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Usage Trends and Biomechanical Evaluation of Tethered Tools

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USAGE TRENDS AND BIOMECHANICAL EVALUATION OF TETHERED TOOLS

by

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ABSTRACT

BIOMECHANICAL AND PREFERENTIAL EVALUATION OF TETHERED AND UNTETHERED HAND TOOLS

by

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Under the Supervision of Professor Naira Campbell-Kyureghyan

Struck-by injuries and death caused by dropped objects continue to be a prevalent problem in industries where work is conducted at height. Securing objects from height with tethers, especially hand tools used to conduct work, and an increase in regulatory oversight would reduce these incidences. To date, no research has been conducted to investigate tethered tool usage patterns in industry to include user preference, task performance and the biomechanical impact of using tethered tools in lieu of their untethered counterparts. Due to the lack of information on tethered tool usage, it was necessary to develop and distribute a survey to gather data on tethered tool usage patterns, tool carrying methods, drop history and perceived risks while working at height. This thesis is a two-part study aimed at 1) identifying tethered tool usage trends in industries that conduct work at height and 2) identifying the biomechanical impact of using a tether on a tool to conduct in comparison to using the tool without a tether. Study 1 found that when employers provided tethered tools and means of carrying tethered tool, their usage was significantly increased. Study 2 found that tethered tool usage resulted in no statistically significant biomechanical impact to the user when conducting a task.

To:

Steve, the tether that keeps me from falling.

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Chapter I Introduction

1. Background

Over the past several decades there has been a rapid increase in global infrastructural demands in the forms of construction, renewable energy generation systems, and military presence to name a few. Various aspects of conducting work at height have been recognized as highly dangerous due to potential risk of injury to workers, such as dropping a tool, which can lead to devastating consequences, like loss of productivity, interrupted work, equipment damage, injury and death. An available resource, DROPSonline.org, developed a tool to calculate the potential impact of an incident when an object of up to 1 kilogram is dropped from a height of 15 meters (Figure 1). What is seen is that an object of approximately 0.65 kilograms dropped from a height of 15 meters could cause a fatality if a person is struck from above.

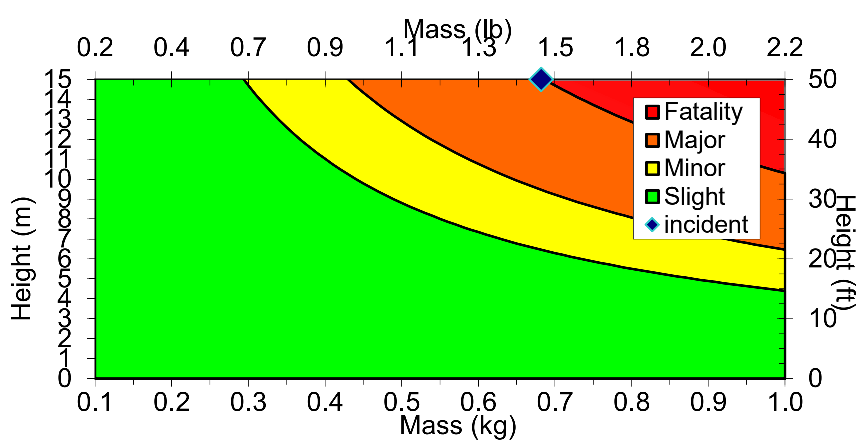


Figure 1: Electronic DROPS calculator. Adapted from DROPS online, 2015, Retrieved from http://www.dropsonline.org/resources-and-guidance/drops-calculator/e-drops-calculator/.

As infrastructural needs are evolving and increasing, so do the demands of those who work at height. In an industry employment and output projections analysis conducted by the Bureau of Labor Statistics (BLS), construction, defined as construction of buildings, heavy and civil engineering construction and specialty trade contractors, is predicted to be one of the fastest growing sectors, projected to reach 7.3 million jobs by 2022 (BLS, 2013). This type of expansion leads to an increase in vertical construction, and therefore an increase of work at height, naturally resulting in a greater likelihood and risk of dropping tools at height.

Falling objects is the second most common cause of injury and death in the steel construction industry. The BLS 'National Census of Fatal Occupational Injuries in 2014' reported that the largest proportion of fatal injuries in caused by falling objects (34%) occurred when workers were struck by falling objects or equipment (BLS, 2015). In addition, OSHA reported that in 2014, the total number of deaths accounted for by BLS, 20.5% were in the construction industry. Within that percentage, over half were caused by one of the 'fatal four': falls (39.9%), electrocutions (8.5%), struck by object (8.4%) and caught-in/between (1.4%) (OSHA, 2015). OSHA reports that the most frequently cited standard that was violated in 2015 was 29 CFR 1926.501 "Fall protection, construction" (OSHA, 2015). Figure 2 shows that of the ten leading causes and direct costs of the most disabling workplace injuries based on 2013 data (Liberty Mutual, 2016), struck by object or equipment accounted for 8.9% or $5.31 billion of the total cost burden of U.S. worker compensation costs. Struck-by injuries and death caused by dropped objects could be eliminated with increased safety measures and precautions, such as lanyard that ensure tools will not fall if misplaced or dropped (Krishnamurthy, 2013).

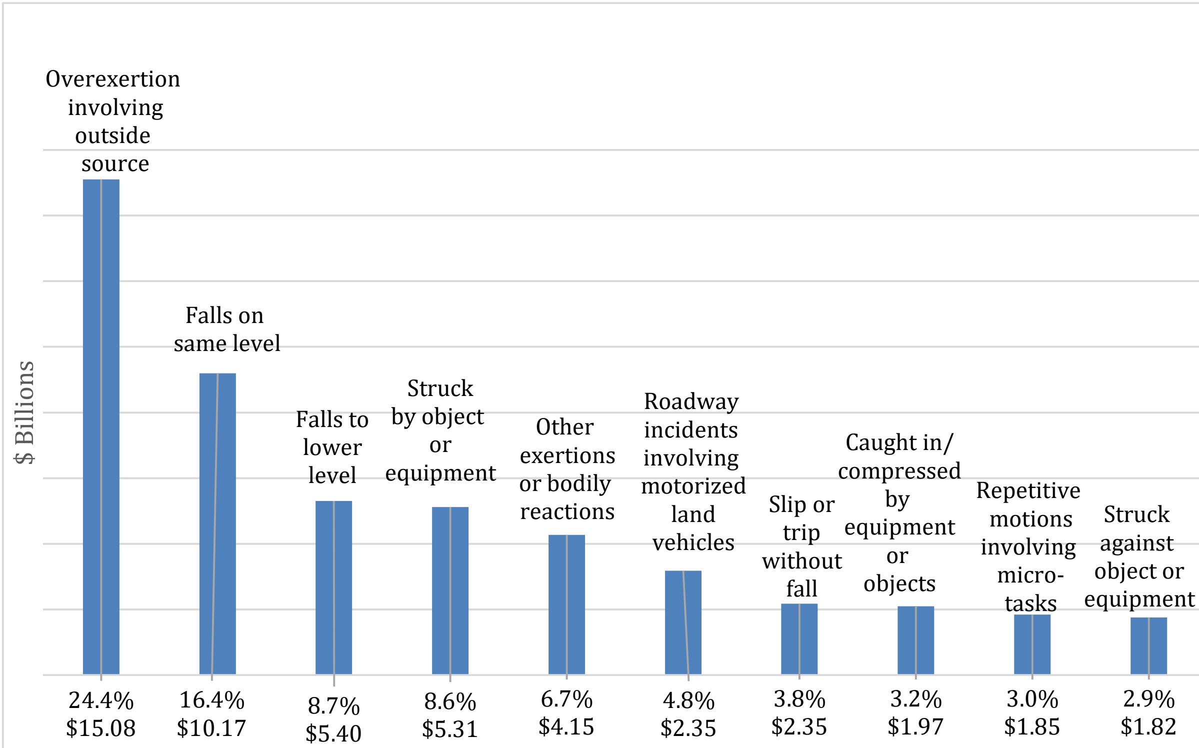


Figure 2: “Top 10 Causes and Direct Costs of the Most Disabling U.S. Workplace Injuries”. Adapted from Liberty Mutual Group, 2016, Retrieved from https://www.libertymutualgroup.com.

It is industry common knowledge that tethering tools prevents drop accidents, yet tethered tool use is not consistently practiced across industries where personnel work at heights. At height, all tools and equipment needed must be carried with the individual, potentially affecting their balance, ability to arrest a fall, increased fatigue and risk of dropping a tool. Carefully selected harness systems should also incorporate tool carrying accessories (Jervis, 2009). It is evident that tethers assist in prevention of undesired circumstances, but the reason why they are not commonly being used to secure tools is not discussed in the research.

Retractable gear attachment systems that offer the benefits of safety, productivity and comfort for workers are vital in at height work environments. If an instrument or tool is dropped, a tether easily absorbs the stress produced by these heavier instruments thus preventing loss or damage. When the instrument or tool needs to be used, the worker simply needs to pull it out and use it and, when the work is finished, let it go, at which point it automatically retracts (Dvorak, 2011). Oftentimes, construction accidents occur through bad equipment selection, misuse, and lack of inspection (Pinto, et al., 2015), yet many accidents can be avoided, especially accidents involving dropped objects from an at-height work environment. Possible reasons that users may not prefer using tethered tools is due to tether properties, such as creating a loop that may snag or catch on surrounding areas, increasing restriction of maneuverability, limited reach or through causing other nuisances to the user.

Unlike fall protection devices, such as body harnesses, existing regulatory standards for tool use are vague and do not mandate securing of tools at height while not in use. For example, OSHA's steel erection falling protection regulation 29 CFR 1926.759 (a) states: "all materials, equipment, and tools, which are not in use while aloft, shall be secured against accidental displacement." This regulation neglects the importance of securing tools while in use, where dropping due to slips, misuse or other general accident could occur. OSHA states in their General Industry Standard: "Tools, materials and debris not related to the work in progress shall not be allowed to accumulate on platforms." Securing tools is mandated to prevent them from falling or dropping, but the method of securing tool and industry standards are not provided. Methods differ and safety or reliability of these methods may also differ, which may or may not increase safety.

Working at height is inevitable during construction and maintenance in the wind turbine industry. It is a relatively new industry that continues worldwide growth annually. At the end of 2012, over 69,000 wind turbine units were installed across the United States (Orrell, et al., 2013), and at the end of 2011, over 20,000 were installed in Germany and Spain alone (OSHA, n.d.). The height at which workers have to climb ranges between 9 meters to 49 meters for small turbines, between 30 meters to 100 meters for mid-size and multi-MW turbines (1 MW=1,000 kW=1,000,000 W) (Orrell, et al., 2013). Due to the increase of wind turbines, there has been a coinciding increase in accidents. A European wind turbine industry study revealed that on average, there were 141 accidents per year from 2008 to 2012, and, in 2013, by 30th September, 112 accidents had occurred. Since 1970, 104 fatal accidents have occurred causing 144 fatalities, and, of these, 87 deaths were among support workers within construction, maintenance and engineering or among small turbine owners and operators (Webster, et al., 2013). Although specific details in causation were not provided, it can be assumed that the potential for dropping a tool from height increases with the increase in wind turbine construction and maintenance.

Within the U.S. Coast Guard (CG), employees are often required to conduct work at height in various scenarios and missions. For example, Aids to Navigation (ATON) requires working to climb waterway structures such as navigational aids (Figure 4) to conduct repair and maintenance. Another example is the internal maintenance and service CG employees conduct on critical antenna and navigation systems on towers (COMDTINST M11000.4A, 2002). CG guidance mandates that workers at height must attach all tools and equipment to a tether to prevent hazards. Due to the nature of work conducted by the CG, it is apparent that work is frequently conducted at height, and like the WPI, little data and information is readily available on injury statistics and means of preventing risks associated with work at height.

Much research has been conducted on fall prevention of the human body, with emphasis on worker body harnessing and body harness lanyard integrity. Information and research on whether a lanyard affects performance, comfort or time spent on a task is lacking and is vital component to potentially establishing guidelines and standards for tethered tools, and in the study of ergonomic applicability to industry. Claims speaking to overall efficiency or tether interference with a task do exist, but the lack of scientific information and data provide little credibility to those claims. For example, the claim that tethered tools can decrease or increase productivity or ease of task (Salentine, 2011) is unsupported by experimental data.

Although the prevention of dropped objects is necessary in reducing injury and fatality rates in industries that require work at height, research is needed to mitigate these risks, specifically in the realm of tethering tools. To date, no research on the biomechanical impacts of using tethered tools in comparison to their untethered counterparts, including how tethers interfere with time spent on a task and user preference, has been conducted. Research into tethered tool usage trends, biomechanical impact and user preference could potentially unearth why workers are not using tethered tools to prevent drop incidents.

2. Aims/Hypothesis

This study is consisted of two parts that are related to tethered tool usage. Study 1 focuses on survey results received from Coast Guard (CG) and Wind Power Industry (WPI) respondents regarding in-field tethered tool usage. Study 2 focuses on biomechanical differences between tethered and untethered tool usage at different reaches and while on and off a ladder. Two of the most commonly used hand tools identified in Study 1, hammer and wrench, will be used to perform their associated tasks in order to investigate the effects of the tether on the operator. Changes in biomechanical markers and user perceptions between tethered tool use and untethered tool use for each of the tools tested will be quantified.

This thesis describes two studies that are related to the usage trends and biomechanical impact of tethered tool usage. Study 1 focuses on the factors associated with in field usage and identification of most commonly used hand tools for workers at height. Study 2 focuses on how tethering biomechanically impacts the user while conducting a task.

Study 1

Goal 1: Identify which tools are most commonly used in the CG and WPI.

Goal 2: Identify trends associated with tethered tool usage in the CG and WPI.

Goal 3: Identify most common methods of carrying tools to at height work sites in the CG and WPI.

Goal4: Identify subject opinion regarding tethered tool usage in the CG and WPI.

Goal 5: Identify the trends, gaps and suggest future recommendations regarding tethered tool usage

Study 2

Goal 1: To determine the biomechanical effects of using a tether during hammering at four different reaches while on the ground and at elevation.

H1: Tether will not affect muscle activity, grip pressure and time on task during hammering at different heights or reach conditions.

a. Ladder condition will not impact muscle activity, grip pressure and time on task during hammering.

b. Reach will impact muscle activity and grip pressure, but not the time on task during hammering.

Goal 2: To determine the biomechanical effects of using a tether during wrenching at four different reaches while on the ground and at elevation.

H2: Tether will not affect muscle activity, grip pressure and time on task during wrenching at different heights or reach conditions.

a. Ladder condition will not impact muscle activity, grip pressure and time on task during wrenching.

b. Reach will impact muscle activity and grip pressure, but not the time on task during wrenching.

Goal 3: To determine participant's subjective opinion on tethered tool usage after completion of each experimental condition:

H3: Subjects will not have a preference between tethered or untethered tool usages.

Chapter II

Study 1: Survey based assessment of tethered tool usage in the power generation industry and U.S. Coast Guard

1. Introduction

Over the past several decades there has been a rapid increase in global infrastructural demands in the forms of construction, renewable energy generation systems, and military presence to name a few. As infrastructural needs are evolving and increasing, so are the demands on those who work at height. Various aspects of conducting work at height have been recognized as highly dangerous due to potential risk of injury to workers, such as dropping a tool, which can lead to devastating consequences including loss of productivity, interrupted work, equipment damage, injury and death.

In an industry employment and output projection analyses conducted by the Bureau of Labor Statistics (BLS), construction, defined as construction of buildings, heavy and civil engineering construction and specialty trade contractors, is predicted to be one of the fastest growing sectors, with the projected number of construction jobs to increase from 5.6 million in 2012 to 7.3 million by 2022 (BLS, 2013). This type of expansion leads to an increase in vertical construction, and therefore an increase in construction and work at height, naturally resulting in a greater likelihood and risk of dropping tools at height.

Construction growth and fatal injury increase has been apparent within the industry. In 2014, BLS reported that the greatest proportion of fatal injuries caused by contact with objects was by struck-by objects, resulting in 708 deaths, which was slightly down from 2013 where 721 deaths occurred. In fact, the largest proportion (34%) of deaths caused by contact with objects occurred during struck-by incidents (BLS, 2015). According to the same source, fatal injuries in the construction industry rose from 828 in 2013 to 874 in 2014, implying that continued attention and means to increase safety is necessary to keep incidents from occurring.

Limited statistical data for injuries and dropped object incidences is available pertaining to the wind power industry (WPI). The Caithness Wind Farm Information Forum (CWIF) is an organization that gathers information on wind turbine incidents on a global scale, and is believed to be the most comprehensive data available regarding such incidents (Webster et al., 2013). A 2013 report by the European Agency for Safety and Health at Work referenced collected CWIF data, and conveyed that since 1970 a total of 1,370 accidents have occurred, resulting in 144 fatalities, most of them being in the last five years of the report (Webster, et al., 2013). In addition, the report also states that the database may have captured only 9% of actual accidents, and that WPI accident data are hard to find and not very complete (Webster, et al., 2013).

Figure 3: WPI worker carrying tools in a tool bag/bucket

Based on our team observations, WPI workers carry all the tools and equipment needed for their job, which may affect their balance while working on a tower or inside or outside of the nacelle, fall arrest ability, fatigue and chance of dropping items (Figure 3). It is imperative that appropriate harnesses are selected for the job, including the appropriate tool-carrying accessories (Jervis, 2009). Dvorak (2011) recommends that a retractable attachment system provides the benefits of comfort, safety and productivity to workers at height. Oftentimes construction accidents occur through bad equipment selection, misuse, or lack of inspection (Pinto, et al., 2015). Struck by falling objects is the second most common cause of injury and death in the steel construction industry, and protection from falling objects is practiced by wearing hard hats and securely fastening tools and materials through the use of tethers will ensure objects will not fall if misplaced (Krishnamurthy, et al., 2013). In fact, 66% of struck by falling object accidents have the potential to be avoided (Wu, et al., 2013). Although suggestions seem to indicate that appropriate tool carrying methods such as lanyards or tethers are essential in drop prevention, frequency of use in industries where work at height is conducted is unknown.

Within the U.S. Coast Guard (CG), employees are often required to conduct work at height in various scenarios and missions. For example, Aids to Navigation (ATON) requires working to climb waterway structures such as navigational aids (Figure 4) to conduct repair and maintenance. Another example is the internal maintenance and service CG employees conduct on critical antenna and navigation systems on towers (COMDTINST M11000.4A, 2002). CG guidance mandates that workers at height must attach all tools and equipment to a tether to prevent hazards. Due to the nature of work conducted by the CG, it is apparent that work is frequently conducted at height, and like the WPI, little data and information is readily available on injury statistics and means of preventing risks associated with work at height.

Figure 4: CG employee working on hanging a day board on a navigational aid. Photo courtesy of ET1 R. Beatty, USCG

A potential reason that little is known about tether usage in industry may be due a lack of regulatory mandate. OSHA regulations primarily focus on body harnesses (Choi, 2006), and are very vague concerning tether requirements. For example, OSHA's steel erection falling protection regulation, 29 CFR 1926.759 (a), states: "all materials, equipment, and tools, which are not in use while aloft, shall be secured against accidental displacement." This regulation acknowledges the importance of securing idle loose items, but neglects the need for securing tools while in use, where slips, misuse or other general accidents could occur. Securing tools when not in use is mandated to prevent them from falling, but the method of securing tools and industry standards are not provided. Methods differ, and the safety or reliability of these methods may also differ, which may or may not increase safety. In general, there is no industry standard on the methodology of securing tools while working at height.

Another possible reason that users may not prefer using tethered tools is due to tether properties, such as extra effort for reaching or creating a loop that may snag or catch on surrounding areas, increasing restriction of maneuverability, and limited reach or cause other restricting nuisances to the user.

Research into tethered tool usage trends, circumstances that encourage or discourage usage, types of tools commonly used and methods of securing tools is necessary in understanding why incidents occur and how to prevent them. To date no study considered factors affecting tethered tool usage within the field.

The goal of this project was to perform a survey based assessment of the types of tools used by workers in the WPI and CG, identify the tools that should be tethered, and tool drop history as well as the frequency of tethered tool usage and the reasons behind the usage. Other factors such as age, work experience, employer provision of tethered tools, tool drop history and means of carrying tools to a work-site were also considered to further identify how these factors relate to tethered tool use.

2. Materials and Methods

A customized questionnaire was designed to gather tethered tool usage trends among WPI and CG technicians. The survey specifically covered the following topics: personal demographics, job details, dexterity, list of routinely used tools and associated tasks for those tools, tethered tool availability and frequency of usage, tool drop history, overall job risk assessment, and based on the participant's feedback which commonly used tools should be tethered.

Personal demographics included age, gender, weight, height, handedness, extra-curricular activities, education level, and self perception of safety. The job-related information concerned details regarding job position, experience in the position, years of employment, hours worked, and provision of tethered tools. Other questions included time spent at height, likelihood of injury during each season, percentage of time spent indoors and outdoors, frequency of tethered tool usage, tool carrying methods, and tool drop history.

An extensive list of tools that are typically used at height, as determined through onsite visits, preliminary interviews, industry periodicals, and video of work being conducted at height, was presented at the end of the survey. Next to each listed tool the participant was asked to check whether they used the tool when working at height, if it was tethered, and if it was not tethered but should be.

Because of the different job criteria between the WPI and the CG, several questions within each survey, as well as the survey length, varied. The WPI questionnaire consisted of 27 questions, while the CG personnel were asked 24 questions. The differences in questions were as follows:

<u>CG</u>

1. Does your position require you to conduct maintenance at height?
2. If yes, then which at height environments do you conduct work on?
3. Do you like using tethered tools?

<u>WPI</u>

1. Do you encounter any of the following climbing systems: internal ladder, internal elevator, external ladder, power climb assist, or other?

Upon the approval from the Institutional Review Board (#15.375) two separate anonymous online surveys were created using the Qualtrics (2016, USA) program and distributed to several wind power generation companies, as well as to Coast Guard employees, spanning across 14 of the United States collectively. A cover letter explaining the nature of the survey was included at the beginning of each survey. Online participants were provided with a PDF version of the survey and return mailing address, should they prefer to print out and send their survey directly to the research team.

The number of surveys distributed via email is unknown, since supervisors forwarded the anonymous survey to their employees and the survey was voluntary. 31 WPI and 57 CG maintenance technicians took the survey, and of the 88 total surveys started, 80 were completed within the deadline of 4 weeks. No mailed-in surveys were received.

A combination of descriptive and inferential statistics was used to analyze questionnaire outcomes and tool usage trends. Participants were divided into two groups- those who use tethered tools and those who do not use tethered tools, and proportions were calculated to illustrate prevalence of tool usage and usage patterns by those who use tethered tools.

Pearson correlation coefficient and significance were calculated to investigate the relationships between usage patterns, drop history and tool carrying methods. Statistically significant associations are represented by p values <0.05, and marginal associations are represented by p values ranging from 0.05 to 0.10. All statistical analysis was conducted using Minitab 16 (2016, USA).

3. Results

The largest proportion of survey respondents were between the ages of 30-39 (45%), followed by 18-29 (40%) and 40-49 (15%), and of the tethered tool users, 51.7% were in the 30-39 age group, while 34.5% were 18-29 age, and 13.8% were 40-49. Only 6.25% of the respondents were female, all of whom were in the Coast Guard. A majority (90%) was right handed, 6.25% were able to use both hands equally and 3.75% were left handed. Within the CG, most of the respondents were Boatswain's Mates (63%), followed by Electrician's Technician (14%), Non-rate (14%), Machinery Technician (4%), and Other (5%). Within the WPI, a majority were Technicians (83%), followed by Site Manager/Supervisor (10%) and other (7%).

Work-related information identifying tool usage is presented in Table 1 and summarized in 3 categories: overall, CG and WPI. Although the two industries conduct work at height, the WPI and CG have different job requirements, and it is important to see the overall trends, identified by the categories of "Overall", "Use Tethered Tools", and "Do Not Use Tethered Tools", and to distinguish the differences in work related factors between the two surveyed groups.

As shown in Table 1, the median number of years with the respondent's current employer was 7.8. Within occupation, the WPI median years with the current employer was 5.2, while the CG median was 13.0, and such a large difference could be due to the fairly new nature of the WPI. Although respondents in the CG have been with their employer for longer, work experience in their current position had a median of 2.5 years, which can be explained by the fact that a typical CG tour or assignment in a particular unit lasts between 2 to 4 years.

The majority (72.5%) of respondents used tethered tools as a general practice, while 27.5% of respondents did not. 87.9% of tethered tool users are provided with them by their employer, whereas only 18.2% of those who do not use tethered tools are provided with them, indicating that access to and provision of equipment influences likelihood of use. In fact, only a small number (7%) of those who were provided with tethered tools did not use them on a regular basis. To the contrary, about same number of respondents (7.5%) that were not provided with tethered tools through their employer used tethered tools at their work site. Table 1 summarizes the survey result findings to provide a broad perspective of overall responses of those who use tethered tools, those who do not, and responses within the surveyed industries.

The results also show specifics of the dropped tool history amongst the different user categories. Half of the respondents who did not use tethered tools admitted to dropping a tool while working at their jobsite. On the other hand, 84.5% of tethered tool users admitted to having dropped a tethered tool. When specifically asked what tethering point a tools were dropped from, 27.6% of tethered tool users had said the tool was tethered to them, and 19% said the tool was tethered to the structure on which they were working. 0% of those who did not use tethered tools had dropped a tool tethered to themselves or tethered to the structure on which they were conducting work. This suggests that tethered tool users have dropped tethered tools, and recognize the importance of using them, while those who do not use tethered tools have not dropped a tethered tool, and may not recognize the importance in using them.

Table 1: Summary of work-related statistics and tool usage

Work related factors	Overall	Use TT	Do Not Use TT	WPI	WPI Use TT	WPI Do Not Use TT	CG	CG Use TT	CG Do Not Use TT
	n=80	n=58	n=22	n=29	n=24	n=5	n=51	n=34	n=17
Approximately how long have you worked with your current employer? (years)	7.8	7.9	7.1	5.2	5.2	4.6	13	14.3	9.25
Approximately how much experience do you have in your current position? (years)	3	3.1	2.8	4.2	4.6	4.0	2.5	3	2.5
How many hours do you work per shift?	8.7 (±1.6)	8.9 (±1.7)	8.4 (±1.0)	9.23 (±1.3)	9.4 (±1.4)	9.0 (±1.4)	8.5 (±1.6)	8.6 (±1.6)	8.5 (±1.0)
Avg. Likelihood of Injury Spring (scale 1-5)	2.7 (±1.0)	2.7 (±1.0)	2.6 (±0.9)	2.2 (±0.9)	2.4 (±1.01)	2.0 (±0.0)	2.98 (±0.9)	3.1 (±0.8)	2.7 (±0.9)
Avg. Likelihood of Injury Summer (scale 1-5)	3.1 (±1.1)	3.1 (±1.1)	2.9 (±0.9)	2.6 (±1.3)	2.8 (±1.3)	1.5 (±0.7)	3.3 (±0.9)	3.4 (±1.0)	3.1 (±0.8)
Avg. Likelihood of Injury Fall (scale 1-5)	2.8 (±1.0)	2.8 (±1.0)	2.5 (±0.9)	2.3 (±1.1)	2.6 (±1.12)	1.5 (±0.7)	3.0 (±0.8)	3.2 (±0.9)	2.8 (±0.8)
Avg. Likelihood of Injury Winter (scale 1-5)	2.9 (±1.0)	2.9 (±1.0)	3.0 (±0.8)	3.1 (±1.2)	3 (±1.01)	3.5 (±0.7)	2.7 (±0.9)	2.7 (±0.9)	2.9 (±0.9)
Percentage of work day spent indoors:	46.4%	45.2%	49.9%	39.1%	35.9%	85.0%	50.6%	51.5%	48.8%
Percentage of work day spent outdoors:	53.6%	54.8%	50.1%	61.0%	64.1%	15.0%	49.4%	48.5%	51.2%
Conducts work at height in position (CG):	x	97.1%	94.1%	x	x	x	96.0%	96.6%	94.1%
Encounter internal ladder climbing system (WPI):	x	95.8%	100.0 %	96.5%	94.7%	100.0%	x	x	x
Encounter internal elevator climbing system (WPI):	x	16.7%	0.0%	13.8%	21.1%	0.0%	x	x	x
Encounter external ladder climbing system (WPI):	x	29.2%	40.0%	31.0%	26.3%	0.0%	x	x	x
Encounter power climb assist (WPI):	x	87.5%	100.0 %	89.7%	94.7%	100.0%	x	x	x
Encounter other climbing systems (WPI):	x	8.3%	20.0%	6.9%	5.3%	50.0%	x	x	x

Use tethered tools:	72.5%	x	x	82.8%	x	x	66.7%	x	x
Never	26.3%	x	x	17.2%	x	100.0%	31.4%	x	94.1%
Sometimes	35.0%	46.6%	4.5%	55.2%	78.9%	x	23.5%	32.4%	5.9%
Usually	35.0%	24.1%	x	17.2%	15.8%	x	17.6%	26.5%	x
Always	21.3%	29.3%	x	10.3%	5.3%	x	27.5%	52.9%	x
Employer provides tethered tool	68.7%	87.9%	18.2%	89.7%	91.7%	60.0%	56.86 %	82.4%	5.9%
Uses a tool bag/bucket:	95.0%	96.6%	95.5%	96.6%	100.0%	100.0%	94.1%	79.4%	94.1%
Like using tethered tools (CG):	x	61.8%	23.5%	x	x	x	50.0%	61.8%	23.5%
Dropping tools is a problem in industry:	62.5%	67.2%	50.0%	86.2%	94.7%	100.0%	49.0%	50.0%	47.1%
Have dropped a tool while at jobsite:	75.0%	84.5%	50.0%	67.7%	100.0%	100.0%	68.0%	88.2%	52.9%
Have dropped tool tethered to self:	62.5%	27.6%	0.0%	20.7%	21.1%	0.0%	19.6%	29.4%	0.0%
Have dropped tool tethered to work structure:	63.8%	19.0%	0.0%	10.3%	10.5%	0.0%	15.7%	23.5%	0.0%
Wear vest:	28.8%	32.8%	18.2%	3.4%	5.3%	0.0%	43.1%	50.0%	23.5%
Wear tool belt:	18.8%	24.1%	4.5%	6.9%	5.3%	0.0%	25.5%	35.3%	5.9%
Wear backpack:	32.5%	39.7%	13.6%	6.9%	10.5%	0.0%	47.1%	61.8%	17.6%
Wear bucket:	31.3%	27.6%	40.9%	37.9%	42.1%	50.0%	27.5%	23.5%	35.3%
Wear other:	28.8%	29.3%	27.3%	37.9%	31.6%	50.0%	23.5%	26.5%	17.6%

As shown in Table 1 only 68.7% of employers provided their employees with tethered tools. Within the CG only 56.9% were provided with tethered tools, although 96% of CG members conducted work at height. In general, most tethered tool users utilized them sometimes (46.6%), but job description and percentage of time spent working at height may be an influencing factor in usage frequency.

