curve exists and operators become more efficient using the lift assist, then vibration exposure will be reduced along with an increase in productivity.

There are potentially additional benefits to be gained from using the lift assist that have not been explored. For example, reducing the lifting required by the operator could possibly increase the population capable of performing this task. A larger available workforce could allow for more job rotation and thus decrease the exposure per operator. Further research is required to fully comprehend the impact of using the lift assist device in the jackhammering task.

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APPENDICES

Appendix A: Lifting RMS Muscle Activity

Table 6: RMS lifting muscle activity for the 90lb jackhammer with and without the lift assist

	Muscle Activity (volts)											
	Left Bicep		Right Bicep		Left Deltoid		Right Deltoid		Left Erector Spinae		Right Erector Spinae	
Subject	A	ALA	A	ALA	A	ALA	A	ALA	A	ALA	A	ALA
1	N/A	N/A	N/A	N/A	0.000119	7.33E-05	0.000165	2.84E-05	N/A	N/A	N/A	N/A
2	0.0001	7.11E-05	0.000136	6.41E-05	5.47E-05	3.42E-05	4.13E-05	3.58E-05	4.28E-05	3.28E-05	2.49E-05	1.89E-05
3	9E-05	4E-05	0.000102	7.39E-05	2.66E-05	1.86E-05	4.56E-05	3.47E-05	2.59E-05	3.49E-06	2.22E-05	1.22E-05
4	0.0003	9E-05	0.000265	7.57E-05	8.22E-05	2.2E-05	9.38E-05	3.55E-05	3.21E-05	2.18E-05	3.71E-05	2.59E-05
5	0.000142	3.47E-05	5E-05	3E-05	5.72E-05	5.43E-05	2.66E-05	3.99E-05	2.08E-05	1.51E-05	2.01E-05	1.7E-05
6	N/A	N/A	0.000129	8.95E-05	9.66E-05	4.99E-05	0.00014	9.74E-05	2.93E-05	2.71E-05	2.29E-05	2.21E-05
7	Did not used 90lb jackhammer w/ LA											
8	0.0002	0.0001	0.000224	4.76E-05	0.00015	5.37E-05	0.000147	7.37E-05	8.41E-05	4.96E-05	7.17E-05	3.03E-05

Table 7: RMS lifting muscle activity for the 60lb jackhammer with and without the lift assist

	Muscle Activity (volts)											
	Left Bicep		Right Bicep		Left Deltoid		Right Deltoid		Left Erector Spinae		Right Erector Spinae	
Subject	B	BLA	B	BLA	B	BLA	B	BLA	B	BLA	B	BLA
1	0.00022	0.00013	0.000323	0.000199	8.97E-05	8.09E-05	6.04E-05	3.62E-05	3.72E-05	3.29E-05	4.97E-05	4.05E-05
2	6.48E-05	2.45E-05	0.000111	2.69E-05	3.68E-05	1.99E-05	3.34E-05	4.14E-05	3.76E-05	2.8E-05	2.68E-05	1.21E-05
3	6.66E-05	2.63E-05	N/A	N/A	2.18E-05	1.09E-05	4.45E-05	2.56E-05	2.07E-05	7.95E-06	1.28E-05	1.05E-05
4	N/A	N/A	0.000173	6.87E-05	4.17E-05	2.43E-05	3.65E-05	2.37E-05	3.3E-05	1.89E-05	4.14E-05	2.53E-05
5	N/A	N/A	1.7E-05	1.34E-05	N/A	N/A	2.58E-05	3.92E-05	8.92E-06	8.47E-06	1.07E-05	8.87E-06
6	0.000161	8.28E-05	0.000122	0.000118	N/A	N/A	7.47E-05	7.73E-05	N/A	N/A	N/A	N/A
7	0.00017	4.71E-05	0.000176	3.9E-05	4.78E-05	3.36E-05	8.54E-05	2.87E-05	7.14E-05	3.67E-05	5.6E-05	2.7E-05
8	0.000103	9.53E-05	8.31E-05	4.88E-05	6.74E-05	4.66E-05	5.68E-05	5.78E-05	4.49E-05	4.33E-05	3.58E-05	3.56E-05

Appendix B: Operating RMS EMG Data

Table 8: RMS operating muscle activity for the 90lb jackhammer with and without the lift assist

	Muscle Activity (volts)											
	Left Bicep		Right Bicep		Left Deltoid		Right Deltoid		Left Erector Spinae		Right Erector Spinae	
Subject	A	ALA	A	ALA	A	ALA	A	ALA	A	ALA	A	ALA
1	N/A	N/A	N/A	N/A	6.95E-05	6.67E-05	0.000106	2.79E-05	N/A	N/A	N/A	N/A
2	2.4E-05	2.02E-05	3.01E-05	2.07E-05	2.33E-05	2.06E-05	2.2E-05	2.14E-05	1.73E-05	1.37E-05	1.16E-05	1.17E-05
3	2.16E-05	1.75E-05	2.69E-05	3.61E-05	1.06E-05	1.07E-05	1.65E-05	1.49E-05	9.56E-06	2.11E-06	1.02E-05	8.92E-06
4	8.63E-05	7.24E-05	7.55E-05	5.7E-05	2.75E-05	1.95E-05	2.5E-05	2.43E-05	1.93E-05	1.85E-05	1.98E-05	2.3E-05
5	2.76E-05	2.38E-05	1.98E-05	1.78E-05	2.97E-05	4.2E-05	2.61E-05	3.82E-05	1.39E-05	1E-05	1.2E-05	1.17E-05
6	N/A	N/A	2.02E-05	2.11E-05	2.87E-05	2.39E-05	5.28E-05	3.77E-05	8.07E-06	1.12E-05	8.81E-06	8.98E-06
7	Did not use 90lb jackhammer w/ LA											
8	3.2E-05	4.19E-05	2.52E-05	2.63E-05	4.98E-05	3.85E-05	3.81E-05	3.49E-05	1.96E-05	3.56E-05	1.53E-05	1.57E-05

Table 9: RMS operating muscle activity for the 60lb jackhammer with and without the lift assist

	Muscle Activity (volts)											
	Left Bicep		Right Bicep		Left Deltoid		Right Deltoid		Left Erector Spinae		Right Erector Spinae	
Subject	B	BLA	B	BLA	B	BLA	B	BLA	B	BLA	B	BLA
1	1.9E-05	2.4E-05	1.58E-05	2.95E-05	1.95E-05	2.03E-05	1.57E-05	1.59E-05	9.42E-06	1.21E-05	8.88E-06	1.49E-05
2	1.83E-05	1.74E-05	2.11E-05	1.83E-05	2.61E-05	1.89E-05	2.26E-05	2.04E-05	1.22E-05	1.35E-05	9.69E-06	1.11E-05
3	2.31E-05	1.03E-05	N/A	N/A	1.29E-05	8.4E-06	1.45E-05	1.2E-05	1.35E-05	5.13E-06	7.27E-06	7.13E-06
4	N/A	N/A	5.18E-05	3.45E-05	2.35E-05	1.81E-05	1.95E-05	1.83E-05	1.77E-05	1.51E-05	2.29E-05	1.81E-05
5	N/A	N/A	1.37E-05	1.25E-05	N/A	N/A	2.74E-05	3.29E-05	7.79E-06	1.03E-05	9.32E-06	1.09E-05
6	1.13E-05	2.13E-05	2.17E-05	5.33E-05	N/A	N/A	7.1E-05	2.47E-05	N/A	N/A	N/A	N/A
7	4.58E-05	2.47E-05	4.51E-05	1.73E-05	3.52E-05	3.73E-05	2.95E-05	2.07E-05	2.67E-05	3.27E-05	2.79E-05	2.73E-05
8	1.02E-05	2.76E-05	7.99E-06	1.61E-05	4.46E-05	3.86E-05	2.85E-05	2.59E-05	1.52E-05	1.89E-05	8.3E-06	1.5E-05

Appendix C: Overall RMS EMG Data

Table 10: RMS overall muscle activity for the 90lb jackhammer with and without the lift assist

	Muscle Activity (Volts)											
	Left Bicep		Right Bicep		Left Deltoid		Right Deltoid		Left Erector Spinae		Right Erector Spinae	
Subject	A	ALA	A	ALA	A	ALA	A	ALA	A	ALA	A	ALA
1	N/A	N/A	N/A	N/A	1.06E-04	7.00E-05	1.60E-04	2.85E-05	N/A	N/A	N/A	N/A
2	3.48E-05	1.67E-05	4.41E-05	1.90E-05	2.72E-05	1.90E-05	2.46E-05	1.99E-05	2.07E-05	1.31E-05	1.33E-05	1.07E-05
3	4.34E-05	2.08E-05	6.52E-05	4.10E-05	3.22E-05	1.20E-05	3.89E-05	1.76E-05	2.66E-05	2.33E-06	1.77E-05	9.42E-06
4	1.03E-04	7.68E-05	9.75E-05	6.09E-05	3.26E-05	1.91E-05	3.30E-05	2.50E-05	2.12E-05	1.91E-05	2.25E-05	2.42E-05
5	3.36E-05	2.64E-05	2.14E-05	2.03E-05	3.16E-05	4.41E-05	2.68E-05	4.28E-05	1.43E-05	1.05E-05	1.25E-05	1.26E-05
6	N/A	N/A	3.249E-05	3.02E-05	2.79E-05	2.40E-05	4.65E-05	4.12E-05	7.78E-06	1.14E-05	8.50E-06	9.33E-06
7	Did not use 90lb jackhammer w/ LA											
8	3.09E-05	3.11E-05	2.53E-05	2.00E-05	5.08E-05	3.51E-05	3.62E-05	2.86E-05	1.93E-05	3.94E-05	1.53E-05	1.43E-05

Table 11: RMS overall muscle activity for the 60lb jackhammer with and without the lift assist

	Muscle Activity (Volts)											
	Left Bicep		Right Bicep		Left Deltoid		Right Deltoid		Left Erector Spinae		Right Erector Spinae	
Subject	B	BLA	B	BLA	B	BLA	B	BLA	B	BLA	B	BLA
1	*3.61E-05*	*5.73E-05*	5.02E-05	4.18E-05	*2.71E-05*	*2.07E-05*	2.03E-05	1.47E-05	1.27E-05	1.41E-05	1.50E-05	1.51E-05
2	2.24E-05	2.00E-05	2.90E-05	2.14E-05	2.68E-05	2.05E-05	2.34E-05	2.17E-05	1.44E-05	1.43E-05	1.11E-05	1.15E-05
3	2.52E-05	9.82E-06	N/A	N/A	1.32E-05	7.75E-06	1.61E-05	1.18E-05	1.34E-05	5.04E-06	7.57E-06	6.88E-06
4	N/A	N/A	6.10E-05	3.61E-05	2.49E-05	1.83E-05	2.11E-05	1.85E-05	1.90E-05	1.53E-05	2.47E-05	1.86E-05
5	N/A	N/A	1.57E-05	1.75E-05	N/A	N/A	2.77E-05	3.31E-05	8.48E-06	1.09E-05	1.04E-05	1.08E-05
6	1.24E-05	2.17E-05	2.46E-05	2.02E-05	N/A	N/A	5.18E-05	2.55E-05	N/A	N/A	N/A	N/A
7	4.29E-05	4.47E-05	4.44E-05	3.24E-05	3.51E-05	3.47E-05	2.87E-05	3.07E-05	2.86E-05	3.58E-05	2.87E-05	2.80E-05
8	4.29E-05	4.47E-05	4.44E-05	3.24E-05	4.28E-05	3.71E-05	2.87E-05	3.07E-05	1.79E-05	1.76E-05	1.10E-05	1.38E-05

Appendix D: Grip Data

Table 12: Grip pressure results for lifting and operating the 90lb and 60lb jackhammer with and without the lift assist

	Grip Pressure (PSI)							
	Lifting				Operating			
Subject	A	ALA	B	BLA	A	ALA	B	BLA
1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2	511.94	452.79	563.8	416.91	119.04	97.61	90.55	71.53
3	492.79	447.15	465.29	302.67	59.68	51.94	68.38	76.69
4	380.32	275.24	N/A	N/A	97.42	98.87	N/A	N/A
5	N/A	N/A	531.86	232.78	N/A	N/A	138.04	55.9
6	378.82	315.19	393.24	298.42	65.89	43.55	57.16	63.38
7	195.78	N/A	168.55	142.8	30.57	N/A	33.36	34.44
8	273.03	232.65	279.45	189.26	28.97	27.17	27.81	30.14

