ABSTRACT

DIERING, MATTHEW RYAN. Ergonomic Evaluation of Scaffolding Task Interventions for Power Plant Maintenance. (Under the direction of Dr. David B. Kaber.)

A nuclear power plant is a complex operation requiring a large number of maintenance operations. Examination of a local power utility's injury database revealed that maintenance personnel had the highest injury incidence rates. Maintenance jobs were analyzed from an ergonomics perspective and scaffolding tasks, including walk-board tie-down to frames and frame tube coupling, were found to pose high risks. Ergonomic risks included excessive torques at joints and awkward posture positions in both tasks. The purpose of this research was to conceptualize interventions to reduce these risks and to conduct experiments to empirically assess the impact of the proposed interventions on worker posture and performance.

The standard procedure for walk-board tie-down at the nuclear power plants calls for the use of #9 gauge wire. The wire is looped around a walk-board and a scaffolding tube, and then twisted with pliers to tighten. The ergonomic analysis showed that this task involved extreme wrist posture positions with high rotational forces. To alleviate these problems, the replacement of wire tie-downs with plastic zip ties was proposed.

In scaffold frame assembly, tubes are clamped together using right-angle and swivel couplers. To tighten a standard coupler a nut and bolt mechanism is ratcheted. The ergonomics analysis showed that this task required very high torques to be applied to the ratchet. A coupler utilizing a "ski-boot"-type clamping mechanism was designed to eliminate the repetitive ratcheting motion and the excessive torque requirements.

Two experiments were conducted to test the interventions using electro-goniometers to record wrist angle measurements. The tie-down experiment recorded wrist flexion, extension, radial deviation, ulnar deviation and the average task-to-time completion (TTC). The coupling experiment measured wrist flexion, extension, radial deviation, ulnar deviation, forearm pronation and the average TTC. Multivariate and univariate Analyses of Variance were conducted on each response measure to assess the impact of each intervention. It was expected that the zip ties and lever-based coupler would significantly reduce wrist joint angles as well as TTC.

By replacing the wire ties with more flexible plastic zip ties, angular response measures and TTC were positively affected. Maximum flexion angle was reduced by 37%, maximum extension angle was decreased by 4.0% and maximum ulnar deviation angle was decreased by 17.0%. While there was no reduction in radial deviation solely due to the plastic zip ties, a decrease was seen during certain subtasks (tie-down/tightening). TTC was reduced by 1.6 seconds when using the plastic zip ties. It was recommended that plastic zip ties replace the #9 gauge wire for the walk-board tie-down task.

Results of the coupling experiment revealed coupler type to interact with the subtask being performed (i.e., coupler placement/removal or tightening/loosening) to effect the angular response measures. Due to the elimination of the ratcheting task, a 9.0% decrease in maximum flexion was achieved while there was no effect on maximum extension angle. A 19.5% decrease in maximum radial deviation angle and a 6.6% decrease in maximum ulnar deviation angle were found when tightening the lever couplers. There was no significant reduction in forearm pronation. While there was reduction in the angular response measures, the lever coupler was found to slightly increase the TTC for frame tube coupling (approximately 12%) as compared to the ratcheting couplers. Based on the improvement in the angular response measures, the lever couplers were recommended for further examination as a viable alternative to the standard scaffolding couplers. An avenue of future research would be a comparison of the force requirements for the existing couplers versus the lever couplers.

Ergonomic Evaluation of Scaffolding Task Interventions for
Power Plant Maintenance

by
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Biography

Matthew Ryan Diering was born on November 2, 1985 in Raleigh, North Carolina. The son and brother of NC State graduates, Matt was destined to attend NC State. In May 2008 he graduated from the Edward P. Fitts Department of Industrial and Systems Engineering with a B.S. The following August he enrolled in graduate school at the same department where he was awarded the National Institute for Occupational Safety and Health (NIOSH) Occupational Safety & Ergonomics Graduate Education and Research Program Fellowship. In May 2010 he will be graduating with a M.S in industrial engineering.

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List of Expert Acronyms

NPP: Nuclear power plant

ECNC: Ergonomics Center of North Carolina

SIMS: Safety Information Management System

OSHA: Occupational Safety and Health Administration

LI: Lifting index

UL: Underwriters Laboratories

FM: Factory Mutual Engineering Corporation

E1: Experiment 1

E2: Experiment 2

SLA: Stereolithography

RCB: Randomized complete bock

TTC: Time-to-task completion

T_O: Test operator

O_A: Operator’s assistant

S: Spotter

ANOVA: Analysis of variance

MANOVA: Multivariate analysis of variance

HSD: Honestly Significant Difference

EMG: Electromyography

1 Introduction

1.1 Motivation for Study

Nuclear power plants (NPP) are extremely complex systems requiring massive operations and maintenance staff to ensure that the plant is running at peak efficiency. From the servicing of the reactors to pipe repair to fuel rod exchange, maintenance is a primary concern that requires each plant to shut down for two to three months per year to allow for a complete sweep. The North Carolina State University Ergonomics Lab, part of the Edward P. Fitts Department of Industrial and Systems Engineering, and the Ergonomics Center of North Carolina (ECNC) recently contracted with a local power utility company to implement an ergonomics program in the utility's nuclear power division designed to reduce work related musculoskeletal injuries. This partnership provided the framework that supported the present thesis.

On the basis of prior worker injury cases, environmental safety and health personnel at the company speculated that maintenance employees were at a higher risk for ergonomic related injuries. In order to quantify this risk, the local power utility company provided the Ergonomics Lab and ECNC with access to their Safety Information Management System (SIMS) databases for all nuclear power plants (NPP) in the company's fleet. The SIMS data covered all occupations at the NPPs and allowed for identification of injuries with significant ergonomic root causes as well as identification of specific job areas that accounted for the highest rates of lost time. The database included Occupational Safety and Health Administration (OSHA) logs covering the period from January 2002 through July 2007. During this time, 162 recordable incidents occurred. After a study of the descriptions of causes of these recordable incidents, it was found that 58 out of 162 (35.8%) of injuries had ergonomically related root causes. This motivated ergonomic evaluation of NPP manual work tasks to potentially reduce the number of recordable incidents.

Once incidents with ergonomic root causes were identified, the proportion involving personnel in maintenance operations was determined. Strain and sprain injuries accounted for 54 of 162 (33.3%) of the total injuries; of the strain and sprain injuries, 13 of 54 (24%) were sustained by maintenance workers. Additionally, 50% of tendinitis cases were found among maintenance personnel. Finally, half of all reported back strains occurred among maintenance workers. Injury incidence rates were higher for maintenance workers than for any other type of personnel at the NPPs. Even though maintenance jobs accounted for a significant proportion of ergonomic related injuries, they did not account for a significant proportion of lost days. The reason for this is that other work groups in the NPPs, primarily security, produce incidents with comparatively large number of lost days. Maintenance worker incidents only accounted for 11.7% of all lost days. Therefore, the database analysis revealed that while more injuries happened to maintenance personnel, they tended to be less severe.

Due to the large percentage of recordable incidents that could be attributed to maintenance personnel, the focus of the Lab research and this thesis was to develop ergonomic interventions for maintenance operations with the intent to reduce ergonomic related injuries. More specifically, non-repetitive maintenance tasks involving scaffolding assembly were selected for analysis. These tasks are one-off and are customized to the situation (more information is provided below).

1.2 Preliminary Job Analysis

Based on the number of ergonomic related injuries occurring in maintenance operations, further analysis was conducted to narrow the focus of the study. This job hazard analysis was constrained to ergonomic hazards and did not include slip and fall injuries, for example. There were two major steps in the analysis, including:

(1) Screening of maintenance jobs for ergonomic risk factors using a review tool developed by the ECNC - The job review tool was partially based the RULA (Rapid Upper Limb Assessment) method and the NIOSH lifting equation. RULA was used to determine the acceptability of arm postures and forces. An observational survey method, RULA assesses upper limb risk from work-related activities (McAtamneya & Corlett, 1993). The NIOSH lifting equation was used to determine acceptable lifting limits. Weight, lifting postures, and repetition are used to analyze specific lifting situations (Waters, Putz-Anderson, & Garg, 1994). The review tool was developed to subjectively establish ergonomic risk based on an ergonomist's inspection of jobs. A wide array of maintenance jobs was evaluated using the review tool, including chemical technicians, maintenance mechanics, scaffolding crews, shipping staff, turbine maintenance personnel, and water treatment facility maintenance staff. Each job was divided into component tasks that comprised the job. These tasks were assigned subjective ratings (1-10) for three potential hazards: extreme posture, force and repetitive motion. The ratings were assigned across 10 different areas of the body. By combining the ratings across

hazard types, a risk priority (low, moderate, high) was assigned to each of the 10 body areas. These priorities were then weighted and summed to create an overall job risk score. The job scores were then compared in order to determine the specific aspects most likely to cause ergonomic related injuries.

This initial job screening revealed scaffolding, shipping and receiving, and cable pulling to be maintenance jobs falling in the "high" ergonomic risk category. These tasks shared a common set of characteristics including generation of very large body forces, maintenance of extreme posture positions during tasks, and use of tools requiring high application forces or excessive repetition.

(2) Performing a "deep dive" analysis on high risk jobs - A "deep dive" analysis involves a detailed risk assessment using existing validated ergonomics job analysis tools including the NIOSH lifting equation, the Strain Index, and the Liberty Mutual psychophysical lifting limits to quantify the extent to which jobs exceed established criteria and to provide a basis for intervention recommendations. The Strain Index is used to assess a task's risk to the hands, wrists, and elbow. Duration of the task, postures, and intensity of exertion are all used to determine risk (Moore & Garg, 1995). The Liberty Mutual psychophysical lifting limits are used to determine the relationship between psychological limits and actual lifting capacity. By combining perception and biomechanics, safe lifting limits can be implemented (Snook, 1978).

All of the identified ergonomic analysis tools have been computerized and are packaged as a part of the Ergonomic Decision-making Guide for Assessing Risk® software application, developed by the ECNC. In using this tool, first the entire job is divided into elements, including carries, lifts, postures, and hand-intensive tasks. These task elements are then processed using the appropriate computational aid (e.g., RULA for hand-intensive task assessment). Each element is then assigned a ranking of ‘Passed’, ‘Cautioned’, or ‘Failed’. ‘Passed’ elements pose no ergonomic risk to the worker, ‘Cautioned’ elements are considered to represent an “acceptable” risk, while ‘Failed’ elements should be ceased immediately.

Upon reviewing the results of the deep dive analysis, it was determined that scaffolding operations included the most tasks posing an ergonomic risk. Sixteen elements were found for scaffolding operations. One received ‘Passed’ ranking, ten received ‘Cautioned’ rankings, and five received ‘Failed’ rankings. Two of the ‘Failed’ elements involved the loosening of scaffold joints. This task required an estimated 300 in-lbs torque at the wrist, far exceeding the recommended hand torque limit of 180.75 in-pounds (Mital & Channaveeraiah, 1988). Lifting and lowering of scaffolding equipment accounted for next ‘Failed’ element. Scaffolders used one handed lifts and lowers to transport 35 lb scaffold walk-boards, greatly exceeding the University of Michigan 3DSSPP recommended lift of 7.10 lbs. Similarly, the transport of scaffold equipment (up to 40 lbs) to and from the worksite violated Snook’s (1978) recommendation of 37.4 lbs for a general work population with a two handed lift. Among the ‘Cautioned’ elements was the tying down of the scaffold walk-boards with #9 gauge wire that according to Moore and Garg (1995)involved “Very Bad” hand and wrist postures as well as a “Somewhat Hard” perceived intensity of exertion.

From these results, there was quantitative evidence that scaffolding was an area of maintenance activity which placed the worker at a heightened risk. Thus, scaffolding was selected as the specific focus for the present research. Of the high risk scaffolding elements posing a heightened risk to the worker, two were selected for this study. The first was the tying down of scaffold walk-boards using #9 gauge wire. The second was the tightening and loosening of the scaffold couplers to construct scaffolding frames. Both of these tasks require high forces and potentially hazardous hand postures. The tasks were also selected because there are limited alternate methods for performance and the fact that they could be easily replicated in an experimental setting for detailed analysis.

1.3 Existing Equipment for Scaffolding Operations

Scaffolding is a job that requires use of specialized equipment not used elsewhere in the NPP. The scaffolds most commonly used are of the tube and coupler type. A series of two inch diameter pipes are connected using steel couplers which join two adjacent pipes. The pipes and couplers create a framework upon which the maintenance staff can perform their tasks. While various other scaffolding systems are used throughout the NPP, tube and coupler scaffold is predominately used due to its flexibility. For this reason, tube and coupler scaffolding is also used in all NPPs as part of the utility’s fleet making it a good candidate for study. While the elements used in the construction of scaffolds, tubes and couplers, may be manufactured by different companies, the different brands function in an identical manner, allowing utilities freedom in the selection of equipment for maintenance operations.

1.3.1 Walk-board Tie-Down Task

At each working level of the scaffold, walk-boards are placed as a work surface. There are two primary materials from which walk-boards are constructed including metal and wood. Metal walk-boards (Figure 1.1) are lighter, have slip resistant surfaces, and last longer. However, they only come in predetermined lengths. Wood walk-boards (Figure 1.2) are able to be cut to size, but are heavier and deteriorate quicker. When paired with wooden walk-boards, tube and coupler scaffolds can be erected around any obstacle or at any location in the NPP. Due to its flexibility, wooden walk-boards are most commonly used. Metal walk-boards are commonly used with tube and coupler assembly in large open areas where frames must be erected quickly. Both metal and wood walk-boards were analyzed in this study.

Figure 1.1: Common Metal Walk-board

Figure 1.2: Common Wood Walk-boards

The securing of the walk-boards to the scaffolding frames was identified as a hazardous task by the deep dive analysis. In general, tie-down wire is used to prevent lateral end-to-end movement and vertical travel of walk-boards once they are placed on an assembled frame. The NPPs of the utility company currently use #9 gauge wire (0.1144” diameter) for this task. In the tie-down task, the scaffolder first positions a walk-board on a frame, then a precut length of #9 gauge wire (18-36”) is looped around both the walk-board and a horizontal tube. The #9 gauge wire is then tightened using a pair of pliers, grasping both ends with the pliers and twisting them together until the wire loop is secure. To ensure the safety of the maintenance workers, the ends of the wire are cut to a suitable length by scaffolders and then twisted out of the way to prevent poking injuries. Due to the thickness of the #9 gauge wire, high forces are required in manipulation and twisting. This issue coupled with the repeated wrist motion required to tighten the wire around the walk-boards, poses a significant ergonomic hazard for scaffolders.

Figure 1.3: Scaffolder Performing the Tie-down Task

1.3.2 Scaffolding Couplers

While constructing a scaffold, scaffold couplers are used to secure scaffold tubes in place. There are two primary types of load bearing couplers used at the NPP: right angle and swivel. Right angle couplers are used to connect horizontal tubes with vertical tubes at 90 degree angles. Swivel couplers are able to secure tubes at any other angle. Typically, swivel couplers are used to secure diagonal braces. Both types of couplers utilize an integrated bolt and nut to secure the coupler's arm over the tube, using friction to keep the tube secure. Once the tube has been placed on the base of the couplers, the coupler's arm is fitted over the tube. The bolt is then inserted into the arm and the bolt is tightened down onto the arm. A ratchet is used to tighten the bolt, requiring the scaffolder to perform repetitive motions under high forces and awkward postures for tightening.

Figure 1.4: Scaffolders Performing the Coupling Task

1.4 Literature Review

Once scaffolding was identified as the focus of this research, a literature review was conducted to identify any prior work in the area developing ergonomic interventions for tie-down and coupling tasks. After reviewing a number of articles, it was found that there existed three primary groups of literature pertaining to scaffolding including low back pain, ergonomic assessment methods of scaffolding, and end frame handling.

1.4.1 Low Back Pain

Back pain is a common complaint among scaffolders. A study was conducted by Elders and Burdorf (2001)to determine how physical, psychosocial, and individual risk factors relate to low back pain in scaffolders. Both a survey and postural loading was conducted. The survey was used to gather data on the presence of low back pain as well as physical, psychosocial, and individual risk factors, while the review of postural loads was intended to examine actual working conditions. From an examination of postural loads, a number of interesting results were found: scaffolders held awkward back posture positions 8% of the time, held their arms raised above their heads 27% of the time, and lifted more than 10 pounds 22.2% of the time. More than half of the scaffolders surveyed reported that they had experienced low back pain in the past year (58%). Furthermore, 23% reported chronic low back pain while 30% reported serious low back pain. Statistical analysis was performed on the results of the survey to determine correlations among responses and to identify any relationship with the incidence of low back pain. High correlations were found between reporting of manual handling, awkward back posture, strenuous arm positions, and perceived exertion. Associations between these factors and low back pain were also present. High manual material handling, strenuous arm positions, awkward back postures, high perceived exertion, high job demand, low job control, and moderate perceived general health were all significantly correlated with low back pain. Reporting of the activity of scaffolding was not found to be significantly associated with low back pain. Finally, there was a significant relationship between perceived exertion and chronic low back pain. The purpose of this paper was not to identify intervention strategies, but to highlight the risk factors related with low back pain.

In a continuation of the previous study, Elders and Burdorf (2004)performed a four year longitudinal study on the same scaffolder population while assessing the prevalence, incidence, and recurrence of lower back pain. A yearly questionnaire gathered information on the presence of low back pain as well as additional information on physical, psychosocial, individual risk factors, and measures of health.

At the baseline survey, 60% of scaffolders had low back pain, while in the three follow-up surveys it varied between 44% and 46%. In the follow-up surveys, the incidence of new lower back pain was between 20% and 28%, while recurrence was between 64% and 77%. Of the 127 scaffolders that responded to all four surveys, 74% had at least one incidence of low back pain, while only 26% were unaffected. A univariate analysis was performed on risk factors and their relation to low back pain. For the incidence of low back pain, moderate health was the only significant predictor, while strenuous arm movements, awkward back posture, high job demand and low job control led to elevated but statistically insignificant relationships. For recurrence of low back pain, manual material handling, awkward back posture, high job demand, low job control and moderate general health had significant association, while strenuous arm movement and high BMI had no significant associations. From this research, Elders and Burdorf (2004) concluded that it is very difficult to establish the independence of an incidence of low back pain from previous episodes.

1.4.2 Ergonomic Assessments

Scaffolding can be broken down into four major categories: construction of scaffold (50% of time), dismantlement of scaffold (20%), transport of scaffold parts (20%), and material preparation time (10%). Van der Beek, Mathiassen, Windhorst and Burdorf (2005) conducted a study comparing the revised NIOSH lifting equation, Arbouw method, practitioners' method of the NIOSH lifting equation, and systematic observations for assessing the physical impact of manual material handling tasks during scaffolding. The first three methods used a self-administered checklist combined with observations of lifting frequencies and other input for each lifting situation. The final method used a set of systematic observations of scaffolders in the field. The NIOSH lifting equation (Waters, Putz-Anderson, & Garg, 1994) is used to define recommended weight limits for a task. The Arbouw method was developed for the Dutch construction industry and is a simplified version of the NIOSH lifting equation. The practitioners' method of the NIOSH equation was designed for this study, and examines only the 'worst' lifting scenario among the set of observations. All three of these methods calculate a lifting index (LI) which is used to determine the acceptability of a lift. Systematic observation requires a very large amount of data which is then used to calculate an action category and to determine whether the lift is acceptable or not. The entire scaffolding process was found to have a LI of 3.85, 3.29 and 3.98 for the first three methods, accordingly. In general, it was found that scaffolding procedures put workers at a substantially increased risk for injury. The subtask with the highest LI was the transport of material followed by construction and dismantlement. For the systematic observations, construction was found to present the highest risk to scaffolders, followed by dismantlement and transportation. While all four method of analysis revealed that scaffolders have an elevated risk for injuries, there were only slight differences in which activity posed the highest risk. This was partially due to the fact that a number of observations had to be eliminated for each method, due to altered lifting situations. Van der Beek et al. (2005) found that the NIOSH lifting equation was a good predictor of risk in scaffold operations, but very time consuming. However, the method is limiting in that it requires a very rigid set of components to be present in the examined activity. The

Arbouw and practitioners' methods were quicker, but still considered too difficult to apply in the field. Finally, Van der Beek et al. (2005) offered that systematic observations are useful for design, but they are very time consuming and expensive to conduct.

Another study that examined the application of ergonomic assessments in scaffolding was conducted by Vink, Urlings and van der Molen (1997). Because scaffolders are exposed to extreme postures and high forces, they were recruited for a participatory ergonomic study towards improving work methods and reducing injuries. The participatory ergonomics approach was used to allow the scaffolders to have some influence on the redesign of tasks. The six steps of the participatory ergonomic approach are: (1) preparation, (2) analysis of workers, (3) selection of improvements, (4) pilot study of improvements, (5) implementation, and (6) evaluation. During Step 2, a number of task issues were revealed by the scaffolders to be problematic from an ergonomics perspective. Among the issues were high forces and repetition in transport of materials, assembly and disassembly tasks, and cleaning after disassembly. The shoulder, wrist, elbow, and upper back were all found to be body parts with a higher frequency of scaffolder complaints than normal laborers. Based on these results, an ergonomics steering committee decided to focus on reducing the physical load during cleaning and during manual material transport. In Step 4, it was decided that heart rate would be monitored to identify any reduction in heavy work load based on the redesign. The researchers found a significant decrease in heart rate as well as a decrease in the percentage of time the workers moved more than 20kg. Scaffolders also indicated a decrease in shoulder, leg and total body discomfort; albeit with a slight rise in back discomfort. These improvements were then implemented in the work place and a survey was completed after 6 months. The scaffolders were asked which improvements were still used and if they were beneficial. The improvements suggested by management were found to be less frequently used than the ones suggested by the scaffolders. In general, the participatory ergonomics approach can be used as an effective alternate method of improving scaffold task design through using the involvement of employees to ensure the validity of recommendations. One of the major shortcomings of the approach is the potential for a hazard to not be identified by workers, leading to it being ignored.

1.4.3 End Frame Handling

Due to the construction industry having the highest injury rate of any major United States industry, many ergonomics and safety studies have been conducted. Scaffolding in construction poses risks with overexertion being one of the key problems. Hsaio and Stanevich (1996) undertook a study to identify activities which increase a worker's risk of exposure to overexertion hazards and to determining strategies to reduce occurrence of overexertion. Visits were made to construction sites to observe and record scaffolding task performance. It was found that many sites used a welded-tubular end-frame, a hollow metal structure with two legs that can be inserted into the top of a lower end frame to construct scaffold tiers. During the erection and dismantling of scaffolds, workers were videotaped and the frequency of task components counted. Some common task components included: (1) preparing foundations, (2) carrying scaffold parts, (3) erecting/removing end frames, (4) erecting/removing cross braces, (5) installing/removing access ladders, (6) installing/removing walk-boards, (7) installing/removing guardrails, and (8) securing/removing scaffold tiebacks. From this list of components, biomechanical stresses were calculated using 3DSSPP. The biomechanical analysis identified lifting scaffold end frames, carrying end frames, handling scaffold walk-boards, removing cross braces, and removing guardrails as activities that increase risk of overexertion injuries.

Some common features of this include: handling bulky materials, awkward working postures, restricted work spaces, or elevated work surfaces. In transporting scaffold end frames, video analysis revealed that there are six lifting and five carrying methods commonly used. All of these methods were found to create stresses which exceeded the strength capacity of some portion of the general work population. Symmetric front lifts at either elbow or knuckle height were identified as the postures allowing for the greatest isometric strength. In summary, Hsaio and Stanevich (1996) found the majority of scaffolding tasks to cause significant biomechanical stress and increase the risk of an overexertion injury.

In a continuation of the previous study, Cutlip, Hsiao, Garcia, Becker, and Mayeux (2000) further examined the stresses caused by the transport of welded-tubular scaffold end frames. In this study, a cohort of 46 experienced scaffolders was selected. Two experiments, using force platforms, were designed to determine if scaffolders possessed increased muscle strength over the general population and to determine if various postures were beneficial to muscular strength when disassembling scaffolds. Seven postures were examined in the experiments. Scaffolders performed a series of exertions in the various posture positions. These exertions were then measured and compared to a general industrial worker population. The study found that the scaffolders examined in the study had a higher muscular strength capacity than the general population of industrial workers studied by Chaffin, Herrin and Keyserling (1978). Of the seven postures examined, four were found to be conducive to generating the necessary force to carry end frames. In summary, Cutlip et al. (2000) found that while some postures allows for a relatively safe transport of end frames by scaffolders, there are portions of the population which would be still be at significant risk using similar work methods.

1.4.4 Summary

While the literature review confirmed many of the findings from the “deep dive” analysis of the scaffolding tasks at the power utility, no literature was found documenting studies on the specific problems in coupling and walk-board tie-down discussed above. Papers concerning carrying welded end frames indicated similar areas of ergonomic concern as the “deep dive” analysis: handling of material, handling scaffolding walk-boards, and the removal of scaffolding tubes; however, end frames are not used at the NPPs under study. Similarly, the literature confirmed that awkward postures and high forces placed the scaffolders at elevated risk of low back pain. While low back pain is not the focus of this study, the studies reviewed here indicated the same risk factors as found in the “deep dive” analysis of the work tasks at the NPPs. The literature concerning different ergonomic assessments, while not directly related to this study, highlights the usefulness of engineering controls in reducing hazard exposures in scaffolding tasks. In general, the scaffolding literature reinforces our preliminary job analysis and indicates that there is room for further research on ergonomic interventions to scaffold frame coupling and walk-board handling.

1.5 Objectives

The objectives of this study are twofold. First, to conceptualize interventions to reduce scaffolding injuries pertaining to the tying down of scaffolding walk-boards with #9 gauge wire and the tightening and loosening of scaffold couplers. Second, to conduct experiments in which the impact of the proposed interventions is empirically evaluated.

2 Methods

2.1 Participants

The participants recruited for the experiments in this study were nine males ranging in age from 33 to 60. All participants were NPP scaffolding staff. The primary qualifications for participation were expertise in scaffold assembly and familiarity with current NPP scaffolding practices. Each participant was presented with a consent form prior to participation in the experiments (see Appendix A).