In general, there was a strong positive correlation and statistical significance found between the employers providing tethered tools and use of tools, as well as frequency of use (Table 2).

Table 2: Results of the correlation analysis for tethered tools usage and other work conditions
*indicates strong statistical significance (p<0.05)

** indicates marginal statistical significance (0.05≥ *p* ≤0.10)

	Use TT	Freq.	Provide w/TT	Use tool bag	Drop tool prob.	Have dropped	Teth. to self	Teth. to struct	Vest	Tool belt	Back Pack	Bucket
Freq.	0.64**											
Provided w TT	0.70 **	0.48**										
Use tool bag/bucket	0.08	-0.05	-0.10									
Drop is problem industry	0.16	0.10	0.16	0.05								
Dropped tool teth. to: self	0.35 **	0.22*	0.29**	-0.06	0.21*							
Dropped tool teth. to: struc	0.28**	0.34**	0.26**	-0.22*	0.04	-0.22						
Wear vest	0.20*	0.35**	0.09	0.12	0.02	0.12	0.04	0.42**				
Wear tool belt	0.27**	0.43**	0.21*	0.09	-0.07	-0.01	0.15	0.27**	0.20			
Wear back pack	0.29 **	0.30**	0.18	-0.05	0.05	0.23*	-0.01	0.26*	0.57**	0.09		
Wear bucket	-0.08	-0.13	-0.06	0.12	0.07	0.01	-0.31*	-0.03	-0.05	0.13	-0.02	
Wear other	0.17	0.15	-0.03	0.16	0.08	0.03	0.03*	-0.11	-0.15	0.01	-0.07	-0.03

Whether an employer provided tethered tools to their employee was a major factor in increased tethered tool usage. Amongst those who were provided with tethered tools, 87.9% were provided with them, while only 18.2% of those who did not use tethered tools were provided with them. A positive correlation is seen between those who are provided with tethered tools and the belief that dropping tools is a problem within their industry (Table 2), and a positive correlation that is statistically significant is seen between being provided with tethered tools and having a history of dropped tethered tools. This could suggest that employers recognize the link between employee drop history and the need to provide proper personal protective equipment (PPE).

Respondents were asked to identify how they carried their tools to their worksite, which tools were most commonly used while working at height, which tools were tethered, and which tools were not tethered but should be tethered. The least commonly worn tool carrying method was a tool belt (18.8%), while backpack (32.5%), bucket (31.3%), vest (28.8%) and other means (28.8%) of carrying tools were more common (Table 1). Other means included hand bags, tool pouches, a secured closed pouch with tethers and pant pockets. Positive and significant correlations are seen between using tethered tools and wearing a vest, tool belt and backpack, and negative correlation with using tethered tools and using a bucket. The same trend is seen regarding frequency of tethered tool use, with vest, tool belt and backpack showing positive and significant correlations, while the bucket shows a negative correlation.

Within those people who did not use tethered tools, 5 were in the WPI, and 17 were in the CG. Of that group, only two were not required to conduct maintenance at height: one was in a CG position where their job was administrative, and the other was a regional manager within the WPI. The remaining CG personnel who did not use tethered tools responded “yes” when asked if their position required them to conduct maintenance at height, while the remaining WPI employees were all wind technicians. None of the CG personnel who conducted work at height were provided with tethered tools. Of the 4 wind technicians, 2 of were provided with tethered tools, while the other 2 were not. The 2 technicians who were provided with tethered tools but did not use them answered that they wore buckets during their work, but did not wear any other means of carrying tools at height. This coincides with the results that bucket use is associated with not using tethered tools when conducting work at height.

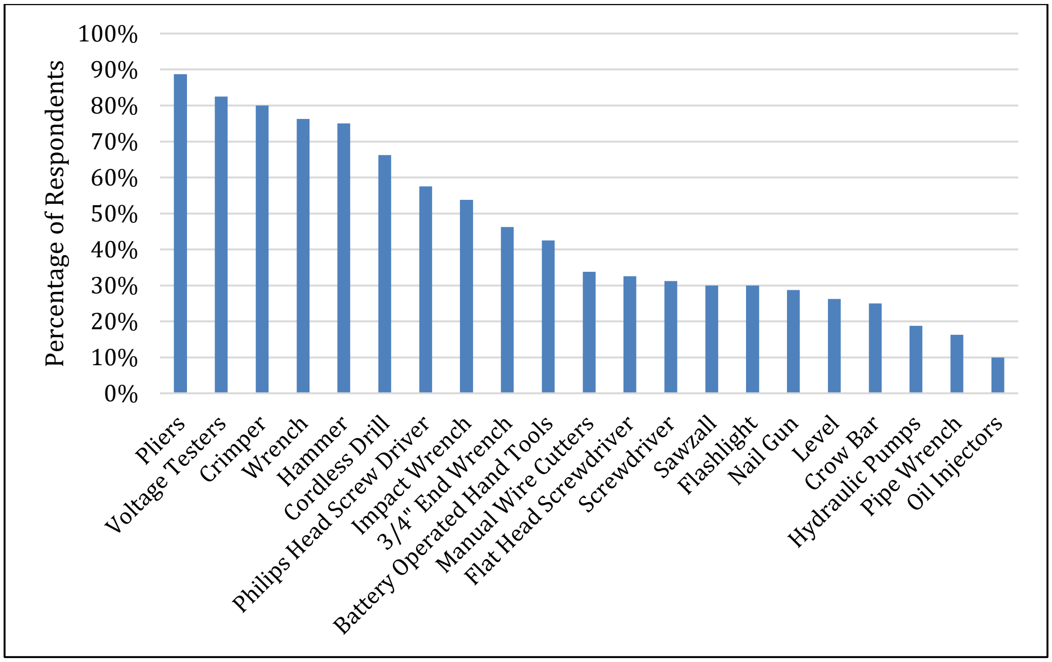


Figure 5: Most commonly used tools in the WPI and CG

Figure 5 represents the survey results with respect to most commonly used hand tools within both surveyed industries and the percentage of respondents who used them, while Figure 6 represents the which tools users believed should be tethered but were commonly not. All the tools shown in Figure 5 were also seen in Figure 6, indicating that many of the most frequently used hand tools were not tethered, but should be.

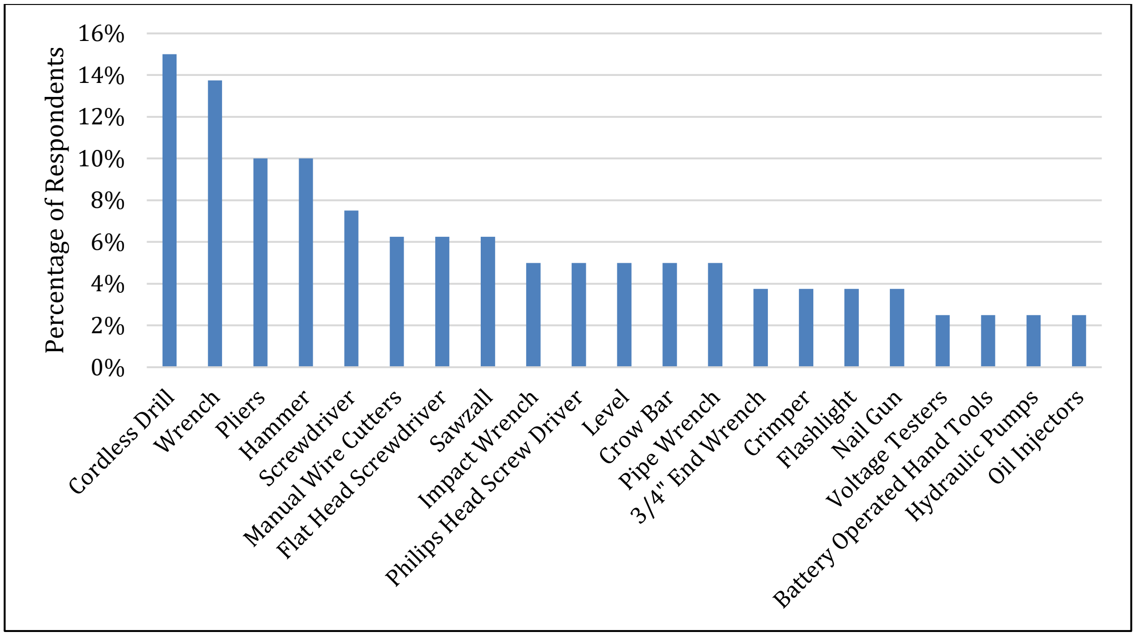


Figure 6: Tools WPI and CG respondents believe should be tethered

Table 3 provides further detail into the trends of tethered tool users by looking into percentages of responses within each question. For example, within 39 respondents who believe that dropping tools is a problem within their industry, 84.6% had dropped a tethered tool, and the most common means of carrying tools is a backpack (35.9%) or other (33.3%). Overall, the table provides data of the subcategories within each response to highlight the relationships between questions and answers.

Table 3: Sub-categorical responses amongst respondents who use tethered tools (in percent)

			Age 18-29	Age 30-39	Age 40-49	Provided w/ TT	Frequency of TT use			Use tool bag/ bucket	Problem of tool drop	History of tool drop	Dropped tool T to Self	Dropped tool T to Structure	Wear vest	Wear tool belt	Wear back pack	Wear bucket	Wear Other
							Some times	Usually	Always										
n=58	Use Tether Tools		34.5	51.7	13.8	87.9	46.6	24.1	29.3	96.6	67.2	84.5	27.6	19	32.8	24.1	39.7	27.6	29.3
n=20	Age 18-29					85	70	15	15	100	75	75	35	10	40	5	35	20	0
n=30	Age 30-39					90	43.3	20	36.7	93.3	66.7	93.3	23.3	26.7	30	26.7	43.3	33.3	26.7
n=8	Age 40-49					87.5	0	62.5	37.5	100	50	75	25	12.5	12.5	50	25	12.5	37.5
n=51	Provided Tethered Tools						47.1	23.5	29.4	98	66.7	84.3	29.4	19.6	33.3	25.5	95.2	27.5	25.5
n=27	Use TT	Some times								100	70.4	85.2	25.9	11.1	25.9	11.1	33.3	29.6	25.9
n=14	Use TT	Usually								92.9	57.1	78.6	7.1	14.3	21.4	21.4	42.9	35.7	28.6
n=17	Use TT	Always								94.1	70.6	47.1	88.2	35.3	47.1	47.1	41.2	17.6	35.3
n=56	Use a tool bag/bucket										67.9	83.9	26.8	17.9	33.9	25	37.5	26.8	30.4
n=39	Believe dropping tools is a prob.											84.6	28.2	17.9	28.2	20.5	35.9	25.6	33.3
n=49	Have dropped a tool												24.5	20.4	32.7	22.4	42.9	30.6	30.6
n=16	Dropped a tool T to self													31.3	31.3	31.3	31.3	6.3	37.5
n=11	Dropped a T tethered to														63.6	45.5	54.5	27.3	18.2
n=19	Wear a vest															31.6	68.4	26.3	15.8
n=14	Wear a tool belt																28.6	35.7	21.4
n=23	Wear a back pack																	26.1	21.7
n=16	Wear a bucket																		12.5

4. Discussion

To date, no studies have looked into tethered tool usage trends, user drop history and tool carrying methods. A majority of available statistics represents the construction industry, but little to no data is available regarding damage, injury or death caused by dropped objects in the WPI and the military. The results of this survey allowed identification of tethered tool usage patterns, tool carrying methods, and types of tools used in the field. This is an imperative first step in identifying how to increase tethered tool use in industry, and what factors encourage or hinder their usage, to ultimately decrease the likelihood of accidents or injuries in the field due to the tool drop.

Understanding why accidents occur is a fundamental first step towards mitigating them. A 2005 study into OSHA data between 1997 to 2000 revealed that misjudgment was the most common human factor contributing to "struck-by" accidents, contributing to 35.8% of the studied cases (Hinze, et al., 2005). Respondents in this study believed that tool dropping while at work was a common problem, and the majority of the respondents have dropped a tool while working. WPI personnel had a larger proportion of respondents who believed that dropping a tool is a problem within their industry, possibly because their work is conducted at greater heights and more of their time is spent at height than those in the Coast Guard.

It is also notable that those participants who did not use tethered tools had different tool drop history than tethered tool users. 50% of the respondents who do not use tethered tools reported incidences of dropping a tool. Of the tethered tool users, 84.5% reported that they have dropped a tool, and over half of the time the tool was tethered. This could explain the positive correlation and significance seen between dropping a tethered tool (tethered to structure or tethered to oneself) and having dropped a tool while working at height in general. Tethered tool users also showed slightly higher average rating of likelihood of injury that may indicate that they tend to be more cautious regarding potential injury, and have a greater understanding of the benefits tethering plays in preventing loss of time, injury, equipment damage, loss of productivity, or other consequences of not using a tether while working at heights.

A majority of the respondents used tethered tools, but did not do so all the time. The frequency of usage ranged from sometimes (46.6%), usually (24.1%) and always (29.3%). As identified earlier, 7% of those who were provided with tethered tools did not use them and explained that choice as a result of dislike. Perhaps a reason for infrequent use or preference in using tethered tools is due to comfort or difference in usability. For example, tethers may induce extra effort while reaching, create a loop that may snag or catch on surrounding areas, restrict maneuverability, limit reach or cause other nuisances to the user.

Haslam, et al., 2005, found that usability and safety of PPE is not typically a factor that employers consider when making purchases, and that the primary focus is on price and performance. A majority of the respondents in the study agreed that much of the PPE found in use on construction sites were uncomfortable and interfered with the user's ability to conduct work (Haslam, et al., 2005). Design flaws, discomfort or interference may have been a reason that respondents did not always tethered tools, indicating that perhaps there is a disconnect between tethered tool usability and user preference should be reevaluated.

When an employer makes gear and PPE available and accessible it increases the likelihood of use of that equipment (Lombardi, et al., 2009). A strong positive correlation between the use of tethered tools with frequency of use and being provided with tethered tools by the employer is seen in the results of this study. When provided with tethered tools, a majority of the survey participants (87.9%) used them. Subjects identified that the most commonly used hand tools were also in need of being tethered. In fatal accidents caused by falls from height, most cases were caused by the employer not provided safety equipment such as belts/harnesses (Chi et al., 2005), and although this is not a study in safety harnesses, the same logic applies to dropping tethered tools and the need for employers to identify the PPE necessary to create a safe working environment.

The same could be said for the methods by which the subjects carried tethered tools to their work sites. Overall a tool belt was the least common method of carrying tools (18.8%), while a backpack (32.5%), bucket (31.3%), vest (28.8%) and other means (28.8%) of carrying tools were more common. Regarding tethered tool usage, a negative correlation is seen between wearing a bucket and using tethered tools (-0.08), while the other means of carrying tools and the usage of tethered tools show positive correlations. Although the backpack was slightly more commonly used to transport tools to a work site, wearing a bucket accounted for 31.3% of how subjects work at their worksite. While wearing a bucket, the likelihood of using tethered tools is reduced since buckets commonly carry loose tools. Employers must be aware of this and encourage alternate tool transportation means that allow for tethered tool usage, such as vests, tool-belts, and back packs that have the capability of being designed with tethering points, and have positive correlation to tethered tool use.

The prevalent use of tool buckets is due to convenience, availability and low cost, however this is the most dangerous means of carrying tools, since tools are loosely placed in them and are not tethered. Buckets also pose the greatest risk of dropping an unsecured tool. Research shows that improving PPE accessibility, availability, affordability and improving comfort and fit are necessary factors concerning PPE usage (Lombardi, et al., 2009).

Employers and tool designers must also recognize which tools are most commonly used by workers at height, and subsequently which tools should be tethered. Survey respondents indicated that the most frequently used hand tools are not commonly tethered but should be. For example, the top five tools that are not commonly tethered but respondents thought should be are the wrench, cordless drill, screwdriver, hammer and pliers. These tools are also listed at the most frequently used hand tools in general. Identifying tethering points to facilitate comfort and ease of work without causing interference to the worker are considerations in tool design to encourage usage and not hinder productivity. In addition, developing appropriate tether attachment points on commonly worn tool-carrying methods, such as vests, backpacks and tool belts is another consideration in tethered tool design. Without an appropriate means of tethering tools, frequency of usage may be reduced.

A potential reason that the in-field frequency of tethered tool usage is unmonitored and not statistically represented may be due a lack of regulatory mandate. OSHA regulations primarily focus on body harnesses (Choi, 2006), but existing regulatory standards for tool use are vague regarding tool usage at height. For example, OSHA's steel erection falling protection regulation, 29 CFR 1926.759 (a), states: "all materials, equipment, and tools, which are not in use while aloft, shall be secured against accidental displacement." This regulation acknowledges the importance of securing idle loose items, but neglects the need for securing tools while in use, where slips, misuse or other general accidents could occur. Securing tools is mandated to prevent them from accidental displacement, but the method of securing tools and industry standards are not provided. Methods differ, and the safety or reliability of these methods may also differ, which may or may not increase safety. Once accident prevention methods are determined, regulatory officials and industry leaders must be involved in the process to ensure regulatory implementation (Hinze, et al., 2005). In general, there is no industry standard on the methodology of securing tools while working at height.

Further research into tethered tool usage trends could potentially unearth many aspects of what factors encourage or discourage tethered tool usage in the field. To date no study considered the impact of using tethered tools on safety in comparison to using untethered tools while at height. Future research may aim to investigate reasons into what personnel who work at height look for in tethered tools, what carrying means would be most appropriate and how design could be improved to benefit the user. The outcome of this study may only reflect user opinions from the WPI and CG, and may not represent other industries that frequently conduct work at height. Nevertheless, this study provides a necessary first step in identifying trends within tethered tool usage with an overall aim of contributing to the prevention and eradication of the consequences caused by dropping tools from height.

It is recommended that tool designers identify means of creating tethered tools and appropriate carrying apparatuses for work at height. Industry leaders and regulators must publish statistical data regarding the potential injuries or damage caused by dropping of tools within the WPI, since that information is currently lacking. Ultimately, regulatory development on tethered tool standards should be developed to increase usage in the field.

Chapter III

Study 2: Biomechanical evaluation of tethered hand tools during hammering and wrenching tasks

1. Introduction

Struck-by falling objects is one of the leading causes of death and injury in construction sites, accounting for 8.4% of fatal injuries (OSHA, 2015). A 2013 Liberty Mutual study reported struck by object or equipment ranked as the third most common workplace injury, resulting in $5.31 billion, or 8.6 percent of the injury cost burden of worker compensation that year (Liberty Mutual, 2016). In year 2014, out of 4,251 worker fatalities in private industry, 20.5% were in construction, and struck-by object accounted for 8.4% of those deaths (OSHA, 2016). Although debilitating, many of these incident can be avoided. For example, construction accidents often occur through bad equipment selection, misuse, or lack of inspection (Pinto, et al., 2015), which with proper attention can be avoided, especially concerning dropped objects from an at-height work environment.

It is believed these injuries and deaths are preventable by eliminating the potential of dropping loose objects and tools through using a tethering system while conducting work at height (Salentine, 2011). Therefore, introducing tethers and their proper usage into the work place could result in a decrease of death and injury caused by struck-by objects.

Much research has been conducted on fall prevention of the human body, with emphasis on worker body harnessing and body harness lanyard integrity. For example, the study 'Dynamic strength test for low elongation lanyards', (Baszcynski, 2007) tests and compares the performance of low elongation lanyards to traditionally used lanyards, but does so with the simulation of a human body fall, not tool fall, in mind.

Claims speaking to overall efficiency or tether interference with a task do exist, but the lack of scientific information and data provide little credibility to those claims, which is necessary to implement ergonomic tool or tether re-design. In a NASA conducted study aimed at providing their casting pit personnel with a method to tether sockets and wrenches to ratchets that were already tethered to the user, results show that the crows foot wrench's tether was awkward to properly use (Johnson, 1990). These finding indicate tethering could cause inconvenience and discomfort while conducting a task, and explain why users may have a general aversion to tethered tool use.

Another possible reason that users may not prefer using tethered tools is due to tether properties, such as creating a loop that may snag or catch on surrounding areas, increasing restriction of maneuverability, limiting reach, or cause other nuisances to the user. Identifying the biomechanical impact of tethered tools during work may be an effective strategy at increasing the use of tethers in the workplace and to reduce the damage, lost time, injury and death potential caused by a dropped tool.

Furthermore, our latest survey of the Wind Power Industry and US Coast Guard workers revealed that the majority of those surveyed (72.5%) used tethered tools as a general practice, while 27.5% of respondents did not. The most important factor influencing tethered tool usage was whether an employer provided them. In fact, 88% of tethered tool users are provided with them by their employer. Of those who were not tethered tool users, only 18.2% were provided with tethered tools by their employer.

To date no study has considered the biomechanical impacts of using tethered tools in comparison to their untethered counterparts, including how tethers interfere with time spent on a task and user preference. The purpose of this study was to investigate and quantify the impact of tethering two of the most commonly used hand tools, hammers and wrenches, on the user while working on the ground or at elevation. Specifically, the analysis considers the impacts of tether, reach position, and work height on muscle activity, time on task, hand grip pressure and user-defined preference. Changes in biomechanical markers and user perceptions between tethered tool use and untethered tool use for each of the scenarios tested were quantified and compared. To date no study has considered the biomechanical impacts of using tethered tools in comparison to their untethered counterparts, including how tethers interfere with time spent on a task and user preference.

The first research question considers the biomechanical impact of tethering a hammer while the subject is required to complete a hammering task in four different reach conditions on the ground and while on the ladder:

H1: Tether will not affect muscle activity, grip pressure and time on task during hammering at different heights or reach conditions.

a. Ladder condition will not impact muscle activity, grip pressure and time on task during hammering.
b. Reach will impact muscle activity and grip pressure, but not the time on task during hammering.

The second research question considers the biomechanical impact of tethering a wrench while the subject is required to complete a wrenching task in four different reach conditions on the ground and while on the ladder:

H2: Tether will not affect muscle activity, grip pressure and time on task during wrenching at different heights or reach conditions.

a. Ladder condition will not impact muscle activity, grip pressure and time on task during wrenching.
b. Reach will impact muscle activity and grip pressure, but not the time on task during wrenching.

The third research question considers participant's subjective opinion on tethered tool usage after completion of each experimental condition:

H3: Subjects will not have a preference between tethered or untethered tool usages.

2. Materials and Methods

2.1 Subjects

In this study, approved by the University of Wisconsin-Milwaukee Institutional Review Board (Protocol #: 16.151), twelve right handed males volunteered to participate in the hammering and wrenching tasks. The participants ranged between 21 to 47 years of age with averages of 29.7±7.1 years, 71.0" ±2.2" tall, and 58.3" ±2.4" shoulder height. All subjects were right handed, familiar with using a wrench and hammer and were equipped with eye protection before the trial.

2.2 Experimental Design and Equipment

Before the experiment, wireless surface electromyography sensors (Delsys Trigno) were placed on the subject's right Pectoralis Major (rPM), left and right Trapezius (lTr and rTr), right Biceps Brachii (rBB), right Triceps Brachi (rTB), right Deltoid (rDel), and right Latissimus Dorsi (rLD) (Figure 7). Prior to placement, skin was cleaned with rubbing alcohol and upon placement the EMG sensors were additionally secured with tape. EMG data was collected with the EMGworks 4.0 Acquisition software (Delsys, MA) at 2,000 Hz and processed in EMGworks 4.0 Analysis software (Delsys, MA). The sEMG sensors have an analog bandpass filter of 20Hz to 450Hz and were additionally filtered with a bandstop filter of 58Hz to 62Hz. The smoothing technique of calculating the root mean square (RMS) was used on the filtered data. A window of 0.125 seconds and a window overlap of 0.0625 were used in the RMS calculation.

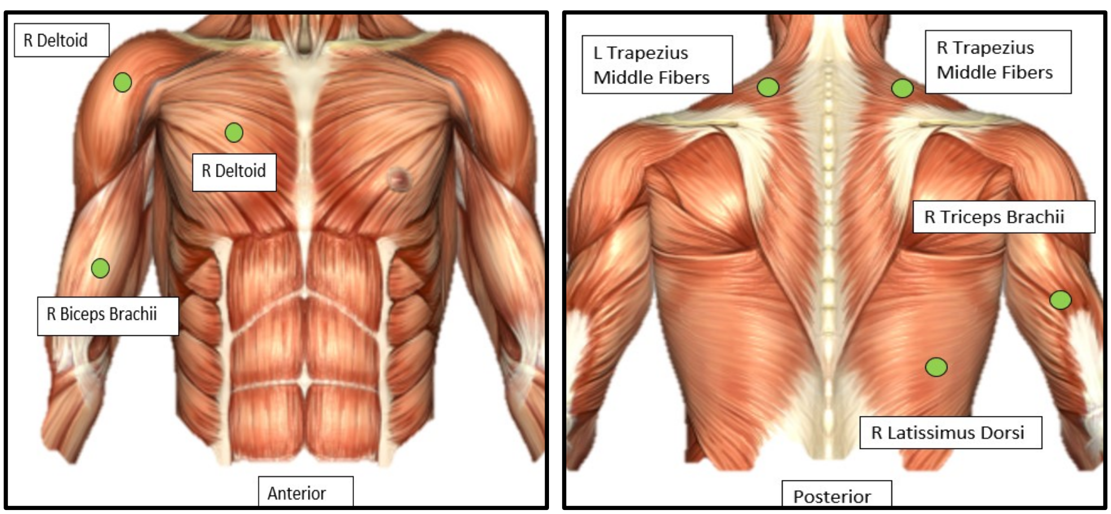


Figure 7: EMG placement on body

Grip pressure was collected using a pressure mapping glove (Vista Medical, CA) which was calibrated to 100 psi according to the manufacture's guidelines. The grip pressure glove was placed on the subject's right hand. Twenty-four individual sensors were attached externally and were distributed across the fingers and palm as shown in Figure 8. An identical template for the sensor configuration was used that was consistent between all trials and subjects. The data was continuously acquired using FSA 4.1, software at a frequency of 5 Hz from the beginning to the end of each trial.

