ABSTRACT

UY, CHAD CAESAR. The Effect of Handle Design on the Kinetics and Kinematics of a Pouring Task. (Under the direction of Dr. Simon Hsiang and Dr. David Kaber.)

Immediate-use containers for carrying and pouring liquids come in a wide variety of shapes, sizes, and designs. Research has shown that handle designs for such containers have considerable impact on users. Unfortunately, handles on immediate-use containers are often designed for aesthetic purposes. This is an important issue as the handle can greatly affect the comfort and safety of a user. The purpose of this investigation is to identify handle parameters that have an effect on muscle activity, grip force, and joint postures during a pouring task. Optimal handle configuration would be expected to lower each of these measures. Different levels of diameter, height, and angle of the handle were tested in a simulated pouring task. Muscle activity of the anterior, middle, and posterior deltoid; trapezius; infraspinatus; biceps brachii; extensor and flexor carpi radialis was measured. Average grip force was measured as well as peak shoulder abduction, shoulder flexion, and wrist ulnar deviation.

Results showed that typically a low and vertical handle lowered the amount of muscle activity in the anterior, middle, and posterior deltoid; trapezius; and infraspinatus. That configuration also lowered the amount of shoulder abduction and flexion. Conversely, a high and sloped handle lowered the amount of muscle activity in the biceps brachii, extensor carpi radialis, and flexor carpi radialis. It also lowered the amount of grip force and wrist ulnar deviation. The effect of diameter was not as definitive, though typically 18 mm and 24 mm diameter handles were favored. The study recommends an 18 mm, low, and vertical handle configuration as the overall optimal handle.

The Effect of Handle Design on the Kinetics and Kinematics of a Pouring Task

by
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LIST OF ACRONYMS

MMH: Manual materials handling

EMG: Electromyography

RPE: Rating of perceived exertion

AD: Anterior deltoid

MD: Middle deltoid

PD: Posterior deltoid

TR: Trapezius

IF: Infraspinatus

BB: Biceps brachii

ECR: Extensor carpi radialis

FCR: Flexor carpi radialis

SA: Shoulder abduction

SF: Shoulder flexion

WUD: Wrist ulnar deviation

BNC: Bayonet Neill-Concelman

RVC: Reference voluntary contraction

P1: Lifting Phase

P2: Pouring Phase

MANOVA: Multivariate analysis of variance

ANOVA: Analysis of variance

HSD: Honestly significant difference

1 Introduction

1.1 Specific Aims

The goal of this study was to examine how handle diameter, height of attachment, and slope of attachment on an immediate-use container affects a user's upper extremity muscle activity, grip force, as well as postures a user takes in performing a pouring task.

1.2 Motivation for Study

Immediate-use containers used for carrying and pouring liquid come in a wide variety of shapes, sizes, and design. These bottles can also be found in different locations from the household to workplace. Despite being so commonplace, there seems to be little evidence validating the different design parameters in terms of their ergonomics. Liuzzo and Morawsky (1966) found that visual appearance and design were the two main factors considered in the design of handles for luggage and portable equipment (as referenced by Drury, 1980). Woodson & Conover (1964) also concluded handles were designed more for aesthetic purposes, as he found many to either be too small or insufficient to fit a person's hand. This suggests the use of intuitive design as opposed to explanatory design for many of these bottles. Intuitive designs are those that do not use biomechanical principles to support design decisions (Niemela & Saariluoma, 2003). These are, at times, less applicable to a wider population due to small sample sizes that are used to validate these choices. A move to explanatory design would reduce the chance of a design not working for consumers.

The laundry detergent bottle was used as one specific example for the pouring task. It was chosen because of its ubiquity in households. The most common types of laundry detergents are relatively heavy and might be difficult to use, especially for people with upper extremity disorders or weaknesses. It also requires a certain level of precision to pour out the desired amount of laundry detergent liquid. Spilling the detergent could be potentially hazardous to the user. Although the laundry detergent bottle and the tasks associated with laundry are being used as a model for this research, connections could easily be made to manual materials handling (MMH) in a workplace setting. The task of pouring liquid out of a container occurs in many different workplace settings, such as hospitality or food service facilities, where this act may be repeated hundreds of times in a day. High frequency coupled with suboptimal physical working conditions and time constraints could accentuate shortcomings of certain handles. Research has shown that even with light loads, awkward arm postures led to rapid onset of fatigue and discomfort in the shoulder (Wiker, Chaffin, & Langolf, 1990). In an effort to use objective measures to validate design decisions, the design of handles on liquid containers should be further researched and developed.

2 Literature Review

There has been little research done directly relating to liquid container handles. In general, having a handle provides increased comfort and performance compared to none. The handle reduces the risk of dropping objects and increases the amount of force a user can exert (Drury, 1980). The handle can also be used to reduce the potential for high forces or awkward postures (Drury, Begbie, Ulate and Deeb, 1985). A study by Okunribido and Haslegrave (2003) showed that while pouring liquid out of a pot, a curved handle caused a weaker grip than either a vertical or a sloped handle. Curved handles also increased the chance of slippage and musculoskeletal loading than when compared with the other handles. Overall, it was found that a vertical handle design was optimal for lifting a filled pot.

Despite the lack of literature related to immediate-use container handles, much work has been done on handle design in hand tools and in manual materials handling situations. A summary of the findings can be found in Table 2.1.

2.1 Shoulder Posture

One area particularly susceptible to discomfort and injury due to high forces or awkward postures is the shoulder. Handle design is related to the shoulder because users often abduct their shoulders in an effort to relieve stresses resulting from extreme wrist deviations. In general, shoulder abductions should be kept below 20° to avoid creating large moment arms (Chaffin, Andersson and Martin, 2006).

2.2 Wrist Posture

Another area susceptible to discomfort and injury from awkward postures and high forces is the wrist. Discomfort in the wrist can be kept to a minimum if the hand is kept in neutral position. Hand tools can help promote this posture (Lewis and Narayan, 1993). Tichauer (1966) showed that the use of hand tools in a deviated position over time will cause inflammation and pain due to injury to the synovial sheaths surrounding the tendons of the wrist and to the median nerve passing through the wrist (as referenced by Lewis and Narayan, 1993).

Drury, Begbie, Ulate and Deeb (1985) performed a series of studies looking at wrist deviations during manual materials handling. In the pilot study, subjects were asked to hold a 12 kg rectangular box at their side for 30 s. Nine handle angles were presented to the subject varying between 20° ulnar deviation to 20° radial deviation in 5° increments. The muscle activity of the finger flexor muscles, grip strength, and anatomical measurements were recorded as well as a rating of perceived exertion (RPE) using Borg's scale. Electromyography (EMG) measurements for the finger flexor muscles were significantly higher in the 10°, 15°, and 20° radial deviations and in the 15° and 20° ulnar deviations. Discomfort ratings were significantly higher during 10° and 15° radial deviation. Because the same level of muscle activity was seen beginning at 10° radial deviation and 15° ulnar deviation, the results suggest that when deviations cannot be avoided, ulnar deviations may be less taxing on a user than radial deviations.

In the main study, the number of handle angles was reduced to 5 (between 20° ulnar deviation to 20° radial deviation in 10° increments) and the task duration was reduced to 25 s. The box weights were 9 and 13 kg. Response measures were changed to include heart rate, body part discomfort frequency, and body part discomfort severity. Statistics showed a significant effect of weight on all the response measures and handle angle on all response measures except heart rate. Results indicated that 20° radial deviation was the worst condition. This produced the same effect as increasing the box weight by 16%. Slippage angle, which is used as an indication of the amount of hand to handle contact, increased significantly as wrist deviations increased in both directions. This shows that when wrist deviations become uncomfortable, operators often compensate by loosening their grip, thus increasing the risk of droppage. The researchers concluded that a handle angle from 0° to 10° ulnar deviation would be optimal to decrease stress on the operator.

2.2.1 Effect of Wrist Posture on Grip Strength

Wrist posture can also affect grip strength. In a study by Pryce (1980), participants were asked to give a maximal grip exertion while the wrist was constrained in different positions. Grip strength was measured while the wrist was held in either 0°, 15°, or 30° ulnar deviation and in either 15° volar flexion, 0° volar-dorsiflexion, and 15° dorsiflexion. Statistics showed a significant effect of both ulnar deviation and volar-dorsiflexion. Post-hoc tests did not show a significant difference for 0° ulnar deviation and 15° dorsiflexion; 15° ulnar deviation and 15° dorsiflexion; 15° ulnar deviation and 0° volar-dorsiflexion; and 0° ulnar deviation and 0° volar-dorsiflexion. These means were, however, statistically higher than the other grip conditions. This study showed that as the deviation from neutral wrist position increased, the maximum grip force produced by the hand decreased. The reduction in strength was found to be up to 10%. The researchers postulated that the optimal muscle length of the hand flexors for force production is achieved while in the neutral position and any deviation takes the muscle away from optimal length.

2.2.2 Handle Size

Several studies have been conducted to explore the optimal diameter of the handles. Ayoub and LoPresti (1971) conducted a study looking at optimal cylindrical handle diameter during a simulated work task. Subjects were instructed to reach for a handle using a power grip, pull the handle straight down to a target marked on a horizontal surface, hold for 3 s, return the handle back to the original position, and then release the handle. Muscle activity was recorded on the flexor and extensor muscles of the forearm. A cylindrical dynamometer was used as the handle to allow for the recording of grip force. Handle diameter was varied from 13-76 mm in 13 mm increments. The weight resistance in the handle was 1.1, 2.3, or

3.4 kg. Statistical analysis showed that handle size and weight were highly significant. Based on these results, the 64 mm diameter handle produced the lowest total forearm muscle activity. As would be expected, the higher weights produced more muscle activity. Ayoub and LoPresti used the criterion that the optimum handle diameter would be the one which had the highest ratio between grip force and EMG activity. Though no significant difference was found between the handles, the 38 mm diameter handle produced the highest ratio. This handle also was the slowest in terms of onset of fatigue.

In a similar study by Khalil (1973), different handle sizes as well as shapes were tested in a torque activity. The three cylindrical hands were 32, 51, and 70 mm in diameter. There was also a spherical shaped handle 50.8 mm in diameter and an elliptical handle 50.8 mm long and 31.75 mm wide. During the task, subjects were to apply and hold torques for a specified period of time. The torques were equivalent to .0203, .0407 and .0610 N-mm. Muscle activity was recorded for the deltoid, biceps, triceps, and brachioradialis. Results showed that the 31.75 mm cylindrical handle produced the lowest muscle activity in all levels of torque.

Edgren, Radwin and Irwin (2004) performed a study looking at maximum voluntary grip and handle diameters. The handle diameters being tested were 25.4, 38.1, 50.8, 63.5, and 76.2 mm. While shoulders adducted and neutrally rotated and the elbow flexed at 90° and forearm and wrist in a neutral position, subjects were asked to exert a maximum grip force on the handle for 5 s. Results showed that the 38.1 mm handle allowed for the greatest force generation.

These studies, however, suggest an optimal handle size for all users and do not take into account different hand sizes. Several studies have shown a dependence of hand size in selecting an optimum handle diameter. In a study by Seo, Armstrong and Arbor (2008), they looked at the relationship of grip force, contact area, hand size, and handle size. Participants were instructed to perform a maximum grip exertion with their upper arm in a neutral posture, elbow bent at 90°, and forearm semi-pronated. The cylinder diameters tested were 38, 45, 51, 58, 64, 76, and 83 mm. Results showed a significant decrease in grip strength when the ratio of handle diameter to hand length increased. The contact area was greatest for handles of 51 and 58 mm but decreased for handles larger than these. As expected, the contact area increased with increasing hand size. Based on these findings, Seo et al. suggested that the best handle diameter was one in which the center tips of all the fingers line up along the major axis of the handle and there is full contact between the handle surface and hand. Normal force is decreased when a smaller handle is used possibly because there is less contact area for the hand to work with. Another theory is that when gripping a smaller handle, the fingers muscles are not at their optimal length to produce maximum force. When the diameter increases past the optimal diameter, the fingers are producing less and less force against the palm and instead are working against each other. Using a formula developed from this research, a mean inside grip breadth of 49 mm (from the U.S. Air Force population) would produce an optimum handle diameter of 40 mm in terms of greatest grip strength production.

In another study by Grant, Habes and Steward (1992), the influence of grip diameter on reducing manual effort was examined. Participants were instructed to perform the same pulling task as described in the study by Ayoub and LoPresti (1971). The handle diameters tested were customized for each participant's hand size. One handle was equal to the participant's inside grip diameter. The other two handles were 1 cm smaller and 1 cm larger than the inside grip diameter. Dependent variables included average grip force, peak grip force, and EMG data for the flexor pollicis longus, flexor digitorum superficialis, and extensor digitorum. Data showed a significant effect of handle diameter on grip strength. Grip strength was the largest when the smaller handle was used. Results revealed an average 39% increase in maximum grip strength for every 1 cm decrease in handle diameter. The EMG data showed that as handle diameter increased, muscular effort also increased (as indicated by the increased muscle activity to lift the same absolute weight). The results of this study suggest that a handle that allows for a slight overlap between the thumb and forefinger would be optimal. The researchers postulated that handles that are too small reduce the mechanical advantage of the muscles in the hand to produce force. Those handles may also create stress concentrators on the palm, which would increase the discomfort during use.

Table 2.1 - Literature review summary

Source	Description	Key findings
(Okunribido & Haslegrave, 2003)	Liquid container handle	Overall, a vertical handle was better for musculoskeletal loading and grip than a sloped or curved handle
(Don B. Chaffin et al., 2006)	Shoulder posture	Shoulder abduction performed when trying to reduce extreme wrist deviations
(Drury et al., 1985)	Effect of grip angle on muscle activity in a holding task	A significant muscle activity increase was seen starting at the 10° radial deviation and 15° ulnar deviation. Ulnar deviations may be less taxing on users than radial ones. Users may loosen grip when wrist deviations are high
(Pryce, 1980)	Wrist deviation and grip strength	Decreases of up to 10% are seen in grip strength as wrist deviation increases
(Khalil, 1973)	Effect of handle size on grip in a torquing task	Handle diameter of 32 mm produced the lowest muscle activity

2.3 Research Needs

The literature review revealed a relatively small amount of information with respect to the ergonomics of handles on liquid containers. Often, research has been done on related areas like in MMH or on handle size. However, information yielded from these studies may not always be applicable to all situations. As can be seen with handle size, the "optimal" handle diameter was often task or hand size dependent (Ayoub and LoPresti, 1971; Edgren et al., 2004; Grant, Habes and Steward, 1992; Khalil, 1973; Seo et al., 2008).

While the study by Okunribido and Haselgrave (2003) explored the effect of handle shape and slope on a pouring task, it is only one of the many parameters that can be altered on a handle. Moreover, the study did not look into the effect of handle design on muscle activity and joint postures. These responses can be used as indicators for discomfort and ease of use. Further research is needed on other parameters, such as diameter and height, to see their effect on those responses. Based on the literature review, a larger diameter would reduce muscle activity in the forearm muscles (Ayoub and LoPresti, 1971; Edgren et al., 2004; Khalil, 1973). A handle deviating from a vertical one would increase forearm muscle activity, wrist deviation, grip force, and shoulder abduction (Chaffin et al., 2006; Drury et al., 1985).

3 Methods

3.1 Participants

Twenty subjects (10 males and 10 females) were recruited for testing. Their average age was 34.6 (SD 14.3) years with a range of 18 - 60. Prior to testing, all subjects were screened to make sure they had no previous history of upper extremity or back injury. All subjects had normal or corrected vision. Handedness was noted and equipment preparations were made accordingly.

3.2 Task

The participants were instructed to pick up a container, pour a specified amount of liquid into a cup (approximately 8 ounces), and set the container back down. Participants used their dominant hand and set their own pace for the task. Foot position was marked at the beginning of the experiment and they were told to go back to this position before every trial. They were also told not to move their feet during the trials and to avoid making contact with the cup and the spout of the container. The container was placed in front of the participant on the dominant hand side while the cup was placed on the non-dominant hand side (Figure 3.1). The cup and container were set a shoulder width apart for each subject and the height of the table was adjusted to approximately 1 to 2 inches below elbow height (Konz, 1967). The non-dominant hand stayed at the participant's side. Each condition was tested three times, consecutively, thus there were three trials per condition.

Figure 3.1 - Experimental setup

3.3 Testing Apparatus

A modular liquid container with changeable handles was fabricated for the experiment (Figure 3.2). The handles contained an instrumented core with strain gauges, allowing it to measure grip forces and moments (Figure 3.3). Though the instrumented core was not wireless, enough space and slack was given to prevent any constraints in hand motion.

Figure 3.2 - Modular liquid container

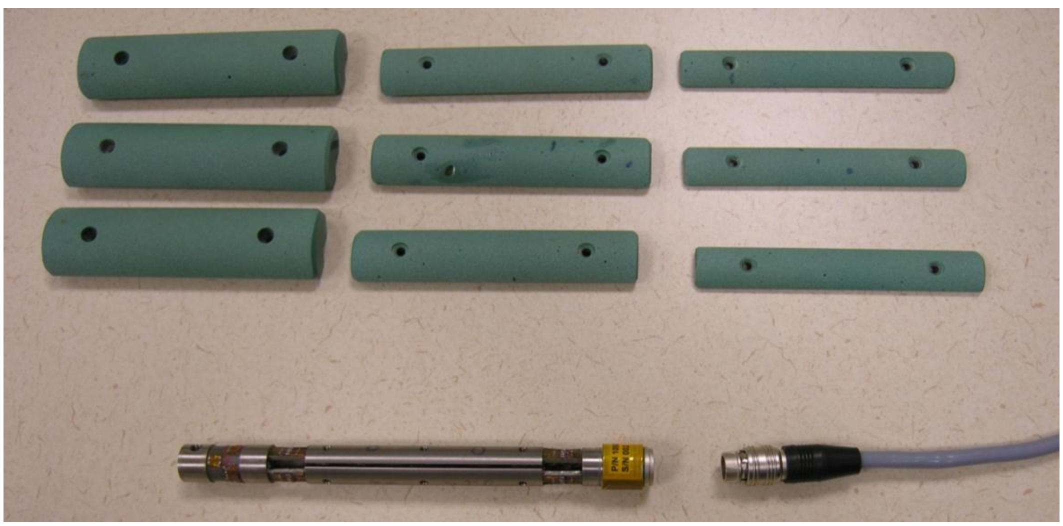

Figure 3.3 - Changeable handles and instrumented core

Muscle activity was measured using the wireless TeleMyo2400 (Noraxon, Scottsdale, AZ), a telemetric EMG system. This system had a 1st order 10Hz high-pass filter, and an 8th order Butterworth low-pass filter set to 500Hz. This data were sampled at 1000Hz. The system consisted of a data acquisition unit, a Bayonet Neill-Concelman (BNC) breakout box, receiver, transmitter belt unit (with 8 channels), electrode leads, and electrodes. Disposable Noraxon Dual Electrodes (Ag/AgCl, 1 cm conductive area, 2 cm inter-electrode distance) were attached to the distal ends of the leads, which were connected to the wireless transmitter belt unit worn by the participant. The signal from the transmitter was transmitted to the receiver. The receiver was also used to adjust the gain on the signal to avoid clipping of the data beyond 5 v. The receiver and instrumented handle were plugged into the BNC box to convert the signal from analog to digital. The BNC box was then connected to the data acquisition unit.

An active marker infrared motion tracking system called Optotrak Certus (NDI, Waterloo, Ontario, Canada) was used to measure kinematic data. This data were sampled at 100Hz. The system consisted of individual markers, marker clusters, a wireless strobe, cameras, and a four marker digitizing probe. The cameras tracked the position of the markers in space. The wireless strobe controlled the frequency and sequence of illumination of the markers, which allowed the software to differentiate among markers. The wireless strobe was attached to the belt unit. The digitizing probe was used to create virtual markers based on the location of the clusters. The digitizing probe was attached directly to the cameras. All data was collected and synched using the NDI First Principles software.

3.4 Experimental Design

3.4.1 Independent Variables

The independent variables included handle height, slope and diameter (see Table 3.1 for structure of experiment data collection table). Handle height was defined as high or low; slope was defined as sloped or vertical; diameter was defined as 18, 24, or 32 mm. The 18 and 24 mm diameters represented handles found in bottles currently on the market. The smallest bottle handle was 18 mm. The most common diameter of bottle handles was 24 mm. Based on research by Khalil (1973), a 32 mm diameter required the least effort when resisting several levels of torque in a static loading task. For the high handle position, the top of the handle lined up with the top of the container. The midpoint of the handle lined up with the midpoint (of the height) of the container in the low position. The sloped handle was attached 20° relative to vertical. The vertical handle was attached 0° relative to vertical.

Table 3.1 - Experiment data collection table

Attachment		Diameter (mm)		
Height	Slope	18	24	32
High	Sloped	xxxxx	xxxxx	xxxxx
	Vertical	xxxxx	xxxxx	xxxxx
Low	Sloped	xxxxx	xxxxx	xxxxx
	Vertical	xxxxx	xxxxx	xxxxx

3.4.2 Dependent Variables

The dependent variables were mean normalized muscle activity, peak joint postures, and average grip force. The muscles of interest included the anterior deltoid (AD), middle deltoid (MD), posterior deltoid (PD), trapezius (TR), infraspinatus (IF) biceps brachii (BB), extensor carpi radialis (ECR), and flexor carpi radialis (FCR). The EMG data collected during the trials were normalized by a reference contraction, specifically using a three pound weight. The contractions performed isolated the individual muscle. Research has shown a significant effect of handle design on the amount of shoulder abduction (SA), shoulder flexion (SF), and wrist ulnar deviation (WUD) (Okunribido & Haslegrave, 2003). Peak joint postures were calculated based on joint positions relative to the low-back marker in space.

3.5 Experimental Procedure

3.5.1 Informed Consent Process

All subjects gave informed consent prior to participating in the study. The informed consent explained the experimental procedures and any risks involved with participating in the study. The study protocol was approved by the North Carolina State University and Liberty Mutual Research Institute for Safety Institutional Review Boards.

3.5.2 Facility

All testing was done at the Liberty Mutual Research Institute for Safety, located at 71 Frankland Road, Hopkinton, MA 01748.

3.5.3 Experimental Testing

3.5.3.1 Equipment Preparation

At the start of the session, subjects were given background information about the purpose of the study and were quickly introduced to the task. Areas of electrode application were rubbed with abrasive alcohol pads and then marked, indicating the location of placement of the electrodes for EMG analysis as well as the location of digitization points for motion tracking. All electrodes were placed over the muscle belly parallel to the muscle fiber orientation. The electrode for the AD was located approximately three finger widths anterior to the acromion. The MD electrode was located below the acromion along the lateral edge of the arm, approximately a quarter of the distance between the acromion and elbow. The PD electrode was located approximately two finger widths posterior to the acromion. The TR electrode was placed approximately halfway between the acromion and the C7 vertebra. The electrode for the IF was located approximately two finger breadths below the spine of the scapula. The BB electrode was placed on the greatest bulge of the muscle, approximately midway between the elbow and shoulder joint. The ECR electrode was placed along a line running between the middle of the wrist and the lateral end of the elbow crease, approximately 1/3 that distance distal to the elbow. The FCR electrode was located approximately halfway between the biceps tendon and the pisiform bone (see Figures 3.4, 3.5 and 3.6 for pictures of electrode locations) (Basmajian & Blumenstein, 1980; Perotto, 1994).

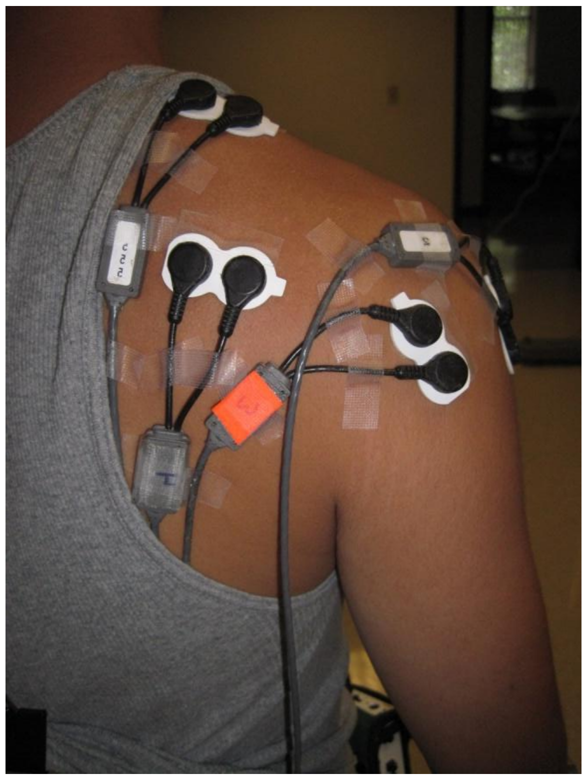

Figure 3.4 - Electrode placement of the TR, IF, and PD

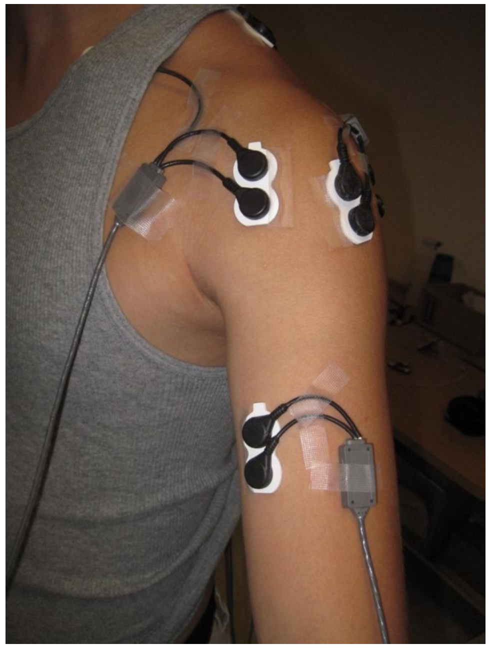

Figure 3.5 - Electrode placement of the AD, MD, and BB

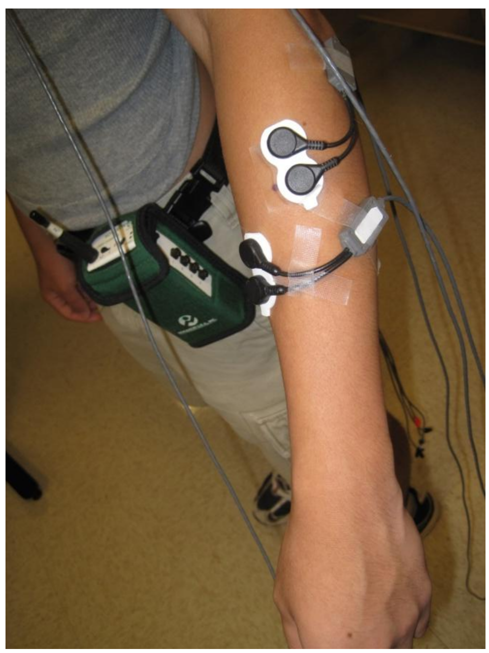

Figure 3.6 - Electrode placement of the ECR and FCR

After electrode placement, small contractions were performed with the muscles of interest to confirm proper placement. The participants were then led through a series of reference voluntary contractions (RVC). These contractions were chosen to isolate muscles and reduce postural contribution. Activity was recorded and used as reference by which all muscle activity from experimental trials was normalized. The contractions were held for 3 s each. All contractions except for the IF were done holding a 3 lb weight. For the AD, the participant flexed the shoulder at 90° with the arm straight out with the hand in the neutral position. For the MD, the participant abducted the arm at 90° with the hand in pronation. For the PD, the participant extended the shoulder while keeping the elbow flexed at 90° and the hand in a neutral position. For the TR, the participants performed a shoulder shrug with the arms at the sides. For the IF, the participants held the elbow flexed at 90° with the upper arm fully vertical. A loop attached to a strain gauge was placed around the participants' wrist. The researcher then pulled the loop, attempting to rotate the arm medially across the transverse plane while the participants resisted until 3 lbs was reached. For the BB, the participants held the elbow flexed at 90° with the hands supinated. For the ECR, the participants rested the lower arm on a table with the hand hanging off the edge. The participants then extended the wrist with a slight twist in the radial direction. For the FCR, the participants rested the lower arm on the table with the hand hanging off the edge. With the hand supinated, the participants flexed the wrist with radial deviation (Perotto, 1994).

The motion tracking points were located at the approximate center of rotation for the shoulder (rotation along the frontal plane) on both the anterior and posterior side; on the medial and lateral epicondyles; and on the radial and ulnar styloids. A tracking point was also identified on the spout of the container. These points were later used for the motion tracking analysis.

The points on the body were used to calculate the joint centers. Infrared markers were placed on the lower back (on the spine at the height of the iliac crest), C7 vertebra, upper arm, lower arm and container (Figure 3.7). Markers on the lower back, upper arm, lower arm, and container were rigid body smart markers. The C7 vertebra used individual smart markers. Rigid body smart markers were used as the reference point for the tracking points. They work on the assumption that there is no relative motion between the tracking points and their reference markers. Because their relative distance does not change, the exact location of the tracking points can be calculated. These types of tracking points are useful in situations where there may be restrictions on smart marker placement due to camera placement or activity being performed.

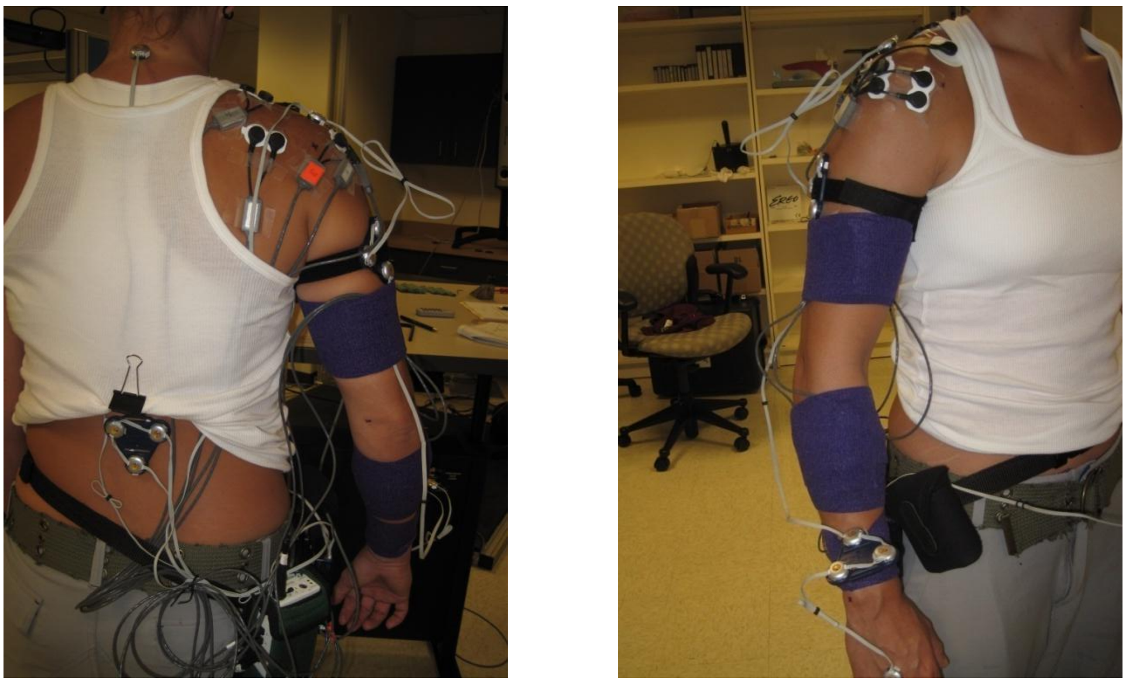

Figure 3.7 - Final placement of electrodes and markers

3.5.3.2 Experimental Trials

After all markers were tested, participants performed several practice pours. Once the practice was finished, experiment trials began. The task was performed three consecutive times per handle configuration. The presentation of the different conditions was randomized. Breaks were given between trials to prevent fatigue. Between trials, the cup was emptied back into the container and the cup and container positions were returned to their original starting positions.

3.6 Hypothesis

Based on previous research (Ayoub and LoPresti, 1971; Edgren et al., 2004; Khalil, 1973), as handle diameter increases, muscle activity in the ECR and FCR should decrease. Specifically, the 32 mm handle was expected to produce the lowest response compared to the 18 and 24 mm handles. Based on a static analysis of the container and hand/wrist system, the high handle was expected to lower ECR and FCR muscle activity compared to the low handle due to the change in location of the center of mass of the container and its implications on torque production on the wrist. Compared to the sloped handle, the vertical handle will reduce the muscle activity in the ECR and FCR and will also reduce the amount of WUD (Drury et al., 1985; Lewis and Narayan, 1993) Because it was expected the sloped handle would cause extreme wrist deviations, the vertical handle would also indirectly reduce the amount of SA (Chaffin et al., 2006).

With respect to interactions, there was no literary basis for forming hypotheses. It was expected that the interactions would yield the same results as the main effects.

3.7 Data Processing

Data were processed using MATLAB code created specifically for this experiment. EMG data were rectified by taking the root mean square (RMS) with a 5 ms averaging constant. The data were then smoothed using a 2nd order Butterworth low-pass filter ($\frac{f_{sample}}{f_{cut-off}} = 4$) and then normalized. The following equation was used for the normalization:

$$Normalized\ EMG = \frac{EMG_{task} - EMG_{rest}}{EMG_{RVC} - EMG_{rest}}$$

Motion tracking data were also smoothed using a 2nd order Butterworth low-pass filter ($\frac{f_{sample}}{f_{cut-off}} = 4$). Peak joint postures were calculated from the motion of the joints over time. Grip data was smoothed using a 2nd order Butterworth low-pass filter ($\frac{f_{sample}}{f_{cut-off}} = 4$). Grip force was calculated by averaging the output of the six strain gauges.

With respect to the recording and analysis of response measures, the task was divided into three main phases to denote distinct actions and movements. The first phase, known as the lifting phase (P1), was defined as the time from when the handle was first grasped to right before the container was about to be tilted to initiate the pour. The second phase was called the pouring phase (P2). This was defined as the time when the container was tilted to start the flow of liquid to the time when the container was turned upright to stop the pour. The third phase, known as the lowering phase, began after the flow of liquid stopped and ended when the container handle was released. Due to the unique characteristics of each phase, response measures were recorded on a per phase basis. The third phase was not studied due to its symmetry with the first. In pilot studies, Okunribido and Haslegrave (2003) also found performance in this phase to be highly variable. They postulated that the lowering phase was highly influenced by events of the pouring phase. If pouring caused discomfort for the user, a hasty and uncontrolled replacement might have occurred.

3.8 Statistical Analysis

A repeated measures multivariate analysis of variance (MANOVA) was used to identify any significant effects of the independent variables on the normalized muscle activity and peak postures. A repeated measures analysis of variance (ANOVA) was used to identify significant effects on average grip force. In both cases, trial was used as the repeated measure. Assumptions of the ANOVA procedure were evaluated using graphical methods. A p-value of <0.05 was considered statistically significant.

3.8.1 Testing Assumptions of ANOVA

The normality assumption was assessed using the quantile plot of the residuals. Substantial deviations of the residuals from a linear trend were considered to be a violation of the normality assumption. The constant variance assumption was tested by plotting the residuals against the predicted values. Any systematic patterns, including an increasing or decreasing range of residuals across the range of model predictions, were considered to be violations of the constant variance assumption. The independence of observations assumption was tested by plotting the model residuals versus time or replication number. Related to this, randomization procedures were also used to counter any effect of fatigue.

3.8.2 Data Analysis

The response measures from both phases were analyzed using a similar method. First, ANOVAs were applied to the main effects and interactions of interest for each response variable, as a basis for diagnostics on the data sets. Then, the MANOVA was applied to determine significant main effects and interactions for the muscle activity and for the peak joint postures. Finally, an ANOVA was performed to determine significant effects for the average grip force.

The ANOVA was used to identify any potential outliers in the responses. Visual inspection of the model residuals versus predicted value plots for each main effect was conducted to identify points deviating from the mean response by ±2 standard deviations. Outliers in the data were attributed to subject errors, recording errors, involuntary reflex activity, movement artifacts, cross-talk among EMG electrodes from adjacent muscle activity, electrode malfunction, camera error, and motion tracking marker error. Any outliers were removed from the dataset and replaced with a mean value. A summary of the outliers is included in Appendix G.

Next, the MANOVA was applied to the muscle and posture response measures. Separate MANOVAs were run for each phase of the task and for each type of response measure (muscle activity and joint posture). MANOVAs were run on these responses because of the lack of independence between the activity of the different muscles and between the peak joint postures of the shoulder. A separate ANOVA was applied to each phase of the task for the average grip force. Significant multi-level effects were analyzed using Tukey's Honestly Significant Difference (HSD) tests.

The preliminary ANOVA used for outlier identification can be represented by the following equation:

$$Y_{ijkl} = Sub_i + D_j + H_k + S_l + (D*H)_{jk} + (D*S)_{jl} + (H*S)_{kl} + (D*H*S)_{jkl} + \varepsilon_{ijkl}$$

(i=1-20, j=1-3, k=1-2, l=1-2)

Where:

Y = response measure

Sub= subject

D = diameter

H = height

S = slope

ε = model error

The model used for the MANOVA can be represented by the equation below:

$$Y_{ijklm} = Sub_i + D_j + H_k + S_l + (D*H)_{jk} + (D*S)_{jl} + (H*S)_{kl} + (D*H*S)_{jkl} + T_m + (Sub*T)_{im} + (Sub*D)_{ij} + (D*T)_{jm} + (Sub*D*T)_{ijm} + (Sub*H)_{ik} + (H*T)_{km} + (Sub*H*T)_{ikm} + (Sub*S)_{ij} + (S*T)_{jm} + (Sub*S*T)_{ijm} + \varepsilon_{ijklm}$$

(i=1-20, j=1-3, k=1-2, l=1-2, m=1-3)

Where:

Y = response measure

Sub= subject

D = diameter

H = height

S = slope

T = trial

ε = model error

Note: Interactions with subject or trial were included in order to achieve finer decomposition of variance in response measures as compared to lumping variance components into the error.

The model used for the ANOVA to analyze significant effects on average grip force can be represented by:

$$Y_{ijklm} = Sub_i + D_j + H_k + S_l + (D*H)_{jk} + (D*S)_{jl} + (H*S)_{kl} + (D*H*S)_{jkl} + T_m + (Sub*T)_{im} + (Sub*D)_{ij} + (D*T)_{jm} + (Sub*D*T)_{ijm} + (Sub*H)_{ik} + (H*T)_{km} + (Sub*H*T)_{ikm} + (Sub*S)_{ij} + (S*T)_{jm} + (Sub*S*T)_{ijm} + \varepsilon_{ijklm}$$

$$(i=1\text{-}20,\ j=1\text{-}3,\ k=1\text{-}2,\ l=1\text{-}2,\ m=1\text{-}3)$$

Where:

Y = response measure

Sub= subject

D = diameter

H = height

S = slope

T = trial

ε = model error

Note: Interactions with subject or trial were included in order to achieve finer decomposition of variance in response measures as compared to lumping variance components into the error.

4 Results

4.1 Lifting Phase of Task

4.1.1 Muscle Activity

For the AD response, it was found that there was an under-prediction of the model at low values. Hence, a square root transformation was applied to correct this violation of ANOVA assumptions. The transformed data conformed to the normality and constant variance assumptions. Results indicated that height ($F(1,413)=60.87$, $p=0.0002$, $\omega^2=0.0233$) and slope ($F(1,413)=8.59$, $p=0.0475$, $\omega^2=0.0085$) had significant effects on the activity of the AD. The two-way interactions of diameter and slope ($F(2,413)=5.15$, $p=0.0063$, $\omega^2=0.0014$) and height and slope ($F(1,413)=4.30$, $p=0.0387$, $\omega^2=0.0006$) were also significant (see full results in Table 4.1). Subjects had lower muscle activity in the low handle condition (Figure 4.1) and in the vertical handle condition (Figure 4.2). Subjects had the lowest muscle activity under the 18 mm diameter and vertical handle condition (Figure 4.3). Subjects also had the lowest muscle activity under the low and vertical handle condition (Figure 4.4).