Table 1 shows the means and standard deviations of relevant anthropometric characteristics of the participants, including average work experience, height, weight, grip strength, linear force, back strength, and upper arm strength. The information was collected using the demographic questionnaire found in Appendix B. Grip strength, linear force, back strength, and upper arm strength were to be used in future analysis to determine if scaffolders possessed greater strength than an average person. Since participants were required to meet the power utility's qualifications to work as scaffolders, range of motion was assumed to be normal for all participants.

Table 2.1: Participant anthropometry.

	Mean	Std. Dev.	Min.	Max.
Average Experience (years)	11.5	7.3	0	25
Height (in)	69.7	2.8	66	75
Weight (lbs)	215.7	61.1	170	345
Grip Strength (lbs)	101.2	16.5	68.7	122
Linear Force (lbs)	89.0	20.9	59.9	122.5
Back Strength (lbs)	288.6	97.3	95	391.7
Upper Arm Strength (lbs)	86.8	24.0	40	113.3

2.2 Tasks

Two separate tasks were examined in this study, including walk-board tie-down and scaffold frame tube coupling.

2.2.1 Walk-Board Tie-Down

This involved securing wood or metal walk-boards to the scaffolding frame. Walk-boards provide maintenance personnel with a standing surface as well as a surface to store equipment. Additionally, walk-boards provide lateral stiffness to the scaffolding frame, preventing failure. Currently, #9 gauge wire is used to prevent walk-boards from moving on a frame (Duke Energy, 2006). Vertical and lateral travel would place maintenance personnel at risk as well as compromise the structural integrity of the entire scaffold.

There are two primary types of walk-boards utilized in the NPPs of the power utility, including wood and metal. Each type is sized differently and secured differently to the scaffolding frame. Wood walk-boards are 10 in. wide, 2 in. thick, and can vary in length from 8 to 16 feet. The power utility's standard operating procedure stated that wood walk-boards must be "Southern pine, dense industrial 65 scaffold plank" (Duke Energy, 2006). Once a scaffolding frame has been constructed and the proper wood walk-board length has been selected, the walk-board is transported to the worksite and simply laid on top of the desired horizontal scaffolding tubes. Walk-boards are placed with overhangs of at least 6" to add stability. Once in place, a walk-board is tied down on both ends using length of #9 gauge wire. The wire must be of an adequate length to wrap entirely around the walk-board and the scaffolding tube while still maintaining enough excess to be tightened. Typically, the length of a tie-down is approximately 36”. The #9 wire is transported to the worksite in bundles and then cut to size. Once the #9 wire tie-down has been looped around a board, it is hand twisted two to three times to ensure proper seating. A pair of lineman’s pliers is used to grasp the junction of the wires, which are then rotated in a clockwise fashion to tighten. The #9 wire tie-down is tightened to the maximum hand strength of the scaffolder. Once tight, any excess #9 wire is cut off using the lineman’s pliers. The exposed tips are then curled out-of-the-way using the pliers in order to eliminate any puncture hazard. Secured wood walk-boards are placed a maximum of 2’6” apart, spanning the entire width of the working surface. This spacing allows for scaffolding plywood floor deck to be placed across the tops of the walk-boards. The plywood floor deck is then nailed to the walk-boards to provide the work surface. Figure 2.5 provides a picture of a tie-down on a wood walk-board and Figure 2.6 offers a close-up of a completed tie-down.

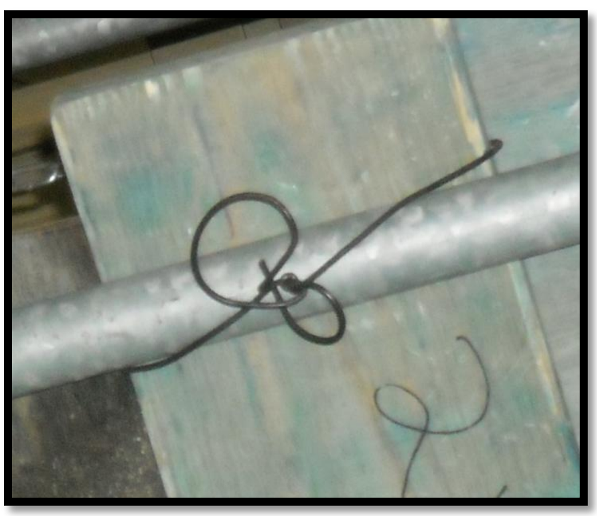

Figure 2.5: Completed tie-down on wood walk-board.

Figure 2.6: Close-up of tie-down.

Metal walk-boards differ in both size and attachment mechanism from wood walk-boards. Metal walk-boards are typically 19" wide (although they can differ) and come in the same lengths as wood walk-boards. The NPP standard operating procedure states that metal walk-boards must "have been tested and listed by Underwriters Laboratories (UL) or Factory Mutual Engineering Corporation (FM)" (Duke Energy, 2006). Instead of simply resting on the scaffolding tubes, metal walk-boards utilize an integrated hook-on mechanism (see Figure 2.7). The hooks are seated over the scaffold tubes diminishing the possibility of any front to back movement. Once in place, the walk-board is tied down using #9 gauge wire. A tie-down is placed through a hole centered near the end of the walk-board and then wrapped around the scaffolding tube. This allows the tie-down to be significantly shorter for the metal versus wood walk-board, approximately 18" in length. Prior to the tie-down, the #9 gauge wire is transported and prepared the same way as for a wood walk-board. Once looped, the tie-down is hand twisted two to three times to ensure proper seating. A pair of lineman's pliers is used to grasp the junction of the wires, which are then rotated in a clockwise fashion to tighten. The #9 wire tie-down is tightened to the maximum hand strength of the scaffolder. Once tight, any excess #9 wire is cut off using the lineman's pliers. The exposed tips are then curled out-of-the-way using the pliers to eliminate any puncture hazard (see Figure 2.8). Metal walk-boards are placed side-by-side across the entire width of the scaffold frame to create the desired work surface.

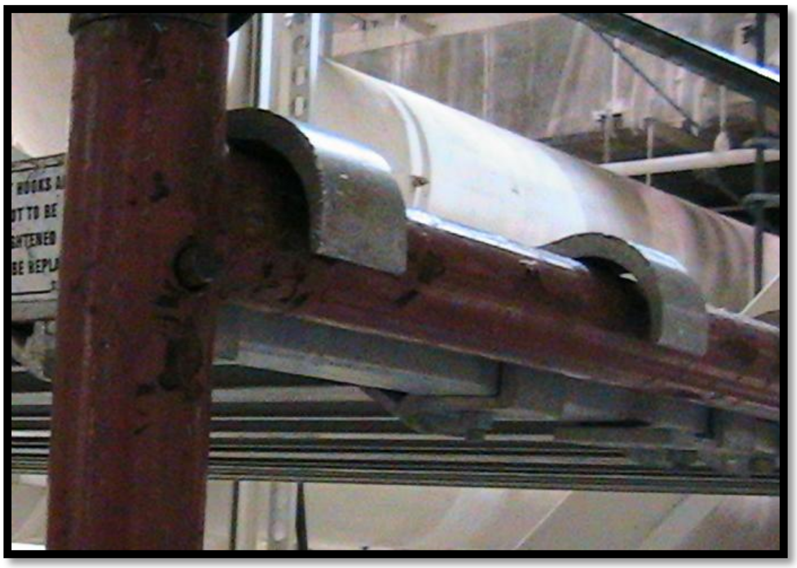

Figure 2.7: Hook-on mechanism used for metal walk-boards.

Figure 2.8: Completed tie-down on metal walk-board.

Both walk-board types are used throughout NPPs. Wood has the advantage of being flexible; it can be used on a scaffold of any size. A disadvantage of wood is that the walk-boards have a shorter lifespan, particularly if stored outside, and a high potential for environmental contamination (radiation). Metal walk-boards are limited to predetermined lengths; the scaffolding frame must be constructed to the precise size of the walk-board or the hooks will not properly fit around a tube. An advantage of the metal walk-boards is their lifespan, typically much longer than a comparable wood walk-board. Since both types of walk-board are being used by NPPs, both types were investigated in this study.

2.2.2 Scaffold Couplers

The second task examined in this study was that of tightening and loosening of scaffold frame tube couplers. Scaffolding couplers are made of a structural metal, typically drop-forged steel, malleable iron, or structural grade aluminum, to ensure strength and lifespan (Occupational Safety & Health Administration, 1996). While multiple manufacturers produce scaffolding couplers (e.g., ThyssenKrupp Safeway, Layher), all models maintain the same functionality. Couplers from different manufacturers utilize the same tightening technique (bolt ratcheting) with only superficial visual differences. Figure 2.9 provides a close-up view of a scaffolding coupler and Figure 2.10 shows a coupler positioned and tightened.

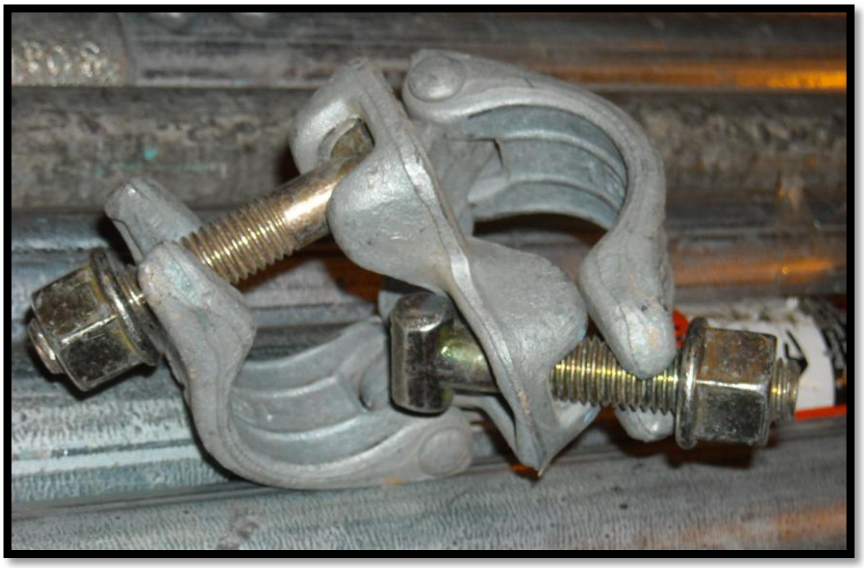

Figure 2.9: Close-up of scaffolding coupler.

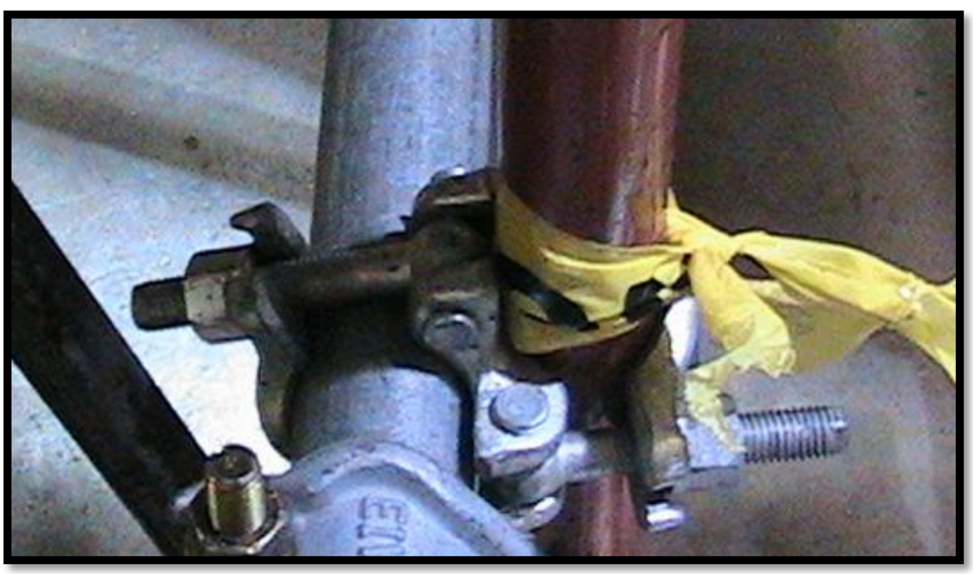

Figure 2.10: Scaffolding coupler in use.

The coupling mechanism utilized by scaffolding couplers is the force of friction between the coupler and the tube to eliminate movement. The tube contacts two parts of the scaffolding coupler, the base and a rotating arm. Once the tube has been placed on the base, the coupler arm is rotated on top of the tube. This alone does not provide adequate friction to prevent movement. To achieve adequate friction, a nut and bolt are used. The bolt is secured to the base of the coupler allowing it to rotate into position. After the tube has been placed between the base and the arm, the bolt is rotated into a slot on the arm. Once seated, the bolt is secured through the use of a nut. The nut is tightened, using a ratchet, onto the upper portion of the arm. The design of the surface allows for a clean mating between the nut and the arm. In practice, scaffolders typically hand-tighten the nut as much as possible before using the ratchet. As more torque is applied to the nut, the coupling arm presses onto the tube increasing friction. The nut is typically tightened as much as possible, with a NPP requiring the manufacturer's recommended torque limit (Duke Energy, 2006). To remove a coupler from a tube, the nut is ratcheted until loose enough to remove the bolt from the arm, thereby releasing the tube. Again, after loosening the nut with a ratchet, scaffolders will typically use their hands to remove the nut.

There are two primary types of scaffolding couplers, including rigid and swivel. Rigid couplers are used to connect vertical with horizontal tubes; they are only capable of joining frame tubes at 90 degree angles. Rigid couplers are typically seen at the corners of any scaffolding frame. Swivel couplers allow for tubes to be joined at angles other than right angles. They are typically used to secure load-bearing diagonal cross members.

Rigid couplers differ from swivel couplers only in the design of the base. For rigid couplers, the base is one solid piece with fittings for two tubes on opposite sides and at right angles to each other. For swivel couplers, there are two pieces to the base attached using a swiveling mechanism. Each coupler weighs approximately 1.5 pounds. Figures 2.9 and 2.10 provide images of rigid couplers while Figures 2.11 and 2.12 present swivel couplers.

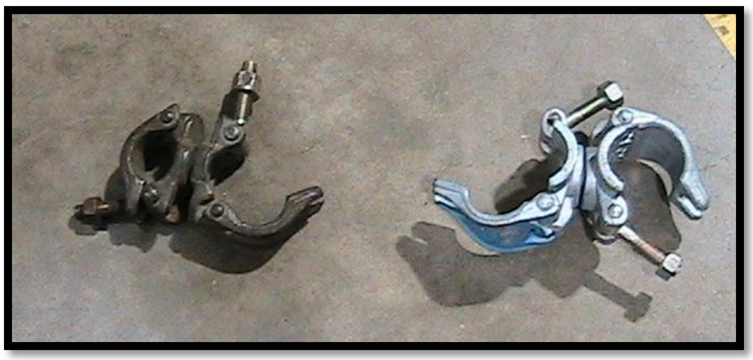

Figure 2.11: Swivel couplers.

Figure 2.12: Swivel couplers in use.

2.3 Testing Apparatus

For this study, two experiments were conducted on custom-built scaffolding frames. At these frames, participants were required to use the current equipment (described above) as well as proposed interventions under a variety of conditions.

2.3.1 Experiment 1 Overview

Experiment 1 (E1) was conducted to assess the impact of various walk-board tie-down methods on scaffolder performance and posture position. As described above, #9 gauge wire is currently used to tie down walk-boards. With a thickness of 0.1144", high forces are required to manipulate the wire and extreme wrist postures are assumed. These work factors coupled with repetitive wrist motion to secure the tie-down place the scaffolder at a heightened ergonomic risk (Putz-Anderson, 1988). The "deep dive" analysis showed that the tie-down task required "Very Bad" postures as well as repetitive and forceful hand activities (Moore & Garg, 1995). Consequently, an ergonomic intervention was proposed towards reducing the force requirements, extreme wrist postures, and repetitive motions.

A survey was conducted to determine if any commercial products existed which could reduce the identified ergonomic hazards in the walk-board tie-down. Unfortunately, an internet search found no products designed specifically for scaffolding work. The next step was to identify other commonly used methods to secure elevated walking surfaces in, for example, construction environments. One idea was to adapt a spring coupler to fit over both a walk-board and the scaffolding tube. A locking mechanism could be used to ensure that the coupler would remain secure. Such a coupler could be reusable and eliminate wrist motion repetition and extreme postures. However, this alternative was deemed unsuitable due to the cost and time required to adapt the couplers to fit a large work area. Another idea was to use rope to secure walk-boards using a knotting tool which would allow the worker to remain standing. This idea was discarded because scaffolders could not afford to carry additional equipment on a tool belt while on the scaffold.

Subsequently, the idea to use industrial plastic zip ties was put forward. Using zip ties was expected to eliminate repetition of wrist motion while reducing harmful postures. It was also expected that zip ties could be applied to walk-boards in the exact same manner as the current #9 wire. The zip tie would be looped over the walk-board and the scaffolding tube. The zip tie would then be pulled through the zip head, tightening upon itself. Once tight, any excess zip tie would be clipped off and the exposed end tucked out of the way. Although the manner of use of the zip tie could be similar to the #9 wire, the capacity of the tie was another issue for consideration. The #9 gauge wire currently used at the NPP is required to have a tensile strength of 250lbs; thus, any plastic zip tie would be required to have the same tensile strength. Plastic zip ties were found with a bundling strength of 250lbs, meeting the requirements of the NPP. The maximum length of #9 gauge wire used in the tie-down task was approximately 18”; plastic zip ties were found with lengths up to 36”. Any zip tie intervention also needed to be robust for application anywhere in the NPP. With temperatures reaching over 120°F in certain areas, any plastic zip tie intervention must be able to withstand high heat. Commercially available plastic zip ties are able to be used under -40°F to 185°F. A final concern was that of cost. A bag of fifty 36” plastic zip ties cost $8.95 for a price per tie of only $0.18. Buying in bulk would allow for an even lower price. A 100 pound coil (1705 feet) of #9 gauge wire costs $121.06 for a price of $0.11 per 18” tie-down.

The ergonomic intervention chosen for examination in the experiment was replacement of the current #9 gauge wire tie-downs with plastic zip ties. The final tie chosen was a Nylon 6.6 Extra Heavy Duty Cable Tie manufactured by Cable Tie Express. For the study, a length of 36” was selected, to ensure adequate length for wood walk-board tie-down. Additionally, a tensile strength of 175lbs was selected because of cost. The experiment did not examine the yield strength of the plastic zip ties. A total of 600 zip ties were procured for the study.

2.3.2 Experiment 2 Overview

Experiment 2 (E2) was conducted to quantify differences between the standard scaffolding coupler and the proposed intervention. The current scaffolding coupler was found to require excessive force to sufficiently tighten, while exposing the wrist to awkward postures and repetitive motions. Specifically, it was the tightening and loosening of the coupler that placed the scaffolder at risk. The results of the “deep dive” analysis estimated that scaffolders exert a force of at least 300 ft-lbs of torque in order adequately tighten scaffold frame couplers. This exceeds the recommended torque limit of 180.75 ft-lbs for this task (Mital & Channaveeraiah, 1988). Additionally, the hand intensive task of tightening and loosening the couplers exceeded the recommended level of the Strain Index (Moore & Garg, 1995). The task was found to require repetitive work in “Bad” postures. Consequently, a search was conducted using scaffolding manufactures and industrial supply stores to see if other coupling options were commercially available that might serve to eliminate these risks. None were found. Once it was determined that there was no readily available solution, an alternate coupling mechanism was designed and prototyped.

Initially, a design concept was developed to simply alter the existing couplers towards alleviating the risks. Eventually, it became apparent that a retrofit was simply not feasible within the time and monetary constraints of the project. Instead, a reverse engineering process was applied to the existing couplers and a revised coupler model was manufactured through a rapid prototyping system. The revised coupler model integrated a "ski-boot" type clamping mechanism. The ski-boot clamping mechanism includes a series of metal hooks on one side of a boot and a metal loop of wire attached on the other. When the loop is put around a hook, it is levered down thereby tightening the coupler. Once the lever was tightening, a cotter pin is inserted to prevent accidental lifting of the lever. This method of clamping, applied to the scaffold coupler, was expected to eliminate any repetitive wrist motion as well as reduce awkward wrist postures in using the couplers. Figure 2.13 shows the initial design drawings for the prototype coupler.

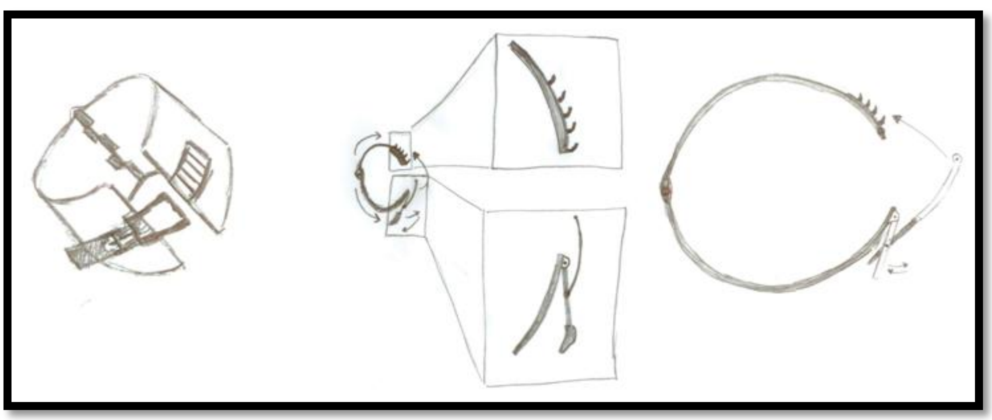

Figure 2.13: Initial design drawings for lever coupler.

Once the clamping mechanism was selected, the prototype was constructed using SolidWorks, 3D CAD software, which allowed easy manipulation of the coupler design. The design went through a number of iterations before arriving at the final design. From SolidWorks, the model was converted into machine code and prototyped. The initial prototype was created by a 3D printer using ABS plastic. This model was used to identify some weaknesses in the design (e.g., proper interior diameter of the coupler), which were then corrected in SolidWorks. The final prototype was constructed using a stereolithography (SLA) machine. Copies of this prototype were used in the actual experiment. Figure 2.14 shows the final design drawings for the lever coupler.

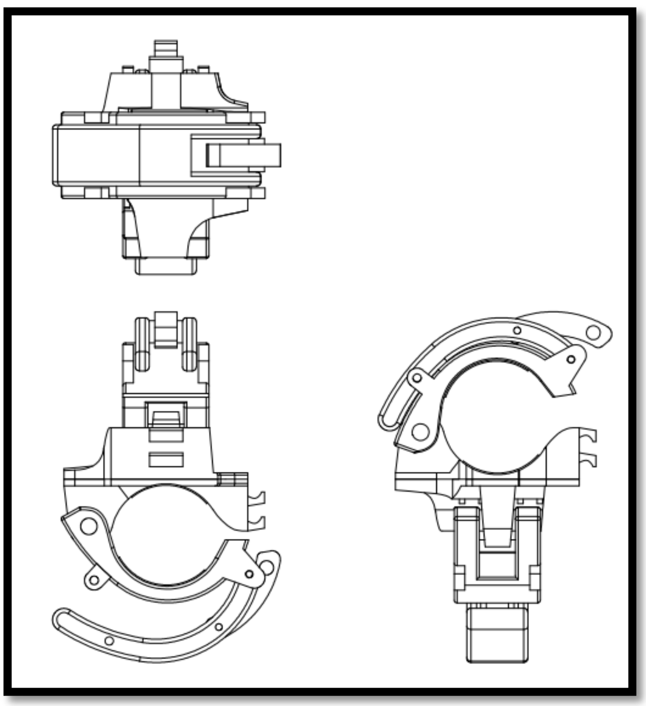

Figure 2.14: Final design drawing for lever coupler.

The revised coupler consists of nine pieces: one base, two upper arms, two upper swing arms, two levers, and two loops. The base is a double-sided piece for two tubes to be placed at a 90 degree angle to each other, as well as incorporating the hooks for tightening the coupler. The upper arms are the portion of the coupler that is lowered on top of the tube; they are connected to the base using a bolt, nut, and locking washer. The levers are the handles used by the scaffolder to either tighten or loosen the coupler. They are fitted to the curvature of the upper arm to allow for a tight fit and are connected to the upper arm using built-in brackets and 1/8” diameter steel dowel pins. The upper swing arms are placed in-between the arms of the lever, and allow for the wire loop to rotate independently of the lever. They are connected to the lever using 1/8” diameter steel dowel pins. The loops currently used consist of a 4” piece of 1/16” diameter braided steel cable held in place using aluminum ferrules. The loops are placed through an opening on the upper swing arms. A total of twelve couplers were built and used in Experiment 2.

2.3.3 Experimental Equipment

The measurement equipment used in Experiment 1 was a biaxial electro-goniometer (SG-150) from Biometrics®. The SG-150 was used to measure flexion-extension and radial-ulnar deviation of the wrist. Any decrease of the angle between the back of the hand and the forearm from the neutral posture was measured as flexion, while an increase in this angle was measured as extension. Flexion was considered a complement of extension because they were measured with the same device. A decrease in the angle between the thumb and forearm from the neutral posture was measured as radial deviation, while an increase of this angle was measured as ulnar deviation. Just as for flexion and extension, radial and ulnar deviations were considered to be complementary. The electro-goniometer was placed on participants with the wrist in a neutral posture (lower portion of Figure 2.15). The distal end of the electro-goniometer was placed over the third metacarpal, while the proximal end was placed over the midline of the forearm. Once the SG-150 was mounted, the cables were moved out of the participant's way by taping them to the back.

