UNPOWERED DRYWALL LIFTING DEVICE: CHARACTERIZATION OF LOAD REDUCTION WHILE LIFTING DRYWALL IN THE CONSTRUCTION ENVIRONMENT

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

The drywall trade is the 4th most hazardous in the construction industry, with a worker injury rate 4 times that of the industry average. On a daily basis, workers are exposed to slips, falls, and falling objects, in addition to the large and awkward loads they must carry. Drywall sheets can weigh more than 100 pounds and be catastrophic to the health of the installer's shoulders and lower back.

For this study, an unpowered lift assist device was developed to carry the load of a drywall sheet during the installation process. The device takes the form of a polar robot similar to a camera jib and allows the installer to move sheets effortlessly through the workspace. Initial calculations indicated a nearly 63% reduced weight in the user's hands.

A testing regimen was developed to simulate a drywall installer's most hazardous lifting motions. These lifting motions were repeated both with and without the device for comparison. During these lifting motions, test subjects were fitted with electromyography (EMG) sensors on 4 lumbar muscles to measure muscle activation. Mean, peak, and effort data for the lifting exercises were extracted and compared to the unassisted lift.

Test data revealed overall muscle activation across all 4 muscle groups on both lifting motions was reduced by 69%. These data support the effectiveness of the device and warrant future development of such a device.

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CHAPTER 1

INTRODUCTION

Undeveloped worksites, exposure to the elements, poor lighting, heavy and powerful equipment, among other factors, make construction trades some of the most dangerous occupations in the world. The fourth most dangerous occupation in the construction industry is drywall installation, which involves lifting of large and bulky sheets of drywall. The subject device is intended to reduce the load in the shoulder and lower back of the installer. This thesis specifically quantifies the reduction in muscle exertion levels on the lower back during the lifting process resulting from use of the device. Muscle exertion levels were measured using established electromyography (EMG) methods.

CHAPTER 2

BACKGROUND

The Drywall Industry

History

Drywall is the flat panel that forms the surface of the interior walls of a residential or commercial building. Plywood or other sheet materials can be used, but drywall is the predominant covering of framing used in the construction industry. Drywall and other gypsum-based products have been used since the late 19th century (Gypsum Association, n.d.). The drywall sold in the 21st-century home improvement store is the same basic form that has been sold since the latter half of the 20th century (Gypsum Association, n.d.). This material is often referred to as drywall, plasterboard, gypsum, or sheetrock. An estimated 97% of new homes are constructed using drywall (Gypsum Association, n.d.). The average American home contains 7.31 metric tons of gypsum, and the U.S. housing market incorporates more than 42 billion square feet of drywall each year (Gypsum Association, n.d.). Worldwide, the drywall industry represents a $48 billion market employing more than 82,000 workers (U.S. Department of Labor, Bureau of Labor Statistics [BLS], n.d.).

Installation Process

The drywall installation process consists of three major steps: framing, hanging, and finishing. *Framing* is the result of the process of assembling wood or metal members to form the shape and structure of the wall (see Figure 1). Framing members are typically spaced vertically at 16- or 24-in. intervals, depending on the type of wall and local building code. The vertical members are attached together by means of a header and footer that extend the horizontal length of the wall. The vertical members are often referred to as *studs*, while the lower and upper attaching members are referred to as *bottom* and *top plate*, respectively.

After framing is completed, the drywall is fitted or “hung” to the framing. Before the sheets can be cut and fitted for installation, they must be delivered and stacked in the building. For a professional project, delivery and stacking is typically done by a supplier, who delivers the drywall on a flatbed truck. Once at the site, the driver will deploy a crane that will lift the drywall to an opening in the building (see Figure 2). Workers will place the drywall in a vertical stack against a framing wall or in horizontal stack on the floor (see Figure 3). In a commercial building, a forklift might be used to move the drywall.

The sheets, once stacked in the house, are cut to length and height. Notches or holes may also be cut into the drywall to accommodate electrical outlets, doors, windows, and ducts. The sheet is lifted into place by the installer (see Figure 4) and attached to the framing using nails or screws (see Figure 5). Nails or screws are spaced 12 in. on center for the field of the sheet and 7 or 8 in. around the perimeter for ceilings and walls, respectively (US Gypsum, n.d.).

The drywall can then be finished using tape and drywall joint compound (commonly referred to as *drywall mud*) to seal joints and provide texture, if desired. Three or four coats of joint compound are typically required to seal and smooth out the joints (see Figure 6). In between each coat, the surface of the dried joint compound is sanded to remove ridges or bumps that may affect the finish of the next coat. A coat of low-viscosity (water-added) joint compound may be applied using a spray gun or other tool to create a texture (see Figure 7). This texture can be created for aesthetic purposes or to hide flaws in the previous processes.

Building Codes and Standards

A *building code* is a set of rules or regulations that govern the construction of a structure. Building codes are meant to protect the health and welfare of the occupants of the structure. Building codes for inhabited structures are organized into residential and commercial categories with subcategories such as plumbing and electrical. There is an international building code (IBC); however, no country is mandated to use that building code. Even in the United States, which has adopted the IBC, each municipality is free to adapt the IBC to its own local needs.

Residential and commercial ceiling are typically 8 ft high at a minimum and can extend up to 12 ft or more. Closets and bathrooms can be quite small, but most bedrooms will be at least 8 ft square. Most bedrooms are 10 ft square or larger.