Table 13: Contact area associated with the grip pressure used while lifting the jackhammer

	Contact Area (Active Sensors)			
	Lifting			
Subject	A	ALA	B	BLA
1	N/A	N/A	N/A	N/A
2	17.75	16.08	17.9	14.281
3	14.07	14	16.89	16.67
4	19	17.2	N/A	N/A
5	N/A	N/A	20.33	12.14
6	14.81	10.889	13.85	13
7	N/A	N/A	11.17	9.33
8	11.83	9.91	11.95	8.77

Table 14: Grip force associated with lifting the jackhammer

	Force (lbs)			
	Lifting			
Subject	A	ALA	B	BLA
1	N/A	N/A	N/A	N/A
2	948.59	553.85	1133.75	659.54
3	570.59	421.60	916.21	602.84
4	921.42	640.19	N/A	N/A
5	N/A	N/A	952.12	275.16
6	629.35	296.94	559.14	376.83
7	N/A	N/A	188.67	123.77
8	383.95	317.23	308.19	138.41

Appendix E: Vibration Data

Table 15: Vibration results calculated from accelerations measured on the jackhammer

Jackhammer Vibration Amplitude (m/s^2)				
Subject	A	ALA	B	BLA
1	N/A	N/A	17.36	16.45
2	16.51	19.41	16.93	19.75
3	18.62	19.57	18.63	20.99
4	12.84	15.20	14.31	15.54
5	N/A	N/A	N/A	N/A
6	21.34	21.511	22.39	19.53
7	20.37	N/A	20.69	17.87
8	21.42	19.55	19.77	17.79

Table 16: Vibration results calculated from accelerations measured on the hand

Hand Arm Vibration Amplitude (m/s^2)				
Subject	A	ALA	B	BLA
1	N/A	N/A	24.37	22.14
2	18.04	21.03	19.38	18.67
3	20.33	22.88	24.18	20.77
4	17.12	17.06	19.00	17.27
5	N/A	N/A	N/A	N/A
6	26.53	22.70	23.22	20.59
7	23.85	N/A	28.59	21.61
8	29.37	25.74	28.60	24.78

Table 17: Vibration dose results calculated from accelerations measured on the hand

Hand Arm Vibration Dose (m/s^2)				
Subject	A	ALA	B	BLA
1	N/A	N/A	3.21	2.68
2	2.25	2.50	3.42	3.48
3	2.34	2.85	3.50	3.61
4	2.58	2.75	2.99	3.15
5	N/A	N/A	N/A	N/A
6	4.09	3.87	4.93	4.29
7	5.58	N/A	7.84	5.00
8	4.10	3.35	5.63	4.62

Appendix F: Task Time Results

Table 18: Task Time for all trials

Subject	Weight	Lift Assist	Task Time (min)
1	90	nLA	4.30
1	90	LA	6.32
1	60	nLA	8.33
1	60	LA	7.02
2	90	nLA	7.45
2	90	LA	6.78
2	60	nLA	14.93
2	60	LA	16.63
2	60	LA	12.28
2	60	LA	8.18
3	90	nLA	6.37
3	90	LA	7.43
3	60	nLA	10.02
3	60	LA	14.52
4	90	nLA	10.85
4	90	LA	12.45
4	60	nLA	11.87
4	60	LA	15.93
5	90	nLA	11.67
5	90	LA	10.93
5	60	nLA	21.13
5	60	LA	18.63
6	90	nLA	11.38
6	90	LA	13.97
6	60	nLA	21.6
6	60	LA	20.83
7	90	nLA	26.27
7	60	nLA	36.03
7	60	LA	25.7
8	90	nLA	9.35
8	90	LA	8.13
8	60	nLA	18.57
8	60	LA	16.67

Appendix G: Statistics Results

Table 19: General Linear Model ANOVA results for lifting grip pressure

General Linear Model: Grip Pressure versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	7	2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Grip Pressure, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	6	244208	250972	41829	19.06	0.000
Weight	1	3316	2299	2299	1.05	0.325
Lift Assist	1	57799	54882	54882	25.00	0.000
Weight*Lift Assist	1	8005	8005	8005	3.65	0.078
Error	13	28534	28534	2195		
Total	22	341862				

S = 46.8503   R-Sq = 91.65%   R-Sq(adj) = 85.87%

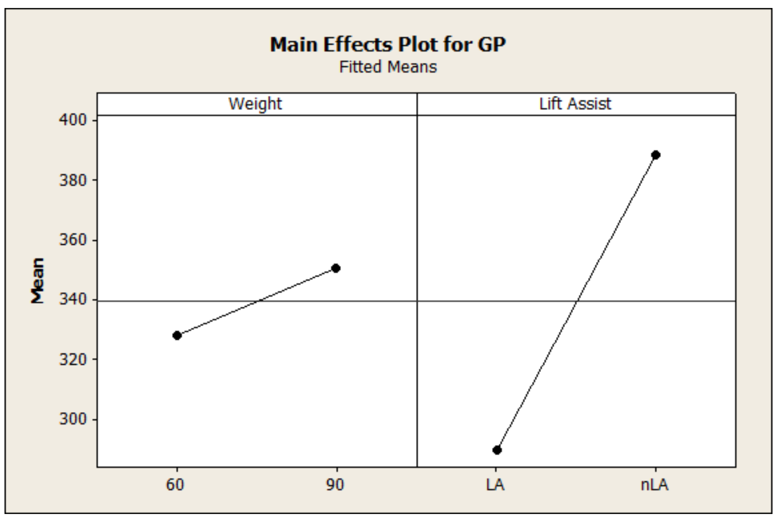

Figure 28: Main effects plot for lifting grip pressure

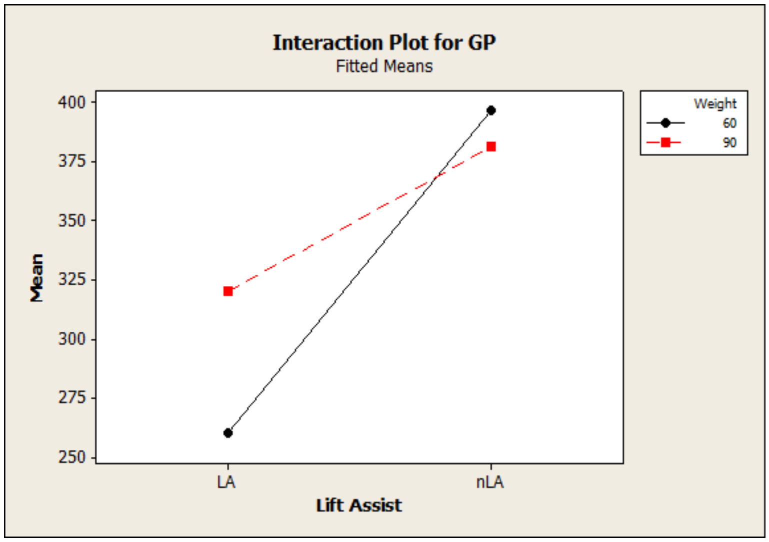

Figure 29: Interaction plot between weight and lift assist for lifting grip pressure

Table 20: General Linear Model results for operating grip pressure

General Linear Model: Grip Pressure versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	7	2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Grip Pressure, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	6	16397.0	16542.0	2757.0	8.19	0.001
Weight	1	0.8	0.3	0.3	0.00	0.976
Lift Assist	1	778.9	756.9	756.9	2.25	0.158
Weight*Lift Assist	1	28.8	28.8	28.8	0.09	0.774
Error	13	4378.1	4378.1	336.8		
Total	22	21583.5				

S = 18.3514   R-Sq = 79.72%   R-Sq(adj) = 65.67%

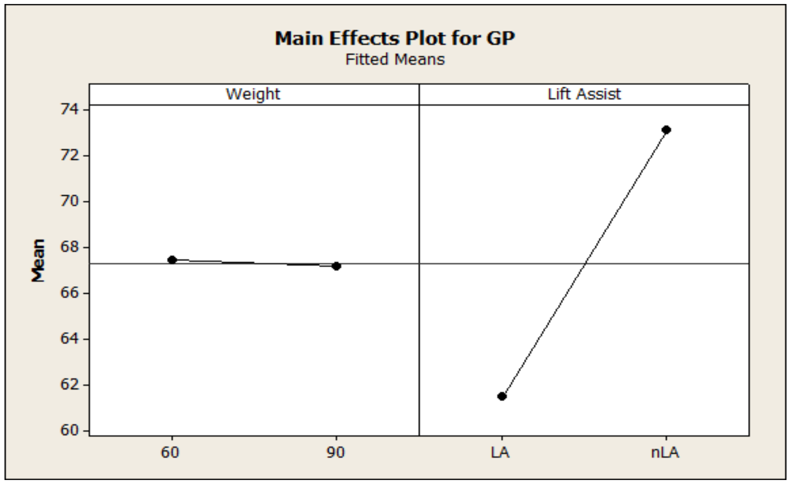

Figure 30: Main effects plot for operating grip pressure

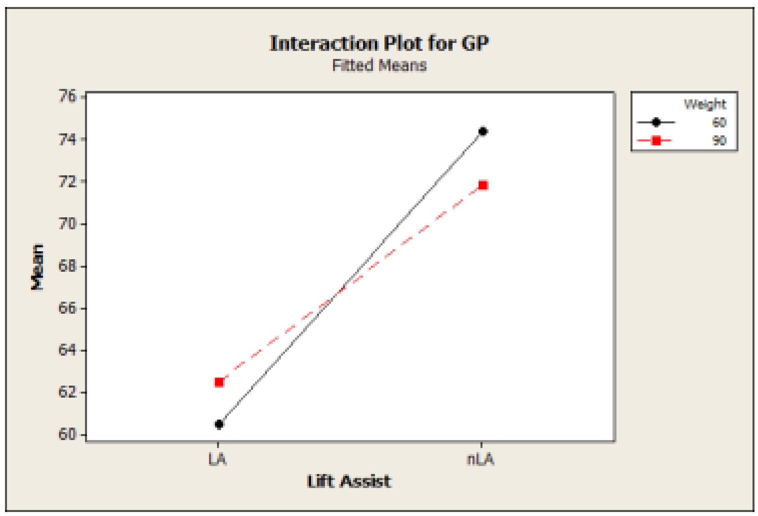

Figure 31: Interaction plot between weight and lift assist for operating grip pressure

Table 21: General Linear Model results for contact area

General Linear Model: Contact Area versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	7	2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Contact Area, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	6	152.833	151.153	25.192	9.43	0.001
Weight	1	0.979	0.979	0.979	0.37	0.556
Lift Assist	1	33.823	32.203	32.203	12.05	0.005
Weight*Lift Assist	1	1.652	1.652	1.652	0.62	0.447
Error	12	32.068	32.068	2.672		
Total	21	221.354				