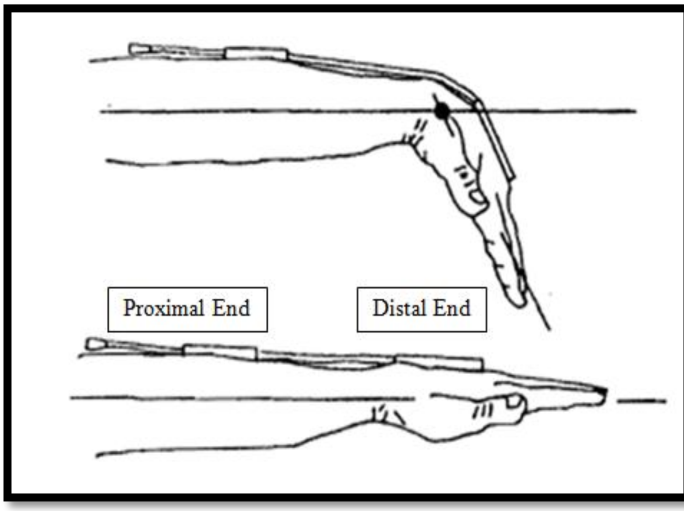

Figure 2.15: Electro-goniometer mounting on the hand and forearm for measuring wrist extension-flexion and radial-ulnar deviation.

The measurement equipment used in Experiment 2 was a biaxial electro-goniometer (SG-75) and a single-axis torsiometer (T-110), both from Biometrics®. The SG-75 was mounted in the same fashion as the SG-150 in Experiment 1 and measured the same wrist angles (flexion, extension, radial deviation, ulnar deviation). The T-110 was used to measure pronation and supination of the forearm. With the arm extended horizontally in front of the participant, the T-110 was mounted with the distal end midpoint on the underside of the forearm and the proximal end placed on the interior portion of the triceps (shown in Figure 2.16).

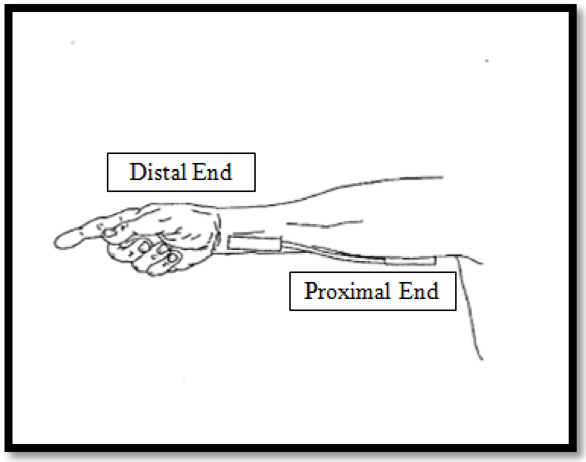

Figure 2.16: Torsiometer mounting on the hand and forearm measuring pronation.

The SG-150, SG-75, and the T-110 were all connected to a single ProComp Infiniti eight channel analog to digital encoder unit using BioGraph Infiniti Software version 5. The data was originally sampled at 2048 Hz and then recorded at 32 Hz for analysis purposes. Similar electro-goniometer studies have used a wide range of recording frequencies ranging from 20 Hz (Hansson, Balogh, Ohlsson, Rylander, & Skerfving, 1996) to 100 Hz (McGorry, Chien-Chi, & Dempsey, 2004) so a selection of 32 Hz was considered acceptable for analysis.

A digital camera was used in both experiments to record the participant work during each test trial. The tapes were then used to break down the tasks into individual components as well as to determine task and component times.

When recording participant anthropometry, two separate measurement devices were used. To measure grip strength and linear force, an Ergo FET hand grip dynamometer was used. To measure back strength and upper arm strength, a NextGen floor mounted dynamometer was used.

2.4 Experimental Design

2.4.1 Independent Variables

For Experiment 1 there were a total of four independent variables. The first was the tie-down type with two levels: the standard #9 wire and the plastic zip ties. The second independent variable was the walk-board type with two levels: wooden boards and metal boards. The third independent variable was the subtask performed in securing a board: the looping the tie-down around a walk-board and tightening of the tie-down. The final independent variable was the position of the tie-down on a scaffold frame with two levels: an upper level or a lower level. The latter two independent variables (subtask and tie-down position) were defined by the job and the design of the test frame. The conditions were representative of real scaffolding operations. The variables that were manipulated during the trials were the tie-down type and walk-board material. Therefore, Experiment 1 followed 2 x 2 x 2 x 2 randomized complete block (RCB) design. Each trial consisted of a unique set of conditions which were presented in different orders across trials for each participant to control for learning and order effects.

For Experiment 2 there were a total of three independent variables. The first was the coupler type with two levels: the existing equipment (ratcheting couplers) and the proposed intervention (lever couplers). The second independent variable was the activity. The activity consisted of two levels: assembly (putting on the coupler) and disassembly (removing the coupler). The final independent variable was the subtask, consisting of two levels: placement (removal) of the coupler around the tubes and clamping (unclamping) the coupler around the tube. The latter two variables were defined by the nature of the work in each trial regardless of the coupler type. The variable manipulated between trials was the coupler type. Therefore, Experiment 2 followed a 2 x 2 x 2 RCB design. Each trial consisted of a unique set of conditions presented in different orders across trials for each participant in order to control for learning and order effects.

2.4.2 Dependent Variables

For Experiment 1, there were a total of five dependent variables. All were objective measures, including four joint movement angles from the electro-goniometer: flexion, extension, radial deviation, and ulnar deviation at the wrist. All angular response measures represent the absolute posture position of the wrist throughout the experiment. The final dependent variable was the average time-to-task completion (TTC) derived from the videotapes and electro-goniometer data.

For Experiment 2, there were a total of six dependent variables. All were objective measures, including five joint movement angles from the electro-goniometer: flexion, extension, radial deviation, and ulnar deviation at the wrist as well as pronation of the forearm measured from a supine position. The sixth dependent variable was the total time-to-task completion derived from the videotapes and electro-goniometer data.

2.5 Experimental Procedure

2.5.1 Facility and Training

This study took place over the course of three days at a training center for the power utility. The scaffold frames were setup in a single training area of approximately 45’ x 25’. The setup of the frames and associated areas is provided in Figure 2.17. Upon arrival on the first day, the nine participants were informed of the purpose of the study, specifically to indentify ergonomic interventions that might serve to reduce the number of maintenance injuries at NPPs. They then read and signed the informed consent for the study (see Appendix A). Finally, they completed a set of stretching exercises to warm-up their muscles for the experiments.

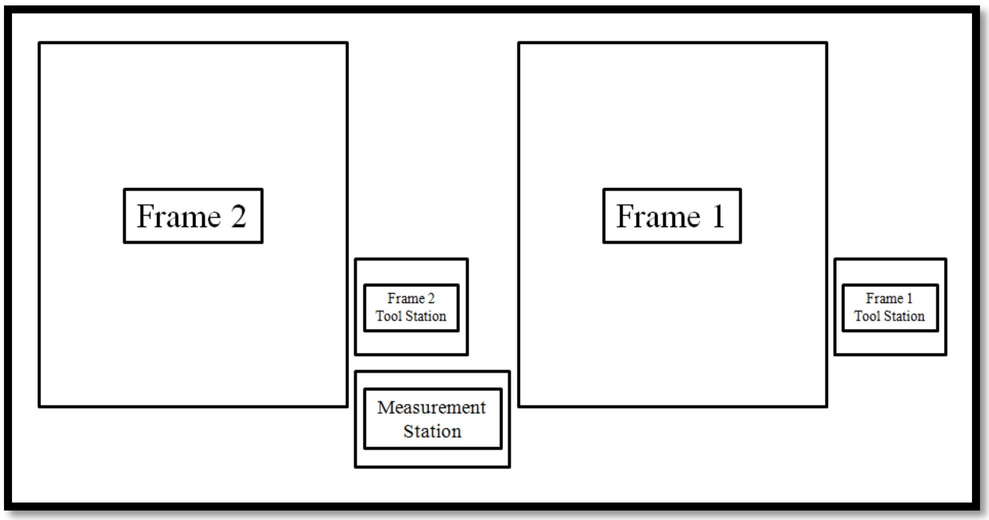

Figure 2.17: Experimental frame setup.

Subsequently, participants were introduced to the equipment used during the study, including the plastic zip ties and the lever couplers. They were shown how to apply the equipment and given time to practice using both interventions. The participants were also shown the measurement equipment (electro-goniometer) and the mounting procedure. Any questions concerning the intervention or the measurement equipment were answered at this time. Finally, the scaffold frame setups were shown to the participants and a walkthrough of the tasks was completed. The participants were then divided into three groups of three scaffolders. These groups remained together throughout all three days of the study. While the previous steps were only performed on the first day of the study, every morning was begun with stretching and a recap of the previous day's activity. Following the stretch, test trials began immediately. Each day was divided into three 2-hour sessions, with each session broken into three 40 minute blocks.

2.5.2 Experiment 1 Testing

For Experiment 1, each block was divided into four trials of roughly 4 minutes each. In each block, participants were assigned one of three roles that were maintained throughout the block. A test operator (T_O) performed all four trials during each block. An operator's assistant (O_A) handed the T_O any equipment needed during the four trials. The final participant was assigned the role of spotter (S). The spotter watched the T_O and O_A to ensure that they were properly carrying out the trials. Additionally, the spotter filled out a survey on the work activity and equipment. Participants swapped roles at the end of each block (every 40 minutes), with the T_O assuming the O_A role and the spotter assuming the T_O role. The breakdown of the time and tasks according to participant roles during a block is presented in Table 2.2.

Table 2.2: Description of Experiment 1 task procedure and estimated test times.

Time (min) within Block	**T_O Duty Set**	**O_A Duty Set**	**S Duty Set**
0-15	Equipment set-up	Be sure that wire tie-downs are ready	Prepare for trial
16-20	Trial 1. 8 tie-downs on predetermined planks	Hand T_O #9 wire for tie-down	Spotter Survey
21-25	Trial 2. 8 tie-downs on predetermined planks	Hand T_O plastic zip-ties for tie-down	Spotter Survey
26-28	Rest	Removal of tie-downs	Removal of tie-downs
29-33	Trial 3. 8 tie-downs on predetermined planks	Hand T_O #9 wire for tie-down	Spotter Survey
34-38	Trial 4. 8 tie-downs on predetermined planks	Hand T_O plastic zip-ties for tie-down	Spotter Survey
39-40	Questionnaire	Prepare for next trial	Prepare for next trial

Experiment 1 used a preassembled frame with eight walk-boards placed on it: four wood and four metal. On the left side of the frame were the four wood walk-boards with two positioned 5’off the ground and the other two positioned 6” off the ground. On the right side of the frame were the four metal walk-boards positioned at the same levels (heights) as the wooden walk-boards. Figure 2.18 shows the relative placement of the walk-boards on the frame.

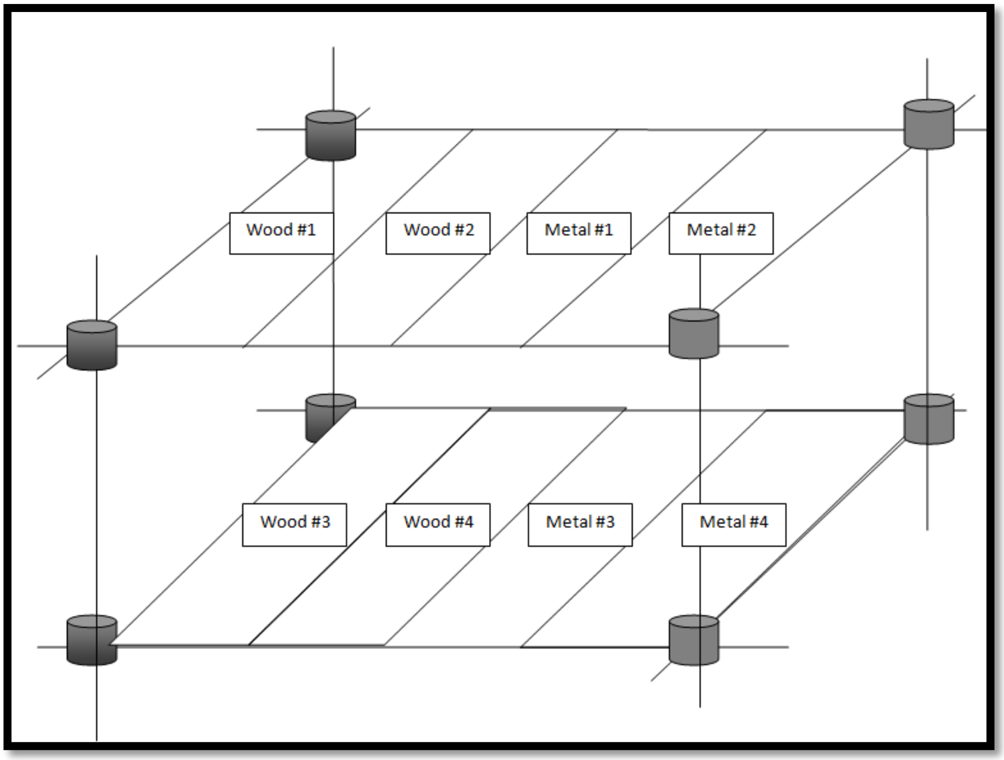

Figure 2.18: Diagram of Experiment 1 scaffolding frame.

At the outset of the experiment, the T_O was fitted with the electro-goniometer while the spotter and O_A ensured the proper tie-downs were ready (both #9 wire and plastic zip ties). To fit the electro-goniometer, the T_O placed his dominant hand palm-down with his arm extended directly forward. With the hand and forearm horizontal, the electro-goniometer was calibrated, with no flexion, extension, radial, or ulnar deviation being read. Once properly positioned, the two sensor heads were taped in place. Once the electro-goniometer was mounted, a check was performed to ensure it was working properly. At the same time the equipment was fit to the T_O, the spotter and O_A ensured that all materials were prepared for the block of trials.

Each of the four trials within a block tested different walk-board materials and tie-down types. The two types of walk-boards and two types of tie-downs were tested in each block. The conditions were presented in random order within block (participant) to reduce the presence of any fatigue effects across blocks. Each trial began with the T_O tying down Board #1 of the proper material (see Figure 2.18). Once this walk-board was tied down using the appropriate tie-down type, the T_O would move in a clockwise direction tying-down the other three walk-boards laying on the frame. Upon completion of the first circuit, the spotter and O_A would remove the four ties. The T_O would then repeat the circuit in the same manner to finish the trial. A total of eight tie-downs were performed during each trial. There was a single maximum posture position observation recorded for each replication along with the times to complete the specific subtasks in the replication. At the end of the trial, the T_O would rest while the spotter and O_A removed the ties from the boards. Trials 2-4 were completed in the exact same manner except the walk-board material and the tie-down type were varied. When the T_O finished the block (four trials), the electro-goniometer was removed. The O_A would take the place of the T_O and the entire block was repeated with the three participants in their different roles.

During the course of the study, each group of three participants performed Experiment 1 in three different sessions. This allowed for multiple trials to be completed by each participant. A total of nine sessions were completed across participant groups with each scaffolder completing a total of 96 tie-downs.

2.5.2 Frame 2

In Experiment 2, each block was divided into four 4 minute trials. As in Experiment 1, in each block participants were assigned one of three roles: the test operator (T_O), the operator's assistant (O_A) and a spotter (S). Each role included different tasks. The T_O placed, tightened, loosened, and removed couplers. The O_A prepared the frame tubes to be coupled as well as handed the T_O any necessary equipment. The spotter observed the T_O and O_A while filling-out the spotter survey. The participants switched roles every 40 min (or block). The breakdown of participant tasks in each block and is presented below in Table 2.3.

Table 2.3: Description of Experiment 2 task procedure and estimated step times.

Time (min) within Block	T_O Duty Set	O_A Duty Set	S Duty Set
0-15	Equipment set-up	Prepares tubes and couplers for trial	Prepare for trial
16-20	Trial 1. Assemble 4 couplers/Disassemble 4 couplers	Assist T_O with positioning of tubes, hand appropriate coupler	Spotter Survey
21-25	Trial 2. Assemble 4 couplers/Disassemble 4 couplers	Assist T_O with positioning of tubes, hand appropriate coupler	Spotter Survey
26-27	Rest	Rest	Rest
28-32	Trial 3. Assemble 4 couplers/Disassemble 4 couplers	Assist T_O with positioning of tubes, hand appropriate coupler	Spotter Survey
33-37	Trial 4. Assemble 4 couplers/Disassemble 4 couplers	Assist T_O with positioning of tubes, hand appropriate coupler	Spotter Survey
38-40	Questionnaire/ Remove equipment	Prepare to switch positions	Prepare to switch positions

Experiment 2 used a preassembled frame with eight couplers supporting eight vertical and eight horizontal tubes. On one end of the frame, four horizontal tubes were mounted with approximately two feet of overhang. This additional tubing provided sites for attachment of new couplers during testing. Figure 2.19 shows the setup of the frame.

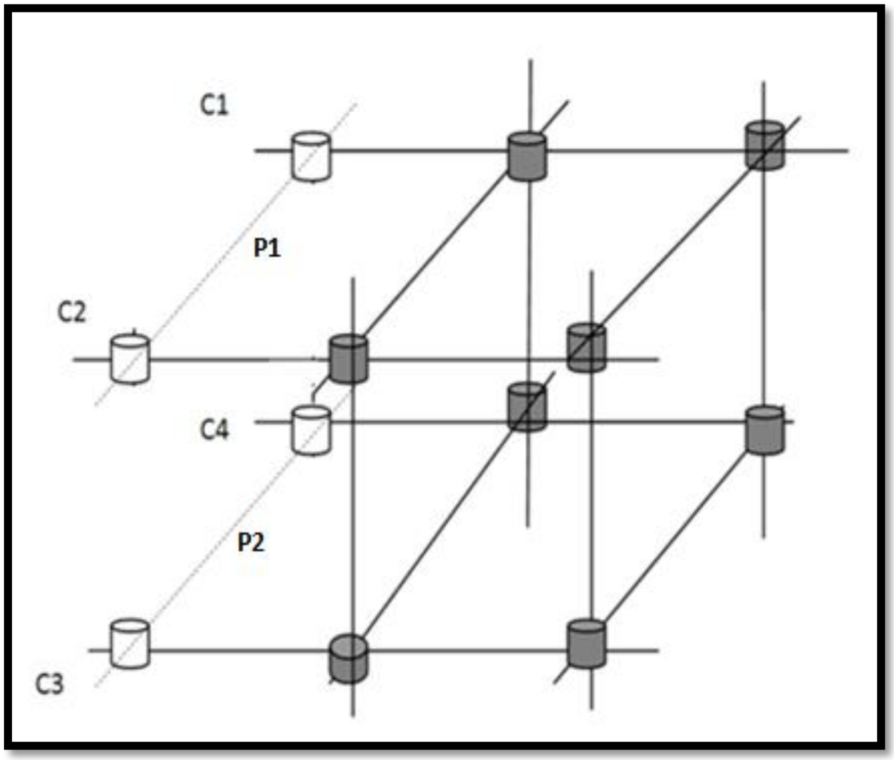

Figure 2.19: Diagram of Experiment 1 scaffolding frame.

At the beginning of a block, the T_O was fitted with the electro-goniometer while the spotter and O_A ensured that both types of couplers were prepared. The electro-goniometer was placed with one end located on the centerline of the underside of the forearm, while the other end was placed on the inside of the arm on the triceps. This placement represented a fully supine posture. The electro-goniometer was calibrated in this position and all measurements represented pronation of the forearm from the supine posture.

Each trial involved mounting of one of the two types of couplers on the two horizontal tubes (P1 and P2). The type of coupler was varied between trials within block. All activities and subtasks occurred during every trial. A trial began with the O_A handing the T_O the first coupler. The O_A then picked-up P1 and positioned it properly. The T_O then placed and tightened C1. Upon completion of C1, the T_O placed and tightened C2. Once The O_A then retrieved P2 and placed it in position. The T_O repeated the same pattern of activities for C3 and C4. The four couplers were always mounted in a clockwise order. Once all four couplers were mounted, the T_O removed them in reverse order. While the O_A held the tubes in position, the T_O would loosen and remove a coupler. The T_O removed C1 first and followed the same clockwise pattern as before. While the TO and OA were conducting the trials, the spotter completed the spotter survey and observed the trial to ensure the proper procedure was being followed.

Trials 2-4 were conducted in a similar manner, with only the coupler type varying between trials. Upon completion of Trial 4, the T_O became the spotter, the O_A became the T_O, and the spotter became the O_A. Each group of three participants completed Experiment 2 three times for a total of three sessions per operator. A total of nine sessions were completed across participant groups with each scaffolder assembling and disassembling a total of 48 couplers.

2.5.3 Debriefing

Following the completion of all trials, an experiment debriefing took place. This session consisted of collection of demographic data. The demographic data form is presented in Appendix B. Once the form was completed, the participants were thanked for their participation and given an NCSU Ergonomics Lab t-shirt.

2.6 Hypotheses

There were two hypotheses for Experiment 1. First, the maximum flexion, extension, radial deviation and ulnar deviation angles were expected to be lower when scaffolders used the plastic zip-ties because of the elimination of the wire twisting subtask. Second, the plastic zip ties were expected to produce shorter average times to task completion than the standard #9 gauge wire because of the elimination of wire twisting subtask.

Similarly, there were two hypotheses for Experiment 2. First, the maximum flexion, extension, radial deviation and ulnar deviation angles, as well as the forearm pronation angle, were all expected to decrease using the lever couplers due to the elimination of the ratcheting subtask. Second, the lever couplers were expected to produce shorter average times to task completion than the standard scaffold couplers because of the elimination of the ratcheting subtask.

2.7 Data Handling

Data handling was carried out in the same way for both experiments. The electro-goniometer data was synchronized with the videos in order for analyses to be conducted on the specific conditions (subtasks, levels, etc…) on each scaffold frame. The videos were reviewed to identify the start and end times for each individual subtask in a trial. By comparing the electro-goniometer time code with these times, the electro-goniometer data was divided into proper lengths. A spreadsheet was developed for each experiment, with a worksheet for each block (participant). The worksheets included condition identifiers for each trial as well as the posture angle measurements and task times. The Experiment 1 worksheet contained the flexion, extension, radial deviation, and ulnar deviation angles, while the Experiment 2 worksheet contained the same with the addition of the pronation angle.

After development of the data worksheets for each block (27 per frame; 54 in total), SAS was used to translate the data in usable form for analysis including maximum and minimum values for each of the angle measurements for each set of conditions. A summary worksheet was then constructed for each experiment. The summary sheet for Experiment 1 included identifiers for the participant, block, trial, tie type, walk-board material, level and subtask, as well as the observations on flexion maximum, extension minimum, ulnar maximum and radial minimum for each replication. The summary sheet for Experiment 2 included identifiers for the participant, block, trial, coupler type, activity and subtask, as well as observations on flexion maximum, extension minimum, ulnar maximum, radial minimum and pronation maximum.

The data set on time-to-task completion was developed based on the start and end times for each trial from the video recordings. These times were broken down into individual subtask times over the entire set of conditions. Using these times, an average time was calculated for each specific set of conditions. A spreadsheet was developed for each experiment with the average time-to-task completion for all conditions.

2.8 Statistical Analysis

Analysis of variance (ANOVA) was used to identify any significant effects of the independent variables on the posture position and time responses. Assumptions of the ANOVA procedure were assessed using graphical methods. Any independent variable with a p-value <0.05 was considered statistically significant.

2.8.1 Testing Assumptions of Analysis of Variance

To assess the constant variance assumption of the ANOVA, plots were constructed of model residuals against predicted values. Systematic patterns in the plots, including expansion or collapse on the range of residual values across the range of model predictions, were considered to indicate heterogeneity of variance. To assess the normality assumption, residuals were plotted using a normal probability plot. Major deviations of the residuals from a linear trend were considered to indicate a violation of the normality assumption. To test for independence of observations, model residuals are typically plotted against time, or trial number. Because the test trials for each operator were distributed across three sessions, it was not possible to analyze model residuals in this way. However, randomization procedures were followed in both experiments to counter any systematic influences of learning or fatigue. ANOVA results confirmed this with an insignificant effect of trial across response measures.

2.8.2 Data Analysis

A four step process was used to separately analyze the data from each experiment. The first step was to use ANOVA for main effects modeling. The second step was to use multivariate analysis of variance (MANOVA) to determine significant effects across all angular response measures due to their dependence on one another. A full-factorial model was used for each experiment. The third step was to use ANOVA to identify the specific significant effects for each response among the main effects and interactions found to be significant through the MANOVA procedure. The final step was a correlation analysis on all responses for each experiment.

The main effects modeling was used to identify any significant learning effects across sessions and trials, and to identify potential outliers in the responses. The models were used to generate residuals for diagnostic purposes. Visual inspection of the model residuals versus predicted values and leverage plots for each main effect was conducted to identify data points statistically deviating from the mean response by ±2 standard deviations. Further investigation was undertaken to determine if these data points could legitimately be removed from the data set. Trial videotapes were reviewed to determine if a participant did not follow instructions or if there was an equipment problem. If a valid reason could be found for the outlying observation, the data point was removed from the dataset. A summary of outliers for both experiments is included in Appendix C.

The next step was to conduct a MANOVA on all related responses. Two MANOVAs were run: one for flexion, extension, radial deviation and ulnar deviation for Experiment 1 and another for flexion, extension, radial deviation, ulnar deviation and pronation for Experiment 2. Because the joint angle measurements all have some bearing on each other, it was necessary to identify those experiment effects (main effects and interactions in the full factorial model), which were significant across the family of responses. Joint angle measurements are related due to the electro-goniometers measuring multiple responses at one time. The average time-to-task completion values were not included in the MANOVA because they were recorded separately.

Subsequently, additional ANOVAs were run on the individual responses using only the significant factors identified by the MANOVAs. Any effects found to be significant with these ANOVA are the effects which have a significant impact on performance. Any significant interaction was analyzed using a post-hoc Tukey's Honestly Significant Difference (HSD) test.

Pearson product-moment correlation coefficients were computed to determine the degree of linear association among the joint angles and time-to-task completion. In general, it was expected that smaller joint angles would be associated with shorter task times.