Material Size and Dimension

Sheets of drywall are always 4 ft tall, but range in length from 8 ft to as much as 16 ft. Sheet thickness can vary from 1/4 in. to 5/8 in. in the U.S. market. The thicker (5/8 in.) drywall is mandated for firewalls around stairs and garages. The weight of a drywall sheet varies from 30 lbs to 200 lbs. In recent years, drywall manufacturers have begun producing lightweight drywall by reducing the density of the gypsum core. A typical 4 ft x 8 ft x 1/2 in. sheet weighs approximately 50 lbs. Table 1 is a sample of typical drywall sheet weights from the manufacturer, US Gypsum (n.d.). While this information is not intended to represent the entirety of drywall options, it does give a sampling of expected weights.

Drywall manufactures also produce many specialty drywalls in addition to lightweight panels. These specialty panels are made to meet specific environmental or strength demands such as moisture, mold or fire resistance, high strength or flexibility, and damage resistance. The weights of these panels may be different from those of standard drywall.

Drywall Tools and Equipment

There are many tools used during the drywall installation process ranging from a simple razor knife for cutting drywall to truck-mounted cranes (see Figure 2) for stacking and installing the drywall in a building. For purposes of this study, we will focus on the tools and equipment used for the lifting and moving of the drywall from the stack on the floor or leaned against a wall to the point of attachment to the framing. This task poses the highest risk of injury to the installer.

Many tools are available to help reduce hazards during the lifting and attachment task. They range from simple hand tools to large lifts and poles. Hand tools include handles to extend the reach of the installer to reduce bending motion (see Figure 8), as well as levers or wedges to lift the sheet from the ground. There are also lifts to help hoist the drywall sheet into place on a ceiling and on some walls (see Figure 9).

Drywall Installers

Demographics

According to the 2014 data published by the BLS (n.d.) for the drywall and ceiling tile installer industry, there are more than 85,000 workers employed in the industry. These workers make a median annual salary of $43,000. Two studies placed the male demographic of the workforce at approximately 98–99%. Worker ages ranged from 18 to 71, with a mean of 31 years.

Exposures

During the installation process, drywall workers are exposed to slips and falls at ground and elevated levels, as well as falling material and tools (Chiou, Pan, & Keane, 2000). Workers also must lift heavy loads in awkward positions on ladders and scaffolding (Pan & Chiou, 1999). The drywall panel installation task poses a severe threat to the safety and musculoskeletal health of drywall workers (Dasgupta et al., 2014) because, in most cases, the weight of the drywall panel exceeds recommended loading limits for the back (Dasgupta et al., 2014; Pan & Chiou, 1999).

The preponderance of data point to the lifting, carrying, and attaching of drywall as the most hazardous phases of the installation process (Lipscomb et al., 2000; Lipscomb, Dement, Nolan, Patterson, & Cameron, 2003). Although the rates of injuries in some demographics have reduced over time, overexertion back injuries continue to make up a large portion of overall injuries, and many of these injuries may go unreported

(Schoenfisch et al., 2014). Lifting of drywall is especially dangerous to the back because the heavy loads lifted must be from the ground and the task requires the worker to stand in an awkward position.

The carrying phase can be equally hazardous because the worker typically twists his or her trunk while under the load and the possibility exists for slips and falls (Lipscomb, Dement, Nolan, et al., 2003). Although the attaching phase does not appear to be as hazardous as the lifting phase because little movement is required to affix the drywall to the framing, the task poses a hazard because it is often done on scaffolding or ladders, and for extended durations of time with one hand.

Safety Recommendations

Prior research studies (Lipscomb, Dement, Li, Nolan, & Patterson, 2003; Spielholz, Davis, & Griffith, 2006; Yuan & Buchholz, 2014), as well as government organizations (Bernard, 1997; The Center for Construction Research and Training, 2013; U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health [NIOSH], 2006), have recommended several means of reducing the injury rate for drywall installers. These recommendations have included

- having two workers while lifting and transporting material instead of only one worker;
- lifting one sheet at a time;
- minimizing movement by stacking material close to installation location;

- ensuring safer working conditions, such as clean and flat floor, good light, and so forth;
- using equipment such as handles, lifts, and carts to aid in lifting;
- reducing the size and weight of the sheet; and
- providing better training on safe handling practices.

While efforts have been made to address these issues, including reducing the density of material, the sheets have gotten bigger to minimize installation time and finishing effort. In addition, many workers are set in their ways and change is a slow process (de Jong & Vink, 2000).

Figure 1. Framing of a house ready for drywall installation. Adapted from “CotY 2013 Award: Entire House, Framed House Structure,” by EDW Builders, 2013. Copyright 2013 by Bob Graham, Jr. Photography.

Figure 2. Delivery of drywall to jobsite. Adapted from “FASS Crane Lifting Drywall,” by The Blue Book Network, n.d. Copyright 2015 by Contractors Register.

Figure 3. Drywall stacking in building. Adapted from “Nohasslecastle.com,” by Joe, 2011. Copyright 2011 by Joe.

Figure 4. Worker fitting and installing drywall in residential building. Adapted from “Ultralight Sheetrock Drywall Panels from USG,” by Charles and Hudson, n.d. Copyright 2015. by Charles and Hudson.

Figure 5. Workers attaching drywall to framing.

Figure 6. Worker applying joint compound. Adapted from “Craftsman Finishing Drywall Joint,” by Earley Construction, 2009. Copyright 2009 by Earley Construction.

Figure 7. Worker applying drywall texture. Adapted from “Skip-Trowel Texture,” by K. B. Marks, n.d. Copyright n.d., by Bill Marks Painting.

Figure 8. Examples of carrying handles. Adapted from “Drywall Repair, Installation, and Finishing,” by K. LaRue, n.d. Copyright 2015 by K. LaRue.

Figure 9. Example of a drywall lift. Adapted from “How to Hang Drywall on Ceiling with a Lift,” by Baixar Musica, n.d. Copyright 2015 by Baixar Musica.