Table 4.1 – Lifting Phase AD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	51.93	19	413	<.0001
Diameter (D)	0.43	2	413	0.6613
Height (H)	60.87	1	413	0.0002
Slope (S)	8.59	1	413	0.0475
D*H	0.16	2	413	0.8512
D*S	5.14	2	413	0.0063
H*S	4.30	1	413	0.0387
D*H*S	0.88	2	413	0.4137

Note: Darkened areas denote a p-value <0.05

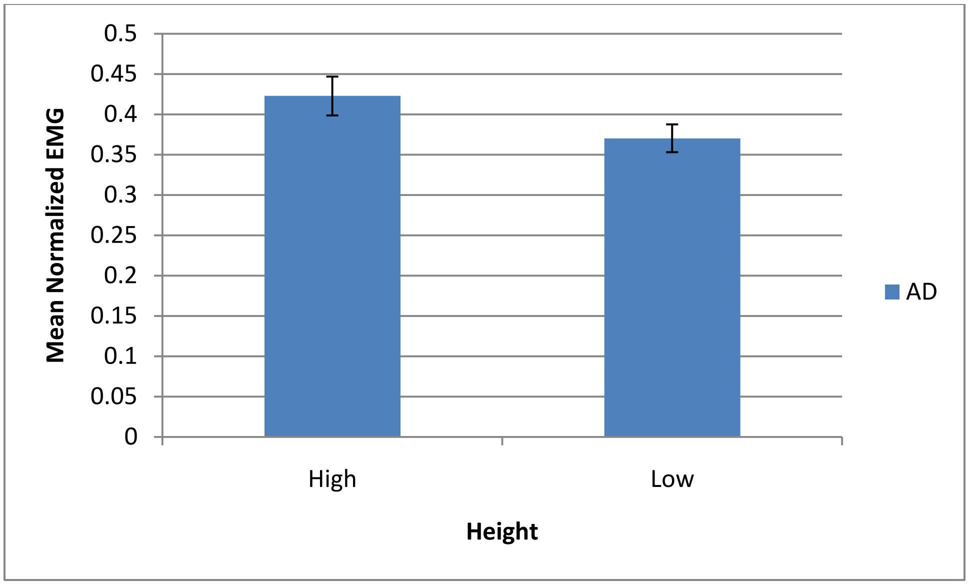

Figure 4.1 - Mean EMG of AD for Height

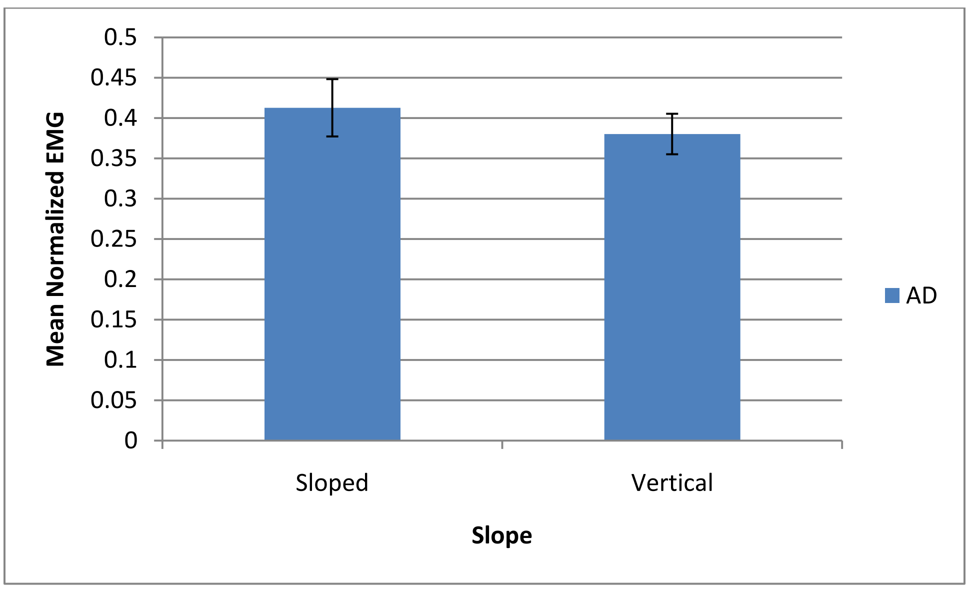

Figure 4.2 - Mean EMG of AD for Slope

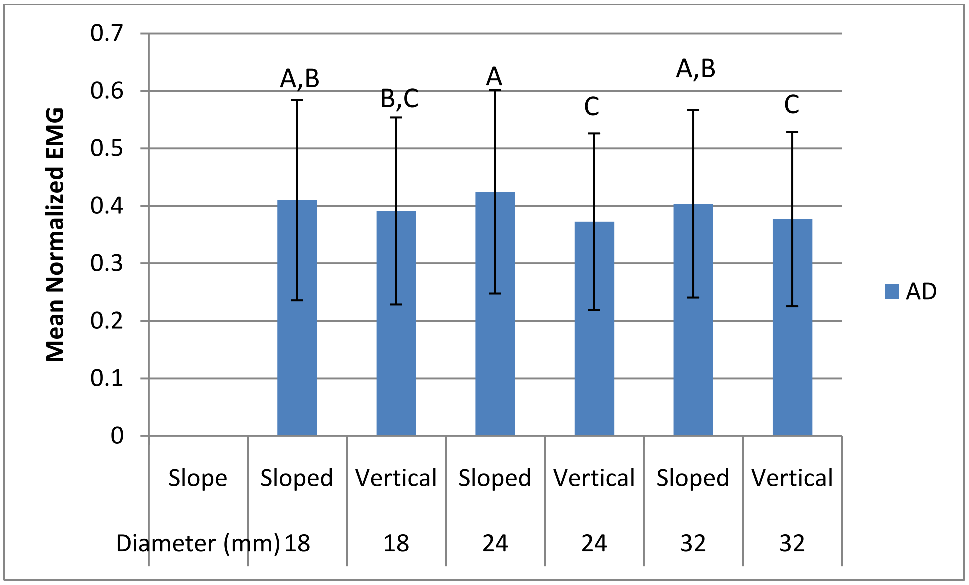

Figure 4.3 - Mean EMG of AD for Diameter x Slope
(Note: The plot presents the trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values)

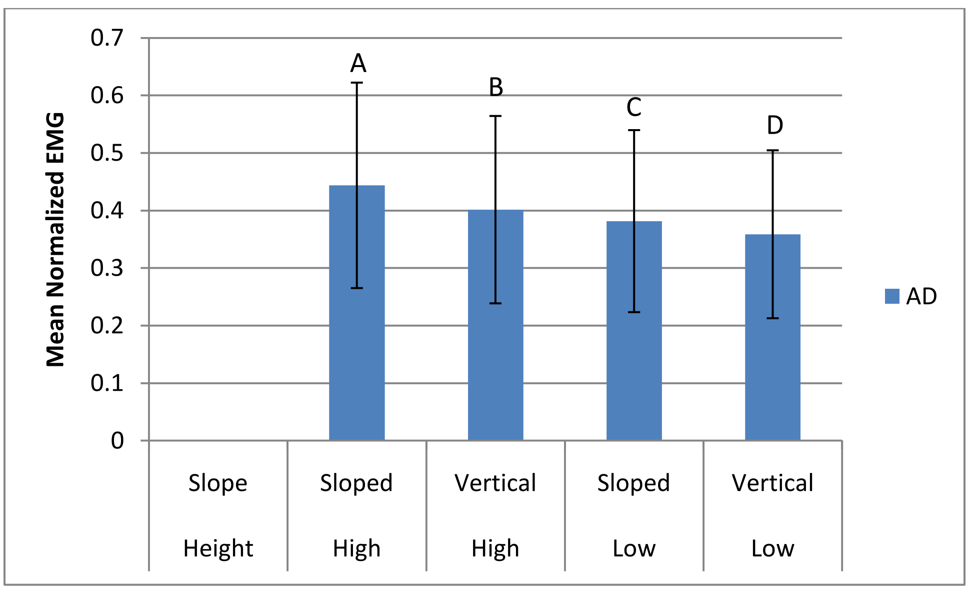

Figure 4.4 - Mean EMG of AD for Height x Slope

A square root transformation was applied to the MD response to correct ANOVA assumptions violations. This was chosen due to an over-prediction of the model at high values. Results showed that height ($F(1,412)=24.43$, $p=0.0009$, $\omega^2=0.0180$) and slope

(F(1,413)=64.70, p=<.0001, ω^2=0.0388) had significant effects on the response of the MD. The two-way interaction of height and slope was also significant (F(1,413)=15.75, p=<.0001, ω^2=0.0024) (see full results in Table 4.2). Subjects had lower muscle activity with the low (Figure 4.5) and vertical (Figure 4.6) handle conditions. For the interaction, there was lower muscle under the low and vertical handle conditions (Figure 4.7).

Table 4.2 - Lifting Phase MD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	28.18	19	413	<.0001
Diameter (D)	1.74	2	413	0.2149
Height (H)	24.43	1	413	0.0009
Slope (S)	64.70	1	413	<.0001
D*H	0.45	2	413	0.6368
D*S	1.45	2	413	0.2358
H*S	15.75	1	413	<.0001
D*H*S	1.67	2	413	0.1895

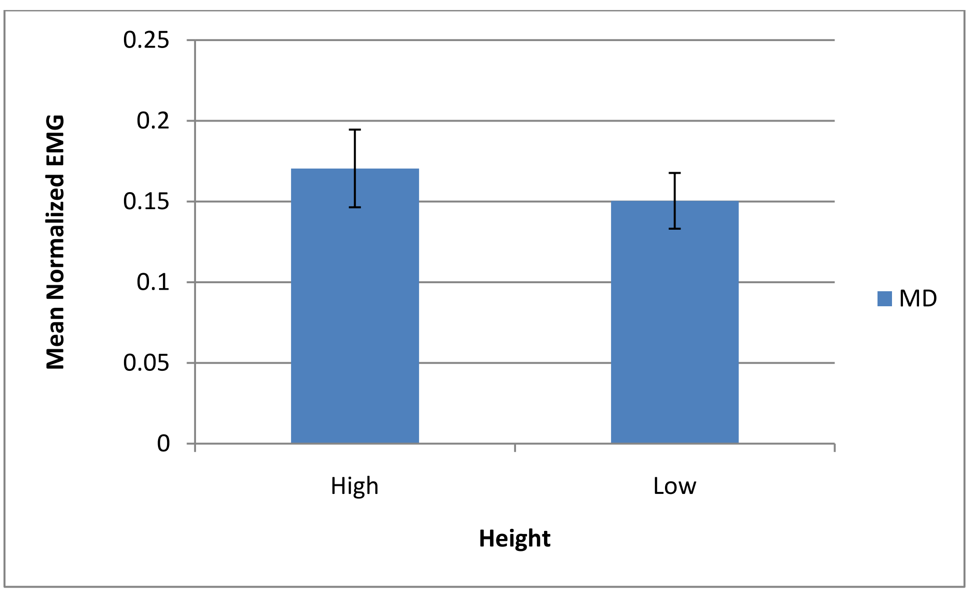

Figure 4.5 - Mean EMG of MD for Height

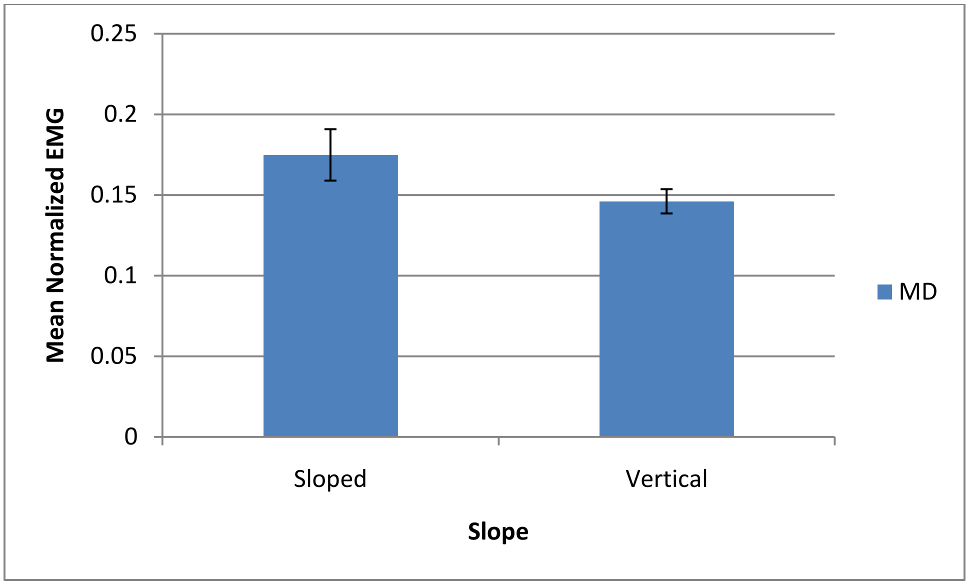

Figure 4.6 - Mean EMG of MD for Slope

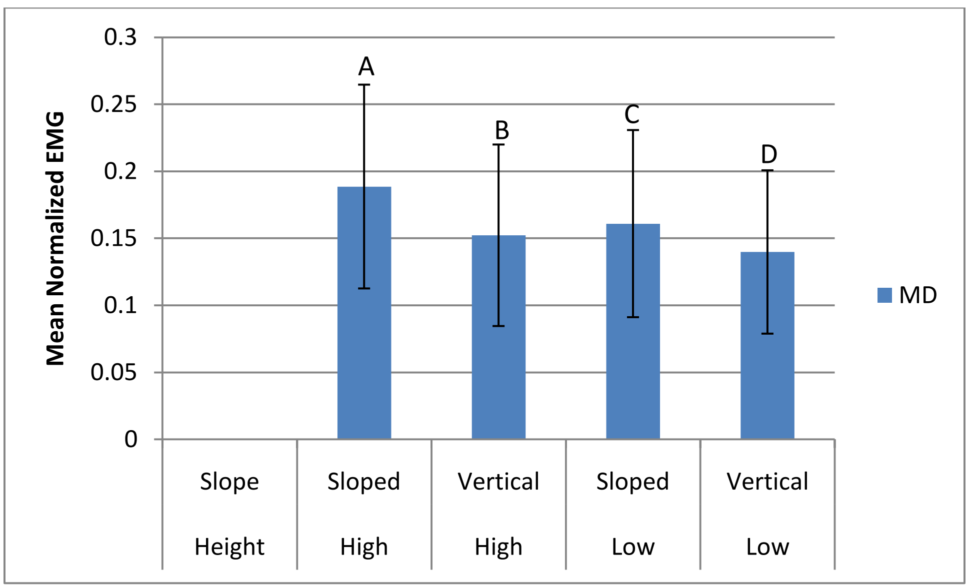

Figure 4.7 - Mean EMG of MD for Height x Slope

For the PD response, it was found that there was an over-prediction of the model at high values. Consequently, a square root transformation was applied. The transformed data conformed to the assumptions of ANOVA. Results showed that the effects of height ($F(1,413)=24.20$, $p=0.0008$, $\omega^2=0.0155$) and slope ($F(1,413)=31.84$, $p=<.0001$, $\omega^2=0.0360$)

as well the interaction effect of height and slope ($F(1,413)=16.66$, $p=<.0001$, $\omega^2=0.0023$) were all significant (see full results in Table 4.3). The PD showed lower muscle activity with the low (Figure 4.8) and vertical (Figure 4.9) handles. The interaction showed that the low and vertical handle produced the lowest muscle activity (Figure 4.10).

Table 4.3 - Lifting Phase PD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	28.18	19	413	<.0001
Diameter (D)	1.84	2	413	0.1957
Height (H)	24.20	1	413	0.0008
Slope (S)	31.84	1	413	<.0001
D*H	0.52	2	413	0.5974
D*S	1.28	2	413	0.2779
H*S	16.66	1	413	<.0001
D*H*S	1.67	2	413	0.1895

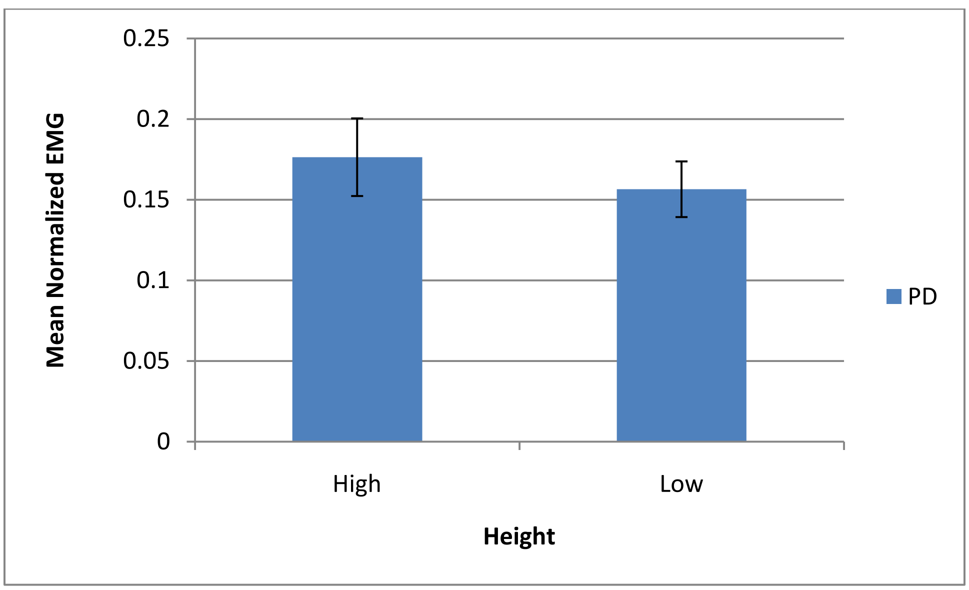

Figure 4.8 - Mean EMG of PD for Height

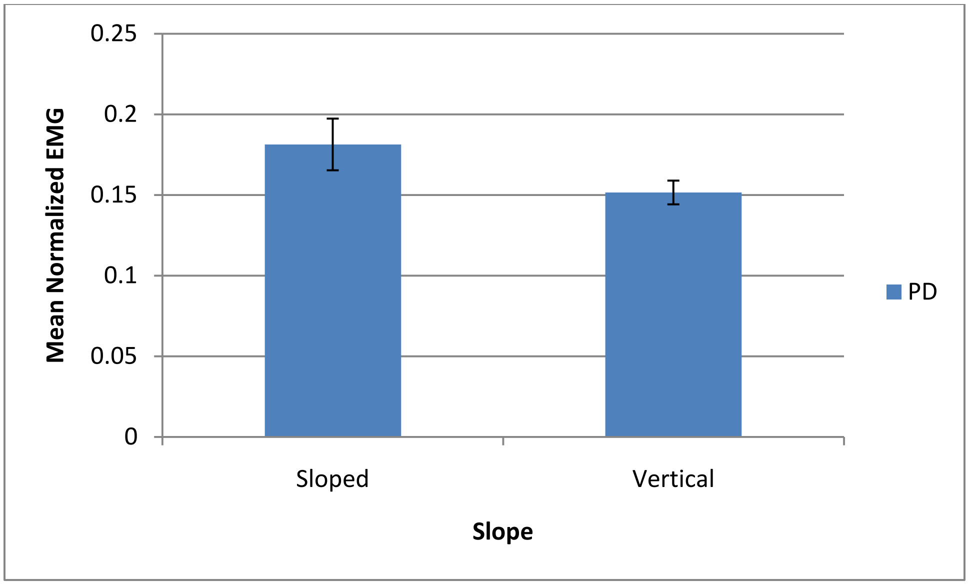

Figure 4.9 - Mean EMG of PD for Slope

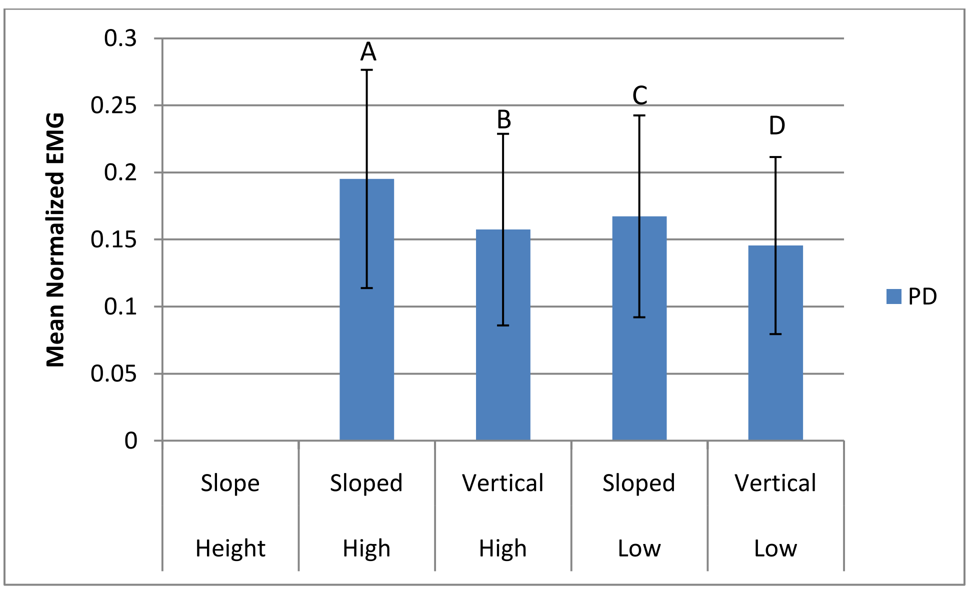

Figure 4.10 - Mean EMG of PD for Height x Slope

A log transformation was applied to the TR response because there was an increasing range of residuals across the range of model predictions. Results indicated a significant effect of height ($F(1,413)=350.17$, $p=0.0003$, $\omega^2=0.0387$) and slope ($F(1,413)=121.57$, $p=0.0027$,

ω^2=0.0487) on the response variable (see full results in Table 4.4). The TR muscle activity was the lowest with the low (Figure 4.11) and vertical (Figure 4.12) handle configurations.

Table 4.4 - Lifting Phase TR MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	82.24	19	413	<.0001
Diameter (D)	1.38	2	413	0.2804
Height (H)	350.71	1	413	0.0003
Slope (S)	121.57	1	413	0.0027
D*H	0.10	2	413	0.9021
D*S	1.36	2	413	0.2571
H*S	0.98	1	413	0.3233
D*H*S	1.68	2	413	0.1872

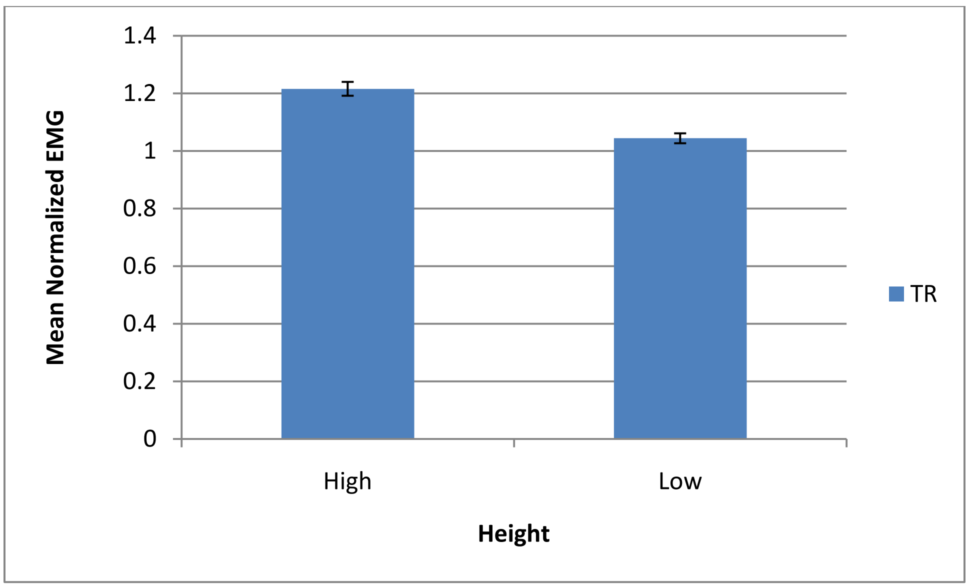

Figure 4.11 - Mean EMG of TR for Height

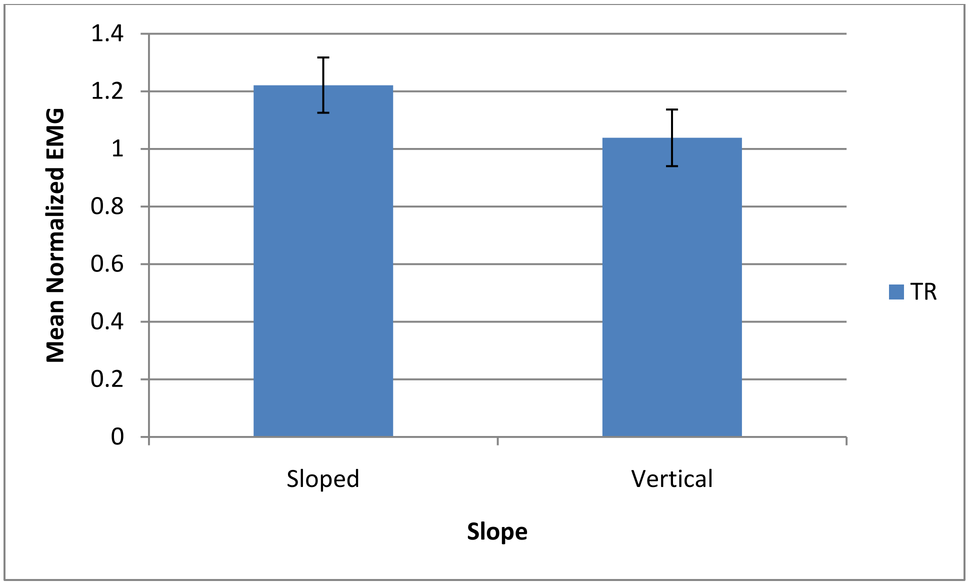

Figure 4.12 - Mean EMG of TR for Slope

A Box-Cox transformation was used on the IF response because there was an increasing range of residuals across the range of model predictions. There was a significant effect of height ($F(1,413)=80.54$, $p=0.0029$, $\omega^2=0.0041$) and slope ($F(1,413)=32.49$, $p=0.0006$, $\omega^2=0.0056$) on this response (see full results in Table 4.5). Results showed that the lowest muscle activity was found under the low (Figure 4.13) and vertical (Figure 4.14) handle conditions.

Table 4.5 - Lifting Phase IF MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	168.96	19	413	<.0001
Diameter (D)	0.51	2	413	0.6250
Height (H)	80.54	1	413	0.0029
Slope (S)	32.49	1	413	0.0006
D*H	1.58	2	413	0.2070
D*S	0.98	2	413	0.3750
H*S	0.06	1	413	0.8133
D*H*S	0.01	2	413	0.9945

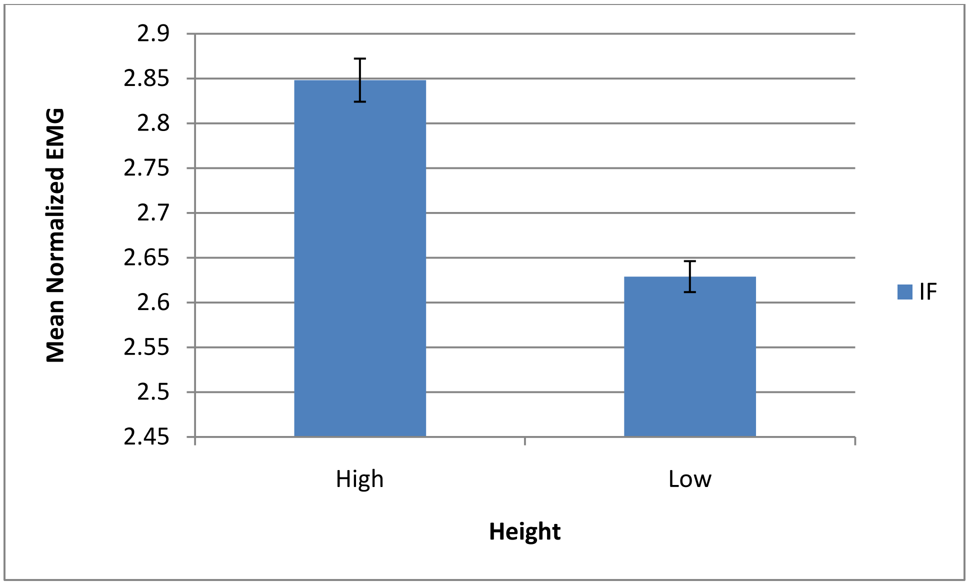

Figure 4.13 - Mean EMG of IF for Height

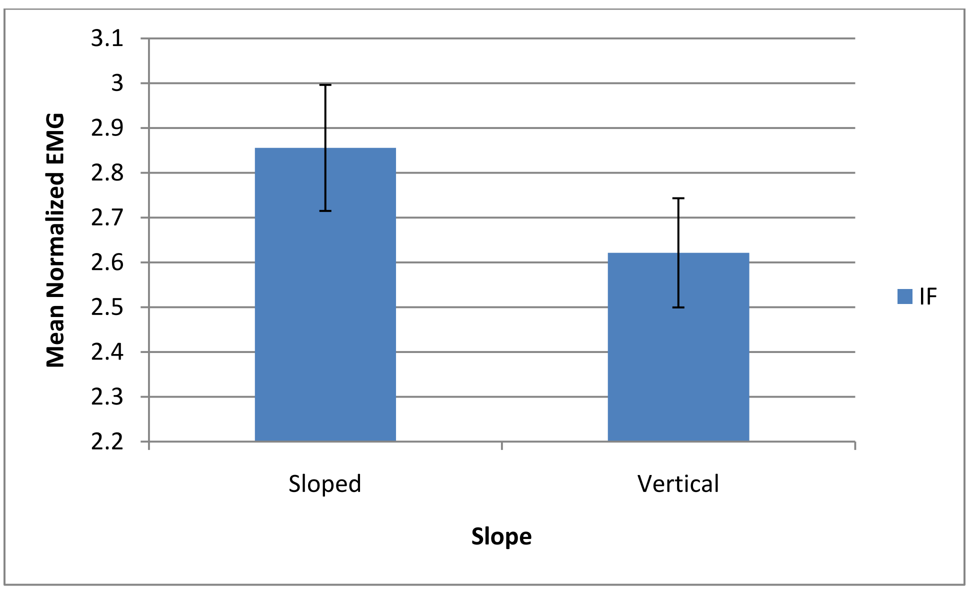

Figure 4.14 - Mean EMG of IF for Slope

A logarithmic transformation was applied to the BB response to correct for the increasing range of residuals across the range of model predictions. The transformed data conformed to the assumptions. Results showed a significant effect of diameter ($F(2,413)=14.87$, $p=0.0001$, $\omega^2=0.0068$), height ($F(1,413)=51.18$, $p=<.0001$, $\omega^2=0.0191$), and slope (F(1,413)=29.74, p=<.0001, ω^2=0.0188). The two-way interactions of diameter and slope (F(2,413)=9.31, p=0.0001, ω^2=0.0014) and height and slope (F(1,413)=4.46, p=0.0354, ω^2=0.0003) were also significant (see full results in Table 4.6). The BB response revealed lower muscle activity under the 18 mm diameter (Figure 4.15), high (Figure 4.16) and sloped (Figure 4.17) handle configurations. For the diameter and slope interaction, the 18 mm diameter and sloped handle yielded the lowest muscle activity (Figure 4.18). For the height and slope interaction, the high and sloped handle produced the lowest muscle activity (Figure 4.19).

Table 4.6 - Lifting Phase BB MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	40.60	19	413	<.0001
Diameter (D)	14.87	2	413	0.0001
Height (H)	51.18	1	413	<.0001
Slope (S)	29.74	1	413	<.0001
D*H	0.88	2	413	0.4165
D*S	9.31	2	413	0.0001
H*S	4.46	1	413	0.0354
D*H*S	0.95	2	413	0.3864

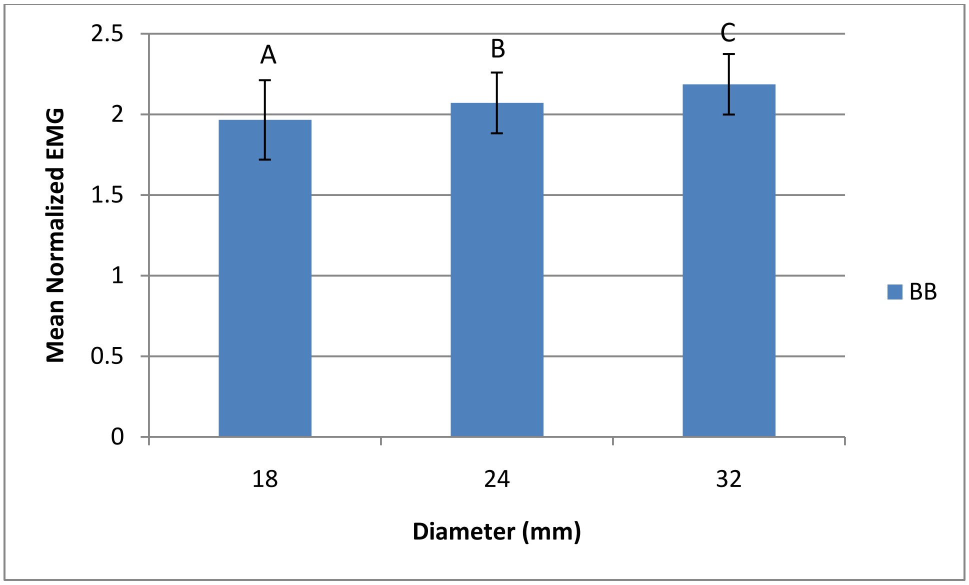

Figure 4.15 - Mean EMG of BB for Diameter

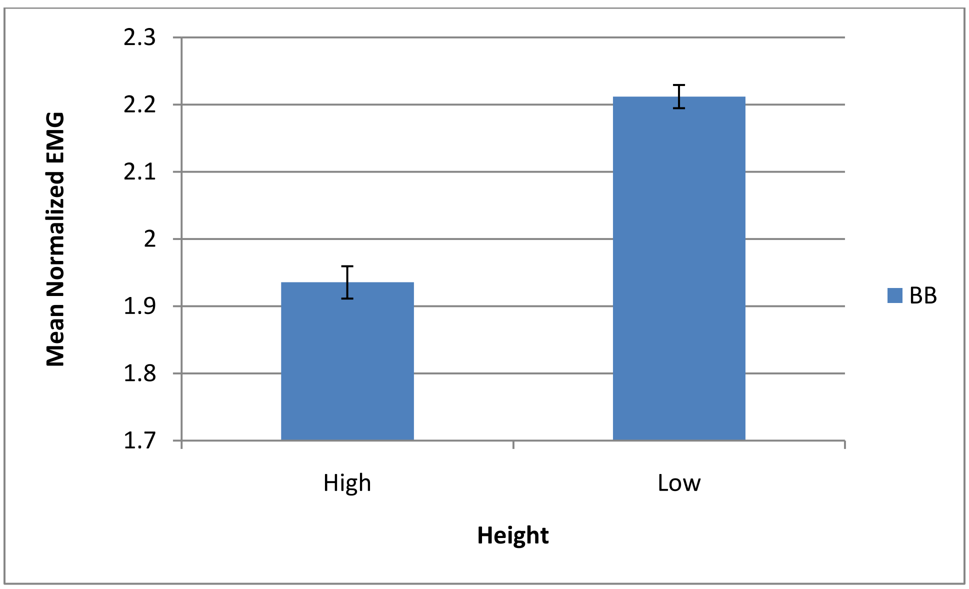

Figure 4.16 - Mean EMG of BB for Height

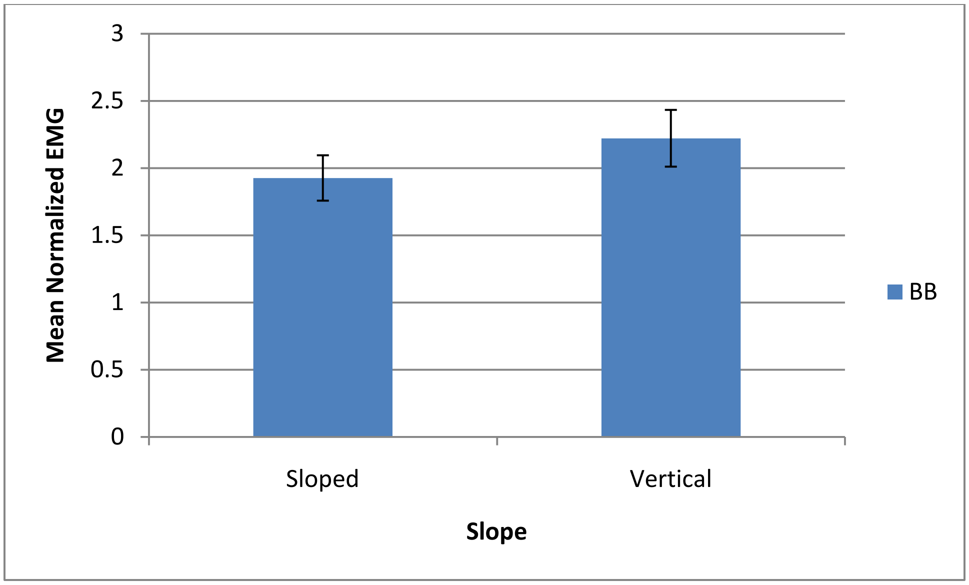

Figure 4.17 - Mean EMG of BB for Slope

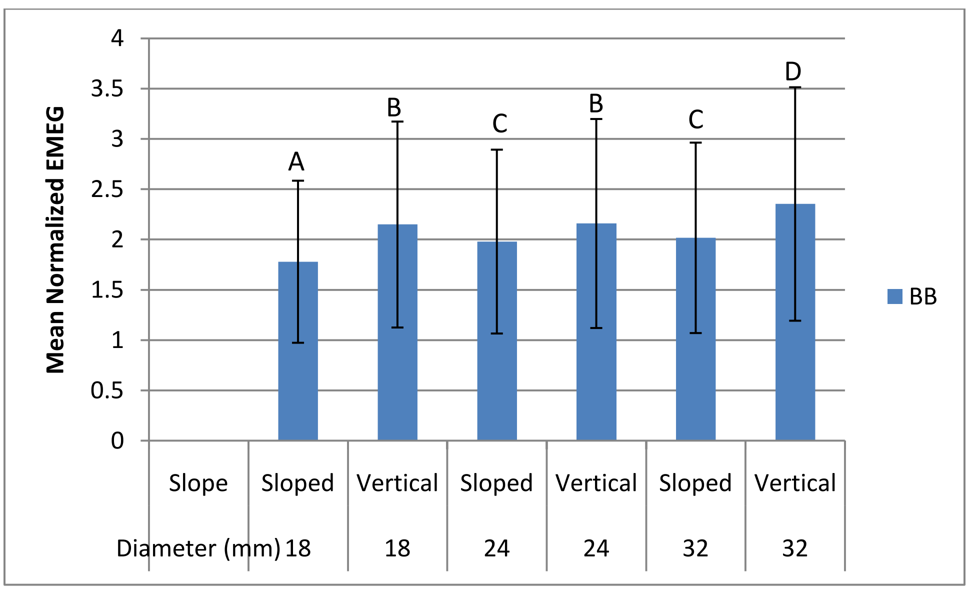

Figure 4.18 - Mean EMG of BB for Diameter x Slope

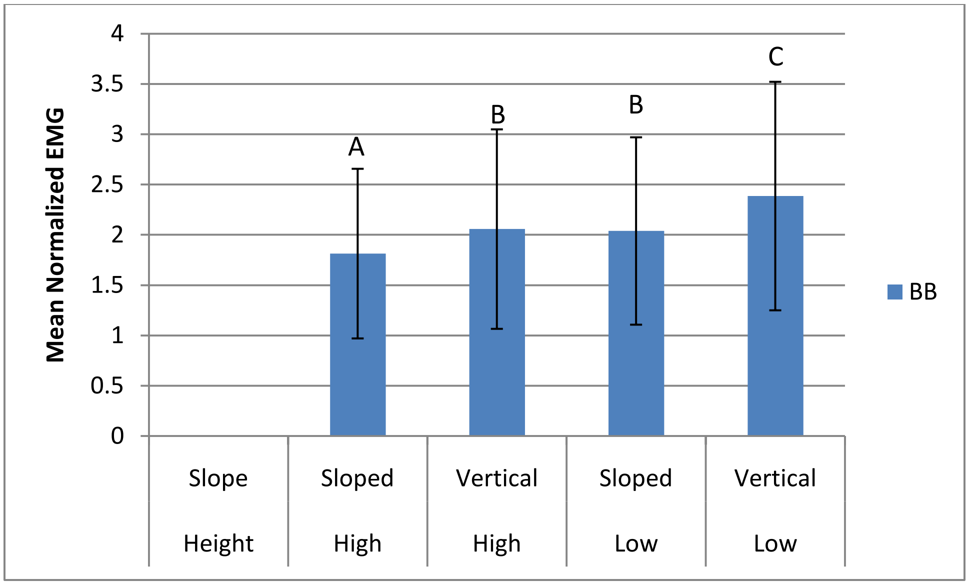

Figure 4.19 - Mean EMG of BB for Height x Slope

A logarithmic transformation was applied to the ECR response to correct for the increasing range of residuals across the range of model predictions. The test revealed a significant effect of diameter ($F(2,413)=30.26$, $p=<.0001$, $\omega^2=0.0084$) and height ($F(1,413)=18.49$, $p=0.0175$, $\omega^2=0.0065$). The two-way interactions of diameter and slope ($F(2,413)=5.51$, $p=0.0043$, $\omega^2=0.0009$) and height and slope ($F(1,413)=5.78$, $p=0.0167$, $\omega^2=0.0005$) were also significant (see full results in Table 4.7). The 18 mm diameter configuration (Figure 4.20) and the sloped configuration (Figure 4.21) produced the lowest responses. Their interaction also resulted in the lowest muscle activation (Figure 4.22). The high and vertical handle interaction produced the lowest response (Figure 4.23).