There were a total of 432 (9x3x2x2x2x2) observations for Experiment 1. The 9 operators completed 3 blocks of test trials. During each block, there were a total of 2 tie types, 2 walk-board materials, 2 levels and 2 subtasks. Each unique set of conditions comprised an observation. For Experiment 2, there were a total of 432 (9x3x2x2x2x2) observations. As in Experiment 1, the 9 operators completed 3 blocks of test trials. During each block, there were 2 coupler types, 2 activities and 2 subtasks. Each set of conditions were repeated twice per block.

2.8.2.1 Experiment 1

A statistical model was constructed for each of the first three steps listed above. The model used for the first main effects ANOVA was as follows:

$$Y_{ijklmno} = \mu + \tau_i + S_j + TT_k + TT(T)_l + WB_m + L_n + Sub_o + \varepsilon_{ijklmno}$$

$$(i=1\text{-}9,\ j=1\text{-}3,\ k=0\text{-}1,\ l=1\text{-}4,\ m=0\text{-}1,\ n=0\text{-}1, o=0\text{-}1)$$

Where:

y= response measure

μ= grand mean

τ= participant

S= session

TT= tie-type

T= trial nested within tie-type

WB= walk-board type

L= level

Sub= subtask

ε= model error

The model developed for the MANOVA was as follows:

$$Y_{ijklmn}= \mu + \tau_i + S_j + TT_k + WB_l + (TT*WB)_{kl}+ L_m + (TT*L)_{km}+ (WB*L)_{lm}+ (TT*WB*L)_{klm}+ Sub_n + (TT*Sub)_{kn}+ (WB*Sub)_{ln}+ (TT*WB*Sub)_{kln} +(L*Sub)_{mn}+ (TT*L*Sub)_{kmn}+ (WB*L*Sub)_{lmn}+ (TT*WB*L*Sub)_{klmn}+ \varepsilon_{ijklmn}$$

$$(i=1\text{-}9,\ j=1\text{-}3,\ k=0\text{-}1,\ l=0\text{-}1,\ m=0\text{-}1,\ n=0\text{-}1)$$

Where:

Y= response measure

μ= grand mean

τ= participant

S= session

TT= tie-type

WB= walk-board type

TT*WB= interaction of tie-type and walk-board type

L= level

TT*L= interaction of tie-type and level

WB*L= interaction of walk-board type and level

TT*WB*L= interaction of tie-type, walk-board type, and level

Sub= subtask

TT*Sub= interaction of tie-type and subtask

WB*Sub=interaction of walk-board type and subtask

TT*WB*Sub= interaction of tie-type, walk-board type, and subtask

L*Sub= interaction of level and subtask

TT*L*Sub= interaction of tie-type, level, and subtask

WB*L*Sub= interaction of walk-board type, level, and subtask

TT*WB*L*Sub= interaction of tie-type, walk-board type, level, and subtask

ε= error

The final ANOVA model developed for analysis of the wrist angle measurements (based on the MANOVA results) was as follows:

$$Y_{ijklm} = \mu + \tau_i + S_j + TT_k + L_l + Sub_m + (TT*Sub)_{km} + \varepsilon_{ijklm}$$

$$(i=1\text{-}9,\ j=1\text{-}3,\ k=0\text{-}1,\ l=0\text{-}1,\ m=0\text{-}1)$$

Where:

Y= response measure

μ= grand mean

τ= participant

S= session

TT= tie-type

L= level

Sub= subtask

TT*Sub= interaction of tie-type and subtask

ε= error

The final ANOVA model constructed for the average time-to-task completion was as follows:

$$Y_{ijklmn} = \mu + \tau_i + S_j + TT_k + WB_l + (TT*WB)_{kl} + L_m + (TT*L)_{km} + (WB*L)_{lm} + (TT*WB*L)_{klm} + Sub_n + (TT*Sub)_{kn} + (WB*Sub)_{ln} + (TT*WB*Sub)_{kln} + (L*Sub)_{mn} + (TT*L*Sub)_{kmn} + (WB*L*Sub)_{lmn} + (TT*WB*L*Sub)_{klmn} + \varepsilon_{ijklmn}$$

(i=1-9, j=1-3, k=0-1, l=0-1, m=0-1, n=0-1)

Where:

Y= response measure

μ= grand mean

τ= participant

S= session

TT= tie-type

WB= walk-board type

TT*WB= interaction of tie-type and walk-board type

L= level

TT*L= interaction of tie-type and level

WB*L= interaction of walk-board type and level

TT*WB*L= interaction of tie-type, walk-board type, and level

Sub= subtask

TT*Sub= interaction of tie-type and subtask

WB*Sub=interaction of walk-board type and subtask

TT*WB*Sub= interaction of tie-type, walk-board type, and subtask

L*Sub= interaction of level and subtask

TT*L*Sub= interaction of tie-type, level, and subtask

WB*L*Sub= interaction of walk-board type, level, and subtask

TT*WB*L*Sub= interaction of tie-type, walk-board type, level, and subtask

ε= error

2.8.2.2 Experiment 2

As for Experiment 1, a statistical model was constructed for each step of the statistical analysis on the data from Experiment 2. The model used for the main effects ANOVA was as follows:

$$Y_{ijklm} = \mu + \tau_i + S_j + T_k + C_l + A_m + Sub_n + \varepsilon_{ijklm}$$

$$(i=1\text{-}9,\ j=1\text{-}3,\ k=1\text{-}4,\ l=0\text{-}1,\ m=0\text{-}1,\ n=0\text{-}1)$$

Where:

Y= response measure

μ= grand mean

τ= participant

S= session

T= trial

C= coupler type

A= activity

Sub= subtask

ε= model error

The model constructed for the MANOVA was as follows:

$$Y_{ijklm} = \mu + \tau_i + S_j + C_k + A_l + (C*A)_{kl} + Sub_m + (C*Sub)_{km} + (A*Sub)_{lm} + (C*A*Sub)_{klm} + \varepsilon_{ijklm}$$

$$(i=1\text{-}9,\ j=1\text{-}3,\ k=0\text{-}1,\ l=0\text{-}1,\ m=0\text{-}1)$$

Where:

Y= response measure

μ= grand mean

τ= participant

S= session

C= coupler type

A= activity

C*A= interaction of coupler type and activity

Sub= subtask

C*Sub= interaction of coupler type and subtask

A*Sub- interaction of activity and subtask

C*A*Sub= interaction of coupler type, activity, and subtask

ε= model error

The model constructed for the final ANOVAs (based on the MANOVA results) was as follows:

$$Y_{ijklm} = \mu + \tau_i + S_j + C_k + A_l + Sub_m + (C*Sub)_{km} + (A*Sub)_{lm} + \varepsilon_{ijklm}$$

$$(i=1\text{-}9,\ j=1\text{-}3,\ k=0\text{-}1,\ l=0\text{-}1,\ m=0\text{-}1)$$

Where:

Y= response measure

μ= grand mean

τ= participant

S= session

C= coupler type

A= activity

Sub= subtask

C*Sub= interaction of coupler type and subtask

A*Sub- interaction of activity and subtask

ε= model error

The final ANOVA model constructed for the average time-to-task completion was as follows:

$$Y_{ijklm} = \mu + \tau_i + S_j + C_k + A_l + (C*A)_{kl} + Sub_m + (C*Sub)_{km} + (A*Sub)_{lm} + (C*A*Sub)_{klm} + \varepsilon_{ijklm}$$

(i=1-9, j=1-3, k=0-1, l=0-1, m=0-1)

Where:

Y= response measure

μ= grand mean

τ= participant

S= session

C= coupler type

A= activity

C*A= interaction of coupler type and activity

Sub= subtask

C*Sub= interaction of coupler type and subtask

A*Sub- interaction of activity and subtask

C*A*Sub= interaction of coupler type, activity, and subtask

ε= model error

3 Results

The results are presented in two sections. Section 3.1 covers Experiment 1, while Section 3.2 presents the results from Experiment 2. Each section begins with the main-effects ANOVA followed by the diagnostics on model residuals concerning assumption violations. The MANOVA results are presented along with univariate ANOVAs on each response measure. Finally, the results of the correlation analyses are presented.

3.1 Experiment 1

The main-effects statistical modeling yielded results on the potential impact of a learning effect due to the order of trial and session, and produced model residuals for diagnostic purposes. The effects of trial and session were evaluated for the joint angle and TTC responses. For the angular response measures trial order was found to be insignificant for flexion ($p=0.7696$), extension ($p=0.0727$), radial deviation ($p=0.9064$) and ulnar deviation ($p=0.8539$) all. Consequently, trial was dropped from any further statistical analysis. Session was found to be significant for three out of four angular response measures, including flexion ($p=0.0006$), extension ($p<0.0001$) and ulnar deviation ($p<0.0001$). Only radial deviation ($p=0.1298$) showed an insignificant effect. Consequently, session was retained in all other models of the joint angle responses. For the TTC, trial ($p=0.4742$) was found to be insignificant while session ($p<0.0001$) was found to be significant. Thus, trial was dropped from subsequent models while session was retained.

Regarding model residual diagnostics, the plots for assessing constant variance and normality assumptions are included in Appendix D. There were no violations of the assumptions for any of the angular response measures. However, the TTC appeared to violate the constant variance assumption. There appeared to be an over-prediction of the model at high and low values and an under-prediction near the mean time value. To correct for the over-prediction, a logarithmic transformation was applied to the TTC data. The plot of the transformed TTC data can also be seen in Appendix D. The transformation appeared to be successful in addressing the assumption violations. For the residual versus predicted plots it is interesting to note that the expected flexion angle ranges from 0° to 70° while the expected extension angle ranges from -50° to -100°. It is possible that the inertia required during the ratcheting task caused the absolute deviation to be larger for extension. The flexion angle was impeded by the force required to move the ratchet. Regarding the residual versus predicted plot for TTC, it is important to note that there was a lower bound, or minimum motor performance time, for the task. Furthermore, the dispersion of the residuals may be attributable to measurement error in recording task time based on the video analysis.

The MANOVA results for Experiment 1 are presented in Table 3.1. A total of six main effects and interactions were found to be significant across all four angular response measures. Subject ($p<0.0001$), session ($p<0.0001$), tie ($p<0.0001$), level ($p=0.0266$), subtask ($p<0.0001$) and tie*subtask ($p=0.0003$) were all found to be significant. The remaining eleven main effects and interactions were removed from follow-on univariate ANOVAs.

Table 3.1: Experiment 1 MANOVA results.

Effect	F-value	P-value
Subject	27.7734	<.0001**
Session	8.7511	<.0001**
Tie	10.1101	<.0001**
Walk-board	2.1019	0.0802
Tie*Walk-board	0.7072	0.5875
Level	2.7852	0.0266*
Tie*Level	1.8518	0.1185
Walk-board*Level	1.3844	0.2389
Tie*Walk-board*Level	0.481	0.7497
Subtask	19.4117	<.0001**
Tie*Subtask	5.451	0.0003**
Plank*Subtask	1.0496	0.3815
Tie*Walk-board*Subtask	0.41	0.8014
Level*Subtask	1.1383	0.3383
Tie*Level*Subtask	2.0554	0.0863
Walk-board*Level*Subtask	0.4233	0.7918
Tie*Walk-board*Level*Subtask	1.0975	0.3576
* represents p-value <0.05; ** represents p-value <0.01		

Including the significant main-effects and interactions from the MANOVA, univariate ANOVAs were conducted on the angular response measures. The subject term was found to be significant in the models for flexion (p<0.0001), extension (p<0.0001), ulnar deviation (p<0.0001) and radial deviation (p<0.0001) indicating individual differences in the responses. The participant performing a trial accounted for some of the variability in the angular response measures. The ANOVA results revealed that session was found to be significant for flexion (p<0.0001), extension (p<0.0001) and ulnar deviation (p<0.0001). It was found to be insignificant for radial deviation (p=0.1014). This indicated that as participants progressed through the experiment some joint angle responses varied. The maximum flexion angle decreased across sessions. The maximum extension and ulnar deviation angles increased in the final session as compared with the first session.

ANOVA results on the tie type manipulation revealed flexion ($p=0.0341$), extension ($p<0.0001$) and ulnar deviation ($p<0.0001$) to be significantly impacted. It was found to be insignificant for radial deviation ($p=0.8856$). Although significant when compared to chance, the effect of tie type on flexion ($p=0.65$), extension ($p=0.45$) and ulnar deviation ($p=0.15$) was insignificant in the presence of individual differences. The mean flexion angle for the existing #9 gauge wire tie-downs was 42.8° and for the plastic zip ties flexion angle was 26.8°; a difference of 16°. The mean extension angle for the existing ties was -79.7° and for the plastic zip ties it was -76.6°; a reduction of 3.1°. For ulnar deviation, the means were 49.3° and 40.8°, respectively. This represents a reduction of 8.5° in the joint angle. For radial deviation there was no difference.

The level of the tie-down was found to be significant for flexion ($p<0.0001$) and extension ($p=0.0003$) but not for ulnar deviation ($p=0.5814$) and radial deviation ($p=0.0773$). Although significant when compared to chance, the effect of level on flexion ($p=0.39$) and extension ($p=0.64$) was insignificant in the presence of individual differences. The flexion angle for the upper level was on average 36.9° and for the lower level it was 33.3°. The extension angle was -76.6° for the upper level and -79.7° for the lower level. These results show that changing the level at which the scaffolding work is conducted had an effect for flexion and extension only.

ANOVA results revealed the subtask main effect to be significant for flexion ($p<0.0001$), extension ($p<0.0001$), ulnar deviation ($p=0.0007$) and radial deviation (p<0.0001). Although significant when compared to chance, the effect of subtask on extension (p=0.58), ulnar deviation (p=0.45) and radial deviation (p=0.30) was insignificant in the presence of individual differences. The flexion (p=0.0040) effect of subtask remained significant in the presence of individual differences. The flexion angle for the looping subtask was 27.8° and 42.3° for the clamping subtask. The extension angle was -78.9° for looping and -77.4° for clamping. The ulnar deviation for looping was 43.0° and 47.1° for clamping. The radial deviation was -25.8° for looping and -31.6° for clamping. From these results, it can be observed that the angular response was more extreme for the clamping subtask as compared to the looping subtask.

The interaction of tie*subtask was significant for wrist flexion (p<0.0001), extension (p=0.0001) and radial deviation (p=0.0029), it was insignificant for ulnar deviation (p=0.8892). The flexion angle interaction plot for tie*subtask can be seen in Figure 3.20, the extension interaction plot in Figure 3.21, and the radial deviation interaction plot in Figure 3.22. It can be observed that the flexion angle due to tie*subtask was significantly different between tie type for the clamping subtask. Post-hoc analysis using Tukey's HSD test supported this observation. The value of 55.7° for the existing #9 gauge wire tie-downs was significantly different (p<0.05) than 27.4° for the plastic zip ties. From Figure 3.21 it can be seen that the extension angle due to tie*subtask was significantly different between tie type for the looping subtask. Tukey's HSD test supported this observation, demonstrating that the value of -82.1° for the #9 gauge wire tie-downs and -75.9° for the plastic zip ties were significantly different (p<0.05). From Figure 3.22 it can be seen that the radial deviation angle due to tie*subtask was significantly different between tie-down types for the clamping subtask. Tukey's HSD test supported this observation, demonstrating that the value of -34.6° for the #9 gauge wire tie-downs and -28.4° for the plastic zip ties were significantly different ($p<0.05$).

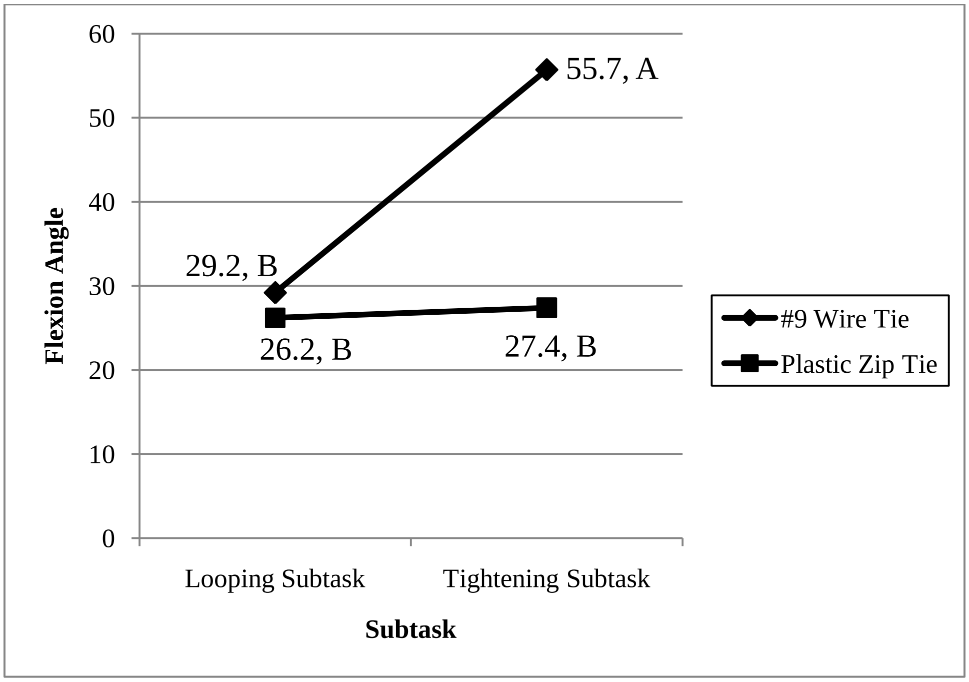

Figure 3.20: Flexion angle tie*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

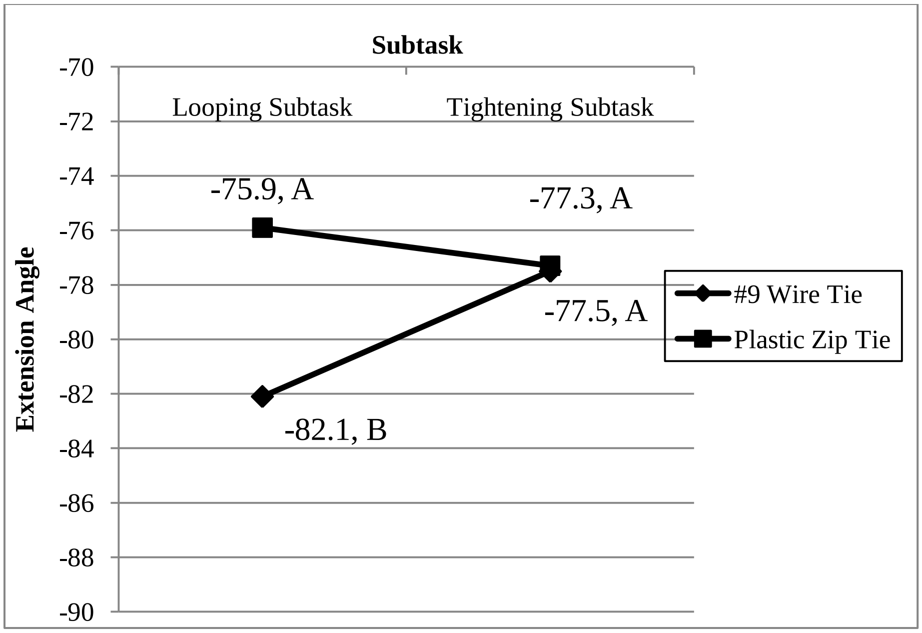

Figure 3.21: Extension angle tie*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

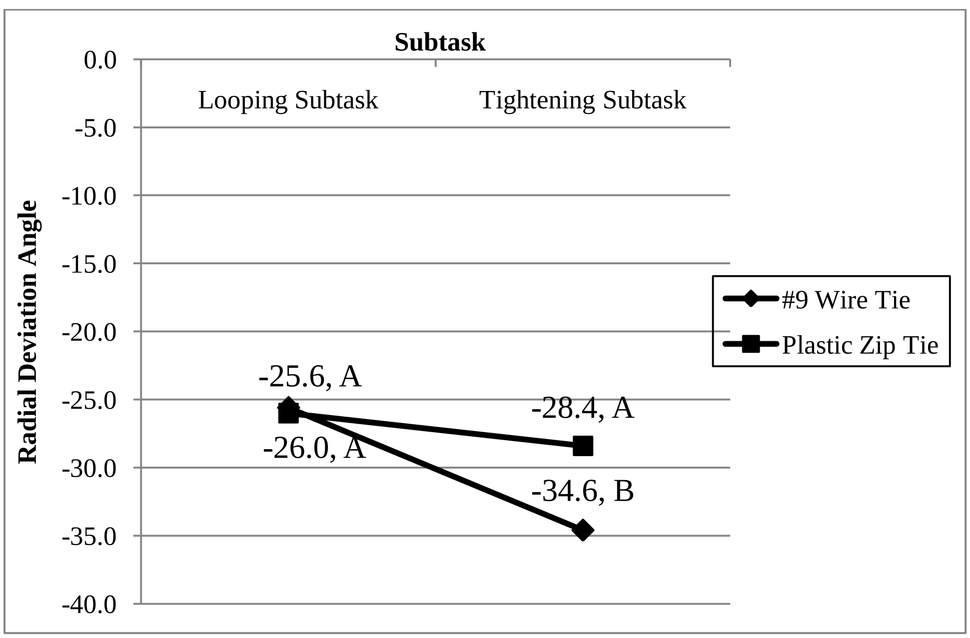

Figure 3.22: Radial deviation angle tie*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

Following the analysis of the angular response measures, an ANOVA was conducted on the log (TTC) for Experiment 1. As previously mentioned, trial was identified as an insignificant main-effect and eliminated from further analysis. Subject ($p<0.0001$) and session ($p<0.0001$) were both found to be significant in TTC. Both individual differences and time in the experiment appeared to influence the TTC for the walk-board tie-down.

ANOVA results also revealed tie type ($p=0.0016$) to be significant in TTC. Although tie type was significant compared to chance, it was insignificant in the presence of individual differences ($p=0.54$). The TTC for the #9 gauge wire tie-downs was 10.6 seconds and for the plastic zip ties it was 8.4 seconds; a reduction of 2.2 seconds per tie. The walk-board manipulation was also found to significantly affect ($p<0.0001$) TTC. Although walk-board type was significant compared to chance, it was insignificant in the presence of individual differences ($p=0.42$). Wood walk-boards had an average TTC of 9.8 seconds, while metal walk-boards had a TTC of 8.1 seconds. The metal walk-boards had a shorter TTC due to the reduced distance required to loop the tie-down around the walk-board.

The level ($p=0.0017$) at which the participants worked on the tie-downs also had a significant effect on TTC. Although level was significant compared to chance, it was insignificant in the presence of individual differences ($p=0.54$). While working on the upper level of the scaffold frame, the TTC was 9.0 seconds. The lower level produced a TTC of 9.8 seconds. It is likely that the awkward posture (kneeling and spinal forward flexion) and difficult reaches required to tie-down a walk-board at the lower level accounted for the increase in TTC. Subtask ($p<0.0001$) was also found to be significant. Subtask remained marginally significant in effect on TTC in the presence of individual differences in the response ($p=0.052$). The looping subtask produced a TTC of 7.0 seconds and the clamping subtask produced a TTC of 11.8 seconds. This was not surprising as the actions for binding ties were complex and more extensive than looping.

The interaction of tie*walk-board ($p<0.0001$) was also found to significantly affect TTC. Figure 3.23 shows the interaction plot. It can be observed that the #9 gauge wire tie-downs produced a lower TTC for metal walk-boards while plastic zip ties produced an increased TTC for the metal walk-boards compared to wood. Post-hoc analysis with Tukey's HSD test supported this observation. The #9 gauge wire tie-downs produced a TTC of 11.9 seconds for wood walk-boards, significantly longer ($p<0.05$) than the TTC of 9.3 for the metal walk-boards. Plastic zip ties were found to produce a TTC of 7.7 seconds for wood walk-boards, significantly shorter ($p<0.05$) than the TTC of 8.8 seconds for the metal walk-boards. Each tie type was significantly different from the other tie type at each level of walk-board. During the experiment, it was observed that the plastic zip ties were bound around the wood walk-boards perpendicular to the long axis of the boards. The zip ties were bound around the metal walk-boards parallel to the long axis of the boards. Operators found that with some additional effort (and time) they could bind the zip ties tighter around the ends of the metal boards than the wood and they did so.

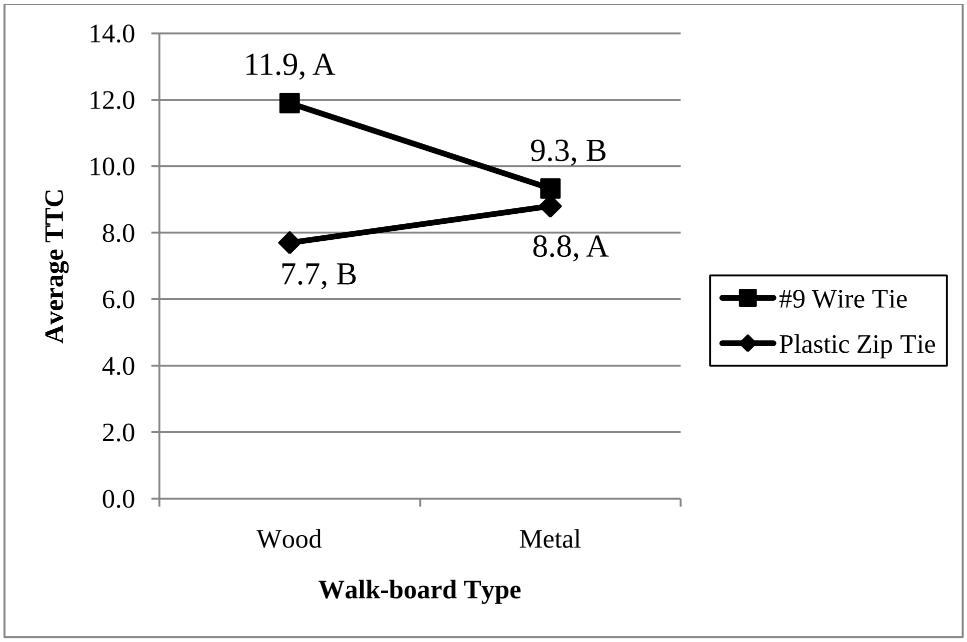

Figure 3.23: TTC tie*walk-board interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

A walk-board*level ($p<0.0001$) interaction was also found to be significant in TTC. Figure 3.24 shows the interaction plot. It can be seen that TTC varied across the different combinations of walk-board and level. Tukey's HSD test revealed that each combination was statistically significant from one another. Wood walk-boards produced a significant increase ($p<0.05$) in TTC from the upper level of the scaffold (9.2 seconds) to the lower level (10.3 seconds). Metal walk-boards also produced an increase in TTC from the upper level (8.9 seconds) to the lower level (9.3 seconds). Each level of walk-board was significantly different ($p<0.05$) in TTC.