Table 1. Sample Drywall Weights

Size	Weight (lbs)
4' x 8' x 3/8"	38
4' x 8' x 1/2"	51
4' x 12' x 1/2"	77
4' x 14' x 5/8"	123

CHAPTER 3

DEVELOPMENT

Material versus Nonmaterial Solution

There are two main ways to address many of the hazards: tools and training. Training consists of thoroughly understanding the task, identifying the hazard or exposure, developing methods to reduce the hazards, teaching them to workers, and then following up to ensure the training was effective. Training has been adequately provided to the population for years. However, the fact is that sheets of drywall are heavy and cumbersome. Alternatively, tools can be manufactured to assist in reducing the weight and awkwardness of the sheets handled by the installer.

Material Solution

Many tools have been developed with the objective of helping to reduce the effort required to lift the sheets of drywall. Among these tools are handles and lifts. Although handles and lifts are useful, they do not solve the entire problem. Innovations such as handles and lifts have been slow to be adopted into the construction industry (Kramer et al., 2010), especially if the tools hamper productivity. Devices such as handles merely allow the user to adopt a better ergonomic position without relieving the user of the load (Hess, Kincl, & Davis, 2010; Lipscomb, Dement, Silverstein, Cameron, & Glazner, 2009). In most cases, users found the handles to be more of a hindrance than a help. Lifts reduce the weight in the user’s hands for a portion of the time, but the installer must still lift the sheet onto the lift before using it. These devices tend to be unstable at extended heights.

A solution is needed that places the installer in a good ergonomic position as well as reduces the weight in the user’s hands for the entire duration of the installation process. The ideal solution would be to use a fully automated robot with full motion control to cut, move, and attach the sheets of drywall (see Figure 10). Due to the working environment, costs, and ever-changing locations in the construction industry, large robots with heavy bases would not be economical or feasible.

Other industries in manufacturing that face similar problems have used lift-assisting devices for more than 50 years. While the human user must interface with the object being moved or the machine doing the lifting, the machine bears a majority of the weight and receives input from the user. Forklifts, pallet dollies, and hand trucks are examples of this category of lifting devices. None of these devices are viable solutions for use in the construction environment.

In the assembly and packaging industry, many devices are used that remove the load from the user while still allowing the user to control the position of the load via simple hand controls (see Figure 11). For example, glass panels can be lifted via cable support arms or mobile-base cranes (see Figure 12). All these devices are useful in their intended settings, but they often require heavy, fixed bases or are slow and awkward in confined spaces, such as those found in a home under construction.

Device Design

Desired Device

A new class of lifting device is needed to address the following concerns:

- is easily portable in the construction environment by one installer;
- limits floor loading to 30 lbs per square foot to meet design loads (American Wood Council, 2015);
- limits power consumption to generator capabilities;
- is able to reach the entire working envelope (from sheets laying on the ground to a 12-ft ceiling); and
- reduces loads placed on installers’ musculoskeletal frame, specifically the erector spinae muscles.

Motivation

National and local government agencies, workers’ unions, insurance companies, employers, and employees are all interested in reducing the injury rate among drywall workers. Profits and time are lost and personal lives are affected when workers are injured on the job (Lipscomb et al., 2009). The goal of this thesis and the motivation for conducting the project is to reduce the accident and injury rates of drywall installers by achieving a comprehensive understanding of the lifting task and developing tools and methods to reduce accidents and injuries.

Inspiration

A machine to facilitate the drywall lifting task might take many different forms. It could mimic one of the existing mobile machines or even an industrial robot. Although these options are viable solutions, they often require large bases and power supplies. A major factor in reducing cost and power consumption is reducing the number of actuators incorporated into the system to manipulate or move the drywall. A simple single actuated device, as shown in Figure 11, could be used for transporting drywall from one location to another, but it would not allow for installing drywall on ceilings. The overhead crane system (see Figure 12) would allow for installation of drywall on ceilings, but would be limited by height of walls or the overall structure.

Another industry that offers inspiration for a drywall lifting device is the film industry. Jibs are used to hold cameras in place at extended distances and heights while still allowing the camera operator to have considerable control over the camera. Figures 13 and 14 contain two extreme examples of camera jibs. Figure 13 shows a simple unpowered, fixed-length jib that is counterbalanced to lift a camera. Figure 14 shows a fully powered telescoping jib that allows for the camera to have a full 6 degrees of freedom of movement. In essence, these camera jibs are examples of a polar robot. This configuration is particularly desirable as a model for a drywall lift in that it offers the following advantages:

- counterbalanced to eliminate need for large or heavy base,
- no requirement for actuation,
- portable, and
- mechanically simple.

Concept Device

After considering a number of options, the decision was made to use a polar robot configuration for the conceptualized lifting device (see Figure 15). The base consists of a tripod for stability and wheels for mobility. The wheels can be locked for stability during operation. At the top of the base is a two-axis joint that allows for yaw and pitch motions. The arm is telescoping to allow for extension to reach walls and the ceiling throughout the working environment without having to relocate the device. The three previous joints (pitch, roll, and yaw) will allow for positioning in space. Most residential homes have rooms not smaller than 10 ft square and 8 ft tall. The device must be able to be operated within this space without compromising the integrity or safety of objects already in the space.

At the distal end of the arm is a head that allows for three degrees of freedom for orienting the sheet of drywall in space. At the back end of the arm are weights, which are used to counterbalance the head and drywall. The head must be able to pick up a sheet of drywall that is lying flat on the ground or leaning against a wall. It should also be able to place the sheet on a vertical wall, horizontal surface (ceiling), or any angle in between. In addition, it should be able to rotate the sheet about an axis normal to the sheet plane so that the sheet can be oriented horizontally or vertically.