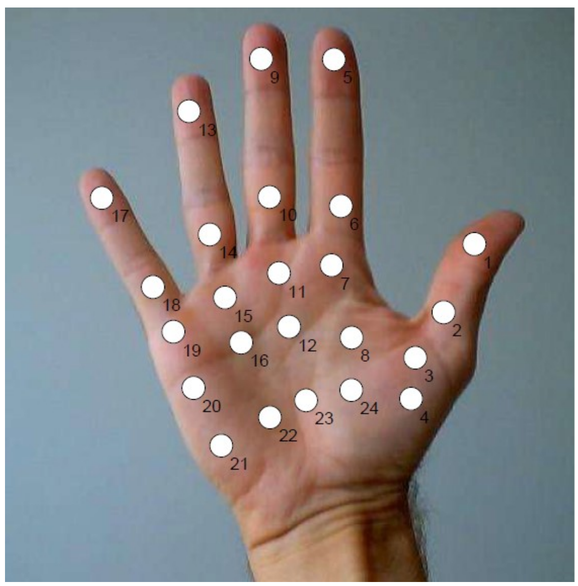


Figure 8: Grip pressure sensor placement on hand

Each participant completed sixteen different scenarios of the hammering and sixteen of the wrenching tasks depicted in Figure 9. Up to three trials were conducted per each scenario/tool, totaling between 64 and 96 trials per subject. If two trials per condition were sufficient, no third trial was conducted. Sufficiency was determined by visual inspection upon the completion of the task and the data.

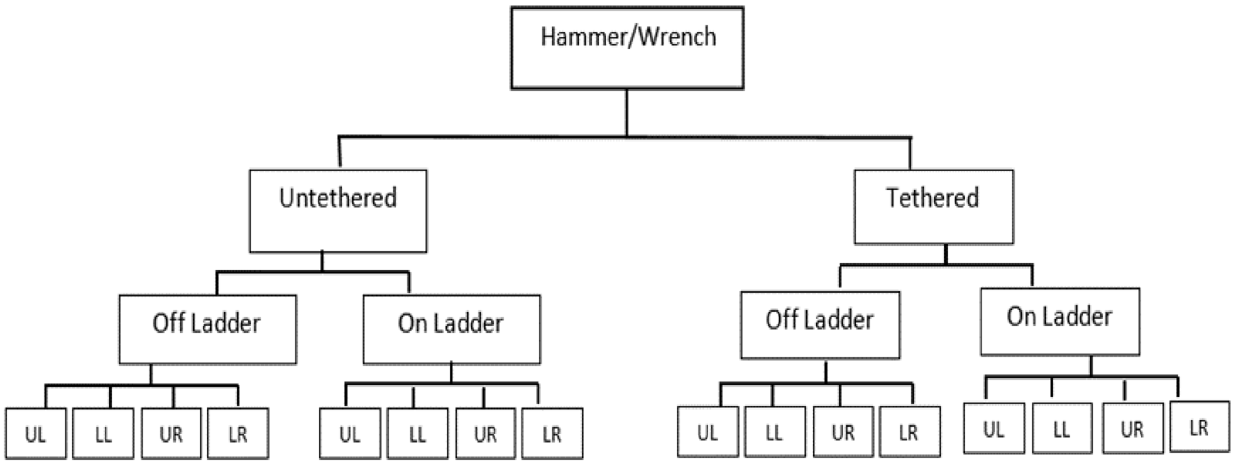


Figure 9: Diagram of experimental design

A standard hammer and crescent wrench were used, with a metal ring attached to the bottom of their handles for tether connection (Figure 10). A tethered tool belt was worn around the subjects' waist, with the tether located on the left side of the belt due to belt design. The same tools were used for both tethering conditions, with the difference that in case of the tethered tool testing a retractable tether line was attached to the tool belt and to the tool itself.

Figure 10: Hammer and wrench used during experiment. Metal ring is where tether would attach and reattach between trials

Subjects used the tethered and untethered tools at two different heights – on the ground (off ladder) and at 8" inches off the ground (on ladder), at four different reach positions: upper left (UL), lower left (LL), upper right (UR), lower right (LR) (Figure 11). The ladder used was a fold out stepping stool to simulate elevation without introducing the risk of falling if a subject were to lose balance or needed to step down for any reason.

The hammering task was conducted on a custom built plywood board with two tracks where interchangeable wood blocks (length= $3\frac{1}{2}$", width=4", thickness= 2") were used for each subject to complete the task in the four different reach positions as depicted in Figure 11. The two tracks were 12 inches apart, so that the subject conducted hammering at shoulder level, and at a higher reach. The board was always adjusted so that the lower track was at the subject's shoulder height regardless of whether they were standing on the ground or the step ladder. Each block had pre-drilled pilot holes of 0.5 inch to facilitate the task and reduce strain on the subject, while using a $2\frac{1}{8}$" nail, which ensured the nail penetrated straight and all the way through the wood block while leaving no space between the nail head and wood. Upon each use at one reach position, the block was discarded and a new wooden block was used at next reach position.

Subjects were asked to stand facing the center of the board while on the ground, and the ladder was placed at the center of the board during the ladder condition. After blocks at each reach were hammered twice, or up to three times (if the second trial was not sufficiently completed), the subjects were given a short questionnaire regarding their preference of the tethered or untethered hammer.

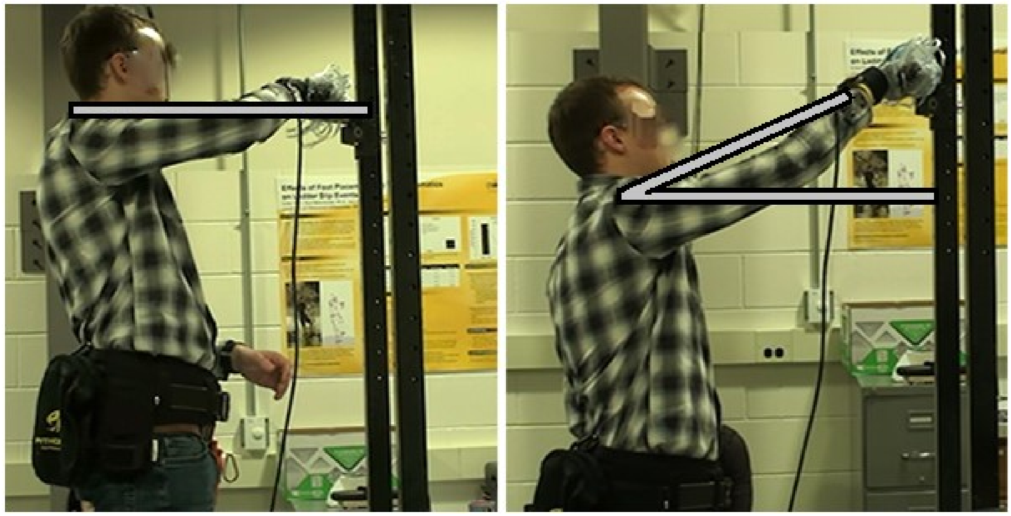
Figure 11: Hammering board setup with four reach positions

The same experimental procedure was followed in the case of wrenching. A custom structure for the wrenching task was designed (Figure 6) to allow loosening of a bolt, tightened at 30 ft-lbs, in four different reach positions.

Figure 12: Wrenching structure with adjustable wrenching piece

An adjustable wrenching piece (Figure 12) was moved to shoulder height to simulate the two lower reaches (LL, LR) and was adjusted to approximately 30 degrees from shoulder height to simulate the upper reaches (Figure 13). Only loosening of the bolt was conducted due to the lack of ability to control tightening. After the bolt was loosened at each position, subjects were given a short questionnaire regarding the tool preference and ease of use.

Grip pressure, muscle activity, and time spent on task were continuously recorded during each trial. The user preference of the tethered versus untethered tool was also assessed at the end of each trial.



(A) (B)

Figure 13: Subject performing wrenching task at two different reach positions
(A) Lower reach (B) Upper reach

3. Analysis

3.1 Muscle Activity Analysis

A five second standing baseline was taken for each subject, and the standing baseline RMS of each muscle was averaged. These values were used to normalize subject muscle activity during each task condition. The average normalized RMS was calculated for each muscle for the duration of the task, then the values for each condition for all the subjects were averaged to obtain overall means and standard deviations for each muscle, used to compare muscle activity between different tool conditions.

Ratios of tethered over untethered (T/UT) muscle activity were calculated to depict how the tethered tools affected muscle activity in comparison to untethered tools. Ratios between 0.90 and 1.10 were considered to be close to 1, indicating no major affect on muscle activity was caused by tethering. The ratio was calculated as follows (Equation 1):

$$Ratio_{RMS} = \frac{T_{ijk}}{UT_{ijk}} \tag{1}$$

Where:
T= Tethered tool average normalized RMS
UT= Untethered tool average normalized RMS
i= subject
j= reach condition (LL, LR, UL, UR)
k= ladder condition (off ladder, on ladder)
RMS= average normalized RMS

3.2 Grip Pressure

Hand grip pressure (HGP) was quantified by averaging the sum of each individual sensor for the duration of the trial (Equation 2):

$$Average_{HGP} = \sum_{n=1}^{24} \frac{(t\ s1) + (t\ s2) + \cdots .(t\ \mathrm{sn})}{\mathrm{n}} \tag{2}$$

Where:
t= total pressure
s= sensor
n= total number of sensors

In order to compare hand grip pressure difference between different tool conditions, the ratio of average HGP was calculated as follows (Formula 3):

$$Ratio_{HGP} = \frac{T_{ijk}}{UT_{ijk}} \tag{3}$$

Where:
T= Tethered tool average normalized RMS
UT= Untethered tool average normalized RMS
i= subject
j= reach condition (LL, LR, UL, UR)
k= ladder condition (off ladder, on ladder)
HGP= grip pressure

3.3 Task Time

Task time (TT) was determined by the total amount of time in second it took the subject to complete a task. Any trials with delays due to errors in data collection, such as equipment adjustment or a faulty trial (slipping of the wrench during wrenching, missing a nail when swinging the hammer), were disregarded and not included in the analysis. In order to compare task time difference between different tool conditions, the ratio of average total task time was calculated as follows (Equation 4):

$$Ratio_{TT} = \frac{T_{ijk}}{UT_{ijk}} \tag{4}$$

Where:
T= Tethered tool average normalized RMS
UT= Untethered tool average normalized RMS
i= subject
j= reach condition (LL, LR, UL, UR)
k= ladder condition (off ladder, on ladder)
TT= task time

3.4 User Preference

After completion of each condition, each subject was asked the following question: "Did you prefer the tethered tool, untethered tool, or did you have no preference?"
After every answer the subject was encouraged to explain their answer and suggest ways the task could have been improved. Responses also included reasons why they preferred the tethered, untethered or had no preference for each condition. Common answers to why tether was not preferred were because it pulled on the tool, interfered with natural range of motion or because they were not accustomed how it felt. Some instances where subjects preferred the tether was because they felt that it corrected the swing of the hammer, or felt more secure

during their task. Each response was recorded on the data collection sheet, as well as any additional opinions or feedback on the differences or their preferences.

3.5 Statistical Analysis

These calculated values were used in a general linear model ANOVA statistical analysis of wrenching and hammering activities at the previously discussed conditions. The factor of subject was blocked to control subject variability. The significance of Tether condition (tethered v/s untethered), ladder condition (off ladder v/s on ladder), reach condition (LL, LR, RL, UR) and their interactions were tested in an ANOVA at a 95% confidence limit. When statistical significance was observed within a factor, a post hoc Tukey test was conducted, to determine which factor levels were significantly different. When a statistically significant interaction was observed within the ANOVA results, an interaction plot was generated to graphically explore the levels at which the interaction occurred. A power of 0.91 was calculated using G*Power 3.1.9.2 (Germany, 2014).

With regards to user tool condition preference, the McNemar's test was applied to assess whether a statistically significant change in proportions occurred between the matched pairs of "no preference" and "untethered preference", and, "no preference" and "tethered preference". McNemar's test results were calculated using Minitab 16 (2016, USA).

4. Results

4.1 Muscle Activity

4.1.1 Hammering

Ratios were calculated between the average RMS of tethered muscle activity for each condition over the average RMS of tethered muscle activity (Table 4) to depict how the tethered hammer affected muscle activity in comparison to the untethered hammer. Ratios between 0.90 and 1.10 were considered to be close to 1, indicating no major affect on muscle activity was caused by tethering. ANOVA results (Table 5) show the use of a tether resulted in no statistically significant impact on muscle activity. None of the factors or their interactions statistically affected the rBB. Ladder condition affected the rLD, and reach was statistically significant within five of the seven studied muscles.

Table 4 displays that the LL reach off ladder showed an increase in muscle activity during tethered activity for the rTr, while the remainder of the muscles showed approximately the same exertion between tethered and untethered activity. On the ladder, the LL reach also showed that tethering increased muscle activity by 29%, however the large standard deviation of 0.54 could be contributed to the increased ratio. Within individual subject results, subjects exhibited T/UT ratios ranging between 0.47 to 2.26, which accounts for a large variation within individual subject activity.

The LR reach off ladder showed tethered hammering increased muscle activity in the rBB by 12% and rDel by 11% and the rLD by 10%. The remainder of the muscles showed ratios of approximately 1. On the ladder, the LR reach displayed ratios of approximately 1 across all muscles.

The UL reach off ladder showed ratios of approximately 1 across all muscles, and a slight decrease of 8% during tethered hammering in the rBB. The UR off ladder reach showed an increased ratio in the rLD. The UL reach on ladder displayed a ratio of 1.18, or an increase of

18% during tethered hammering in the rTB. Two subjects exhibited T/UT ratios below 1, while the rest showed ratios ranging from 1.08 to 1.97.

The UR reach while on the ladder resulted in greater muscle activity within most muscles in comparison to off ladder. Interestingly, the tethered hammer impacted the rLD the most in the UR reach compared to other reaches, both on and off the ladder. Although statistically insignificant, both cases show that at least half the subjects exerted greater muscle activity during tethered hammering in comparison to untethered hammering, with overall ratios ranging between 0.96 and 1.43 within the UR reach.

Table 4: Average ratios of T/UT (SD) during hammering

Avg. T/UT Off	rPM	SD	lTr	SD	rTr	SD	rBB	SD	rTB	SD	rDel	SD	rLD	SD
LL	1.04	0.20	1.07	0.20	1.11	0.19	0.94	0.31	0.96	0.17	0.96	0.36	0.94	0.16
LR	1.01	0.22	0.99	0.09	1.01	0.12	1.12	0.31	1.07	0.17	1.11	0.27	1.10	0.37
UL	1.00	0.15	0.99	0.21	1.00	0.16	0.92	0.26	0.97	0.20	1.03	0.27	1.04	0.13
UR	1.06	0.34	1.09	0.19	0.99	0.16	0.92	0.44	0.98	0.16	1.01	0.17	1.13	0.57
Avg. T/UT On	rPM	SD	lTr	SD	rTr	SD	rBB	SD	rTB	SD	rDel	SD	rLD	SD
LL	1.09	0.34	0.98	0.19	1.29	0.54	1.07	0.39	1.12	0.28	1.32	0.57	1.04	012
LR	1.01	0.22	0.99	0.16	0.93	0.22	1.05	0.29	1.04	0.22	1.05	0.38	0.93	0.22
UL	1.05	0.44	0.93	0.17	1.07	0.26	1.06	0.27	1.24	0.17	1.07	0.40	1.16	0.51
UR	1.03	0.19	0.91	0.14	1.12	0.21	1.04	0.32	1.13	0.16	1.08	0.21	1.15	0.22

The general linear model ANOVA revealed that reach significantly affected muscle activity in all muscles except for rBB and rLD, however no significant difference was shown between tethered and untethered muscle activity. Ladder condition only showed significant effect on muscle activity for the rLD while hammering. Tethering had insignificant affect (p>0.05) across all muscles in all reach and ladder conditions.

Table 5: Results of General Linear Regression ANOVA for muscle activity during hammering task

* indicates significance (*p*<0.05)

Muscles	rPM	lTr	rTr	rTB	rBB	rDel	rLD
Factors	*p-values*						
UT or T	0.179	257	0.521	0.946	0.369	0.930	0.307
Reach	0.001*	0.020	0.001*	0.014*	0.730	0.001*	0.222
Ladder	0.713	0.341	0.443	0.473	0.229	0.227	0.024*
Reach*Ladder	0.892	0.509	0.656	0.841	0.909	0.246	0.201
Reach * UTorT	0.938	0.854	0.647	0.948	0.700	0.666	0.597
Ladder*UTorT	0.505	0.170	0.908	0.807	0.419	0.618	0.938
Ladder*Reach*UTorT	0.767	0.469	0.984	0.791	0.569	0.387	0.938

Figure 14 demonstrates averaged normalized muscle activity for rPM during the hammering task. The analysis revealed significant (p<0.05) difference between UL and LR, and UL and UR reaches off ladder, however within these reaches, tethered and untethered activity was approximately the same. This indicates that tethering was not a factor in muscle exertion, but that the LR reach required the rPM to work more. The same results were seen on the ladder, with statistical significance between LR and UL reaches (*p*<0.05), but within tethered and untethered activity, the LR reach showed a 1% increase when using the tethered hammer and a 5% increase in the UL reach.

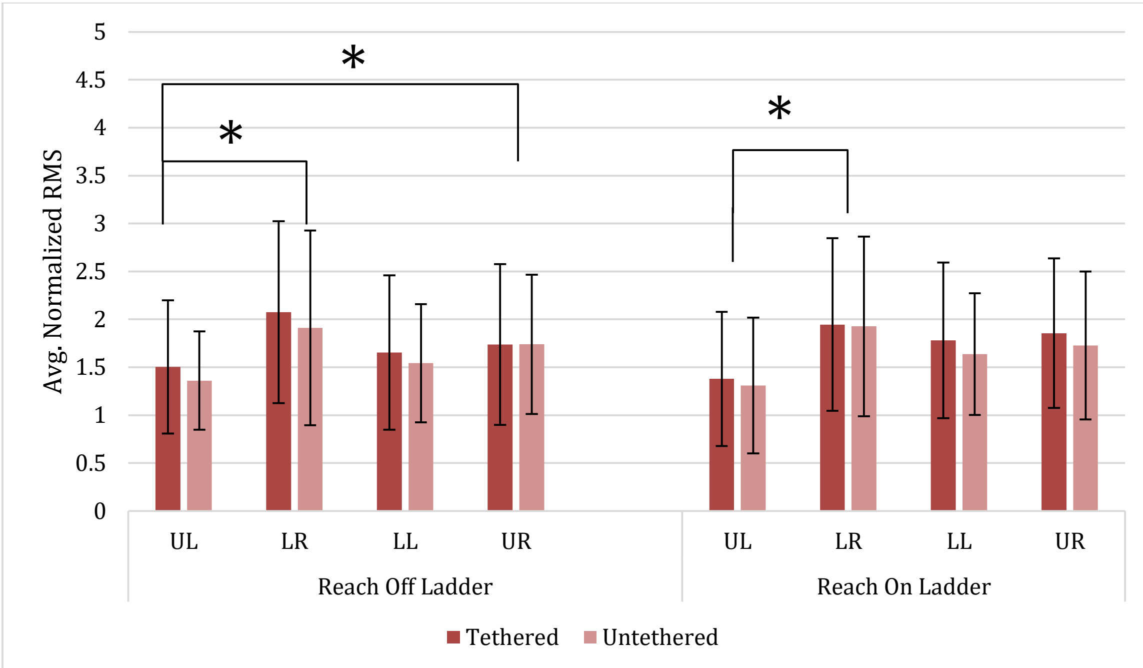


Figure 14: Average normalized muscle activity rPM hammering
* indicates significance (p<0.05)

Figure 15 shows that tethered and untethered muscle activity in the rPM followed the same trend between reaches on and off the ladder. Muscle activity during tethered hammering showed a slight increase of 4% off the ladder, and 9% on the ladder. In general, tethered and untethered muscle activity during hammering was approximately the same in the rPM.

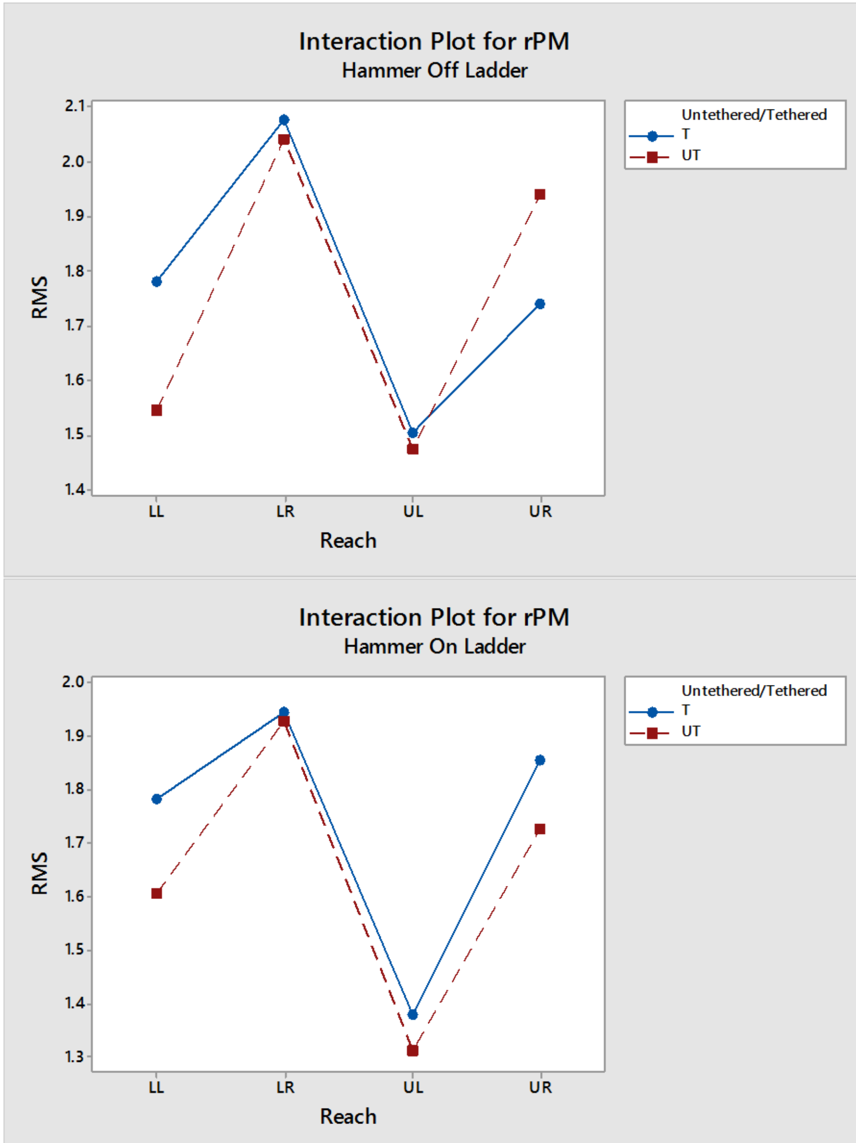


Figure 15: rPM interaction plot between reach and tethering off and on ladder

Figure 16 illustrates where reach was found to be statistically significant ($p<0.05$) in the lTR. Off the ladder, the UR reach was statistically different to the other three reaches, and on the ladder, the lTr showed statistically significant difference ($p<0.05$) between the UR and LL reach. Within ratios, tethering was shown to cause a slight reduction in muscle activity in the

UL and UR reach, or resulted in approximately the same muscle activity as untethered hammering.

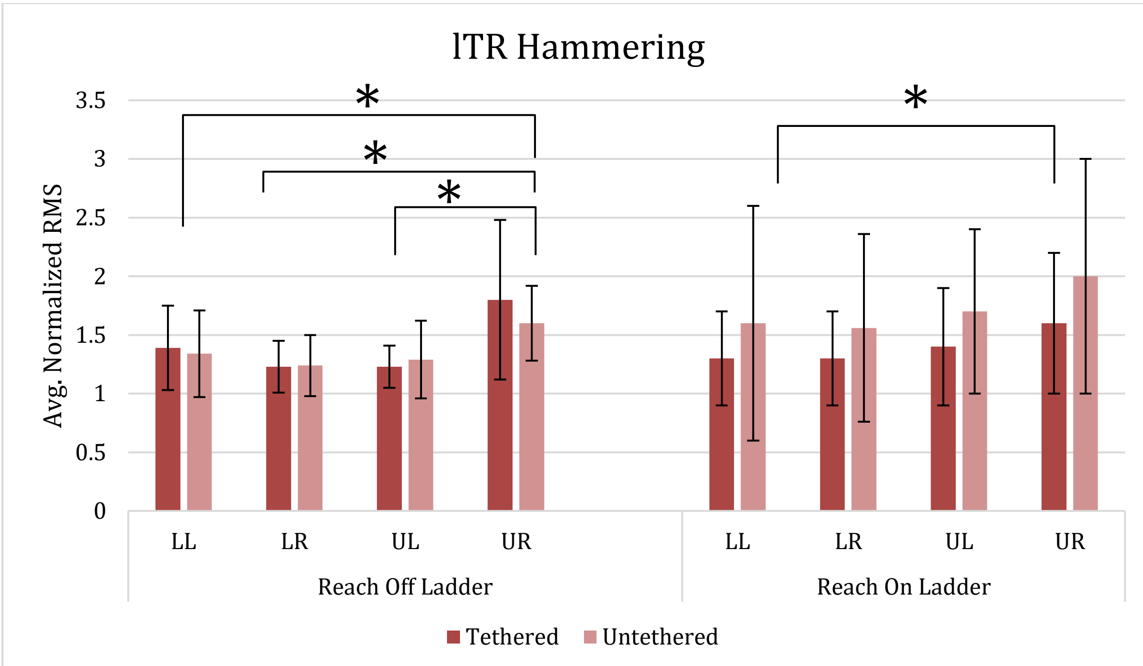


Figure 16: Average normalized muscle activity for lTr during hammering
* indicates significance ($p<0.05$)

The reductions are illustrated in Figure 17, which depicts that tethered and untethered muscle activity was similar between reaches while off the ladder However while on the ladder, the untethered muscle activity showed an increase in muscle activity. Additionally, untethered muscle activity shows large variation, which may have contributed to lack of statistical significance.

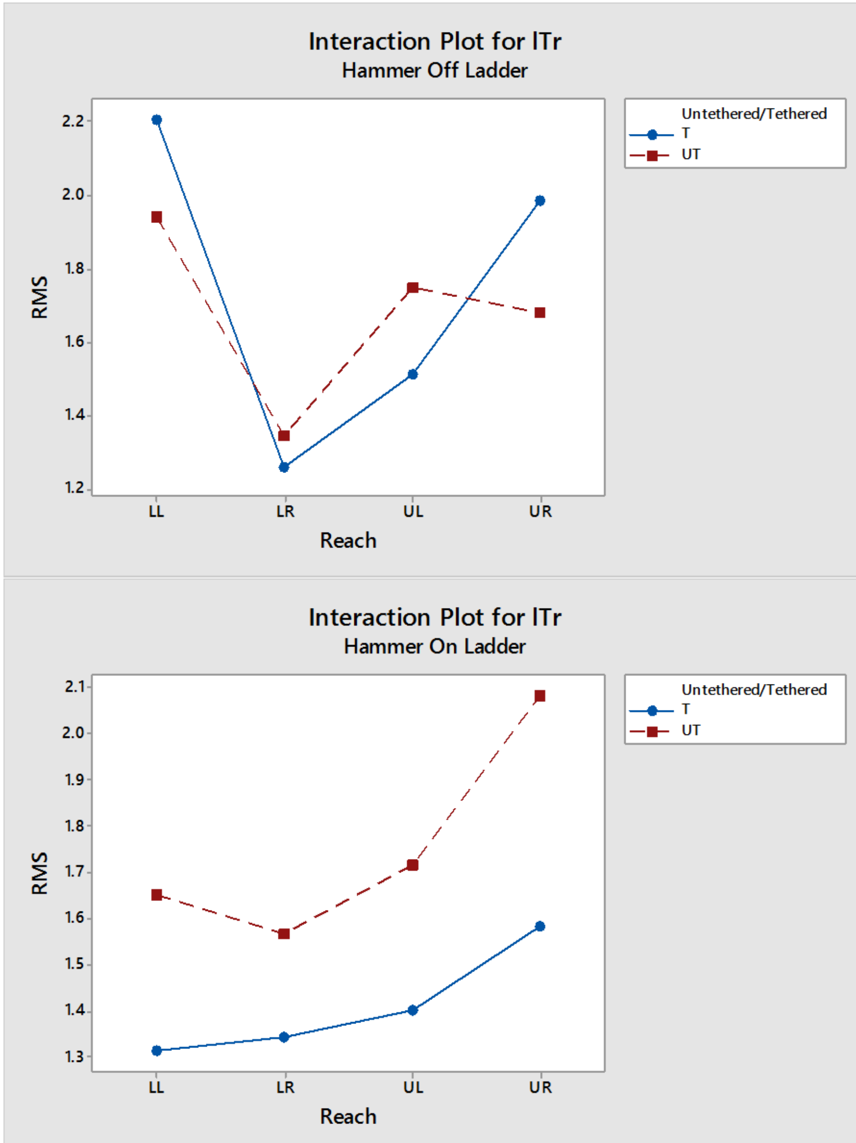


Figure 17: lTr interaction plot between reach and tethering off and on ladder

Figure 18 depicts the statistical significance (*p*<0.05) between rTr muscle activity between the LR and LL, UL and LR, and UR and LR reaches off the ladder. On the ladder, statistical significance was seen between the UL and UR, Lr and LL, UL and LR, and UL and LL reaches, essentially indicating that all the reaches resulted in the same muscle activity.