Figure 3.24: TTC walk-board*level interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

The tie*subtask ($p<0.0001$) interaction was found to be significant in effect on TTC. Figure 3.25 shows the interaction plot. It can be seen that both types of ties produced differences in TTC across the levels of subtask. Tukey's HSD test confirmed this. The existing #9 gauge wire tie-downs yielded a TTC of 7.0 seconds for the looping subtask, significantly lower ($p<0.05$) than the TTC of 14.2 seconds for the clamping subtask. The plastic tie-downs yielded a TTC of 7.1 seconds for the looping subtask, significantly lower than the TTC of 9.4 seconds for the clamping subtask. Each tie type was found to be significantly different from the other ($p<0.05$) for each level of subtask.

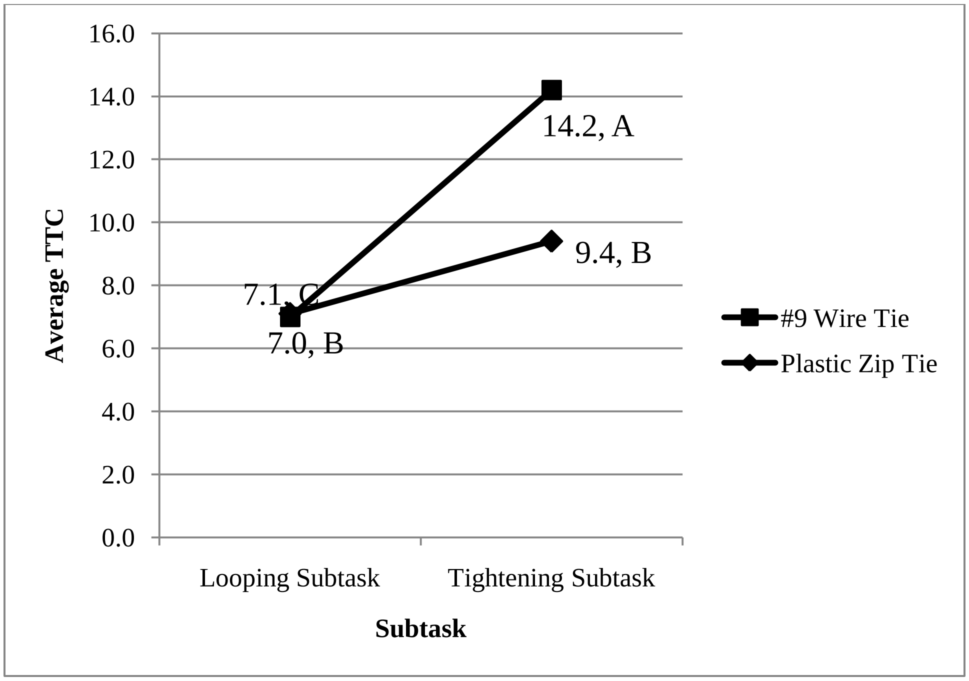

Figure 3.25: TTC tie*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

The second-order interaction of tie*plank*level (p=0.0066) was also found to be significant. Table 3.2 presents the results of the post-hoc analysis with Tukey's HSD test. While holding walk-board and level constant, the impact of tie type can be identified. For wood walk-boards on the upper level, the plastic zip ties were 4.2 seconds quicker (p<0.05). For metal walk-boards on the upper level, plastic zip ties were 0.3 seconds faster (p<0.05). When tying down wood walk-boards on the lower lever, the plastic zip ties were 4.8 seconds quicker (p<0.05). For metal walk boards on the lower level, zip ties were 0.5 seconds quicker than #9 wire (p<0.05).

Table 3.2: TTC results for interaction of tie*walk-board*level.

Tie*Walk-board*Level								
Tie Type	**Walk-board Type**	**Level**						**Mean**
0	0	1	A					12.7
1	1	1	A	B				9.1
0	0	0		B				11.1
1	1	0		B	C			8.5
1	0	1		B	C	D		8.0
1	0	0			C	D		7.4
0	1	0				D	E	9.2
0	1	1					E	9.5
Settings without the same grouping letter are significantly different.								

The second-order interaction of walk-board*level*subtask (p=0.0061) was also found to be significant. Table 3.3 presents the results of the post-hoc analysis with Tukey's HSD test. While holding the level and subtask constant, the impact of the walk-board type on TTC can be identified. For the looping subtask on the upper level, wood walk-boards were 0.2 seconds faster than metal walk-boards (p<0.05). In the tightening task on the upper-level, wood walk-boards were not faster than metal walk-boards. Performing the looping subtask for metal walk-boards on the lower level was 0.9 seconds quicker than for wood walk-boards (p<0.05), while the tightening task was 0.3 seconds faster for metal walk-boards (p<0.05).

Table 3.3: TTC results for interaction of tie*walk-board*level.

Walk-board*Level*Subtask								
Walk-board Type	**Level**	**Subtask**						**Mean**
0	1	1	A					12.7
0	0	1	A	B				11.5
1	1	1		B				12.0
1	0	1		B				11.0
0	1	0			C			8.0
0	0	0				D		6.9
1	0	0					E	6.7
1	1	0					E	6.5
Settings without the same grouping letter are significantly different.								

The final step of the analysis of Experiment 1 was the construction of a correlation table. Table 3.4 presents the Pearson coefficients for linear associations of the response measures. It was expected that extension and flexion would be correlated due to these angles being measured using the same device and from the same zero point. Ulnar deviation and radial deviation were recorded in a similar manner and were also expected to be correlated. As for the correlation of the angular response measures with TTC, it was expected that as the joint angles decreased there would be a corresponding decrease in TTC. In fact, as the angular displacement decreased for all angular measures, the TTC also decreased.

Table 3.4: Experiment 1 correlation table.

		Flexion	Extension	Ulnar	Radial	TTC
Flexion	Correlation	1				
	P- value					
Extension	Correlation	0.2365	1			
	P- value	<.0001**				
Ulnar	Correlation	0.2904	-0.0859	1		
	P- value	<.0001**	0.0933			
Radial	Correlation	-0.1043	0.2027	0.2669	1	
	P- value	0.0383*	0.0002**	<.0001**		
TTC	Correlation	0.4754	-0.0861	0.2635	-0.3469	1
	P- value	<.0001**	0.1505	<.0001**	<.0001**	

3.2 Experiment 2

The main-effects ANOVA revealed the effect of trial to be insignificant for the flexion (p=0.5753), extension (p=0.9822), radial deviation (p=0.4013), ulnar deviation (p=0.7047) and pronation (p=0.0746). On this basis, the trial was dropped from all statistical analysis. Session was found to be significant for four out of five angular response measures, including extension (p<0.0001), radial deviation (p<0.0001), ulnar deviation (p=0.0001) and pronation (p<.0001). Only flexion (p=0.4404) proved to be insensitive to session. Consequently, session was included in all other statistical analyses. For the TTC response, trial (p=0.2743) was not significant while session (p=0.0003) was found significant. Thus, trial was dropped from subsequent models while session was retained, as in the analysis of the Experiment 1 data set.

Regarding the model residual diagnostics, the plots for testing constant variance and normality assumptions are included in Appendix D. There were no violations of the assumptions for any of the angular response measures. However, the TTC appeared to violate both the constant variance and normality assumptions. There was an over-prediction of the model at high and low values and an under-prediction near the mean time values. The normal probability (quantile-quantile) plot on the TTC residuals deviate from the expected linear trend. To correct for these violations, a logarithmic transformation was applied to the TTC data. The plots for the transformed TTC data can also be seen in Appendix D. The transformation appeared successful in addressing the identified assumption violations.

The results of the MANOVA for Experiment 2 are presented in Table 3.5. A total of five main effects and interactions were found to be significant across all four angular response measures, including subject (p<0.0001), session (p<0.0001), subtask (p=0.0189), coupler*subtask (p=0.0423) and activity*subtask (p=0.0076). The remaining three main effects and interactions were not significant. Although coupler and activity were not significant, they could not be eliminated from further analysis because they were included in significant interactions. The only interaction eliminated from the full factorial model was coupler*activity*subtask.

Table 3.5: MANOVA results for Experiment 2.

Effect	F-value	P-value
Subject	19.1373	<.0001**
Session	26.1297	<.0001**
Coupler	0.9359	0.4578
Activity	2.0697	0.069
Coupler*Activity	0.020878	0.2642
Subtask	0.0442227	0.0189*
Coupler*Subtask	2.3318	0.0423*
Activity*Subtask	3.2147	0.0076**
Coupler*Activity*Subtask	1.5681	0.1687
* represents p-value <0.05; ** represents p-value <0.01		

Including the significant main-effects and interactions from the MANOVA, univariate ANOVAs were conducted on each angular response measure. The subject term was found to be significant for flexion ($p<0.0001$), extension ($p<0.0001$), ulnar deviation ($p<0.0001$), radial deviation ($p<0.0001$) and pronation ($p<0.0001$). These results indicate that there were significant individual differences in the angular response measures. ANOVA results also revealed that Experiment 2 session was significant for extension ($p<0.0001$), radial deviation ($p=0.1014$), ulnar deviation ($p<0.0001$) and pronation ($p<0.0001$). The only response measure for which it was insignificant was flexion ($p=0.4417$). This indicated that joint angle responses varied over the course of the experiment. The maximum extension, radial deviation and pronation angles decreased from session-to-session, while the maximum ulnar deviation angle increased across sessions.

ANOVA results on the coupler type manipulation revealed a marginally significant effect on ulnar deviation ($p=0.0680$). However, there was no statistically significant effect on flexion ($p=0.1545$), extension ($p=0.6498$), radial deviation ($p=0.6788$) or pronation ($p=0.1613$). Although marginally significant when compared to chance, the effect of coupler type on ulnar deviation was insignificant in the presence of individual differences ($p=0.61$). All other angular response measures remained insignificant in the presence of individual differences ($p>0.05$). The mean ulnar deviation for the ratcheting coupler was 64.2° and it was 63.2° for the lever couplers. It is possible that the new coupler was important in reducing the angular response in the clamping portion of the task.

The coupling activity type was found to be significant in the flexion (p=0.0147) and extension (p=0.0026) responses. It was not significant for radial (p=0.9598) and ulnar (p=0.3001) deviations or and pronation (p=0.2492). Although significant when compared to chance, the effect of activity on flexion (p=0.46) and extension (p=0.71) was insignificant in the presence of individual differences. All other angular response measures were also insignificant in the presence of individual differences (p>0.05). Flexion had a mean of 69.1° for the assembly activity and a mean of 68.3° for the disassembly activity. Extension had mean angles of -72.5° and -70.4° for the assembly and disassembly activities, respectively.

The subtask was also found to be significant for extension (p=0.0405), radial deviation (p=0.0304), ulnar deviation (p=0.0038) and pronation (p=0.0130) angles. Only for flexion (p=0.7612) was subtask not significant. Although significant when compared to chance, the effect of activity on extension (p=0.80), radial deviation (p=0.60), ulnar deviation (p=0.42) and pronation (p=0.69) was insignificant in the presence of individual differences. Flexion remained insignificant in the presence of individual differences (p>0.05). Extension had a mean of -69.0° for the placement subtasks and a mean of -73.8° for the clamping subtask. The ulnar deviation angle had a mean of 63.0° for placement of the coupler and a mean of 64.4° for clamping the coupler. Radial deviation also showed a smaller angle for placement (-18.3°) than for clamping (-19.9°). Finally, pronation had a mean of 91.5° for placement and a mean of 96.1° for clamping. All four angular responses that revealed a significant effect of subtask had a smaller mean for the placement subtask than for the clamping subtask.

The interaction of coupler type*subtask was significant for flexion angle (p=0.0003) and radial (p=0.0132) and ulnar (p=0.0002) deviation. Extension (p=0.7759) and pronation (p=0.8586) showed no significant effect of the interaction. Figure 3.26 shows the interaction plot for flexion. It can be observed that the lever couplers produced a smaller flexion angle for the clamping subtask than the standard scaffolding couplers. Post-hoc analysis with Tukey's HSD supported this observation. The lever couplers had a mean of 64.7° significantly lower ($p<0.05$) than the standard scaffolding couplers with a mean of 70.9°. Both coupler types were not significantly different for the placement subtask. Figure 3.27 shows the interaction plot of coupler type*subtask for radial deviation. From the figure it can be observed that the coupler types produced different angles in the clamping subtask. Post-hoc analysis with Tukey's HSD supported this observation. For clamping, the lever couplers had a mean deviation of -17.7°, significantly lower than the existing scaffolding couplers with a mean deviation of -22.0°. Figure 3.28 shows the interaction plot for ulnar deviation. From the figure it can be observed that the coupler types differed for the clamping subtask. Tukey's HSD test results supported this observation. For clamping, the lever couplers had a deviation of mean=62.2°, which was significantly lower than the existing scaffolding couplers with a mean=64.2°.

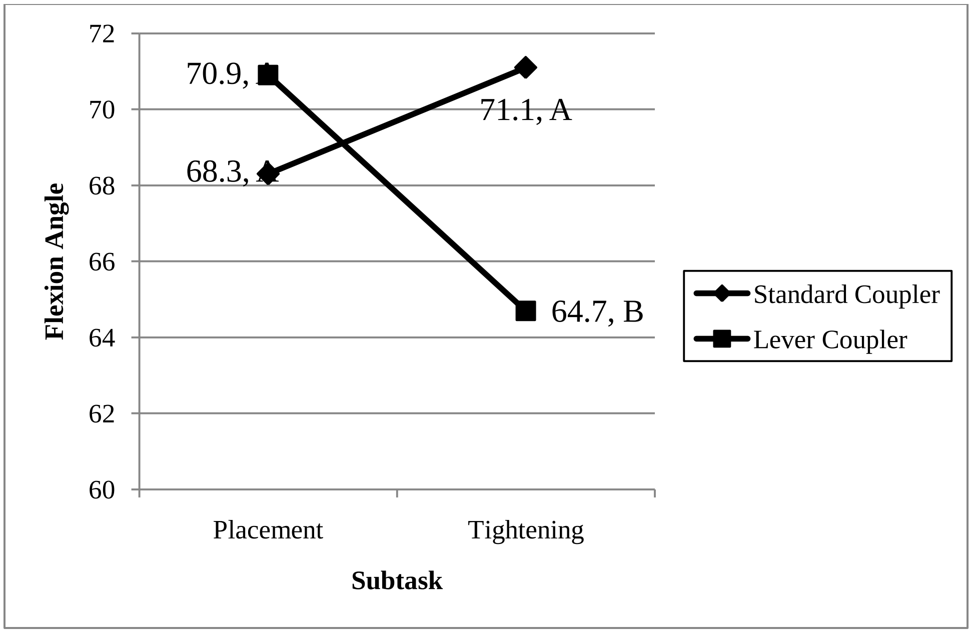

Figure 3.26: Flexion angle coupler*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

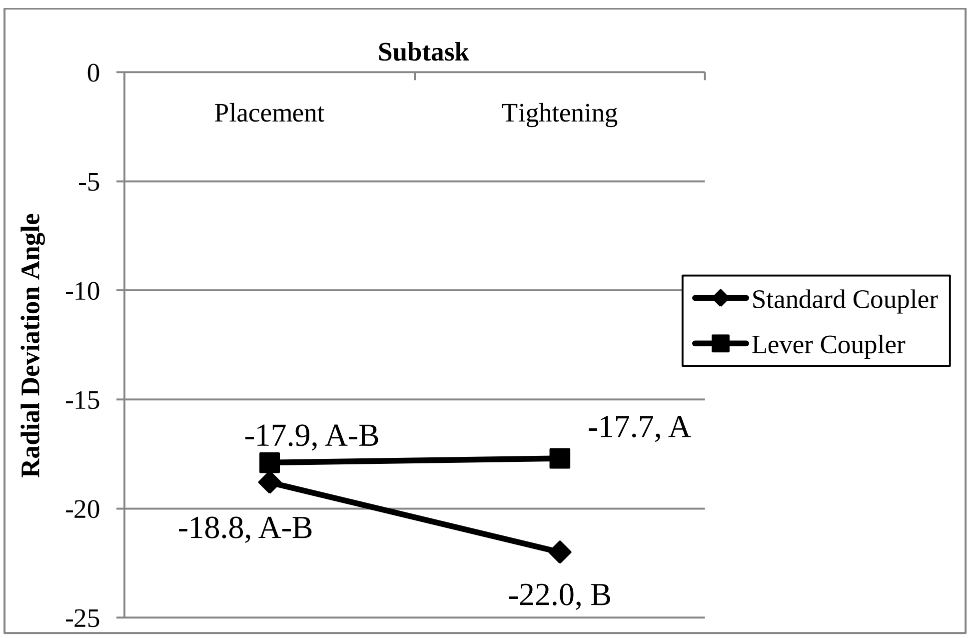

Figure 3.27: Radial deviation angle coupler*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

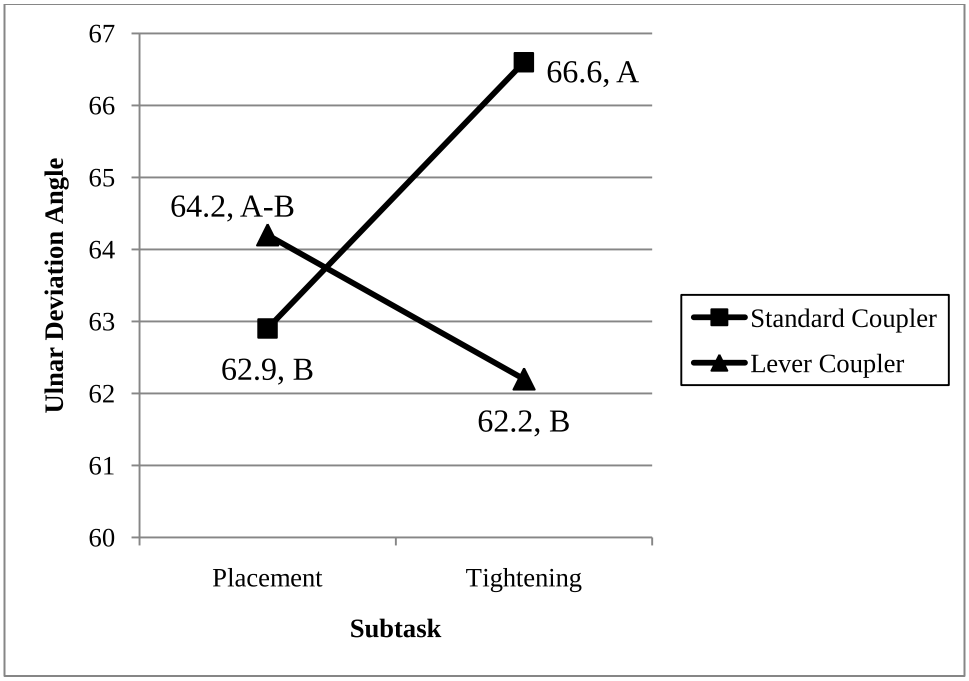

Figure 3.28: Ulnar deviation angle coupler*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

The interaction of activity*subtask was also found to be significant for flexion ($p=0.0049$) and extension ($p=0.0429$). It was not significant for radial ($p=0.8442$) and ulnar ($p=0.7477$) deviation, or pronation ($p=0.2124$). Figure 3.29 shows the interaction plot of activity*subtask for flexion. Tukey's HSD tests revealed that there was a significant difference ($p<0.05$) among flexion angles between the coupler removal subtask (mean=67.4°) and the unclamping subtask (mean=69.2°) during the disassembly activity. Figure 3.30 presents the interaction plot for extension. From the figure, it can be observed that there was a difference in angles among activity type for coupler placement/removal. Tukey's HSD test results supported this observation. The assembly activity produced extension with mean of -71.0°, significantly higher ($p<0.05$) than the extension in the disassembly activity with mean of -67.1° across coupler removal.

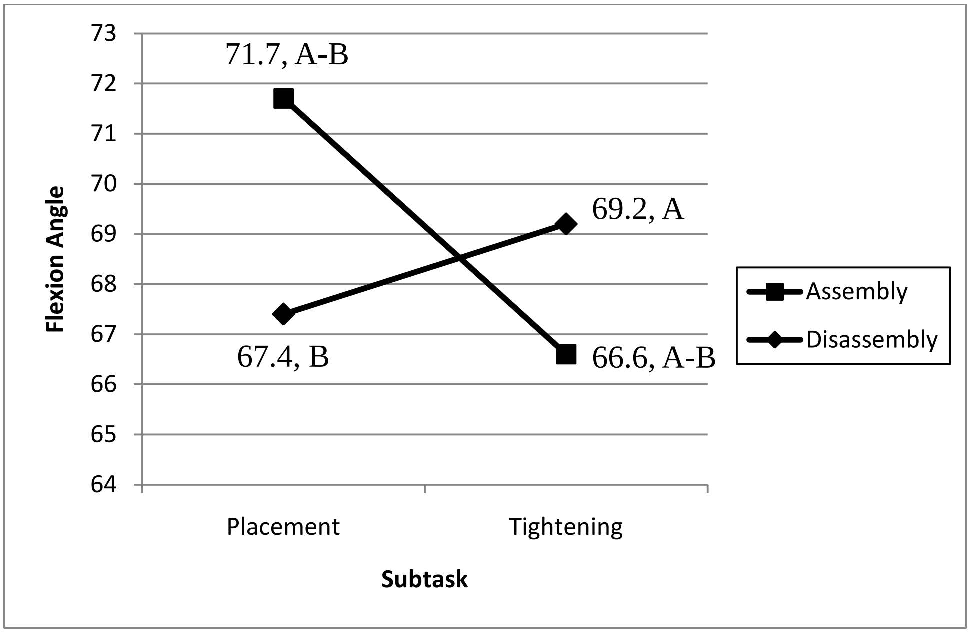

Figure 3.29: Flexion angle activity*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

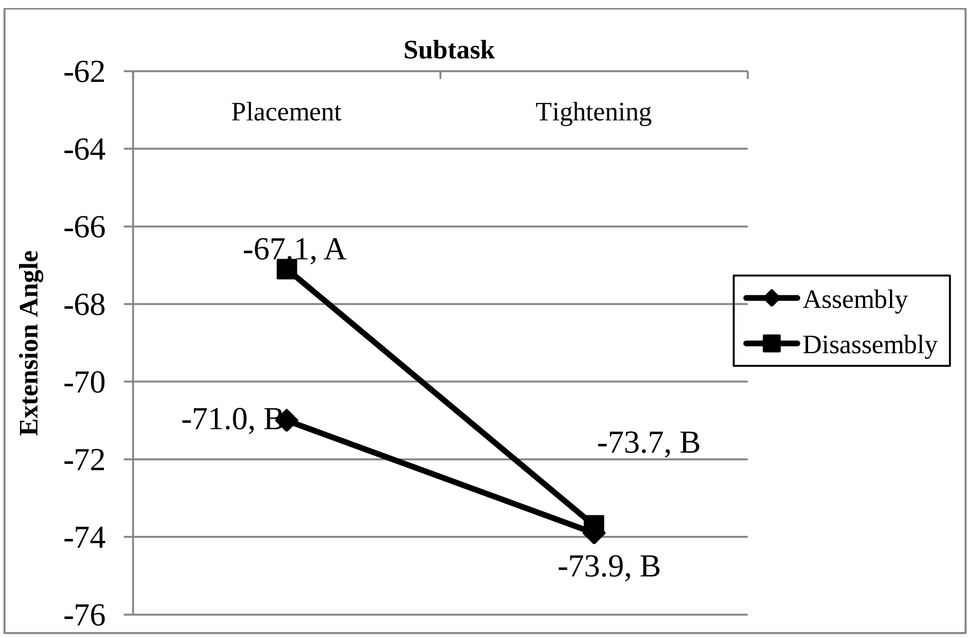

Figure 3.30: Extension angle activity*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

Following the analysis of the angular response measures, an ANOVA was conducted on the log (TTC) response for Experiment 2. As previously mentioned, trial was identified as an insignificant main-effect and eliminated from further analysis. Subject ($p<0.0001$) and session ($p=0.0001$) were both found to be significant in TTC. Both individual differences and time in the experiment appeared to influence the TTC for the frame coupling.

ANOVA results revealed the coupler type to have a significant effect on TTC ($p<.0001$). Although coupler was significant compared to chance, it was insignificant in effect on TTC in the presence of individual differences ($p=0.20$). The mean TTC for the existing couplers was 11.0 seconds and for the lever couplers it was 12.5 seconds. The higher mean time with the lever couplers was likely due to less operator familiarity with the equipment. Activity was also found to be significant in TTC ($p<0.0001$). Activity was significant compared to chance and remained significant in effect on TTC in the presence of individual differences ($p<0.001$). The assembly activity had a mean of 15.5 seconds while the disassembly activity had a mean of 8.0 seconds. This was primarily due to the need to ensure proper tightness of the coupler while assembling. Subtask was also found to be significant in TTC ($p<0.0001$). Subtask was significant compared to chance and remained marginally significant in effect on TTC in the presence of individual differences ($p=0.07$). Subtask 0 (placement/removal) had a mean of 12.8 seconds and Subtask 1 (clamping/unclamping) had a mean of 10.7 seconds.

The interaction of activity*subtask was also significant for TTC ($p<0.0001$). Figure 3.31 presents the interaction plot. It can be observed that the assembly activity had a shorter TTC for Subtask 0 than for Subtask 1, while the disassembly activity had a longer TTC for Subtask 0 than for Subtask 1. Tukey's HSD test results supported these observations. All levels of the interaction were significantly different ($p<0.05$) from one another. The assembly activity produced a mean of 17.6 seconds for Subtask 0 and mean of 13.4 seconds for Subtask 1. The disassembly activity has a mean of 8.0 seconds for Subtask 0 and a mean of 8.1 seconds for Subtask 1.