The machine should also have a means for attaching to and releasing from the drywall quickly while still holding the panel securely during the full range of motion. The forces on this connection will be highest while lifting vertically from a stack lying flat on the ground. Throughout the lift, not only will the sheet be supported, but also it will be subject to acceleration, surface tension with the other sheets in the stack, and air resistance. One viable solution to this attachment need is suction cups, which are widely used in other industries.

This Project

Time and fiscal constraints led to the project making use of a simple design that included the minimum number of features to test the overall concept of the design (see Figure 16). The device is an unpowered system so that the focus could be on the configuration and effectiveness of lifting, as opposed to the controls. The arm will not include the option to telescope, which will limit the working envelope, but along with using a standard 4 ft by 8 ft sheet of drywall, this design eliminates the need for a dynamic counterbalance (see Figure 17).

Lifting Device Design

The device consists of four main components:

- mobile base,
- arm,
- counterweights, and
- head.

The base is constructed of t-slot extrusions (see Figure 18) for ease of manufacture and configuration. There are three legs for stability, and each leg is equipped with a 4 in. caster at the end. Each caster can be locked to secure the entire device in place on the floor. At the top of the base is a caster assembly that has been repurposed to provide motion along the yaw and pitch axes. The entire base weighs 16 kg. The distance between casters is 0.7 meters and the overall height to the pitch axis of the caster is 1.3 m. Articulation of the arm is made possible by a repurposed caster (see Figure 19) that allows for yaw and pitch motions.

The arm is a single piece of 2 in. x 4 in. rectangular aluminum tube extrusion. It is attached to the base via clamping plates and a bearing axle. The arm is 3.15 m. long, of which 1.83 m. is forward of the pitch axis. The arm has a total weight of 7.7 kg with a calculated moment of inertia about the pitch axis of 0.7 kg*m^2.

The counterweights are two 45-lb. Olympic weights purchased from a local sporting goods store. They are located on the end of the arm behind the pitch axis. They are mounted on the arm using a tube and plate assembly.

The head (see Figure 20) is a two-axis manipulator that allows rotation about the pitch and yaw axes. Although this device is only intended for use in installing sheets on a vertical wall, some rotation was needed along the pitch axis to be able to attach to sheets leaning at an angle against the wall. The head can also rotate about the yaw axis so that the head can be oriented to a wall when the arm is not perpendicular to that wall. The head also has arms that are used to attach to the sheet of drywall through some means. It is envisioned that a future device will have suction cups to attach to the drywall. For the purposes of this project, the drywall was rigidly attached to the arms of the head using bolts and nuts.

The entire head assembly is counterbalanced about its pitch axis to keep the drywall sheet in a near-vertical orientation with little input from the user. It can be pitched with little effort to allow attachment of the head to the drywall. The entire head assembly weighs 11.23 kg and its center of mass is located 1.88 m. forward of the arm pitch axis.

The inertial parameters for each of the components are provided in Table 2. The Denavit-Hartenberg (DH) parameters for the proposed device are presented in Table 3. It is assumed that the device will be used with the wheels locked in place to prevent lateral translation.

The torque at the pitch axis of the arm is the parameter of primary concern because lifting the sheet requires either a torque at this joint or a force at some point on the arm. This torque can be produced by a rotary actuator at the joint or a force at some point acting on the arm. In the present configuration, the force is created by the user lifting up on the sheet of drywall. The torque required at the pitch axis is determined as shown in Equation (1):

$$\tau = I\alpha + B\omega + mgr \tag{1}$$

where

I = combined moment of inertia for the arm, counter weights, head, and drywall;

α = angular acceleration of the arm;

B = damping coefficient for the bearing;

ω = rotational speed of the arm;

m = combined mass of the arm, counterweights, head, and drywall; and

r = distance from pitch axis to the center of mass of the arm assembly.

Equation (1) assumes the sheet of drywall remains in a relatively vertical orientation during the lift. This orientation is feasible, given it is balanced to do so. Because the damping coefficient of the bearing is not provided by the manufacturer, it must be estimated or empirically calculated. However, upon inspection, the torsional force due to the bearing is much lower than the inertial effects of the arm. In addition, Equation (2) by Beardmore (2010) was used to estimate the friction torque for a single-row ball bearing.

$$M_f = F * f * d/2 \tag{2}$$

where

M_f = friction torque (N*m),

F = radial or axial load (N),

f = coefficient of friction of roller bearing (0.0015 for single-row ball bearing), and

d = inside diameter of the bearing (m).

This calculation resulted in a friction torque of 0.0012 N*m, well below the approximately 85 N*m due to the inertial load. For this reason, it is assumed that the damping term in Equation (1) is sufficiently small with respect to the inertial term that it can be ignored. The arm position and counterweights are adjusted until the arm is virtually balanced on the pitch axis, which eliminates the third term, which leaves only the first term in Equation (1), as shown in Equation (3).

$$\tau = I\alpha \tag{3}$$

This torque can be converted into a force that the user would apply at the drywall sheet by dividing it by the moment arm of the force (1.83 m; see Equation 4).

$$f_u = \frac{\tau}{r_s} = \frac{I\alpha}{r_s} \tag{4}$$

Because the torque depends on angular acceleration, it is necessary to determine the motion of a sheet during a typical lifting cycle. To achieve this objective, the vertical position of a sheet of drywall (center of mass) was tracked during a lift from ground level to a carrying position. This lift is typical of picking up a sheet from a stack on the ground to a carrying position. Figure 21 shows this profile with respect to time. The motion of the sheet can also be approximated by Equation (5) and is represented in Figure 21.

$$y_1(t) = -1.0577x^3 + 2.013x^2 - 0.2971x + 0.0114 \tag{5}$$

These data must be converted to joint space (arm pitch angle) so that the joint space can be used to calculate forces (see Equation 4) for an assisted lift. Figure 22 shows the arm pitch axis (see Figure 19), angle (theta), velocity (omega), and acceleration (alpha) over time, as would result in the sheet of drywall moving along the same vertical trajectory (approximated), as shown in Figure 21. The angle of the arm is negative at the beginning of the lift because the arm pivot is above the center of the sheet when the sheet is resting on the ground.