S = 1.63472   R-Sq = 85.51%   R-Sq(adj) = 74.65%

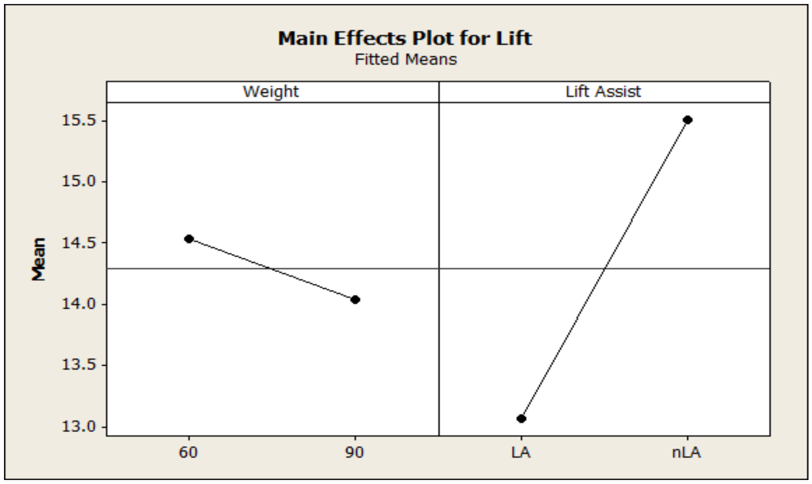

Figure 32: Main effects plot for contact area

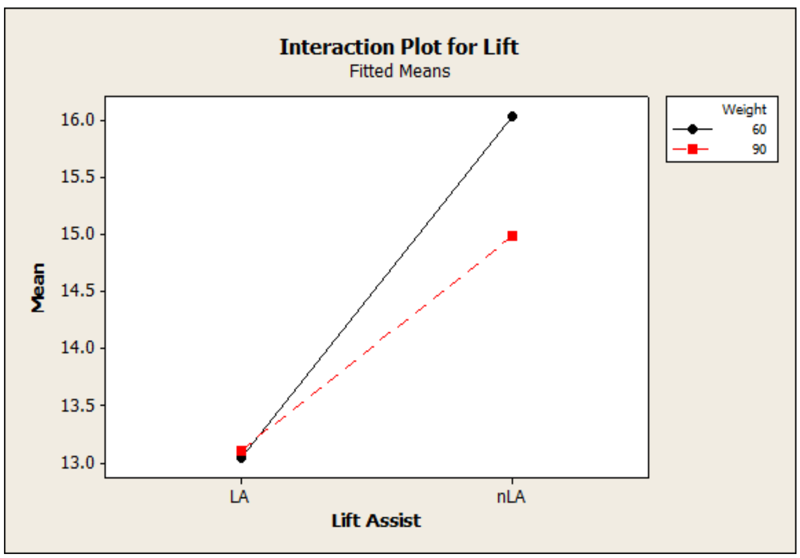

Figure 33: Interaction plot between weight and lift assist for contact area

Table 22: General Linear Model ANOVA results for lifting grip force

General Linear Model: Grip Force versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	7	2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Grip Force, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	6	1052951	1060459	176743	8.44	0.001
Weight	1	20508	20508	20508	0.98	0.342
Lift Assist	1	438410	425212	425212	20.31	0.001
Weight*Lift Assist	1	6449	6449	6449	0.31	0.589
Error	12	251250	251250	20938		
Total	21	1769567				

S = 144.698   R-Sq = 85.80%   R-Sq(adj) = 75.15%

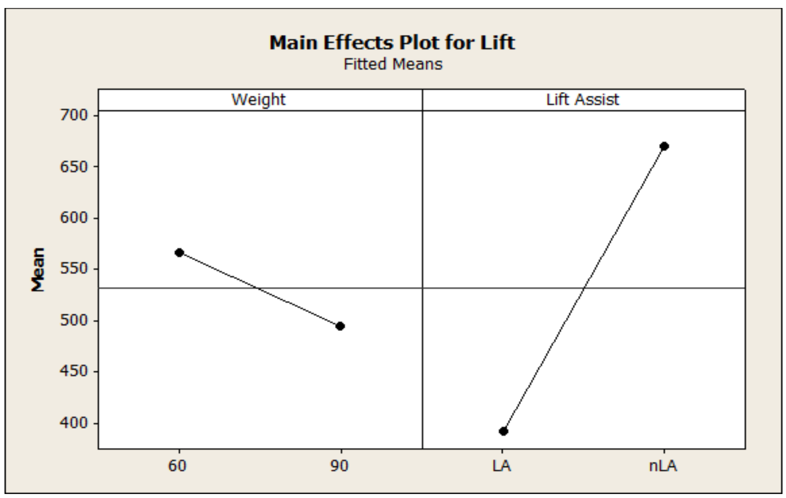

Figure 34: Main effects plot for lifting grip force

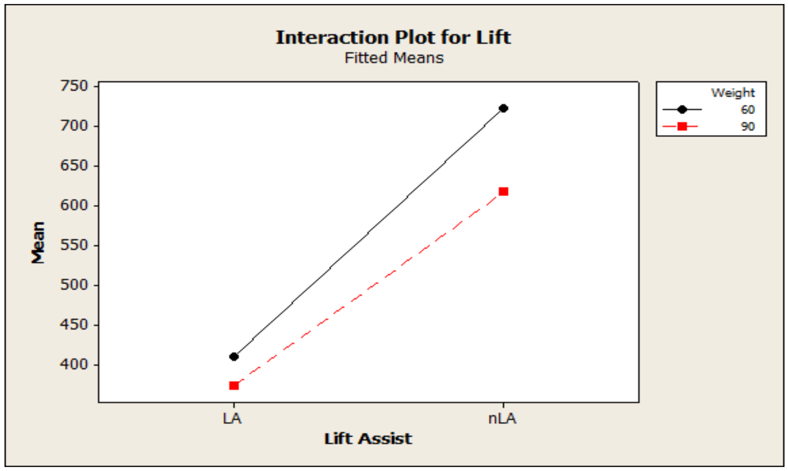

Figure 35: Interaction plot between weight and lift assist for grip force

Table 23: General Linear Model ANOVA results for lifting muscle activity in the left Bicep

General Linear Model: Muscle Activ versus Subject, Lift Assist, Weight

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Lift Assist	fixed	2	LA, nLA
Weight	fixed	2	60, 90

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	6.20	0.004
Lift Assist	1	0.0000000	0.0000000	0.0000000	33.12	0.000
Weight	1	0.0000000	0.0000000	0.0000000	5.39	0.040
Lift Assist*Weight	1	0.0000000	0.0000000	0.0000000	1.14	0.309
Error	11	0.0000000	0.0000000	0.0000000		
Total	21	0.0000001				

S = 0.0000315349 R-Sq = 87.69% R-Sq(adj) = 76.50%

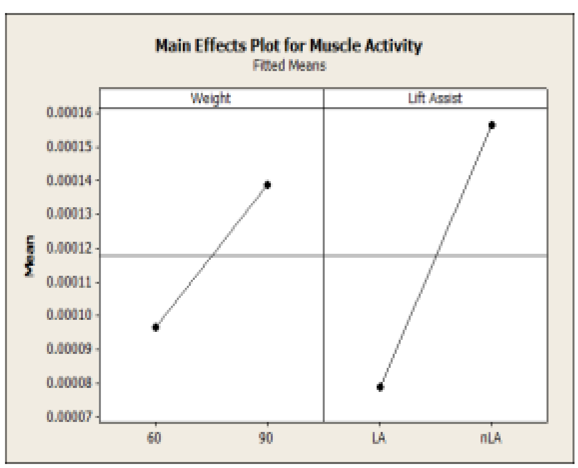

Figure 36: Main effects plot for lifting muscle activity in the left Bicep

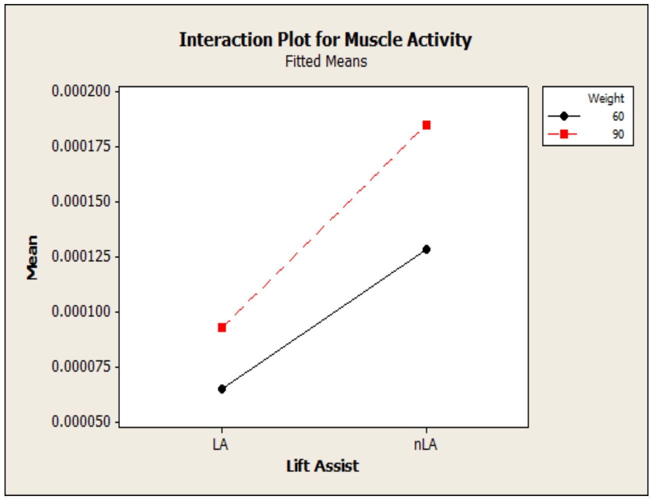

Figure 37: Interaction plot for lifting muscle activity in the left Bicep

Table 24: General Linear Model ANOVA results for lifting muscle activity in the right Bicep

General Linear Model: Muscle Activ versus Subject, Lift Assist, Weight

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Lift Assist	fixed	2	LA, nLA
Weight	fixed	2	60, 90

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000001	0.0000001	0.0000000	7.97	0.000
Lift Assist	1	0.0000000	0.0000000	0.0000000	22.20	0.000
Weight	1	0.0000000	0.0000000	0.0000000	7.98	0.013
Lift Assist*Weight	1	0.0000000	0.0000000	0.0000000	0.27	0.612
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000002				

S = 0.0000426163   R-Sq = 83.99%   R-Sq(adj) = 73.31%

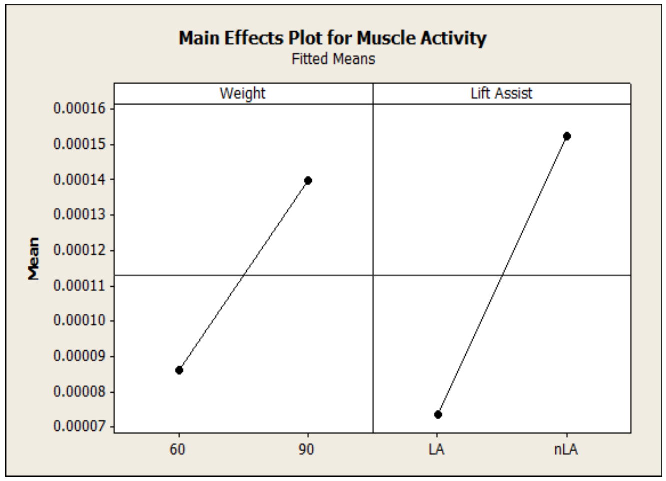

Figure 38: Main effects plot for lifting muscle activity in the right Bicep

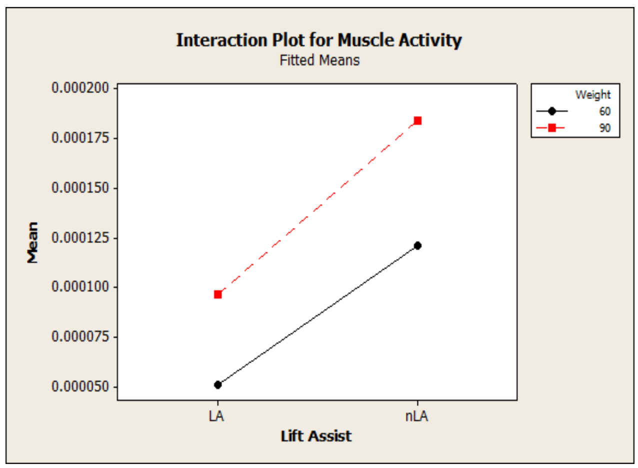

Figure 39: Interaction plot for lifting muscle activity in the right Bicep

Table 25: General Linear Model ANOVA results for lifting muscle activity in the left Deltoid

General Linear Model: Muscle Activ versus Subject, Lift Assist, Weight

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Lift Assist	fixed	2	LA, nLA
Weight	fixed	2	60, 90

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	7.63	0.001
Lift Assist	1	0.0000000	0.0000000	0.0000000	17.51	0.001
Weight	1	0.0000000	0.0000000	0.0000000	6.81	0.020
Lift Assist*Weight	1	0.0000000	0.0000000	0.0000000	3.70	0.074
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 0.0000166801   R-Sq = 85.09%   R-Sq(adj) = 75.14%

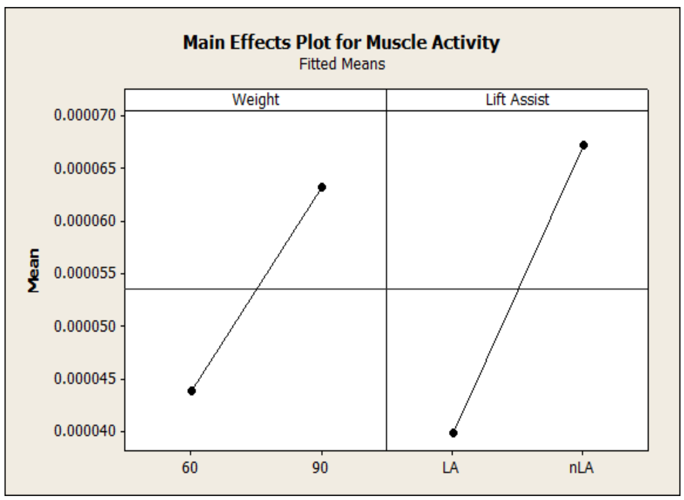

Figure 40: Main effects plot for lifting muscle activity in the left Deltoid

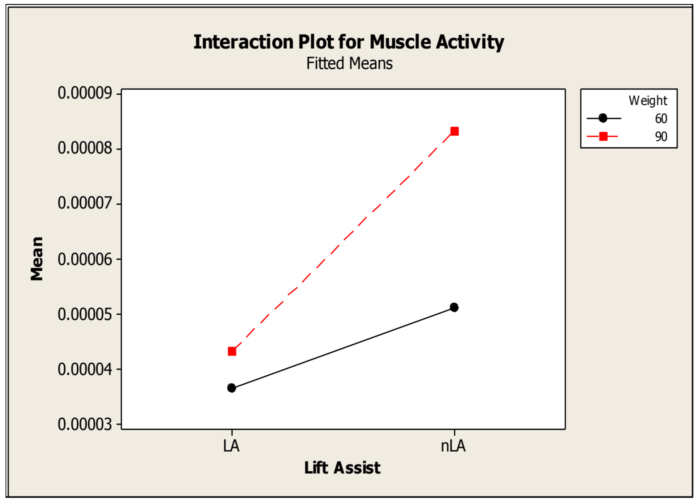

Figure 41: Interactions plot for lifting muscle activity in the left Deltoid

Table 26: General Linear Model ANOVA results for lifting muscle activity in the right Deltoid