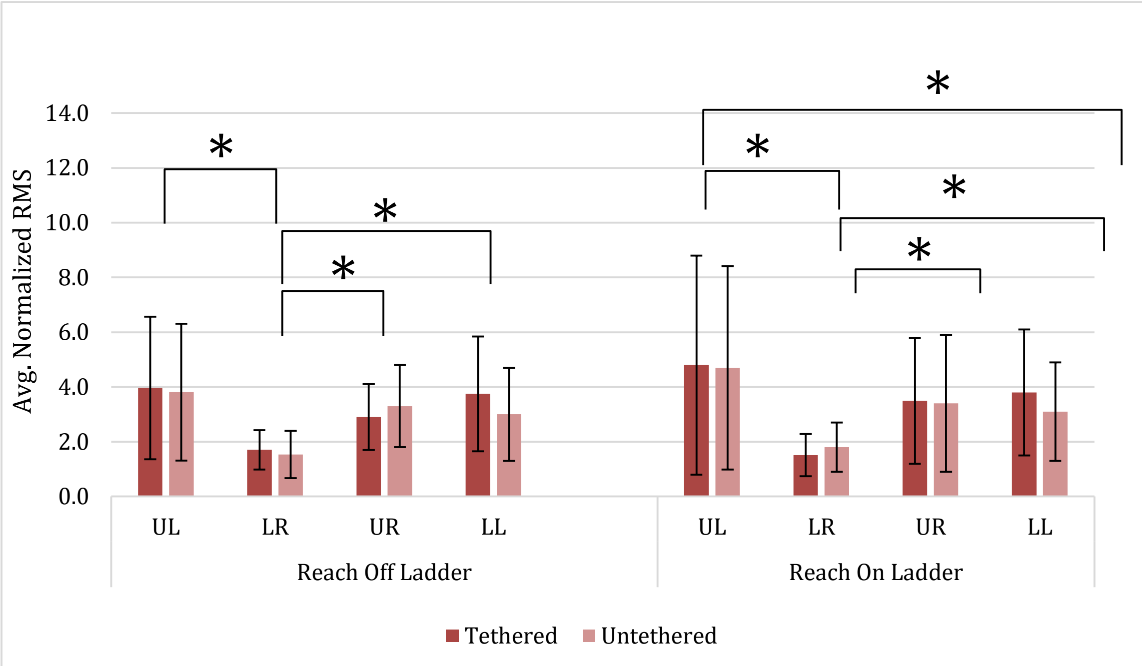


Figure 18: Average rTr muscle activity during hammering

* indicates significance (p<0.05)

Figure 19 shows that within the rTr, tethered and untethered muscle activity are approximately the same, except in the LL reach. Tethering increased muscle activity in the LL off ladder condition 11%. Tethered hammering caused a 29% increase in muscle activity in the LL reach and 12% in the UR reach on the ladder. A slight decrease of 7% in muscle activity in the LR reach was seen, and a slight increase of 7% in the UL reach was seen, but since these values are between 0.90 and 1.10, are considered approximately the same in comparison to untethered muscle activity.

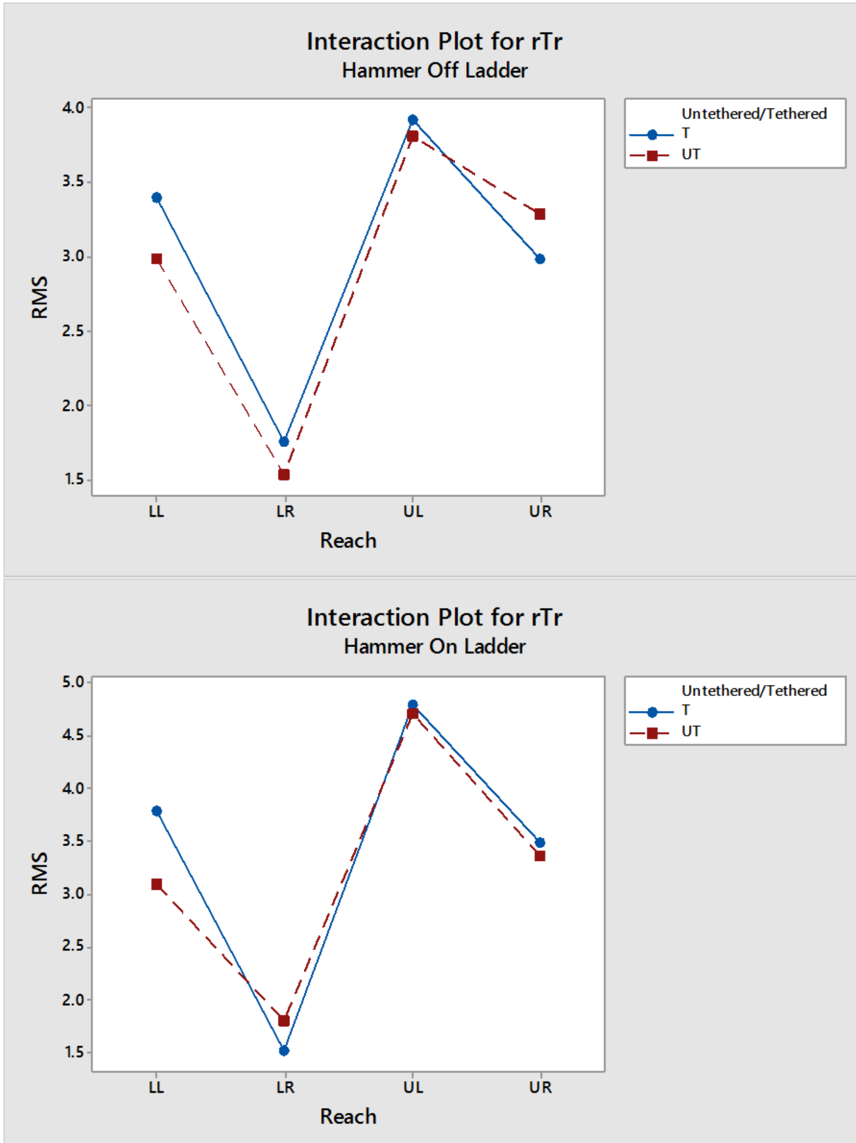


Figure 19: rTr interaction plot between reach and tethering off and on ladder

Figure 20 shows that while off the ladder, there was a significant difference in means between the LR and UR reaches (p<0.05), and on the ladder between the UL and LL reaches (p<0.05). Muscle activity within the rTB varied greatly between conditions, and showed large variation, and in some cases as large as the averaged normalized muscle activity. This may explain the lack of statistical significance between tethered and untethered hammering activity within this muscle, despite ratios of 1.13 on the ladder in the UL reach, and 1.24 on the ladder in the UR reach.

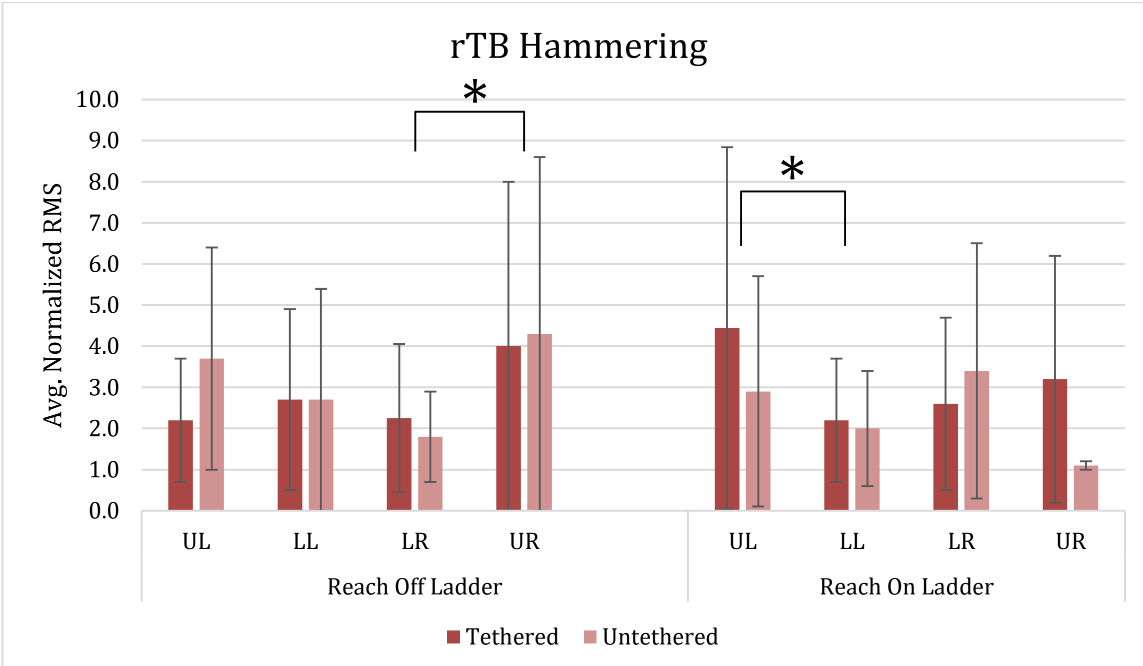


Figure 20: Average rTB muscle activity during hammering

* indicates significance (*p*<0.05)

The interaction plot between reach and tethering conditions (Figure 21) show that the lower reaches resulted in similar muscle activity in the tethered and untethered conditions both on and off ladder, but upper reaches varied greatly. Table 4 shows that off the ladder, tethered hammering reduced muscle activity by 2% to 4% in the LL, Ul and UR reach, while an increase of 7% was seen in the LR reach. Essentially, tethered and untethered muscle activity was approximately the same. On the ladder, the opposite was seen in the UL reach, where tethering increased muscle activity by 22%. Individual overhead hammer swing movement may have been a factor affecting the outcome of these results in the rTB.

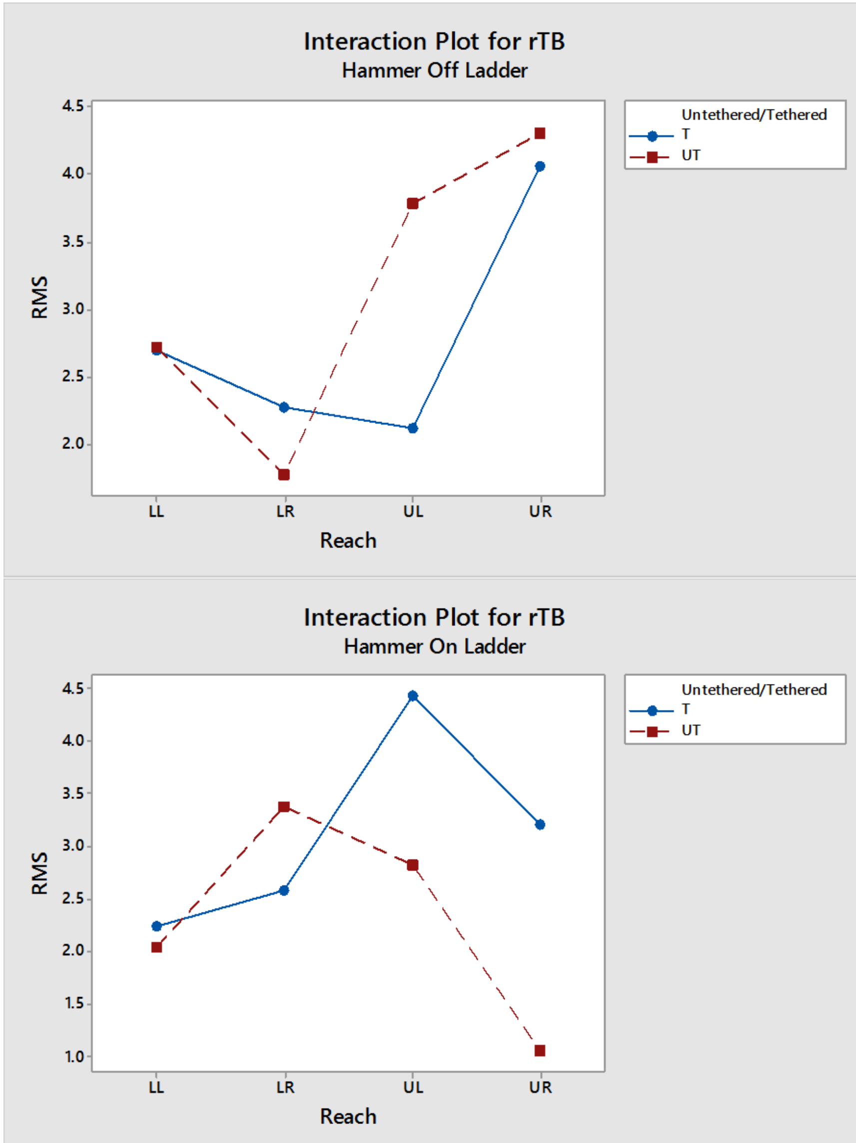


Figure 21: rTB interaction plot between reach and tethering off and on ladder

The ANOVA showed that the rBB was not statistically affected by tether, reach or ladder condition. Although Figure 22 does not represent the ratio results of Table 4, it illustrates the general trend of rBB muscle activity. Off the ladder, lesser rBB muscle activity was exerted when using the tethered hammer, with only the LR reach resulting in a ratio of 1.12, or 12% greater muscle exertion during tethered hammering. The rBB on the ladder showed tethered and untethered muscle activity followed a similar pattern within reaches and ratios showed that valued of approximately 1. The rBB is a major muscle that is used during hammering, and the lack of consistency between on and off ladder results may be due to large variation between subjects.

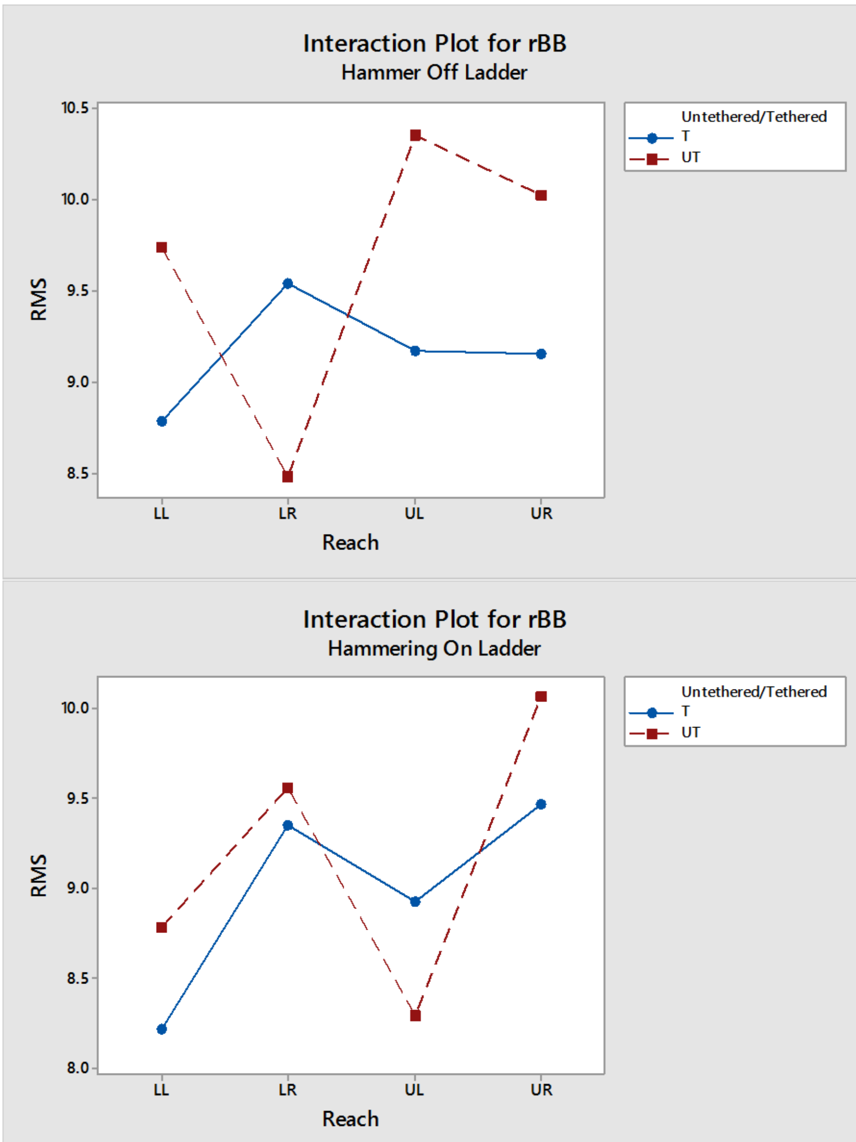


Figure 22: rBB interaction plot between reach and tethering on and off ladder

Off the ladder, the rDel muscle showed significant difference (*p*<0.05) in the LR and LL, UL and LL, UL and LR, and UR and LR reach positions (Figure 23). Essentially, off the ladder, all reaching positions during the hammering task caused significant differences in rDel muscle activity.

On the ladder, statistical significance was seen between the UL and LR reaches (*p*<0.05). Within ratios, the UL reach shows a T/UT ratio of 1.07, and the UR reach shows a T/UT ratio of 1.08, resulting in a 1% difference between ratios. This indicates that the muscular exertion between these two reaches is 7-8% greater during tethered hammering.

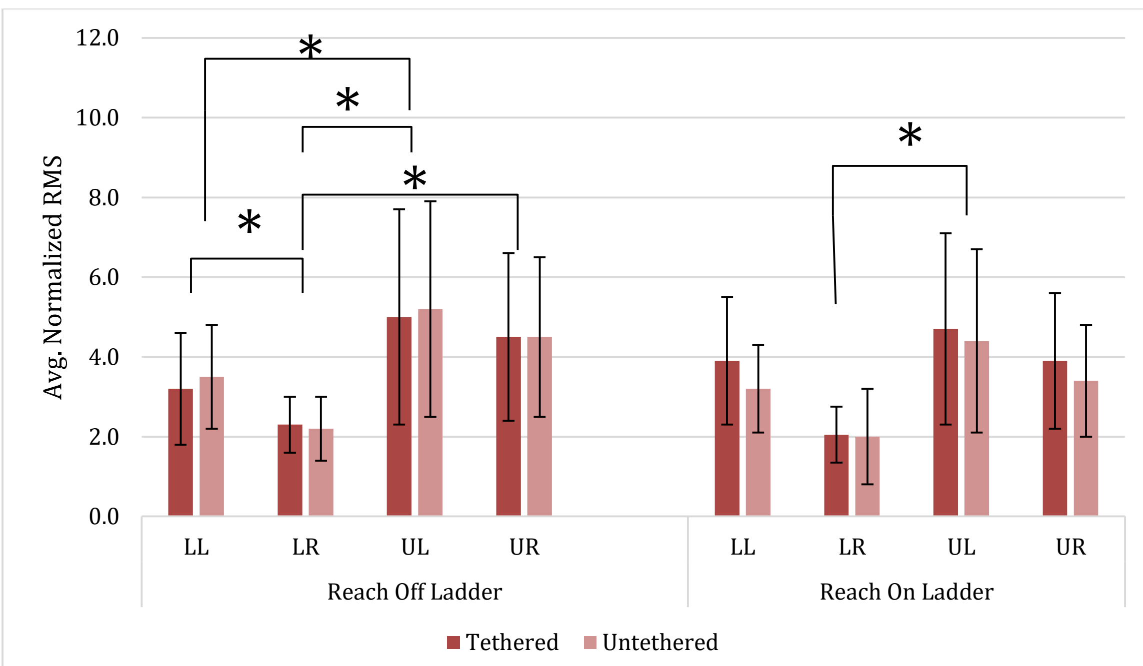


Figure 23: Average rDel muscle activity during hammering
* indicates significance (p<0.05)

Off the ladder, the rDel shows almost identical muscular exertion within each reach, while on the ladder shows similar exertion, with the tethered hammer requiring slightly more effort (Figure 24). Table 4 indicates that the rDel off the ladder showed ratios of approximately 1, and despite similar trends between on and off ladder reaches, the LL reach on ladder showed an increase of 32% during tethered muscle activity on the ladder.

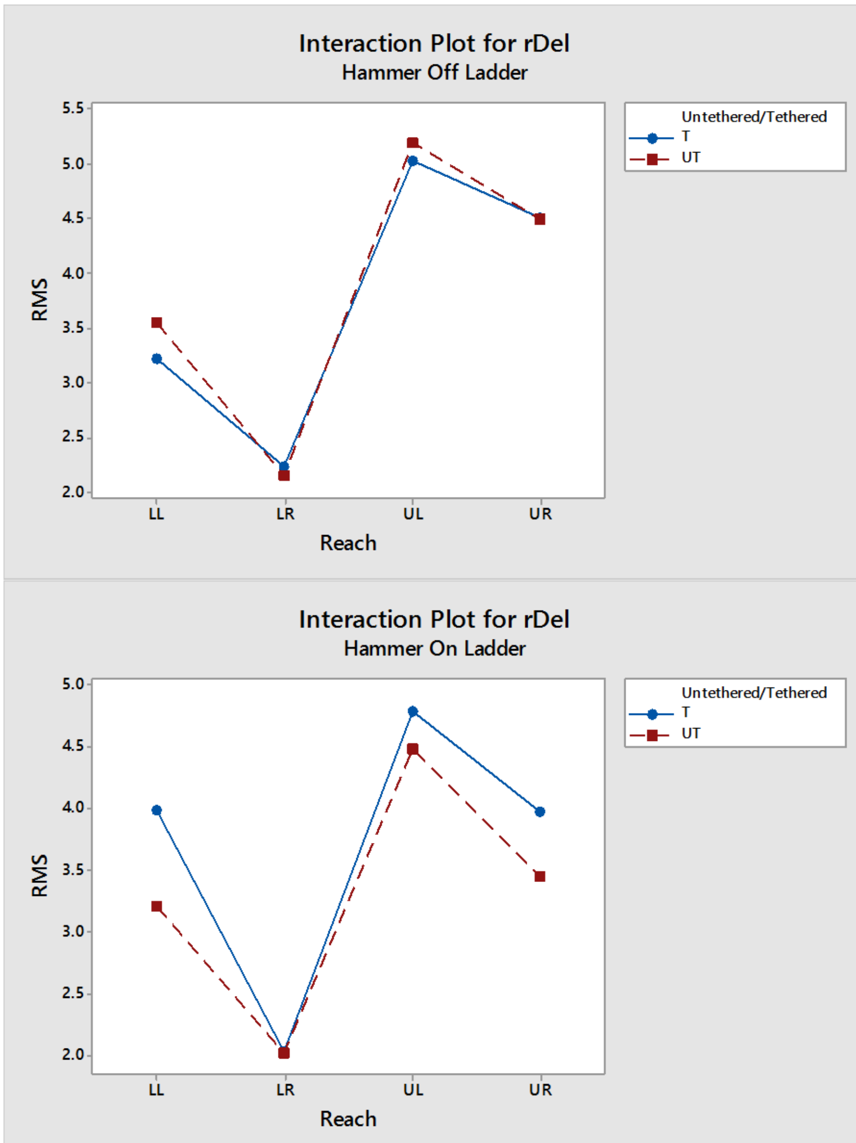


Figure 24: rDel interaction plot between reach reach and tethering off and on ladder

In Figure 25 the rLD muscle showed a statistical significant difference (p<0.05), when hammering off the ladder versus on the ladder with overall muscle activity means of 1.39 off ladder and 1.25 on ladder, or an overall 10.6% difference between the means. However, this does not show whether or not tethering affected muscle activity. Statistically, tethering was insignificant to muscle activity.

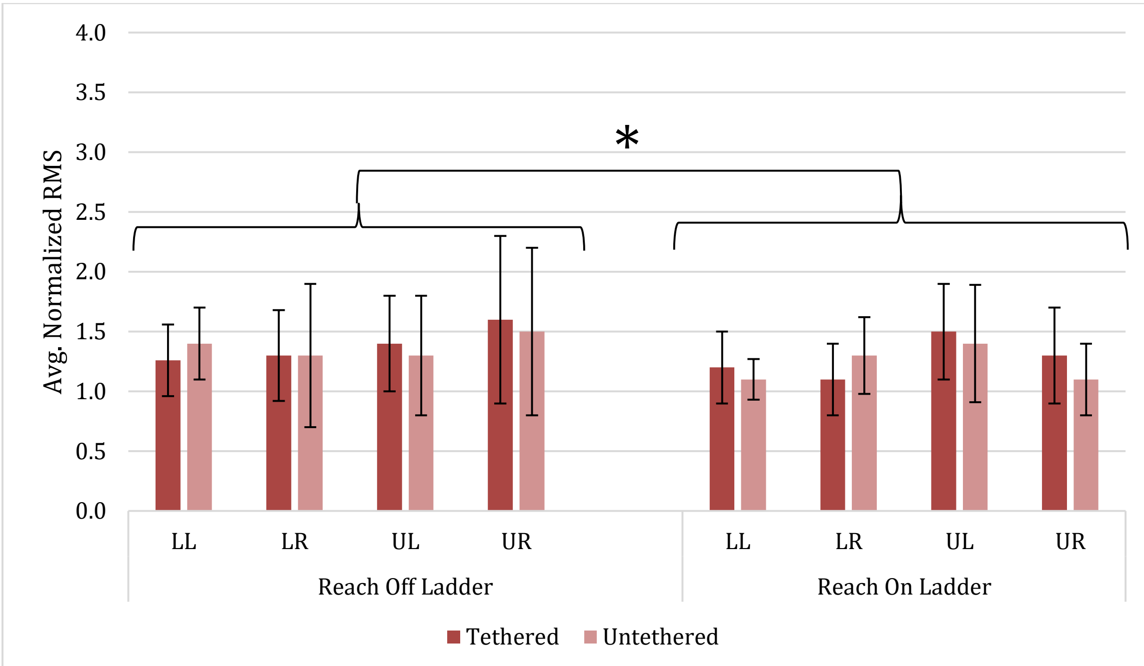


Figure 25 : Average normalized muscle activity rLD hammering

* indicates significance ($p<0.05$)

Although tethered and untethered hammering are similar within rLD reaches, Figure 26 shows that tethered muscle activity slightly increased during tethered hammering, although not statistically significantly. When looking at Table 4, it can be seen that the UR reaches both off and on ladder showed a greater T/UT ratio. A 13% increase in muscle activity during tethered hammering was seen off the ladder in the UR reach, and on the ladder, tethering increased muscle activity by 15% in the UR reach and 16% in the UL reach.

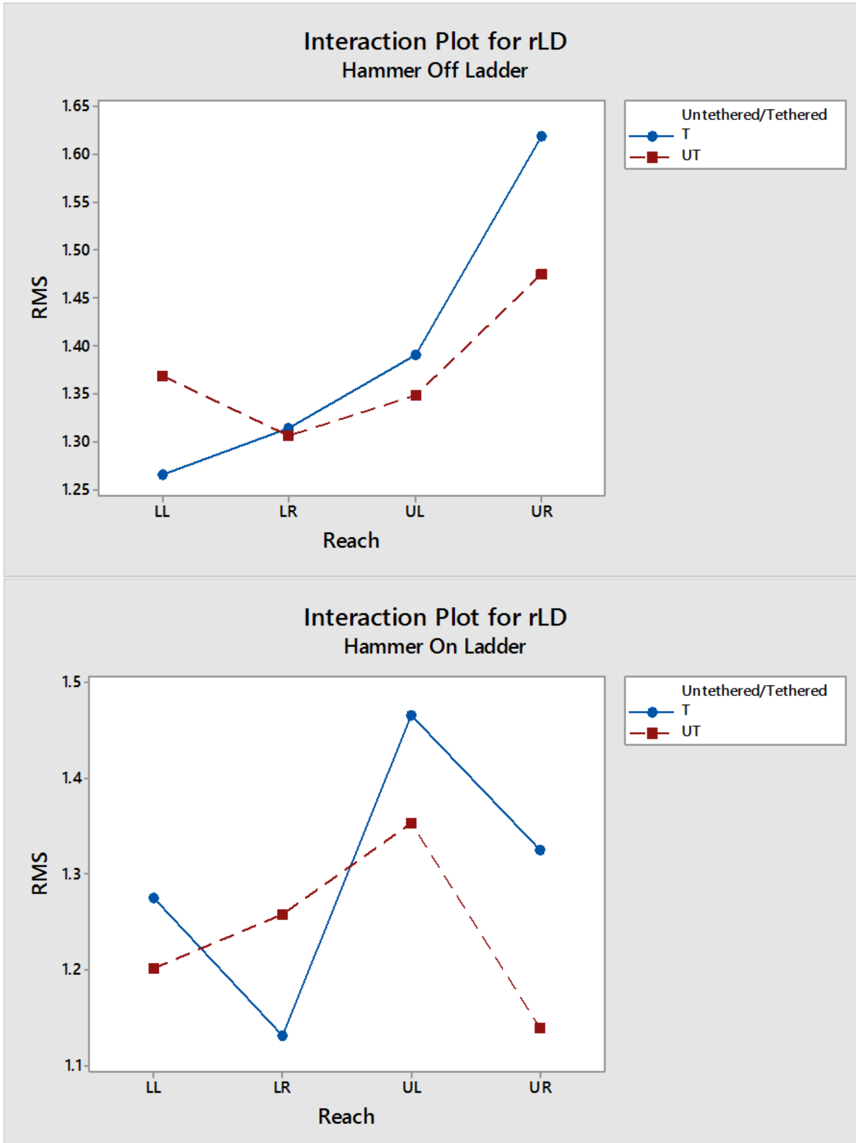


Figure 26: rLD interaction plot between reach and tethering on and off ladder

4.1.2 Wrenching Muscle Activity

Ratios were calculated between the average RMS of tethered muscle activity for each condition over the average RMS of tethered muscle activity (Table 6) to depict how the tethered wrench affected muscle activity in comparison to the untethered wrench. Ratios between 0.90 and 1.10 were considered to be close to 1, indicating no major affect on muscle activity was caused by tethering. In general, the use of a tether during wrenching did not cause a consistent increase in muscle activity compared to untethered wrenching, except during the off ladder LL reach where tethered wrenching resulted in a 16%-25% increase in muscle activity. Half the subjects while off the ladder during the LL reach showed ratios greater than 1 in the rTr, rBB, rTB and rDel.