The force expected in the user's hand during the assisted lifting cycle is determined using the second derivative of Equation 5 (acceleration) as input to the force equation (Equation 4). The force that would be expected in a user’s hand during an unassisted lift is determined by the equation ($F = ma$). Figure 23 shows the expected force in a user’s hand during both an assisted and an unassisted lifting cycle. During the unassisted lift, the force in the user’s hands is, on average, 250 N. During the assisted lift, the maximum load in the user’s hands is 196 N, and the maximum load decreases to zero during the first half of the lift.

It is expected that the user will experience, on average, a 63% reduction in force during the first half of the lift. During the second half of the lift, when the mass is decelerating, the user will realize a negative force from the assisted lift. This negative force results from the user decelerating the rotating mass. While the deceleration is of equal magnitude to the forces experienced by the user during first phase of the assisted lift, the user is now pulling down on the sheet. This effort results in the load being shifted primarily to the abdominal muscles. While the abdominal muscle do contribute to spinal compressive loads, they have a significantly lower contribution.

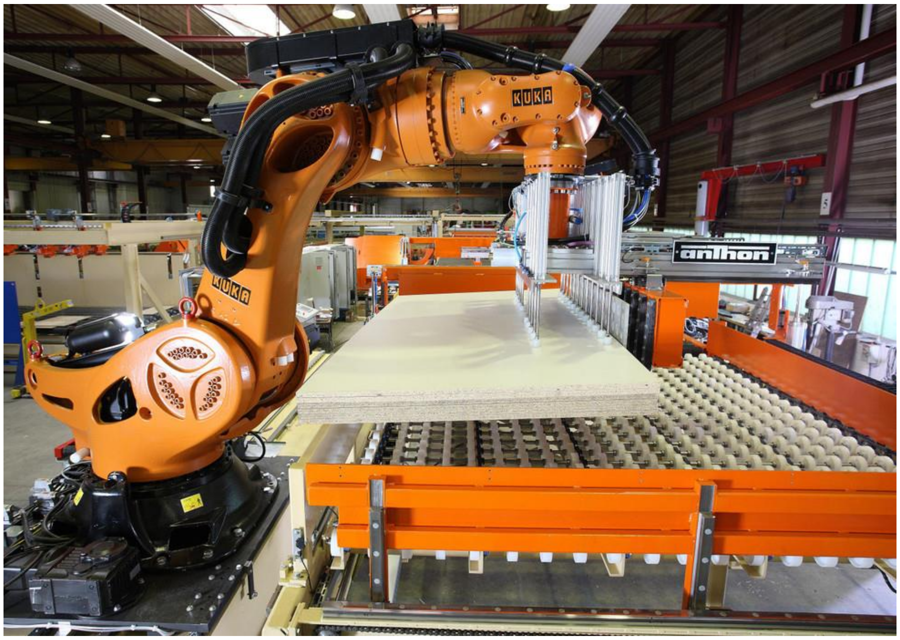

Figure 10. Industrial robot lifting panels. Adapted from “KUKA Robot Lifting Panels in Factory,” by Eplan, n.d. Copyright 2015 by Eplan.

Figure 11. Example of a warehouse-based panel lift. Adapted from “Worker Lifting Solar Planes in Warehouse,” by Millsom, n.d. Copyright 2015 by Millsom.

Figure 12. Example of a mobile panel lift.

Figure 13. Example of operator using camera jib. Adapted from “Standard Porta-Jib Shown with Optional LWT Tripod, 36" Extension Kit,” by Hollywood General Machining.

Figure 14. Multiple views of mobile camera crane. Adapted from “Telescopic Camera Crane Supertechno 30,” by Active Camera Systems, 2015. Copyright 2015 by Active Camera Systems.

Figure 15. Concept for drywall lifting device.

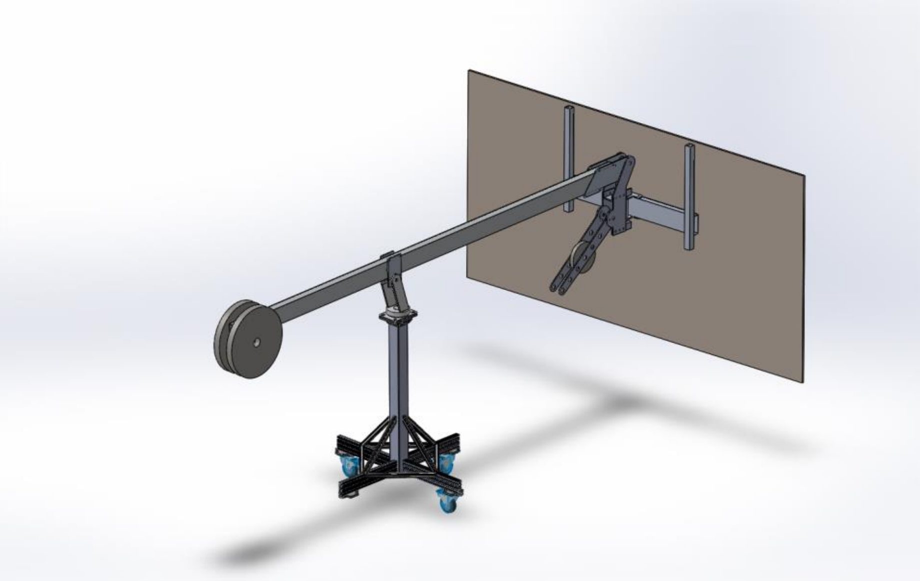

Figure 16. Basic lifting device.