General Linear Model: Muscle Activ versus Subject, Lift Assist, Weight

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Lift Assist	fixed	2	LA, nLA
Weight	fixed	2	60, 90

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	2.17	0.086
Lift Assist	1	0.0000000	0.0000000	0.0000000	7.02	0.016
Weight	1	0.0000000	0.0000000	0.0000000	3.32	0.084
Lift Assist*Weight	1	0.0000000	0.0000000	0.0000000	2.27	0.149
Error	19	0.0000000	0.0000000	0.0000000		
Total	29	0.0000000				

S = 0.0000294063   R-Sq = 58.92%   R-Sq(adj) = 37.30%

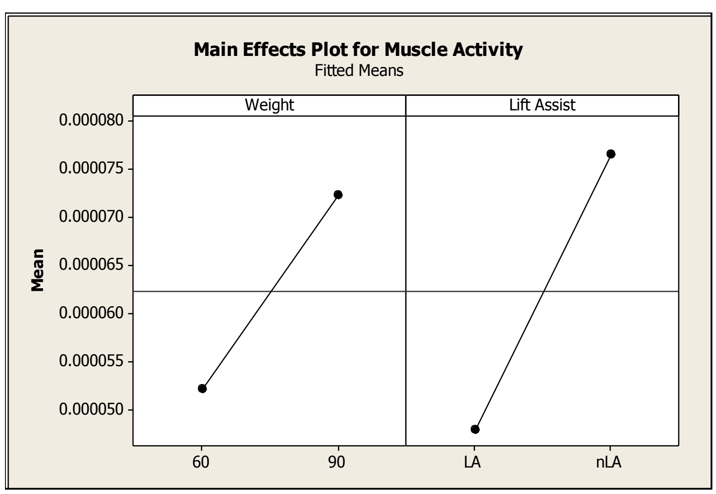

Figure 42: Main effects plot for lifting muscle activity in the right Deltoid

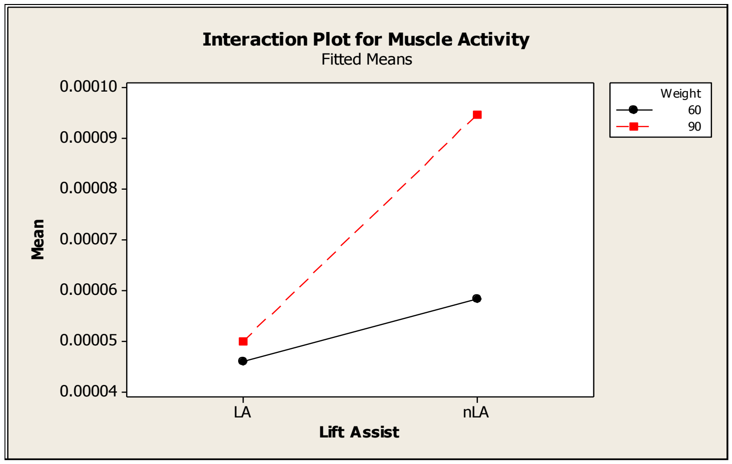

Figure 43: Interaction plot for lifting muscle activity in the right Deltoid

Table 27: General Linear Model ANOVA results for lifting muscle activity in the left Erector Spinae

General Linear Model: Muscle Activ versus Subject, Lift Assist, Weight

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Lift Assist	fixed	2	LA, nLA
Weight	fixed	2	60, 90

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	12.14	0.000
Lift Assist	1	0.0000000	0.0000000	0.0000000	13.97	0.002
Weight	1	0.0000000	0.0000000	0.0000000	3.99	0.064
Lift Assist*Weight	1	0.0000000	0.0000000	0.0000000	0.21	0.652
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 8.602513E-06   R-Sq = 86.85%   R-Sq(adj) = 78.09%

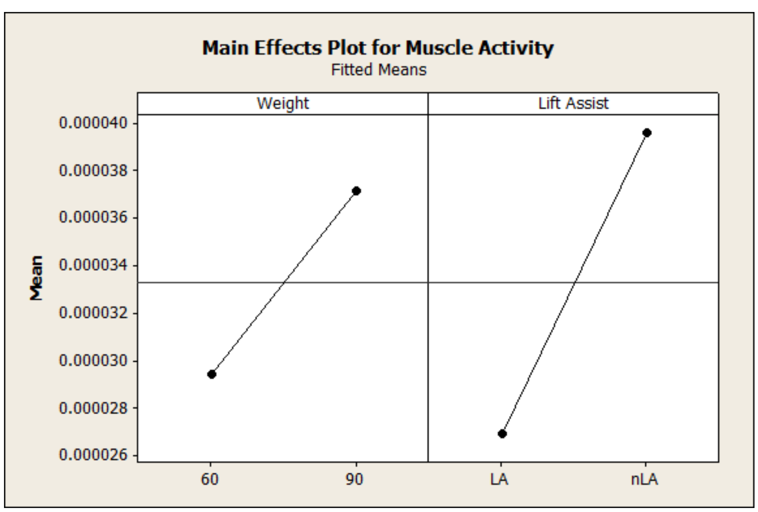

Figure 44: Main effects plot for lifting muscle activity in the left Erector Spinae

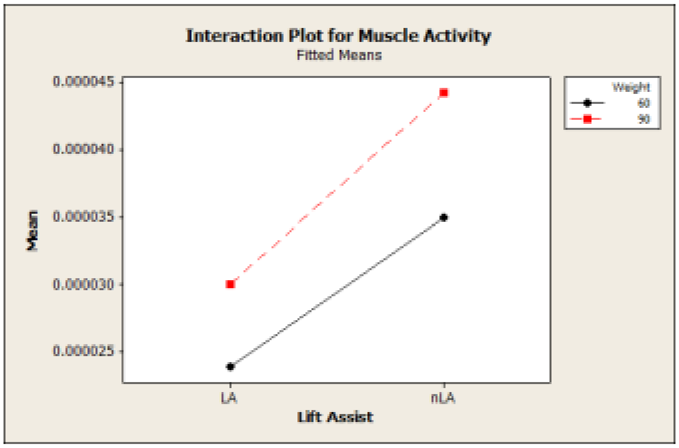

Figure 45: Interaction plot for lifting muscle activity in the left Erector Spinae

Table 28: General Linear Model ANOVA results for lifting muscle activity in the right Erector Spinae

General Linear Model: Muscle Activ versus Subject, Lift Assist, Weight

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Lift Assist	fixed	2	LA, nLA
Weight	fixed	2	60, 90

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	6.90	0.001
Lift Assist	1	0.0000000	0.0000000	0.0000000	10.93	0.005
Weight	1	0.0000000	0.0000000	0.0000000	2.59	0.129
Lift Assist*Weight	1	0.0000000	0.0000000	0.0000000	0.12	0.734
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 8.403525E-06 R-Sq = 79.80% R-Sq(adj) = 66.34%

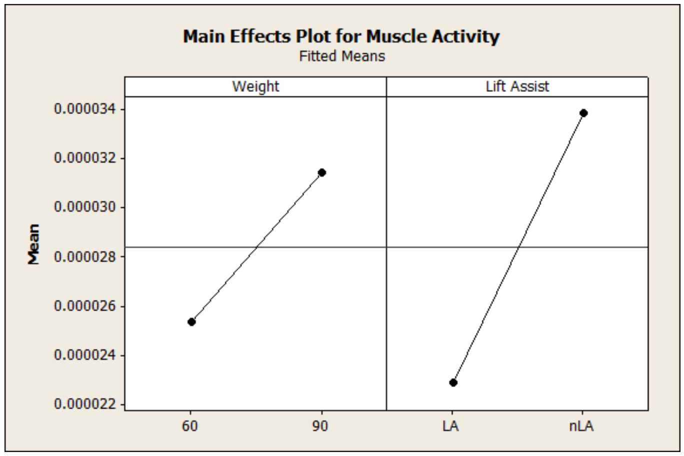

Figure 46: Main effects plot for lifting muscle activity in the right Erector Spinae

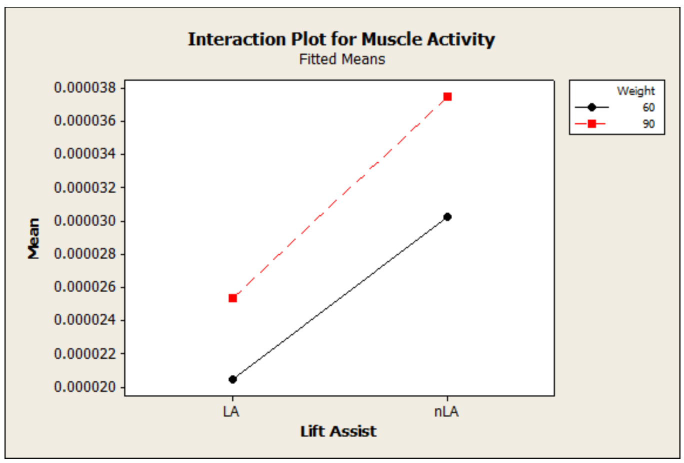

Figure 47: Interaction plot for lifting muscle activity in the right Erector Spinae

Table 29: General Linear Model ANOVA results for operating muscle activity in the left Bicep

General Linear Model: Muscle Activ versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	10.32	0.000
Weight	1	0.0000000	0.0000000	0.0000000	2.89	0.117
Lift Assist	1	0.0000000	0.0000000	0.0000000	0.23	0.639
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.14	0.714
Error	11	0.0000000	0.0000000	0.0000000		
Total	21	0.0000000				

S = 8.545009E-06 R-Sq = 89.21% R-Sq(adj) = 79.40%

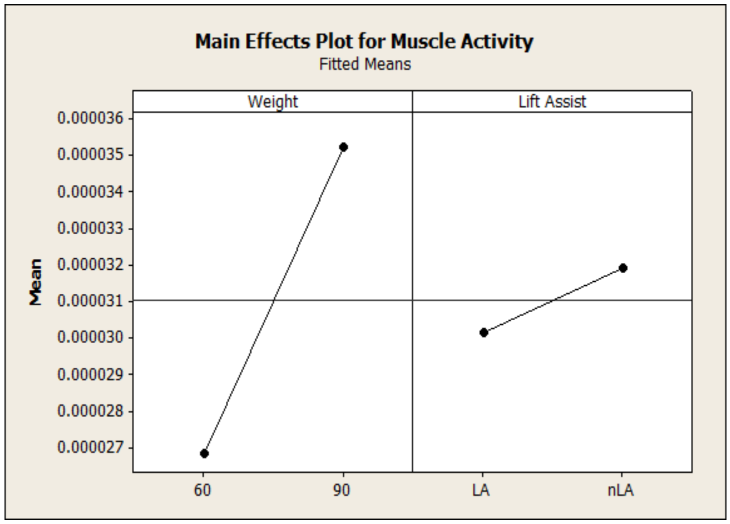

Figure 48: Main effects plot for operating muscle activity in the left Bicep

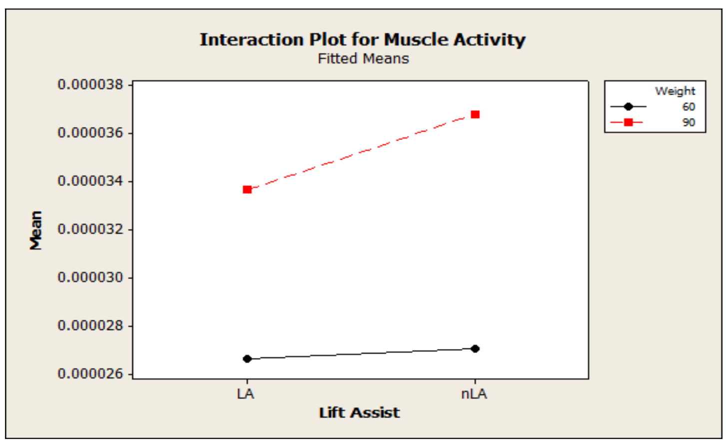

Figure 49: Interaction plot for operating muscle activity in the left Bicep

Table 30: General Linear Model ANOVA results for operating muscle activity in the right Bicep