Table 4.7 – Lifting Phase ECR MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	53.92	19	413	<.0001
Diameter (D)	30.26	2	413	<.0001
Height (H)	18.49	1	413	0.0175
Slope (S)	0.46	1	413	0.5070
D*H	2.90	2	413	0.0562
D*S	5.51	2	413	0.0043
H*S	5.78	1	413	0.0167
D*H*S	0.62	2	413	0.5390

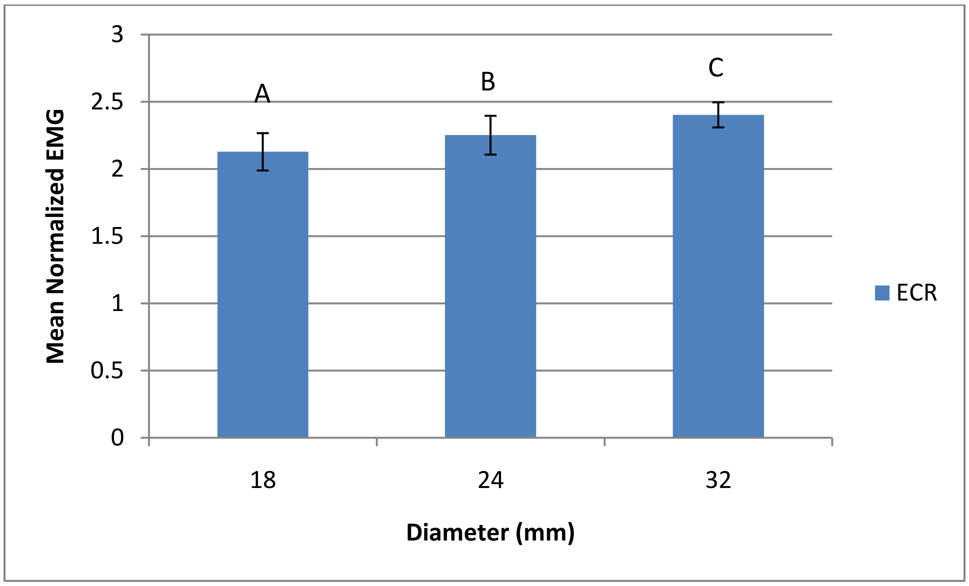

Figure 4.20 - Mean EMG of ECR for Diameter

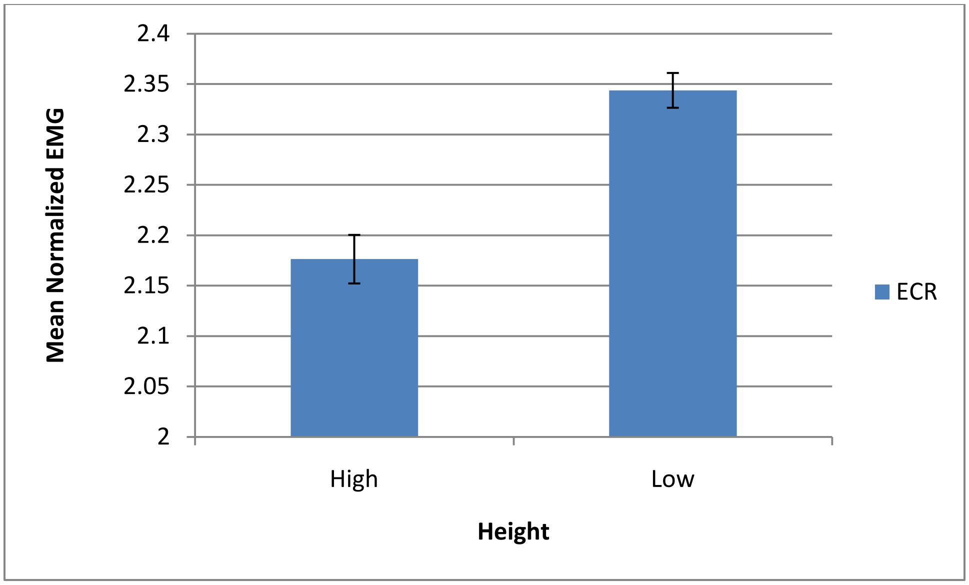

Figure 4.21 - Mean EMG of ECR for Height

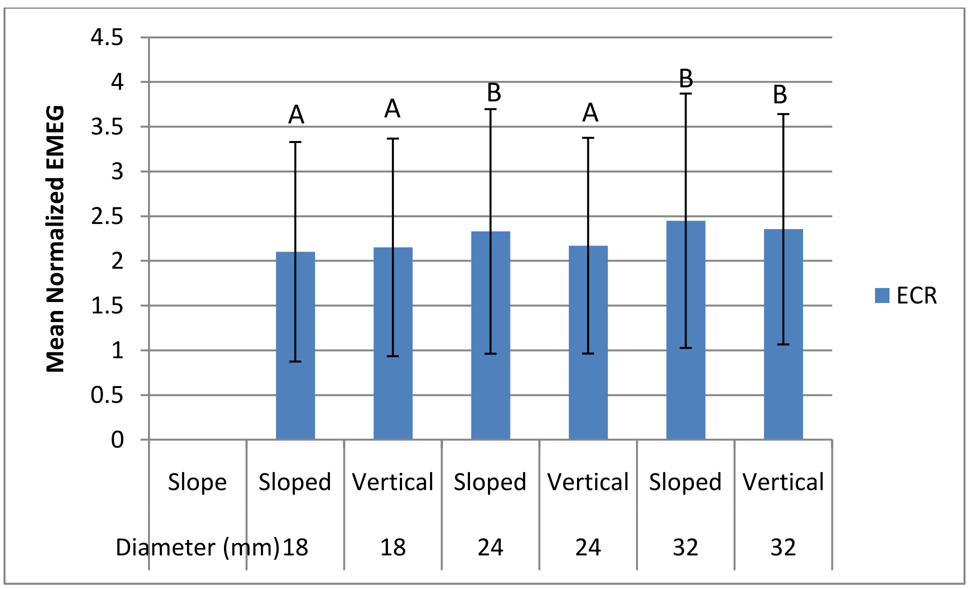

Figure 4.22 - Mean EMG of ECR for Diameter x Slope

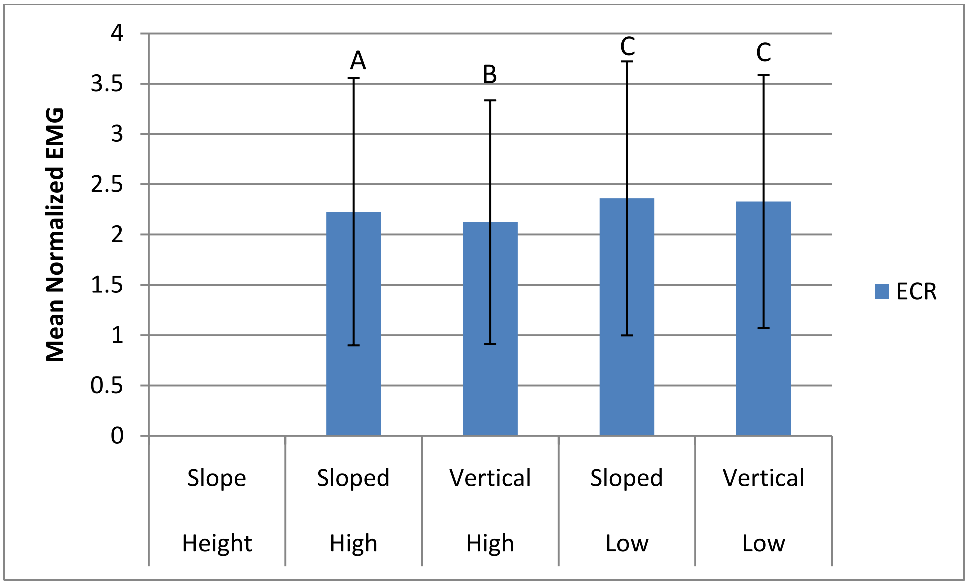

Figure 4.23 - Mean EMG of ECR for Height x Slope

A logarithmic transformation was applied to the FCR response because there was an increasing range of residuals across the range of model predictions. Results showed that height (F(1,413)=23.20, p=0.0002, ω^2=0.0081) had a significant effect. The interactions of diameter and slope (F(2,413)=3.48, p=0.0317, ω^2=0.0006) and height and slope (F(1,413)=10.54, p=0.0013, ω^2=0.0012) were also significant (see full results in Table 4.8). The high height had the lowest response (Figure 4.24). For the diameter and slope interaction, the 32 mm and sloped handle produced the lowest response (Figure 4.25). For the height and slope interaction, the high and vertical handle produced the lowest response (Figure 4.26).

Table 4.8 - Lifting Phase FCR MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	39.78	19	413	<.0001
Diameter (D)	1.91	2	413	0.1724
Height (H)	23.20	1	413	0.0002
Slope (S)	0.47	1	413	0.5078
D*H	1.81	2	413	0.1651
D*S	3.48	2	413	0.0317
H*S	10.54	1	413	0.0013
D*H*S	2.25	2	413	0.1067

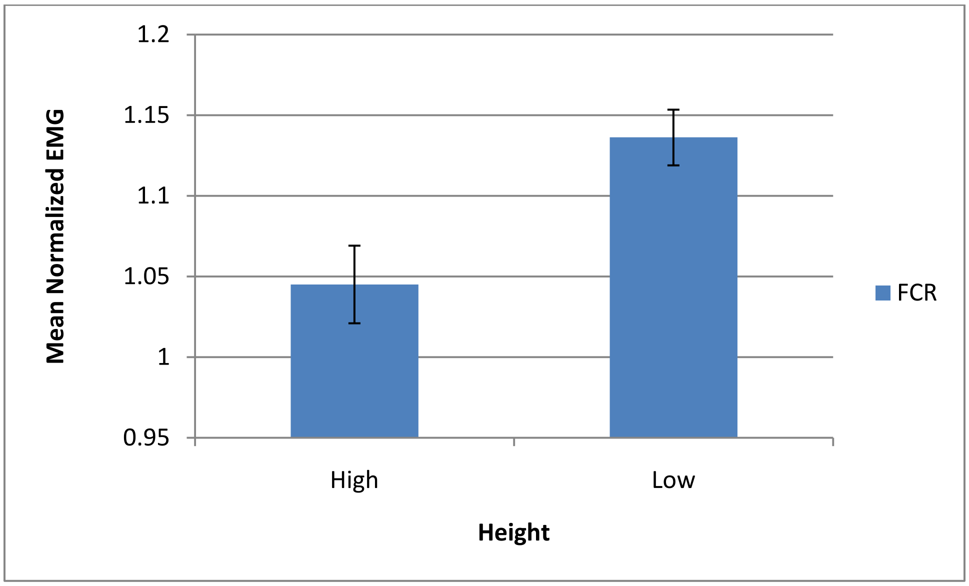

Figure 4.24 - Mean EMG of FCR for Height

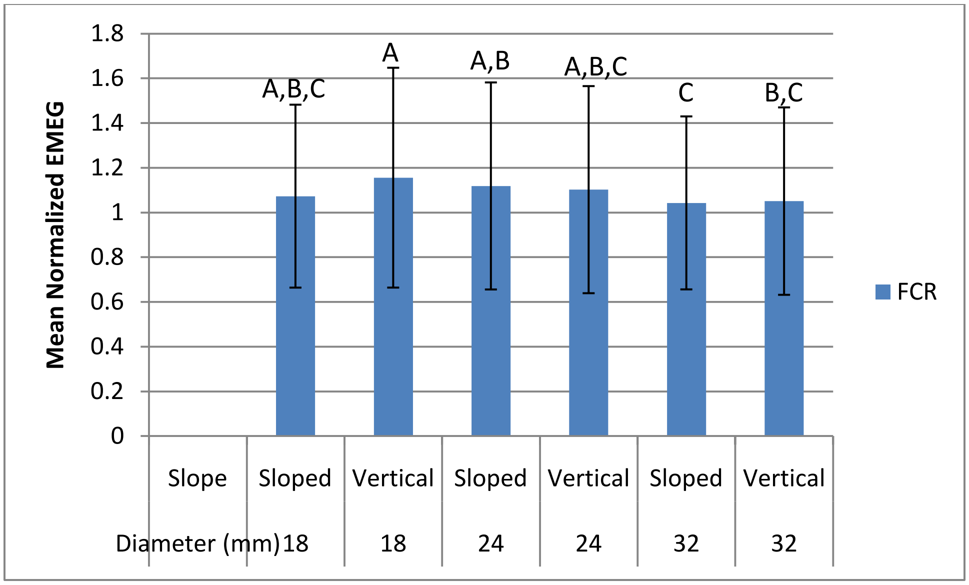

Figure 4.25 - Mean EMG of FCR for Diameter x Slope

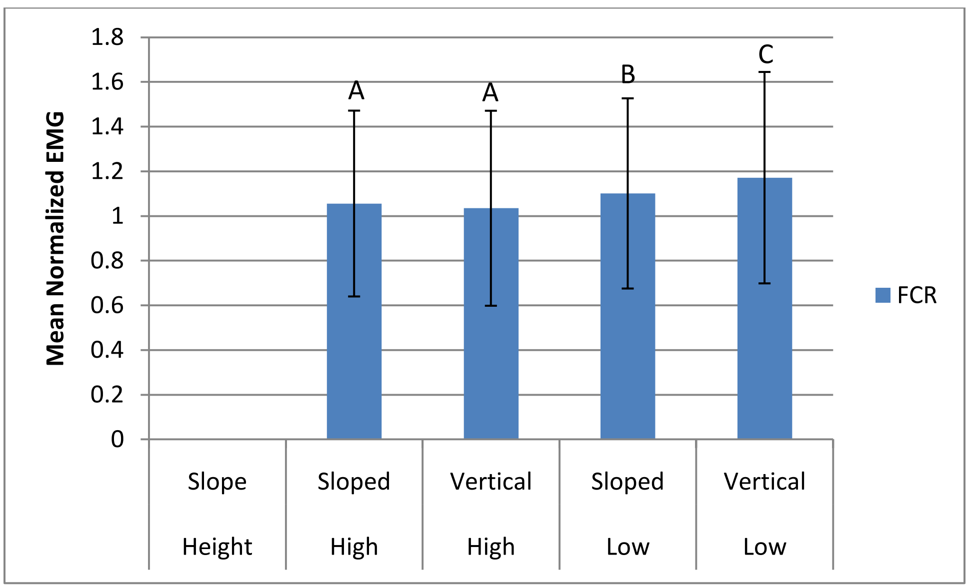

Figure 4.26 - Mean EMG of FCR for Height x Slope

4.1.2 Joint Postures

The SA response conformed to the assumptions of the ANOVA. Results showed that diameter ($F(2,413)=6.48$, $p=0.0049$, $\omega^2=0.0055$), height ($F(1,413)=9.71$, $p=0.0077$, $\omega^2=0.0051$), and slope ($F(1,413)=31.31$, $p=<.0001$, $\omega^2=0.0349$) all had significant effects on the response measure. The interactions of diameter and slope ($F(2,413)=3.92$, $p=0.0206$, $\omega^2=0.0008$) and height and slope ($F(1,413)=17.42$, $p=<.0001$, $\omega^2=0.0024$) were also significant (see full results in Table 4.9). For the main effects, the lowest peak postures were found with the 24 mm diameter (Figure 4.27), low (Figure 4.28), and vertical (Figure 4.29) handle configurations each. The diameter and slope interaction results showed that the 18 mm diameter and vertical handle produced the lowest response, though this was not found to be significantly different from the 24 mm diameter and vertical handle response (Figure 4.30). For the height and slope interaction, the low and vertical handle resulted in the lowest peak SA angles (Figure 4.31).

Table 4.9 - Lifting Phase SA MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	20.46	19	413	<.0001
Diameter (D)	6.48	2	413	0.0049
Height (H)	9.71	1	413	0.0077
Slope (S)	31.31	1	413	<.0001
D*H	0.41	2	413	0.6653
D*S	3.92	2	413	0.0206
H*S	17.42	1	413	<.0001
D*H*S	0.54	2	413	0.5844

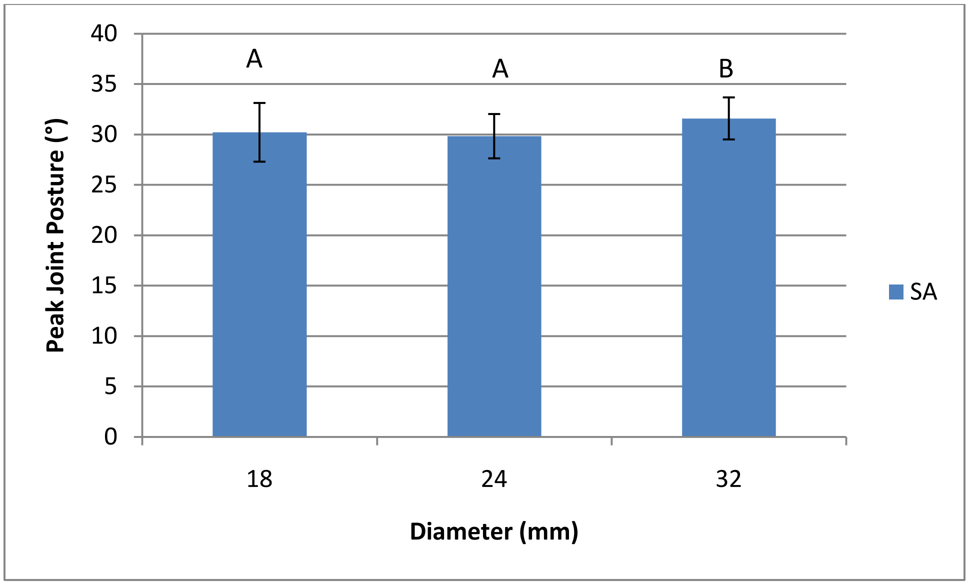

Figure 4.27 - Peak SA for Diameter

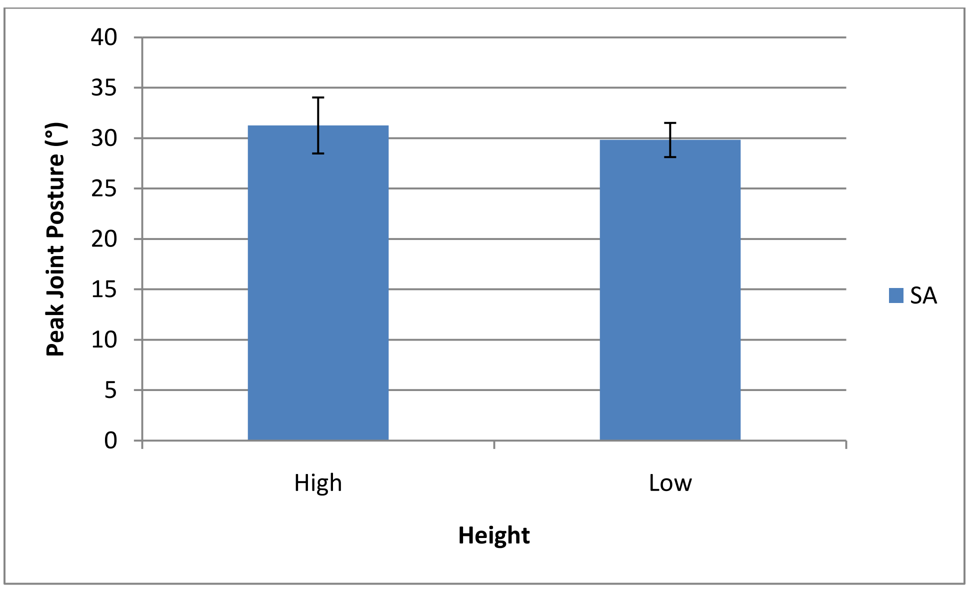

Figure 4.28 - Peak SA for Height

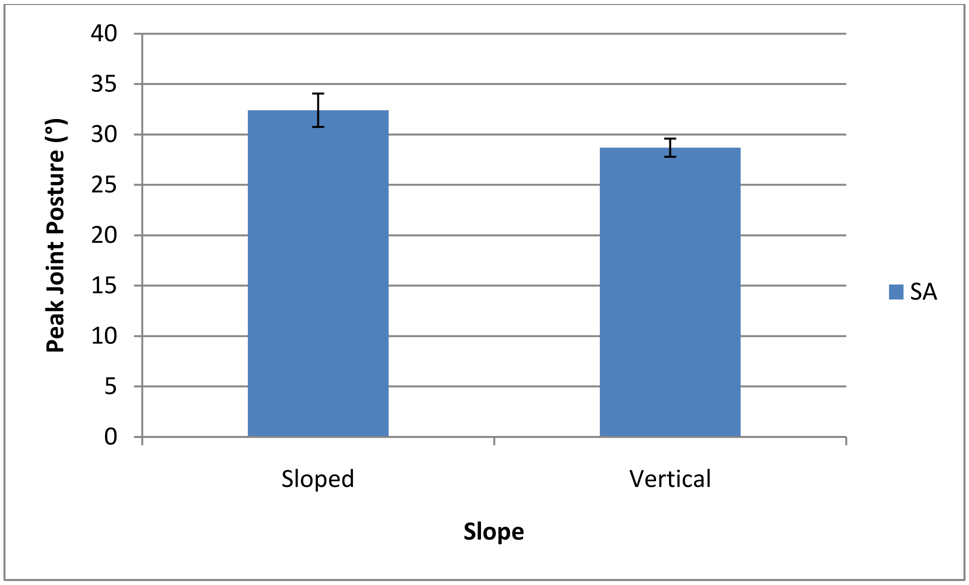

Figure 4.29 - Peak SA for Slope

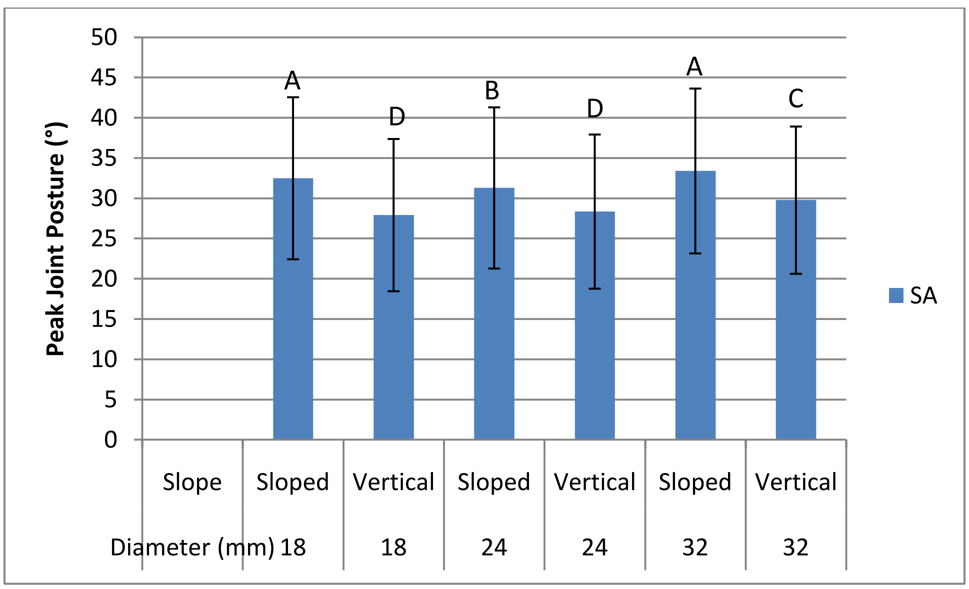

Figure 4.30 - Peak SA for Diameter x Slope

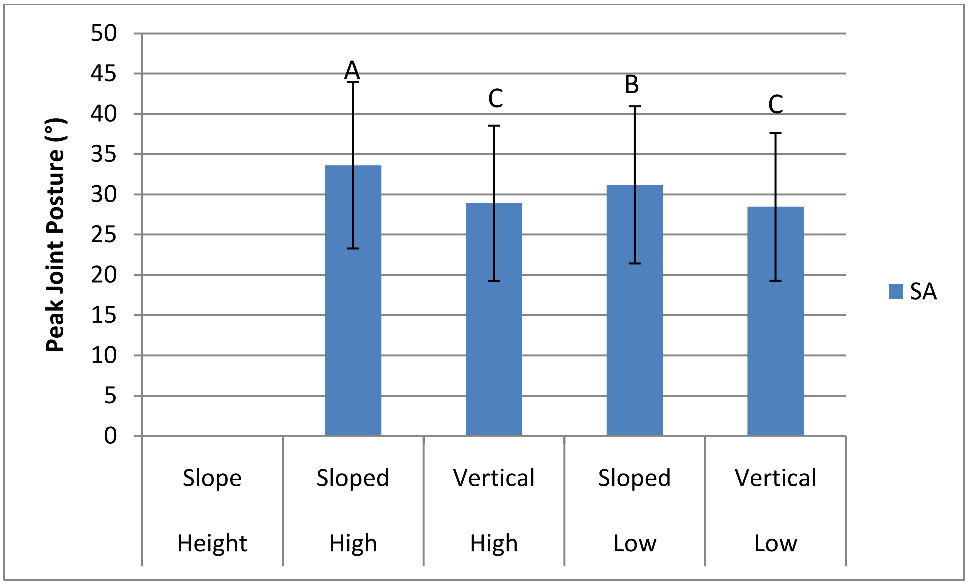

Figure 4.31 - Peak SA for Height x Slope

A Box-Cox transformation was applied to the SF response because it was found that there was an over-prediction of the model at high values. Diameter ($F(2,413)=7.43$, $p=0.0097$, $\omega^2=0.0039$) and height ($F(1,413)=20.41$, $p=0.0007$, $\omega^2=0.0206$) were found to be significant effects. The two-way interactions of diameter and slope ($F(2,413)=4.09$, $p=0.0174$, $\omega^2=0.0021$) and height and slope ($F(1,413)=10.13$, $p=0.0016$, $\omega^2=0.0031$) were also found to be significant (see full results in Table 4.10). Results revealed that the 32 mm diameter produced the lowest response (Figure 4.32). The low handle height also produced the lowest response (Figure 4.33). For the interaction of diameter and slope, the 32 mm diameterand vertical handle together produced the lowest response (Figure 4.34). The low and vertical handle had the lowest peak joint angle (Figure 4.35).

Table 4.10 - Lifting Phase SF MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	8.70	19	413	<.0001
Diameter (D)	7.43	2	413	0.0097
Height (H)	20.41	1	413	0.0007
Slope (S)	2.90	1	413	0.1064
D*H	2.72	2	413	0.0672
D*S	4.09	2	413	0.0174
H*S	10.13	1	413	0.0016
D*H*S	0.04	2	413	0.9640

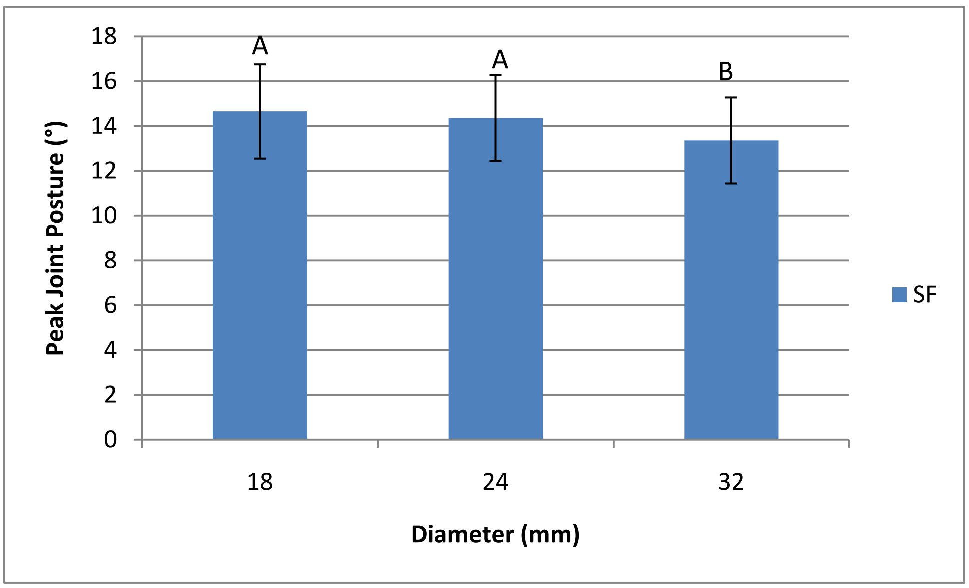

Figure 4.32 - Peak SF for Diameter

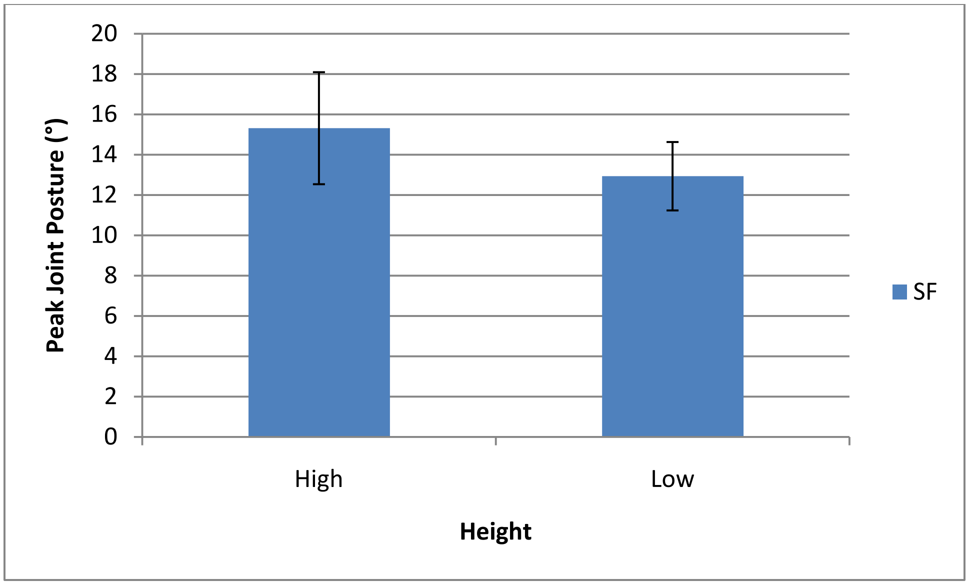

Figure 4.33 - Peak SF for Height

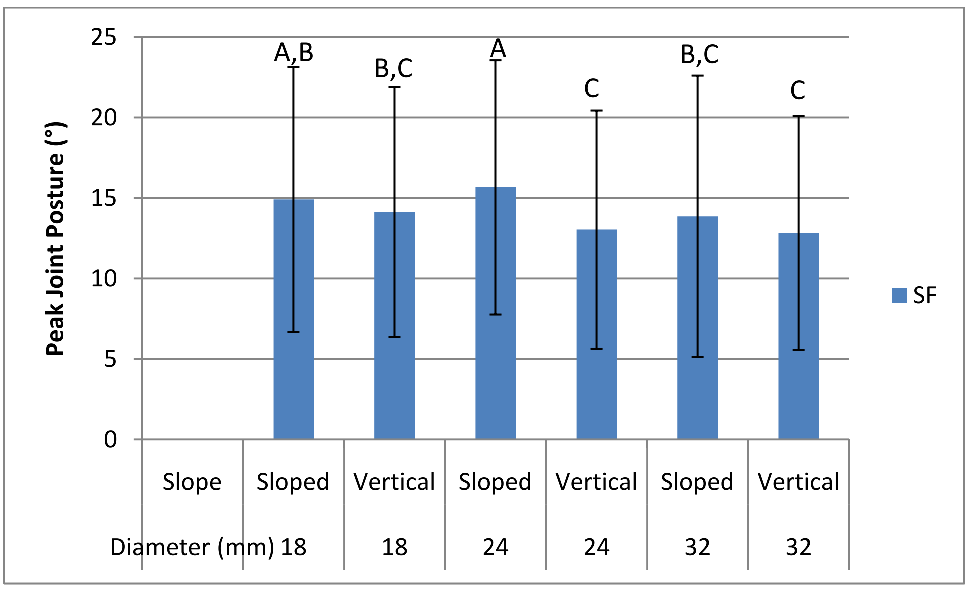

Figure 4.34 - Peak SF for Diameter x Slope

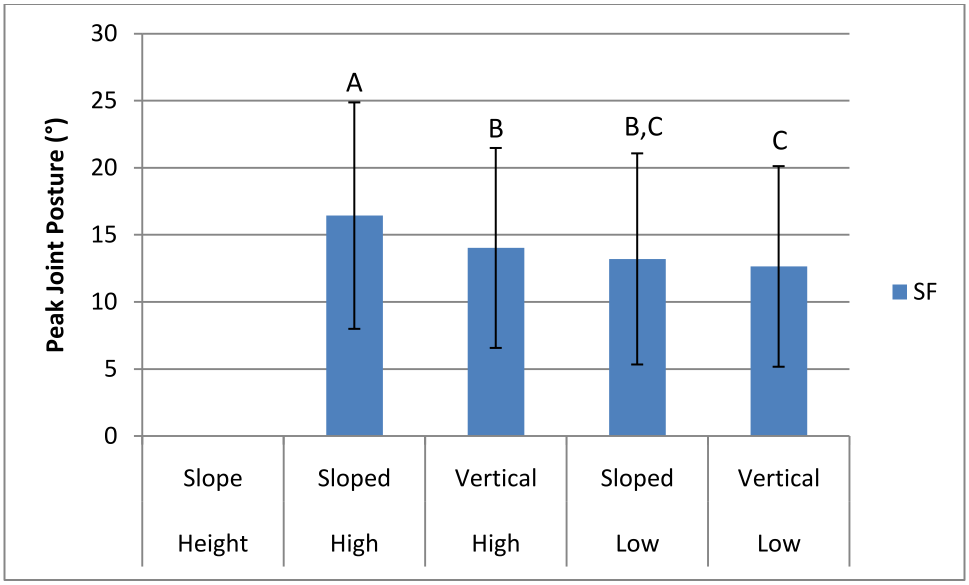

Figure 4.35 - Peak SF for Height x Slope

The WUD response did not violate assumptions of ANOVA. The main effect of slope was found to have a significant effect on the response ($F(1,413)=25.69$, $p=0.0002$, $\omega^2=0.0802$). The two-way interactions of diameter and slope ($F(2,413)=4.09$, $p=0.0174$, $\omega^2=0.0027$) and height and slope ($F(1,413)=10.13$, $p=0.0016$, $\omega^2=0.0037$) were found to be significant. The three-way interaction of diameter, height, and slope was also found to have a significant effect ($F(2,413)=6.40$, $p=0.0018$, $\omega^2=0.0067$) (see full results in Table 4.11). The WUD response was lower under the sloped handle (Figure 4.36). The diameter and slope interaction results showed that peak joint posture was lowest with the 32 mm diameter and sloped handle (Figure 4.37). The high and sloped handle configuration produced the lowest peak joint angle in the wrist (Figure 4.38). The three-way interaction results showed that the 32 mm diameter, high, and sloped handle configuration produced the lowest response (Figure 4.39).

Table 4.11 - Lifting Phase WUD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	3.12	19	413	0.0008
Diameter (D)	0.04	2	413	0.9595
Height (H)	1.65	1	413	0.2252
Slope (S)	25.69	1	413	0.0002
D*H	0.36	2	413	0.6977
D*S	3.21	2	413	0.0415
H*S	7.06	1	413	0.0082
D*H*S	6.40	2	413	0.0018

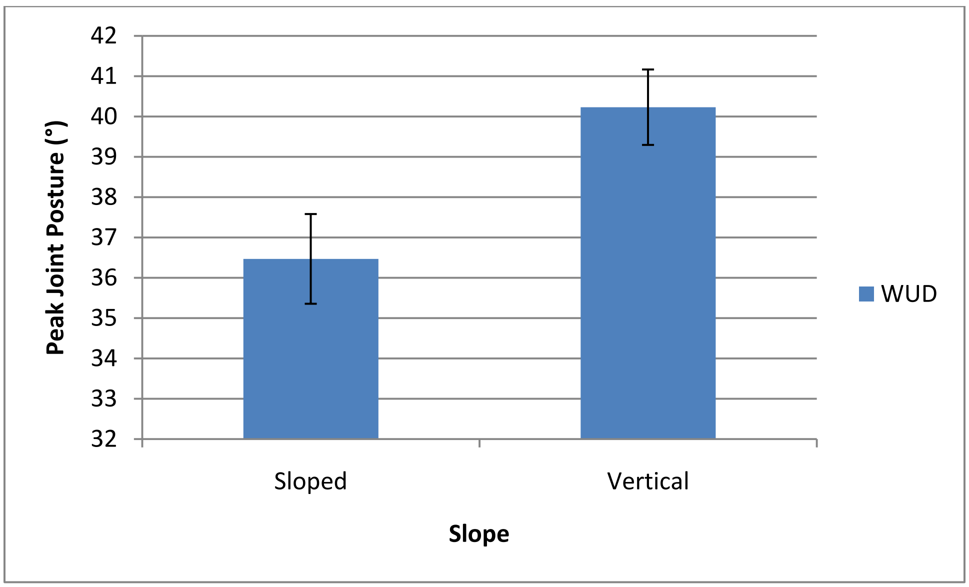

Figure 4.36 - Peak WUD for Slope

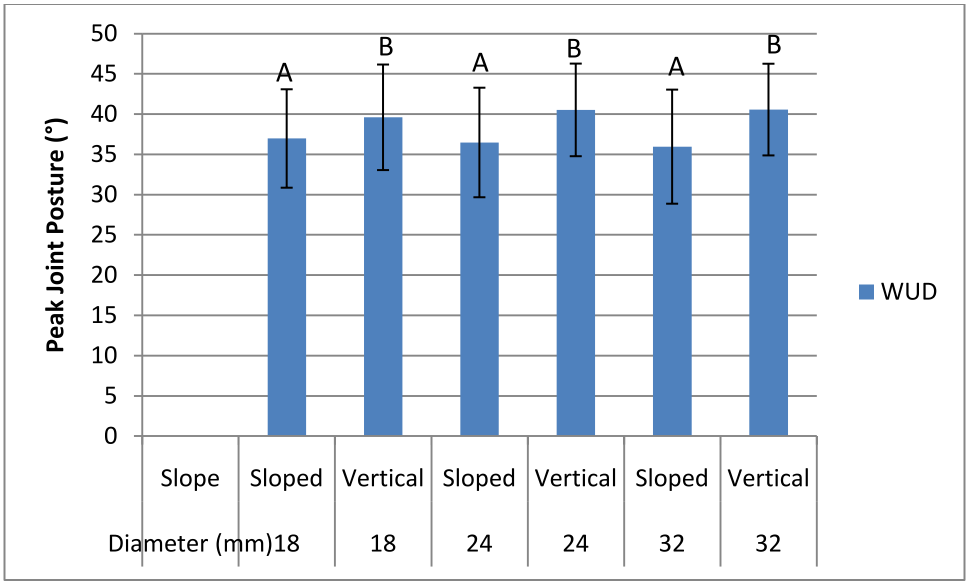

Figure 4.37 - Peak WUD for Diameter x Slope

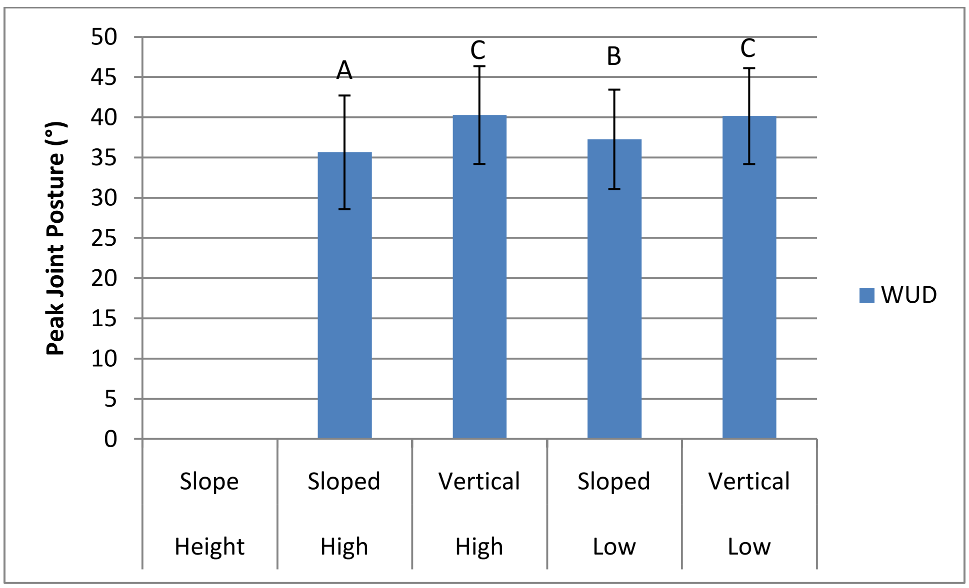

Figure 4.38 - Peak WUD for Height x Slope

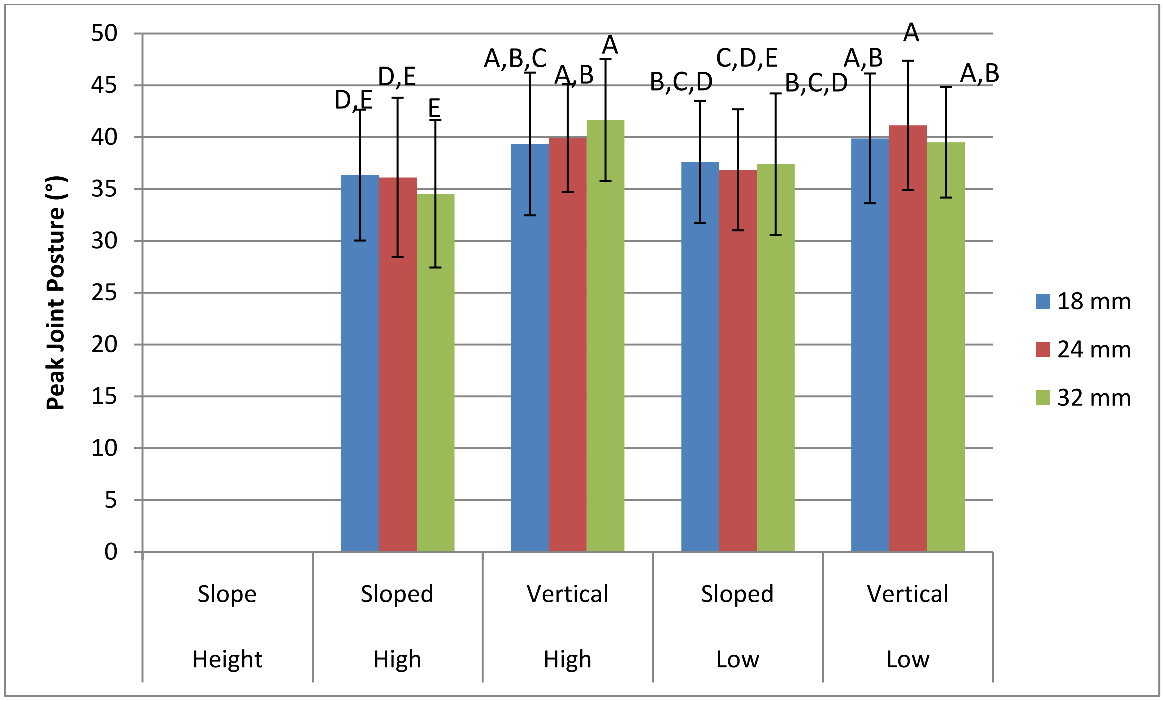

Figure 4.39 - Peak WUD for Diameter x Height x Slope

4.1.3 Average Grip Force

For the average grip force, it was found that there was an under-prediction of the model at low values. A square root transformation was applied to correct this. The transformed data conformed to the assumptions. Results showed that height ($F(1,413)=81.76$, $p=<.0001$, $\omega^2=0.0202$) and slope ($F(1,413)=231.91$, $p=<.0001$, $\omega^2=0.0541$) had significant effects (see full results in Table 4.12). The interaction of diameter and slope was also shown to be significant. The average grip force was lower in the high handle configuration (Figure 4.40). The response was also lower in the sloped handle configuration (Figure 4.41). For the interaction, the 18 mm diameter and sloped handle generally produced a lower response under all levels of height compared to the vertical handle with the 18 mm diameter and sloped handle producing the lowest response (Figure 4.42).