On the ladder, upper reaches showed a greater frequency of T/UT ratios greater than 1 across most muscles. This indicates that the tether had an influence in across the body and upper reaches, and did not result in much impact while conducting wrenching on the dominant hand side, at shoulder level.

The LR reach, which was directly in front of the subject at shoulder height, was approximately 1 across all muscles both on and off the ladder. The lack of awkward reach across the body or overhead may be justification for this.

rTB showed a decrease of 15% between when on ladder LL reach, compared to off ladder LL reach, and a decrease of 4.4% in the on ladder UR reach compared to the off ladder UR reach. Overall, being elevated off the ground contributed to lower ratios for the rTB. Although differences between certain conditions show increases and decreases in ratios, tethering was found to be statistically insignificant to muscle activity.

Table 6: Ratio Table Average T/UT (SD) during wrenching

Avg. T/UT Off	rPM	SD	lTr	SD	rTr	SD	rBB	SD	rTB	SD	rDel	SD	rLD	SD
LL	0.99	0.13	0.90	0.26	1.21	0.24	1.15	0.24	1.22	0.24	1.25	0.27	1.05	0.25
LR	0.97	0.15	0.93	0.31	0.93	0.27	0.90	0.30	1.03	0.21	1.03	0.33	0.94	0.15
UL	0.96	0.17	1.03	0.33	1.05	0.28	0.97	0.26	0.99	0.21	1.15	0.33	1.04	0.31
UR	1.01	0.32	1.06	0.33	1.00	0.19	0.94	0.17	1.16	0.36	1.06	0.30	1.11	0.16

Avg. T/UT On	rPM	SD	lTr	SD	rTr	SD	rBB	SD	rTB	SD	rDel	SD	rLD	SD
LL	1.09	0.26	0.93	0.12	1.10	0.23	1.04	0.20	1.05	0.29	1.07	0.35	0.93	0.18
LR	0.99	0.15	1.01	0.33	1.00	0.23	1.01	0.25	1.01	0.36	1.04	0.23	1.05	0.23
UL	1.02	0.15	1.14	0.38	1.15	0.32	1.18	0.26	1.11	0.23	1.16	0.34	1.16	0.31
UR	1.21	0.26	0.95	0.19	1.00	0.22	1.08	0.41	1.11	0.34	1.09	0.28	1.00	0.32

General linear model ANOVA results (Table 7) show that tethering did not impact muscle activity compared to untethered wrenching, while reach position did affect muscle activity. ANOVA results show that there was significant interaction between reach and ladder in the rPM and within the rDel ($p<0.05$).

Table 7: General Linear Regression ANOVA results for wrenching RMS

*indicates significance ($p<0.05$)

Muscles	rPM	lTr	rTr	rTB	rBB	rDel	rLD
Factors	*p-values*						
UT or T	0.692	0.438	0.467	0.389	0.830	0.575	0.217
Reach	0.001*	0.045*	0.001*	0.001*	0.057*	0.023*	0.010*
Ladder	0.178	0.557	0.719	0.025*	0.072	0.278	0.443
Reach*Ladder	0.001*	0.770	0.892	0.157	0.024*	0.121	0.285
Reach * UTorT	0.609	0.948	0.630	0.786	0.644	0.968	0.517
Ladder*UTorT	0.336	0.469	0.647	0.827	0.524	0.921	0.944
Ladder*Reach*UT or T	0.990	0.713	0.968	0.748	0.806	0.730	0.947

Figure 27 shows statistical significance in the rPM between the UL and LR reach, and the UL and LL reach while off ladder. Amongst these reaches ratios of approximately 1%-4% reduction in muscle activity during tethered wrenching were measured. During on ladder wrenching, the LL left reach was statistically different to the other three reaches, requiring greater overall muscle activity. Within ratios, the UR reach showed the greatest difference, with tethered wrenching requiring 21% greater muscular exertion than untethered wrenching. Compared to the LL reach on ladder, it required 11% greater exertion.

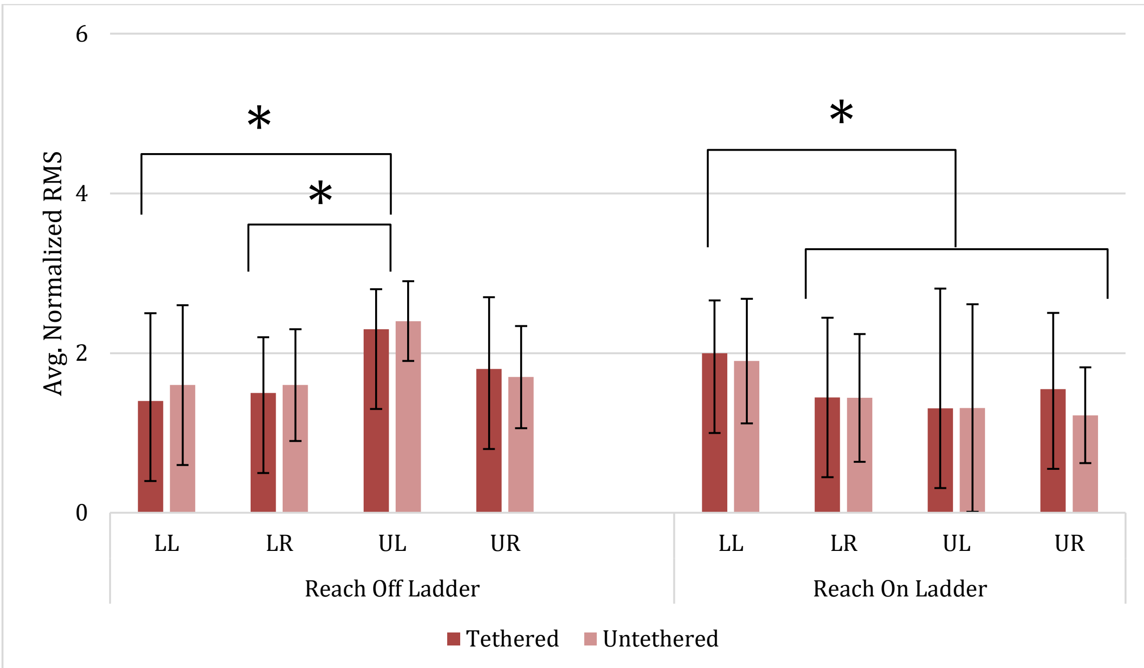


Figure 27: Average normalized muscle activity rPM wrenching

* indicates significance (*p*<0.05)

Figure 28 shows that the UR off ladder reach required the largest amount of muscle exertion out of all the conditions. ANOVA results show that an interaction between reach and ladder occurred within rPM muscle activity ($p<0.001$). The factor levels within ladder elevation and reach affected rPM muscle activity, particularly in the UL and UR reaches. Tethered and untethered wrenching muscle activity showed the same trends within reach both on and off ladder, with ratios of approximately 1 within most reaches. On the ladder, the UR reach showed that tethering increased muscle activity by 21% from the untethered condition.

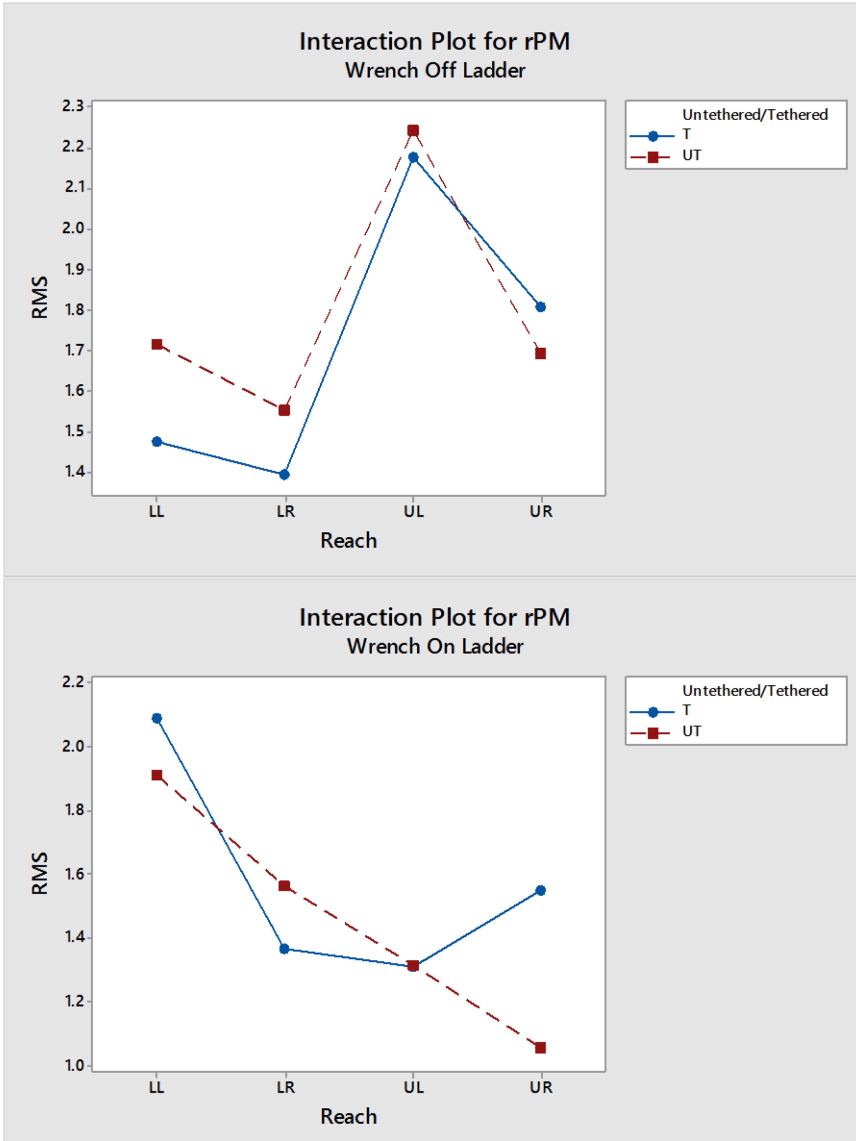


Figure 28: Interaction plot between factors of reach and ladder for rPM muscle during wrenching

The lTr displayed statistical significance (p<0.05) between the means of the UL and LR reach off the ladder (Figure 29). T/UT ratios were approximately 1 for the off ladder conditions, indicating that tethering did not influence reach. No statistical significance was seen between tethered or untethered muscle activity or between reaches for the lTr during the on ladder condition.

On the ladder the lTr showed statistical significance between the LR and UL, and the UL and the UR reaches. Within these reaches, the UL showed a ratio of 1.14, and greater muscle exertion compared to the LR and UR reaches. The lTr was primarily engaged when the subjects used their left arm to braced or support their body weight on the wrenching structure while their right arm conducted wrenching. The left hand was typically placed below the adjustable wrenching piece while subjects were conducting the task in the UL reach. Essentially, the left arm was raised and overhead, which explains why the lTr reach showed greater muscle activity compared to the other reaches.

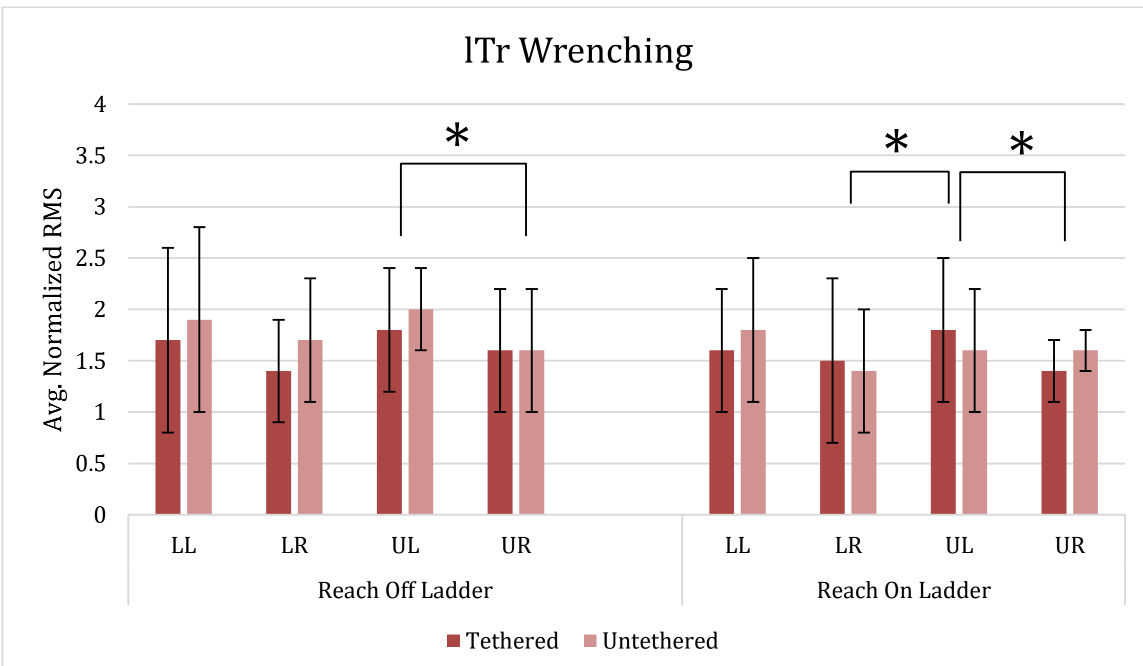


Figure 29: Average normalized muscle activity lTr wrenching

* indicates significance (p<0.05)

Figure 30 shows that there is increased muscle activity during untethered wrenching off the ladder, although not statistically significant. Reach is the only statistically significant factor that was seen within the lTr. Both on and off the ladder, reach shows similar trends in muscle activity between reaches.

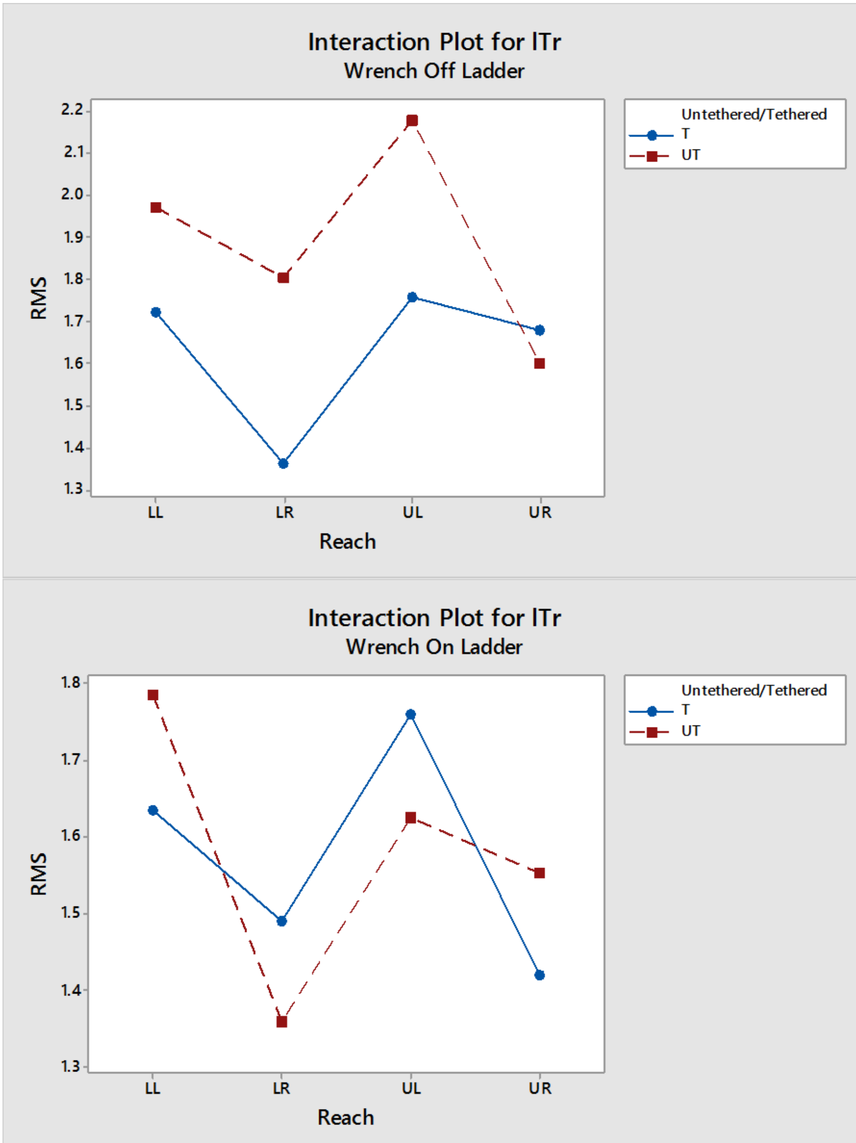


Figure 30: lTr interaction plot between reach and tethering off and on ladder

While off ladder, the rTr (Figure 31) required greater exertion in the UL reach, showing a 5% increase in the T/UT ratio during tethered wrenching, and statistical significance to the LR (*p*<0.05). Tethering caused a 7% decrease in muscle activity in the off ladder LR reach, resulting in a ratio of 0.93, indicating effort between tethered and untethered wrenching were approximately the same. The greatest increase in ratio was seen the LL and LR reach off ladder, with tethering increasing muscle activity in the LL reach by 29% compared to the LR.

On the ladder statistical significance between reach was seen between the LL and LR, UL and LR, and UL and UR conditions. Tethering was statistically insignificant, however LL showed 10% increased muscle activity during tethered wrenching within that reach, while the UR showed a 15% increase. The right reaches (LR and UR) showed ratios of approximately 1 between tethered and untethered wrenching.

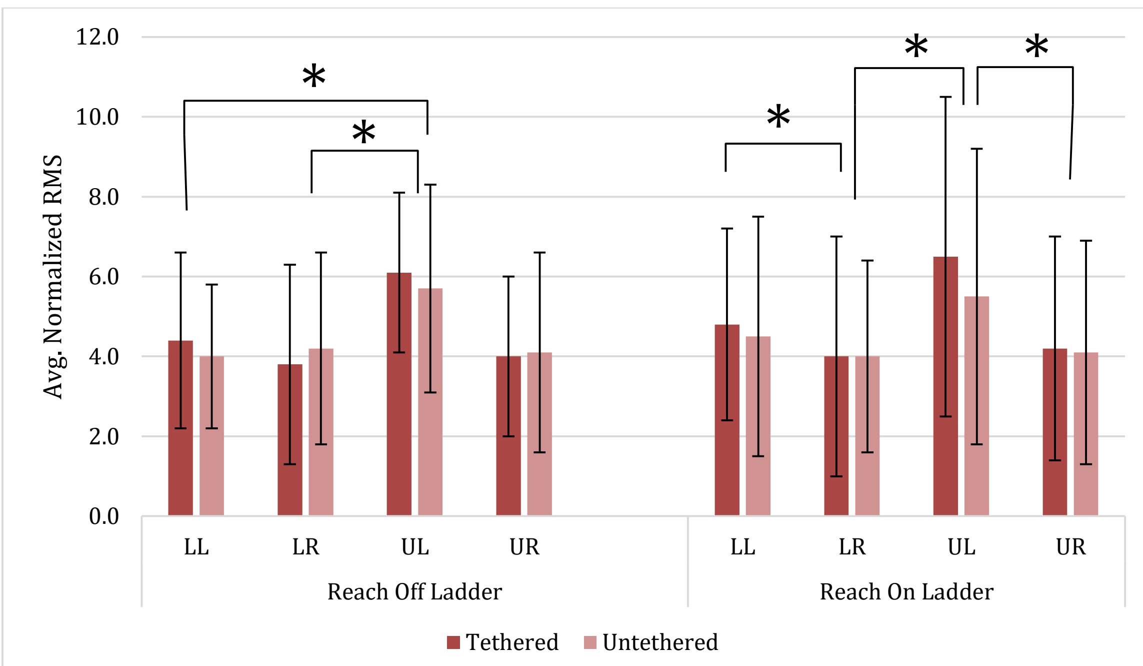
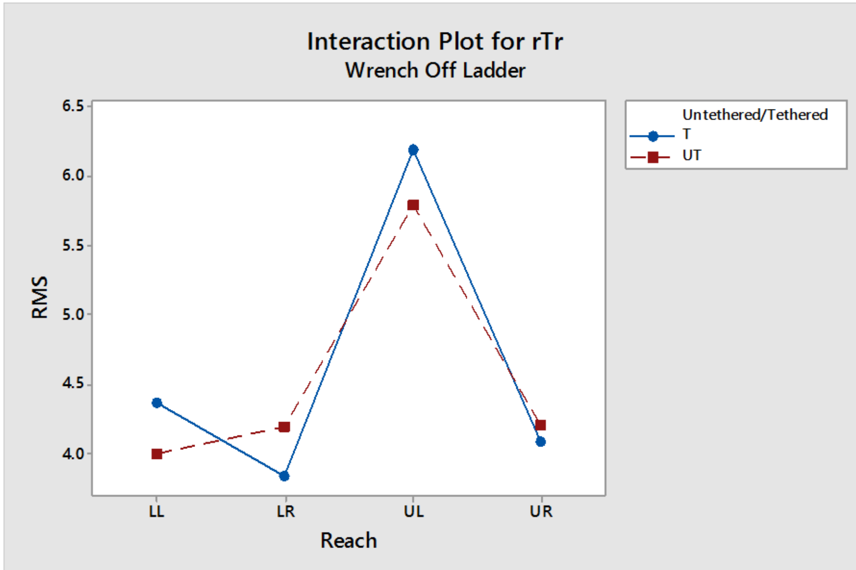


Figure 31: Average normalized muscle activity rTr wrenching

* indicates significance (p<0.05)



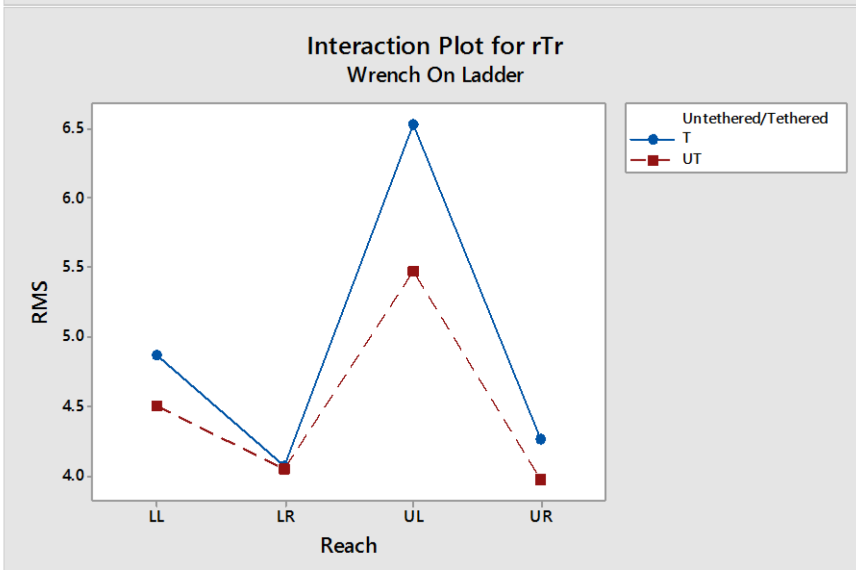


Figure 32: rTr interaction plot between reach and tethering off and on ladder

Figure 32 shows that tethered and untethered muscle activity is approximately the same for the rTr both on and off the ladder, except for the on ladder UL reach condition, and follow the same trend despite ladder condition.

The rTB showed large variances in all conditions (Figure 33), particularly while off ladder and in the UL reach. Off the ladder, statistical significance was seen between the UL and LR reaches (p<0.05), and the UL and UR reaches (p<0.05). Within reaches off ladder, ratios show that the LL reach resulted in 22% greater activity during tethered wrenching, while the UR showed 16% greater activity, while the other two reaches showed a ratio of approximately 1. On the ladder, the tether increased muscle activity by 11%, implying that tethered wrenching may have contributed to slightly higher muscular activity in the rTB during overhead reaches, depicted in figure 34. The lower reaches showed ratios of approximately 1.

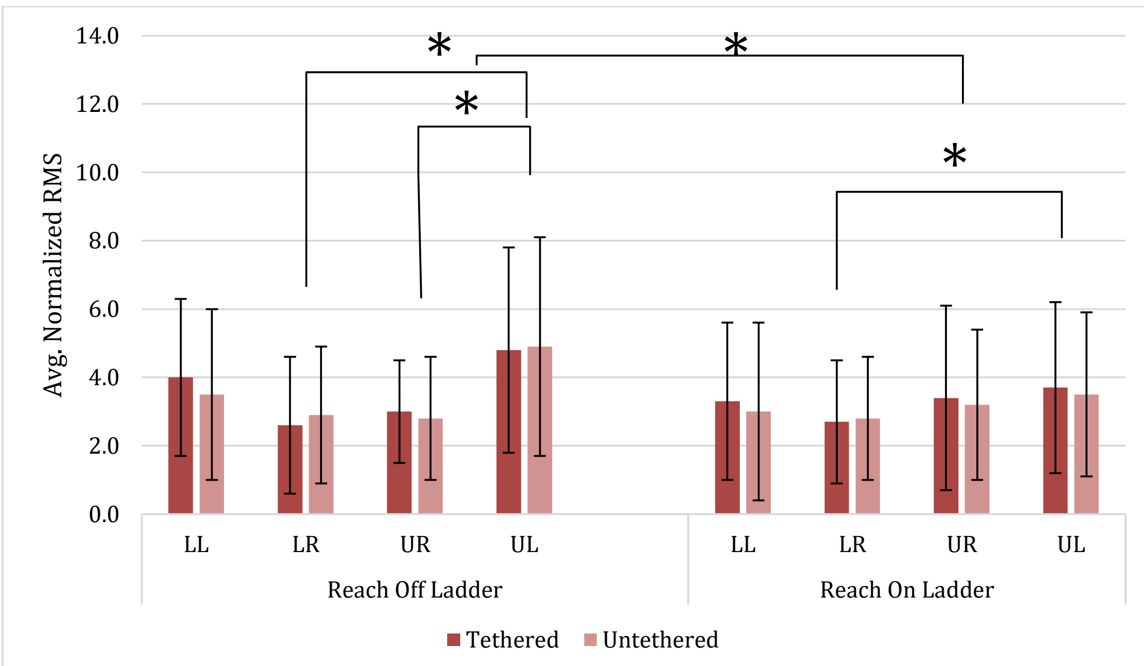


Figure 33: Average normalized muscle activity rTB wrenching

* indicates significance (p<0.05)

Figure 34 also depicts that the LL reaches showed that the tethered wrench caused slightly increased muscle activity in the LL reaches, with ratios of 1.22 off the ladder, and 1.05 on the ladder. The trend in muscle exertion at different reaches in the rTB is similar both on and off the ladder, however muscle activity in the UR is slightly increased for both tethered and untethered wrenching while on the ladder.