General Linear Model: Muscle Activ versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	3.76	0.015
Weight	1	0.0000000	0.0000000	0.0000000	1.30	0.273
Lift Assist	1	0.0000000	0.0000000	0.0000000	0.07	0.801
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.15	0.704
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 0.0000122928   R-Sq = 65.05%   R-Sq(adj) = 41.74%

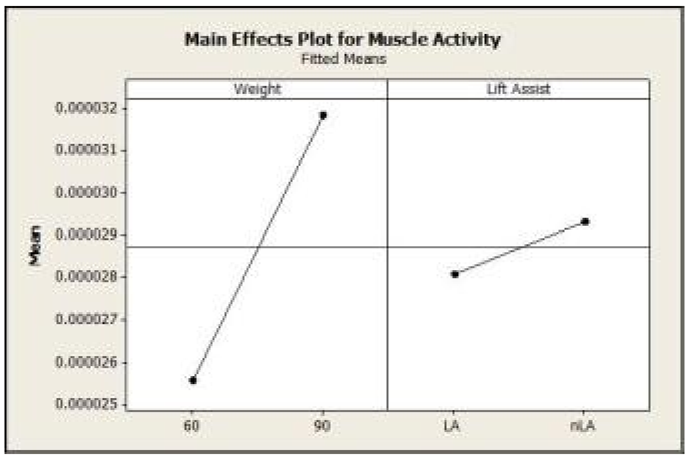

Figure 50: Main effects plot for operating muscle activity in the right Bicep

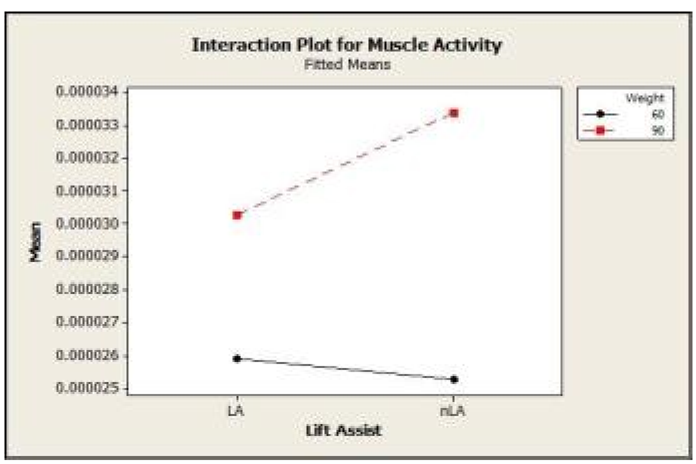

Figure 51: Interaction plot for operating muscle activity in the right Bicep

Table 31: General Linear Model ANOVA results for operating muscle activity in the left Deltoid

General Linear Model: Muscle Activ versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	4.09	0.011
Weight	1	0.0000000	0.0000000	0.0000000	4.23	0.057
Lift Assist	1	0.0000000	0.0000000	0.0000000	0.42	0.528
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.01	0.923
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 0.0000115005   R-Sq = 68.01%   R-Sq(adj) = 46.69%

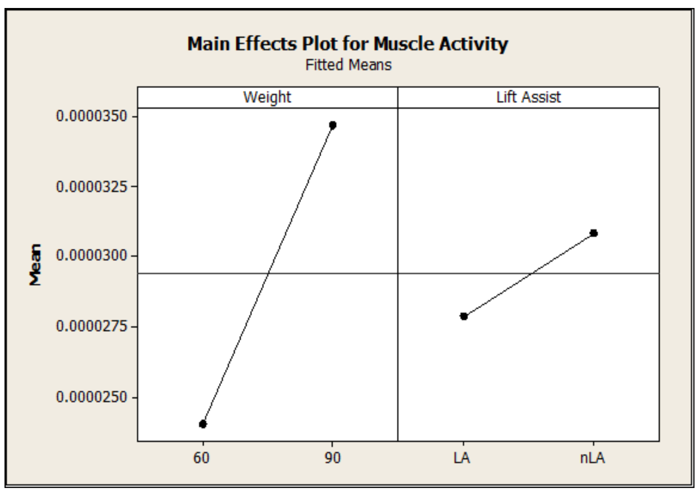

Figure 52: Main effect plot for operating muscle activity in the left Deltoid

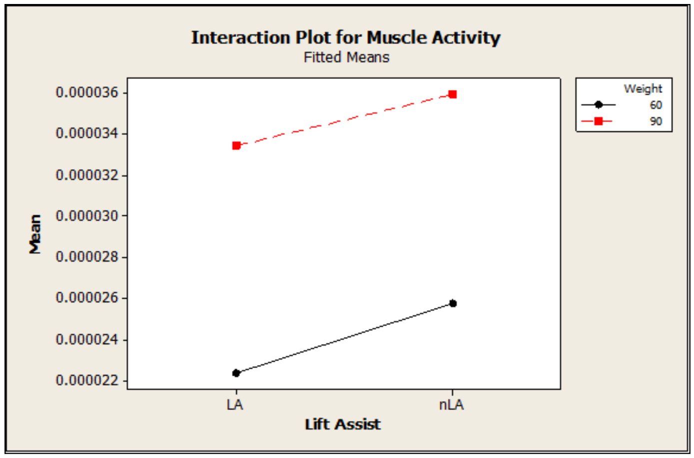

Figure 53: Interaction plot for operating muscle activity in the left Deltoid

Table 32: General Linear Model ANOVA results for operating muscle activity in the right Deltoid

General Linear Model: Muscle Activ versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	1.49	0.230
Weight	1	0.0000000	0.0000000	0.0000000	2.21	0.153
Lift Assist	1	0.0000000	0.0000000	0.0000000	2.40	0.138
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.17	0.684
Error	19	0.0000000	0.0000000	0.0000000		
Total	29	0.0000000				

S = 0.0000174069   R-Sq = 44.56%   R-Sq(adj) = 15.38%

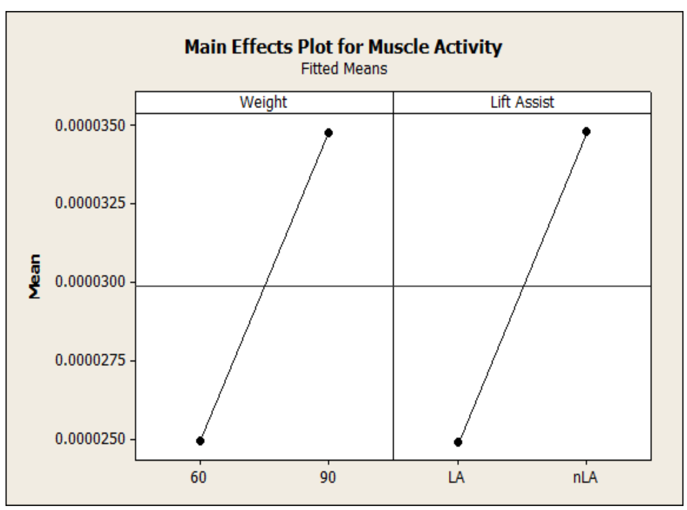

Figure 54: Main effects plot for operating muscle activity in the right Deltoid

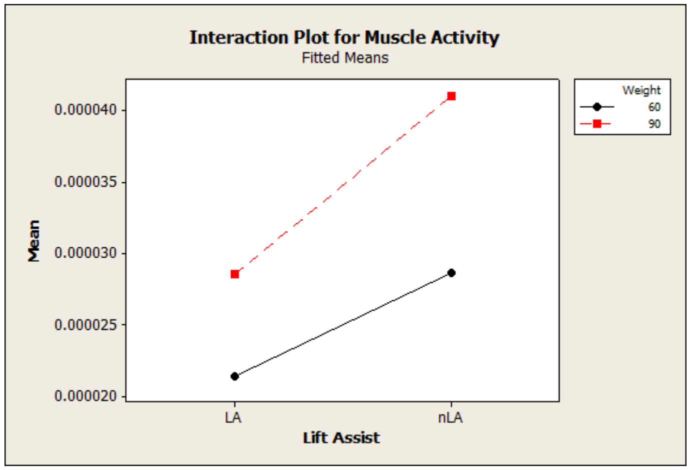

Figure 55: Interaction plot for operating muscle activity in the right Deltoid

Table 33: General Linear Model ANOVA results for operating muscle activity in the left Erector Spinae

General Linear Model: Muscle Activ versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	7.00	0.001
Weight	1	0.0000000	0.0000000	0.0000000	1.99	0.179
Lift Assist	1	0.0000000	0.0000000	0.0000000	0.13	0.728
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.00	0.964
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 4.781265E-06   R-Sq = 76.61%   R-Sq(adj) = 61.01%

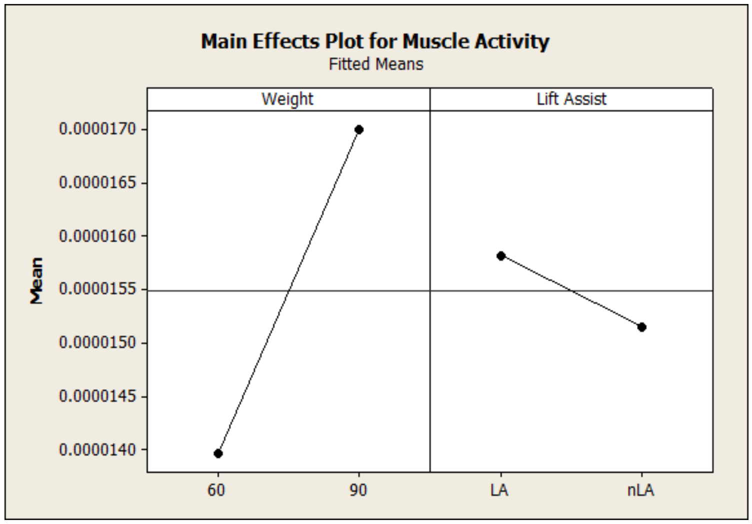

Figure 56: Main effects plot for operating muscle activity in the left Erector Spinae

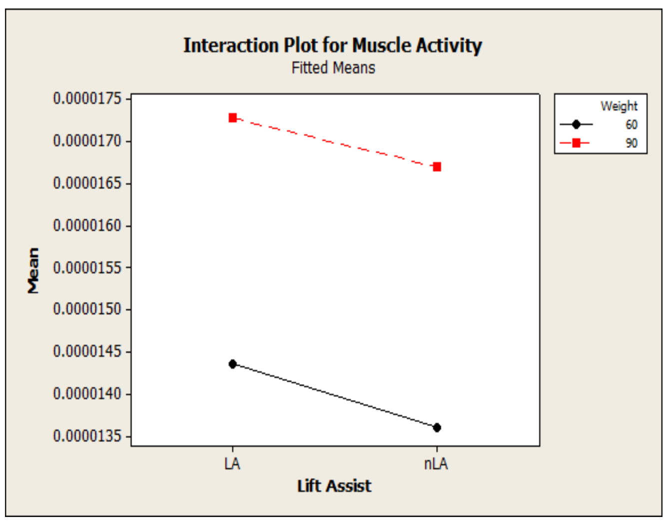

Figure 57: Interaction plot for operating muscle activity in the left Erector Spinae

Table 34: General Linear Model ANOVA results for operating muscle activity in the right Erector Spinae

General Linear Model: Muscle Activ versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	0.0000000	0.0000000	0.0000000	30.80	0.000
Weight	1	0.0000000	0.0000000	0.0000000	5.29	0.036
Lift Assist	1	0.0000000	0.0000000	0.0000000	1.35	0.263
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.47	0.502
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 1.969057E-06   R-Sq = 93.60%   R-Sq(adj) = 89.33%