Table 4.12 – Lifting Phase Average Grip Force MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	34.22	19	413	<.0001
Diameter (D)	1.41	2	413	0.2623
Height (H)	81.76	1	413	<.0001
Slope (S)	231.91	1	413	<.0001
D*H	1.04	2	413	0.3552
D*S	3.21	2	413	0.0413
H*S	2.24	1	413	0.1356
D*H*S	0.45	2	413	0.6406

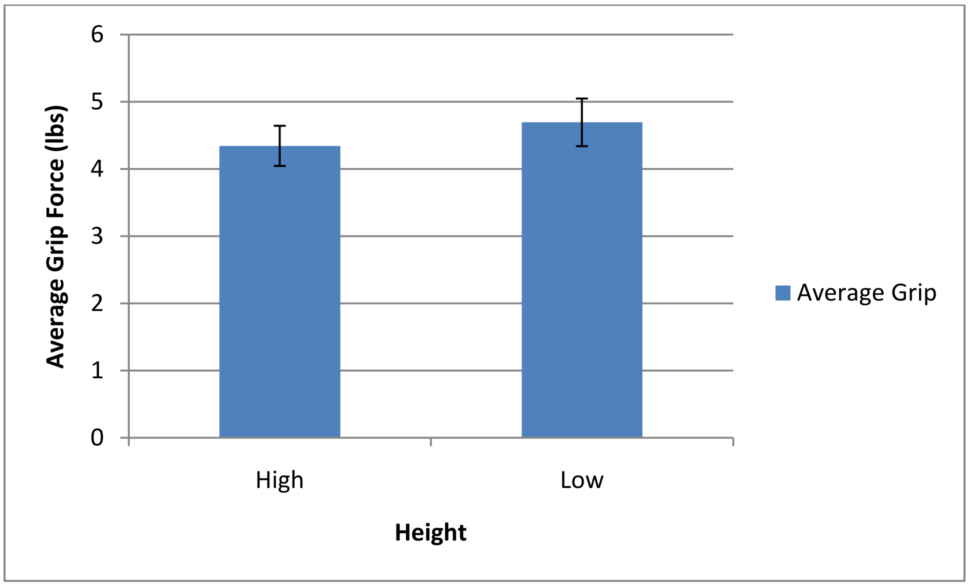

Figure 4.40 - Average Grip for Height

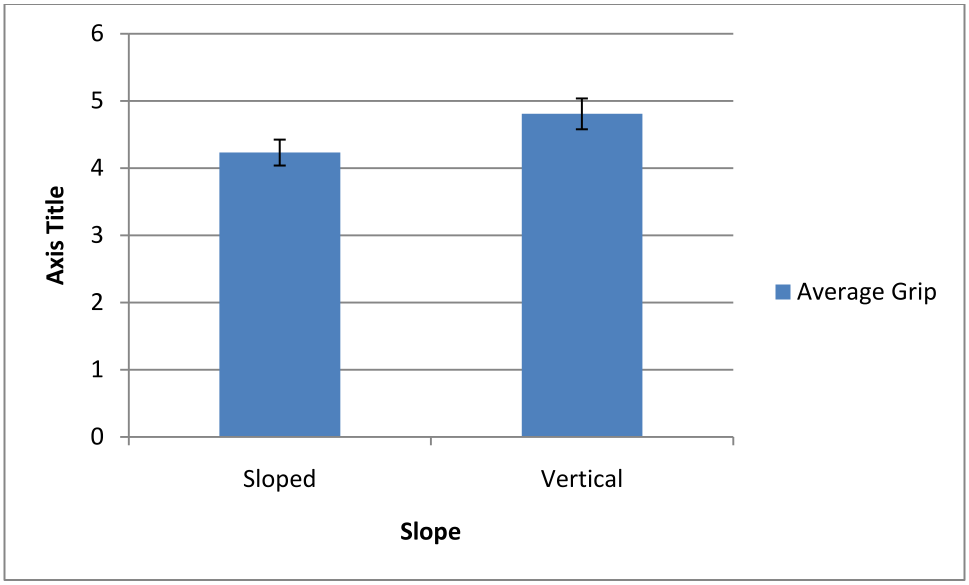

Figure 4.41 - Average Grip for Slope

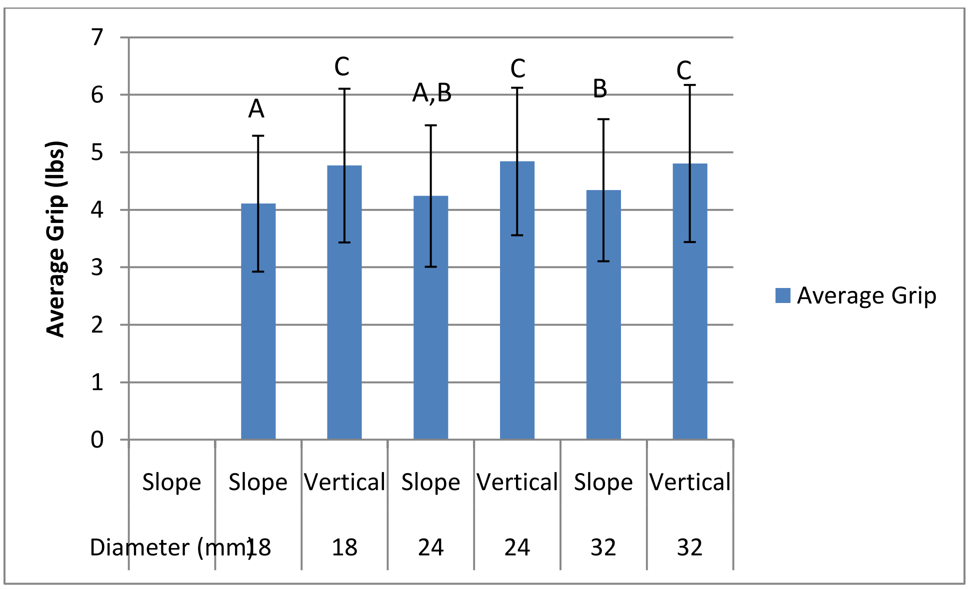

Figure 4.42 - Average Grip for Diameter x Slope

4.2 Pouring Phase of Task

4.2.1 Muscle Activity

A square root transformation was applied to the AD response because it was found that there was an under-prediction of the model at low values and an over-prediction of the model at high values. Results showed a significant effect of diameter ($F(3,413)=9.88$, $p=0.0016$, $\omega^2=0.0039$), height ($F(1,413)=68.87$, $p=0.0009$, $\omega^2=0.0400$), and slope ($F(1,413)=30.59$, $p=0.0002$, $\omega^2=0.0278$) (see full results in Table 4.13). The 32 mm diameter (Figure 4.43), low (Figure 4.44), and sloped (Figure 4.45) handle configurations each produced the lowest responses for the diameter, height, and slope variables, respectively.

Table 4.13 – Pouring Phase AD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	36.49	19	413	<.0001
Diameter (D)	9.88	2	413	0.0016
Height (H)	68.87	1	413	0.0009
Slope (S)	30.59	1	413	0.0002
D*H	1.75	2	413	0.1747
D*S	1.24	2	413	0.2892
H*S	0.07	1	413	0.7946
D*H*S	1.39	2	413	0.2500

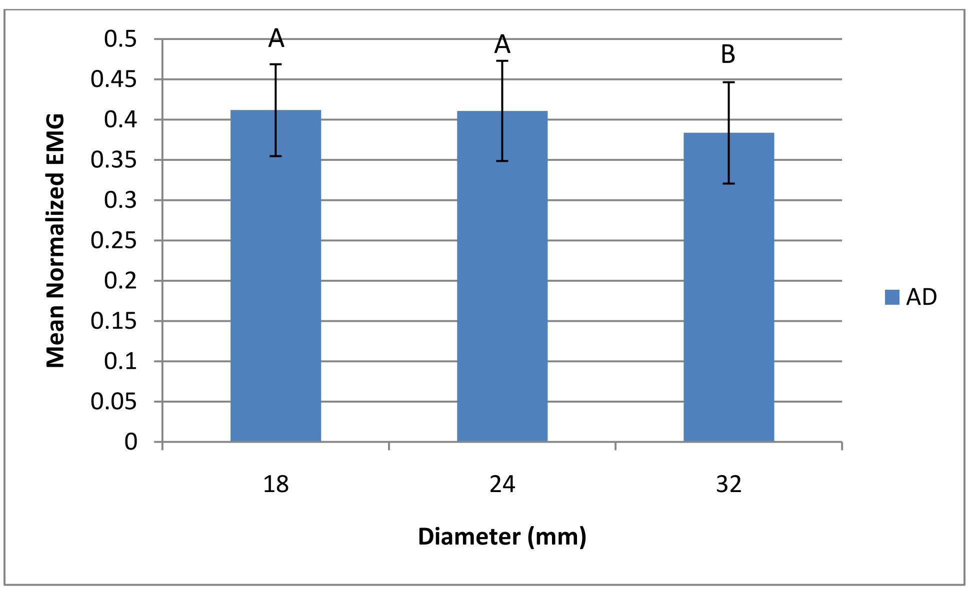

Figure 4.43 - Mean EMG of AD for Diameter

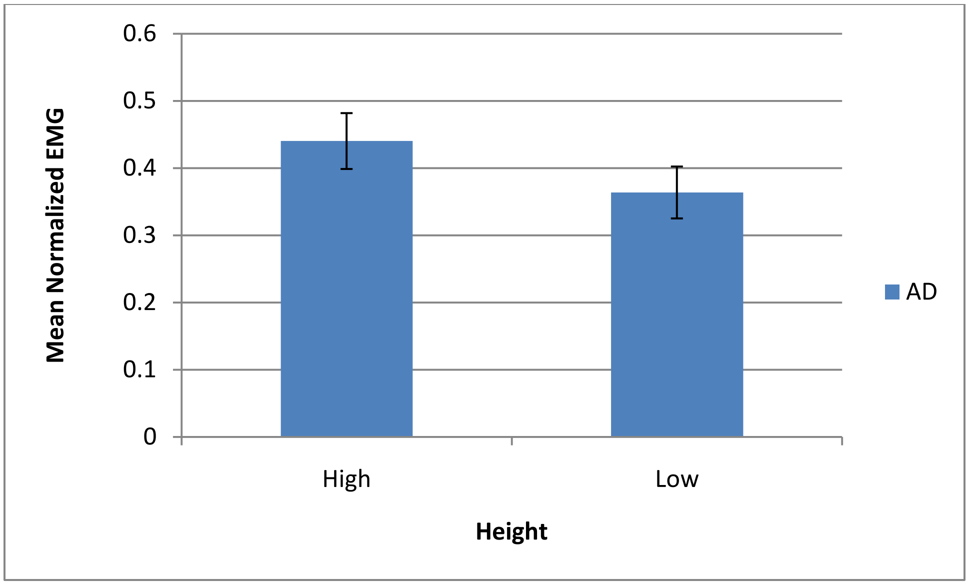

Figure 4.44 - Mean EMG of AD for Height

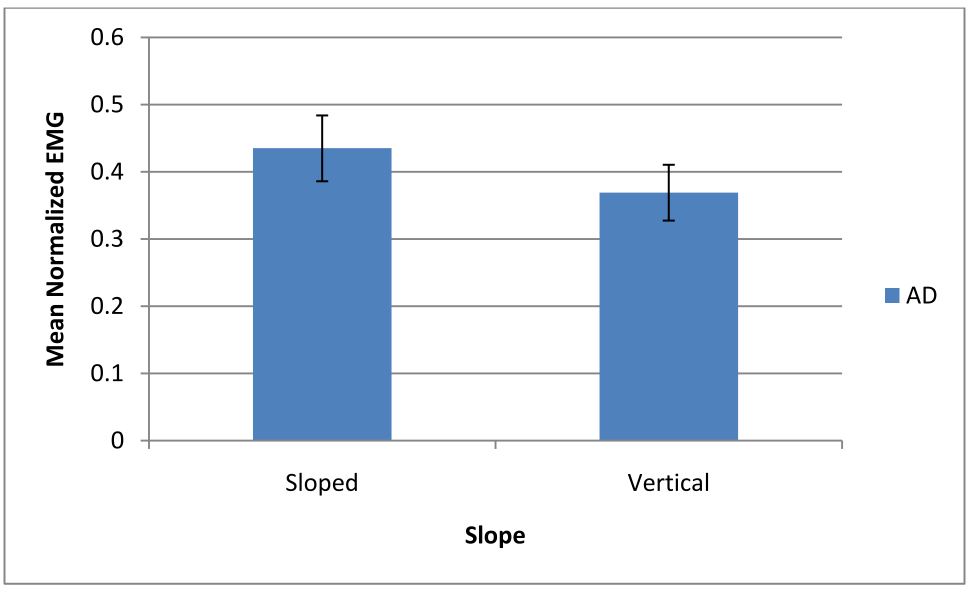

Figure 4.45 - Mean EMG of AD for Slope

Due to an over-prediction of the model at high values, the MD response was transformed using a logarithmic transformation. The transformed data conformed to the assumptions. Results showed that diameter ($F(2,413)=4.34$, $p=0.0336$, $\omega^2=0.0034$), height ($F(1,413)=24.64$, $p=0.0001$, $\omega^2=0.0283$), and slope ($F(1,413)=57.16$, $p=<.0001$, $\omega^2=0.0718$)

had significant effects on the response. The interaction of height and slope ($F(1,413)=25.04$, $p=<.0001$, $\omega^2=0.0046$) also had a significant effect (see full results in Table 4.14). The 18 mm diameter produced the lowest muscle activity for the MD (Figure 4.46). The low height resulted in a lower response than the high one (Figure 4.47). The vertical handle also produced the lower response (Figure 4.48). For the interaction, the low and vertical handles together produced the lowest muscle activity (Figure 4.49).

Table 4.14 – Pouring Phase MD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	13.22	19	413	<.0001
Diameter (D)	4.34	2	413	0.0336
Height (H)	24.64	1	413	0.0001
Slope (S)	57.16	1	413	<.0001
D*H	0.66	2	413	0.5180
D*S	0.02	2	413	0.9774
H*S	25.04	1	413	<.0001
D*H*S	0.02	2	413	0.9769

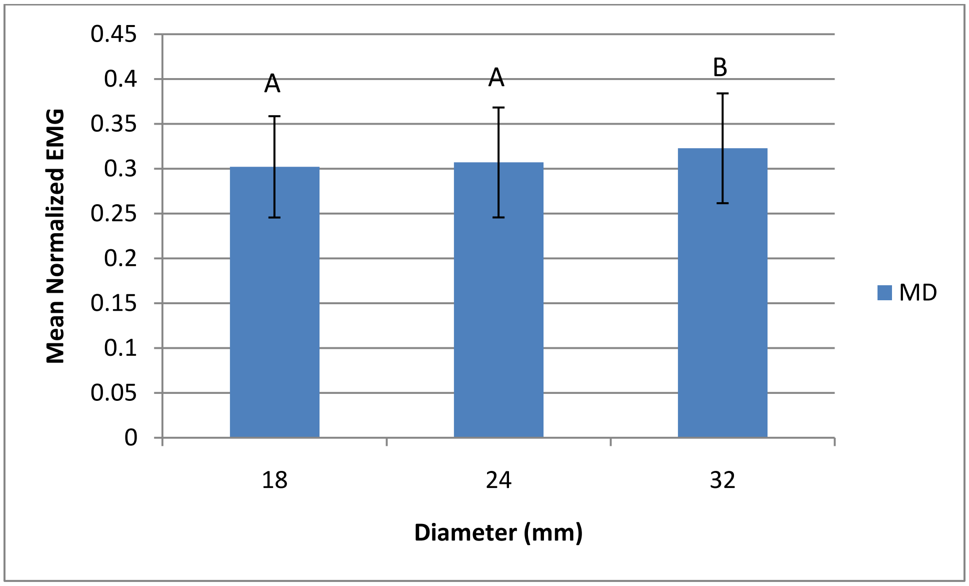

Figure 4.46 - Mean EMG of MD for Diameter

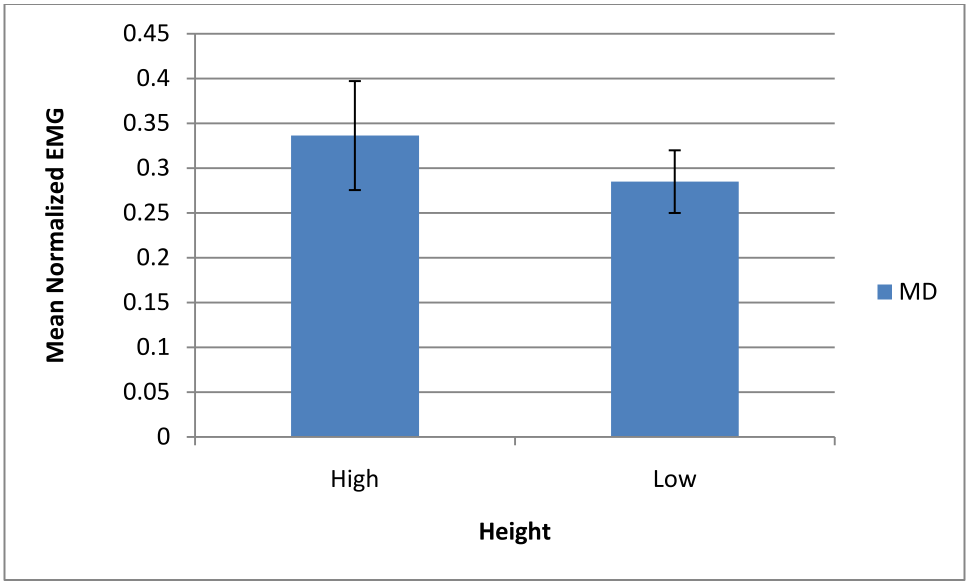

Figure 4.47 - Mean EMG of MD for Height

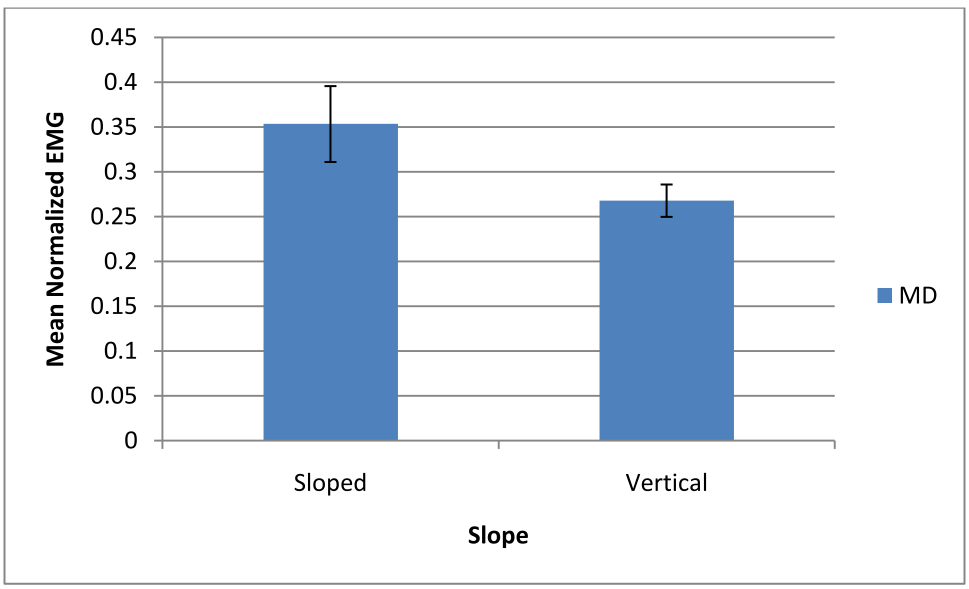

Figure 4.48 - Mean EMG of MD for Slope

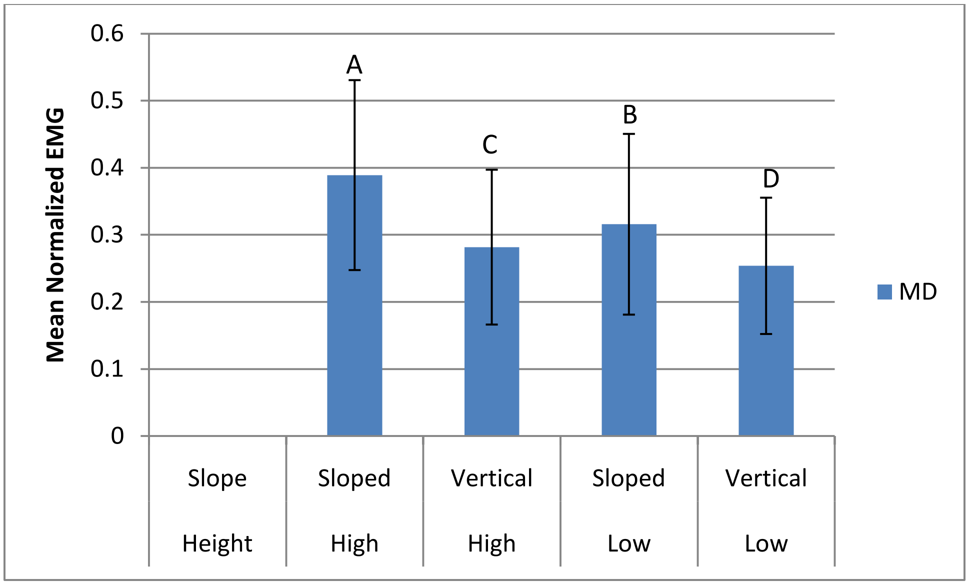

Figure 4.49 - Mean EMG of MD for Height x Slope

A square root transformation was applied to the PD response because of an under-prediction of the model at low values and over-prediction of the model in the high values. Because there was still an under-prediction of the model, another square root transformation was used with success. The test revealed that diameter ($F(2,413)=10.62$, $p=0.0019$, $\omega^2=0.0031$) and slope ($F(1,413)=21.95$, $p=0.0002$, $\omega^2=0.0177$) had significant effects on the response. A two-way interaction of height and slope was also significant ($F(1,413)=12.11$, $p=0.0003$, $\omega^2=0.0013$) (see full results in Table 4.15). The 18 mm diameter (Figure 4.50) and the vertical handle (Figure 4.51) produced the lowest responses. For the interaction (Figure 4.52), the high and vertical handles produced the lowest responses. This was, however, not significantly different from the low and vertical handle response.

Table 4.15 – Pouring Phase PD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	27.48	19	413	<.0001
Diameter (D)	10.62	2	413	0.0019
Height (H)	1.02	1	413	0.3278
Slope (S)	21.95	1	413	0.0002
D*H	0.19	2	413	0.8238
D*S	0.48	2	413	0.6217
H*S	12.11	1	413	0.0006
D*H*S	1.55	2	413	0.2142

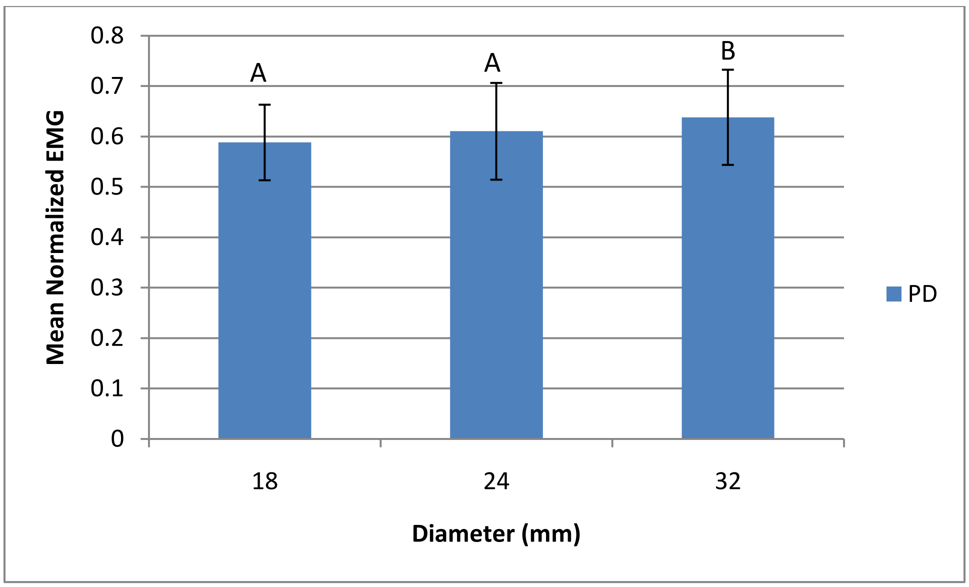

Figure 4.50 - Mean EMG of PD for Diameter

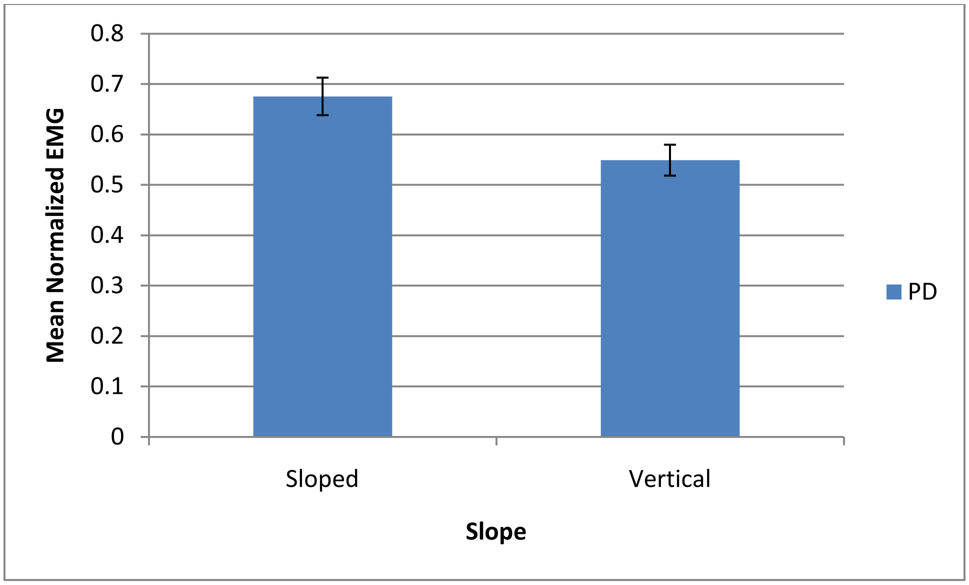

Figure 4.51 - Mean EMG of PD for Slope

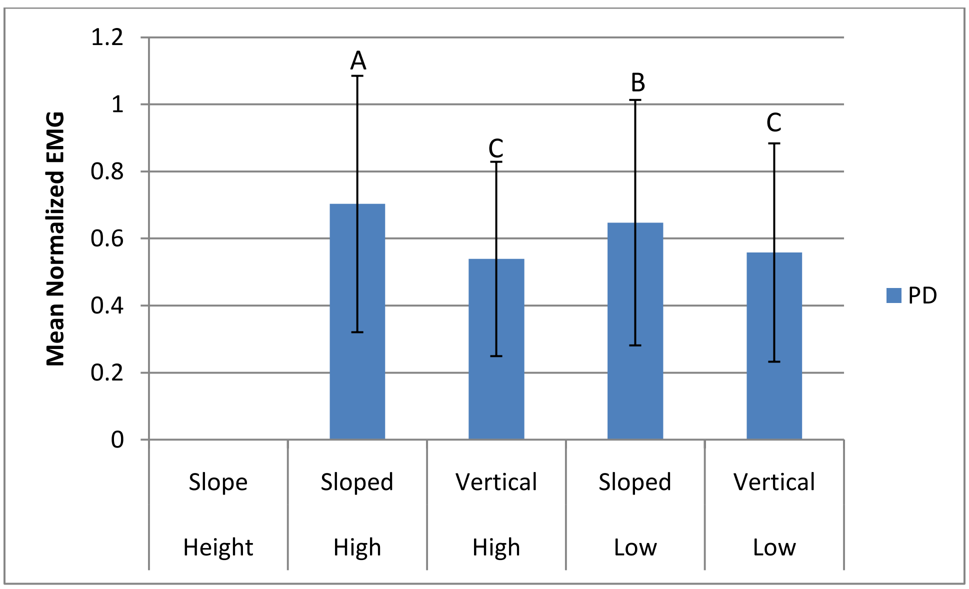

Figure 4.52 - Mean EMG of PD for Height x Slope

Due to an increasing range of residuals across the range of model predictions, a logarithmic transformation was applied to the TR response. The transformed data conformed to the assumptions. Results showed that height ($F(1,413)=16.31$, $p=0.0090$, $\omega^2=0.0054$) and slope ($F(1,413)=67.28$, $p=0.0002$, $\omega^2=0.0114$) had significant effects on the response. Their interaction also had a significant effect (F(1,413)=13.22, p=0.0003, ω^2=0.0013) (see full results in Table 4.16). Results showed that lower muscle activity occurred with the low handle (Figure 4.53) and with the vertical handle (Figure 4.54). The interaction of the low and vertical handle also produced the lowest response (Figure 4.55).

Table 4.16 – Pouring Phase TR MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	90.77	19	413	<.0001
Diameter (D)	1.37	2	413	0.2781
Height (H)	16.31	1	413	0.0090
Slope (S)	67.28	1	413	0.0002
D*H	1.15	2	413	0.3172
D*S	1.56	2	413	0.2104
H*S	13.22	1	413	0.0003
D*H*S	1.05	2	413	0.3512

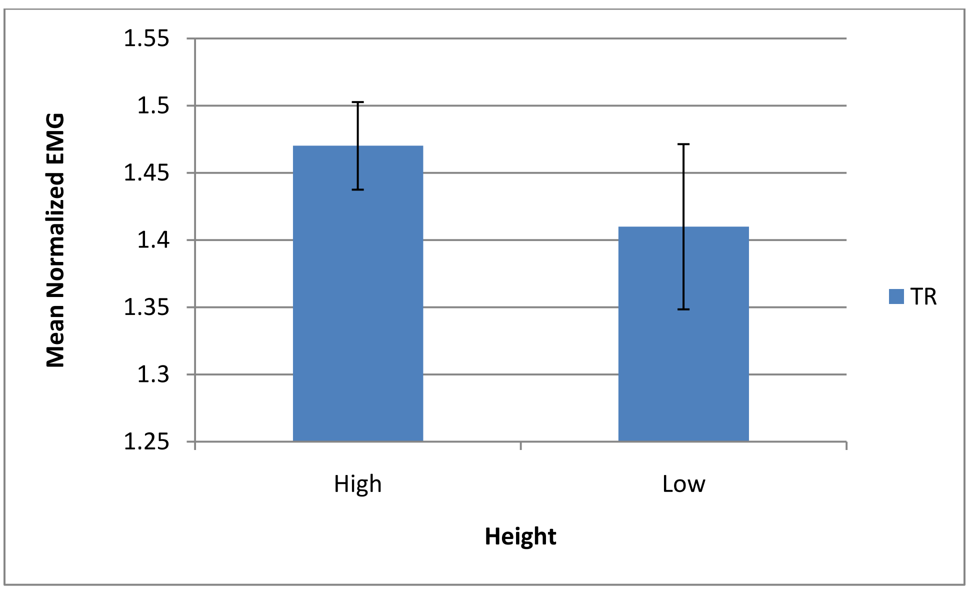

Figure 4.53 - Mean EMG of TR for Height

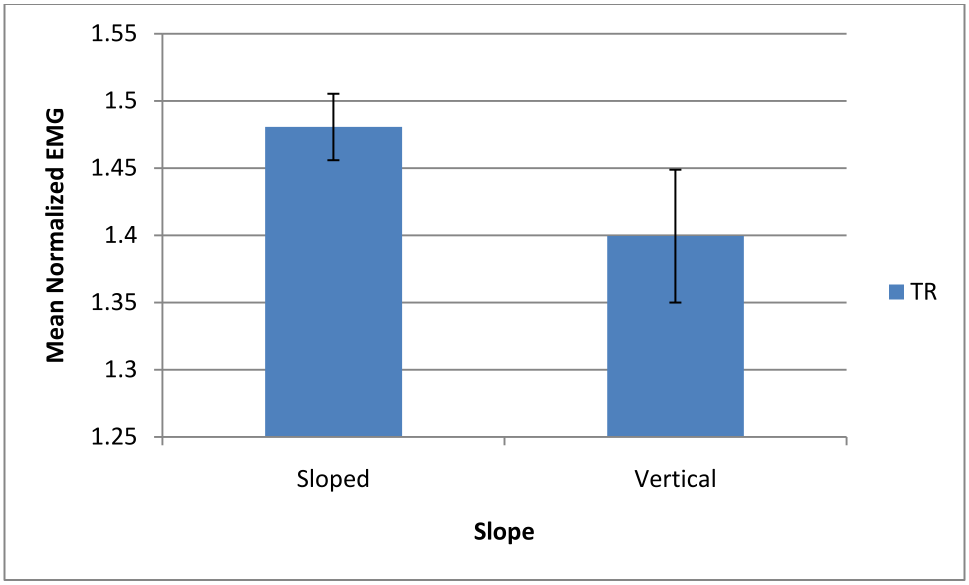

Figure 4.54 - Mean EMG of TR for Slope

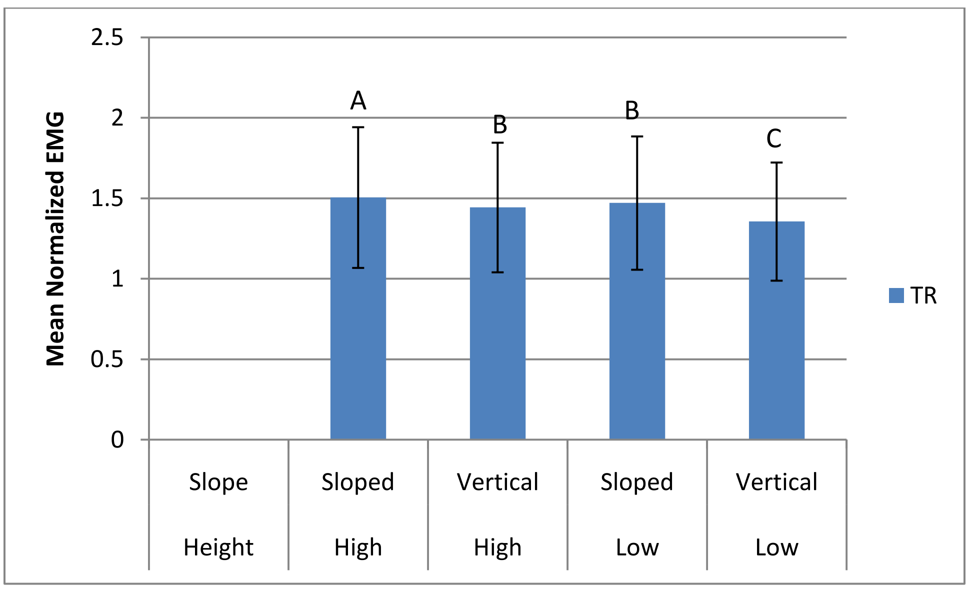

Figure 4.55 - Mean EMG of TR for Height x Slope

A Box-Cox transformation was used on the IF response because there was an increasing range of residuals across the range of model predictions. Results showed that the interactions of diameter and slope (F(2,413)=5.05, p=0.0068, ω^2=0.0003) and of diameter and height (F(2,413)=12.55, p=0.0004, ω^2=0.0000) had significant effects (see full results in

Table 4.17). For the diameter and slope interaction, the 18 mm diameter and vertical handle interaction was shown to have the lowest response, though it was not significantly different from the responses of the 32 mm and sloped handle, and the 18 mm diameter and sloped handle (Figure 4.56). For the height and slope response, the low and vertical handle yielded the lowest response. Post-hoc testing showed that this was not significantly different from the high and sloped handle or from the low and sloped handle (Figure 4.57)

Table 4.17 – Pouring Phase IF MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	100.51	19	413	<.0001
Diameter (D)	2.05	2	413	0.1489
Height (H)	0.27	1	413	0.6079
Slope (S)	0.29	1	413	0.6068
D*H	1.18	2	413	0.3077
D*S	5.05	2	413	0.0068
H*S	12.55	1	413	0.0004
D*H*S	1.39	2	413	0.2509

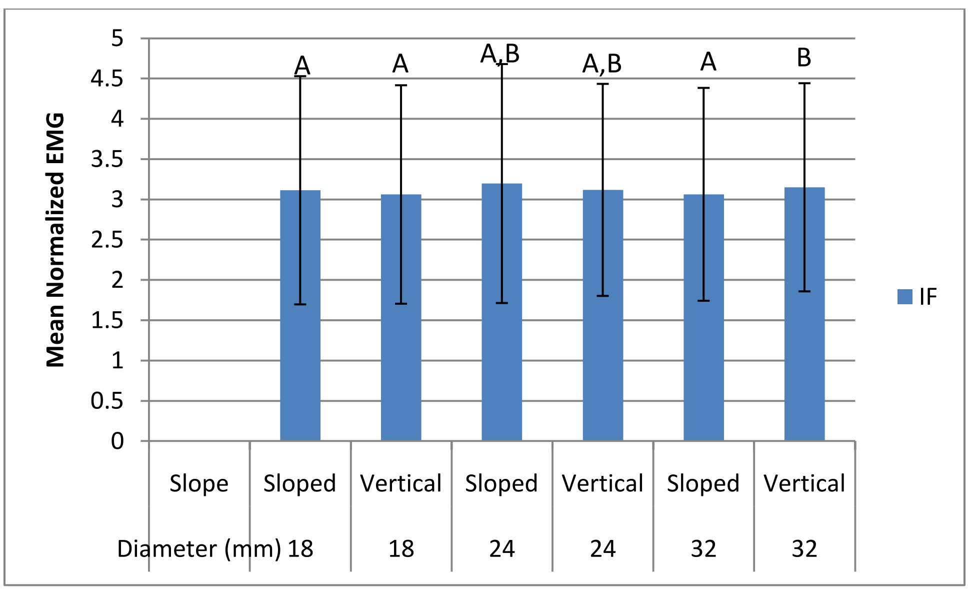

Figure 4.56 - Mean EMG of IF for Diameter x Slope

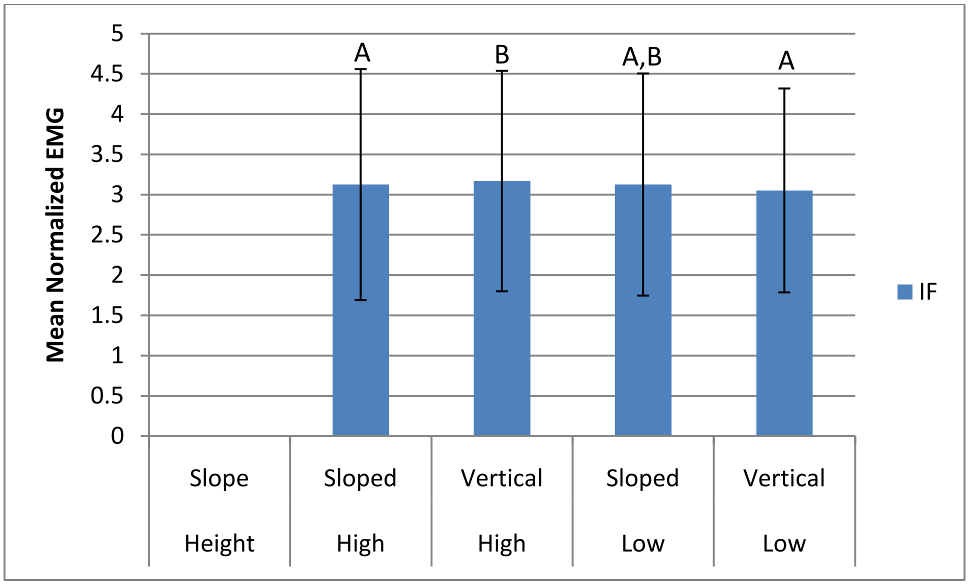

Figure 4.57 - Mean EMG of IF for Height x Slope

For the BB response, there was an increasing range of residuals across the range of model predictions. Hence, a logarithmic transformation was applied. Results showed a significant effect of diameter (F(2,413)=34.34, p=0.0014, ω^2=0.0099), height (F(1,413)=86.80, p=<.0001, ω^2=0.0771), and slope (F(1,413)=28.87, p=<.0001, ω^2=0.0434). Significant interactions included height and slope (F(1,413)=14.02, p=0.0002, ω^2=0.0021) and diameter, height, and slope (F(2,413)=4.99, p=0.0072, ω^2=0.0013) (see full results in Table 4.18). The 18 mm diameter (Figure 4.58), high (Figure 4.59), and sloped (Figure 4.60) configurations each produced the lowest muscle activity in the BB. For the height and slope interaction, the high and sloped handle produced the lowest muscle activity compared (Figure 4.61). For the three-way interaction, 18 mm, high and sloped handle produced the lowest response (Figure 4.62).