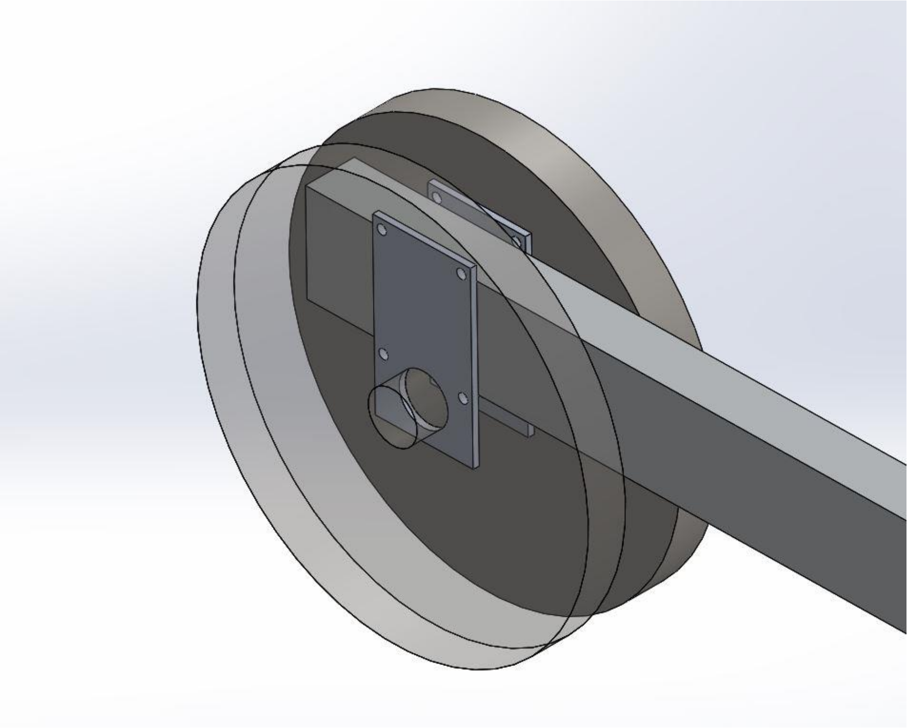

Figure 17. Counterweights on end of arm.

Figure 18. Drywall lift tripod base constructed from t-slot extrusion.

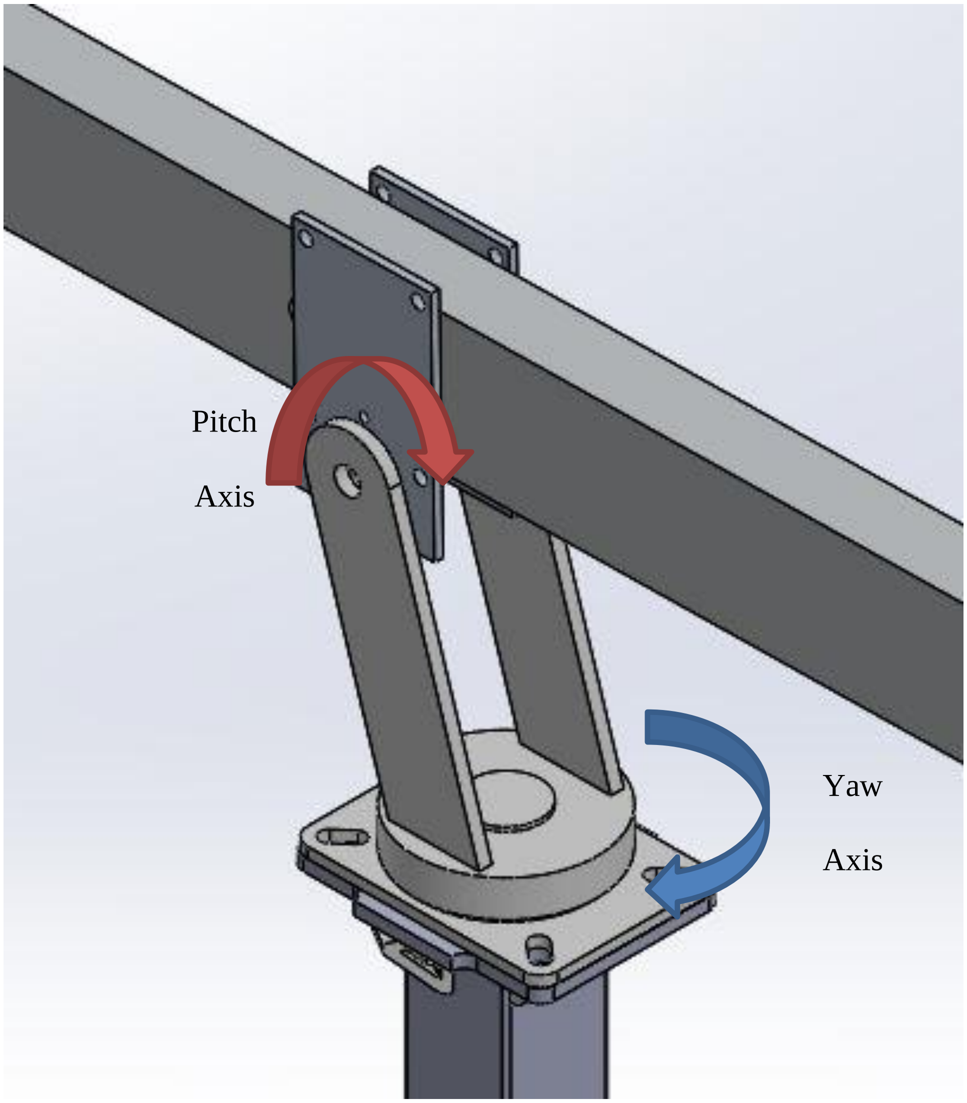

Figure 19. Yaw and pitch axes created from repurposed caster.