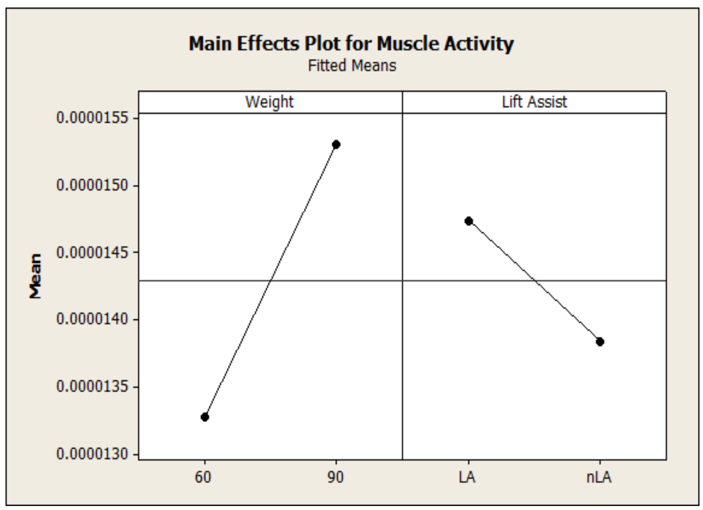

Figure 58: Main effects plot for operating muscle activity in the right Erector Spinae

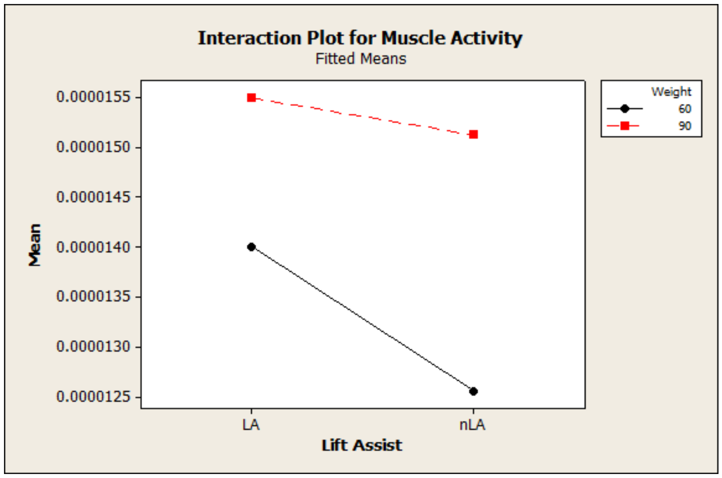

Figure 59: Interaction plot for operating muscle activity in the right Erector Spinae

Table 35: General Linear Model ANOVA results for overall muscle activity in the left Bicep

General Linear Model: Muscle Activ versus Subjects, Weight, Lift Assist

Factor	Type	Levels	Values
Subjects	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60lb, 90lb
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subjects	7	0.0000000	0.0000000	0.0000000	11.17	0.000
Weight	1	0.0000000	0.0000000	0.0000000	0.18	0.678
Lift Assist	1	0.0000000	0.0000000	0.0000000	1.48	0.246
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	1.73	0.212
Error	13	0.0000000	0.0000000	0.0000000		
Total	23	0.0000000				

S = 0.0000102246   R-Sq = 86.65%   R-Sq(adj) = 76.39%

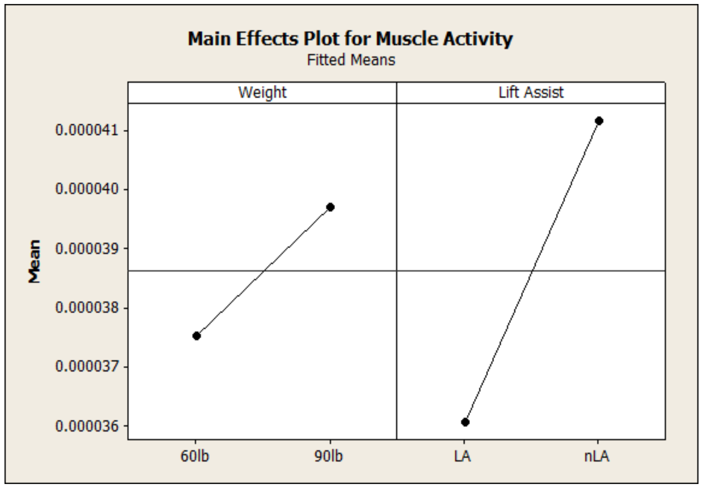

Figure 60: Main effects plot for overall muscle activity in the left Bicep

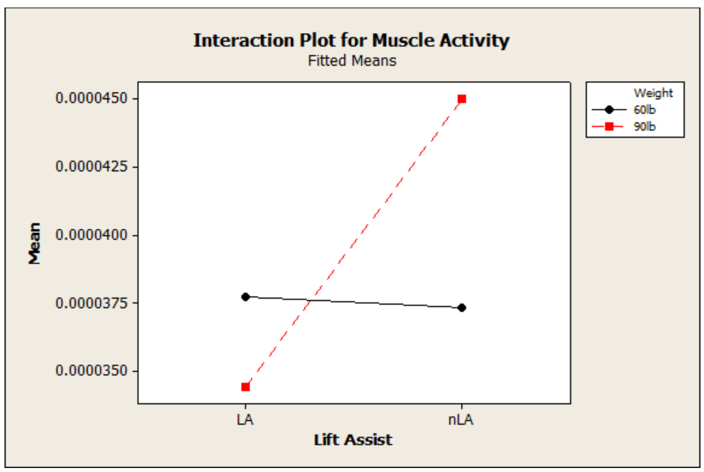

Figure 61: Interaction plot for overall muscle activity in the left Bicep

Table 36: General Linear Model ANOVA results for overall muscle activity in the right Bicep

General Linear Model: Muscle Activ versus Subjects, Weight, Lift Assist

Factor	Type	Levels	Values
Subjects	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60lb, 90lb
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subjects	7	0.0000000	0.0000000	0.0000000	6.71	0.001
Weight	1	0.0000000	0.0000000	0.0000000	1.88	0.191
Lift Assist	1	0.0000000	0.0000000	0.0000000	7.04	0.018
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.83	0.377
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 0.0000112264   R-Sq = 78.87%   R-Sq(adj) = 64.78%

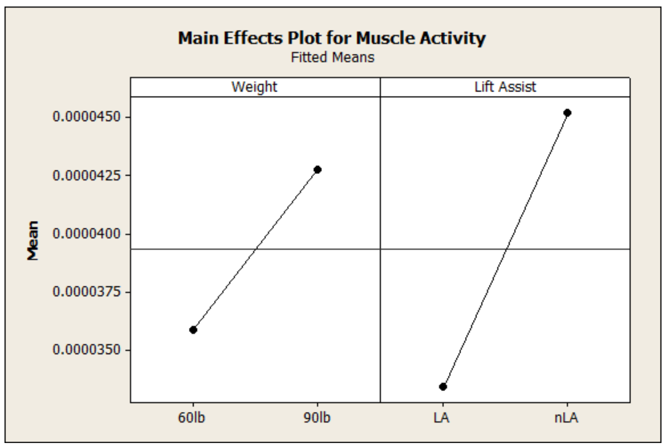

Figure 62: Main effects plot for overall muscle activity in the right Bicep

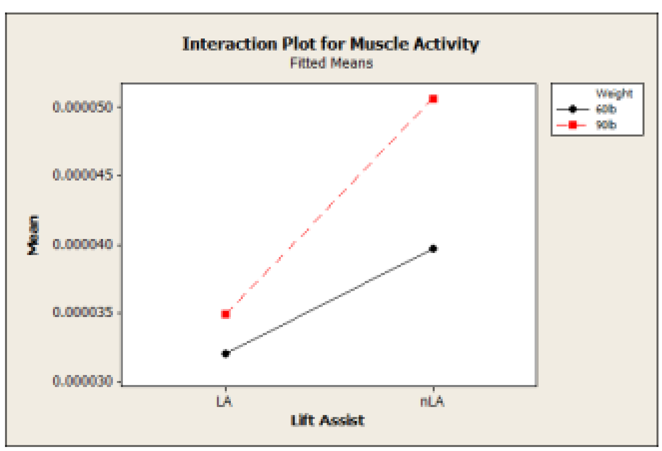

Figure 63: Interaction plot for overall muscle activity in the right Bicep

Table 37: General Linear Model ANOVA results for overall muscle activity in the left Deltoid

General Linear Model: Muscle Activ versus Subjects, Weight, Lift Assist

Factor	Type	Levels	Values
Subjects	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60lb, 90lb
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subjects	7	0.0000000	0.0000000	0.0000000	3.53	0.016
Weight	1	0.0000000	0.0000000	0.0000000	7.14	0.016
Lift Assist	1	0.0000000	0.0000000	0.0000000	3.51	0.078
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	1.37	0.257
Error	17	0.0000000	0.0000000	0.0000000		
Total	27	0.0000000				

S = 0.0000140246   R-Sq = 66.62%   R-Sq(adj) = 46.98%

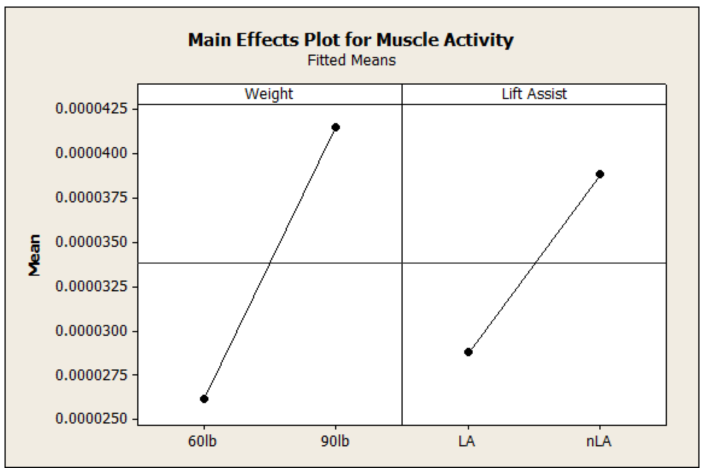

Figure 64: Main effects plot for overall muscle activity in the left Deltoid

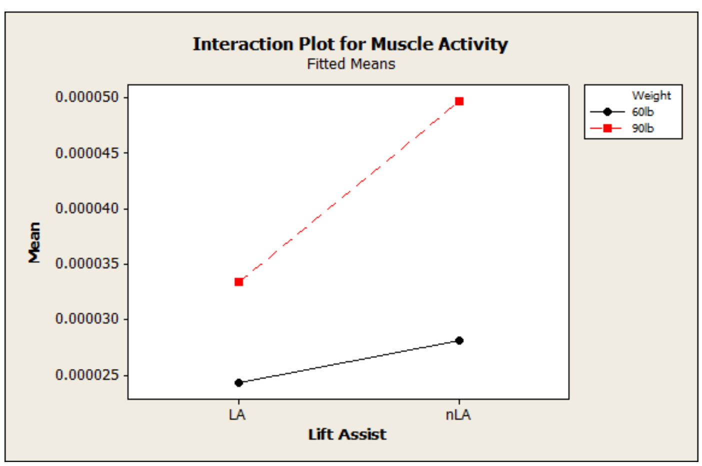

Figure 65: Interaction plot for overall muscle activity in the left Deltoid

Table 38: General Linear Model ANOVA results for overall muscle activity in the right Deltoid

General Linear Model: Muscle Activ versus Subjects, Weight, Lift Assist

Factor	Type	Levels	Values
Subjects	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60lb, 90lb
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subjects	7	0.0000000	0.0000000	0.0000000	0.85	0.565
Weight	1	0.0000000	0.0000000	0.0000000	3.03	0.100
Lift Assist	1	0.0000000	0.0000000	0.0000000	3.02	0.101
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	1.78	0.200
Error	17	0.0000000	0.0000000	0.0000000		
Total	27	0.0000000				