Table 4.18 – Pouring Phase BB MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	16.84	19	413	<.0001
Diameter (D)	34.34	2	413	0.0014
Height (H)	86.80	1	413	<.0001
Slope (S)	31.62	1	413	<.0001
D*H	1.71	2	413	0.1823
D*S	0.92	2	413	0.4001
H*S	14.02	1	413	0.0002
D*H*S	4.99	2	413	0.0072

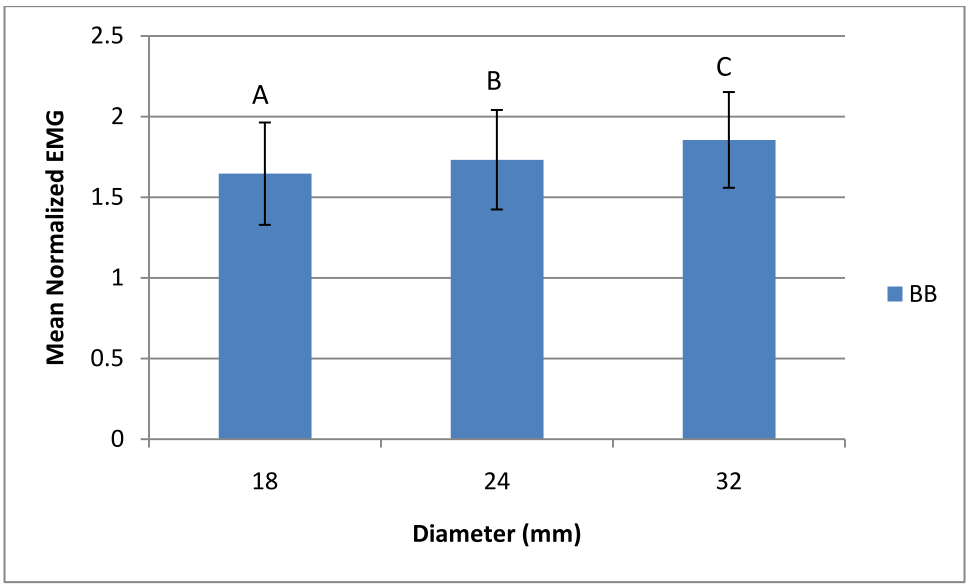

Figure 4.58 - Mean EMG of BB for Diameter

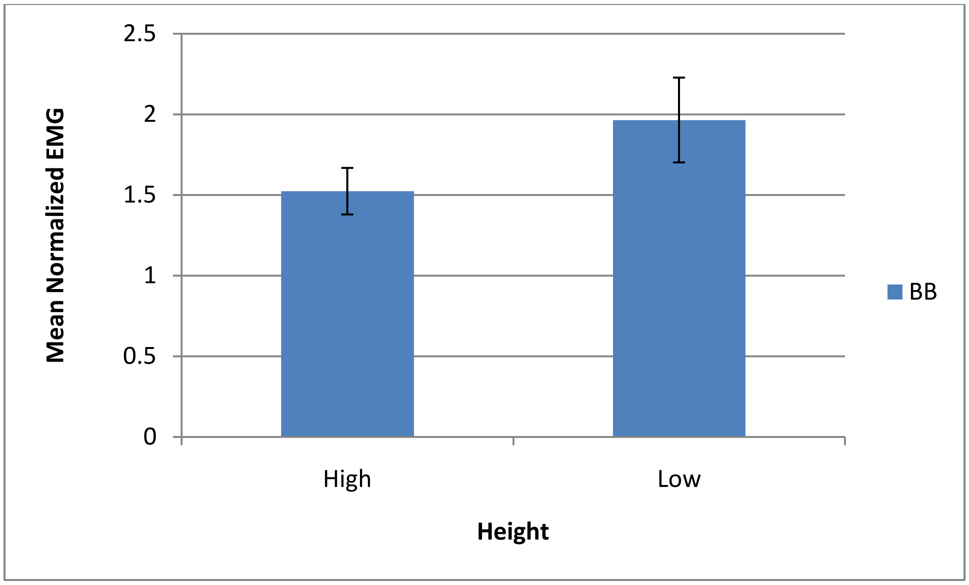

Figure 4.59 - Mean EMG of BB for Height

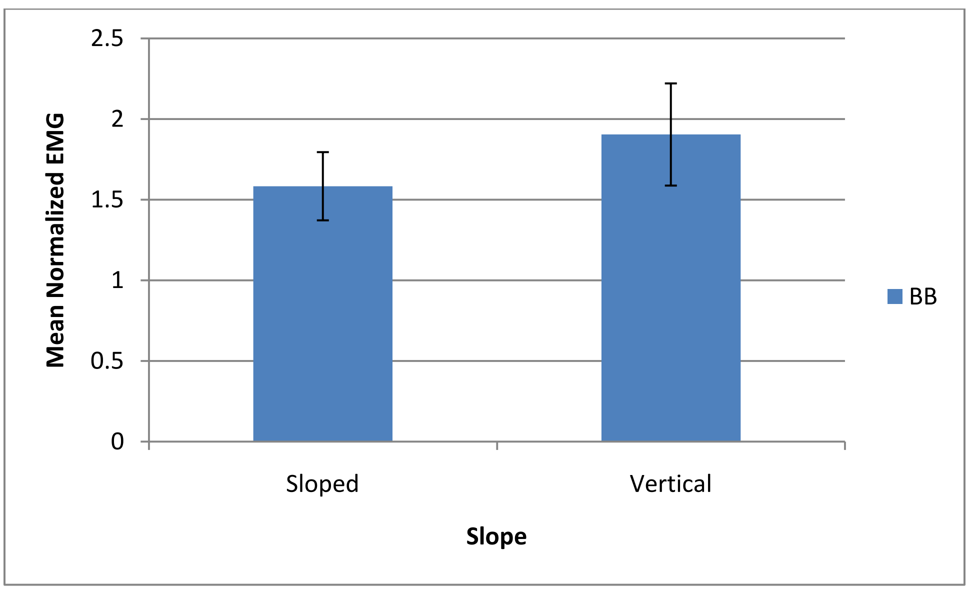

Figure 4.60 - Mean EMG of BB for Slope

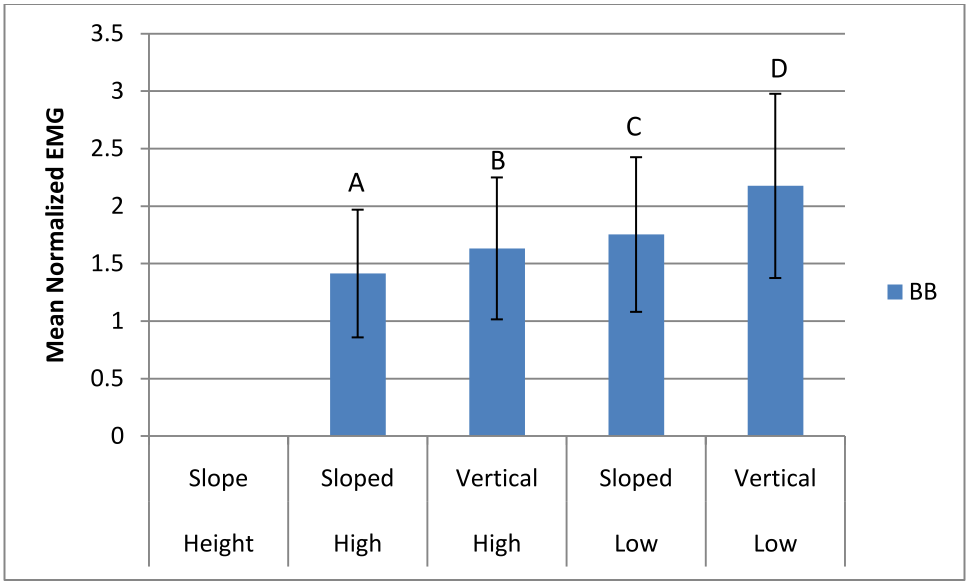

Figure 4.61 - Mean EMG of BB for Height x Slope

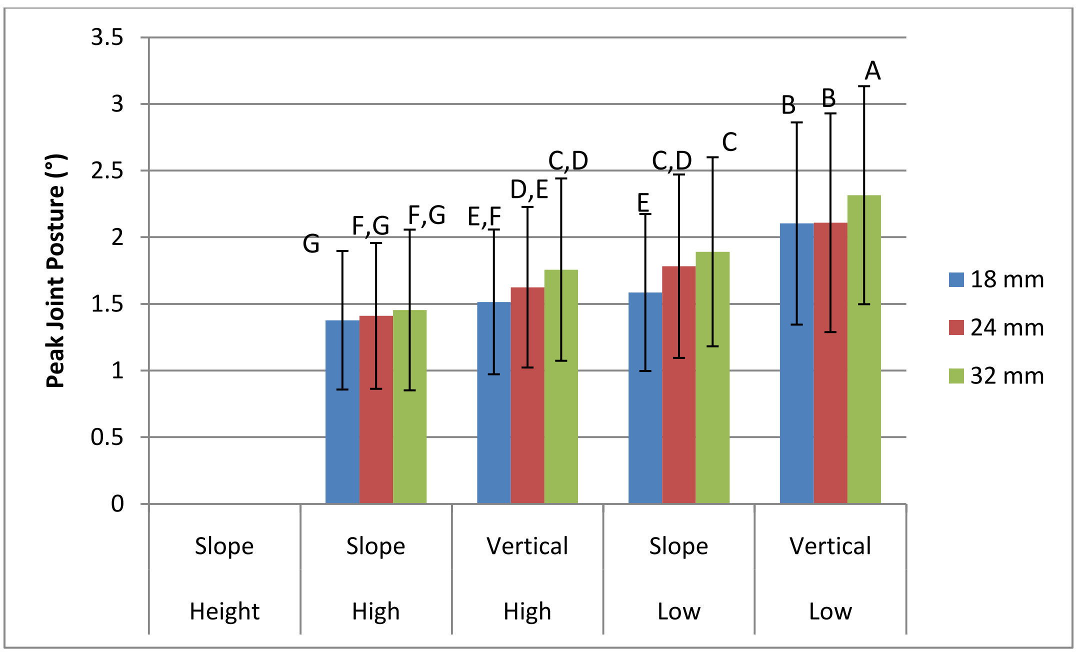

Figure 4.62 - Mean EMG of BB for Diameter x Height x Slope

To correct for the increasing range of residuals across the range of model predictions, A logarithmic transformation was applied to the ECR response. The test showed significant effects of diameter ($F(2,413)=23.40$, $p=<.0001$, $\omega^2=0.0181$), height ($F(1,413)=100.35$, p=<.0001, ω^2=0.0871), and slope (F(1,413)=28.87, p=<.0001, ω^2=0.0332) (see full results in Table 4.19). The 18 mm diameter (Figure 4.63), high (Figure 4.64) and sloped (Figure 4.65) configurations each produced the lowest muscle activity responses.

Table 4.19 – Pouring Phase ECR MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	16.64	19	413	<.0001
Diameter (D)	23.40	2	413	<.0001
Height (H)	100.35	1	413	<.0001
Slope (S)	28.87	1	413	<.0001
D*H	1.03	2	413	0.3562
D*S	0.13	2	413	0.8756
H*S	2.43	1	413	0.1197
D*H*S	1.59	2	413	0.2055

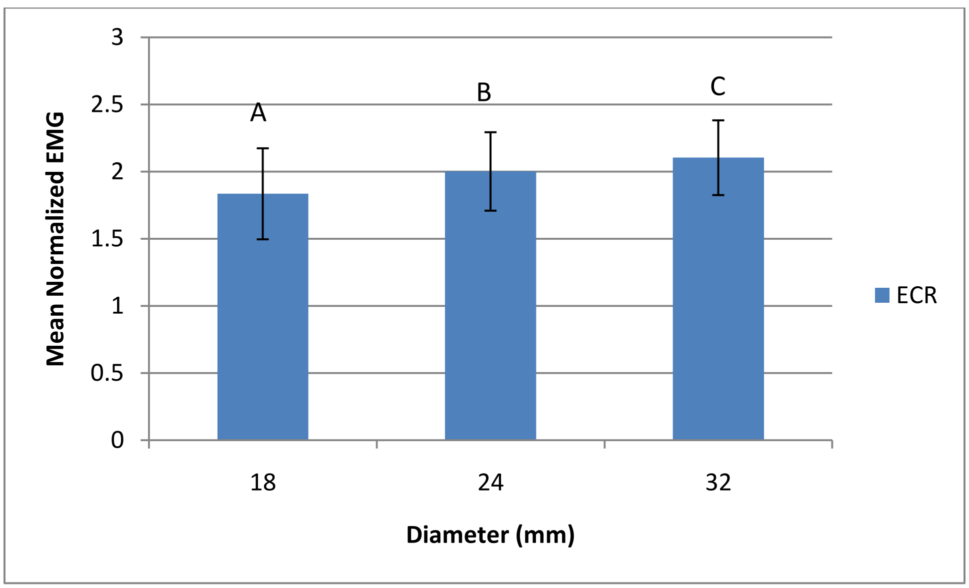

Figure 4.63 - Mean EMG of ECR for Diameter

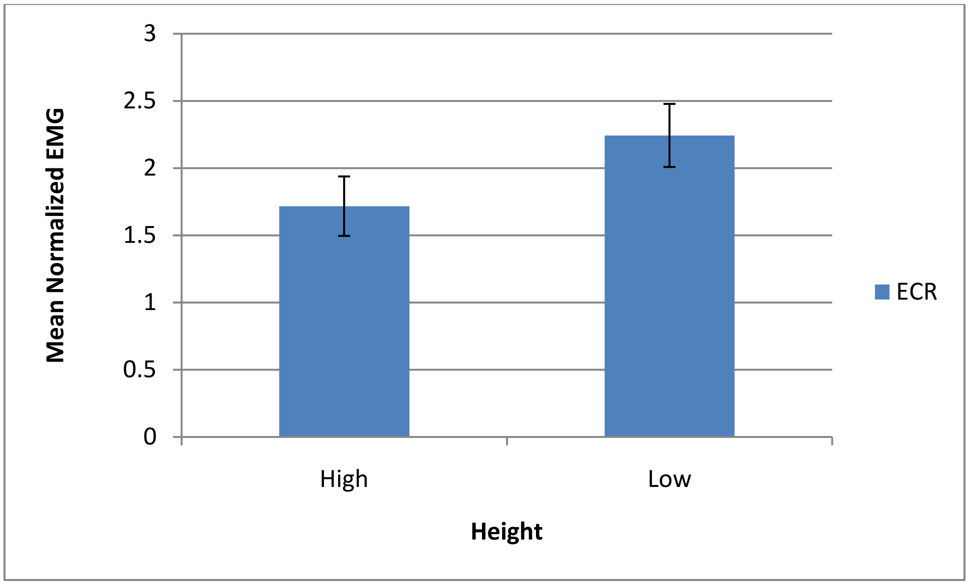

Figure 4.64 - Mean EMG of ECR for Height

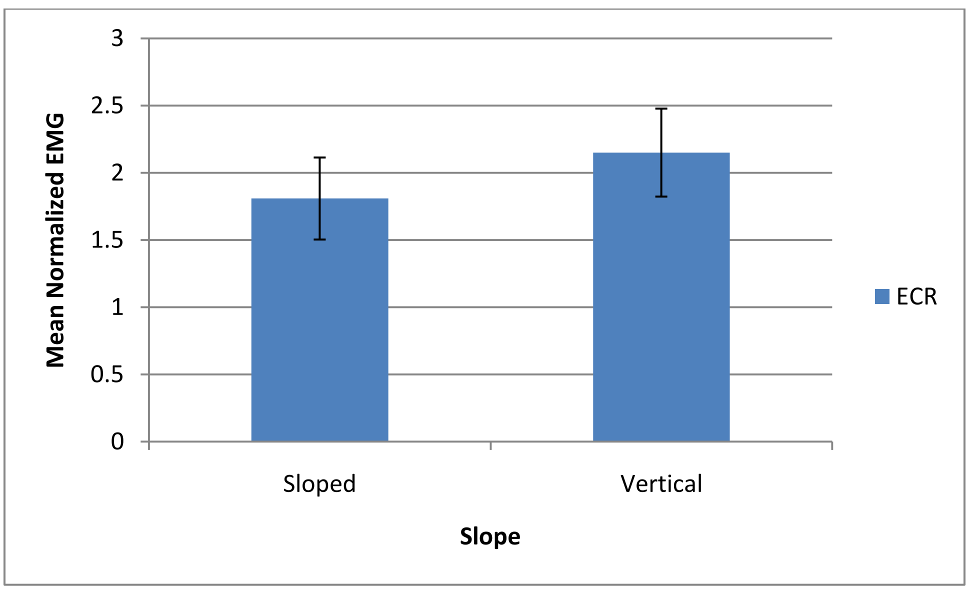

Figure 4.65 - Mean EMG of ECR for Slope

A square root transformation was applied to the FCR response because there was an over-prediction of the model at high values. Because all violations of the ANOVA assumptions were not corrected with this transform, another square root transformation was applied. Results showed that height ($F(1,413)=16.98$, $p=0.0010$, $\omega^2=0.0126$) and the interaction of height and slope ($F(1,413)=42.69$, $p=<.0001$, $\omega^2=0.0067$) both had significant effects on the response (see full results in Table 4.20). For height, muscle activity tended to be lower with a high handle (Figure 4.66). For the interaction, the high and vertical configuration produced the lowest muscle activity (Figure 4.67).

Table 4.20 – Pouring Phase FCR MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	17.13	19	413	<.0001
Diameter (D)	0.27	2	413	0.7686
Height (H)	16.98	1	413	0.0010
Slope (S)	0.01	1	413	0.9266
D*H	0.01	2	413	0.9949
D*S	1.46	2	413	0.2324
H*S	42.69	1	413	<.0001
D*H*S	1.39	2	413	0.2504

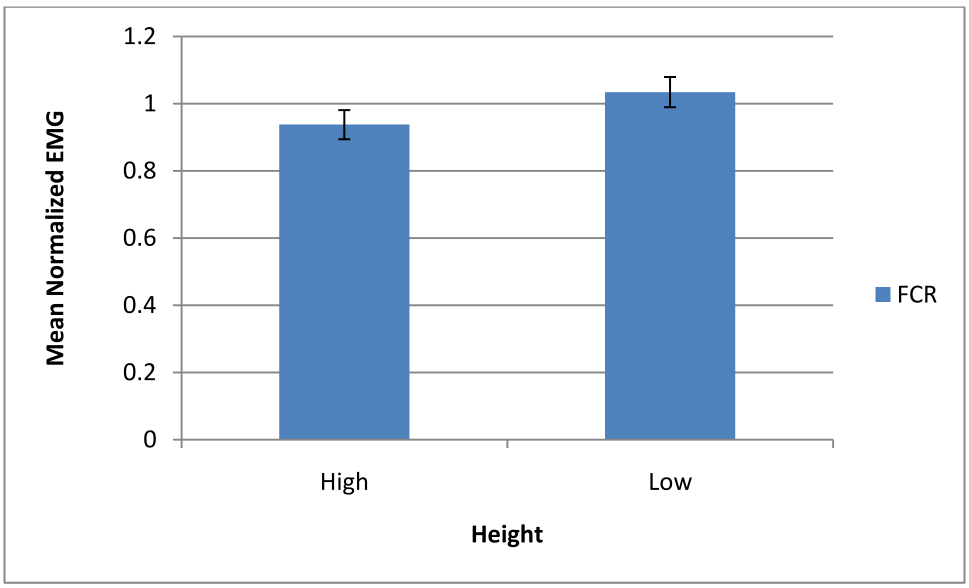

Figure 4.66 - Mean EMG of FCR for Height

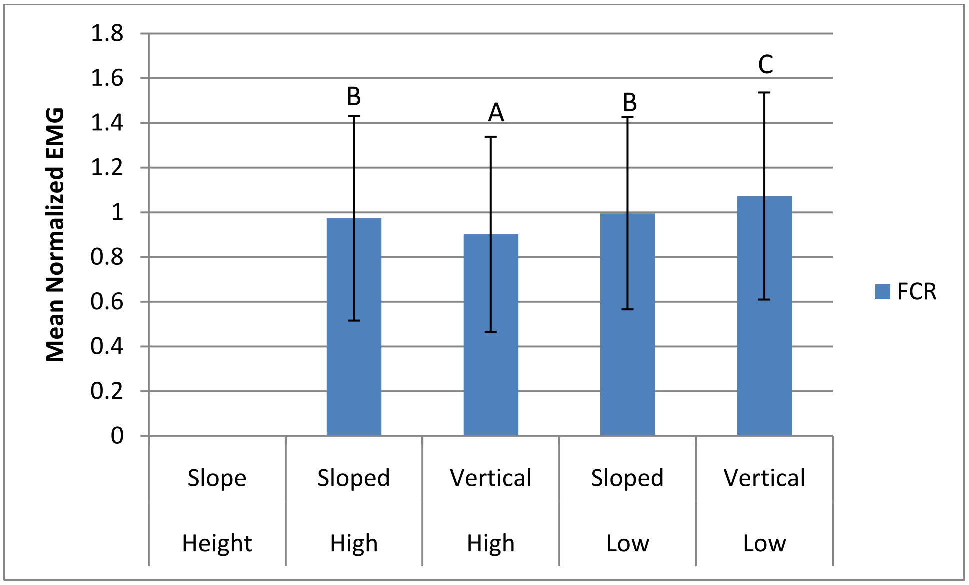

Figure 4.67 - Mean EMG of FCR for Height x Slope

4.2.2 Joint Postures

A Box-Cox transformation was applied to the SA response because there was an under-prediction of the model at low values. Results showed that diameter ($F(2,413)=4.88$, $p=0.0151$, $\omega^2=0.0111$) and the interaction of diameter and slope ($F(2,413)=6.92$, $p=0.0011$, $\omega^2=0.0045$) had significant effects on peak joint postures (see full results in Table 4.21). For the diameter, the 24 mm diameter handle produced the lowest peak joint posture, though this was not significantly different from the 18 mm diameter response (Figure 4.68). The interaction of the 18 mm diameter and vertical handle produced the lowest response; however, this was not significantly different from the 24 mm diameter and vertical handle, or the 24 mm diameter and sloped handle (Figure 4.69).

Table 4.21 – Pouring Phase SA MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	4.90	19	413	<.0001
Diameter (D)	4.88	2	413	0.0151
Height (H)	1.34	1	413	0.2678
Slope (S)	1.41	1	413	0.2508
D*H	0.14	2	413	0.8663
D*S	6.92	2	413	0.0011
H*S	2.63	1	413	0.1057
D*H*S	1.94	2	413	0.1453

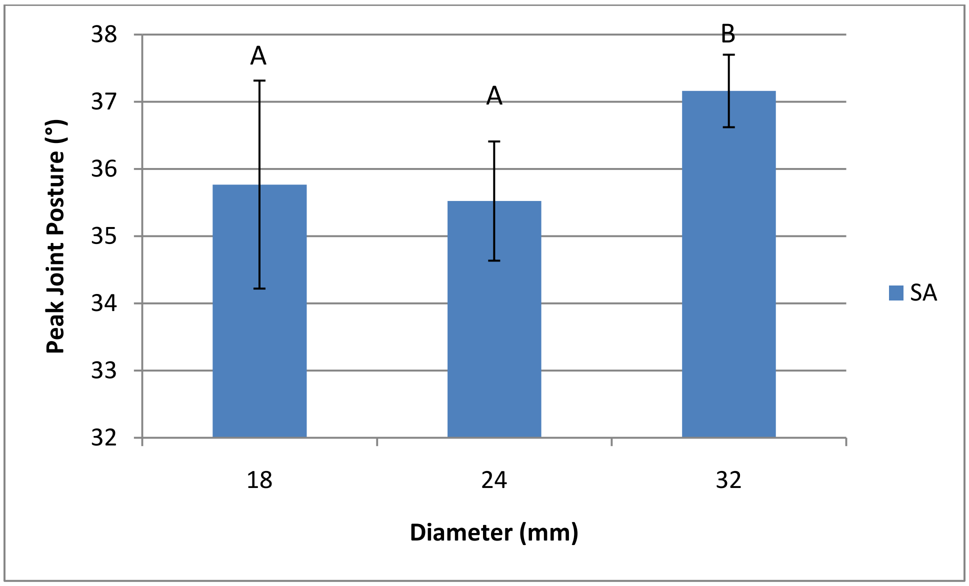

Figure 4.68 - Peak SA for Diameter

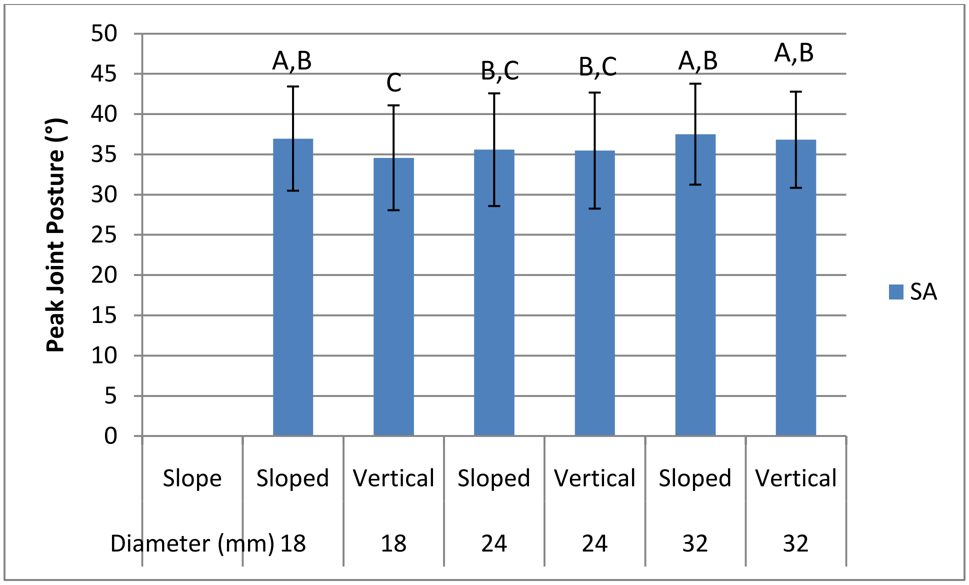

Figure 4.69 - Peak SA for Diameter x Slope

Due to an under-prediction of the model at low values and an over-prediction of the model at high values, a Box-Cox transformation was applied to the SF response. The transformed data conformed to the assumptions. Height ($F(1,413)=28.32$, $p=0.0017$, $\omega^2=0.0304$) and slope ($F(1,413)=16.26$, $p=0.0010$, $\omega^2=0.0335$) were both shown to have significant effects on the response (see full results in Table 4.22). Their interaction also had a significant effect ($F(1,413)=9.22$, $p=0.0025$, $\omega^2=0.0029$). The low configuration (Figure 4.70) and the vertical configuration (Figure 4.71) generally resulted in lower peak joint angles. For the interaction, both the low and vertical configurations together produced the lowest response (Figure 4.72).

Table 4.22 – Pouring Phase SF MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	11.91	19	413	<.0001
Diameter (D)	0.41	2	413	0.6748
Height (H)	28.32	1	413	0.0017
Slope (S)	16.26	1	413	0.0010
D*H	2.86	2	413	0.0585
D*S	0.42	2	413	0.6605
H*S	9.22	1	413	0.0025
D*H*S	0.64	2	413	0.5261

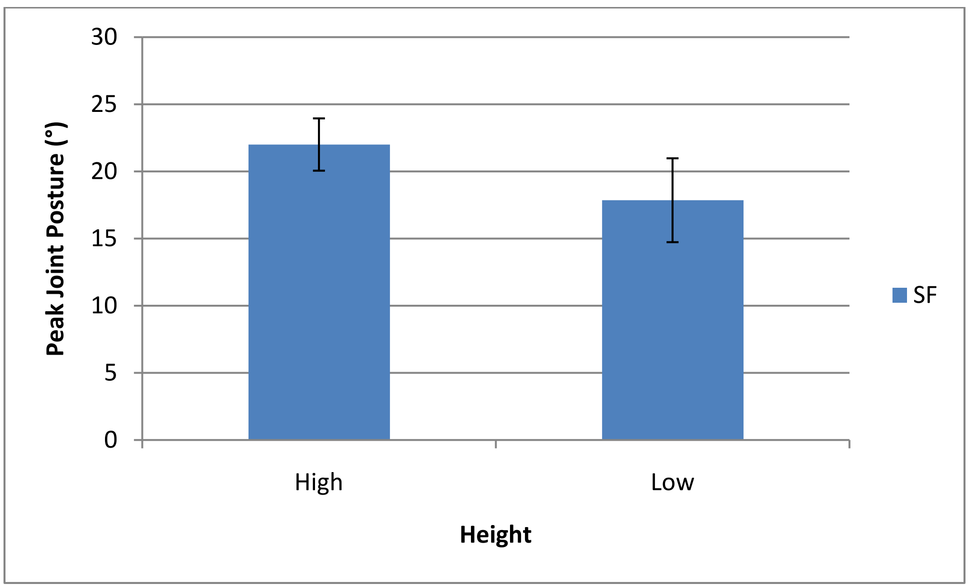

Figure 4.70 - Peak SF for Height

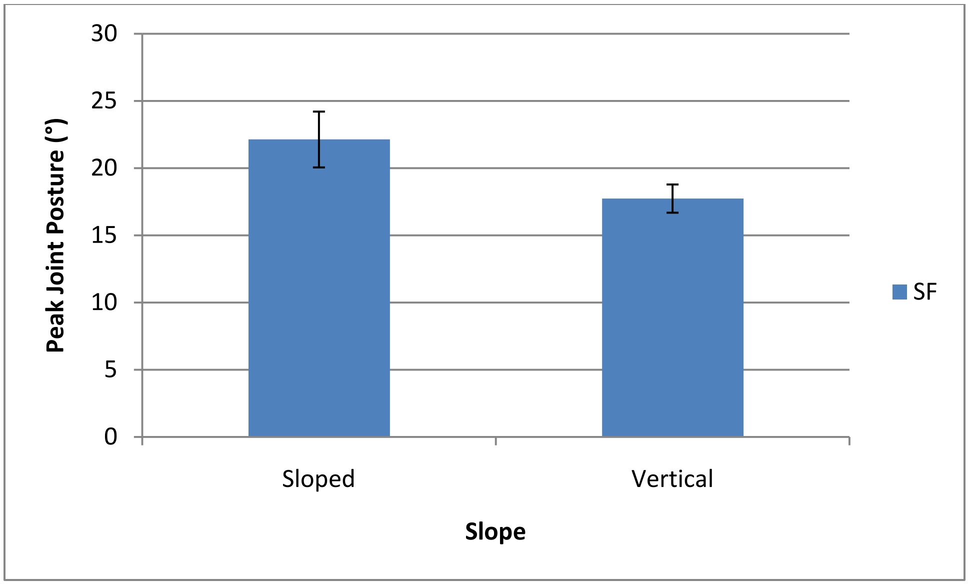

Figure 4.71 - Peak SF for Slope

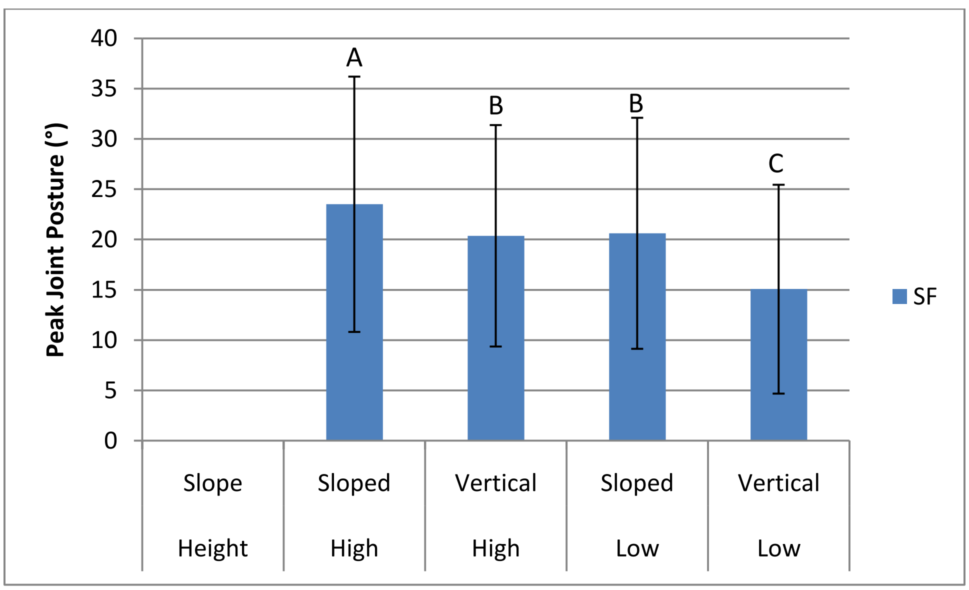

Figure 4.72 - Peak SF for Height x Slope

The WUD response conformed to the assumptions of ANOVA without the use of transformations. The interaction of diameter and height ($F(2,413)=3.04$, $p=0.0489$, $\omega^2=0.0022$) was found to have a significant effect on the response (see full results in Table 4.23). The 32 mm diameter handle and 24 mm diameter handle combined with the low height produced the lowest responses. These two configurations were not shown to be statistically different from each other (Figure 4.73).

Table 4.23 – Pouring Phase WUD MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	10.63	19	413	<.0001
Diameter (D)	1.60	2	413	0.2705
Height (H)	72.24	1	413	0.1604
Slope (S)	0.45	1	413	0.5255
D*H	3.04	2	413	0.0489
D*S	0.70	2	413	0.4969
H*S	1.44	1	413	0.2310
D*H*S	0.79	2	413	0.4537

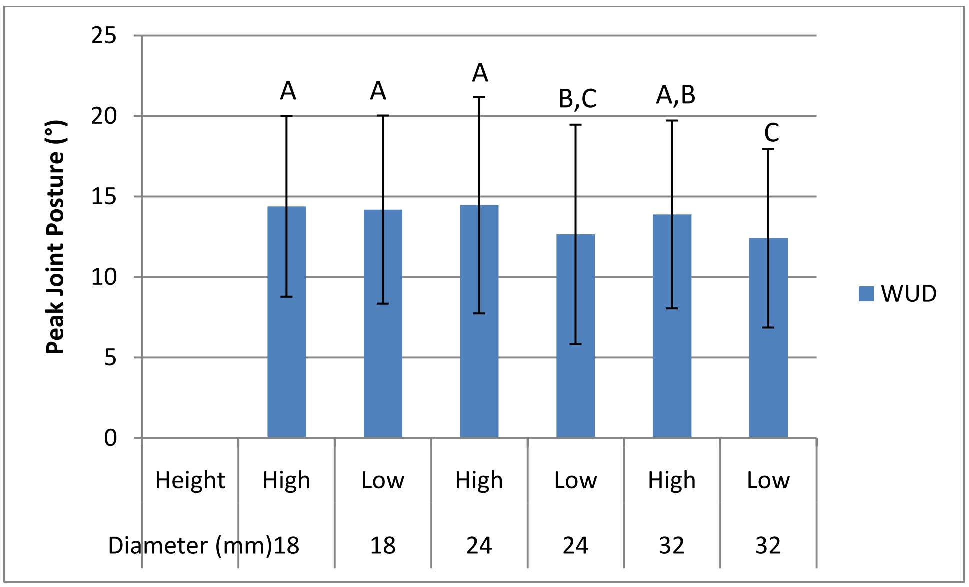

Figure 4.73 - Peak WUD for Diameter x Height

4.2.3 Average Grip Force

To correct for an over-prediction of the model at high values, a square root transformation was applied to the average grip force data. Results showed that diameter (F(2,413)=15.16, p=0.0003, ω^2=0.0124), height (F(1,413)=54.80, p=<.0001, ω^2=0.0706), and slope (F(1,413)=84.05, p=<.0001, ω^2=0.1028) all had significant effects on the response. The two-way interactions of diameter and height ($F(2,413)=7.09$, $p=0.0009$, $\omega^2=0.0020$) and of height and slope ($F(1,413)=89.02$, $p=<.0001$, $\omega^2=0.0147$) were also found to be significant (see full results in Table 4.24). The 18 mm diameter (Figure 4.74), high (Figure 4.75), and sloped (Figure 4.76) handle configurations each produced the lowest average grip force. For the diameter and height interaction, the 18 mm diameter and high configuration together produced the lowest response (Figure 4.77). The interaction of the high and sloped configurations yielded the lowest force output (Figure 4.78).