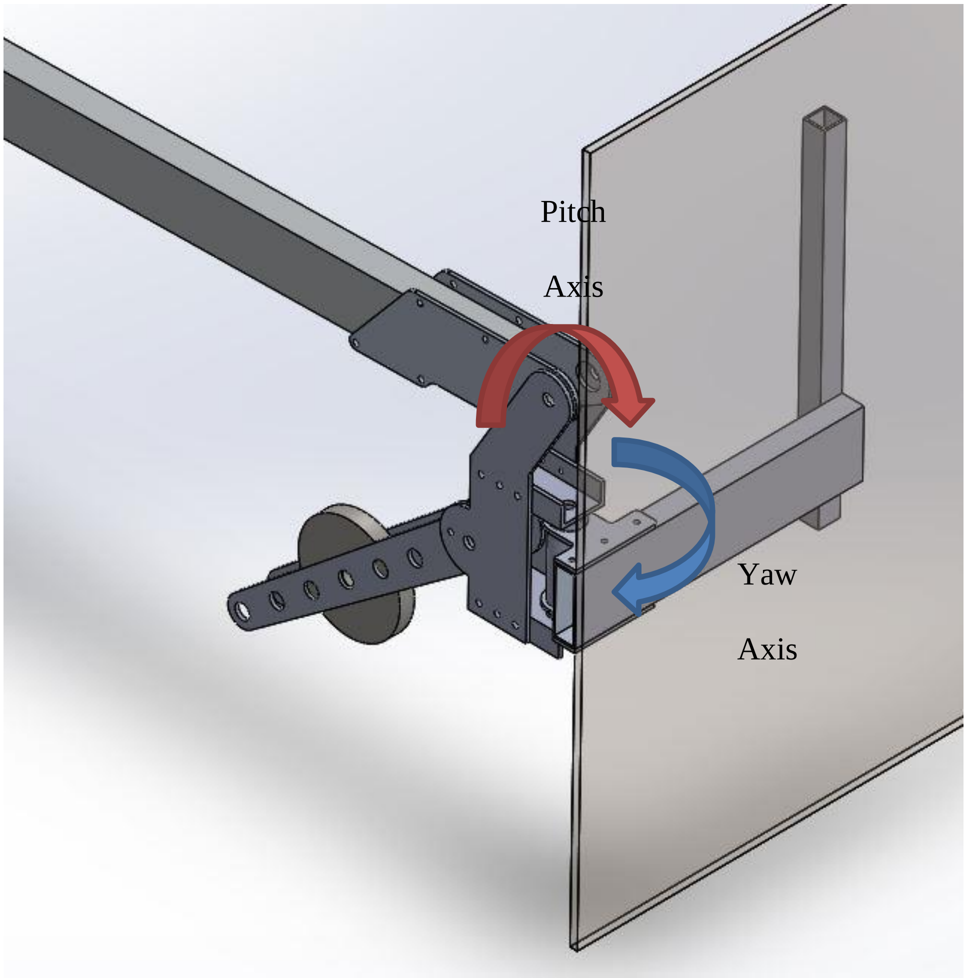

Figure 20. Head assembly consisting of pitch axis and yaw axis.

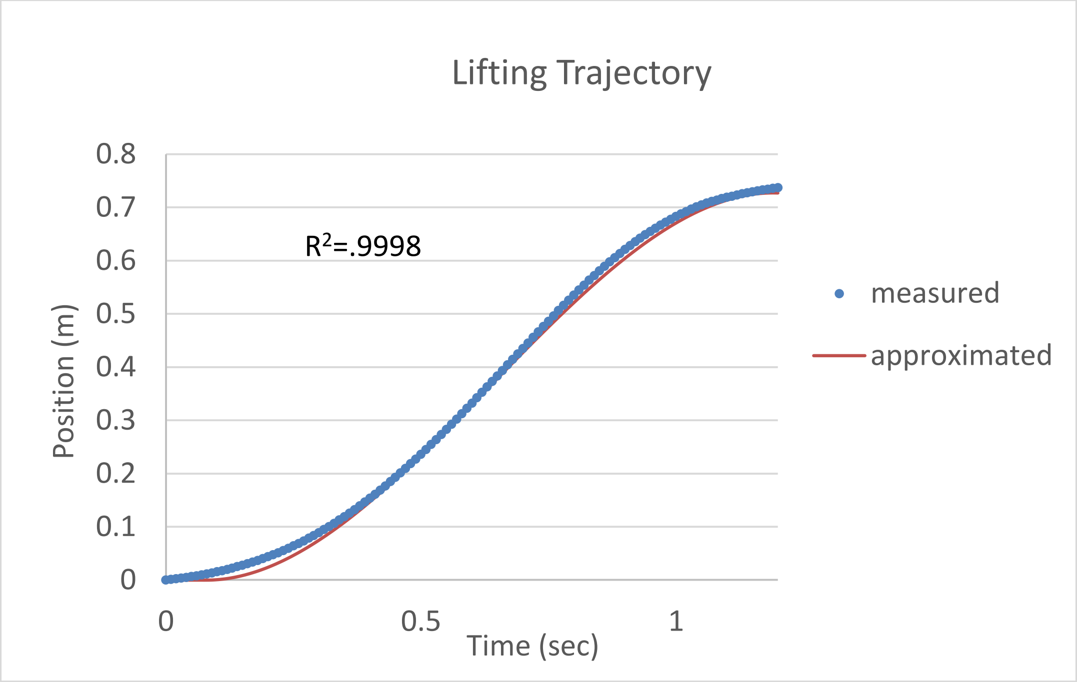

Figure 21. Drywall sheet lifting trajectory.