S = 0.0000252947   R-Sq = 43.37%   R-Sq(adj) = 10.06%

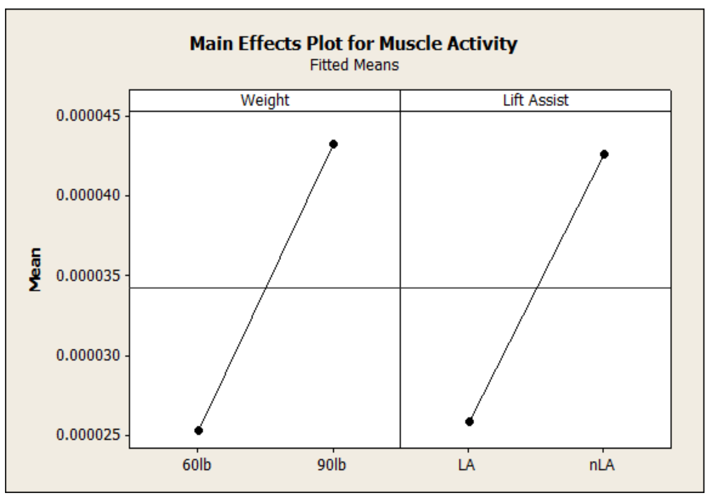

Figure 66: Main effects plot for overall muscle activity in the right Deltoid

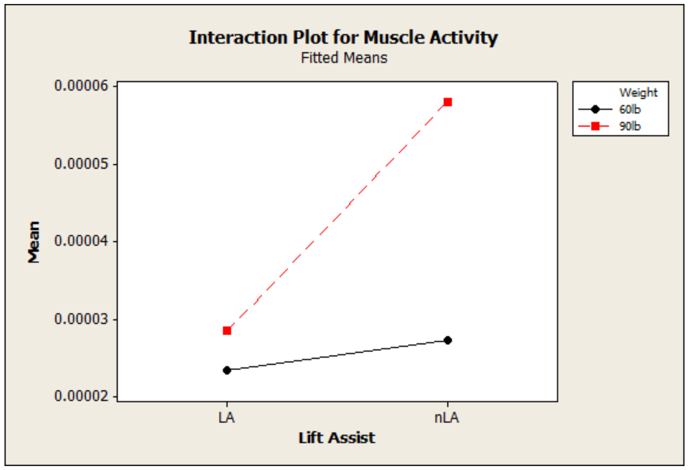

Figure 67: Interaction plot for overall muscle activity in the right Deltoid

Table 39: General Linear Model ANOVA results for overall muscle activity in the left Erector Spinae

General Linear Model: Muscle Activ versus Subjects, Weight, Lift Assist

Factor	Type	Levels	Values
Subjects	random	7	2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60lb, 90lb
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subjects	6	0.0000000	0.0000000	0.0000000	4.05	0.015
Weight	1	0.0000000	0.0000000	0.0000000	2.68	0.124
Lift Assist	1	0.0000000	0.0000000	0.0000000	0.24	0.630
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.11	0.746
Error	14	0.0000000	0.0000000	0.0000000		
Total	23	0.0000000				

S = 6.835498E-06   R-Sq = 63.80%   R-Sq(adj) = 40.52%

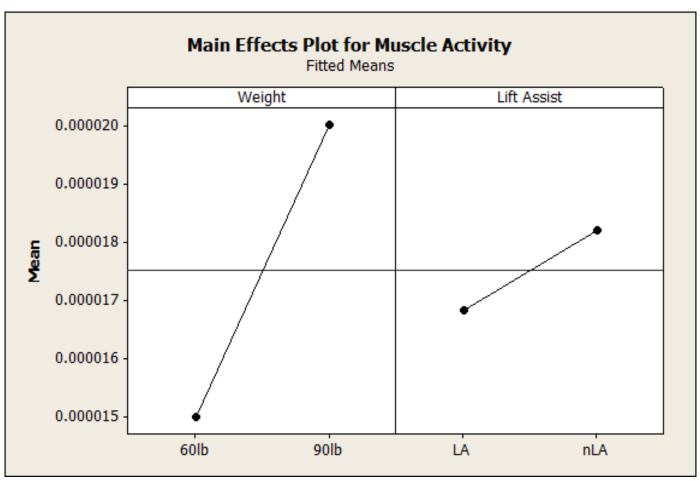

Figure 68: Main effects plot for overall muscle activity in the left Erector Spinae

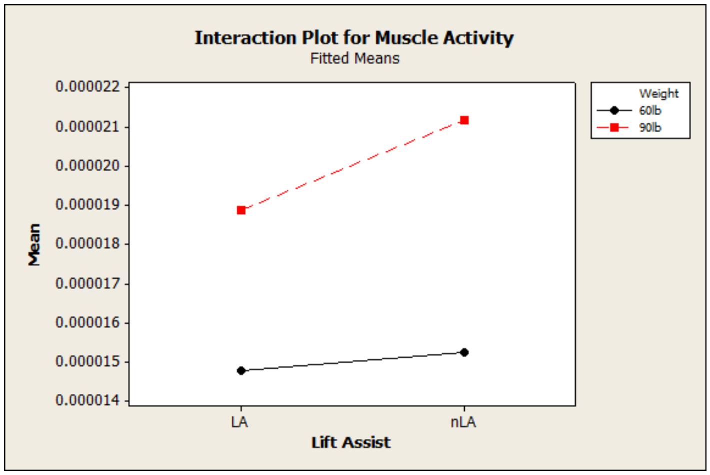

Figure 69: Interaction plot for overall muscle activity in the left Erector Spinae

Table 40: General Linear Model ANOVA results for overall muscle activity in the right Erector Spinae

General Linear Model: Muscle Activ versus Subjects, Weight, Lift Assist

Factor	Type	Levels	Values
Subjects	random	8	1, 2, 3, 4, 5, 6, 7, 8
Weight	fixed	2	60lb, 90lb
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Muscle Activity, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subjects	7	0.0000000	0.0000000	0.0000000	26.27	0.000
Weight	1	0.0000000	0.0000000	0.0000000	6.65	0.021
Lift Assist	1	0.0000000	0.0000000	0.0000000	0.98	0.338
Weight*Lift Assist	1	0.0000000	0.0000000	0.0000000	0.07	0.794
Error	15	0.0000000	0.0000000	0.0000000		
Total	25	0.0000000				

S = 2.268529E-06   R-Sq = 92.50%   R-Sq(adj) = 87.50%

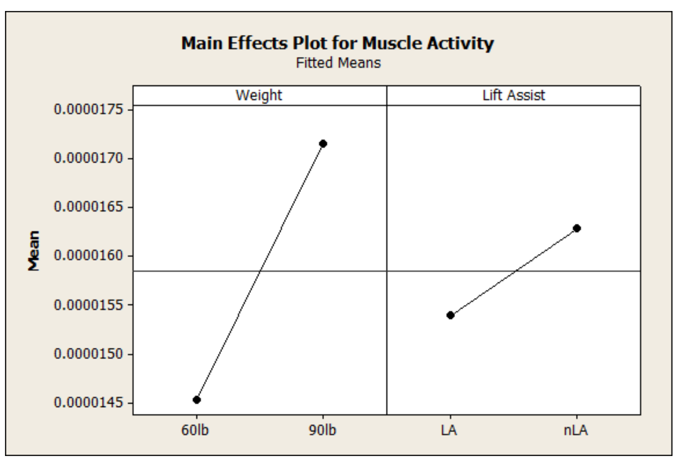

Figure 70: Main effects plot for overall muscle activity in the right Erector Spinae

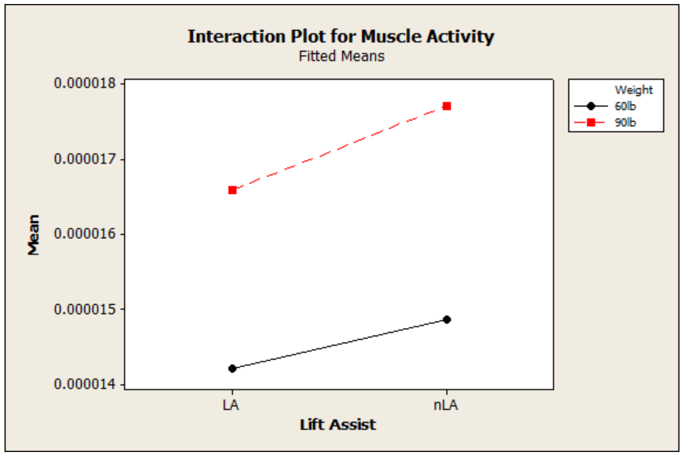

Figure 71: Interaction plot for overall muscle activity in the right Erector Spinae

Table 41: General Linaer Model ANOVA results for jackhammer vibration

General Linear Model: Vibration Am versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	7	1, 2, 3, 4, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Vibration Amplitude, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	6	111.967	112.100	18.683	9.15	0.000
Weight	1	0.138	0.224	0.224	0.11	0.745
Lift Assist	1	0.120	0.272	0.272	0.13	0.720
Weight*Lift Assist	1	1.644	1.644	1.644	0.80	0.384
Error	15	30.639	30.639	2.043		
Total	24	144.508				

S = 1.42919   R-Sq = 78.80%   R-Sq(adj) = 66.08%

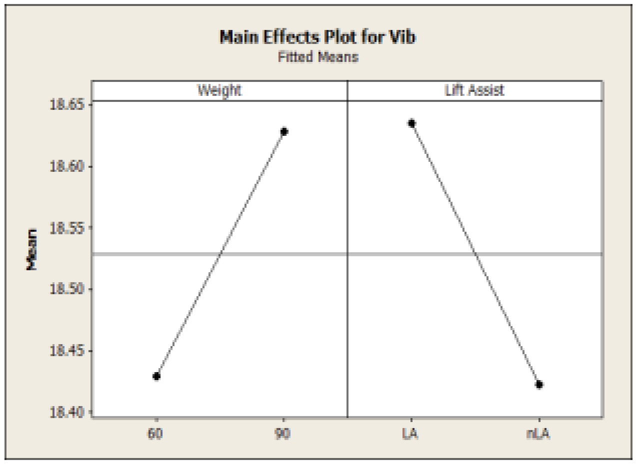

Figure 72: Main effects plot for jackhammer vibration

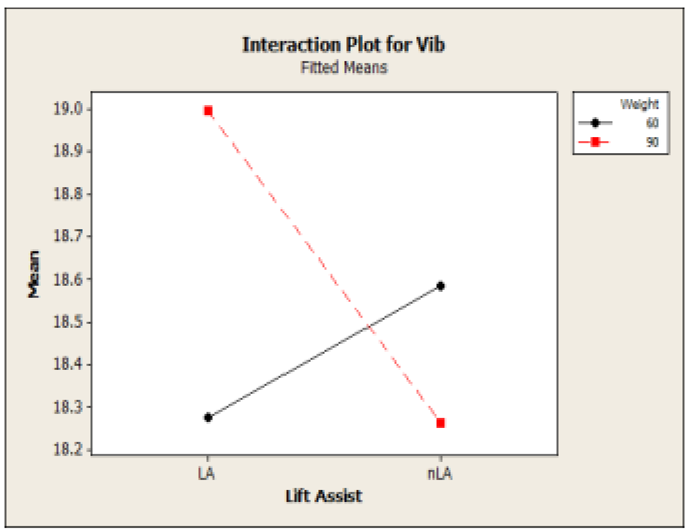

Figure 73: Interaction plot of jackhammer vibration

Table 42: General Linear Model ANOVA results for hand-arm vibration

General Linear Model: Vibration Am versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	7	1, 2, 3, 4, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Vibration Amplitude, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	6	240.255	239.370	39.895	13.42	0.000
Weight	1	0.310	0.279	0.279	0.09	0.764
Lift Assist	1	20.597	16.023	16.023	5.39	0.035
Weight*Lift Assist	1	12.557	12.557	12.557	4.22	0.058
Error	15	44.589	44.589	2.973		
Total	24	318.309				