Table 4.24 – Pouring Phase Average Grip Force MANOVA Results

	F Value	*Num DF*	*Den DF*	*P>F*
Subject (Sub)	18.88	19	413	<.0001
Diameter (D)	15.16	2	413	0.0003
Height (H)	54.80	1	413	<.0001
Slope (S)	84.05	1	413	<.0001
D*H	7.09	2	413	0.0009
D*S	2.10	2	413	0.1241
H*S	89.02	1	413	<.0001
D*H*S	0.33	2	413	0.7193

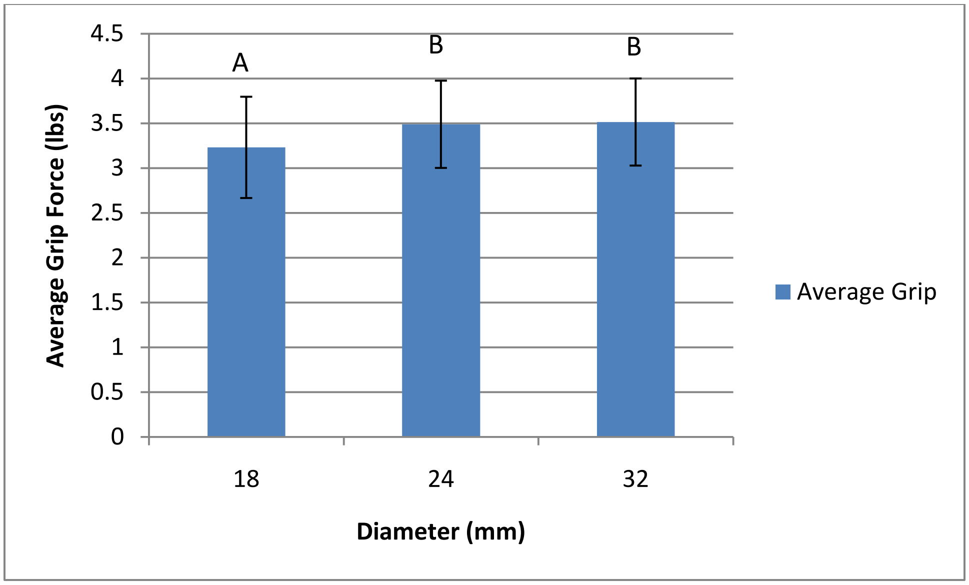

Figure 4.74 - Average Grip for Diameter

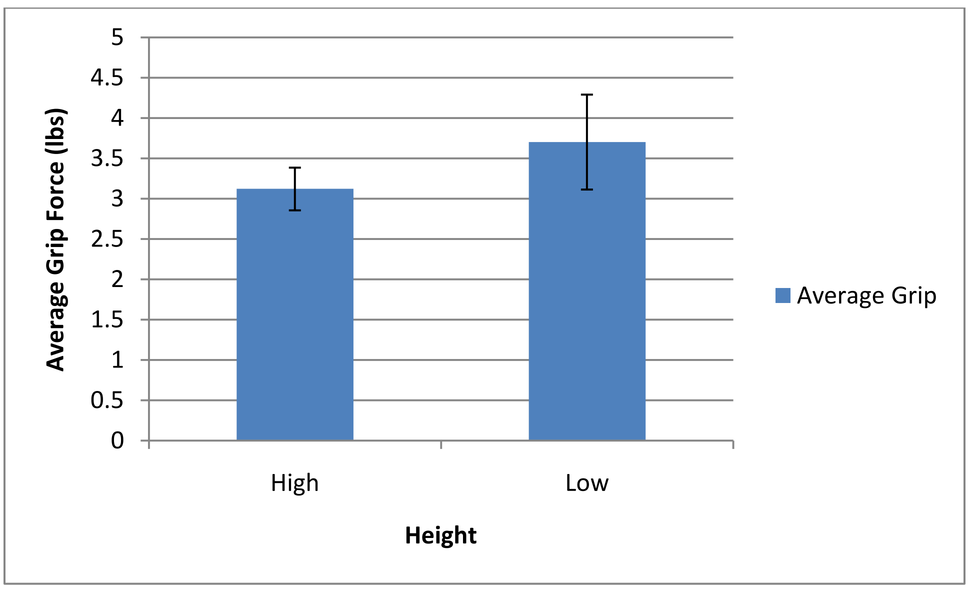

Figure 4.75 - Average Grip for Height

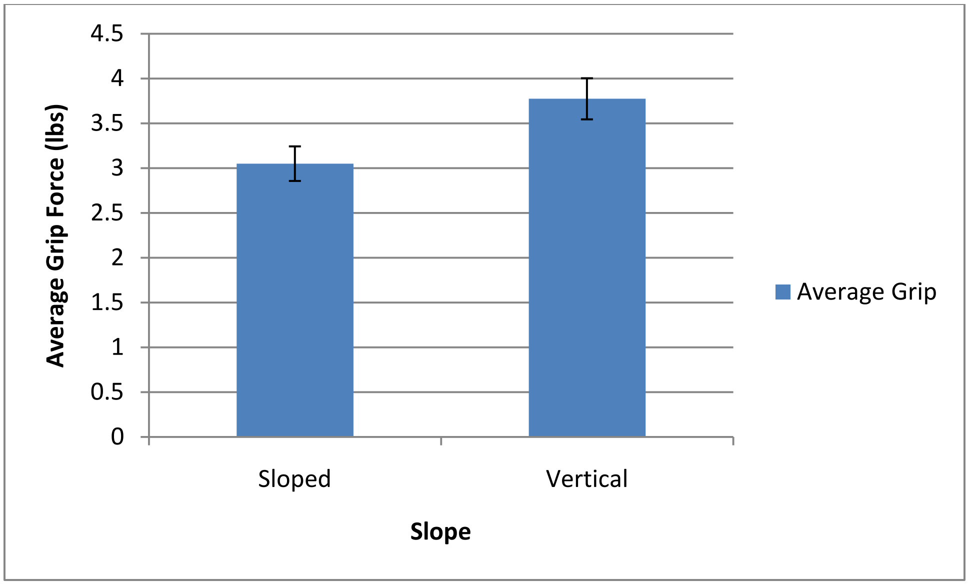

Figure 4.76 - Average Grip for Slope

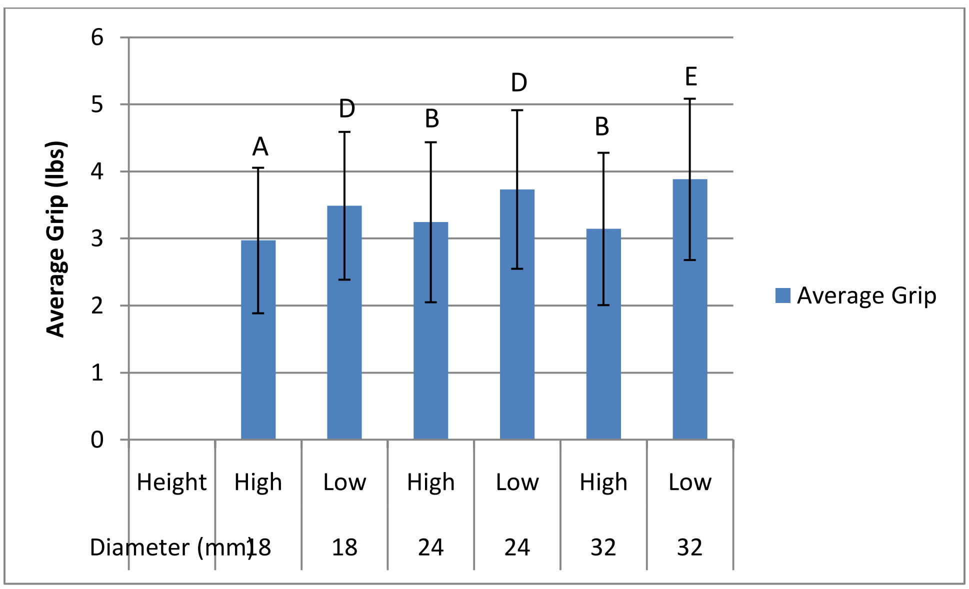

Figure 4.77 - Average Grip for Diameter x Height

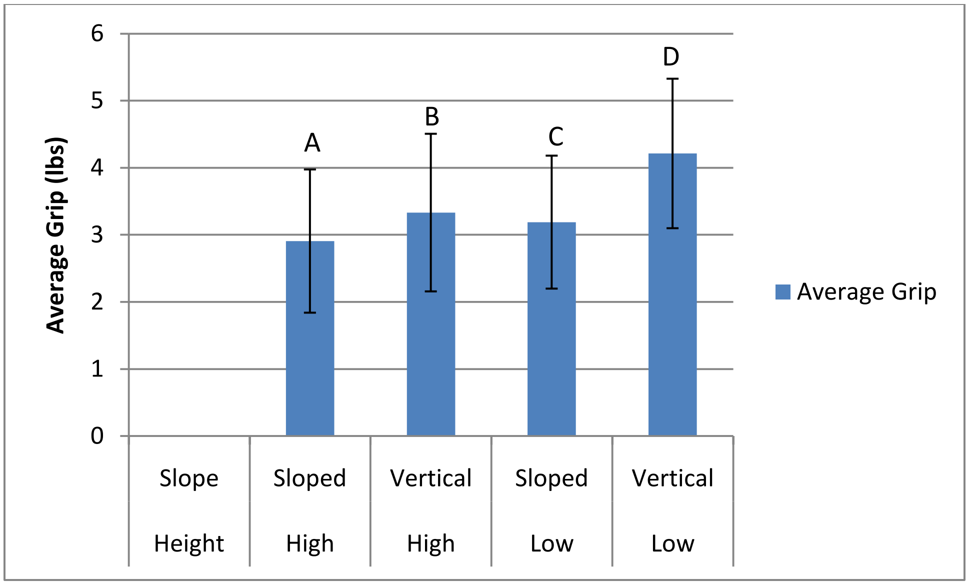

Figure 4.78 - Average Grip for Height x Slope

5 Discussion

Based on previous research (Ayoub and LoPresti, 1971; Edgren et al., 2004; Khalil, 1973), increasing the diameter was expected to lower the muscle activity in the ECR and FCR. The 32 mm handle was expected to produce the lowest response. From a static analysis of a system including the container and the hand/wrist, the high height was expected to lower the muscle activity in the ECR and FCR compared to the low handle. This is due to the change in location of the center of mass of the container. The vertical handle was expected to reduce muscle activity in the ECR and FCR and also reduce peak WUD (Drury et al., 1985; Lewis and Narayan, 1993). Because of the increased WUD the sloped handle would cause, it was also expected that the sloped handle would also increase the peak SA (Chaffin et al., 2006). The interactions were expected to yield the same results as the main effects.

5.1 Lifting Phase

5.1.1 Diameter

A significant effect of diameter was seen on the average normalized muscle activity response of the BB and ECR. A significant effect was also seen on the SA and SF peak postures. For the BB, the 18 mm diameter handle reduced the response by 5.1% and 10.1% compared to the 24 and 32 mm diameter handle, respectively. The ECR response from the 18 mm diameter handle was 5.5% and 11.4% lower compared to the 24 and 32 mm diameter handles, respectively. For the SA peak angles, the 24 mm handle produced the lowest peak joint angle and lowered the peak angle 1.2% from the 24 mm diameter handle and 5.6% from the 32 mm diameter handle. The 32 mm diameter handle lowered the SF response 8.8% and 7.0% when compared to the 18 and 24 mm diameter handles, respectively.

The diameter did not have the expected effect of decreasing muscle activity in the ECR with increasing handle sizes, as seen in previous studies. In fact, ECR muscle activity increased as handle diameter increased. This could be due to the fact that this task required a rotation in the handle that had not been tested in any previous studies. It can be seen from previous studies (Ayoub & LoPresti, 1971; Khalil, 1973) that optimum handle diameter is partially task dependent; thus, this task may favor smaller diameters. The significant effect of diameter on BB suggests that a coactivation of the ECR and BB was perhaps required to perform this task. The significant effect of diameter on SA and SF may imply that the quality of the grip afforded by the diameter may have affected the posture of the shoulder.

5.1.2 Height

A significant effect of height was seen on all muscles of interest including AD, MD, PD, TR, IF, BB, ECR, and FCR. Height also significantly affected the average grip force as well as the peak SA and SF postures. For the AD, the low handle reduced the average normalized muscle activity by 12.4% compared to the high handle. The low handle lowered the MD response by 11.8%. With respect to the PD, the low handle reduced the muscle activity by 11.3% when compared to the high handle. In the TR, the low handle reduced the response by 14.1%. For the IF, the low handle produced an output 7.7% lower than the high handle. For the BB, the high handle lowered the muscle activity by 12.5%. In the ECR, the high handle reduced the response by 7.1%. With respect to the FCR, the high handle lowered the EMG response by 8.0%. With the average grip force, the high handle produced an improvement of 7.5% over the lower handle. The low handle decreased the SA peak joint angle by 4.6%. The low handle decreased the SF peak joint angle by 15.6%.

In general, the shoulder muscles and joints all benefited from a lower handle while the forearm muscles and biceps were better with a higher handle. Average grip force was also lower with the high handle. The higher handle might force participants to reach higher for the bottle; thus, causing greater SA and SF. This would lead to increased muscle activity in the shoulder muscles (AD, MD, PD, TR, IF). The handle height most likely affects grip through a change in the location of center of mass of the container relative to the pivot point (i.e., the wrist). The weight of the bottle acts as the force that naturally tilts the bottle when being held. The grip force, BB, ECR and FCR all help to prevent the weight from tipping the container over during the lifting phase. When the handle is in the high position, the center of gravity of the container is lower relative to the wrist as compared with the low condition. This has the effect of lowering the contribution of weight to tilting the container, which would lower the needed grip force and thus lower the necessary activity in the BB, ECR, and FCR. In the low condition, the contribution of weight to tilting the container would be higher.

5.1.3 Slope

Slope had a significant effect on the AD, MD, PD, TR, IF, BB, average grip force, SA, and WUD. For the AD, the vertical handle reduced the response in the AD by 7.9%. The MD response was lowered by 16.5% when using the vertical handle over the sloped one. The PD response was lowered 16.4% when using the vertical handle over the sloped handle. With respect to TR activity, the vertical handle lowered the activity by 15.0%. The vertical handle had an 8.2% lower IF response compared to the sloped handle. The sloped handle reduced the BB response by 13.3% compared to the vertical handle. Average grip force decreased 11.9% under the sloped handle compared to the vertical handle. The vertical handle decreased the amount of SA by 11.5%. For the WUD, the sloped handle reduced the amount of WUD by 9.4%.

Much like the handle height, the optimum slope of attachment also depended on the general body part in question. The muscles and postures of the shoulder (AD, MD, PD, TR, IF, and SA) generally benefitted from the use of the vertical handle while the BB, grip force, and WUD were better under sloped handle. The sloped handle had a negative effect on the amount of SA and a positive effect on the amount of WUD. Previous studies have shown that people will often abduct their shoulder in an effort to relieve stresses resulting from extreme wrist deviations (Chaffin et al., 2006). The amount of SA done to relieve the wrist could have been enough such that the amount of WUD was greatly reduced and thus caused even less deviation than would have been necessary in the vertical handle condition. The greater SA thus was likely the cause for the increased activity in the shoulder muscles (AD, MD, PD, TR, IF). The smaller amount of wrist deviation required with the sloped handle configuration likely allowed for a better grip on the handle and thus required less grip force to complete the task. It was unexpected that the ECR and FCR were not significantly affected by the slope. Previous studies have shown that with increasing the amount of wrist deviation increased the forearm muscle activity required in a gripping task (Drury et al., 1985). The action of the shoulder to prevent wrist deviation likely negated the effects of the slope on the ECR and FCR.

5.1.4 Interaction of Height and Slope

A significant interaction effect of height and angle of attachment was seen for the AD, MD, PD, BB, ECR, FCR, SA, SF and WUD responses. With the exception of the ECR, all interactions yielded results consistent with the main effects results. For the interaction of height and slope on the ECR response, the high and vertical handle configuration produced the lowest muscle activity. This represents a decrease of 4.7% when compared to the high and vertical handle, which was expected to produce the lowest response based on the hypothesis that the interactions would yield the same results as the main effects. It is possible that the interaction of the high and vertical handle altered the action of the ECR muscle to potentially relocate the exertion to another muscle in the forearm.

5.1.5 Interaction of Diameter and Slope

A significant interaction effect of diameter and slope was seen for the muscle activity of the AD, BB, ECR and FCR. A significant interaction effect was also found for the joint postures in SA, SF, and WUD. Average grip force was also significantly affected. The interaction results were consistent with the pattern of main effects results.

5.1.6 Interaction of Diameter, Height of Attachment, and Slope

A significant three-way interaction between among handle diameter, height, and angle was seen with the peak WUD. The combination with producing the lowest deviation was the consistent with the main effects results.

5.2 Pouring Phase

5.2.1 Diameter

A significant effect of diameter was seen on the mean normalized muscle activity of the AD, MD, PD, BB, and ECR. A significant effect was also found on the average grip force and the SA peak posture. For the AD, the 32 mm diameter handle produced a response 6.8% and 6.6% lower than the 18 and 24 mm diameter handles, respectively. The 18 mm diameter handle produced the lowest MD response, 1.6% and 6.4% lower than the 24 and 32 mm diameter handles. With respect to the PD, the 18 mm diameter handle produced the lowest muscle activity, which was 3.6% lower than the 24 mm diameter handle and 7.8% lower than the 32 mm diameter handle. For the BB, the 18 mm diameter handle was 5.0% lower than the 24 mm diameter handle and 11.3% lower than the 32 mm diameter handle. The mean response in the ECR under the 18 mm diameter handle yielded a result 8.3% and 12.8% lower than the 24 and 32 m diameter handles, respectively. For the average grip force, the 18 mm diameter handle lowered the grip force by 7.4% and 8.1% compared to the 24 and 32 mm diameter handles. The 24 mm diameter handle produced the lowest SA response, lowering the peak joint posture by 0.6% and 4.4% for the 18 and 32 mm diameter handles, respectively.

Diameter had a significant effect on AD, MD, and PD. It is possible that the quality of grip that the different handle diameters afforded for participants affected the posture in the shoulder and thus the associated muscles. This is partially corroborated by the significant effect of diameter on peak SA values. A study by MacDonell and Keir (2005) found that concurrent grip exertions have a deleterious effect on the muscles in the shoulder as well as the ability of the shoulder to generate moments. This shows a potential coactivation between the proximal and distal muscle groups of the arm. Though AD, MD and PD muscle activity did not necessarily decrease with increasing grip force, it reinforces the connection between the two muscle groups and suggests a more complicated interaction than previously found. Increasing diameter also did not have the expected of decreasing muscle activity in the ECR. As diameter increased, so did the ECR response. As stated earlier, it is possible that that the liquid pouring task did not necessarily follow the standard notions of optimum handle size. This is partially corroborated by the significant effect of diameter on average grip force, which also increased as diameter increased. As stated earlier, the significant effect of diameter on BB hints at a possible coactivation of the BB with the ECR to effectively perform the task.

5.2.2 Height

A significant effect of height on the muscle activity of the AD, MD, TR, BB, ECR, and FCR was seen. Height also significantly impacted the average grip force and the peak SF. For the AD, there was a 14.7% decrease for the low handle compared to the high handle. The low handle lowered the MD muscle activity by 15.3% compared to the high handle. For the TR, the change from the high to low handle induced a 4.1% decrease in EMG levels. The high handle decreased muscle activity in the BB by 22.5% when compared to the low handle. For the ECR, the high handle decreased the response by 23.5% over the low handle. In the FCR, the high handle produced an average grip force 15.7% lower than the low handle. For the SF peak joint posture, the low handle decreased the peak posture by 18.9% compared to the high one.

As seen before in the lifting phase, the muscles and postures in the shoulder (AD, MD, TR, and SF) perform with lower muscle activity and lower peak joint postures under the low handle condition. Conversely, the BB, ECR and FCR activation, and average grip force were all lower for the high handle configuration. In the first phase of the task, the muscles were used to stop the tilting of the bottle due to the weight. Because the center of gravity of the container was lower relative to the wrist in the high handle condition, the weight had less of a contribution to the tilt. Based on this interpretation, the low handle height should have resulted in lower muscle activity in the BB, ECR, and FCR during the pouring phase of the task. A higher contribution of weight to the torque would have made it easier to tilt the container to initiate the pour. This, however, was not the case. With the high handle, the lower contribution of the container weight to torque likely increased the amount of SF required to tilt the container. The increased SF would have caused greater activity in the AD, MD, and TR. Participants may have also loosened their grip to aid in the pour. Other muscles in the forearm might have compensated for the reduced activity of the ECR and FCR in the high handle configuration; however, no other forearm muscles were measured in this study.

In the low handle configuration, in order to prevent an uncontrolled pour, the ECR and FCR had to work to keep the container from tilting too far over.

5.2.3 Slope

The slope had a significant effect on the muscle activity of the AD, MD, PD, TR, BB, and ECR. It also significantly affected the amount of average grip force as well as the peak SF. For the AD, the vertical handle decreased the muscle activity by 15.2% compared to the sloped handle. The MD’s EMG response showed a 24.2% decrease in activity when using the vertical handle. The vertical handle lowered the PD muscle activity 18.7% compared to the sloped handle. For the BB, the sloped handle reduced the muscle activity by 16.8% when compared to the vertical handle. The sloped handle resulted decreased the average grip force 19.2% under the sloped handle over the vertical one. The vertical handle lowered the peak SF by 19.9%.

In general, the shoulder muscles and postures (AD, MD, PD, TR, and SF) performed with lower average normalized muscle activity and lower peak joint postures under the vertical handle condition. The BB and ECR had lower activity levels under the sloped handle condition. The average grip force was the lowest under the sloped handle condition as well. The peak SA was most likely not affected by the handle because the position of the arm during the pour did not allow for substantial shoulder abduction and thus forced the participants to compensate for extreme wrist deviations by flexing the shoulder. While the pouring motion itself would have caused WUD and SF, the sloped handle further contributed to this. The sloped handle would have forced the participant to initiate the pouring motion in an already deviated position compared to the vertical handle. The average grip force was also lower during the sloped handle. Research has shown that another tactic to avoid extreme wrist deviations in a gripping task is to loosen the grip (Drury et al., 1985). Although wrist posture can dictate the amount of grip force that can be applied, it was not found to be significantly different between the sloped and vertical handle. Thus, a release in grip to reduce wrist deviations was likely. Both of these strategies (increased SF and loosening grip) could have decreased the amount of WUD necessary to complete the task in the sloped handle configuration to the extent that it was not found to be significantly different than the vertical handle condition. The increased SF required by the sloped handle condition most likely resulted in the higher muscle activity in the corresponding shoulder muscles. The decreased muscle activity in the BB and ECR during the sloped handle condition was most likely from participants reducing the amount of grip force applied.

5.2.4 Interaction of Height and Slope

A significant interaction of height and slope was seen for the mean normalized muscle activity of the MD, PD, TR, IF, BB, and FCR. The interaction was also significant for peak SF values and average grip force. With the exception of the FCR response, all interactions yielded results consistent with the main effects results. While the main effects results suggested a combination of the high and sloped configurations to produce the lowest results, the high and vertical combination actually did. This represents a decrease of 7.3% by the high and vertical handle. Perhaps this combination changed the muscle utilization strategy of the participants and transferred the work to other forearm muscles.

5.2.5 Interaction of Diameter and Slope

The interaction of diameter and slope was seen in the muscle activity response of the IF and in the peak SA posture. All interactions yielded results consistent with the main effects results.

5.2.6 Interaction of Diameter and Height

The interaction of diameter and height was significant for the peak WUD posture and average grip force. For the WUD, the 32 mm diameter and low height produced the lowest response. This represents a 10.7% decrease from the 32 mm and high handle configuration, which was expected to induce the lowest response based on the main effects results. This may have occurred because of the mutual effects of grip force and joint posture. Because higher grip force was seen with the 24 and 32 mm handles (which were not significantly different from each other) compared to the 18 mm handle, the higher grip could have constrained the wrist joint and thus did not allow it further movement. The average grip force yielded results consistent with main effects results.

5.2.7 Interaction of Diameter, Height, and Slope

Mean normalized muscle activity of the BB had a significant three-way interaction of the independent variables. The combination that produced the lowest results was consistent with the main effects results.

5.3 Axiomatic Design

The axiomatic design approach is a method of applying qualitative measures to product or system design features in order to identify an optimal design in terms multiple features. It is considered to be an alternative to historical approaches dominated by intuition and empiricism. A design complexity, or information, axiom postulates that minimizing the complexity or amount of information conveyed by a design will yield the best design. Again, in this approach, information is considered to be equivalent to the degree of complexity of a design from a user perspective. Thus, as the amount of information or complexity increases, the probability of a design falling within recommended ranges for parameters decreases. The following equation was used to calculate the information content of each container handle design in the present study:

$$I = \sum log_2 \frac{1}{p}$$

Where:

I = Information

p = probability of falling within recommended parameters, given by the ratio of the range to the tolerance (Suh, 1990)

Recommended ranges for the EMG data were chosen based on 90th percentile responses for each of the muscles. The SA, SF and WUD peak joint angle recommendations were based on previous research (below 20° in both directions for the shoulder and below 10° in WUD) (Chaffin et al., 2006; Drury et al., 1985). In a 1978 study, Jonsson suggested that moderate work should stay between 10-14% MVC (as cited by Ankrum, 2000). Based on this recommendation and an average maximum grip strength of 109 lbs (Crosby, Wehbé, & Mawr, 1994), a recommendation of below 10 lbs was made. During the lifting phase, none of the handle configurations conformed to the suggested WUD range. In the pouring phase, none of the handle configurations stayed within the range suggested for the peak SA values. Despite this, the 18 mm diameter, low, and vertical handle configuration yielded the best overall results. This is consistent with the findings above.

6 Conclusion

6.1 Overall Recommendations

The objective of this study was to validate the different handle parameters used on immediate-use containers that are often designed solely based on designer personal preferences. More specifically, this study examined the effect of diameter, height, and slope on muscle activation, joint postures, and grip force and used this information to identify an optimal handle configuration.

One possible conclusion to be drawn from the results is that a tradeoff occurs between shoulder and hand/wrist posture in order to reduce the muscle activity and grip force. One caveat to this is that although a sloped handle was generally more beneficial to the hand and wrist during the pouring phase, it did not significantly affect the amount of WUD. This was most likely due to SA to compensate for the increased WUD. In addition to the increased SA, grip force was also lower in the sloped condition for the pouring phase. While a lower grip force would generally be better, reducing grip force could also have been another strategy to reduce extreme wrist postures. Reduced grip force increases the risk of the handle slipping, decreasing the safety of the handle. Based on the findings, an 18 mm diameter, low, and vertical handle configuration is recommended.

Any deviations from the suggested handle configuration would result in sub-optimal performance. The exception to this would be increasing the handle diameter to 24 mm. Many of the responses significantly affected by diameter revealed no significant difference between the 18 and 24 mm handles. The use of a high handle increased average shoulder (AD, MD, PD, TR, IF) muscle activity by 13.0% and also increased SA and SF by an average of 11.6% in the lifting phase. In the pouring phase, the high handle increased shoulder (AD, MD, PD, TR) muscle activity by 11.6% and SF by 23.2%. The sloped handle increased average shoulder (AD, MD, PD, TR, IF) muscle activity 14.9% and increased SA by an average of 13.0% in the lifting phase. For the pouring phase, the sloped handle increased the muscle activity in the AD, MD, PD, and TR by an average of 19.7% and increased the SF response by an average of 24.8%. While the high and sloped configurations are generally good for muscle activity and postures of the hand/wrist, results indicated that it may be due to compensation with the shoulder rather than because of the design itself.

6.2 Limitations

One limitation of this study is that testing was done in a controlled environment. In the real world, speed, space and work conditions are important factors that influence how a task is performed. Awkward postures may need to be assumed in order to perform pouring tasks and will change the effectiveness of handle design. In addition, certain jobs may require high repetition of the task. This may be critical in affecting the pouring strategies.

Another limitation was the lack of additional forearm muscle activity measurements. As mentioned in Section 5.2.2, other muscles may have compensated for the reduced action of the ECR and FCR under the high handle configuration during the pouring phase.

6.3 Intellectual Merit

The findings of this study have broad applicability to immediate-use containers in the home and workplace. The research may benefit those who perform container pouring frequently, such as workers in the service industry. The study increases understanding of how the shoulder and hands function together in container pouring tasks. The information could be used in the future to create a model of the upper limbs in such work. The findings also go against previous research regarding optimal handle diameter. Convention states that a larger handle is better while the results from this study state the opposite. This further shows the complex relationship between optimal handle diameter and task.

6.4 Future Research

Further research in this area should address the previously mentioned limitations. Speed and other motivational factors could be introduced in testing. A field study using video monitoring could be conducted to assess the amount of repetition of the task. Also, additional forearm muscles could be analyzed to confirm whether or not the action of the ECR and FCR was transferred to other muscles in the forearm.

Another area of future research is further investigation of the effect of handle diameter. The diameters chosen for this study represented a fairly small range and thus had little effect relative to the height and slope of handle attachment. In addition, since some results were counter to prior research finding that larger handles decrease forearm muscle activity, it would be beneficial to study whether container pouring has different handle diameter requirements than other tasks.

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APPENDICES

APPENDIX A: Informed Consent Form

Liberty Mutual Research Institute for Safety
Informed Consent Form

This consent form is approved by the North Carolina State Institutional Review Board on July 3, 2010 and is valid until July 3, 2011

Purpose of Study

The purpose of this study is to examine how different handle designs affect how people use the muscles in their shoulder, arm, and hand when doing a pouring task. This is a joint study with researchers from Liberty Mutual Research Institute for Safety and North Carolina State University.

Participation

If you agree to participate, your participation will be for approximately 4 hours. You will be asked to complete required employment paperwork. After, height, weight, hand length, arm length, upper arm length, and maximum grip strength measurements will be taken. Markers will be attached to your arms, hip, and upper back to measure your arm and body motions and muscle activity. The placement sites for the muscle activity markers will be scrubbed with alcohol and will be shaved if there is a noticeable amount of hair on the site. Once the markers are placed and are working correctly, you will be asked to perform muscle contractions using the muscles of interest to confirm correct marker placement. Next, you will be asked to perform specific muscle contractions with a specified weight. Also, a “dry run” will be performed in which the pouring task is executed without liquid in the container. After a 5 minute rest, you will then be instructed to pick up the container using your dominant hand, pour a specific amount of liquid out into a cup, and set the container back down. The task will be completed in a standing position. You can set your own pace for this task. A total of 36 pouring trials will be performed to test different handle designs. One minute of rest will be given after each pouring trial, during which you will have the option to sit. After each trial you will be asked to fill out a discomfort survey. The weight of the container will be no more than 8 lbs. and each pouring trial will last approximately 15 seconds. You will be videotaped and photographed while the tasks are being performed. The focus of these recordings and pictures will be of the task, not of your face.

You will be employed by SELECTSTAFF, a temporary employment agency.

Your participation in this study is strictly voluntary. You are free to decline to participate before or at any time during the study without penalty or question. You will be under no pressure to continue. If you choose to discontinue your participation during the study you will be paid for the time you participated.

Risks

Because the task is an activity of daily living it is not considered strenuous. One possible risk may include slight physical discomfort in the shoulder, arm, and hand during and after the course of the experiment. This would be caused from the repeated pouring tasks. You will be given time to rest between trials to minimize this risk. Skin irritation may occur due to shaving.

If any health problems develop as a result of your participation in this study, you will be covered under the workers' compensation insurance provided through SELECTSTAFF.

Benefits

There will be no direct educational or health benefits to you for participating in this research.

Confidentiality

All data obtained in this experiment will be kept confidential. Individual identifying information will not be disclosed in reports or publications resulting from the study. All data will be kept separate from participants' names and other identifying information. Only researcher team members working on the study and employees involved in processing participant payment will have access to the information.

Compensation

You will be compensated as a temporary employee through the SELECTSTAFF employment agency. The pay rate for this study is $20 per hour. You will receive $80 as compensation upon completing this study. However, if you elect to withdraw from the study prior to completion, you will be paid for the time that you participated. You will need to provide a social security number to be paid. If you choose not to provide this information, you can still participate, but we cannot pay you.

Supervision and Questions

This study will be directly supervised by Chien-Chi "Max" Chang, Ph.D.. Questions or comments about participation should be directed to him at (508) 497-0260. If, after contacting the above person, you do not feel that your concerns were adequately addressed, you may contact Mr. Rick Fleck, Director of Research Operations for the Research Institute, at (508) 497-0222.

Video Monitoring

Video cameras are used in the testing areas. These cameras feed into monitors which are placed outside the room in which you will be tested. These monitors are provided (a) so that other researchers and staff do not enter while an experiment is being conducted, and (b) so that other researchers can monitor the procedures and activity in the room.

Videotaping

In this experiment, you may be photographed and/or videotaped. These photographic or video records will be kept confidential and no personally identifiable images will be used without your express permission.

Smoking Policy

As part of Liberty Mutual's interest in the health of its employees, customers, and guests visiting the Research Institute, there is a complete ban on smoking in, or in front of any of the buildings. Smoking areas have been designated behind each of the major buildings. If you wish to smoke during the experiment rest breaks, please notify the researcher running the study and a smoking area will be arranged.

Consent

Please read the following statement and sign on the line below if you agree to participate in the study.

I have read this document and understand the purpose of the study, and what will be expected of me if I agree to participate. By signing this consent form, I agree freely to participate as a research participant without any pressure having been placed on me to do so and understand that I am free to withdraw at any time without penalty.

______________________	______________________	______________
Print Name	*Signature*	*Date*

______________________	______________________
Witness	*Date*

APPENDIX B: Phone Screening Form

Phone Screening Form

Thank you for your interest in our research study. We are recruiting healthy men and women between the ages of 18 and 70 years for a laboratory study. The purpose of this study is to examine how different handle designs affect how people use the muscles in their shoulder, arm, and hand when doing a pouring task. You will be at the LMRIS for approximately 4 hours on the scheduled day. The pay will be $20 per hour for each hour of participation. We have some general medical questions we would like to ask you to determine whether or not you are eligible to participate. Are you comfortable answering the screening questions (if not, thank them for their time)?

Age? ________________

Height? _______________ Weight? ___________

Are you: Right-handed _____
Left-handed _____
Ambidextrous _____

Any health problems at present that limit your activity?
Yes / No
If yes, describe

Do you require assistance performing daily tasks (ex. bathing, feeding, walking, etc.)?
Yes / No
If yes, describe

Any recent surgeries (within 12 weeks)?
Yes / No
If yes, describe

Anything to prevent you from being on your feet for a good portion of the day?
Yes / No
If yes, describe

Any history of muscle or bone problems or pain?
Yes / No
If yes, describe

Any history of hand or elbow injury?

Yes / No

If yes, describe

Any history of shoulder injury?

Yes / No

If yes, describe

Any history of hip, knee, or ankle injury?

Yes / No

If yes, describe

Do you have normal or corrected to normal vision (at least 20/40)?

Yes / No

(If all the answers to questions are "No" after explanation)
You have completed the initial screening. Therefore, if you are still interested in joining I would like to get some personal information and to schedule a time for you to come in to complete the screening process and for testing.

Name? ______________________________ Phone? _________________________

What days and times are good for you? ____

Testing Date_______________ Testing Time____________________(am / pm)

Ok, we will see you on __(date and time scheduled)_. Please bring workout shorts (running shorts or spandex shorts) and a tank top. If you don't have these they will be provided.

Since you are actually being hired by a temp agency we will also need you to bring 2 forms of proof of employment eligibility and identity such as a social security card and driver license (see list from I-9 form). You will need to provide a social security number to be paid. If you choose not to provide this information, you can still participate, but we cannot pay you. Thank you ____(participant name)____. Have a nice day. (Hang up).

APPENDIX C: Medical Screening Form

Medical Screening Form

This form asks some general questions about your health as it relates to you participating in this study. You can refuse to answer any of the questions.

Visual deficits (not fully corrected)	☐ Yes ☐ No
Chronic dizziness	☐ Yes ☐ No
Vertigo (spinning or dizziness)	☐ Yes ☐ No
Syncope (fainting)	☐ Yes ☐ No
Seizure (epilepsy) disorders (seizure within last 6 months)	☐ Yes ☐ No
Sciatica (low back and leg pain)	☐ Yes ☐ No
Surgery (last 12 weeks)	☐ Yes ☐ No
Recent fracture/broken bone (last 12 weeks)	☐ Yes ☐ No
Recent sprain/strain of trunk or any joint (last 12 weeks)	☐ Yes ☐ No
Acute or chronic neck/upper back pain/strain/injury/surgery	☐ Yes ☐ No
Acute or chronic low back pain/strain/injury/surgery	☐ Yes ☐ No
Osteoarthritis or rheumatoid arthritis (active)	☐ Yes ☐ No
Scoliosis (curvature of the spine) (severe)	☐ Yes ☐ No
Active pain - any joint/extremity	☐ Yes ☐ No
Parkinson's disease	☐ Yes ☐ No
Cerebral palsy	☐ Yes ☐ No

Carpal tunnel syndrome	☐ Yes ☐ No
Dequervain's syndrome	☐ Yes ☐ No
Tenosynovitis / tendonitis / bursitis	☐ Yes ☐ No
Epicondylitis (e.g. tennis elbow, golfer's elbow)	☐ Yes ☐ No
Upper extremity radiculopathy (pinched nerve in neck)	☐ Yes ☐ No

Subject # _______________ **Date ___________**

APPENDIX D: Photo Release Form

Photo Release Form

PHOTOGRAPHY/

VIDEO

RELEASE FORM

I hereby authorize the Liberty Mutual Insurance Company of Boston, Massachusetts, a Massachusetts stock insurance company, and its officers, agents, and employees, to print, reproduce, or publish a photograph, portrait, video picture, or likeness of me taken on or about the below date.

Signed this _________ day of __________________, 20_______.

SIGNED

PRINT NAME

NAME OF ORGANIZATION

PARENT / GUARDIAN

WITNESS

APPENDIX E: Demographic Questionnaire

Demographic Questionnaire

Subject # ______________ **Date __________**

1) Age: _______

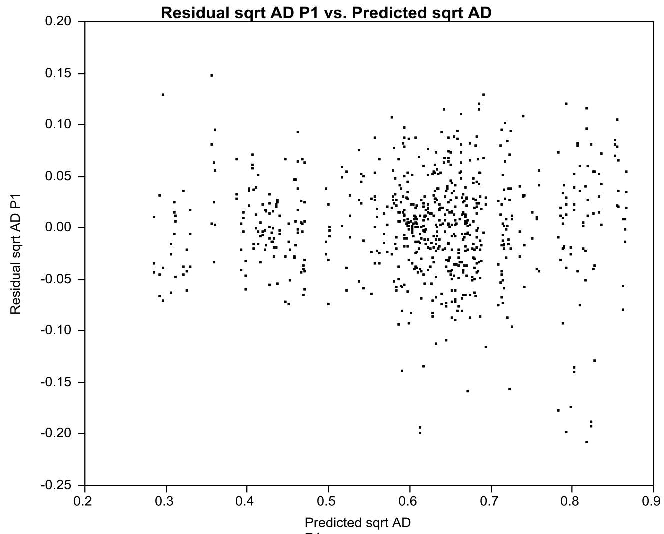
2) Gender (circle): M F

3) Do you currently, or have you previously held a job in which pouring liquid out of a container was a regular task?