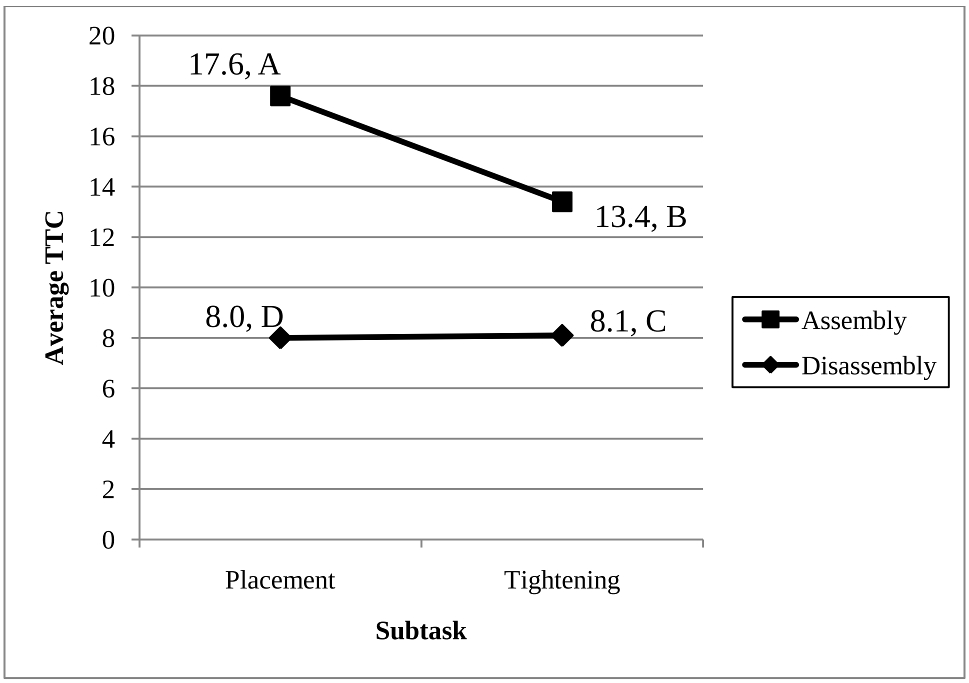

Figure 3.31: TTC activity*subtask interaction plot.
(Note: The plot presents trends on the actual condition means. The Tukey's classification of conditions was based on LS mean values.)

The second-order interaction of coupler type*activity*subtask was also found to be significant for TTC ($p=0.009$). Table 3.6 presents the results of the post-hoc analysis using Tukey's HSD test for all levels of the interaction. When holding activity and subtask constant, the impact of coupler type can be examined. While performing the placement subtask during assembly, the lever couplers were 4.8 seconds slower than the existing couplers ($p<0.05$). In the clamping subtask, performed during assembly, the lever couplers were 1.9 seconds slower ($p<0.05$). During the disassembly activity, the existing couplers were 1.8 seconds faster the removal subtask ($p<0.05$). There were no significant differences in clamping subtask performance between the two coupler types.

Table 3.6: TTC results for interaction of coupler*activity*subtask.

		Coupler*Activity*Subtask						
Coupler Type	**Activity**	**Subtask**						**Mean**
1	0	0	A					19.5
0	0	0		B				15.7
1	0	1		B				14.4
0	0	1			C			12.3
1	1	0				D		7.3
0	1	1				D		8.7
1	1	1				D	E	7.5
0	1	0					E	6.8
Settings without the same grouping letter are significantly different.								

The final step of the analysis of Experiment 2 was the construction of a correlation table. Table 3.7 presents the correlation table. It was expected that extension and flexion to would be correlated due to the angles being measured with the same device and from the same zero point. Ulnar deviation and radial deviation were recorded in a similar manner and were expected to be correlated. As for the correlation of the angular response measures with TTC, it was expected that as the angular displacement at the wrist decreased, the TTC would also decrease. This proved to be the case for the extension, radial deviation and pronation measures. However, ulnar deviation in the frame coupling task was only marginally associated with TTC and flexion angle was not explanatory of the task time.

Table 3.7: Experiment 2 correlation table.

		Flexion	Extension	Radial	Ulnar	Pronation	TTC
Flexion	Correlation	1					
	P- value						
Extension	Correlation	0.2284	1				
	P- value	<.0001**					
Radial	Correlation	-0.1259	0.3646	1			
	P- value	0.0151*	<.0001**				
Ulnar	Correlation	-0.0066	0.0378	0.337	1		
	P- value	0.8423	0.4432	<.0001**			
Pronation	Correlation	-0.0341	-0.0497	-0.1945	0.0209	1	
	P- value	0.4848	0.3916	0.0002**	0.5624		
TTC	Correlation	0.037	-0.2687	-0.1465	0.092	0.1179	1
	P- value	0.5259	<.0001**	0.0289*	0.0555	0.031*	

4 Discussion

4.1 Experiment 1

There were two hypotheses tested through the tie-down experiment. The first hypothesis was that the maximum flexion, extension, radial deviation, and ulnar deviation angles would all be reduced when using the plastic zip ties. The second hypothesis was that the plastic zip ties would produce shorter TTCs than the standard #9 gauge wire in securing walk-boards. For the first hypothesis the results on each joint angle are discussed separately. For the second hypothesis, the TTC results are discussed for each significant effect.

With respect to the maximum flexion angle, both the main effect of tie type and the interaction of tie type*subtask accounted for significant variability in the response. The existing #9 gauge wire tie-downs produced an average maximum angle of 42.8° of flexion while the plastic zip ties produced an average maximum angle of 26.8°. This amounts to a 37% reduction in maximum flexion angle. This difference in flexion angle was attributed to differences in the way the tie types are used on the scaffold. The cause of the difference became more apparent when the interaction of tie*subtask was examined. Figure 3.20 revealed a difference in maximum flexion angle between tie types for the tightening subtask but not the looping subtask. With regard to flexion, Subtask 0 was performed the same way for both types of ties; both ties were looped around the walk-board using the same amount of flexion. In the tightening subtask, the plastic zip ties produced an average maximum angle of 27.4° while the #9 gauge wire tie-downs produced an average maximum angle of 55.7°. For the #9 gauge wire tie-downs, the tightening subtask required the use of pliers and wrist rotation. The plastic zip ties only required one end to be threaded and then pulled. This difference in the way that the looping subtask is performed led to the difference in the maximum flexion angles when using different tie types. The wire tie-downs also showed a large difference between the looping subtask and the tightening subtask indicating that the wrist had a larger variation in flexion angle during the course of the tie-down. Because the plastic zip ties did not produce a significant difference between the two subtasks, the wrist was kept in a more neutral position or moved through a smaller range of postures throughout the tie-down task. Because tie type was involved in any other significant interactions, it can be concluded that the improvement in flexion angle was due to the differences in the subtask. The elimination of the use of pliers and the wrist rotation reduced the average maximum flexion observed while performing the tie-down task.

The next angular response measure examined was the wrist extension angle. The maximum extension angle was found to be significantly different for the main effect of tie type and the interaction of tie*subtask. For the #9 gauge wire tie-downs, the average maximum extension angle was -79.7° while the plastic zip ties had an average maximum angle of -76.6°. The use of the plastic zip ties decreased the maximum extension angle by 4%. This finding led to examination of the interaction of tie type and subtask. Figure 3.21 showed a difference in extension angle across the two tie types for the looping subtask but not for the tightening subtask. Tukey's HSD test showed that there was a significant difference between the maximum extension angles for each tie type within the looping subtask. Plastic zip ties had a maximum flexion angle of -75.9° and #9 gauge wire ties had a maximum flexion angle of -82.1° for the looping subtask, a difference of 6.2°. The difference for Subtask 0 indicated that the looping the tie-down around the walk-board (regardless of the type of walk-board) required a larger amount of extension when using a #9 gauge wire tie-down. By using a more flexible tie-down material, the plastic zip tie, less extension was required to place the tie-down around the walk-board. The plastic zip ties naturally bend around the walk-board reducing the amount of reach required to secure them. Additionally, the flexible ties require less force and, therefore, less extension to wrap around the walk-board. For the #9 gauge wire, it is common for scaffolders to use their hands or a tool to press the wire loop down to the surface of a walk-board. The lack of difference for the tightening subtask indicated that the tightening task required the same amount of extension for both tie types. The tightening method used for the plastic tie required wrist extension when pulling the tie. The wire ties required extension while using the pliers. The plastic zip tie did not produce significantly different angles between subtasks while the wire tie-downs did. This indicates that the wire tie-downs produced a larger amount of variation in the wrist posture during tie down than the plastic zip ties. Because tie type was not involved in any other significant interactions, it can be concluded that the decrease in extension angle was mediated by differences in subtask. The use of a more flexible tie allowed for elimination of some wrist rotation in looping and use of pliers used in tightening leading to a reduction in the average maximum extension observed while performing the tie-down task.

Tie type was the only independent variable found to have a statistically significant effect on ulnar deviation angle. The average maximum ulnar deviation angle for the #9 gauge wire tie-downs was 49.3°. The plastic zip ties had an average maximum ulnar deviation of 40.8°. By using the plastic zip ties a 17.0% reduction in maximum ulnar deviation angle was achieved. Tie type was not involved in any interactions influencing ulnar deviation; therefore, the reduction in deviation occurred for any application of the plastic zip ties. The reduction in ulnar deviation was due to the flexible plastic zip ties requiring less wrist movement in looping around the walk-board. Often while reaching to grab the end of a wire tie, participants used ulnar deviation to extend their reach. Second, once looped around the walk-board, wire tie-downs require the two ends to be overlapped by hand in order for tightening to occur. The participant, having a grasp on each end of a tie, would cross the two ends and twist them together to start tightening. Finally, the plastic tie-downs, although they still require wrist motions in tightening, eliminate much of the ulnar deviation required in use of pliers with wire tie-downs. It can be concluded that the use of plastic zip ties reduces the maximum ulnar deviation required to secure a walk-board to a scaffolding frame.

The final angular response to be examined was radial deviation. The interaction of tie*subtask was significant in the maximum radial deviation angle. Figure 3.22 revealed little difference between tie types for the looping subtask, but there appeared to be some difference for the tightening subtask. For the tightening subtask, wire ties had a maximum radial deviation angle of -34.6° and plastic zip ties had a maximum angle of -28.4°. The tightening of the wire tie-downs required more radial deviation due to the rotation of the pliers. For walk-boards below the shoulders, scaffolders positioned their hands to hold pliers using radial deviation. By eliminating the use of the pliers, there was a reduction in radial deviation. The use of plastic zip ties alone was not significant in general; that is, across subtasks and walk-board types. When the different tie types were paired with the different subtasks, plastic zip ties served to reduce the maximum radial deviation angle.

In conclusion, the use of plastic zip ties had a positive effect for all four angular response measures. A 37% reduction in maximum flexion angle was achieved with a 4% decrease in maximum extension angle. The maximum ulnar deviation angle was reduced by 17.0%. While there was no reduction of radial deviation due to tie type, there was a reduction seen in the interaction of tie*subtask.

The second hypothesis for Experiment 1 was that the plastic zip ties will produce a shorter TTC than the currently used #9 gauge wire tie-downs. A simple comparison of the mean TTC for types indicated the plastic ties did reduce the time compared with the #9 gauge wire tie-downs. The existing tie-downs required an average of 9.5 seconds to complete the task while the plastic zip ties required an average 7.9 seconds. This represents an improvement of 16.8%. While these results suggest that the plastic zip ties are quicker than the #9 gauge wire tie-downs, the reason for the reduction in time can be found in the interaction of tie type with walk-board.

A visual inspection of the interaction plot on the tie*walk-board effect (Figure 3.23) revealed a substantial difference between tie types for each type of walk-board. For wood boards, plastic zip ties were 4.2 seconds faster than the #9 gauge wire ties while for metal boards, plastic zip ties were only 0.5 seconds quicker. A substantial difference was also seen for each tie type across the levels of walk-board. Plastic zip ties took 1.1

seconds longer for metal boards than for wood boards while wire ties were 2.6 seconds quicker. The decrease in time for the wire ties was not surprising. Metal walk-boards required a smaller amount of looping and consequently shorter tightening times. The increase in TTC for metal walk-boards was not expected for plastic zip ties. Further examination revealed that the increase in time was due to the width of the plastic zip ties. Because the area of the walk-board in which the tie was placed was very close in size to the plastic zip ties, they occasionally became stuck. This meant that participants had to take additional time to loosen the plastic zip ties, leading to a corresponding increase in TTC.

The second significant interaction for TTC was that of tie by subtask. Figure 3.25 revealed that the tightening subtask produced longer TTCs than the looping subtask. Wire ties had a TTC of 7.0 seconds for looping and a TTC of 14.2 seconds for tightening. Plastic zip ties had TTCs of 7.1 seconds and 9.4 seconds, respectively, for looping and tightening. For each tie type, a significant difference was found between subtasks. This was a surprising result as looping was performed in nearly the same manner for both tie types. It is possible that this difference was due to a lack of operator familiarity with the plastic zip ties. For the tightening subtask, wire ties took 4.8 seconds longer than the plastic zip ties. The plastic zip ties are tightened using only a pulling motion, providing economy in arm motion. Wire ties require additional motions such as the grasping of the tie with pliers, twisting the wire tie to tighten, and the turning up of the ends to prevent poking. The plastic zip ties require fewer actions and therefore a shorter TTC.

The final interaction for TTC was the second-order interaction of tie type, walk-board type, and level. Tie type was a significant simple effect for each combination of walk-board type and level. In all cases plastic zip ties were quicker than wire ties. For wooden walk-boards on the upper level, plastic ties were 3.7 seconds quicker. For wooden walk-boards on the lower level, plastic ties were 4.7 seconds quicker. For metal walk-boards on the upper level, plastic ties were 0.7 seconds quicker. For metal walk-boards on the lower level, plastic ties were 0.4 seconds quicker. This interaction confirmed that the plastic zip tie produced a shorter TTC while holding the level of walk-board and level constant.

In conclusion, the empirical data supported the hypothesis that the plastic zip ties are quicker to use than the existing #9 gauge wire. An overall improvement of 1.6 seconds can be achieved by replacing the existing #9 gauge wire tie-downs with plastic zip ties in securing a single walk-board.

4.2 Experiment 2

There were two hypotheses tested for the coupler experiment. The first hypothesis was that the maximum flexion, extension, radial deviation, and ulnar deviation angles, as well as the forearm pronation angle, would be reduced using the lever couplers. The second hypothesis was that the lever couplers would reduce the average TTC as compared to the standard scaffold couplers. For the first hypothesis, the results on each joint angle ware discussed separately. For the second hypothesis, the TTC results are discussed for each significant effect.

Surprisingly, coupler type, as a main effect, was not found to be statistically significant for any of the response measures. However, the coupler*subtask interaction was highly significant for the joint angle measures, indicated that subtask type mediated the influence of the coupler on motion behavior.

With respect to maximum flexion angle, Figure 3.26 revealed a slight difference between coupler types for the coupler placement/removal subtask. For the clamping subtask, there appeared to be a larger difference between coupler types. In placement/removal, the lever couplers had a maximum flexion angle of 64.7° while the standard scaffolding couplers had a flexion angle of 71.1°, a difference of 6.4°. The lack of difference for the placement/removal subtask was expected. In the coupler placement or removal task, because the base design for both types of coupler was similar, the task was performed in a similar manner. The clamping subtask is where a difference was expected due to the different tightening techniques for each type of coupler. The existing scaffolding couplers required a bolt to be seated on the upper portion of the coupler. Once seated, a nut was ratcheted until tight. The ratcheting action forced the upper arm onto the tube, thus securing it. The ratcheting action was where the maximum wrist flexion angle occurred. While sweeping the ratchet back and forth, the hand and wrist are placed in a flexed position. The lever couplers are tightened by simply forcing a lever down. When the lever is pressed it pulls the upper arm tight with the base by way of a catch and hook mechanism. The tightening of the lever coupler required a smaller range of motion compared to the standard couplers resulting in the significant decrease in maximum flexion angle for this subtask. Because the lever couplers reduced the maximum flexion for the clamping subtask and did not increase the maximum flexion for placement/removal, they were considered an improvement over the ratcheting coupler.

For extension, neither the main effect of coupler type nor the interaction of coupler type and subtask were statistically significant. When examining the other effects, subtask was significant. These results indicate the lever coupler alone had no effect on the maximum extension angle while performing the various subtasks. It was expected that the elimination of the ratcheting motion would lead to a decrease in the maximum extension angle. The ratcheting motion used in tightening the existing couplers required substantial extension and flexion of the wrist. The postures required to force the lever couplers to tighten, however, required a similar degree of extension. This resulted in the significant difference between subtasks (placement vs. clamping), but not for the interaction of subtask and coupler type. While the lever couplers did not provide a reduction in maximum extension angle they also do not cause an increase.

The maximum radial deviation angle revealed a significant interaction of coupler type and subtask. Figure 3.27 showed that there was little difference between the coupler types for the placement/removal subtask while there was a substantial difference for clamping. The existing scaffold couplers had a radial deviation of –22.0° and the lever couplers had a maximum deviation of -17.7°. This is a 19.5% decrease in the maximum radial deviation angle. The lack of a statistically significant difference for placement/removal was expected. As previously mentioned, this subtask was performed in a nearly identical fashion for both types of coupler. Because the clamping subtask involved different tightening techniques for each coupler type, a statistically significant difference was expected. When using ratcheting to tighten the existing couplers the wrist experienced significant radial deviation, especially when first beginning to tighten. Because the nut was not tight and facing little resistance a looser grip is used on the ratchet. This loose grip leads to additional wrist movement while performing the repetition required to tighten the coupler. The clamping mechanism of the lever couplers eliminated the repetition inherent in the ratcheting task, thus reducing the maximum radial deviation angle experienced during the clamping subtask. Because the lever coupler reduced the maximum radial deviation angle in clamping and did not increase the maximum wrist flexion angle in placement/removal, it was considered to be a preferable alternative.

The interaction of coupler type and subtask was the only significant effect on maximum ulnar deviation. Figure 3.28 indicated a slight difference between coupler types for each level of subtask. For clamping, the maximum ulnar deviation was 66.6° for the existing couplers and 62.2° for the lever-based couplers. The difference of 4.4° amounts to a reduction in ulnar deviation of 6.7%. Just as for the radial deviation, the difference in the way the clamping subtask was performed account for this difference. The lever coupler required less ulnar deviation in clamping. Since only one motion was needed to force the lever into position, less deviation was required. For the existing couplers, the repeated ratcheting motion caused the ulnar deviation. The grasping and rotating of the ratchet put the wrist into deviated posture positions. The reduction in maximum ulnar deviation for the clamping subtask was another reason to consider the lever couplers as a preferable alternative over the existing scaffolding couplers.

For the pronation of the forearm, there was no significant effect for either coupler type or the interaction of coupler type by subtask. However, the main effect of subtask was present in pronation, indicating that the placement/removal subtask was significantly different than the clamping subtask. For flexion, radial deviation, and ulnar deviation the subtask was significant when crossed with the coupler type. For pronation, the coupler type had no effect on the performance of either subtask. The ratcheting motion in the clamping task has been identified as a key component in several of the angular response measures. This was also true for pronation. When swinging the ratchet to tighten the existing couplers, the forearm is pronated at the extents of the swing. Elimination of the ratcheting task was expected to alleviate some of the pronation. However, due to the curved shape of the upper portion of the lever coupler, the forearm is still pronated when clamping. When the lever coupler is fully tightened and the hand is still on the lever, the curvature of the coupler causes the hand to rotate and the forearm to experience pronation. This pronation was equivalent to the pronation caused by the ratcheting in the existing couplers. While the lever couplers did not provide a statistical reduction in maximum pronation angle they also did not cause an increase.

In conclusion, the use of the lever couplers had a positive effect on three of five joint angle response measures. While tightening the couplers, a 4% decrease in maximum flexion was achieved while there was no effect on the maximum extension angle. A 16.5% decrease in the maximum radial deviation angle and a 7% decrease in the maximum ulnar deviation angle were found while using the lever couplers to perform clamping. Finally, the use of the lever couplers had no effect on forearm pronation. With these results, it was concluded that the lever couplers are beneficial for tube frame coupling when compared to the standard scaffolding couplers.

The second hypothesis for Experiment 2 was that the lever couplers would produce a quicker average TTC than the standard scaffold couplers. A simple comparison of the mean TTCs for the task revealed the existing couplers to take 10.0 seconds and the lever couplers to take 11.2 seconds. The lever couplers took approximately 12% longer to clamp frame tubes. It is possible that operator unfamiliarity with the lever couplers caused this increase. In Experiment 1, the plastic zip ties required a method of application very close to that used with the #9 gauge wire ties. The lever couplers, however, required a very different procedure than the standard scaffolding couplers in clamping to frames. The replacement of the ratcheting motion with the lever action caused additional time to be taken. Given additional practice with the lever couplers it is believed that the TTC could be reduced below the TTC for the standard couplers. Another cause for the increase in TTC was the use of locking pins as part of the lever coupler. The locking pins were very small and difficult to manipulate in the hand while the participants were wearing work gloves. An alternate locking mechanism might work better with gloved hands and serve to further reduce the TTC.

The interaction of coupler type, activity and subtask was significant in effect on TTC. While holding the activity type and subtask constant, the impact of coupler type can be assessed. For the assembly activity and the placement/removal subtask, the lever couplers were found to increase the TTC by 3.8 seconds. Similarly for the assembly activity and the clamping subtask, the lever couplers took 2.1 seconds longer. While performing placement/removal during the disassembly activity the lever couplers increased TTC by 1.3 seconds. The only combination in which the lever coupler did not increase TTC was for the disassembly task while performing the clamping subtask. This subtask, performed during the disassembly activity, did not differ between coupler types in terms of TTC. This is because the impact of the locking pin was not observed. When placing the locking pin, it was inserted into a small hole in the upper swing-arm of a coupler and the lever handle. Since the scaffolders were required to wear gloves during the study, this added time to the task. Gloved hands did not hinder the removal of the pin. Thus, there was no difference between coupler types for the clamping subtask during disassembly. These results confirm the observation that fact that in most aspects of the coupling task, the lever couplers caused an increase in TTC.

In conclusion, the empirical data supports the standard scaffolding couplers as being quicker to use than the lever couplers. An overall increase of 1.2 seconds was seen when replacing the standard couplers with lever couplers. It is believed that additional training would decrease the TTC associated with the lever couplers to levels possibly lower than that for the standard couplers.

4.3 Discussion of Individual Differences

For all response measures in both experiments, subject was found to be a significant effect. These individual differences stem from a number of sources. As previously mentioned, the participants ranged in age from 33 to 60. It is known that as the body ages, range of motion tends to decrease (Tayyari & Smith, 1997, p. 218). Associated with an age-related loss of flexibility is reduction in overall strength. In this study, the oldest participants had the lowest strength measurements, which might have contributed to the hand posture positions assumed during the test tasks. However, it was also found that the oldest participants had the most experience they were observed to perform the tasks the most efficiently. They possessed an economy of motion which allowed them to proficiently complete the tasks even with a potentially diminished range of motion and strength. The combination of a wide range of ages, experience levels and strength capacities led to the significant individual differences found during the study. Because the participants met the power utility's qualification requirements for scaffolders, the sample population was considered to be representative of the entire scaffold worker population.

5 Conclusion

5.1 Overall Recommendations

The objectives of this research were to: (1) conceptualize ergonomic interventions to reduce the potential for worker strain and sprain injuries in scaffolding operations, particularly in tube frame coupling and walk-board tie-down to frames; and (2) conduct experiments to empirically evaluate the impact of the proposed interventions on worker postures positions and TTC (time-to-task completion). For the tie-down of scaffolding walk-boards, a plastic zip tie was recommended and compared with #9 gauge wire tie-downs. The ergonomic issues associated with wire tie-down use included extreme wrist posture positions. For the placement of scaffolding couplers, a new lever-based coupler was designed. The proposed coupler eliminated the ratcheting motion required by existing couplers. To test these interventions, two high fidelity experiments were designed.

Experiment 1 examined the differences in angular response measures and TTC for the plastic tie-downs. All four angular response measures and the TTC were positively affected (reduced) by the use of the plastic zip ties. The maximum flexion angle was reduced by 37% while using the plastic zip ties. The maximum extension angle was decreased by 4.0%. A 17.0% reduction was observed in maximum ulnar deviation angle. While there was no reduction in radial deviation solely due to the plastic zip ties, a decrease was seen when using the zip ties in tightening walk-boards to a scaffolding frame. An overall improvement TTC of 1.6 seconds was achieved by replacing the existing #9 gauge wire tie-downs with plastic zip ties. These benefits lead to the recommendation that the plastic zip ties replace the #9 gauge wire for tie-downs at the power utility NPPs.

Experiment 2 examined the impact of the lever couplers on angular response measures and time to task completion. While the coupler type by itself was not significant in the various joint angle measures, there was a significant interaction of coupler with subtask. For the tightening subtask, a 9.0% decrease in maximum flexion was achieved while there was no effect on the maximum extension angle. A 19.5% decrease in the maximum radial deviation angle and a 6.6% decrease in the maximum ulnar deviation angle were found while using the lever couplers to perform the clamping subtask. Finally, the use of the lever couplers had no effect on forearm pronation. While there was a positive impact of the coupler on several angular response measures in specific subtasks, the lever coupler was found to increase the TTC by approximately 12%. Although an increase in TTC was observed, this was likely due to operator familiarity with the use of the existing couplers and less familiarity with the new technology. Based on the improvement in the angular response measures, the lever couplers are recommended as a viable alternative to the standard scaffolding couplers from an ergonomics perspective and may require further examination from a task efficiency perspective. In addition, strength testing of the new clamping mechanism of the lever couplers is required before field use. Because this was a study of the ergonomic impact of the lever coupler, no strength comparison was made between the bolt and nut mechanism of the existing couplers and the “ski boot” type clamping mechanism of the lever coupler.