S = 1.72413   R-Sq = 85.99%   R-Sq(adj) = 77.59%

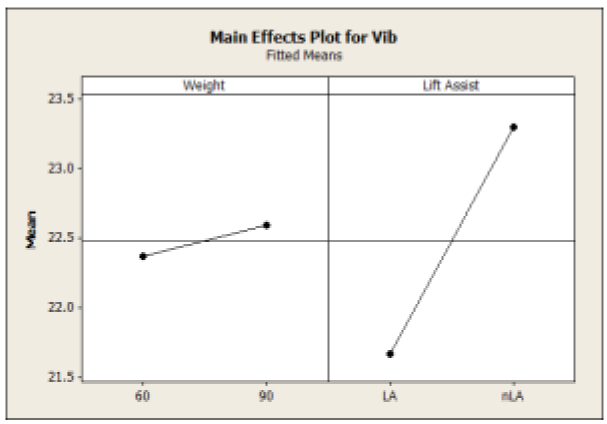

Figure 74: Main effects plot for hand-arm vibration

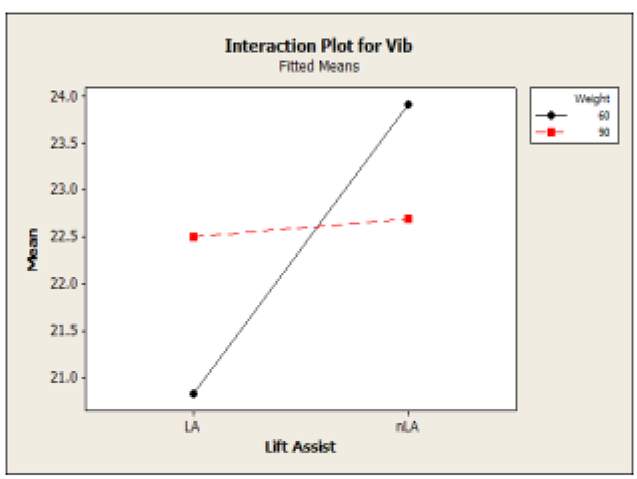

Figure 75: Interaction plot of jackhammer vibration

Table 43: General Linear Model ANOVA results for vibration dose

General Linear Model: Vibration Dose versus Subject, Weight, Lift Assist

Factor	Type	Levels	Values
Subject	random	7	1, 2, 3, 4, 6, 7, 8
Weight	fixed	2	60, 90
Lift Assist	fixed	2	LA, nLA

Analysis of Variance for Vibration Dose, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	6	29.1567	28.4486	4.7414	16.08	0.000
Weight	1	4.4649	4.4400	4.4400	15.06	0.001
Lift Assist	1	0.9222	0.7042	0.7042	2.39	0.143
Weight*Lift Assist	1	0.6495	0.6495	0.6495	2.20	0.158
Error	15	4.4220	4.4220	0.2948		
Total	24	39.6152				

S = 0.542955   R-Sq = 88.84%   R-Sq(adj) = 82.14%

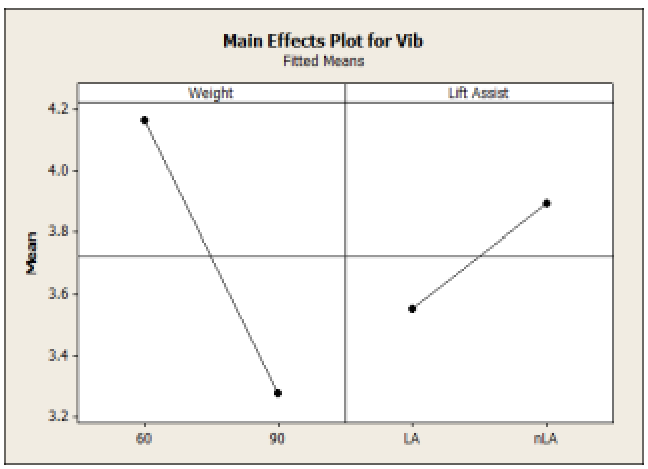

Figure 76: Main effects plot for vibration dose

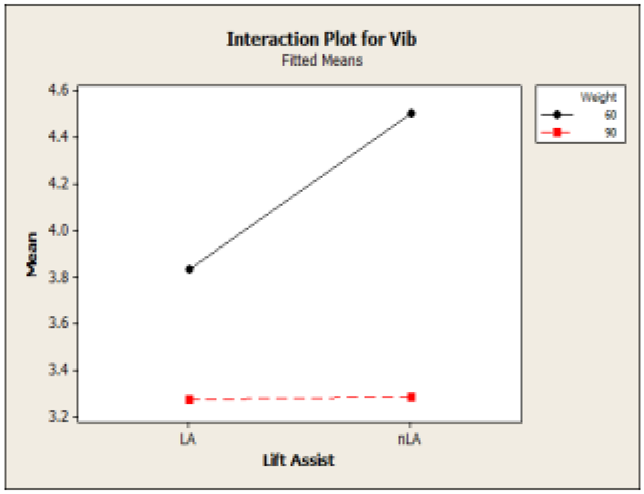

Figure 77: Interaction plot for vibration dose

Table 44: General Linear Model ANOVA results for task time

General Linear Model: Time versus Subject, Lift Assist, Weight

Factor	Type	Levels	Values
Subject	random	8	1, 2, 3, 4, 5, 6, 7, 8
Lift Assist	fixed	2	LA, nLA
Weight	fixed	2	60, 90

Analysis of Variance for Time, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	7	1145.82	1044.64	149.23	20.45	0.000
Lift Assist	1	1.74	3.42	3.42	0.47	0.502
Weight	1	248.96	243.69	243.69	33.39	0.000
Lift Assist*Weight	1	11.11	11.11	11.11	1.52	0.232
Error	20	145.95	145.95	7.30		
Total	30	1553.57				

S = 2.70141   R-Sq = 90.61%   R-Sq(adj) = 85.91%

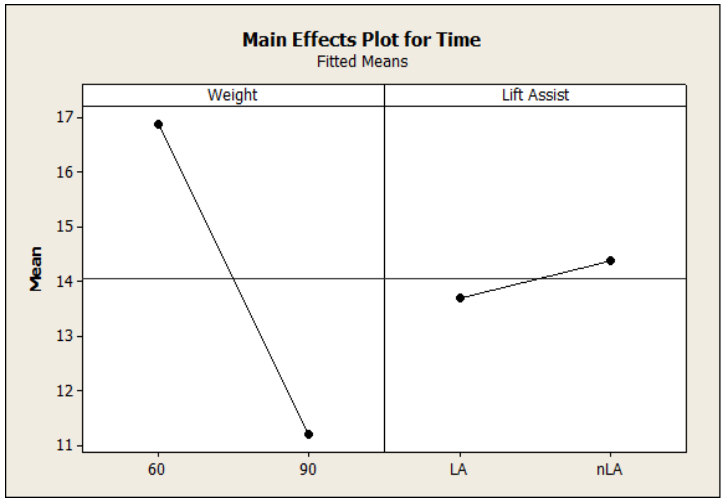

Figure 78: Main effects plot for task time

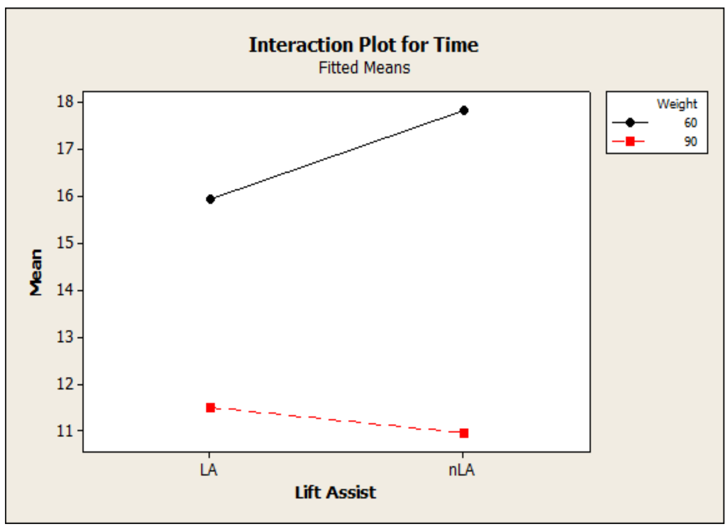

Figure 79: Interaction plot for task time

Appendix H: Structured Interview

Subject ID: _____________________________ Date: _______________________________

1. Interviewer: Ask the subject what best describes your experience using jackhammers?

< 1 month 1 month – 1 year > 1 year but less than 3 years Greater than 3 years

If greater than 3 years, ask the subject to elaborate

____

2. Interviewer: Note the following for the subject:

Gender	M F	Dominant Hand		Right Iliac Height (cm)		Iliac Breadth (cm)	
Age		Hand circumference(mm)		Left Iliac Height (cm)		Iliac Depth (cm)	
Weight (kg)		Hand length (mm)		Upper Arm Length (cm)		Xiphoid Breadth (cm)	
Height (m)		Hand width (mm)		Lower Arm Length (cm)		Xiphoid Depth (cm)	
BMI		Shoulder Height (cm)		Trunk Length (cm)		Upper Leg Length (cm)	
Any Discomforts	Y N	Elbow Height (cm)		Trunk Circumference (cm)		Lower Leg Length (cm)	

3. Interviewer: After a trial is completed read each feature below and ask the subject what word best describes the jackhammer

FEATURES	JH 1 Label:	JH 2 Label:	JH 3 Label:	JH 4 Label:	JH 5 Label:	JH 6 Label:
Ease of loading/unloading	Hard Easy	Hard Easy	Hard Easy	Hard Easy	Hard Easy	Hard Easy
Weight while carrying	Heavy Light	Heavy Light	Heavy Light	Heavy Light	Heavy Light	Heavy Light
Hand grip while loading/unloading	Comfy Awkward	Comfy Awkward	Comfy Awkward	Comfy Awkward	Comfy Awkward	Comfy Awkward
Hand grip while operating the jackhammer	Comfy Awkward	Comfy Awkward	Comfy Awkward	Comfy Awkward	Comfy Awkward	Comfy Awkward

4. Interviewer. Ask the subject to indicate their agreement with the following statements:

I am easily fatigued while using,

Jackhammer 1 1 2 3 4 5

Strongly disagree *Neutral* *Strongly agree*

Jackhammer 2 1 2 3 4 5

Strongly disagree *Neutral* *Strongly agree*

Jackhammer 3 1 2 3 4 5

Strongly disagree *Neutral* *Strongly agree*

Jackhammer 4 1 2 3 4 5

Strongly disagree *Neutral* *Strongly agree*

Jackhammer 5 1 2 3 4 5

Strongly disagree *Neutral* *Strongly agree*

Jackhammer 6 1 2 3 4 5

Strongly disagree *Neutral* *Strongly agree*

It was physically demanding for me to load/unload,

Jackhammer 1	1	2	3	4	5
	Strongly disagree		*Neutral*		*Strongly agree*
Jackhammer 2	1	2	3	4	5
	Strongly disagree		*Neutral*		*Strongly agree*
Jackhammer 3	1	2	3	4	5
	Strongly disagree		*Neutral*		*Strongly agree*
Jackhammer 4	1	2	3	4	5
	Strongly disagree		*Neutral*		*Strongly agree*
Jackhammer 5	1	2	3	4	5
	Strongly disagree		*Neutral*		*Strongly agree*
Jackhammer 6	1	2	3	4	5
	Strongly disagree		*Neutral*		*Strongly agree*

5. Interviewer. Ask the subject to indicate their agreement with the following statements after completing lift assist trials:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Lift Assist is easy to use	1	2	3	4	5
Lift assist is light weight.	1	2	3	4	5
Lift Assist is stable and easy to control during use.	1	2	3	4	5
Lift Assist improves the task performance.	1	2	3	4	5
Lift Assist relieved the muscular effort of removing the tip from the concrete	1	2	3	4	5
Lift Assist enabled me to complete the task in an acceptable amount of time.	1	2	3	4	5
Lift Assist made loading or unloading the jackhammer more difficult	1	2	3	4	5

6. Interviewer. Ask the subject to indicate their agreement with the following statements after using the 90lb and 60lb jackhammer.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
90lb jackhammer is easier to use than 60lb jackhammer	1	2	3	4	5
90lb jackhammer is easier to control while using the jackhammer than 60lb jackhammer	1	2	3	4	5
90lb jackhammer performed better than the 60lb jackhammer	1	2	3	4	5
90lb jackhammer was easier to load and unload than the 60lb jackhammer	1	2	3	4	5
90lb jackhammer was easier to hold while carrying than the 60lb jackhammer	1	2	3	4	5

7. Interviewer. Ask the subject about their preference on the different types of jackhammers.

I would prefer to use a 90lb jackhammer over a 60lb jackhammer Yes No

I would prefer to use a jackhammer with a lift assist than without a lift assist Yes No

Additional comments about loading/unloading and operating the different jackhammers with and without a lift assist.