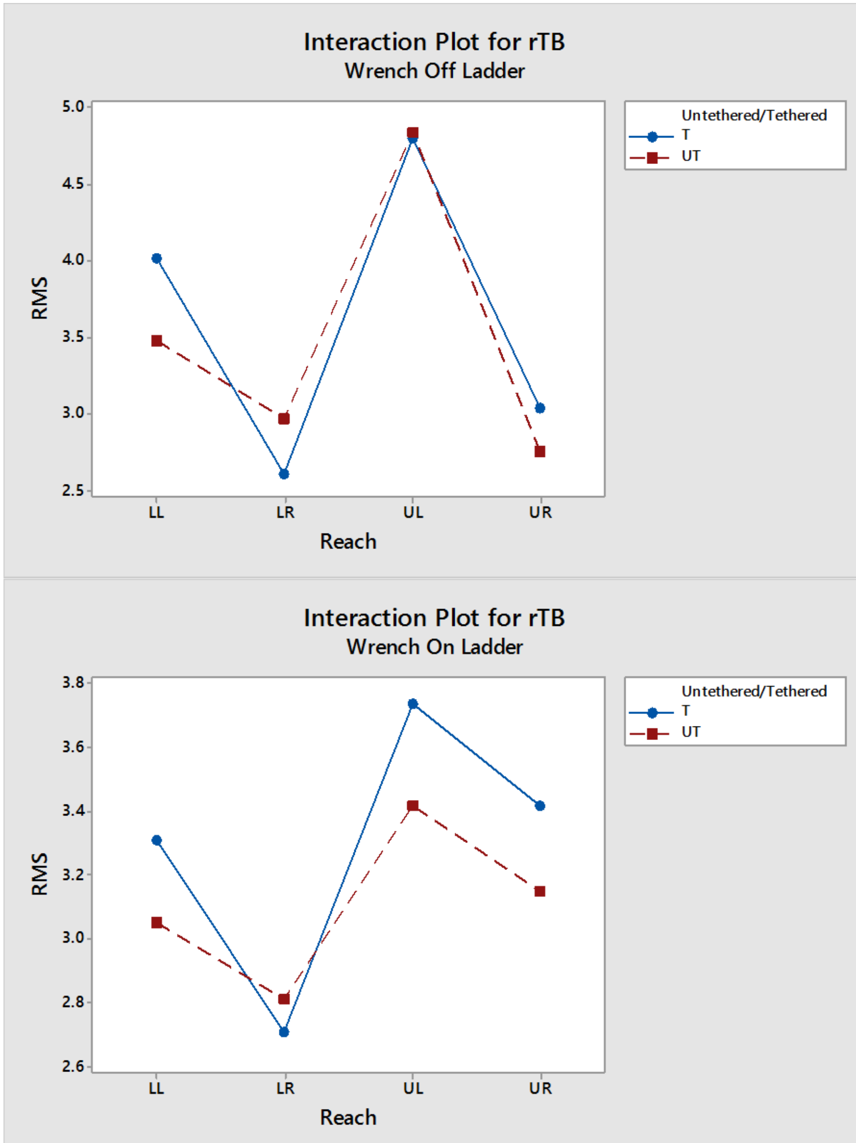


Figure 34: rTB interaction plot between reach and tethering off and on ladder

The rBB showed statistical significance within reach and the interaction of ladder and reach (Figure 35). Significance differences in means was found between the UL and LL reaches, and the UL and LR reaches ($p<0.05$). Within those reaches, tethering showed a 10% decrease compared to untethered wrenching in the LR reach off ladder. The LL reach off the ladder showed an increase of 18% within tethered wrenching, while the UL reach on ladder showed an 18% increase within tethered. This indicates tethered affects left reaches, although not statistically significant.

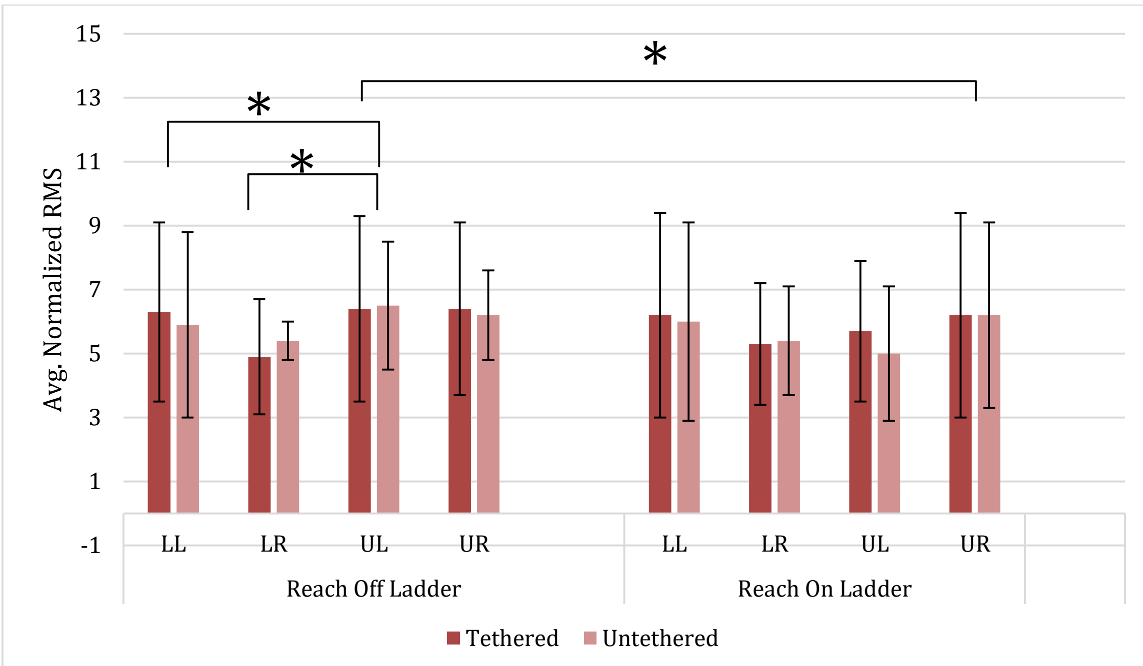


Figure 35: Average normalized muscle activity rBB wrenching

* indicates significance (p<0.05)

An interaction plot between reach and ladder for the rBB further illustrates that ladder and reach affected muscle activity while wrenching in the UL reach (Figure 36). Reach activity between on and off ladder follows the same trend, except in the UL reach, where ladder effect caused an increase in muscle activity off the ladder compared to on ladder, as indicated in Table 6 by a ratio difference of 21%.

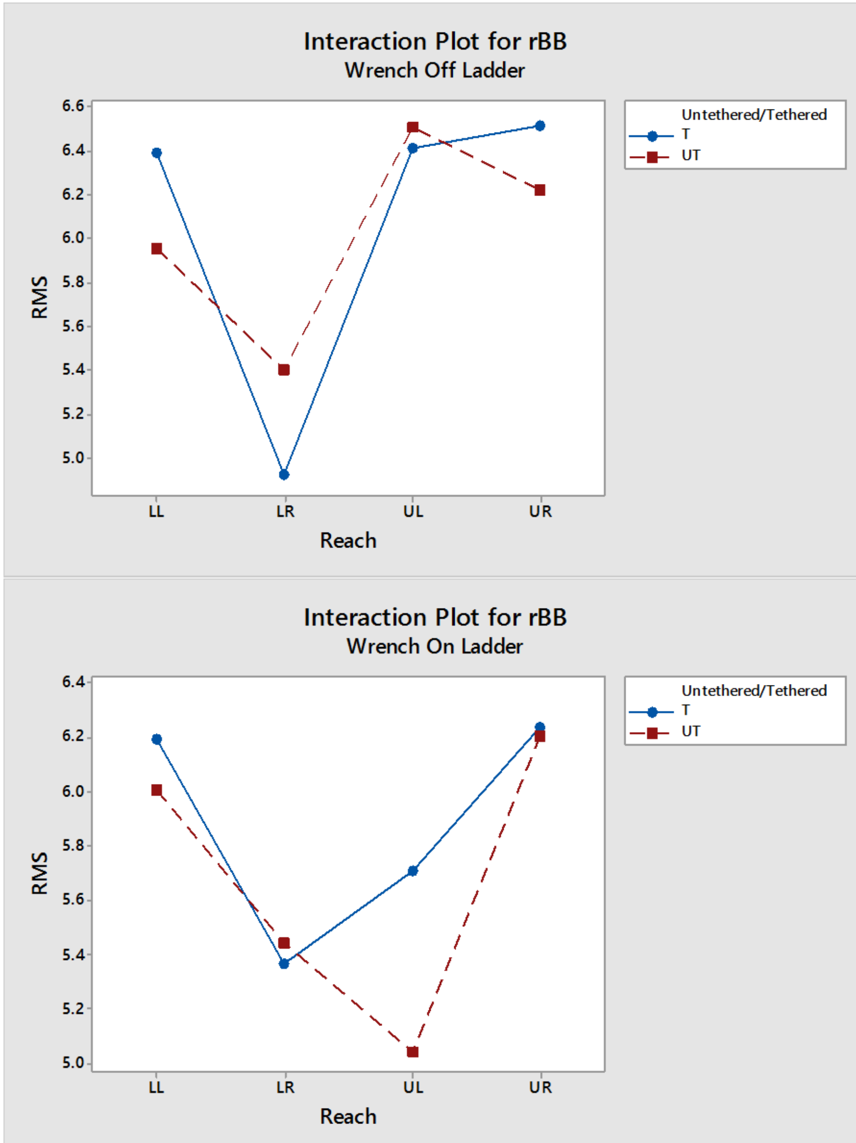


Figure 36: Interaction plot between reach and tethering off and on ladder

Figure 37 shows statistical significance is seen between the LR and LR reaches (p<0.05) in the rDel while off the ladder, and the ANOVA shows there is a significant interaction between reach and ladder. The LL reach off ladder showed that tethering increased muscle activity by 22% and the UR reach off ladder by 16%. Upper reaches show slightly higher ratios, of 1.11 during the on ladder condition. The rest of the reaches showed ratios of close to 1.

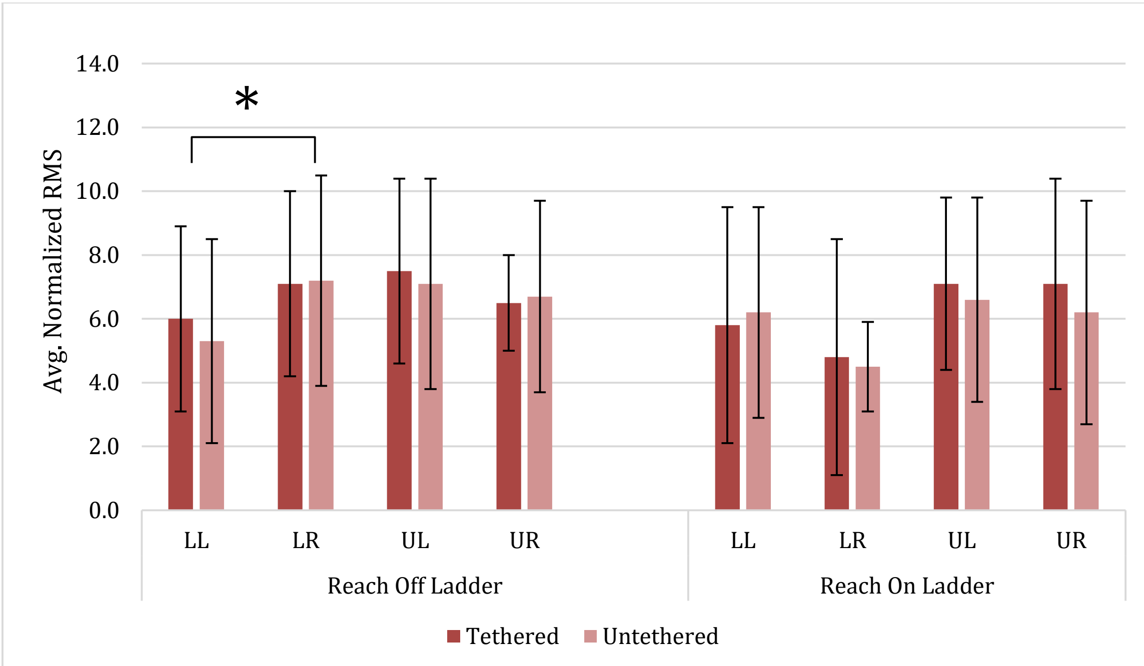


Figure 37: Average normalized muscle activity rDel wrenching

* indicates significance ($p<0.05$)

Interaction between reach and ladder is depicted in Figure 38. Within the rDel, the LL, UL and UR reaches follow the same trend toward each other on and off the ladder. Typically, the LR reach has shown to be the reach that has required the least amount of muscular effort amongst most muscles, but off the ladder, the rDel required 40% greater effort compared to tethered muscle activity and 44% greater effort compared to untethered muscle activity than while on the ladder. Essentially, there was no difference between tethered and untethered muscle activity in the LR condition. Despite it seeming as if this interaction would be statistically significant, ANOVA results show it was not.

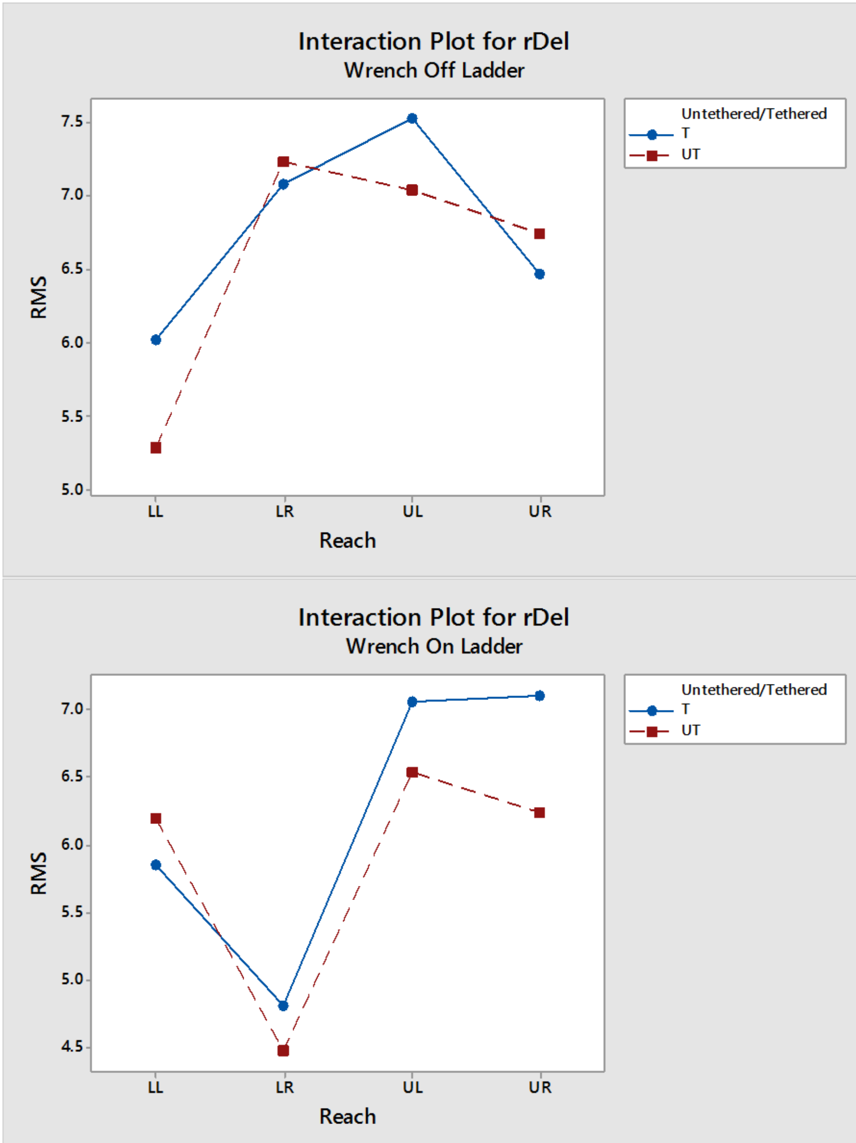


Figure 38: Interaction plot between factors of reach and ladder for rDel muscle during wrenching

The rLD showed significance only off the ladder between the UL and LL reaches (Figure 39). Although the LR off ladder showed the least amount of muscle exertion, it was not found significant, possibly due to the large standard deviation.

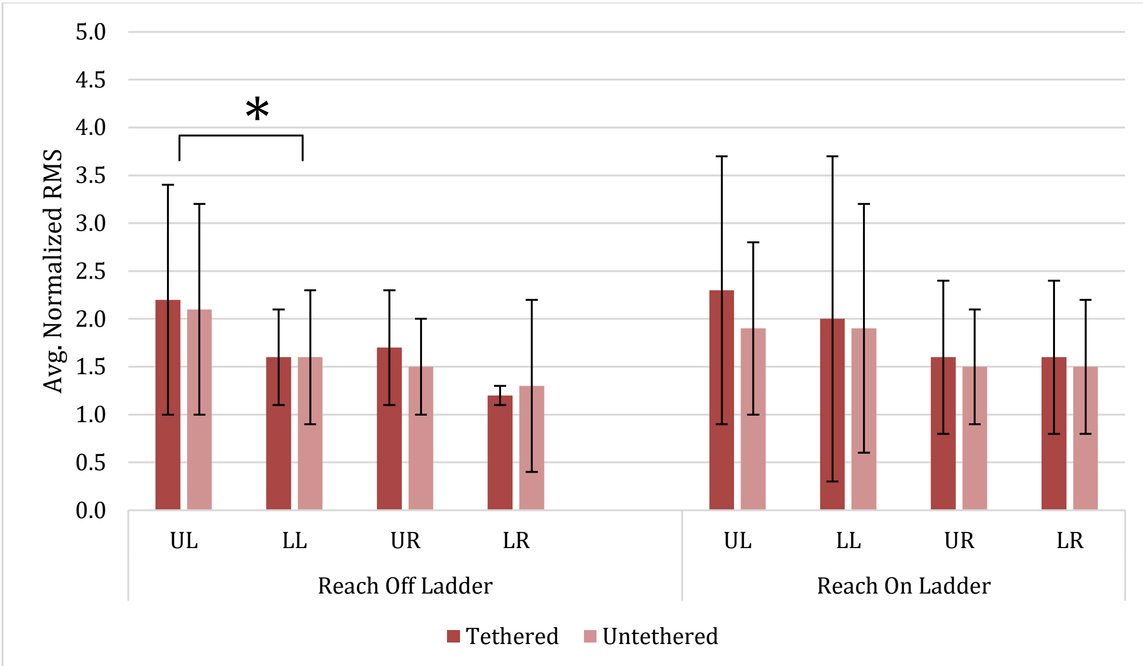


Figure 39: Average normalized muscle activity rLD wrenching
* indicates significance ($p<0.05$)

Overall muscle activity showed similar trends within rLD conditions, both on and off the ladder, and between tethered and untethered muscle activity, depicted in Figure 40. The largest T/UT ratio was seen within the UL on ladder condition showing that tethered wrenching increased muscle activity by 16%. Large standard deviation in this condition is seen which may have caused this increase in ratio, which is not statistically significant.

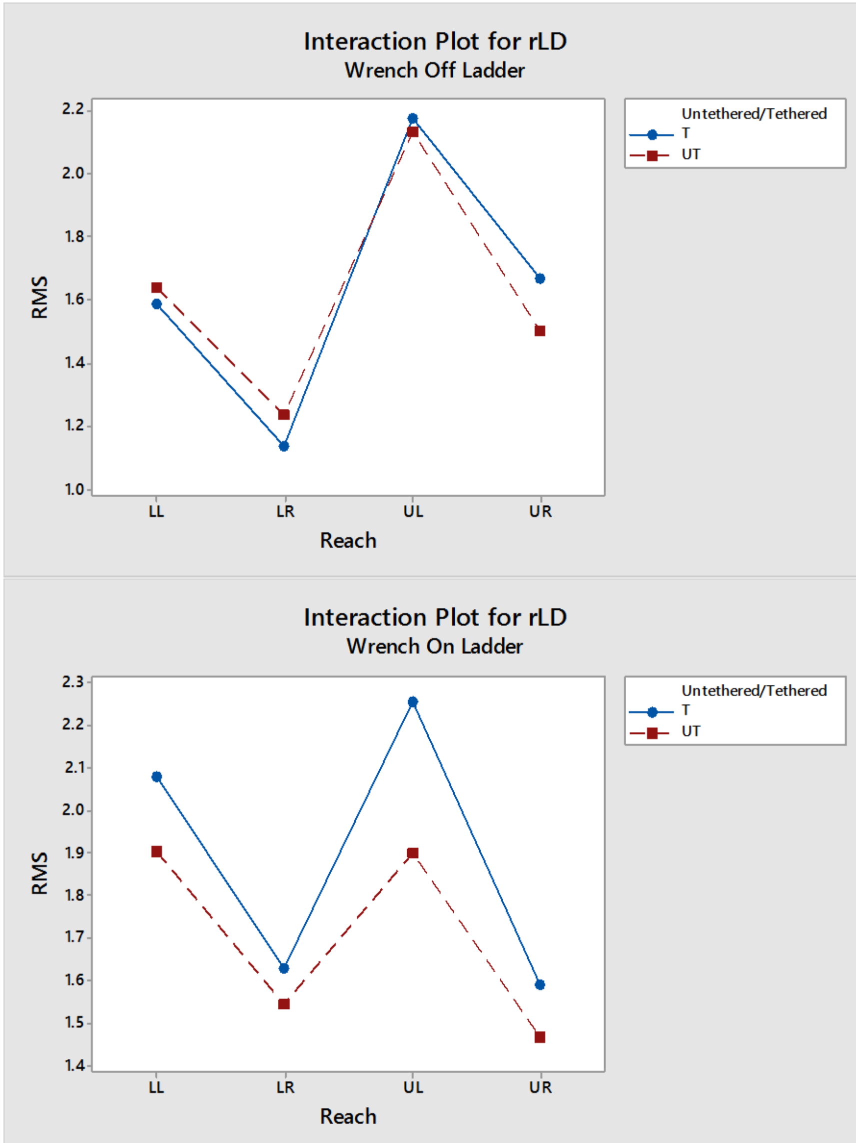


Figure 40: rLD interaction plot between reach and tethering off and on ladder

4.2 Hand Grip Pressure

4.2.1 Hammering Hand Grip Pressure

As with with muscle activity, ratios of T/UT hand grip pressure were calculated for each condition to assess whether the tethering affected hand grip pressure during the hammering task and the results are presented (Table 8).

Table 8: Ratio Table Average PSI (SD) during hammering

Avg. T/UT Off	PSI	SD
LL	1.07	0.18
LR	1.17	0.20
UL	1.04	0.36
UR	0.96	0.41
Avg. T/UT On	**PSI**	**SD**
LL	1.25	0.53
LR	0.94	0.32
UL	0.94	0.47
UR	1.15	0.51

In general, tethering had little or no effect on hand grip pressure while hammering (p=0.84). Nevertheless, a slightly greater overall hand grip pressure was observed during tethered hammering in three conditions. While subjects were off the ladder the LR reach required 17% greater grip pressure during tethered hammering. On the ladder there was greater impact on tethered hammering to hand grip pressure in the LL and UR reach positions. Within the LL on ladder position, there was large variation between subject results, ranging from 13.7 to 41.7 PSI during tethered hammering and 11.5 to 45.6 PSI during untethered hammering. A 5% decrease in hand grip pressure was seen in the UR reach.

Decreases in hand grip pressure when using the tethered hammer were seen in the UR reach off the ladder (5%) and, LR and UL reaches on the ladder by 6%. Overall, the subjects were using less hand grip pressure in the UR on ladder condition, with tethered hammering ranging between 10.9 to 22.3 PSI and untethered hammering from 8.3 to 25.0 PSI. Table 9 shows tether, reach, ladder and interaction between the condition factors were not found to be a significant factor (p<0.05).

Table 9: General Linear Regression ANOVA results hammering PSI

*indicates significance (p<0.05)

Hammering Hand Grip Pressure	
Factors	*p-values*
UT or T	0.976
Reach	0.199
Ladder	0.317
Reach*Ladder	0.124
Reach * UTorT	0.290
Ladder*UTorT	0.576
Ladder*Reach*UTorT	0.868

Figure 41 provides an overview of the similarities and differences within grip pressure between conditions, and the significance of ladder in relation to average PSI. In the off ladder condition, it can be seen that LR reach resulted in the least PSI, despite the showing a T/UT ratio of greater than 1. Similarly, the UR reach condition resulted in the least amount of hand grip pressure in comparison to the other on ladder reaches, but still was affected by tethering of the hammer. This could be because the tether that was located on the subject's left side caused a slight pull which required greater grip for control of the hammer. However, since all subjects were right hand dominant, there was less overall grip pressure needed to hammer in the LR reach off the ladder, and UR reach on the ladder, compared to the across-body left reaches. For further illustration, Appendix A displays the interaction of ladder condition and reach on tethered and untethered hammering. Within reaches there was no statistical significance between the differences in means (p>0.05).

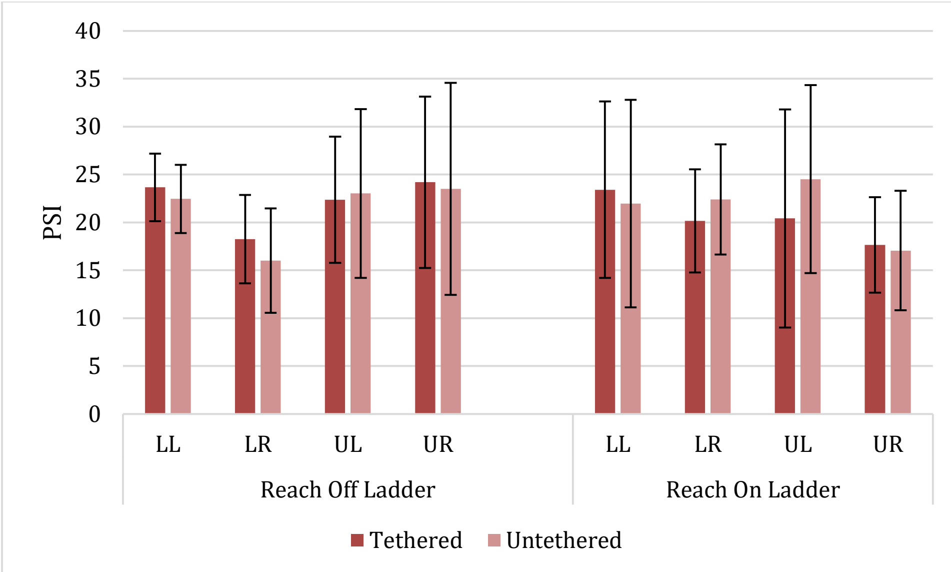


Figure 41: Average hand grip pressure during hammering across reach on and off ladder

* indicates significance ($p<0.05$)

4.2.2 Wrenching Hand Grip Pressure

Large variations were observed in tethered wrenching grip pressure results. Ratios calculated of T/UT hand grip pressure during wrenching are depicted in Table 10, and show that subjects used greater grip pressure during tethered tasks only half of the time. The LL and UR reaches caused the subjects to use greater hand grip pressure while off the ladder compared to on the ladder, and the lower reaches (LL, LR) resulted in ratios greater than 1 while on the ladder. The largest increase in hand grip pressure was seen off ladder in the LL reach by 27%, and UR by 23%, while on the ladder LL showed an increase in tethered wrenching hand grip pressure by 17% and LR by 24%. Ratios below 1 were only seen off the ladder, with the largest decrease being the UL reach, showing a 18% decrease in hand grip pressure during tethered wrenching.

Table 10: Ratio Table Average PSI (SD) during wrenching

Ladder	Reach	T/UT	StDev
Off	LL	1.27	0.73
	LR	0.96	0.46
	UL	0.82	0.24
	UR	1.23	0.81
On	LL	1.17	0.37
	LR	1.24	0.62
	UL	0.93	0.40
	UR	1.06	0.62

ANOVA (Table 11) reveals that tethering, reach and ladder position and their interactions were not statistically significant factors affect hand grip pressure during wrenching.

Table 11: General Linear Regression ANOVA results wrenching PSI

*indicates significance (p<0.05)

Wrenching Hand Grip Pressure	
Factors	*p-values*
UT or T	0.412
Reach	0.223
Ladder	0.488
Reach*Ladder	0.369
Reach * UTorT	0.338
Ladder*UTorT	0.917
Ladder*Reach*UTorT	0.635

Figure 42 displays average hand grip pressure for the wrenching conditions, while Appendix B shows the interaction of reach and ladder on hand grip pressure. Large standard deviations are seen within each mean, and no consistent pattern is seen between tethered and untethered activity, which may account for the lack of statistical significance tethering has on hand grip pressure.