5.2 Limitations

There were a number of limitations of this study due to the facility in which it was conducted. Because the study was conducted in a training room at a NPP, there was limited room for mock-up of the scaffolding frames used at the NPP. Both frames used in the study were of a smaller scale than full size frames used in actual operations. As a result, the locations where the test tasks were conducted may not have been the same as where work normally occurs during operations. In a NPP, tasks often take place at varying heights, including over the heads of scaffolders. During the present study, work never occurred above chest height. Additionally, work occurred at consistent heights throughout the experiment. It is possible that other more extreme, posture positions occur in the workplace as a result of different scaffold frame configurations. Therefore, caution should be taken when applying the results of this study to other scaffolding situations.

Another limitation of the study caused by the NPP training facility was the work environment. The environment for the study was temperature and humidity controlled. Often the temperatures experienced by scaffolders in a NPP can exceed 120°F. The proximity to the reactors and the power generation facilities combined with the lack of air conditioning can lead to high heat stress working conditions (Sanders & McCormick, 1993). The temperature at the training facility was maintained in the lower 70s° F with low humidity. It is possible that the lack of extreme environmental conditions normally faced at the NPP decreased the sensitivity of operators to the potential impacts of the ergonomic interventions. If the study was conducted under extreme temperature conditions, physiological responses could potentially lead to fatigue in the participants contributing to awkward postures. The zip ties and new couplers might have significantly accounted for such problems over the #9 gauge wire and existing couplers

A third limitation of this study was the design of the experiments. Over the course of the experiments, the scaffolders were never exposed to extended periods of work. The average trial length never exceeded 5 minutes of continuous work. While normally working at the NPP, scaffolders will work for extended lengths of time between breaks (2-4 hours, depending on the environment). During the study, between every trial, there was a rest period. These frequent rest periods reduced the fatigue levels of the participants and served to ensure consistent results across all four trials during a block. However, this is not representative of conditions normally faced by the scaffolders, including fatigue occurring throughout the workday. The effect of fatigue over the course of a shift and its relationship to harmful postures would be an intriguing continuation of this study.

Another limitation due to the design of the experiments was the range of tasks examined in test trials. The walk-board tie-down and tube frame coupling may be representative of some portions of NPP scaffolding operations, but they do not cover the entire range. Any continuation of this line of research should include examination of activities or tasks as part of scaffolding operations.

A final limitation of this study was the selection of the measurement equipment. First, the electro-goniometers caused some restriction to the normal range of worker motion. While participants had nearly the full range of motion at the arm with the mounted equipment, they suffered from a reduced range of travel from the encoder. The need for the electro-goniometers to be tethered necessitated the use of only one end of the scaffolding frames. Finally, the measurement equipment was only mounted on one arm. While the test tasks primarily involved a participant's dominant hand, there were some tasks that still required the opposite hand. Any further study should measure posture positions of both arms.

5.3 Future Research

Further research conducted on scaffolding at NPPs should address the aforementioned limitations. The most practical way to address these issues would be to conduct a field study of both the existing equipment and the proposed interventions. By conducting a field study, data could be gathered on a wider range of work positions while scaffolders experience actual environmental conditions. By removing the constraints of the experimental design, fatigue could be also examined along with any impact on body postures. One drawback of this approach would be less experimental control in isolating the effects of the tie-down and coupling interventions on worker postures and task time.

A second line of future research would be the addition of alternative response measures to the study. Repetition has been mentioned as an ergonomic concern in scaffolding operations. By analyzing the number of repetitions in tie twisting, coupler ratcheting, etc., the impact of the interventions could be further quantified. Another response measure to add in future research would be grip force. The current coupling task is known to require excessive grip force and the current tie-down task is suspected of requiring potentially harmful forces to be generated by the scaffolder. By integrating force sensors, force requirement differences could be quantified between the existing equipment and the proposed interventions.

Finally, the Ergonomics Lab at NC State is currently conducting another line of research on analysis of forearm muscle activity, EMG (electromyography) responses, in scaffolder assembly of tube and coupler frames. EMG data was also collected on scaffolders participating in the study described in this thesis. The EMG research will examine the impact of the zip tie and lever coupler interventions on muscle activity, as well as the role of muscle fatigue in material handling tasks on scaffold tube coupling and walk-board tie-down tasks.

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Appendices

Appendix A: Informed Consent Form

North Carolina State University

INFORMED CONSENT FORM for RESEARCH

Title of Study: *Investigation of Ergonomic Interventions for Scaffold Use in Nuclear Power Facility Maintenance Tasks*

Principal Investigator: *DAVID B. KABER* Faculty Sponsor (if applicable)

We are asking you to participate in a research study. The purpose of this study is to identify and reduce repetitive strain injuries (RSI) in maintenance operations at a local power utility, specifically for scaffolding tasks.

INFORMATION

If you agree to participate in this study, you will be asked to assemble/disassemble a scaffold structure. In order to measure biomechanical stresses and anthropometric measures on your body, you will wear electrogoniometer and/or EMG electrodes depending on the experiment trial. You will participate in a total of nine (9) experimental sessions over a three (3) day period. Each session will require 2 hrs to complete. There will be a total of 4 to 6 test trials in each session, Videotaping will be conducted in all trials to record your body movements.

RISKS

Potential risks include: (1) general pain in the hand/wrist and low back region due to ratcheting scaffold tube couplers, kneeling in plank tie-down tasks; and (2) general fatigue due to the biomechanical stress. Adequate rest periods will be arranged in between test trials and between sessions. You will be given detailed information about the electrogoniometer and EMG regarding their functioning. (3) An additional risk of this study is possible skin irritation from adhesive tape used to secure EMG electrodes to your body. All adhesive tapes used in the experiment will be hypoallergenic. If you have very sensitive skin, please inform the researchers now. If you do not have such sensitivities, please mark your initials here: _____.

BENEFITS

There are no direct benefits of this research. You may derive some indirect benefits including an understanding of human factors and ergonomic research methods. You will be exposed to the different techniques used to measure biomechanical stressors.

CONFIDENTIALITY

The information in the study records will be kept strictly confidential. Information such as name, gender, age will be collected only for demographic statistics. Data will be stored securely in the Cognitive Ergonomics Lab in Edward P. Fitts Department of Industrial and Systems Engineering and will be made available only to the persons conducting the study. No reference will be made in oral or written reports, which could link you to the study. Video recordings of subject participation will be made to determine the body postures and measure the repetition rate of hand/wrist exertions. All tapes will be kept in the Cognitive Ergonomics Lab of Dept. of Industrial & Systems Engineering during the study. The tapes will be erased at the close of our data analysis.

Appendix A: Informed Consent Form

COMPENSATION
All participants will be compensated for their time according to their normal wages by NPF.

CONTACT
If you have questions at any time about the study or the procedures, you may contact the researcher**, David B. Kaber, Daniels Hall, Department of Industrial and Systems Engineering,** or **call at 919-515-3086.** If you feel you have not been treated according to the descriptions in this form, or your rights as a participant in research have been violated during the course of this project, you may contact Dr. Arnold Bell, Chair of the NCSU IRB for the Use of Human Subjects in Research Committee, Box 7514, NCSU Campus (919/515-4420) or Mr. Matthew Ronning, Assistant Vice Chancellor, Research Administration, Box 7514, NCSU Campus (919/513-2148)

PARTICIPATION
Your participation in this study is voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty and without loss of benefits to which you are otherwise entitled. If you withdraw from the study before data collection is completed your data will be returned to you or destroyed at your request.

CONSENT
"I have read and understand the above information. I have received a copy of this form. I agree to participate in this study with the understanding that I may withdraw at any time."
Subject's signature____ Date _________________
Investigator's signature____________________________________ Date _________________

Appendix B: Demographic Questionnaire

Demographic Questionnaire

1. Name/Code:
2. Age:
3. Height (inches)
4. Weight (lbs)
5. Typical shift start time:
6. Typical shift end time:
7. Work years: Current (Please provide a maximum of 10 years experience OR a maximum of 5 jobs as part of your work history)

Position	**Title/Description**	**Years**	**Average Borg Rating**
Current			
Prior # 1			
Prior # 2			
Prior # 3			
Prior # 4			
Prior # 5			

8. Do you work on a second job outside of this facility (circle one): Yes No.

   If Yes, please provide the number of years and hours/week you have worked at your second job:

   _______ yrs. __________ hrs./week

9. Dominant hand (circle one): Left Right Both

Appendix B: Demographic Questionnaire

10. Maximum grip strength:

Trial # 1	Trial # 2	Trial # 3	Average

11. Maximum linear force:

Trial # 1	Trial # 2	Trial # 3	Average

12. Maximum back strength:

Trial # 1	Trial # 2	Trial # 3	Average

13. Maximum upper arm strength:

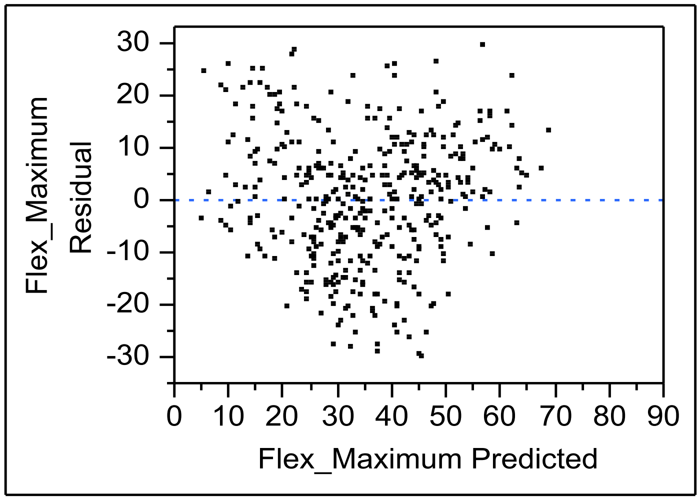
Trial # 1	Trial # 2	Trial # 3	Average

14. Overall worker rating at beginning of shift (Borg CR-10):

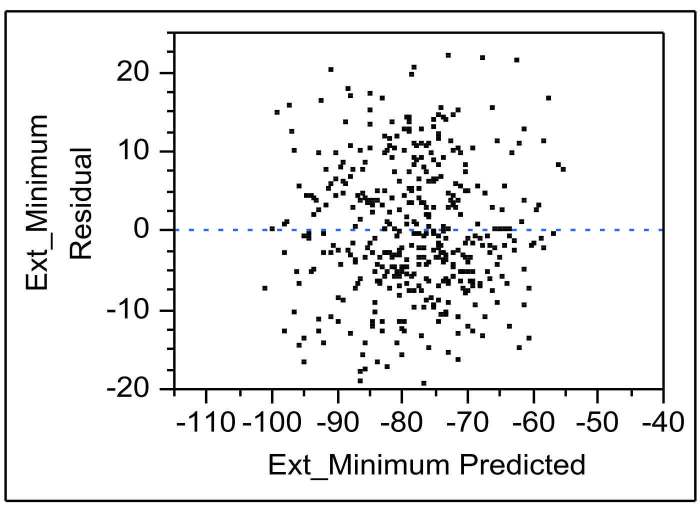
15. Overall worker rating at end of shift (Borg CR-10):

Appendix C: Graphs for the ANOVA Assumptions

Test for Equal Variance

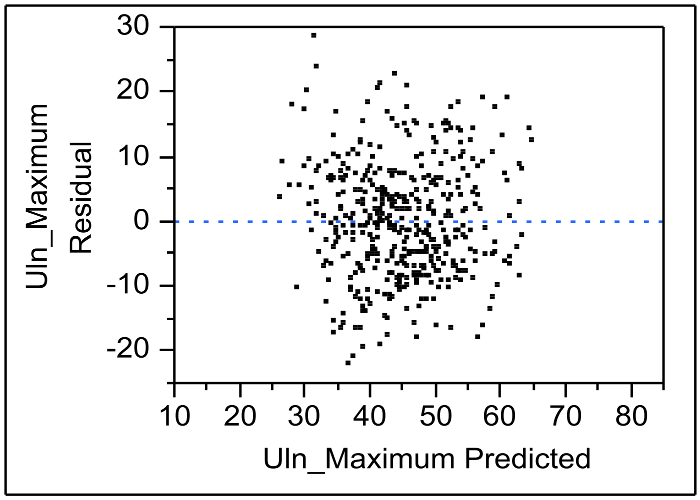


Scatter plot of the residuals as a function of the predicted values for Experiment 1 flexion

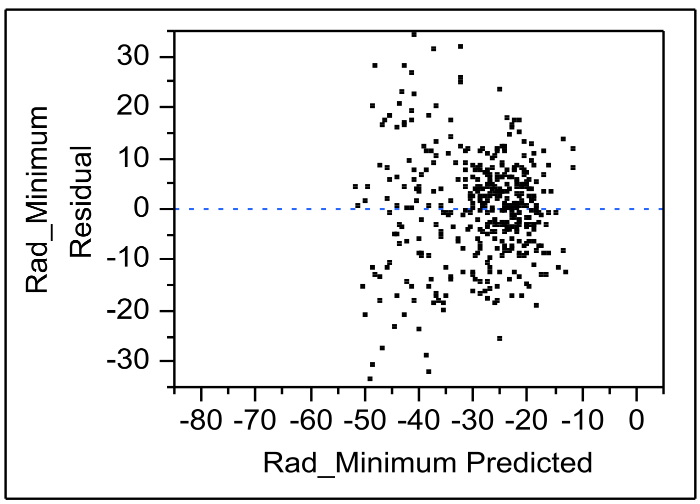


Scatter plot of the residuals as a function of the predicted values for Experiment 1 extension

Appendix C: Graphs for the ANOVA Assumptions

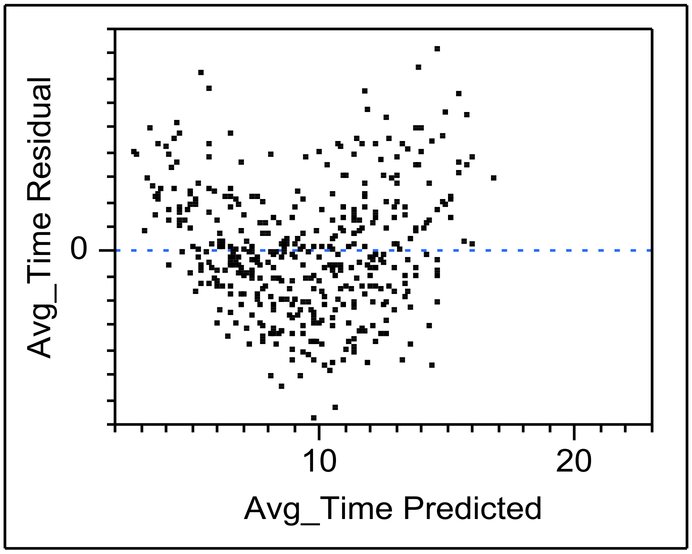


Scatter plot of the residuals as a function of the predicted values for Experiment 1 ulnar deviation

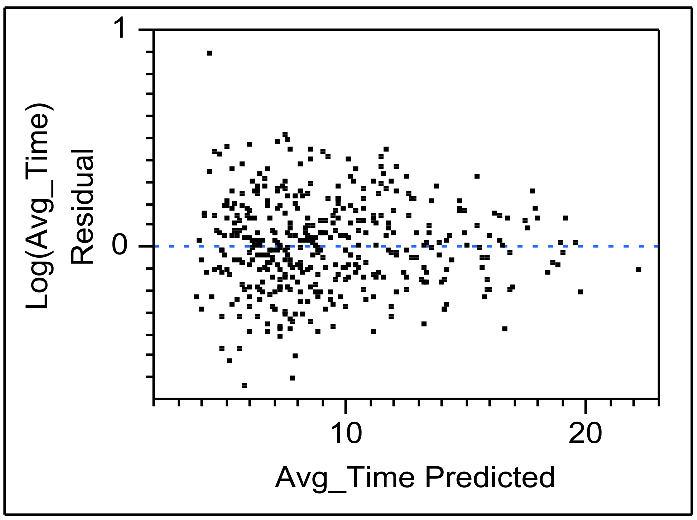


Scatter plot of the residuals as a function of the predicted values for Experiment 1 radial deviation

Appendix C: Graphs for the ANOVA Assumptions

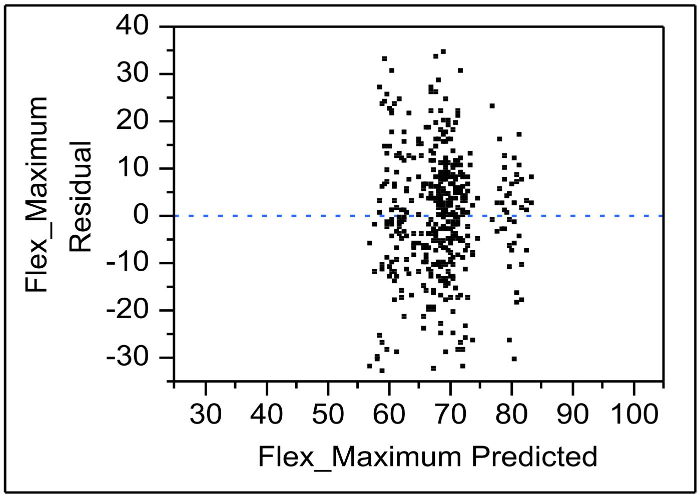


Scatter plot of the residuals as a function of the predicted values for Experiment 1 TTC

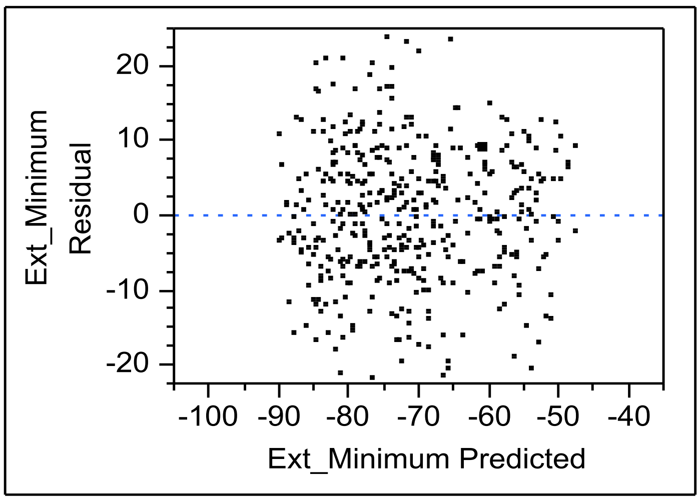


Scatter plot of the residuals as a function of the predicted values for Experiment 1 Log (TTC)

Appendix C: Graphs for the ANOVA Assumptions

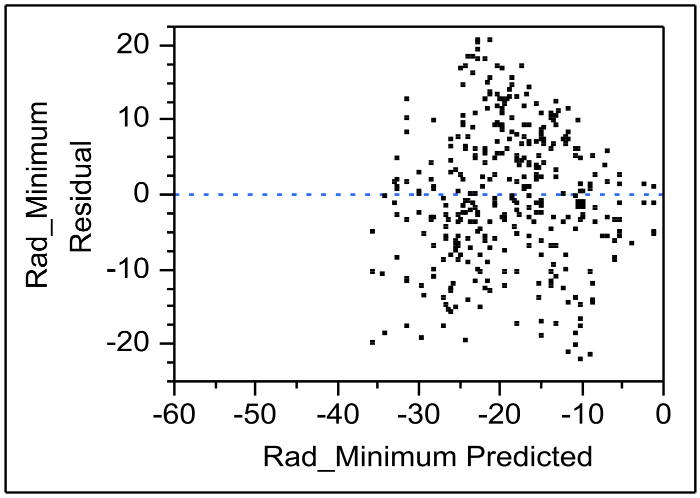


Scatter plot of the residuals as a function of the predicted values for Experiment 2 flexion

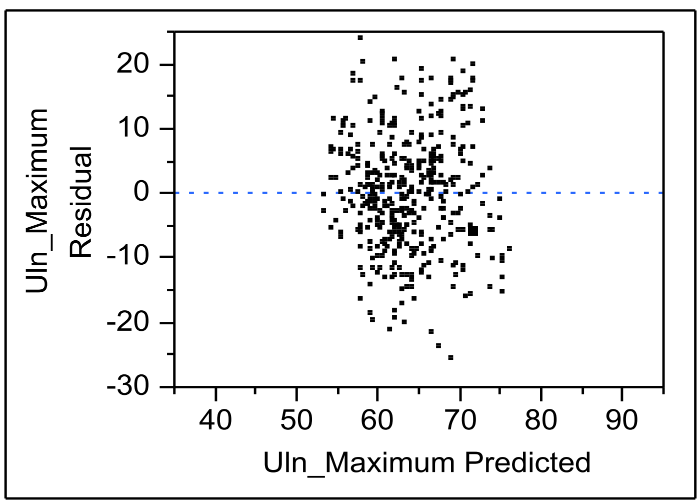


Scatter plot of the residuals as a function of the predicted values for Experiment 2 extension

Appendix C: Graphs for the ANOVA Assumptions

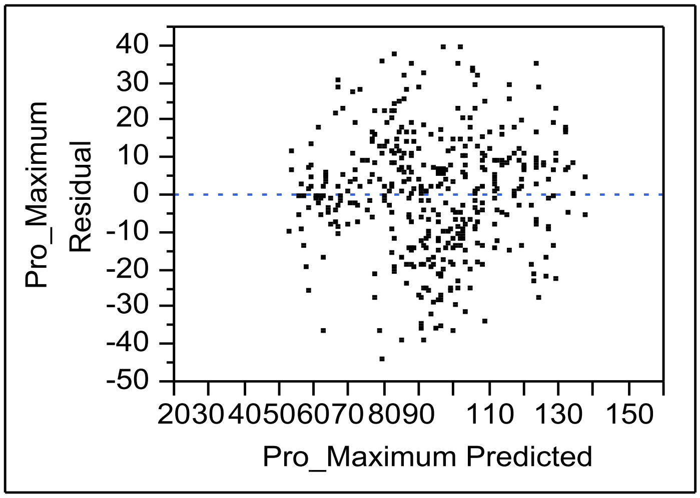


Scatter plot of the residuals as a function of the predicted values for Experiment 2 radial deviation

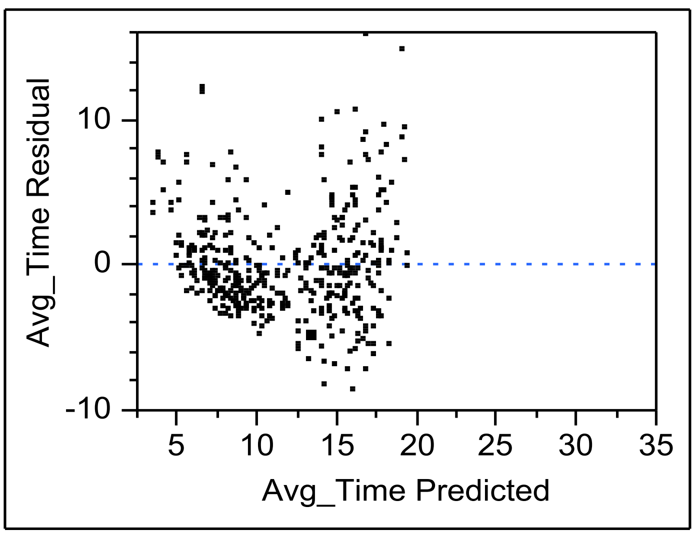


Scatter plot of the residuals as a function of the predicted values for Experiment 2 ulnar deviation

Appendix C: Graphs for the ANOVA Assumptions

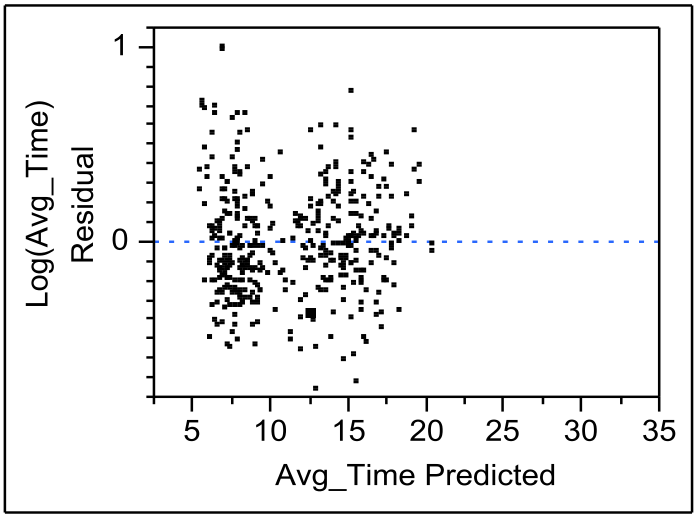


Scatter plot of the residuals as a function of the predicted values for Experiment 2 pronation



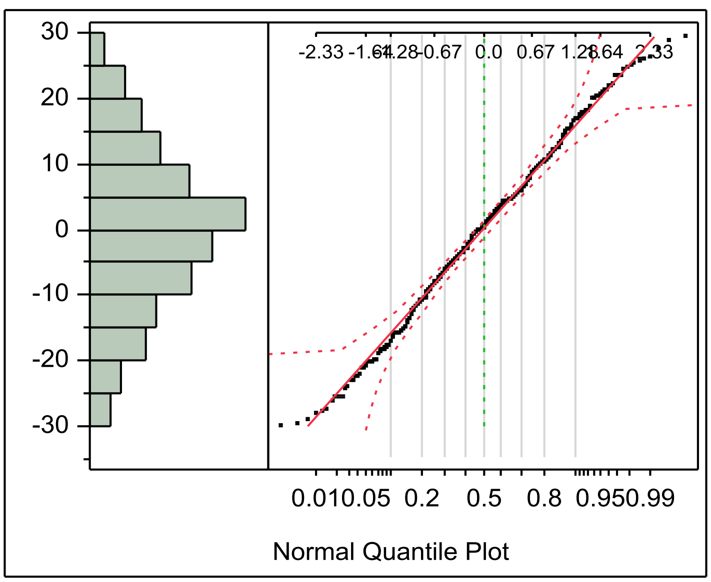
Scatter plot of the residuals as a function of the predicted values for Experiment 2 TTC