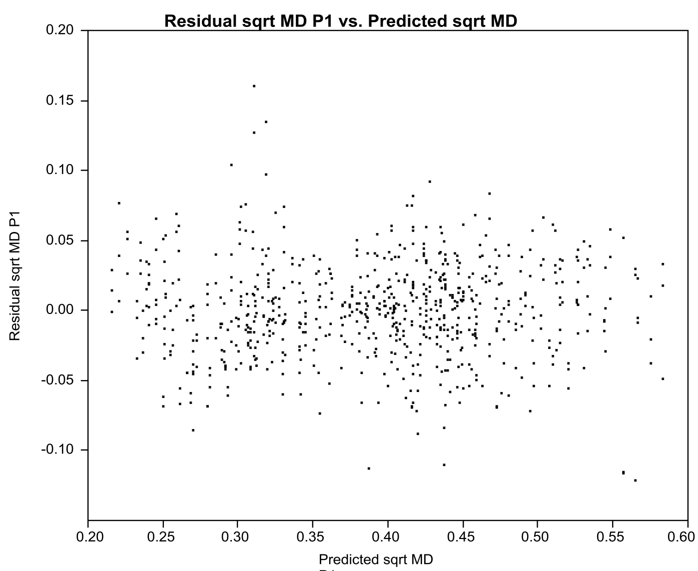
If yes, describe

APPENDIX F: Graphs for the ANOVA Assumptions

Test for Equal Variance

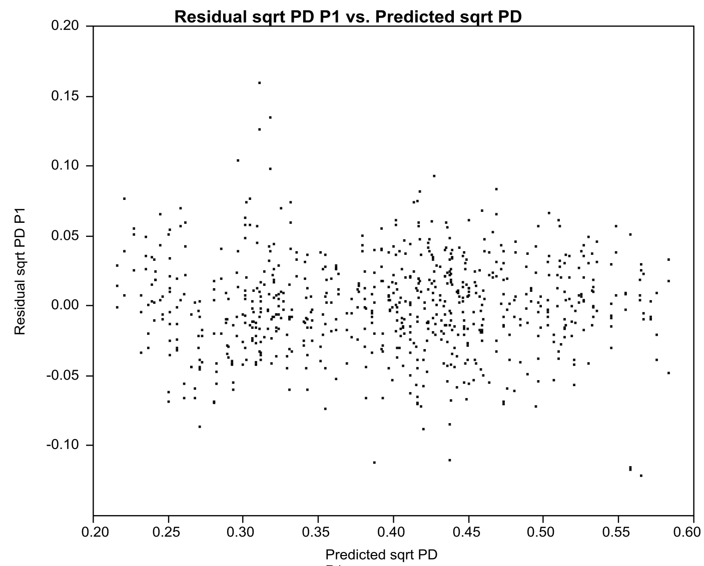


Scatterplot of the residuals as a function of the predicted values for P1 sqrt(AD)

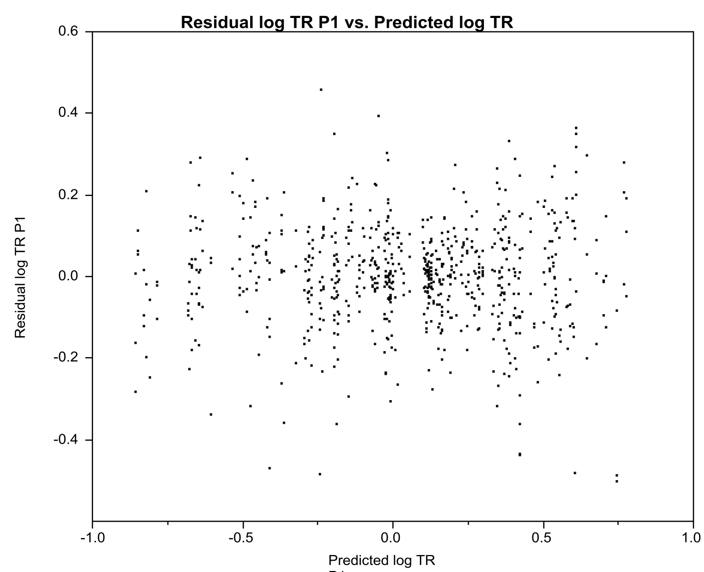


Scatterplot of the residuals as a function of the predicted values for P1 sqrt(MD)

APPENDIX F: Graphs for the ANOVA Assumptions

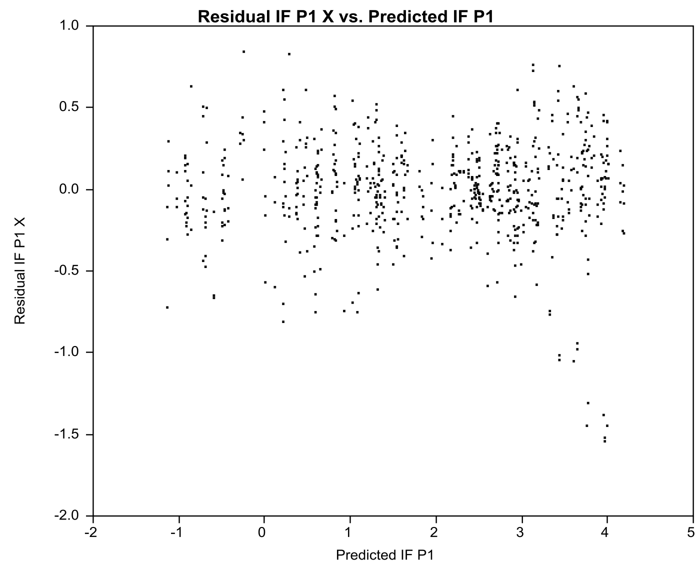


Scatter plot of the residuals as a function of the predicted values for P1 sqrt(PD)

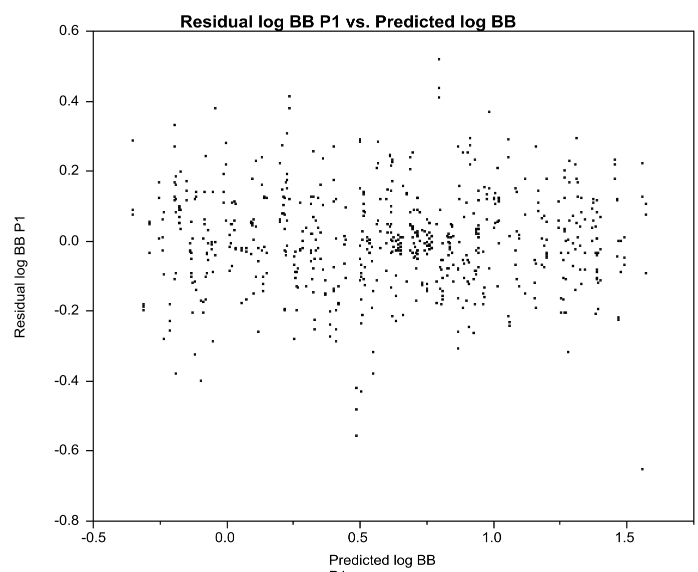


Scatter plot of the residuals as a function of the predicted values for P1 log(TR)

APPENDIX F: Graphs for the ANOVA Assumptions

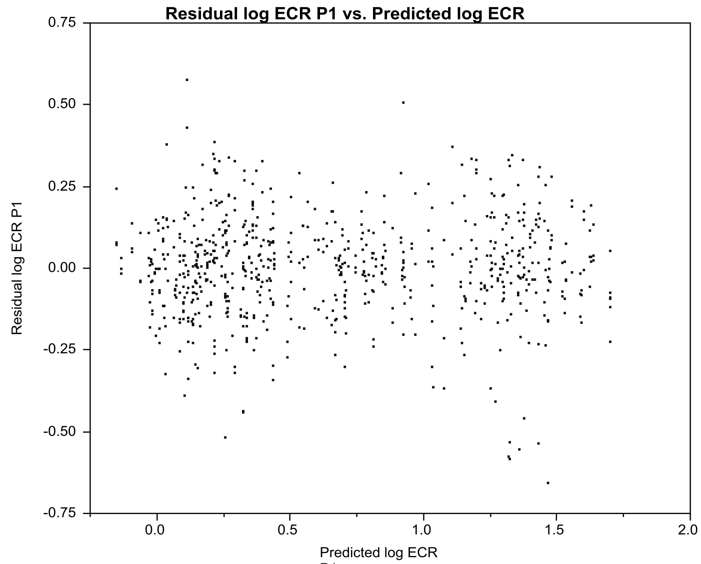


Scatter plot of the residuals as a function of the predicted values for P1 Box-Cox(IF)

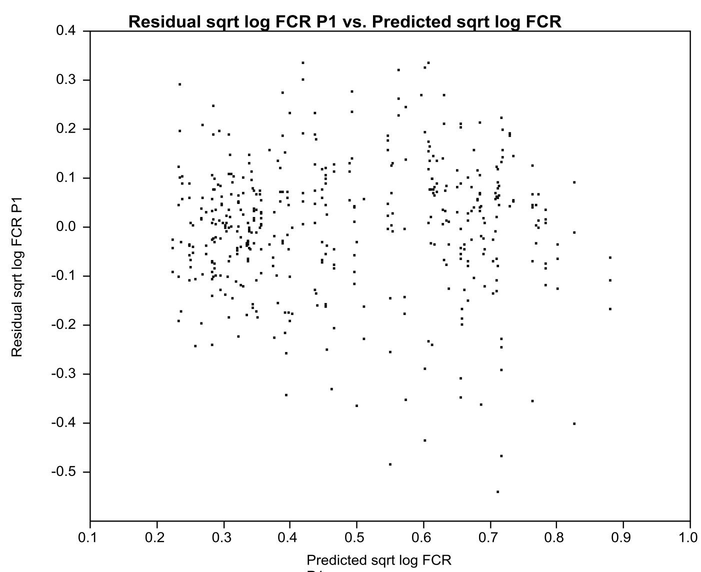


Scatter plot of the residuals as a function of the predicted values for P1 log(BB)

APPENDIX F: Graphs for the ANOVA Assumptions

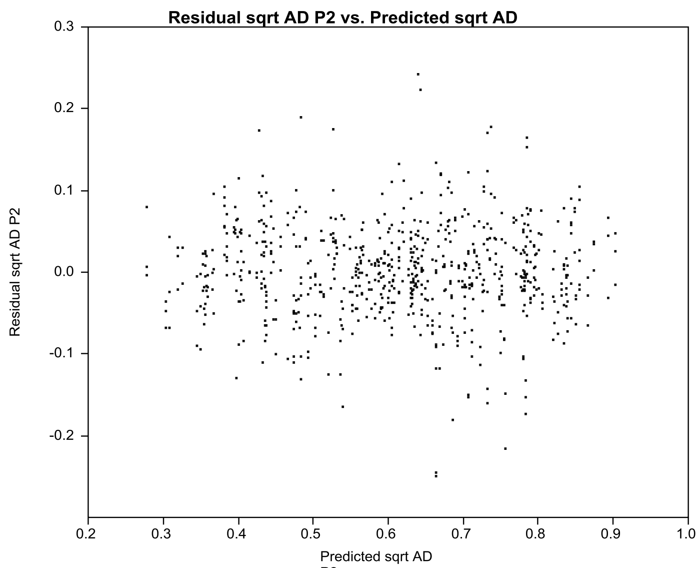


Scatter plot of the residuals as a function of the predicted values for P1 log(ECR)

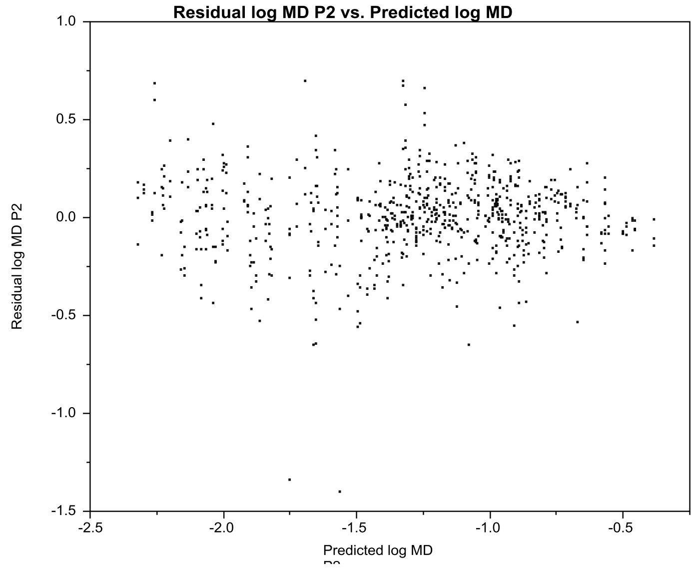


Scatter plot of the residuals as a function of the predicted values for P1 log(FCR)

APPENDIX F: Graphs for the ANOVA Assumptions

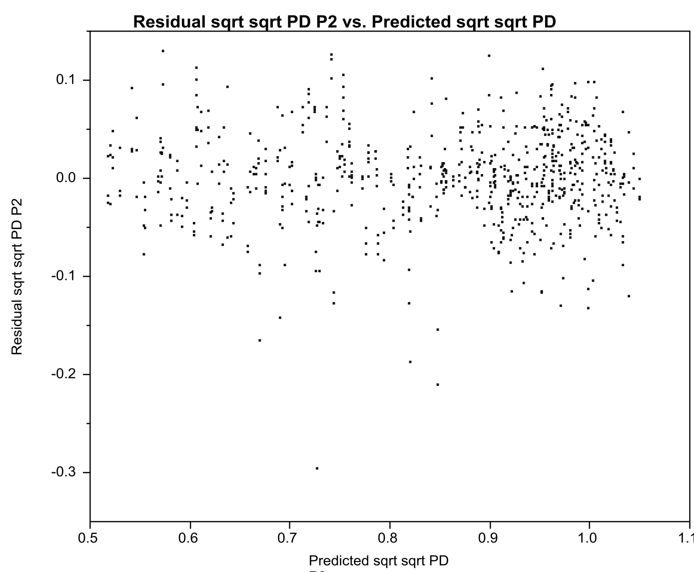


Scatter plot of the residuals as a function of the predicted values for P2 sqrt(AD)

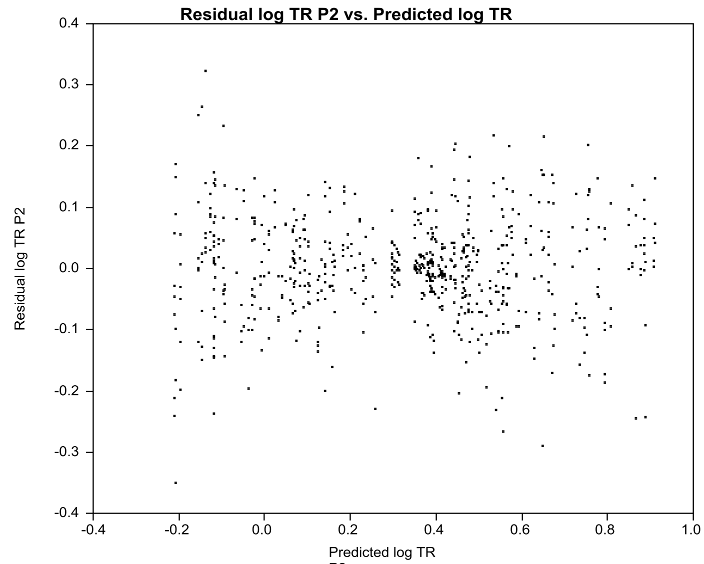


Scatter plot of the residuals as a function of the predicted values for P2 log(MD)

APPENDIX F: Graphs for the ANOVA Assumptions

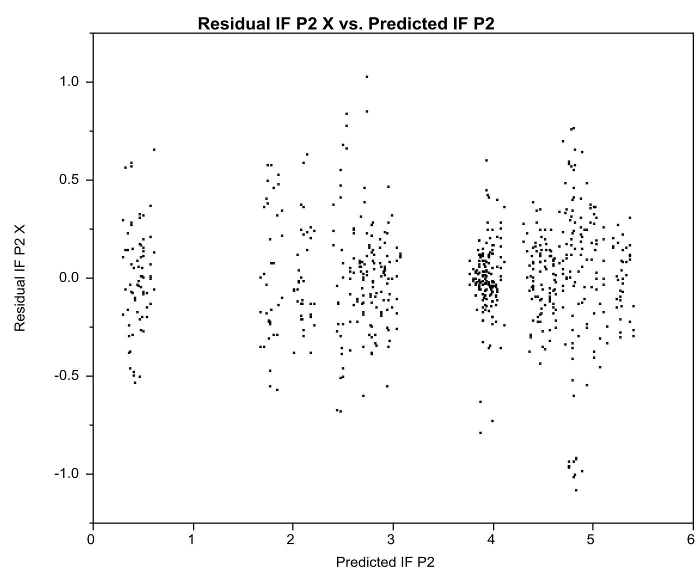


Scatter plot of the residuals as a function of the predicted values for P2 sqrt(sqrt(PD))

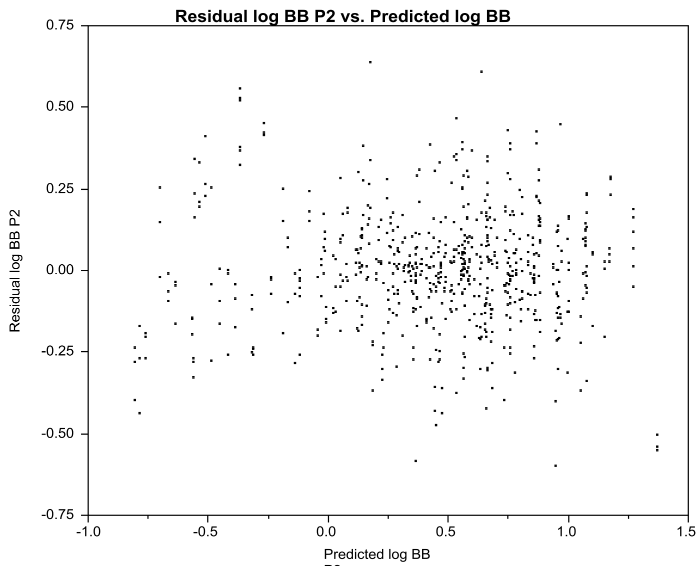


Scatter plot of the residuals as a function of the predicted values for P2 log(TR)

APPENDIX F: Graphs for the ANOVA Assumptions

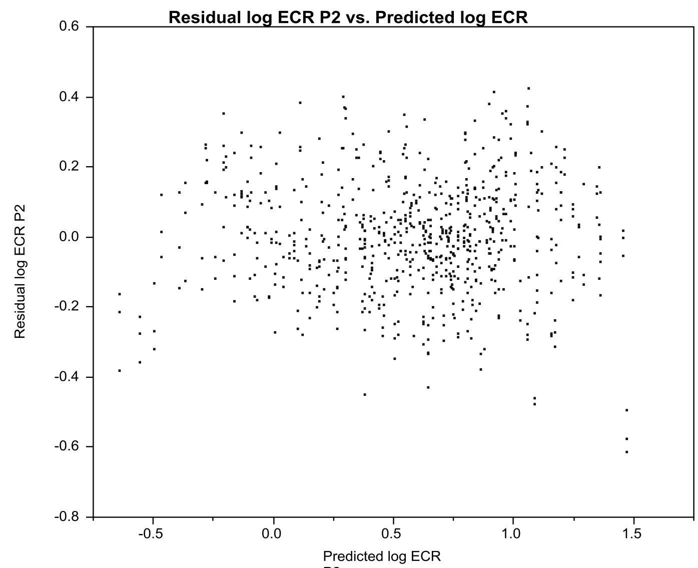


Scatter plot of the residuals as a function of the predicted values for P2 Box-Cox(IF)

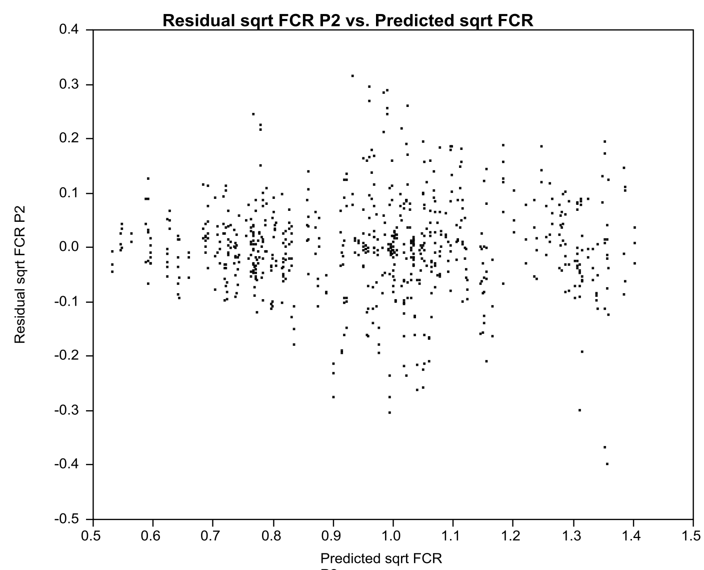


Scatter plot of the residuals as a function of the predicted values for P2 log(BB)

APPENDIX F: Graphs for the ANOVA Assumptions

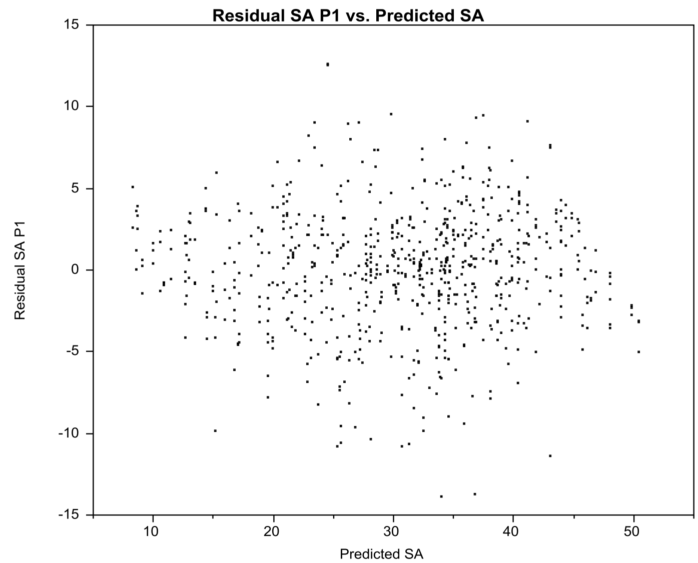


Scatter plot of the residuals as a function of the predicted values for P2 log(ECR)

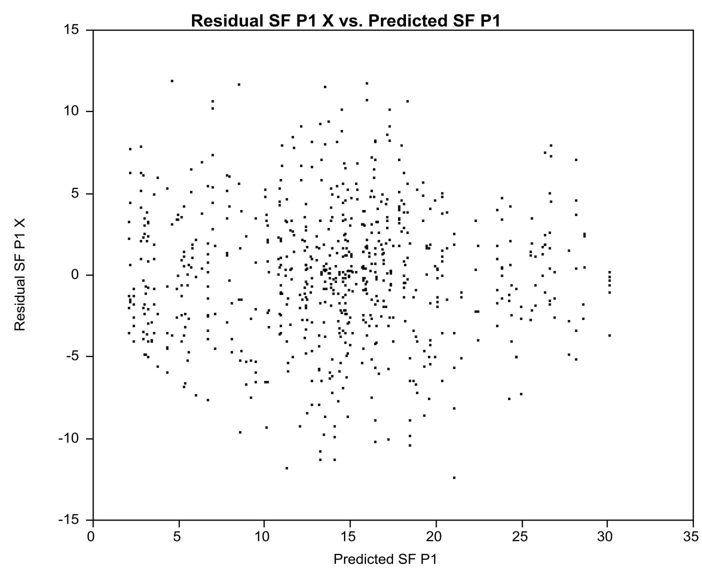


Scatter plot of the residuals as a function of the predicted values for P2 sqrt(FCR)

APPENDIX F: Graphs for the ANOVA Assumptions

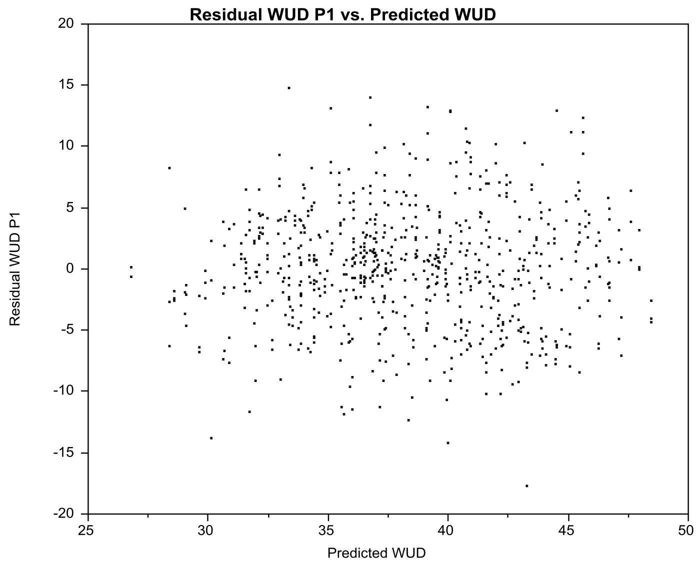


Scatter plot of the residuals as a function of the predicted values for P1 SA

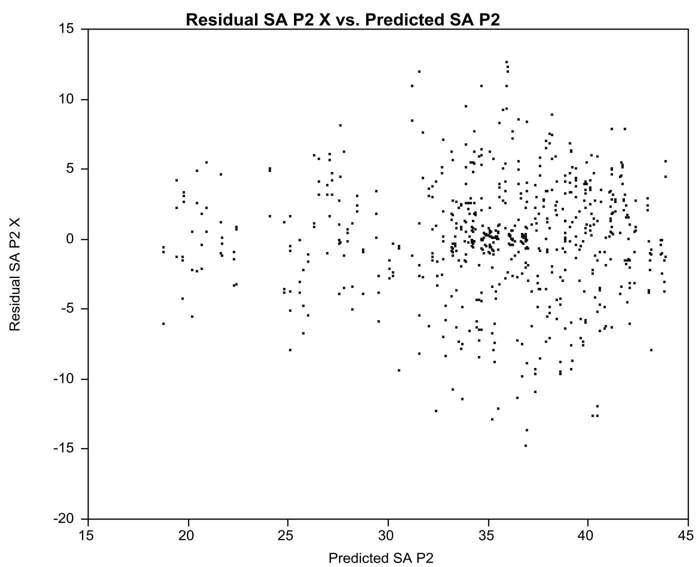


Scatter plot of the residuals as a function of the predicted values for P1 Box-Cox(SF)

APPENDIX F: Graphs for the ANOVA Assumptions

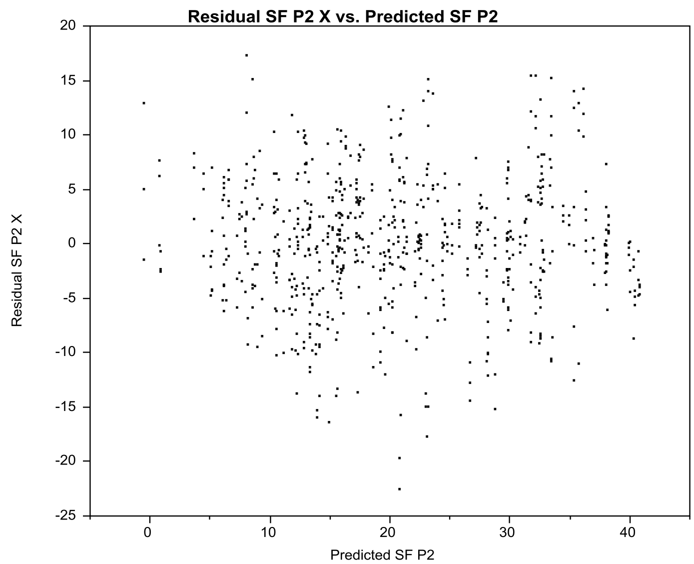


Scatter plot of the residuals as a function of the predicted values for P1 WUD

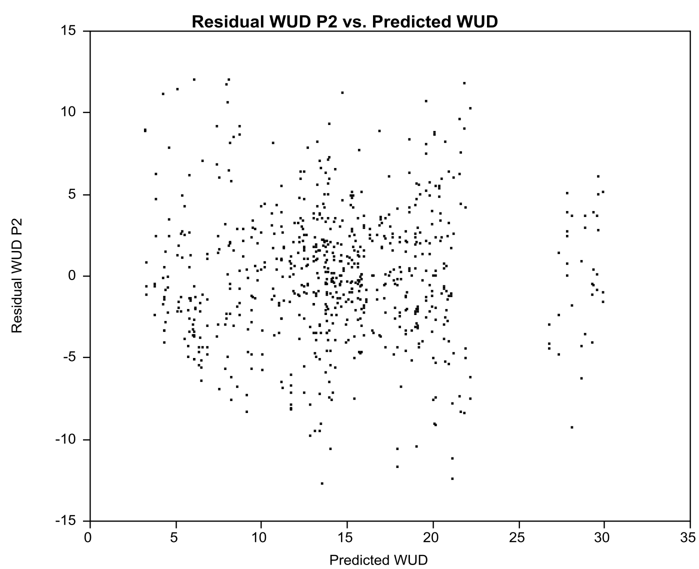


Scatter plot of the residuals as a function of the predicted values for P2 Box-Cox(SA)

APPENDIX F: Graphs for the ANOVA Assumptions

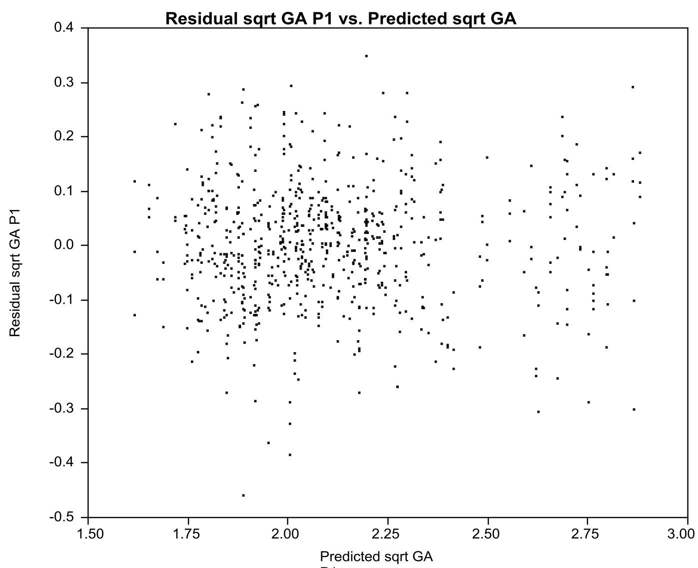


Scatter plot of the residuals as a function of the predicted values for P2 Box-Cox(SF)

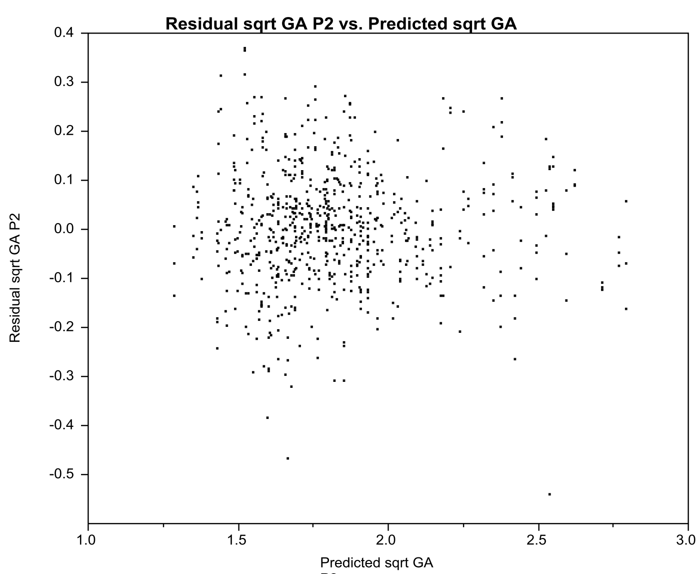


Scatter plot of the residuals as a function of the predicted values for P2 WUD

APPENDIX F: Graphs for the ANOVA Assumptions



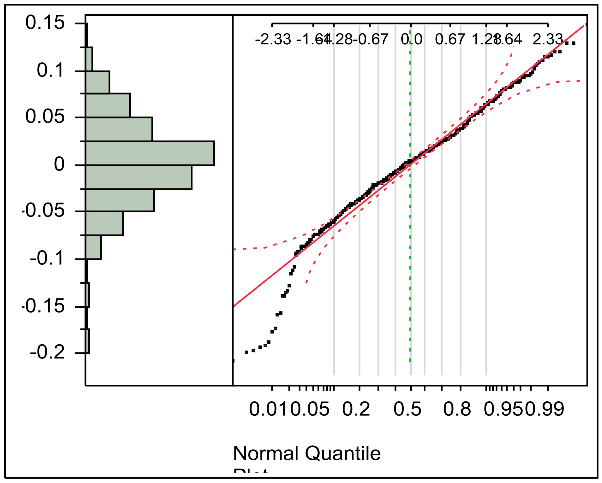
Scatter plot of the residuals as a function of the predicted values for P1 sqrt(average grip)



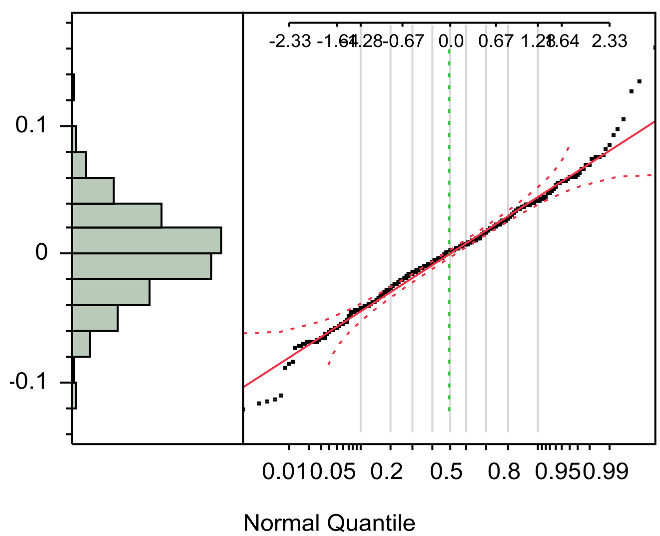
Scatter plot of the residuals as a function of the predicted values for P2 sqrt(average grip)

APPENDIX F: Graphs for the ANOVA Assumptions

Test for Normality

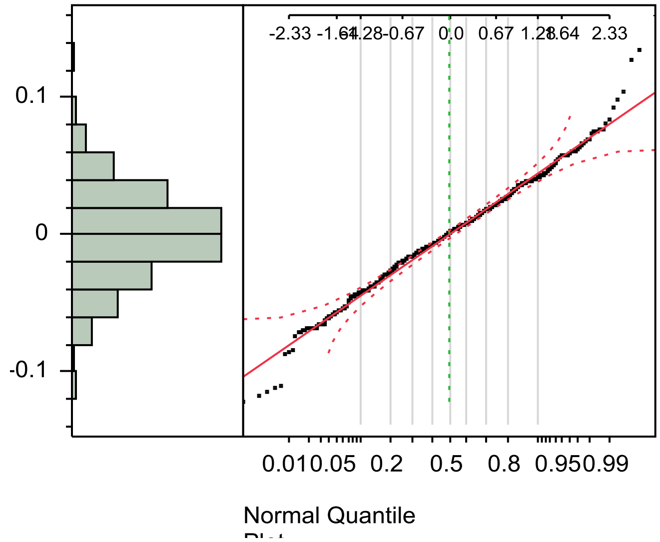


The normal quantile plot of the residuals for P1 sqrt(AD)

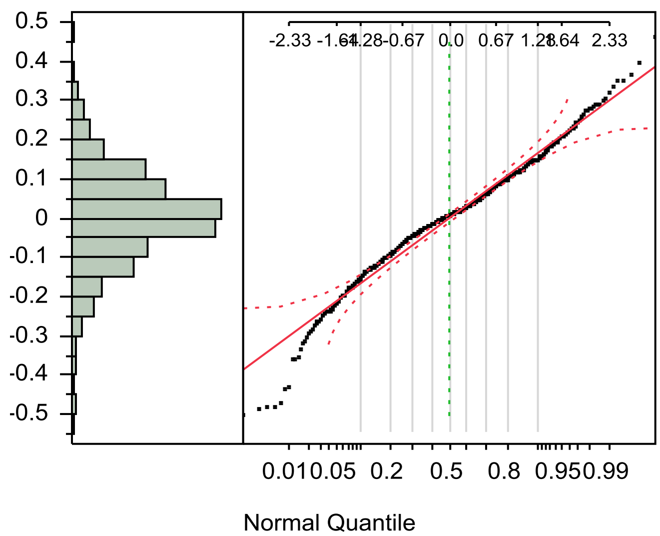


The normal quantile plot of the residuals for P1 sqrt(MD)

APPENDIX F: Graphs for the ANOVA Assumptions

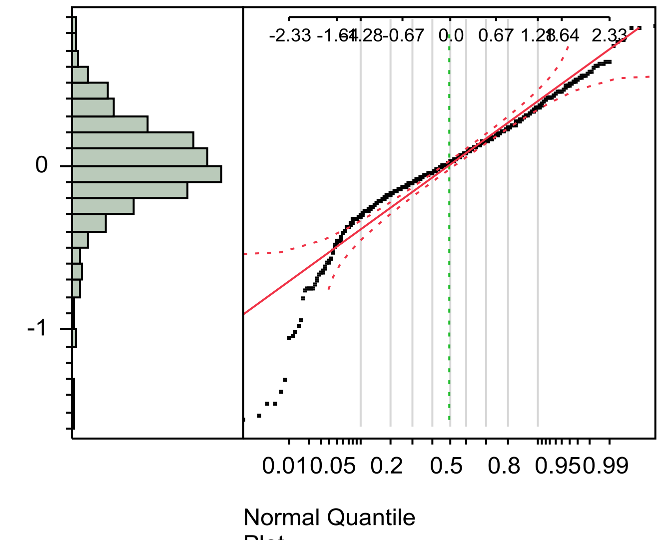


The normal quantile plot of the residuals for P1 sqrt(PD)

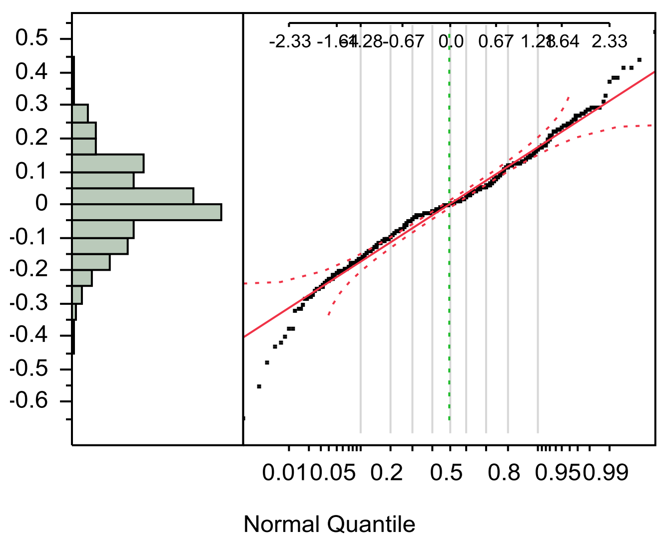


The normal quantile plot of the residuals for P1 log(TR)

APPENDIX F: Graphs for the ANOVA Assumptions

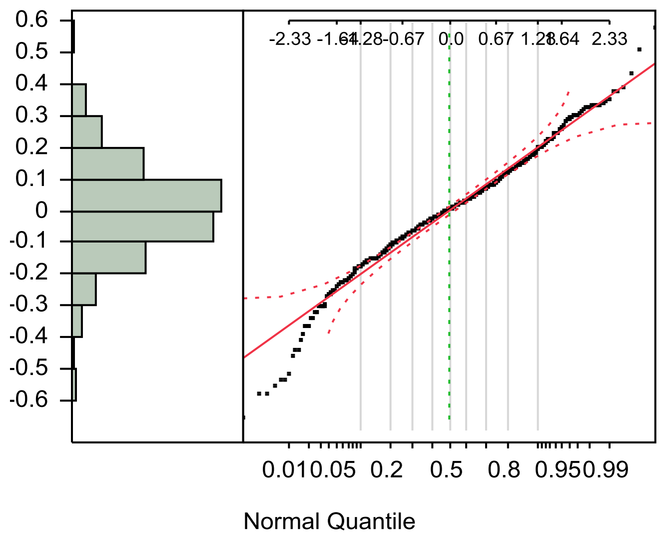


The normal quantile plot of the residuals for P1 Box-Cox(IF)

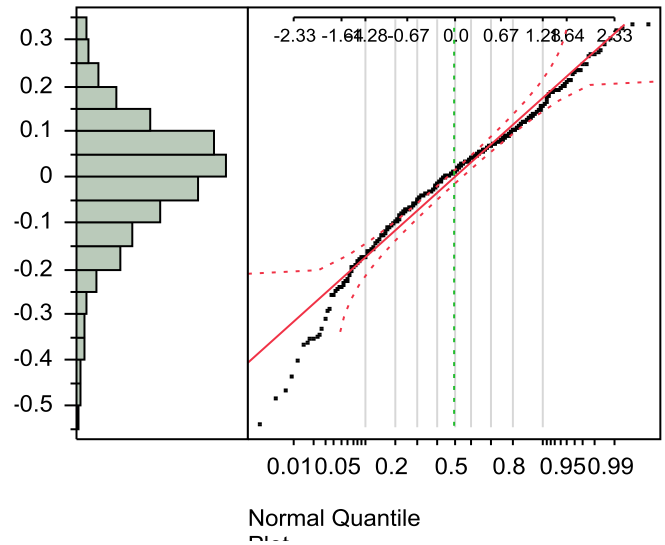


The normal quantile plot of the residuals for P1 log(BB)

APPENDIX F: Graphs for the ANOVA Assumptions

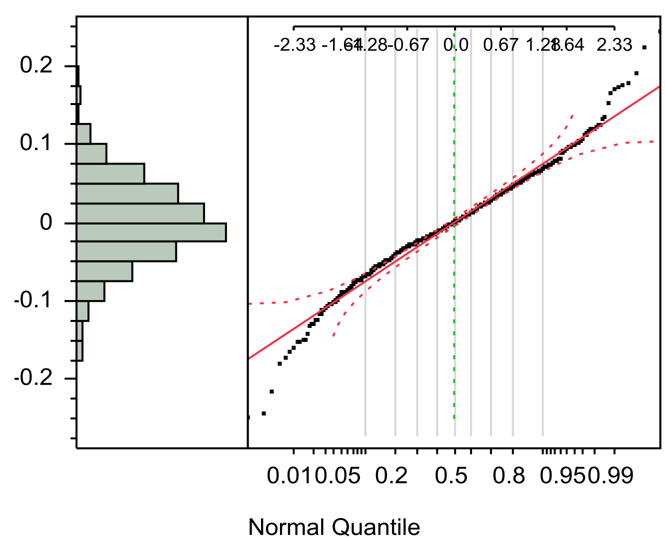


The normal quantile plot of the residuals for P1 log(ECR)