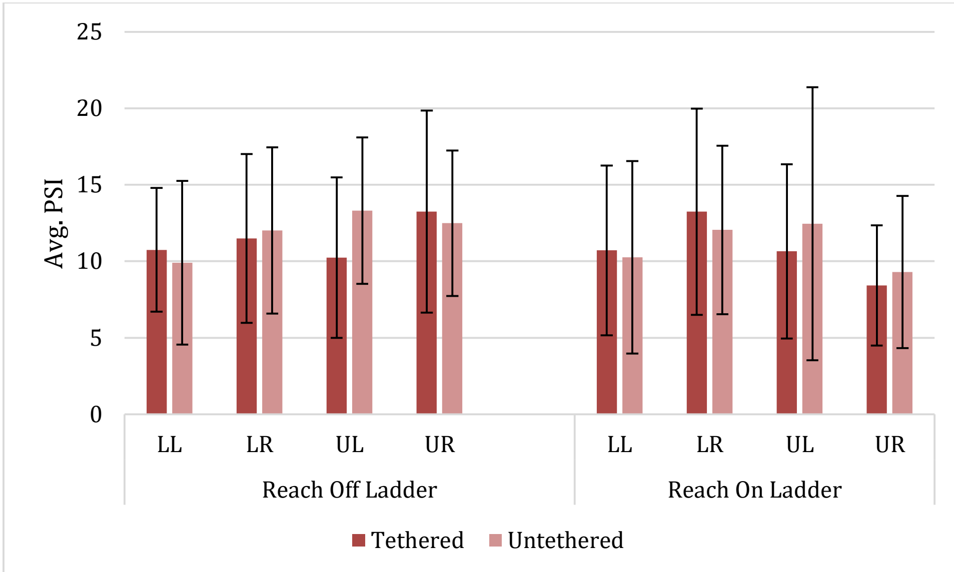


Figure 42: Average hand grip pressure during wrenching

4.3 Task Time

4.3.1 Hammering Task Time

No statistical significance in task time was observed between tethered and untethered hammering between reaches or while on and off the ladder (Table 12). Hammering averaged 3.04 seconds (±2.19). Tethered hammering overall showed an average of 2.96 seconds (±1.94) and untethered hammering overall averaged 3.24 seconds (±2.25).

Table 12: General Linear Regression results hammering

*indicates significance ($p<0.05$)

Hammering Time on Task (s)	
Factors	*p-values*
UT or T	0.311
Reach	0.774
Ladder	0.903
Reach*Ladder	0.204
Reach * UTorT	0.449
Ladder*UTorT	0.447
Ladder*Reach*UTorT	0.607

Table 13 shows that hammering took approximately the same amount of time when tethered and untethered in the LL and UR reaches while off ladder, and the UL and UR reaches while on the ladder. LR and UL off ladder showed decreased ratios by 9%-13% during tethering, while decreases of 10% were seen on the ladder in the LL and LR reaches.

Table 13: Ratio Table Average T/UT Time (SD) during hammering

Ladder	Reach	T/UT	StDev
Off	LL	0.99	0.52
	LR	0.91	0.32
	UL	0.87	0.16
	UR	1.07	0.39
On	LL	0.90	0.23
	LR	0.90	0.31
	UL	1.01	0.26
	UR	1.04	0.34

Figure 43 depicts a side by side comparison between average time on task between the tethered and untethered hammering for each condition, and is illustrated as interaction plots in Appendix C.

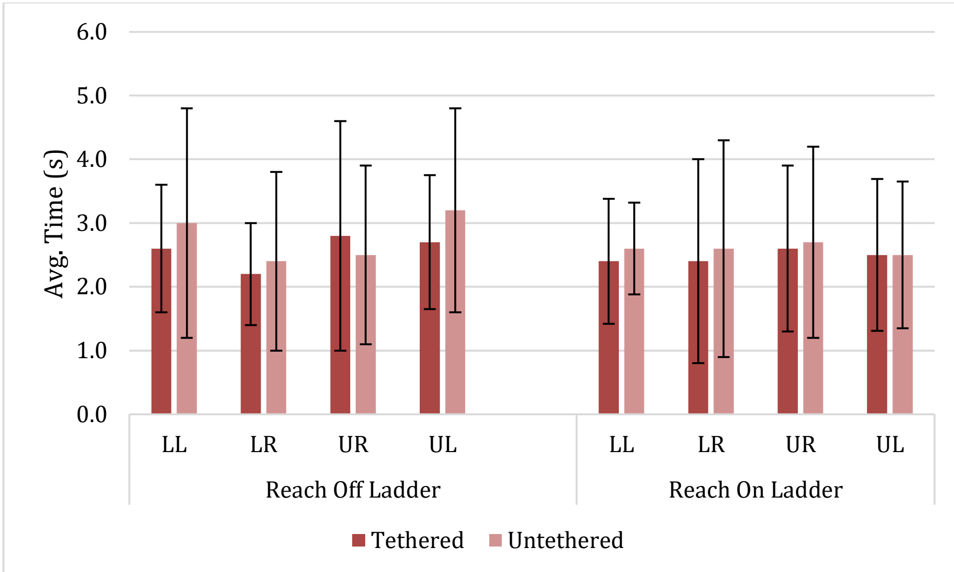


Figure 43: Average time on task (seconds) hammering

4.3.2 Wrenching Task Time

General ANOVA revealed no statistical significance was observed between tethered and untethered wrenching across all four reaches or while on and off the ladder (Table 14). Overall, wrenching averaged 1.99 seconds (±0.77). Tethered wrenching overall averaged 2.0 seconds (±0.80) and untethered hammering overall averaged 1.93 seconds (±0.75).

Figure 44 depicts a side by side comparison between average time on task between the tethered and untethered wrench for each condition, which is further illustrated in an interaction plot in Appendix D.

Table 14: General Linear Regression ANOVA results wrenching

*indicates significance (p<0.05)

Wrench Time on Task (s)	
Factors	*p-values*
UT or T	0.322
Reach	0.453
Ladder	0.965
Reach*Ladder	0.257
Reach * UTorT	0.634
Ladder*UTorT	0.878
Ladder*Reach*UTorT	0.447

Table 15 shows that tethered wrenching resulted in 4%-23% in time increase to complete wrenching tasks, except in the case of the UR reach on ladder, which showed a 9% decrease in time during tethered wrenching.

Table 15: Table Average T/UT (SD) during wrenching

Ladder	Reach	T/UT	StDev
Off	LL	1.05	0.35
	LR	1.10	0.36
	UL	1.16	0.34
	UR	1.23	0.55
On	LL	1.19	0.27
	LR	1.04	0.25
	UL	1.15	0.28
	UR	0.91	0.22

Although tethering overall resulted in no statistical significance within the general linear model ANOVA, between reaches there was a slight increase in time during most tethered wrenching conditions, depicted in Figure 44, and further illustrated in Appendix D. Off the ladder, increased time during tethered wrenching was most prominently seen in the upper reaches, while off the ladder, left reaches showed greater time spent during tethered wrenching compared to untethered wrenching.

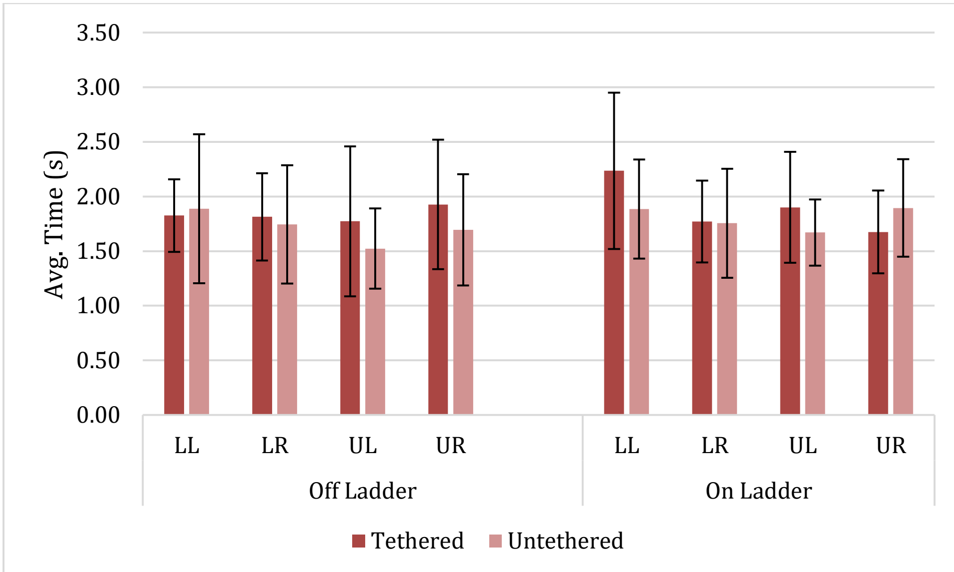


Figure 44: Average time on task (seconds) wrenching

4.7 Subject Opinion

Upon completion of each condition, the subjects were asked whether they preferred the tethered or untethered tool, or if they felt it was the same/no difference. In 63.5% of hammering scenarios, and 69.8% of wrenching scenarios subjects felt there was no difference or had no preference between the tethered or untethered tool. In only 5.2% of the scenarios did subjects prefer tethered hammering, and in 9% of scenarios subjects prefer the tethered wrench. The untethered hammer was preferred in 31.1% of the hammering scenarios, and the untethered wrench was preferred in 20.8% of the scenarios.

For certain instances, subjects were more particular about their preference. The least preferred reach position for the tether was UL while hammering on ladder (Figure 45) where users actively preferred the untethered hammer 58% of the time. The tethered hammer seldom was preferred by 8.3% of users off the ladder in the left reaches, and by 16.7% of users on the ladder during the UR reach.

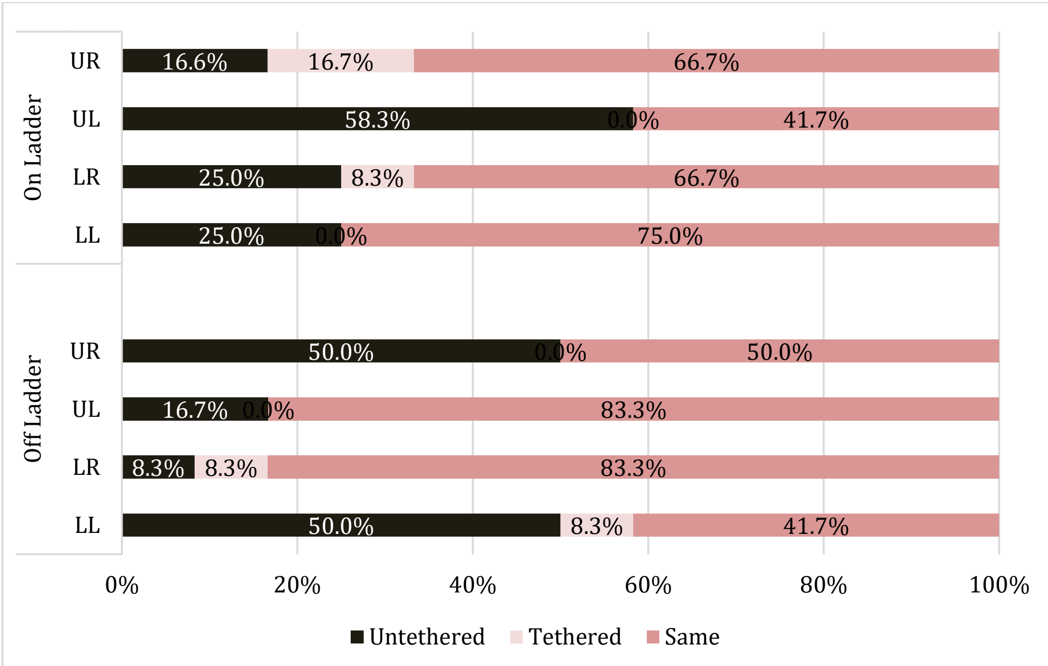


Figure 45: Subject preference during hammering in four reach positions on and off ladder

Statistical significance was verified using McNemar's test (Appendix E) between preferring the tethered hammer compared to having no preference, and, preferring the untethered hammer compared to having no preference. The first McNemar's test identified whether subjects preferred the tethered hammer over believing it felt the same as the untethered hammer, and results showed statistical significance (p<0.001). The second McNemar's test identified whether subjects preferred the untethered hammer over believing it felt the same as the tethered hammer, and resulted were also statistically significant (p<0.001). This ultimately indicates that that subjects did not prefer one condition over the other.

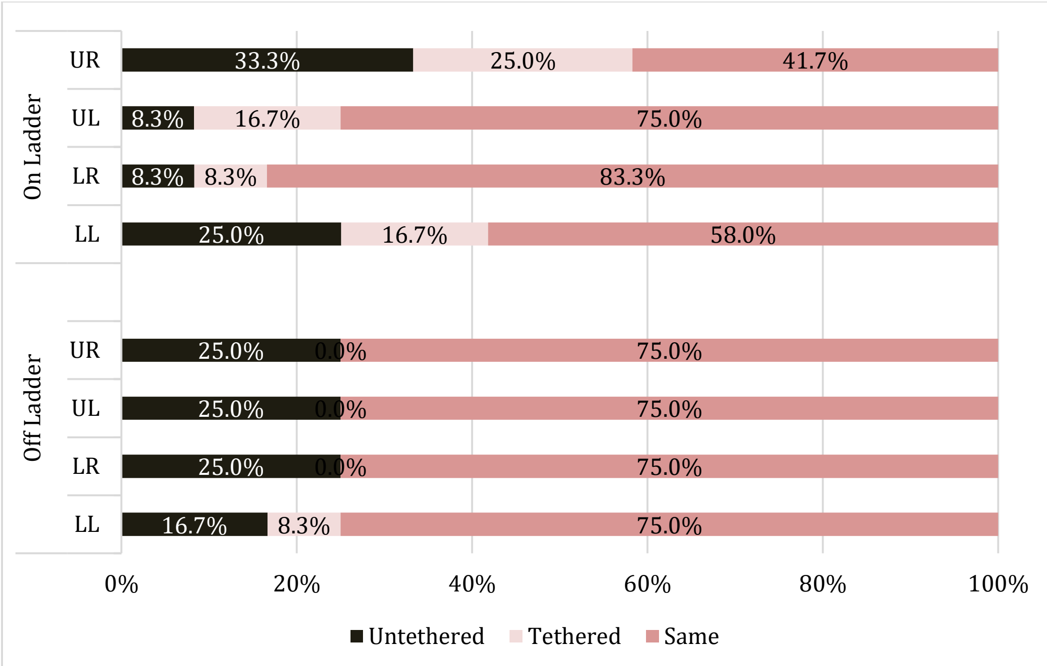


Figure 46: Subject preference during wrenching in four reach positions on and off ladder

More than half the subjects believed there was no difference between the tethered and untethered wrenching activity at every condition, except for in the off ladder UR reach condition. In this condition, the tethered wrench was the preferred by 25% and 33.3% preferred the untethered wrench. Those subjects who preferred the tether stated that while on the ladder it made wrenching feel safer because they knew it was not going to fall from that reach. In other cases, subjects mentioned that the tether made them feel restricted, or that it interfered with their tasks, particularly in reaches that were across the body.

Within wrenching, McNemar's test results showed statistical significance between preferring the tethered wrench and believing it felt the same as the untethered wrench (p<0.001). The second McNemar's test identified whether subjects preferred the untethered wrench over believing it felt the same as the tethered wrench, and resulted were also statistically significant (p<0.001). Like in hammering, this ultimately indicates that that subjects did not prefer one condition over the other.

5. Discussion

The primary focus of the study was to identify the biomechanical impact of using a tethered hammer and a tethered wrench during different reach and elevation conditions in comparison to using the tools without a tether. The secondary goal was to gather subject opinion data on in which conditions they preferred the tethered or untethered tools, or if they felt there was no difference while conducting the task after completing a condition.

5.1 Tether impact on muscle activity, hand grip pressure and time on task

It was hypothesized in H1 and H2 that using tethered tools would not have a significance effect on muscle activity, hand grip pressure and time on task when using a hammer or a wrench. Wrenching and hammering tasks were not compared to each other due to substantial differences between tasks. Results of this study show that tethering did not significantly affect muscle activity, hand grip pressure or time on task when using either tool in comparison to the untethered tools.

Although the ratios of T/UT for both hammering and wrenching show slight increases or decreases during certain conditions, the results were not statistically significant, and may be explained by a normal range of variation between subjects. For example, this is seen in wrenching where the T/UT ratio of the rPM during the on ladder UR reach condition was 1.21

and the standard deviation was ±0.26. This result could indicate that some subjects engaged the rPM much more than others during this condition.

Larger increases in muscle activity during tethered hammering in comparison to untethered hammering were seen in the following three conditions on the ladder: LL and UR within the rTr, upper reaches (UL and UR) in the rTB, LL in the rDel and UR in the rLD. This indicates that although statistically insignificant, tethering may have resulted in a slight pull during overhead reaches or across the body reaches. The location of the tether on the left side of the subjects and the type of tether may have influenced these results. It was also observed that subjects tended to twist their trunks more off the ladder during across the body, or left, reaches, possibly due to more freedom of movement while off the ladder and the ability to adjust body position closer or further to the hammering board. This twisting motion may have engaged other muscles that were not studied, which could have facilitated tool usage. While on the ladder, subjects were limited in their ability to twist their trunks, affecting their overall range of motion, and perhaps used greater upper body exertion when conducting tethered hammering.

For example, within hammering, the rTr in the LL reaches showed the largest T/UT ratios both on and off the ladder, and within the rDel the LL reach on the ladder showed a ratio of 1.32.   Within the rTr, tethering caused a 11% increase in muscle activity off the ladder, and a 29% increase on the ladder. Since the LL required subjects to hammer across their bodies, the tether may have caused a greater pull on the hammer. In addition, while off the ladder, subjects tended to twist more, allowing them to reach the left positions with more ease. While on the ladder, twisting was limited, since the ladder restricted movement of the whole body.

Because of this restriction, the right arm had to extend further when reaching across the body in the LL reach. Greater need for extension coupled with the possible downward pull of the tether may explain the increase in muscle exertion compared to untethered muscle activity.

Subjects' left arms were used to support and leverage their bodies during the wrenching tasks. Within the lTr there was no statistical significance between tethered and untethered wrenching conditions, although ratios and interaction plots show that untethered wrenching resulted in approximately 13% to 31% increase within the LL, LR and UL reaches while off ladder. Variation within subjects or knowledge that no tether was being used may have caused greater leverage or body support onto the wrenching structure than when using the tethered wrench. Further research is needed to determine whether tethering mentally impacts how a subject conducts a task.

Within the rLD , tethered wrenching shows slightly higher muscle activity while on the ladder, particularly in the UL reach, where tethering increase muscle activity by 16% from untethered muscle activity. While subjects were reaching overhead and across their bodies, the tether may have caused a downward pull, causing the subjects to pull upwards with more exertion and thus activating the rLD. This difference between elevations could be due to the fact that subjects supported their bodies using their left arm, thus making the rLD work slightly harder against the downward pull of the tether.

Bar graphs and interaction plots show that overall tethered and untethered muscle activity were approximately the same, with some instances showing that muscle activity was slightly increased while using a tether, while other instances show a slight decrease. Again, these results could be due to the large variation shown between subjects, but ultimately tethering is not a factor that would cause overexertion or fatigue when working.

Tethering resulted in no significant impact to hand grip pressure, and did not cause subjects to change how wrenching or hammering tasks were conducted. As with muscle activity, there were instances where tethering caused increases or decreases in hand grip pressure, but this could be due to the variation between subjects. Greater gripping exertion is associated with discomfort (Kong, et al., 2012), and because tethering was found to be insignificant on hand grip pressure, it can be assumed that tethering will not impact comfort or usability of hand tools.

Time spent to complete each condition was not significantly affected by using the tethered hammer and tethered wrench in comparison to their untethered counterparts.

The average task time during tethered hammering within each condition resulted in a slight decrease in ratios during most cases, however all ratios were between 0.90 and 1.10, indicating that tethered and untethered hammer task time were approximately the same. This was also statistically verified, with ANOVA results showing that there was no statistical difference in means between tethered and untethered hammering.

The average task time during tethered wrenching showed a 4% to 23% increase compared to untethered wrenching for all conditions except for on the ladder in the UR reach. This was found to be statistically insignificant, and considering the difference in average tethered wrenching and untethered wrenching was 0.07 seconds, overall productivity would not realistically be affected.

The differences between average task time within tethered and untethered hammering and within tethered and untethered wrenching were both less than one second apart. This indicates that productivity was not affected by tethering, and in regards to tool design, productivity must be kept in mind (Vedder, et al., 2005). In fact, tethered tools could increase overall productivity because they potentially eliminate time spent retrieving a dropped tool, or damage, injury and death caused by dropping a tool.

5.2 Ladder condition on muscle activity, hand grip pressure and time on task

H1.a and H2.a hypothesized that ladder condition would not impact muscle activity, hand grip pressure and time on task during hammering and wrenching. Ladder condition statistically impacted muscle activity in the rLD during hammering. Ladder condition did not statistically impact hand grip pressure or time spent on task.

Although the hammering board was adjusted so that the lower rung was at shoulder height regardless of whether the subject was on the ground or on the ladder, their bodies were more restricted in movement while on the ladder, and subjects supported their body weight against the hammering board and wrenching structure while on the ladder. Research shows that greater levels of discomfort and reduced performance due to restricted posture is associated with ladder use (Phelan, et al., 2014). Subjects were freer to twist their bodies while off the ladder to execute a task, because there was greater freedom of movement compared to being on the ladder. This twisting motion could explain why, while off the ladder, overall muscle activity was large enough to show statistical significance in the rLD, which was engaged while subjects twisted their trunks.

Ladder significantly affected the rTB during wrenching. Interaction plots clearly show that while on the ladder, there was a decrease in muscle activity in the LL and UL reaches, while increase was seen in the UR reach on the ladder. Across the body reaches engaged the rTB during the outward pushing motion required to loosen the bolt. This was more pronounced while the right arm was elevated overhead and across the body, resulting in increased activity.

Ladder condition did not show statistical significance on hand grip during hammering or wrenching. Off the ladder, hand grip pressure within reaches was approximately the same except within the LR reach, where tethering resulted in a 17% increase in grip pressure compared to untethered hammering. Overall, the LR reach resulted in the smallest hand grip pressure outputs, possibly because it was the closest reach to the subjects' bodies.

On the ladder, tethered hammering showed decreases in hand grip pressure during the LR and UL reaches. As with muscle activity, body positioning while on the ladder may be a causative factor. Because most subjects tended to twist their bodies less while on the ladder, the UL reach may have made it more difficult to properly grasp the hammer while twisting. Another reason could be that subjects felt the untethered hammer may not have been as secure for falling as the tethered hammer, and they held onto it with greater hand grip pressure. Further research should be conducted on how tethering affects subject perception of task completion, to determine if there is a psychological effect of using a tether.

5.3 Reach condition on muscle activity, grip pressure and time on task

In H1.b and H2.b, it was hypothesized that reach will impact muscle activity and grip, but not time on task. Reach did significantly impact muscle activity during hammering and wrenching. Reach did not significantly impact hand grip pressure or time on task during hammering or wrenching.

It was expected that different reaches would show statistical significance within muscles. Research has shown that when a handle is positioned at full reach distance versus half reach distant there is a greater effect on EMG output (Habes, et al., 1996), and is applicable to this study, since when right the arm moves directly overhead, compared to across the body or the left or is at a neutral straight ahead reach, different muscles engage to hold the arm in position.

Within hammering, tethering did not consistently show a pattern of requiring greater or lesser muscle activity within any reach or muscle, compared to untethered hammering. In general, upper reaches typically required greater muscular effort, followed by the LL reach and the least effort in the LR reach. The hammering tasks were less controlled than wrenching tasks that were torqued to 30 foot-pounds before each condition. Hammering was into wood that may not have always had the same density or hardness, which may have affected results, and could explain why there were differences within muscle activity between tethered and untethered hammering amongst the same conditions.

In general, during hammering, upper reaches both on and off the ladder required greater muscular exertion, particularly the UL reach. This reach is awkward due to it being overhead and across the body. Several subjects commented that they normally would have changed the hammer to their left hand if they were in a real world situation. During the lower left position for hammering, subjects had to reach across their bodies to conduct the hammering task, also resulting in an awkward position, which may have contributed to greater muscle activity in comparison to the LR reach.

Research has also shown a closer reach may be more advantageous when performing overhead work (Anton, et al., 2001). The LR reach posed the least amount of muscular effort for almost every muscle for several reasons: it was at shoulder height for the subjects on their dominant side, and did not require full extension of the arm, which the upper and the LL reaches did.

Within wrenching, tethering resulted increased ratios within most muscles in the LL reach off ladder and the UL reach on the ladder, possibly due to the awkward nature of across the body movement. Reach was the only statistically significant factor that affected muscle activity in the lTr during wrenching, and both on and off the ladder followed the same trend in muscle exertion versus reach. The left reaches required the greatest exertion, which may indicate that wrenching across the body necessitated more overall body support and muscle engagement to complete the tasks.

Tethered and untethered wrenching activity was similar amongst all conditions both on and off the ladder in the rTr. While wrenching, the rTr shows a substantial increase in muscle activity during the UL reach both on and off the ladder. This may be due to the reach being overhead and across the body. Pushing the wrench in that position required greater effort in the rTr due to the necessity for the subjects to conduct a motion that required them to shrug their shoulder while pushing up and overhead. This may have been augmented on the ladder in the UL reach, as seen by the 15% increase in muscle activity during the tethered muscle activity. The tether may have caused a slight pull directly downward, creating resistance that necessitated greater effort to keep the right arm overhead. This was also seen to a lesser degree in the UL off ladder condition, with tethering requiring approximately 5% greater effort.

Reach significantly affected rTB muscle activity, with similar reach trends showing both on and off the ladder. The greatest exertion was seen in the UL reaches, followed by the LL. Off ladder, the LR and UR reaches required approximately the same effort, while on the ladder the UR reach required greater effort than the LR reach. In general, tethered and untethered muscle activity was approximately the same within each condition.

Reach did not result in statistically significant changes on hand grip pressure. Within ratios, hammering showed that while on the ladder, the LL and UR reaches required greater hand grip pressure. Since the tether was located on the left side of the subjects, the tether may have caused a pull on the hammer during the LL reach resulting in increased hand grip pressure to counter the downward pull of the tether. The same could be said for the UR reach, where subjects pulled the tether across their body in an overhead position, increasing the grip pressure on the hammer.

Within wrenching, both on and off the ladder, tethered and untethered wrenching resulted in approximately the same hand grip pressure during the LL and UR reaches. The UL reach showed that tethered wrenching resulted in lesser hand grip pressure both on and off the ladder. This could be due to variability in data within subjects, or because that reach reduced the subject ability to properly hold the wrench. In addition, tethering may have affected the holding style of the wrench during the UL reach, resulting in lesser overall hand grip pressure.

5.4 Interaction between reach and ladder condition on muscle activity

The interaction between ladder and reach in the rPM during wrenching indicates that that ladder and reach have a significant effect on muscle activity. The rPM showed significantly greater muscle activity between the UL while off the ladder compared to other reaches. This reach required subjects to raise their right arm and use the wrench across their body which may have contributed to muscular contraction and resulted in greater muscular exertion. While on the ladder, the greatest activity was seen with the LL reach. Again, this across the body reach may have caused increased muscle contraction during the wrenching activity. The UR reach showed lesser exertion on the ladder compared to off. Video showed that subjects had a tendency to use their left hand to grab onto the wrench structure during wrenching both on and off the ladder, but while on the ladder their ability to change their foot placement was limited compared to off the ladder. This may have affected the UR reach because more strength was used with the supporting arm to leverage the body and alleviated the rPM while wrenching.

Previous research has shown that moving up a step on a ladder reduced deltoid and triceps activity when closer to a reach position, however bicep increased in muscle activity output due to the increased myoelectric activity to remain in a closer flexed position (Anton, et al., 2001). This was shown during this study in the wrenching interaction of reach and ladder condition on the rBB. The effect of UL reach on rBB muscle activity changes depending on ladder height. When off the ladder, the rBB showed an increase in UL muscle activity, yet showed the opposite effect while on the ladder. Because the ladder restricted body movement, subjects may not have been able to fully extend their arm, restricting rBB activity and range of motion.

The interaction between factors of reach and ladder height affected muscle activity in the rDel during the LR reach in wrenching. Holding onto the wrenching structure while in a constricted stance on the ladder may have caused subjects to lean forward and use more body weight to loosen the bolt, rather than using their rDel. While off the ladder, subjects did not support themselves as much as while on the ladder, since they were securely on the ground and were able to use their legs to plant themselves into the appropriate wrenching position.