Appendix C: Graphs for the ANOVA Assumptions



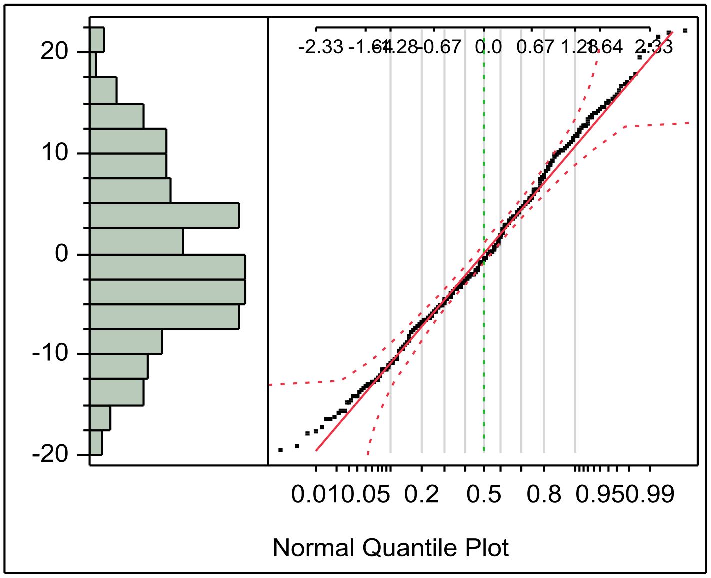
Scatter plot of the residuals as a function of the predicted values for Experiment 2 Log (TTC)

Test for Normality

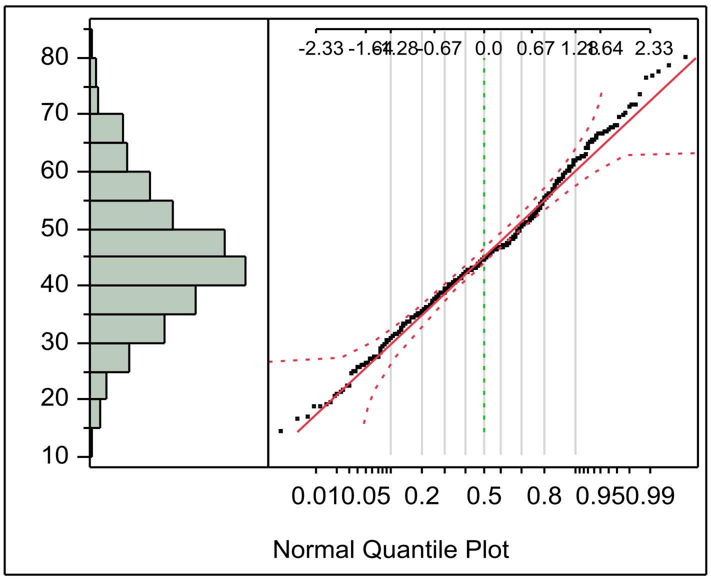


The normal quantile plot of the residuals for Experiment 1 flexion

Appendix C: Graphs for the ANOVA Assumptions

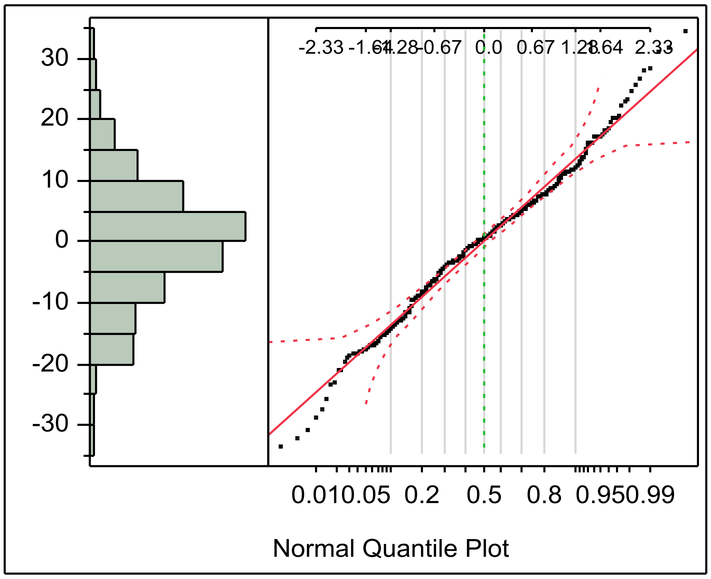


The normal quantile plot of the residuals for Experiment 1 extension

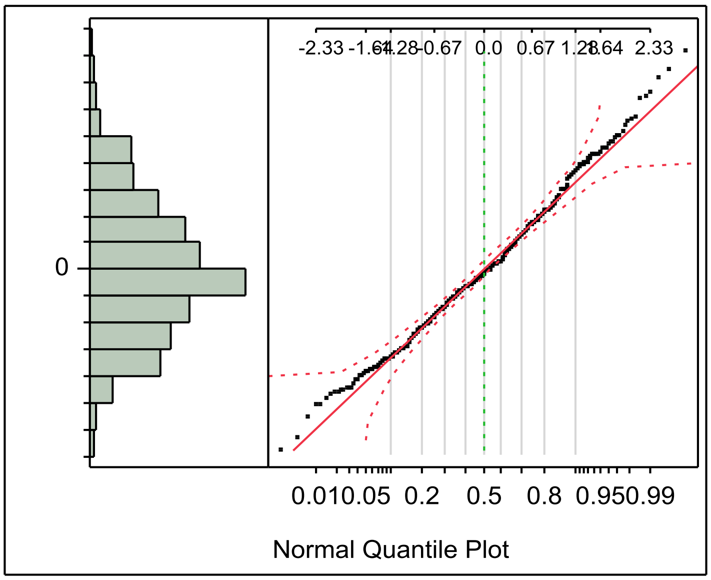


The normal quantile plot of the residuals for Experiment 1 ulnar deviation

Appendix C: Graphs for the ANOVA Assumptions

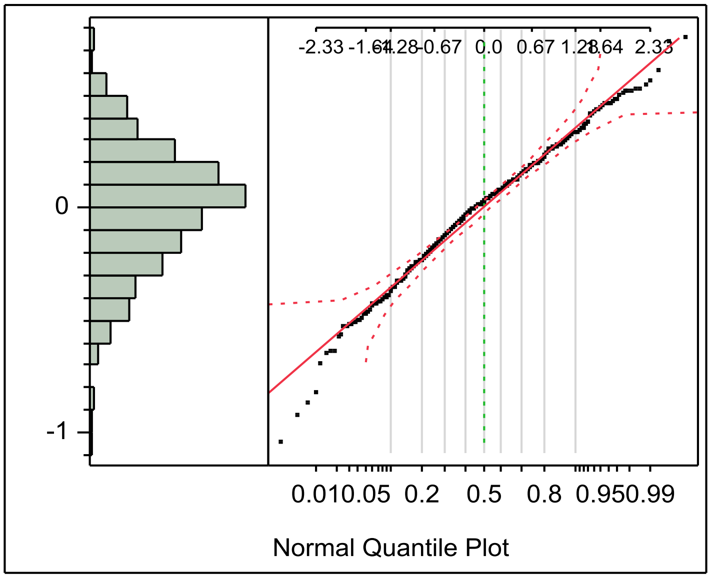


The normal quantile plot of the residuals for Experiment 1 radial deviation

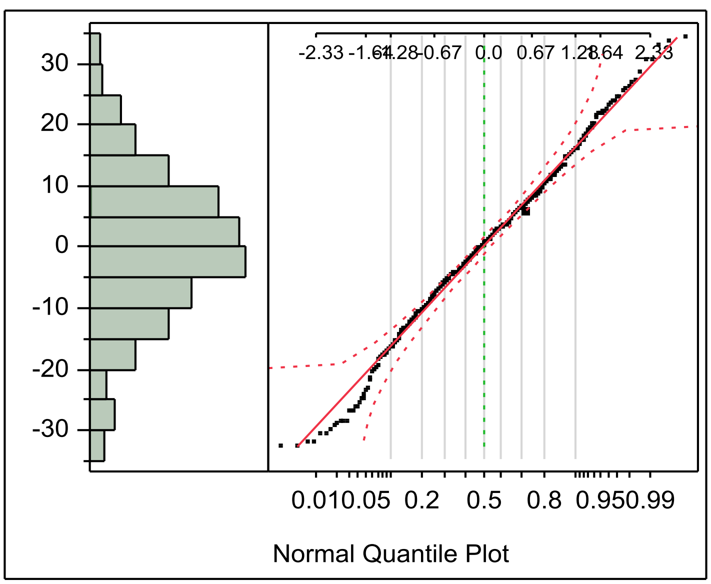


The normal quantile plot of the residuals for Experiment 1 time-to-task completion

Appendix C: Graphs for the ANOVA Assumptions

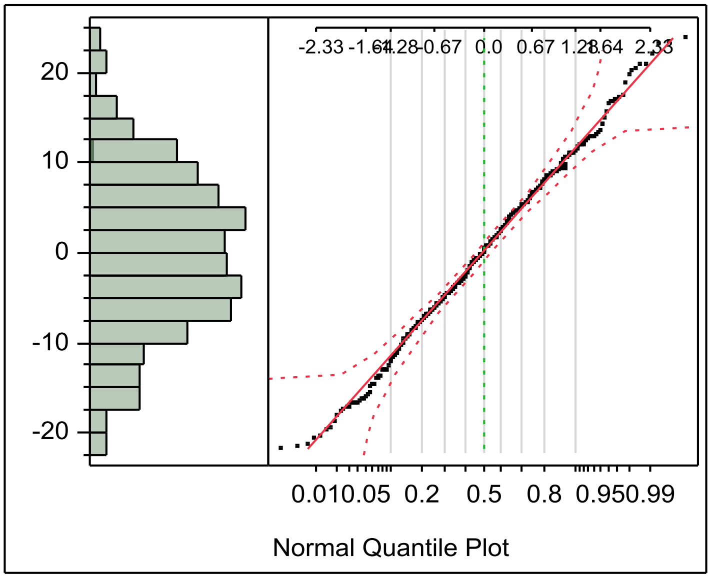


The normal quantile plot of the residuals for Experiment 1 Log (TTC)

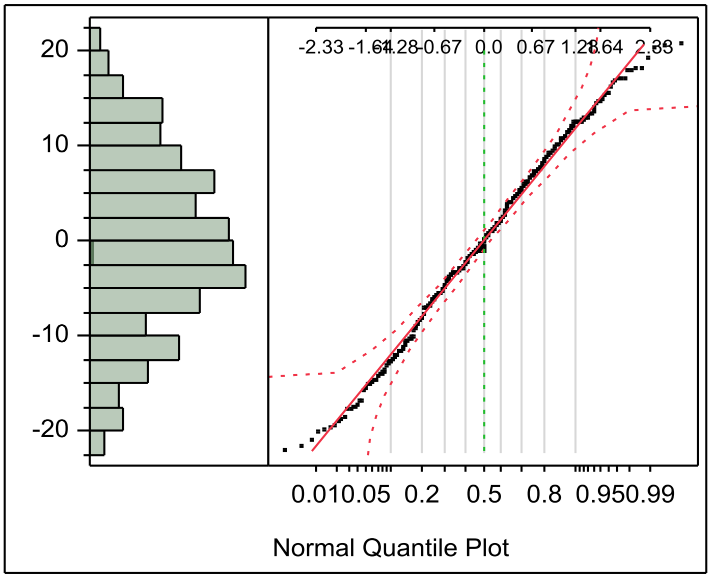


The normal quantile plot of the residuals for Experiment 2 flexion

Appendix C: Graphs for the ANOVA Assumptions

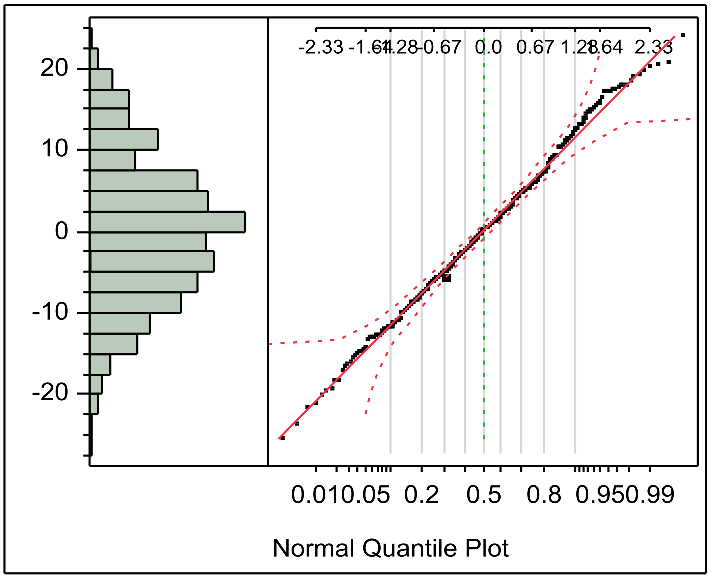


The normal quantile plot of the residuals for Experiment 2 extension

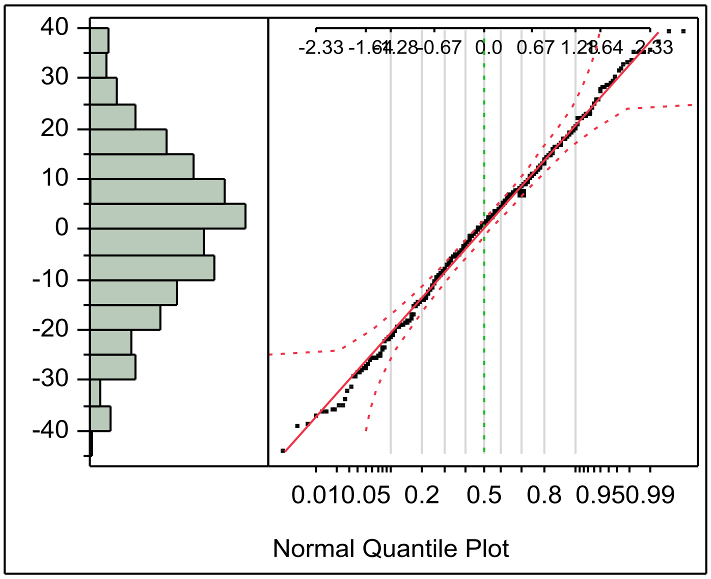


The normal quantile plot of the residuals for Experiment 2 radial deviation

Appendix C: Graphs for the ANOVA Assumptions

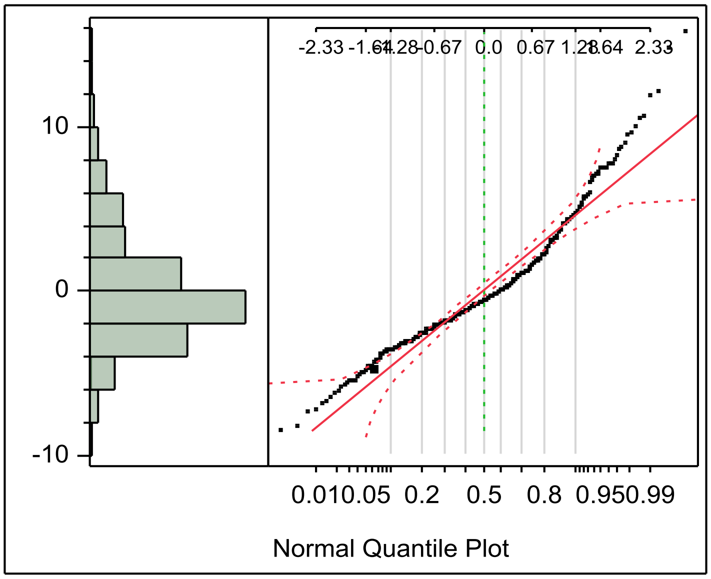


The normal quantile plot of the residuals for Experiment 2 ulnar deviation

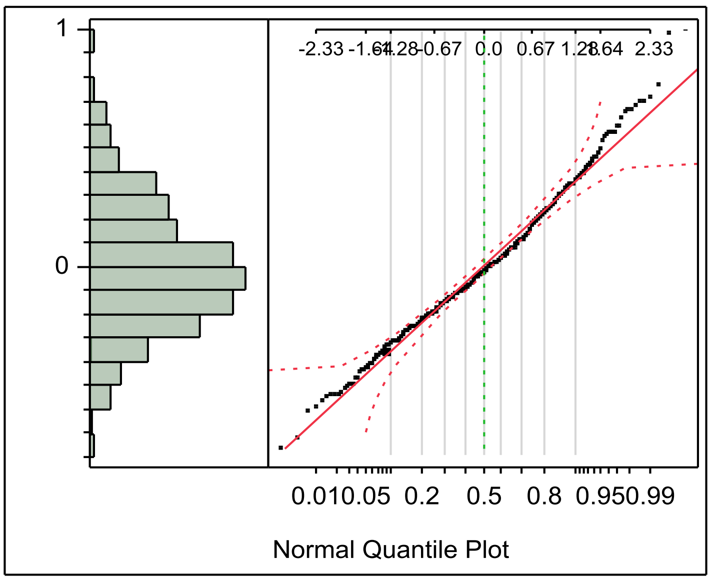


The normal quantile plot of the residuals for Experiment 2 pronation

Appendix C: Graphs for the ANOVA Assumptions



The normal quantile plot of the residuals for Experiment 2 time-to-task completion



The normal quantile plot of the residuals for Experiment 2 Log (TTC)

Appendix D: Outliers

Experiment 1 flexion outliers.

Data Set	Data Point	Value	Graph	Probable Cause
Flexion	59	67.418	Tie/Plank/Level/Session/Subtask	Operator had equipment issues
Flexion	87	3.135	Tie/Plank/Level/Session/Subtask	Operator was rushing
Flexion	293	9.778	Tie/Plank/Level/Session/Subtask	Operator was not using marked hand
Flexion	143	43.463	Tie/Plank/Level/Session/Subtask	Operator had equipment issues
Flexion	321	8.705	Tie/Plank/Level/Session/Subtask	Operator was not using marked hand

Experiment 1 extension outliers.

Data Set	Data Point	Value	Graph	Probable Cause
Extension	295	-23.773	Actual vs Predicted	Operator did not use proper technique
Extension	311	-33.838	Actual vs Predicted	Operator did not use proper technique
Extension	325	-33.368	Actual vs Predicted	Operator used different technique
Extension	327	-29.812	Actual vs Predicted	Operator used different technique
Extension	177	-126.237	Actual vs Predicted	Operator did not follow instructions
Extension	276	-121.137	Actual vs Predicted	Operator did not follow instructions
Extension	179	-120.076	Actual vs Predicted	Operator did not follow instructions
Extension	277	-120.466	Actual vs Predicted	Operator did not follow instructions
Extension	245	-105.033	Tie/Plank/Level/Session/Subtask	Operator did not follow instructions
Extension	97	-48.6	Tie/Plank/Level/Session	Operator did not follow instructions
Extension	309	-47.661	Tie/Plank/Level/Session	Operator was not using marked hand
Extension	142	-98.121	Tie/Plank/Level/Session/Subtask	Operator had equipment issues
Extension	286	-109.864	Tie/Plank/Level/Session/Subtask	Operator did not follow instructions
Extension	141	-100.604	Tie/Plank/Level/Session/Subtask	Operator did not follow instructions

Experiment 1 ulnar deviation outliers.

Data Set	Data Point	Value	Graph	Probable Cause
Ulnar	265	59.776	Plank/Level/Subtask/Session	NO REASON TO REMOVE
Ulnar	267	55.7	Plank/Level/Session	NO REASON TO REMOVE

Appendix D: Outliers

Experiment 1 radial deviation outliers.

Data Set	Data Point	Value	Graph	Probable Cause
Radial	277	-98.967	Actual vs Predicted	Operator did not follow instructions
Radial	136	-6.603	Plank/Level/Subtask/Session	NO REASON TO REMOVE
Radial	139	-0.78	Plank/Level/Subtask/Session	NO REASON TO REMOVE
Radial	129	-6.239	Plank/Level/Subtask/Session	NO REASON TO REMOVE
Radial	270	-20.141	Plank/Level/Session	NO REASON TO REMOVE

Experiment 1 TTC outliers.

Data Set	Data Point	Value	Graph	Probable Cause
TTC	148	30	Actual vs Predicted	Operator did not follow instructions
TTC	242	35.5	Actual vs Predicted	Operator did not follow instructions
TTC	244	34	Actual vs Predicted	Operator did not follow instructions
TTC	275	22.25	Actual vs Predicted	Operator did not follow instructions
TTC	141	13.5	Tie/Level/Session/Subtask	Operator had equipment trouble
TTC	99	3	Tie/Plank/Level/Session/Subtask	NO REASON TO REMOVE
TTC	346	4.25	Tie/Plank/Level/Session/Subtask	NO REASON TO REMOVE
TTC	273	17	Level/Subtask/Session	Operator did not follow instructions

Experiment 2 flexion outliers.

Data Set	Data Point	Value	Graphs	Probable Cause
Flexion	301	113.068	Actual vs Predicted	Operator was using off hand too much
Flexion	105	99.323	Coupler, activity, subtask, trial, session	Operator had equipment issues
Flexion	253	26.146	Actual vs Predicted	Operator did not adequately follow instructions
Flexion	52	101.32	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Flexion	174	58.934	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Flexion	260	102.625	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Flexion	272	103.546	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Flexion	107	92.182	Coupler, activity, subtask, trial, session	Operator had equipment issues
Flexion	105	99.323	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Flexion	253	26.146	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Flexion	301	113.068	Actual vs Predicted	Operator did not adequately follow instructions

Appendix D: Outliers

Experiment 2 extension outliers.

Data Set	Data Point	Value	Graphs	Probable Cause
Extension	209	-42.885	Actual vs Predicted	Operator was using off hand too much
Extension	246	-41.964	Actual vs Predicted	Operator did not adequately follow instructions
Extension	278	-41.964	Actual vs Predicted	Operator did not adequately follow instructions
Extension	291	-48.567	Actual vs Predicted	Operator was using off hand too much
Extension	293	-42.348	Actual vs Predicted	Operator did not adequately follow instructions
Extension	362	-91.875	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Extension	210	-48.644	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Extension	216	-50.794	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Extension	295	-45.726	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Extension	213	-47.953	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Extension	209	-42.885	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Extension	291	-48.567	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Extension	293	-42.348	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Extension	295	-45.726	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Extension	362	-91.875	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions

Experiment 2 radial deviation outliers.

Data Set	Data Point	Value	Graphs	Probable Cause
Radial	404	-180	Actual vs Predicted	Equipment Malfunction
Radial	101	-77.232	Actual vs Predicted	Operator was using off hand too much
Radial	292	-70.809	Actual vs Predicted	Operator did not adequately follow instructions
Radial	246	-2.96	Actual vs Predicted	Operator was using off hand too much
Radial	248	-8.026	Actual vs Predicted	Operator was using off hand too much
Radial	103	-53.44	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Radial	296	-55.792	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Radial	372	-40.051	Coupler, activity, subtask, trial, session	Operator was hurrying too much
Radial	104	-45.841	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions

Appendix D: Outliers

Experiment 2 ulnar deviation outliers.

Data Set	Data Point	Value	Graphs	Probable Cause
Ulnar	103	131.29	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	105	156.62	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	107	128.938	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	114	162.967	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	116	164.384	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	118	163.96	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	120	163.098	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	402	180	Actual vs Predicted	Measurement Equipment Error
Ulnar	404	180	Actual vs Predicted	Measurement Equipment Error
Ulnar	406	180	Actual vs Predicted	Measurement Equipment Error
Ulnar	408	180	Actual vs Predicted	Measurement Equipment Error
Ulnar	121	104.37	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	122	109.464	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	123	119.04	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	124	116.12	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	125	108.717	Actual vs Predicted	Operator did not adequately follow instructions
Ulnar	88	93.837	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Ulnar	101	105.779	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Ulnar	108	40.282	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Ulnar	112	35.668	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Ulnar	119	105.525	Coupler, activity, subtask, trial, session	Measurement Equipment had come loose on operator
Ulnar	127	102.876	Coupler, activity, subtask, trial, session	Measurement Equipment had come loose on operator
Ulnar	151	38.234	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Ulnar	340	81.805	Coupler, activity, subtask, trial, session	No Reason To Remove
Ulnar	113	93.164	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	115	96.492	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	117	97.307	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	126	95.337	Actual vs Predicted	Measurement Equipment had come loose on operator
Ulnar	128	98.937	Actual vs Predicted	Measurement Equipment had come loose on operator

Appendix D: Outliers

Experiment 2 pronation outliers.

Data Set	Data Point	Value	Graphs	Probable Cause
Pronation	32	10.712	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Pronation	67	17.096	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Pronation	68	10.644	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Pronation	72	10.44	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Pronation	76	10.372	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Pronation	99	141.737	Coupler, activity, subtask, trial, session	Measurement Eqipment was not secure
Pronation	100	23.559	Coupler, activity, subtask, trial, session	Operator did not adequately follow instructions
Pronation	108	43.081	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Pronation	110	145.609	Coupler, activity, subtask, trial, session	Measurement Eqipment was not secure
Pronation	111	38.563	Coupler, activity, subtask, trial, session	Operator was using off hand too much
Pronation	112	144.076	Coupler, activity, subtask, trial, session	Measurement Eqipment was not secure
Pronation	261	116.891	Coupler, activity, subtask, trial, session	Measurement Eqipment was not secure
Pronation	22	32.514	Activity, subtask, session	Operator was using off hand too much
Pronation	30	44.603	Activity, subtask, session	Operator was using off hand too much
Pronation	66	17.843	Activity, subtask, session	Operator did not adequately follow instructions
Pronation	69	13.429	Activity, subtask, session	Operator did not adequately follow instructions
Pronation	70	25.858	Activity, subtask, session	Operator was using off hand too much
Pronation	98	45.097	Activity, subtask, session	Operator was using off hand too much