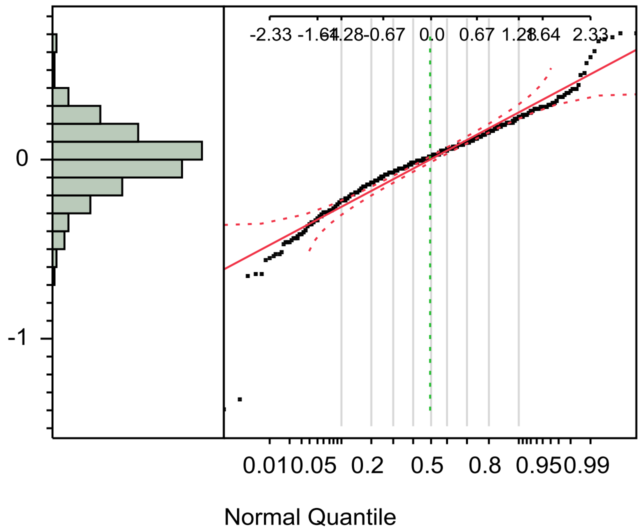


The normal quantile plot of the residuals for P1 sqrt(log(FCR))

APPENDIX F: Graphs for the ANOVA Assumptions

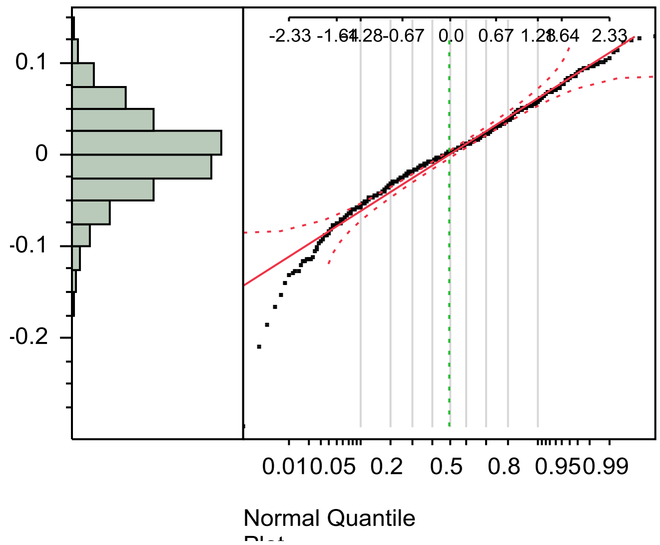


The normal quantile plot of the residuals for P2 sqrt(AD)

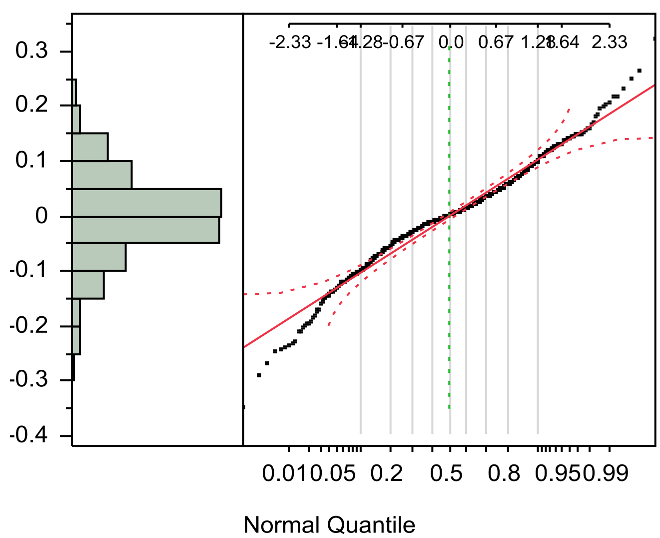


The normal quantile plot of the residuals for P2 log(MD)

APPENDIX F: Graphs for the ANOVA Assumptions

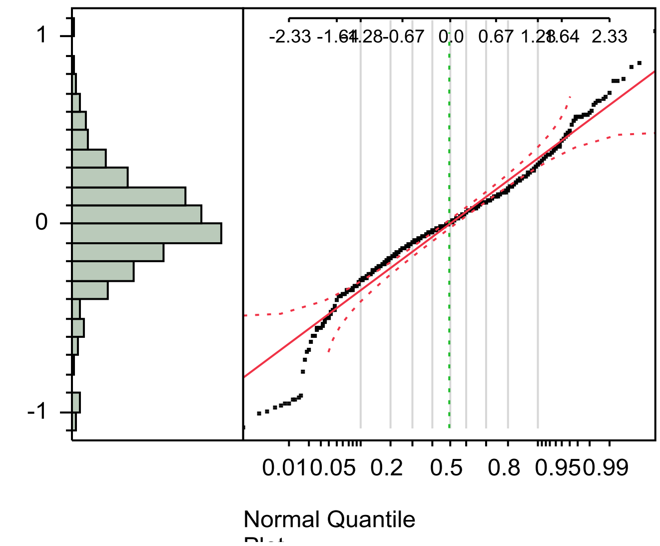


The normal quantile plot of the residuals for P2 sqrt(sqrt(PD))

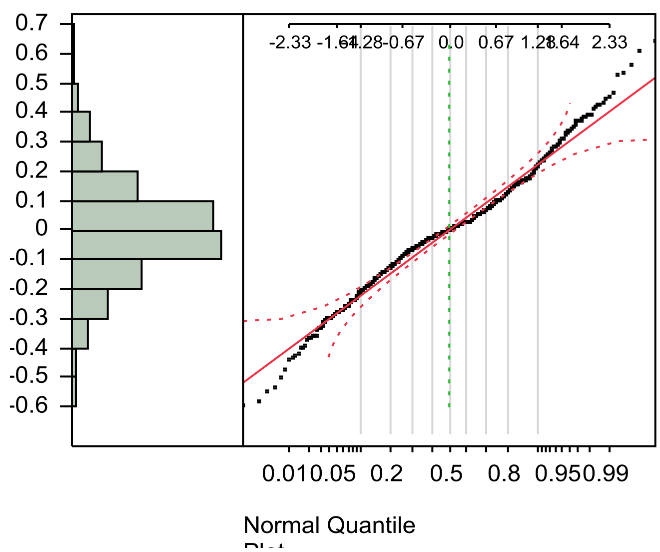


The normal quantile plot of the residuals for P2 log(TR)

APPENDIX F: Graphs for the ANOVA Assumptions

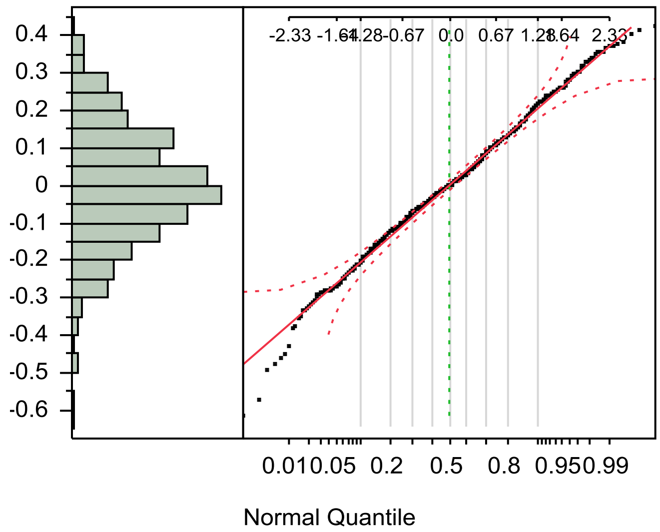


The normal quantile plot of the residuals for P2 Box-Cox(IF)

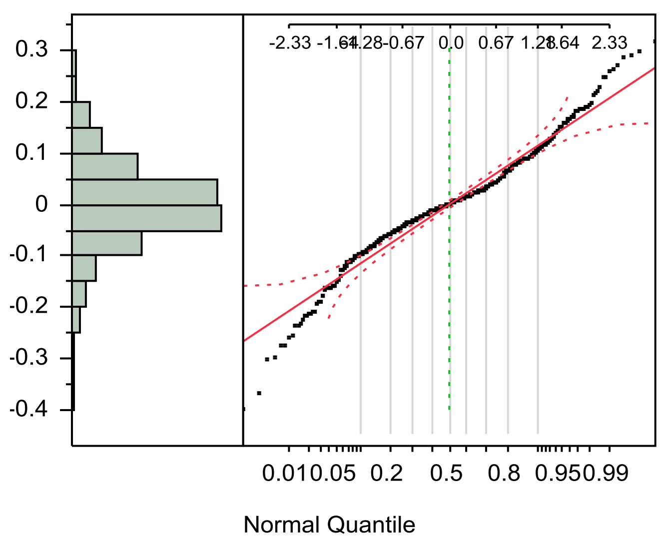


The normal quantile plot of the residuals for P2 log(BB)

APPENDIX F: Graphs for the ANOVA Assumptions

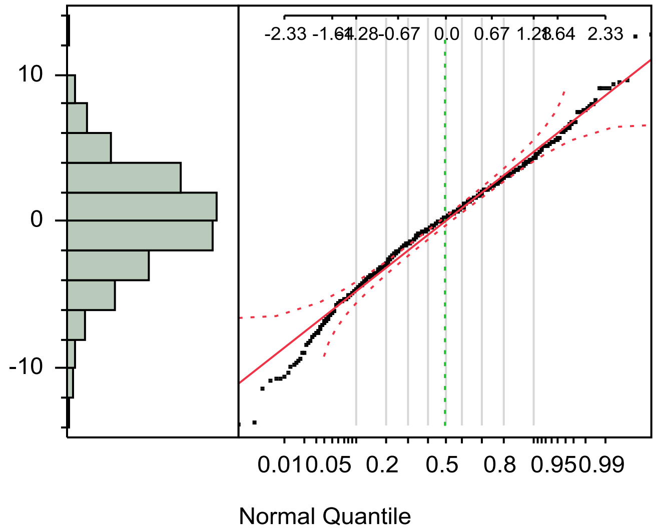


The normal quantile plot of the residuals for P2 log(ECR)

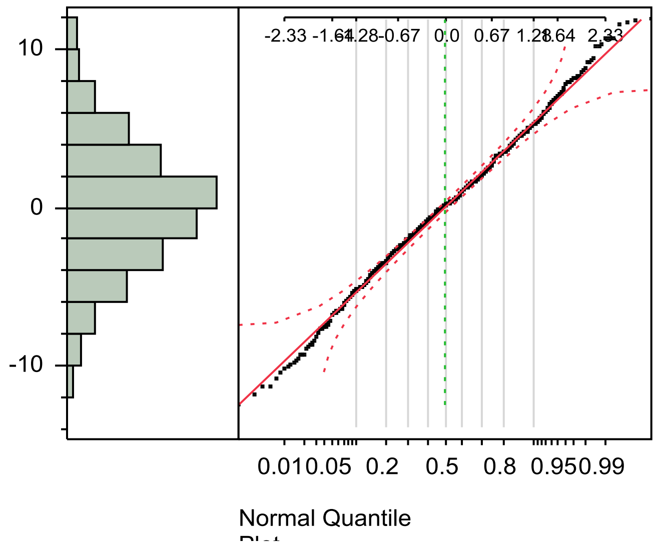


The normal quantile plot of the residuals for P2 sqrt(FCR)

APPENDIX F: Graphs for the ANOVA Assumptions

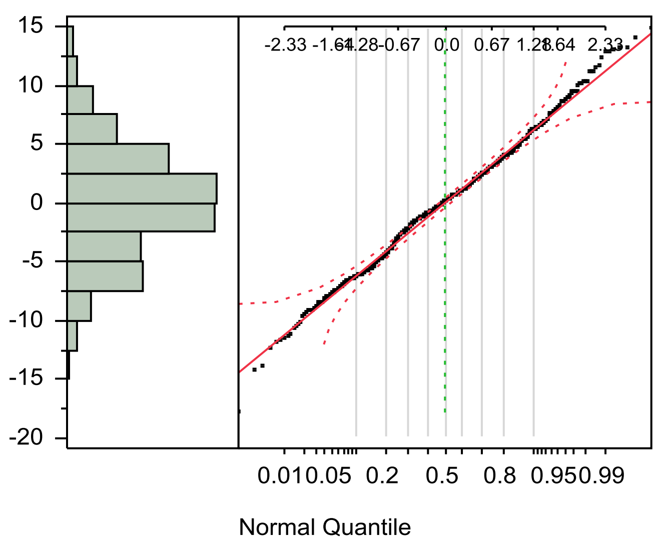


The normal quantile plot of the residuals for P1 SA

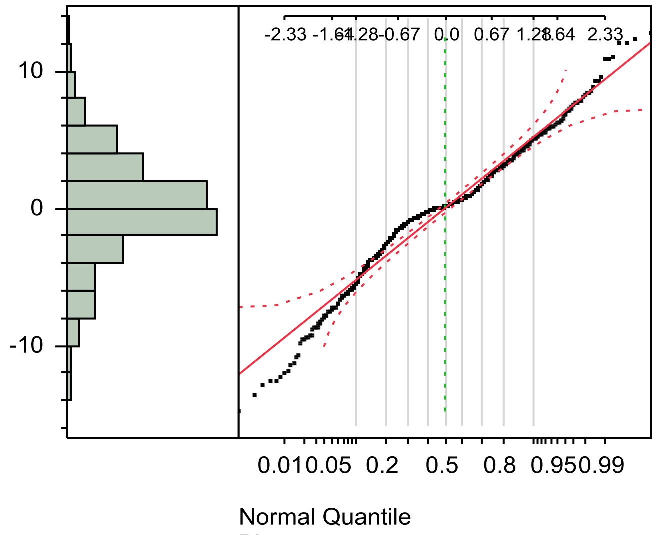


The normal quantile plot of the residuals for P1 Box-Cox(SF)

APPENDIX F: Graphs for the ANOVA Assumptions

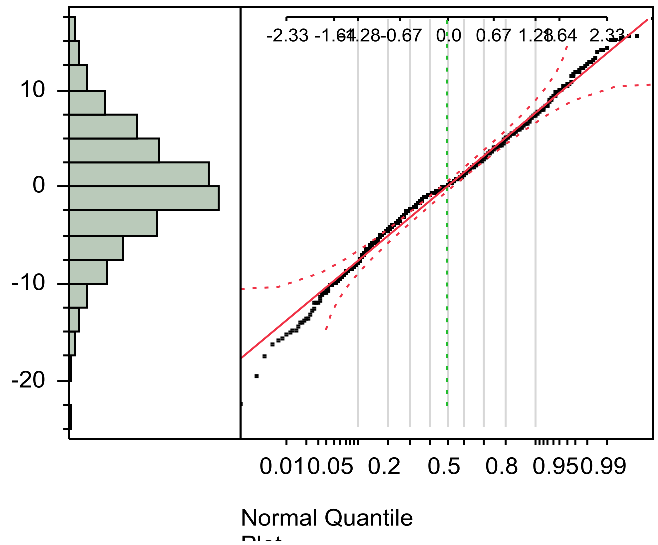


The normal quantile plot of the residuals for P1 WUD

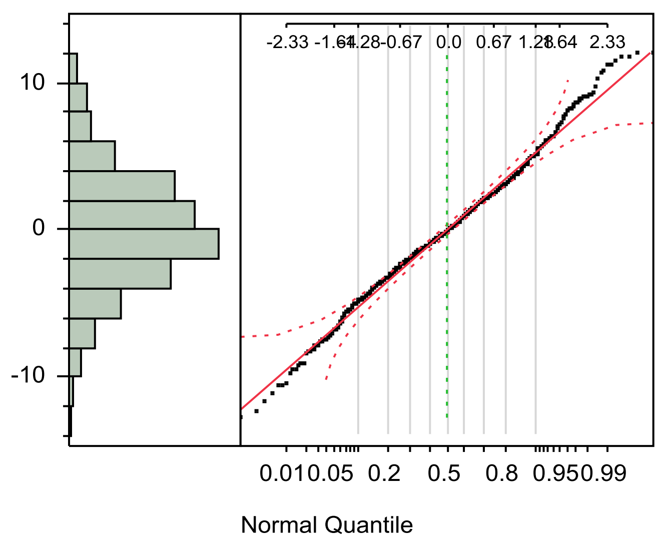


The normal quantile plot of the residuals for P2 Box-Cox(SA)

APPENDIX F: Graphs for the ANOVA Assumptions

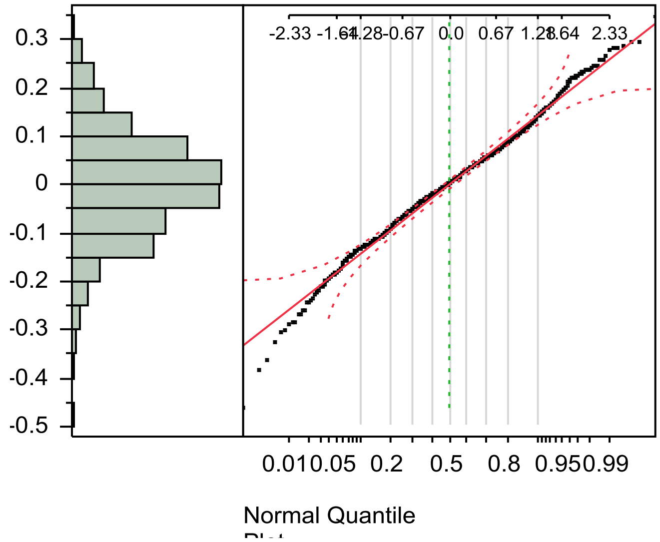


The normal quantile plot of the residuals for P2 Box-Cox(SF)

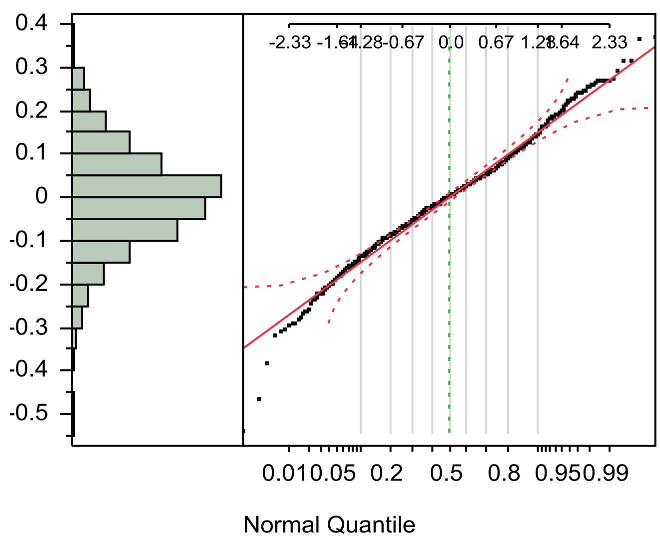


The normal quantile plot of the residuals for P2 WUD

APPENDIX F: Graphs for the ANOVA Assumptions



The normal quantile plot of the residuals for P1 sqrt(average grip)



The normal quantile plot of the residuals for P2 sqrt(average grip)

APPENDIX G: Outliers

P1 AD Outliers

Dataset	Data Point	Value
AD	73	1.30
AD	74	1.13
AD	75	1.25
AD	76	1.23
AD	77	1.32
AD	78	1.26
AD	79	0.93
AD	80	1.30
AD	81	1.19
AD	82	1.09
AD	83	1.25
AD	84	1.28
AD	85	1.01
AD	86	1.15
AD	87	1.31
AD	88	1.17
AD	89	1.15
AD	90	1.24
AD	91	0.92
AD	92	1.17
AD	93	0.99
AD	94	1.02
AD	95	1.19
AD	96	0.99
AD	97	1.03
AD	98	1.13
AD	99	1.23
AD	100	0.94
AD	101	1.23
AD	102	1.33
AD	103	0.99
AD	104	0.91
AD	105	1.04
AD	106	0.89
AD	107	1.03

AD	108	1.12
AD	479	0.87
AD	485	0.89
AD	486	0.98
AD	497	0.97
AD	504	0.85

P1 MD Outliers

Dataset	Data Point	Value
MD	351	0.32
MD	662	0.40
MD	663	0.41
MD	675	0.40
MD	687	0.34
MD	705	0.32
MD	716	0.32

P1 PD Outliers

Dataset	Data Point	Value
PD	129	0.92
PD	160	0.34
PD	161	0.42
PD	162	0.42
PD	163	0.55
PD	217	0.87
PD	218	0.65
PD	219	1.27
PD	220	1.09
PD	221	1.13
PD	222	0.86
PD	223	1.45
PD	224	1.94
PD	225	1.88
PD	226	2.01
PD	227	2.08
PD	228	1.56
PD	229	1.47

APPENDIX G: Outliers

PD	230	1.25
PD	231	0.58
PD	232	0.64
PD	233	1.10
PD	234	0.81
PD	235	2.27
PD	236	2.78
PD	237	2.22
PD	238	1.76
PD	239	1.37
PD	240	1.19
PD	241	1.47
PD	242	1.77
PD	243	2.00
PD	244	0.97
PD	245	0.64
PD	246	1.06
PD	247	1.45
PD	248	1.56
PD	249	2.00
PD	250	1.05
PD	251	1.19
PD	252	1.17
PD	345	0.76
PD	351	0.84
PD	705	0.78
PD	716	0.84

P1 TR Outliers

Dataset	Data Point	Value
TR	181	3.90
TR	182	3.87
TR	183	4.30
TR	184	2.61
TR	185	2.94
TR	186	3.24
TR	187	2.99

APPENDIX G: Outliers

TR	188	4.69
TR	189	4.14
TR	190	3.37
TR	191	3.25
TR	192	2.79
TR	193	4.78
TR	194	4.38
TR	195	4.85
TR	196	3.24
TR	197	4.12
TR	198	3.69
TR	199	3.08
TR	200	3.65
TR	201	4.32
TR	202	2.98
TR	203	3.67
TR	204	3.01
TR	205	4.01
TR	206	4.21
TR	207	4.66
TR	208	2.51
TR	209	3.57
TR	210	3.83
TR	211	2.44
TR	212	3.40
TR	213	3.54
TR	214	2.17
TR	215	2.90
TR	216	2.95
TR	235	2.22
TR	237	2.48
TR	494	3.69
TR	495	3.61
TR	501	3.02

P1 IF Outliers

Dataset	Data Point	Value

APPENDIX G: Outliers

IF	38	7.73
IF	62	7.93
IF	237	7.70
IF	494	8.04
IF	495	7.03
IF	656	6.76
IF	657	6.68
IF	662	8.06
IF	663	7.47
IF	675	7.73

P1 BB Outliers

Dataset	Data Point	Value
IF	109	5.60
IF	110	6.16
IF	111	6.09
IF	112	5.68
IF	113	6.38
IF	114	6.34
IF	115	6.82
IF	116	6.80
IF	117	7.15
IF	118	5.44
IF	119	6.64
IF	120	6.26
IF	121	6.74
IF	122	6.26
IF	123	6.04
IF	124	6.36
IF	125	6.20
IF	126	6.10
IF	127	6.04
IF	128	6.59
IF	129	6.23
IF	130	5.93
IF	131	5.82
IF	132	7.29

APPENDIX G: Outliers

IF	133	6.45
IF	134	6.64
IF	135	6.42
IF	136	6.07
IF	137	6.50
IF	138	6.89
IF	139	6.49
IF	140	7.17
IF	141	6.15
IF	142	6.97
IF	143	6.57
IF	144	6.64
IF	179	4.70
IF	289	5.60
IF	290	7.20
IF	291	6.87
IF	292	5.55
IF	293	4.18
IF	294	4.36
IF	295	4.80
IF	296	6.19
IF	297	6.60
IF	298	7.08
IF	299	4.30
IF	300	5.41
IF	301	5.91
IF	302	6.45
IF	303	8.08
IF	304	6.38
IF	305	6.72
IF	306	6.02
IF	307	5.24
IF	308	7.30
IF	309	6.30
IF	310	5.25
IF	311	6.30
IF	312	6.07
IF	313	5.68

APPENDIX G: Outliers

IF	314	8.25
IF	315	9.07
IF	316	6.10
IF	317	4.62
IF	318	5.71
IF	319	6.14
IF	320	6.50
IF	321	5.77
IF	322	6.58
IF	323	7.04
IF	324	7.44
IF	538	5.88
IF	539	5.92
IF	587	5.44
IF	588	4.78
IF	600	4.47
IF	611	5.21

P1 ECR Outliers

Dataset	Data Point	Value
ECR	132	5.12
ECR	143	5.37
ECR	274	6.61
ECR	275	6.88
ECR	277	5.89
ECR	280	7.30
ECR	286	8.27
ECR	525	5.77

P1 FCR Outliers

Dataset	Data Point	Value
FCR	110	2.26
FCR	116	2.37
FCR	192	2.64
FCR	194	2.30
FCR	203	2.68
FCR	209	2.51

APPENDIX G: Outliers

FCR	210	2.67
FCR	289	4.62
FCR	290	4.43
FCR	291	5.16
FCR	292	4.94
FCR	293	5.94
FCR	294	5.69
FCR	295	6.21
FCR	296	6.47
FCR	297	6.33
FCR	298	6.54
FCR	299	6.23
FCR	300	7.49
FCR	301	5.70
FCR	302	5.32
FCR	303	5.74
FCR	304	4.44
FCR	305	4.80
FCR	306	5.83
FCR	307	5.99
FCR	308	5.44
FCR	309	6.97
FCR	310	6.69
FCR	311	6.34
FCR	312	5.42
FCR	313	7.04
FCR	314	6.77
FCR	315	5.55
FCR	316	5.37
FCR	317	4.97
FCR	318	4.99
FCR	319	7.04
FCR	320	8.29
FCR	321	7.73
FCR	322	6.67
FCR	323	7.26
FCR	324	5.27
FCR	447	2.23

FCR	540	2.03
FCR	588	2.17
FCR	688	2.90
FCR	689	2.35
FCR	692	2.61
FCR	694	3.20
FCR	695	2.66
FCR	696	2.47
FCR	701	2.46
FCR	707	2.32
FCR	708	2.42

P1 SA Outliers

Dataset	Data Point	Value
SA	662	56.98

P1 SF Outliers

Dataset	Data Point	Value
SF	187	-0.14
SF	195	32.63
SF	253	35.35
SF	254	38.41
SF	469	43.89
SF	541	38.69
SF	565	34.31
SF	566	36.54
SF	567	35.23
SF	662	41.14

P1 WUD Outliers

Dataset	Data Point	Value
WUD	68	20.07
WUD	107	0.91
WUD	179	21.84

APPENDIX G: Outliers

WUD	200	17.78
WUD	215	57.44
WUD	263	21.27
WUD	289	20.05
WUD	290	18.14
WUD	291	18.49
WUD	292	9.35
WUD	293	12.02
WUD	294	7.88
WUD	295	9.83
WUD	296	12.99
WUD	297	20.52
WUD	298	4.26
WUD	299	5.35
WUD	300	6.77
WUD	301	12.70
WUD	302	13.46
WUD	303	11.96
WUD	304	5.92
WUD	305	11.94
WUD	306	4.26
WUD	307	10.73
WUD	308	9.93
WUD	309	14.79
WUD	310	12.07
WUD	311	6.50
WUD	312	6.27
WUD	313	17.23
WUD	314	16.18
WUD	315	15.84
WUD	316	6.37
WUD	317	16.14
WUD	318	19.57
WUD	319	6.27
WUD	320	13.53
WUD	321	11.97
WUD	322	16.52
WUD	323	9.69

WUD	324	15.40
WUD	348	23.97
WUD	435	55.51
WUD	448	59.88
WUD	453	56.47
WUD	540	27.36
WUD	541	2.32
WUD	570	6.36

P1 Average Grip Outliers

Dataset	Data Point	Value
Average Grip	446	7.3
Average Grip	447	8.2

P2 AD Outliers

Dataset	Data Point	Value
AD	479	1.04
AD	480	1.01
AD	484	0.99
AD	485	1.03
AD	486	1.11
AD	503	0.92
AD	504	0.96

P2 MD Outliers

Dataset	Data Point	Value
MD	290	0.65
MD	302	0.75
MD	303	0.66
MD	524	0.70
MD	630	0.62
MD	719	0.54

P2 PD Outliers

Dataset	Data	Value

APPENDIX G: Outliers

	Point	
PD	163	1.49
PD	340	1.52
PD	351	1.82
PD	358	1.72
PD	360	1.98
PD	615	1.48

P2 TR Outliers

Dataset	Data Point	Value
TR	181	4.73
TR	182	4.35
TR	183	5.41
TR	184	4.09
TR	185	4.06
TR	186	4.79
TR	187	4.07
TR	188	4.48
TR	189	5.20
TR	190	4.26
TR	191	3.54
TR	192	4.45
TR	193	4.37
TR	194	4.81
TR	195	4.86
TR	196	4.11
TR	197	4.91
TR	198	4.27
TR	199	3.60
TR	200	4.99
TR	201	4.13
TR	202	3.43
TR	203	3.96
TR	204	4.05
TR	205	4.34
TR	206	4.85
TR	207	6.00

APPENDIX G: Outliers

TR	208	4.30
TR	209	3.80
TR	210	4.01
TR	211	3.47
TR	212	4.01
TR	213	3.94
TR	214	3.78
TR	215	3.98
TR	216	4.42
TR	309	2.87
TR	325	2.97
TR	326	3.74
TR	327	2.88
TR	328	2.67
TR	329	3.23
TR	330	3.40
TR	331	2.70
TR	332	2.54
TR	333	2.57
TR	334	2.76
TR	335	2.67
TR	336	2.93
TR	337	3.09
TR	338	3.57
TR	339	3.39
TR	340	3.25
TR	341	3.26
TR	342	3.08
TR	343	3.47
TR	344	3.14
TR	345	3.90
TR	346	2.77
TR	347	2.61
TR	348	3.22
TR	349	2.91
TR	350	2.96
TR	351	3.60
TR	352	3.22

APPENDIX G: Outliers

TR	353	3.65
TR	354	2.69
TR	355	3.55
TR	356	3.10
TR	357	3.46
TR	358	2.62
TR	359	2.46
TR	360	2.56
TR	469	3.79
TR	470	3.21
TR	471	4.22
TR	472	5.00
TR	473	4.25
TR	474	3.96
TR	475	3.04
TR	476	3.36
TR	477	3.66
TR	478	3.18
TR	479	3.77
TR	480	3.88
TR	481	4.15
TR	482	3.62
TR	483	4.30
TR	484	3.25
TR	485	3.49
TR	486	3.47
TR	487	2.67
TR	488	4.41
TR	489	4.77
TR	490	3.30
TR	491	3.08
TR	492	3.02
TR	493	3.15
TR	494	4.66
TR	495	4.74
TR	496	2.61
TR	497	3.96
TR	498	3.64

TR	499	3.71
TR	500	3.25
TR	501	4.19
TR	502	2.68
TR	503	2.96
TR	504	3.04

P2 IF Outliers

Dataset	Data Point	Value
IF	37	10.77
IF	38	10.92
IF	39	9.94
IF	40	11.01
IF	41	9.03
IF	42	10.03
IF	43	7.86
IF	44	7.17
IF	45	9.55
IF	46	8.85
IF	47	7.57
IF	48	8.20
IF	49	9.58
IF	50	11.34
IF	51	8.75
IF	52	9.14
IF	53	10.47
IF	54	9.08
IF	55	9.31
IF	56	8.17
IF	57	8.20
IF	58	8.05
IF	59	8.35
IF	60	9.24
IF	61	10.81
IF	62	11.20
IF	63	10.53
IF	64	8.87

APPENDIX G: Outliers

IF	65	10.91
IF	66	9.94
IF	67	11.09
IF	68	9.52
IF	69	7.63
IF	70	9.27
IF	71	8.55
IF	72	10.92
IF	217	6.28
IF	218	6.36
IF	219	6.74
IF	220	7.37
IF	221	7.42
IF	222	7.54
IF	223	6.77
IF	224	6.89
IF	225	7.04
IF	226	6.42
IF	227	6.68
IF	228	6.59
IF	229	6.24
IF	230	6.55
IF	231	5.97
IF	232	6.22
IF	233	6.79
IF	234	6.83
IF	235	7.11
IF	236	6.54
IF	237	6.95
IF	238	6.86
IF	239	7.30
IF	240	6.59
IF	241	6.41
IF	242	6.83
IF	243	6.69
IF	244	6.76
IF	245	6.47
IF	246	6.83

IF	247	6.75
IF	248	7.25
IF	249	7.46
IF	250	7.95
IF	251	8.65
IF	252	8.40
IF	474	7.08
IF	489	8.19
IF	494	8.74
IF	495	7.22
IF	656	6.79
IF	657	7.54
IF	683	6.89
IF	684	6.82

P2 BB Outliers

Dataset	Data Point	Value
BB	106	4.41
BB	107	5.01
BB	108	4.01
BB	109	5.17
BB	110	5.29
BB	111	5.80
BB	112	6.36
BB	113	7.50
BB	114	7.01
BB	115	6.86
BB	116	7.44
BB	117	7.03
BB	118	6.76
BB	119	6.50
BB	120	6.52
BB	121	6.06
BB	122	5.84
BB	123	5.85
BB	124	6.46
BB	125	6.32

APPENDIX G: Outliers

BB	126	6.22
BB	127	6.00
BB	128	6.42
BB	129	5.04
BB	130	7.54
BB	131	7.03
BB	132	7.82
BB	133	6.48
BB	134	6.30
BB	135	6.54
BB	136	6.61
BB	137	6.86
BB	138	6.19
BB	139	6.45
BB	140	6.56
BB	141	6.34
BB	142	7.25
BB	143	8.11
BB	144	8.82
BB	178	4.67
BB	263	3.98
BB	277	4.12
BB	289	8.51
BB	290	8.29
BB	291	9.47
BB	292	10.03
BB	293	6.25
BB	294	8.61
BB	295	8.71
BB	296	9.15
BB	297	9.84
BB	298	10.75
BB	299	9.55
BB	300	7.56
BB	301	8.85
BB	302	9.40
BB	303	11.08
BB	304	10.91

APPENDIX G: Outliers

BB	305	10.05
BB	306	10.35
BB	307	7.26
BB	308	10.67
BB	309	9.45
BB	310	11.59
BB	311	13.22
BB	312	9.94
BB	313	10.68
BB	314	11.11
BB	315	13.46
BB	316	10.59
BB	317	9.12
BB	318	10.00
BB	319	10.81
BB	320	9.88
BB	321	8.56
BB	322	11.99
BB	323	12.02
BB	324	12.08
BB	574	5.86
BB	575	5.89
BB	576	5.49
BB	706	4.66
BB	707	4.47
BB	708	4.61
BB	715	4.23
BB	716	5.26
BB	718	4.70
BB	719	5.52

P2 ECR Outliers

Dataset	Data Point	Value
ECR	217	6.02
ECR	218	6.38
ECR	219	5.25
ECR	220	6.03

APPENDIX G: Outliers

ECR	221	5.16
ECR	222	6.16
ECR	223	7.64
ECR	224	7.27
ECR	225	7.57
ECR	226	6.74
ECR	227	7.30
ECR	228	7.57
ECR	229	5.66
ECR	230	5.69
ECR	231	4.98
ECR	232	7.42
ECR	233	6.61
ECR	234	5.90
ECR	235	6.34
ECR	236	6.39
ECR	237	5.98
ECR	238	7.81
ECR	239	8.43
ECR	240	7.85
ECR	241	6.18
ECR	242	6.44
ECR	243	6.87
ECR	244	7.36
ECR	245	6.65
ECR	246	6.47
ECR	247	8.20
ECR	248	7.99
ECR	249	8.78
ECR	250	8.51
ECR	251	8.31
ECR	252	7.81
ECR	295	4.79
ECR	296	5.27
ECR	514	5.38
ECR	515	6.23
ECR	516	4.59
ECR	526	5.00

APPENDIX G: Outliers

ECR	527	4.94
ECR	538	4.82
ECR	539	5.83
ECR	540	5.84
ECR	574	5.74
ECR	575	5.65
ECR	576	4.72

P2 FCR Outliers

Dataset	Data Point	Value
FCR	128	2.26
FCR	289	3.75
FCR	290	3.12
FCR	291	3.14
FCR	292	3.99
FCR	293	4.42
FCR	294	3.95
FCR	295	6.82
FCR	296	7.86
FCR	297	3.34
FCR	298	4.42
FCR	299	4.57
FCR	300	4.73
FCR	301	3.49
FCR	302	3.37
FCR	303	4.06
FCR	304	4.95
FCR	305	4.00
FCR	306	5.83
FCR	307	5.62
FCR	308	4.57
FCR	309	4.38
FCR	310	6.08
FCR	311	6.17
FCR	312	5.52
FCR	313	3.84
FCR	314	3.28

APPENDIX G: Outliers

FCR	315	3.95
FCR	316	4.24
FCR	317	3.41
FCR	318	3.85
FCR	319	4.99
FCR	320	5.11
FCR	321	5.22
FCR	322	5.90
FCR	323	6.21
FCR	324	4.68
FCR	446	2.44
FCR	451	2.46
FCR	694	1.94
FCR	696	2.06

P2 SA Outliers

Dataset	Data Point	Value
SA	162	16.21
SA	174	17.16
SA	361	20.69
SA	362	19.14
SA	363	19.27
SA	364	17.24
SA	365	18.91
SA	366	18.75
SA	367	14.93
SA	368	18.31
SA	369	16.09
SA	370	17.16
SA	371	14.62
SA	372	16.26
SA	373	18.87
SA	374	16.76
SA	375	20.64
SA	376	16.87
SA	377	14.54
SA	378	14.65

APPENDIX G: Outliers

SA	379	22.48
SA	380	21.99
SA	381	16.70
SA	382	23.39
SA	383	22.14
SA	384	24.13
SA	385	20.28
SA	386	22.39
SA	387	21.74
SA	388	20.73
SA	389	17.50
SA	390	17.53
SA	391	19.80
SA	392	18.59
SA	393	22.59
SA	394	21.37
SA	395	22.33
SA	396	22.10
SA	433	17.24
SA	434	17.56
SA	435	14.96
SA	436	16.45
SA	437	17.98
SA	438	20.92
SA	439	21.16
SA	440	20.56
SA	441	20.19
SA	442	20.85
SA	443	17.37
SA	444	20.42
SA	445	23.21
SA	446	20.06
SA	447	15.63
SA	448	15.02
SA	449	17.42
SA	450	17.32
SA	451	18.55
SA	452	16.93

APPENDIX G: Outliers

SA	453	17.59
SA	454	17.32
SA	455	18.61
SA	456	18.17
SA	457	22.21
SA	458	15.44
SA	459	22.26
SA	460	16.57
SA	461	17.40
SA	462	13.48
SA	463	21.09
SA	464	22.21
SA	465	16.52
SA	466	18.56
SA	467	18.18
SA	468	18.24
SA	623	21.46
SA	637	50.23
SA	649	38.26
SA	650	40.03
SA	651	38.12
SA	652	20.59
SA	653	27.57
SA	654	26.01
SA	655	30.40
SA	656	28.39
SA	657	31.14
SA	658	23.87
SA	659	21.61
SA	660	22.56
SA	661	38.79
SA	662	53.67
SA	663	40.97
SA	664	24.37
SA	665	24.62
SA	666	28.40
SA	667	29.66
SA	668	33.15

APPENDIX G: Outliers

SA	669	32.98
SA	670	23.37
SA	671	23.46
SA	672	23.61
SA	673	38.00
SA	674	39.91
SA	675	35.66
SA	676	32.65
SA	677	28.65
SA	678	32.28
SA	679	25.57
SA	680	28.51
SA	681	32.75
SA	682	21.50
SA	683	27.80
SA	684	25.19

P2 SF Outliers

Dataset	Data Point	Value
SF	615	56.31
SF	628	49.38
SF	630	55.48
SF	632	51.34
SF	638	56.85
SF	662	66.80
SF	669	53.40
SF	674	55.48
SF	680	52.12

P2 WUD Outliers

Dataset	Data Point	Value
WUD	107	57.14
WUD	303	78.33
WUD	313	78.54
WUD	314	62.33
WUD	317	38.32
WUD	397	34.99

APPENDIX G: Outliers

WUD	398	28.25
WUD	399	28.87
WUD	400	32.47
WUD	401	31.78
WUD	402	25.25
WUD	403	29.50
WUD	404	24.30
WUD	405	22.34
WUD	406	28.12
WUD	407	28.79
WUD	408	25.17
WUD	409	33.15
WUD	410	28.63
WUD	411	29.57
WUD	412	33.23
WUD	413	28.74
WUD	414	29.68
WUD	415	30.49
WUD	416	30.18
WUD	417	27.81
WUD	418	28.70
WUD	419	24.89
WUD	420	22.50
WUD	421	35.70
WUD	422	34.64
WUD	423	32.41
WUD	424	31.76
WUD	425	18.82
WUD	426	26.25
WUD	427	32.89
WUD	428	31.75
WUD	429	28.59
WUD	430	22.28
WUD	431	23.76
WUD	432	22.55
WUD	433	34.21
WUD	446	36.19
WUD	457	38.37

WUD	463	32.63
WUD	465	31.74
WUD	620	41.68
WUD	637	42.84

P2 Average Grip Outliers

Dataset	Data Point	Value
Average Grip	371	8.6
Average Grip	456	6.1
Average Grip	595	0.9