5.5 Tether condition on subject tool use preference

It was hypothesized in H3 that subjects will not have a preference between tethered or untethered tool usages. This was confirmed statistically using McNemar's test, which was used to determine if subjects had a preference between the tethered or untethered tool after each condition, or if they had no preference. The data provides evidence that tethered is not equally preferred over the belief that the tethered and untethered tool conditions felt the same. The same was true for untethered tool usage, in that the untethered tools were not preferred over the belief that they felt the same. Ultimately, there was no statistical difference in preference between the tethered and untethered hammer and wrench, indicating that subjects

Subjects stated that there were certain positions where the tether felt uncomfortable or that it induced a slight pull on their tool while performing a task, particularly in the upper reaches within both tools. This could have also been due to the location of the tethering point on the tool. When tethering was preferred, rational revealed that the subjects felt it either corrected swing during hammering in the lower positions. During wrenching, one subject preferred the tethered wrench because he liked that it felt secure and safe. Re-positioning of the tethering point may alleviate pull, which may a topic of research for future studies.

The most frequent response was that there was no difference between the tethered and untethered tools, which confirms hypothesis H3. Surprisingly subjects in general did not have a preference between tethered or untethered tools. Their responses coincide with statistical data that tethers have no significant impact on the observed variables. When a subject expressed a preference for the untethered tool, it was explained to be due to restrictions in reach, such as across the body reach or overhead reach. Some felt the tether restricted their movement or was a nuisance to work with. When the tether was preferred, which was infrequently, subjects stated that it felt safer, or it helped correct 'swing' while hammering. These statements were made after some time into each trial, which could be seen as a learning curve towards acquiring a feel for the tether. Claims of discomfort or interference are based on personal perception, which was shown in this study in certain reach positions, but ultimately, the tether used on the hammer and the wrench did have significant biomechanical impacts on the subjects.

Tethered versus untethered tool usage was not found to be statistically significant for hammering and wrenching, and other tools should be tested to identify if tethering affects their usage. The range of experience across subjects varied, and none of them had experience using tethered tools. Subjects who regularly used tethered tools may reveal different results. Research shows that workers who are experienced with their work tools and environment tend to alleviate physical stress from awkward postures by frequently altering their body position in their work routine (Vedder, et al., 2005). An assessment into how tethered tool usage impacts the opinion and biomechanics of subjects experienced with their usage may provide more insight into how tethered tools affect people in the field.

The subjects used were all male, which could potentially limit the applicability of the study. In a study identifying the differences in strength and muscle fiber characteristics between males and females (Miller, et al., 1993), females were found to be approximately 52% as strong as males in upper body strength. Future research should test female subjects to identify if muscle activity and other biomechanical markers are affected differently than males during tethered tool use.

Conditions were all simulated inside of a lab and may not represent the broad scope of hammering and wrenching applications. Also, the scope of the tools used in this study was limited. Future research should aim to study if tethering affects the usage of other tools. For example, in this study, within wrenching there some muscles were affected by the interaction of reach and ladder, but not during hammering. This is because different tools require different body movement and therefore different muscle activation in comparison to wrenching and hammering. A broader scope of studied tools will reveal if tethering impacts any particular task type.

Other factors that are limited in this study is tether type and tethering location. Both the hammer and wrench were used with a retractable tether, and the tethering point was at the bottom of the tool handle. Research on other tether types, like a stretch design, or wristlet lanyard, as well as different tethering points, such as the top of the handle, or a rotating piece at the bottom of the handle, could lead to different biomechanical outcomes. This could provide tool designers with insight on tool design to minimize the potential interference of a tether.

The type of ladder used is a limiting factor of the study. The ladder used in this study was 8” off the ground, and was a stepping stool and not a traditional ladder. Research shows that conducting work on different types of elevated platforms impacts time on task and muscle activity. For example, ladders are associated with lesser task time in comparison to raised platforms, because platforms allow workers to take breaks, and ladders are associated with increased muscle activity in the shoulder due greater levels of force required to conduct a task (Phelan, et al., 2014). Future research that identifies tethered tool use at different elevations and ladder types may provide further insight into how performance is affected compared to tool use on the ground.

Tools that provide more comfort and less discomfort are associated with higher productivity (Kuijit-Evers, et al., 2005), and in general subjects claimed there was no difference between using the tethered and untethered tools. These findings are vital to tool designers and employers who want to maintain safety in at-height working environments without losing productivity. Within these finding, conditions overall show that tethering increased muscle activity slightly during some conditions, with decreased or the same muscle activity in other conditions. No specific pattern was seen where tethering caused a consistent increase or decrease amongst all the studied muscles. This further reiterates the justification for employers to supply their workforce with tethered tools, as they did not affect time on task, hand grip pressure, muscle activity or user opinion, and subsequently productivity. In fact, the use of tethered tools could increase productivity through decrease of incidents caused by dropping a tool. Because of insignificant impact to the user, tethered tool use will not contribute to musculoskeletal disorders.

The data in the study can be used by job analysts and tool designers to assess muscle activity and hand grip pressure required by tethering and to assess how tethers affect tool usability to include time spent on task, comfort and perception of task. Future research may aim to determine if the results of the study are generalizable to industries that frequently use hand tools at height. Further research may investigate how tether position on a tool may impact usage, and how tethers on commonly used hand tools impact users biomechanically. Real-world situations in lieu of lab conducted experimentation should be examined to improve tethered tool design and increase usage in the field, in order to diminish the devastating and potentially lethal consequences of dropping a tool from height.

Chapter IV: Conclusion

Tethered tool research is still very limited in nature, although it is evident that usage of tethered tools while working at height is fundamental in preventing injury, equipment damage, lost time on the job and death. Study 1 aimed at identifying tethered tool usage trends within the WPI and CG. Study 2 aimed at identifying the biomechanical impacts of tethered tool usage during different reach and elevation conditions. This chapter develops recommendations and proposed future research based on the results of Studies 1 and 2.

1. Limited statistical data and research is available on tethered tool usage at height.

Recommendation: Future research should look into administering more detailed surveys into tethered tool usage and trends across a greater variety of at-height industries. This information is necessary in identifying further information into types of tools being used, reasons into why employees have particular preferences, and how employers influence work safety culture. Identifying this type of information allows for policy makers, tool designers and ergonomists to develop appropriate tools for safe and proper use at height.

Recommendation: Regulations be developed to mandate tethered tool usage.

Additional Research: Future research should attempt to quantify the number of tools dropped in at height industries, as well as injury, damage and death statistics.

2. There is a strong positive correlation between tethered tool usage and being provided with them by an employer.

Recommendation: Employers and tool designers must also recognize which tools are most commonly used by workers at height, and which tools should be tethered. These findings should be applied to daily industry, so that employees have access to the appropriate safety gear. In addition, employers must ensure that safety gear is always used, and that safety training is provided to their employee on the hazards of not using tethered tools as a means of increasing safety awareness and improving work-safety culture for at-height industries.

Additional research: Elements that may contribute to decreasing costs and increasing affordability in design of tethered tool usage to encourage employer purchasing should be investigated.

3. Tethered tool users are more likely to use alternate means of transporting their tools in addition to using a tool bag or tool bucket.

Recommendation: Further research is needed on which tool carrying methods other than buckets or tool bags are most preferred by at height workers. Tool designers could use this data to develop appropriate apparatuses with tethering points for workers at height. Increasing usability of means alternate to buckets, such as tool vests, tool belts and tool back-packs, could lead to an increase in their usage and a decrease in bucket usage where loose tools are carried.

4. Tethering was not statistically significant to user biomechanics or user preference overall and did not statistically impact tasks during different reaches and ladder conditions.

Recommendation: Because no difference in biomechanical impact was found while using the tethered hammer and wrench in comparison to their untethered counterparts, industry employees and workers should be encouraged to use tethered tools when working at height.

Additional research: Ergonomic assessment on alternate tethering points on a tool, different tether types and different hand tools that are commonly used should be performed to determine if those factors have an effect on user biomechanics and productivity.

5. Reach was statistically significant to user muscle activity, with the LR reach generally resulting in the least muscle exertion across most muscles.

Recommendation: When using hand tools, workers should avoid excessive overhead or across the body reach to avoid increased muscle activity that could potentially lead to fatigue or overexertion.

Additional Research: This study only looked at four reaches. Investigation into additional reach positions, particularly at varying degrees across the body could reveal worker capabilities and limitations when reaching to conduct work at height.

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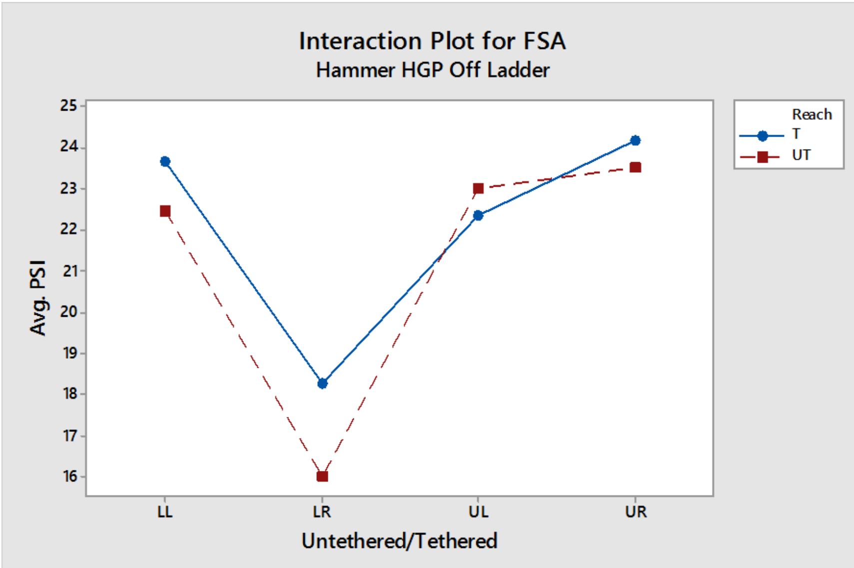
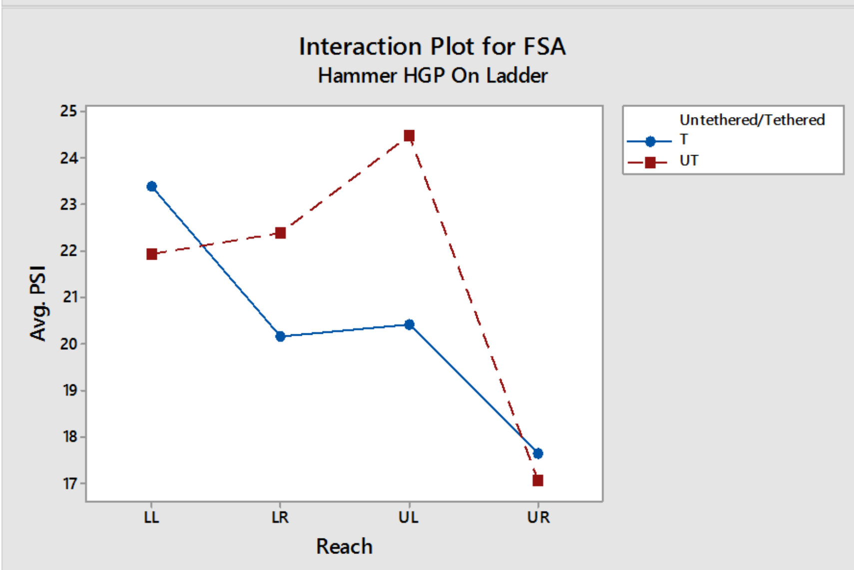
Appendix

Appendix A: Interaction plots for hand grip pressure during hammering





Hammer Off Ladder HGP Results for: FSA Hammer Off Ladder.MTW

General Linear Model: FSA versus Subject, Untethered/Tethered, Reach

Method

Factor coding (-1, 0, +1)

Rows unused 26

Factor Information

Factor	Type	Levels	Values
Subject	Random	11	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Untethered/Tethered	Fixed	4	LL, LR, UL, UR
Reach	Fixed	2	T, UT

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	10	1161.27	116.127	2.77	0.008
Untethered/Tethered	3	189.67	63.223	1.51	0.223
Reach	1	4.42	4.421	0.11	0.747
Untethered/Tethered*Reach	3	63.75	21.250	0.51	0.679
Error	52	2177.08	41.867		
Total	69	3789.74			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
6.47047	42.55%	23.77%	0.00%

Hammer On Ladder HGP Results for: FSA Hammer On Ladder.MTW

General Linear Model: FSA versus Subject, Untethered/Tethered, Reach

Method

Factor coding (-1, 0, +1)

Rows unused 23

Factor Information

Factor	Type	Levels	Values
Subject	Random	11	2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Untethered/Tethered	Fixed	2	T, UT
Reach	Fixed	4	LL, LR, UL, UR

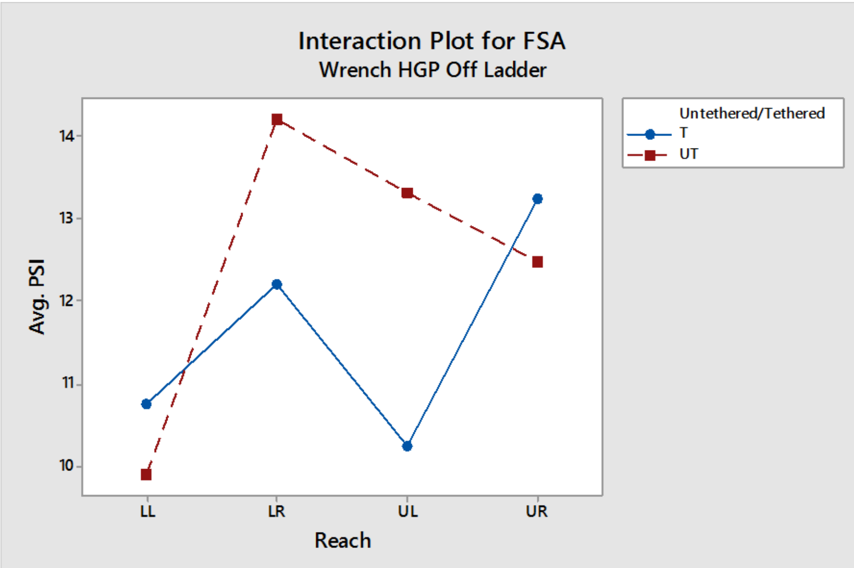
Analysis of Variance

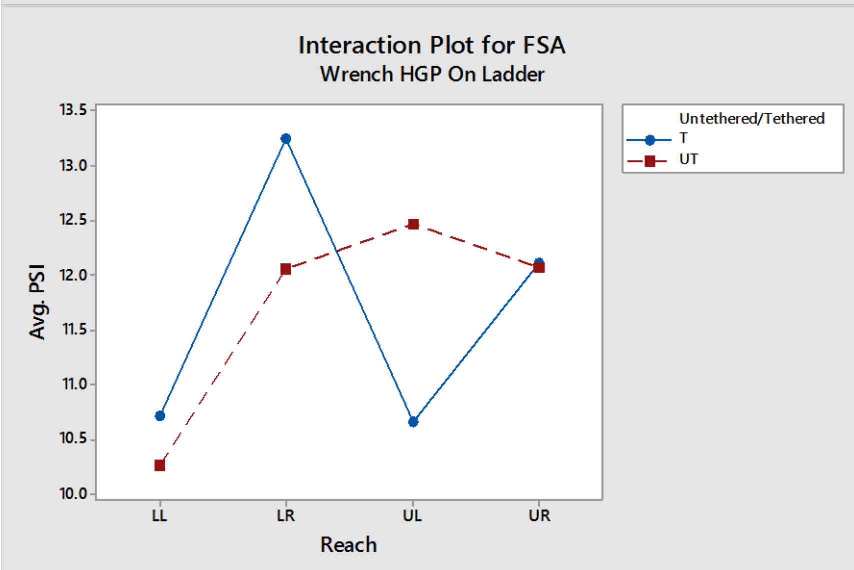
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	10	1886.67	188.667	4.00	0.000
Untethered/Tethered	1	3.29	3.295	0.07	0.793
Reach	3	255.09	85.029	1.80	0.158
Untethered/Tethered*Reach	3	150.88	50.295	1.07	0.371
Error	55	2596.23	47.204		
Total	72	4911.18			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
6.87053	47.14%	30.80%	7.46%

Appendix B: Interaction plots for hand grip pressure during wrenching





Wrench Off Ladder HGP General Linear Model: FSA versus Subject, Untethered/Tethered, Reach

Method

Factor coding (-1, 0, +1)

Rows unused 3

Factor Information

Factor	Type	Levels	Values
Subject	Random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Untethered/Tethered	Fixed	2	T, UT
Reach	Fixed	4	LL, LR, UL, UR

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	11	1344.70	122.25	4.54	0.000
Untethered/Tethered	1	23.91	23.91	0.89	0.349

Reach	3	127.37	42.46	1.58	0.202
Untethered/Tethered*Reach	3	84.21	28.07	1.04	0.379
Error	74	1993.87	26.94		
Total	92	3540.45			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.19078	43.68%	29.98%	10.29%

Wrench On Ladder HGP General Linear Model: FSA versus Subject, Untethered/Tethered, Reach

Method

Factor coding (-1, 0, +1)

Factor Information

Factor	Type	Levels	Values
Subject	Random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Untethered/Tethered	Fixed	2	T, UT
Reach	Fixed	4	LL, LR, UL, UR

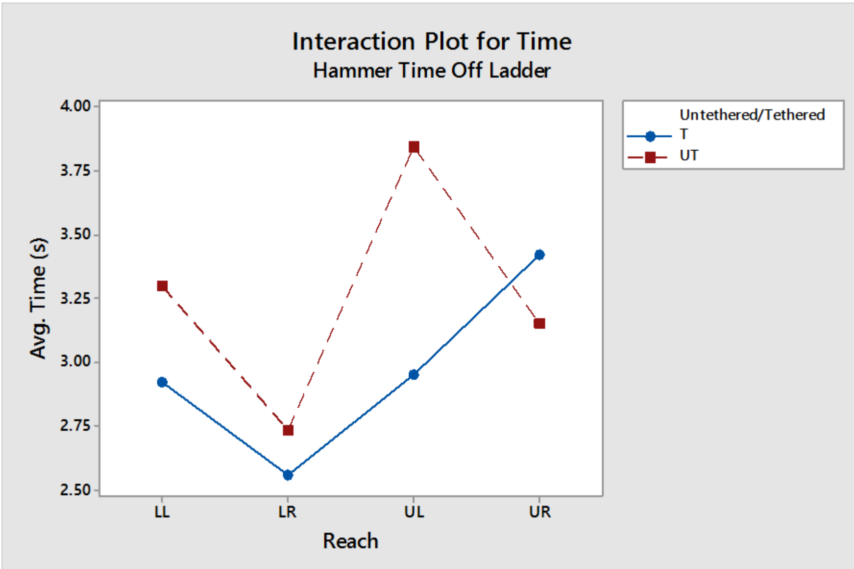
Analysis of Variance

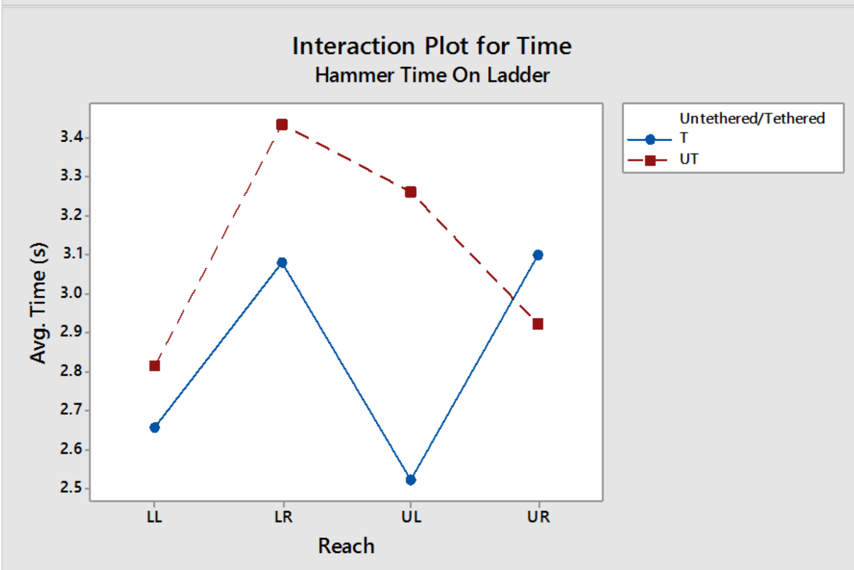
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	11	2368.86	215.351	8.23	0.000
Untethered/Tethered	1	0.02	0.020	0.00	0.978
Reach	3	61.07	20.357	0.78	0.510
Untethered/Tethered*Reach	3	29.47	9.823	0.38	0.771
Error	77	2014.30	26.160		
Total	95	4473.72			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
5.11466	54.97%	44.45%	30.01%

Appendix C: Interaction plots for time on task during hammering





Hammer Time Off Ladder Results for: Hammer Time Off Ladder.MTW

General Linear Model: Time versus Subject, Reach, Untethered/Tethered

Method

Factor coding (-1, 0, +1)

Rows unused 2

Factor Information

Factor	Type	Levels	Values
Subject	Random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Reach	Fixed	4	LL, LR, UL, UR
Untethered/Tethered	Fixed	2	T, UT

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	11	299.376	27.216	21.30	0.000
Reach	3	6.234	2.078	1.63	0.190
Untethered/Tethered	1	2.052	2.052	1.61	0.209

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Reach*Untethered/Tethered	3	4.037	1.346	1.05	0.374
Error	75	95.853	1.278		
Total	93	408.852			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.13050	76.56%	70.93%	63.03%

Hammer Time On Ladder General Linear Model: Time versus Subject, Reach, Untethered/Tethered

Method

Factor coding (-1, 0, +1)

Rows unused 3

Factor Information

Factor	Type	Levels	Values
Subject	Random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Reach	Fixed	4	LL, LR, UL, UR
Untethered/Tethered	Fixed	2	T, UT

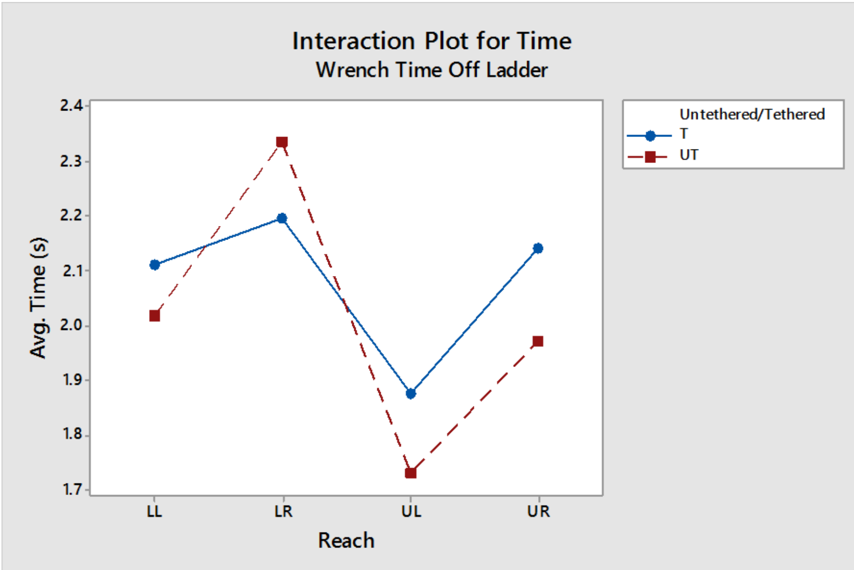
Analysis of Variance

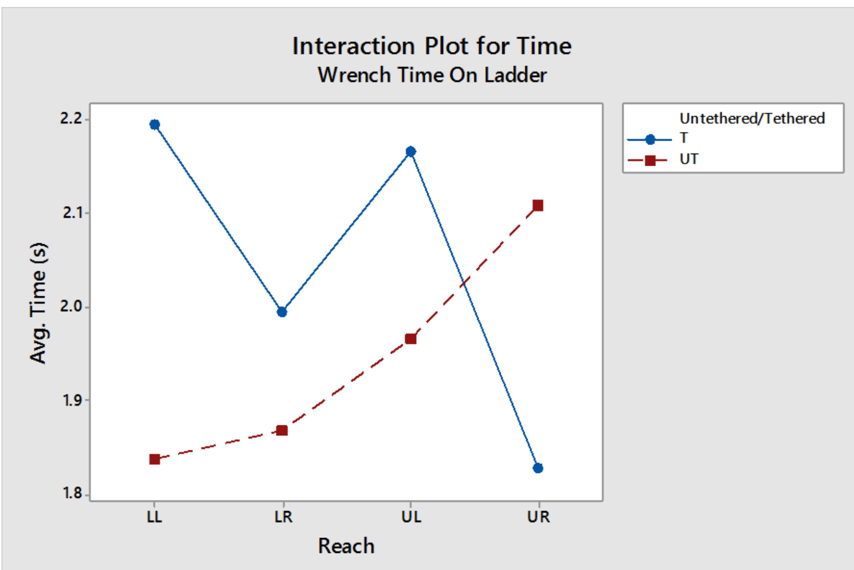
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	11	386.218	35.1107	29.41	0.000
Reach	3	1.404	0.4681	0.39	0.759
Untethered/Tethered	1	0.000	0.0002	0.00	0.990
Reach*Untethered/Tethered	3	2.028	0.6761	0.57	0.639
Error	74	88.347	1.1939		
Total	92	482.079			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1.09265	81.67%	77.22%	70.24%

Appendix D: Interaction plots for time on task during wrenching





Wrench Time Off Ladder General Linear Model: Time versus Subject, Reach, Untethered/Tethered

Method

Factor coding (-1, 0, +1)

Rows unused 2

Factor Information

Factor	Type	Levels	Values
Subject	Random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Reach	Fixed	4	LL, LR, UL, UR
Untethered/Tethered	Fixed	2	T, UT

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	11	44.9934	4.09031	8.41	0.000

Reach	3	2.3899	0.79664	1.64	0.188
Untethered/Tethered	1	0.1392	0.13922	0.29	0.594
Reach*Untethered/Tethered	3	0.2890	0.09634	0.20	0.897
Error	75	36.4638	0.48618		
Total	93	84.4353			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.697269	56.81%	46.45%	31.99%

Wrench Time On Ladder General Linear Model: Time versus Subject, Reach, Untethered/Tethered

Method

Factor coding (-1, 0, +1)

Rows unused 4

Factor Information

Factor	Type	Levels	Values
Subject	Random	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
Reach	Fixed	4	LL, LR, UL, UR
Untethered/Tethered	Fixed	2	T, UT

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Subject	11	24.1896	2.19905	8.76	0.000
Reach	3	0.0518	0.01727	0.07	0.976
Untethered/Tethered	1	0.2339	0.23393	0.93	0.338
Reach*Untethered/Tethered	3	1.2646	0.42153	1.68	0.179
Error	73	18.3262	0.25104		
Total	91	44.2896			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.501043	58.62%	48.42%	34.23%

Appendix E: McNemar's Test results for tool condition preference during hammering

Hammering UT vs Same Tabulated Statistics: Worksheet rows, Worksheet columns

Rows: Worksheet rows   Columns: Worksheet columns

	UT	T	All
1	29	0	29
2	67	5	72
All	96	5	101

Cell Contents: Count

McNemar's Test

Estimated Difference	95% CI	P
-0.6634	(-0.7654, -0.5613)	0.000

Difference = p (Worksheet rows = UT) - p (Worksheet columns = 1)

Hammering T vs Same Tabulated Statistics: Worksheet rows, Worksheet columns

Rows: Worksheet rows   Columns: Worksheet columns

	T	UT	All
1	5	0	5
2	91	67	158
All	96	67	163

Cell Contents: Count

McNemar's Test

Estimated Difference	95% CI	P
-0.5583	(-0.6407, -0.4759)	0.000

Difference = p (Worksheet rows = T) - p (Worksheet columns = 1)

Appendix F: McNemar's Test results for tool condition preference during wrenching

Wrenching UT vs Same Tabulated Statistics: Worksheet rows, Worksheet columns

Rows: Worksheet rows Columns: Worksheet columns

	UT	T	All
1	19	0	19
2	77	9	86
All	96	9	105

Cell Contents: Count

McNemar's Test

Estimated Difference	95% CI	P
-0.7333	(-0.8274, -0.6392)	0.000

Difference = p (Worksheet rows = UT) - p (Worksheet columns = 1)

Wrenching T vs Same Tabulated Statistics: Worksheet rows, Worksheet columns

Rows: Worksheet rows Columns: Worksheet columns

	T	UT	All
1	9	0	9
2	87	77	164
All	96	77	173

Cell Contents: Count

McNemar's Test

Estimated Difference	95% CI	P
-0.5029	(-0.5832, -0.4226)	0.000

Difference = p (Worksheet rows = T) - p (Worksheet columns = 1)