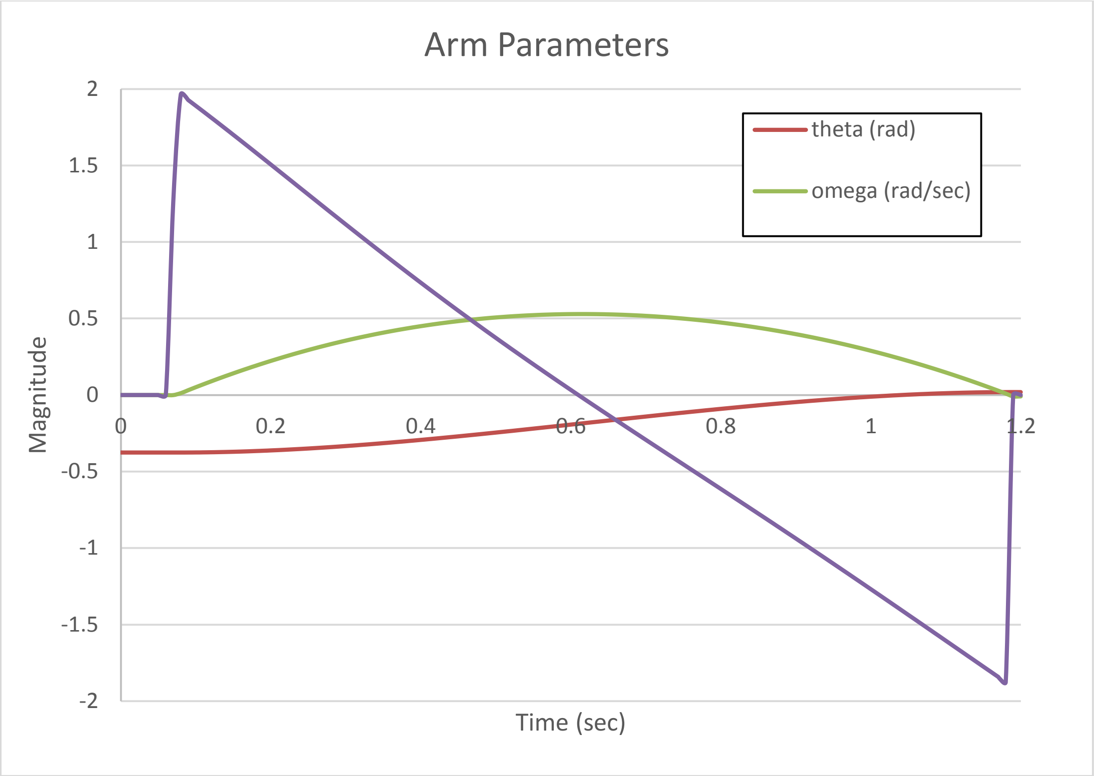

Figure 22. Arm position parameters during lifting cycle.

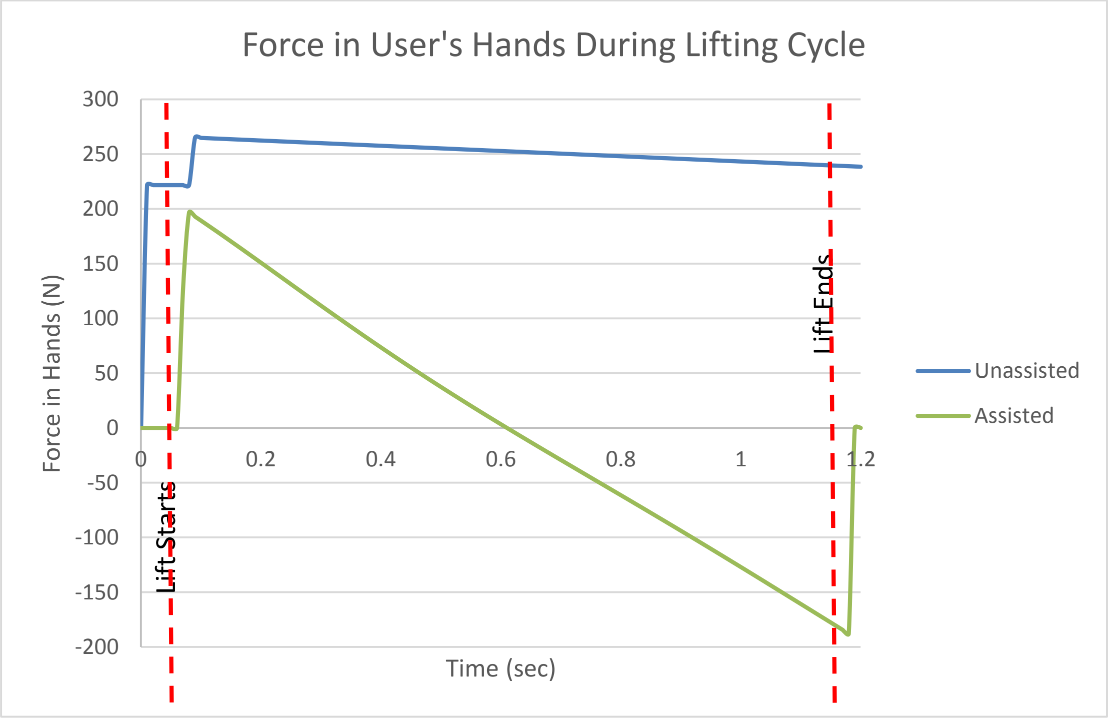

Figure 23. Force in user's hands during lifting cycle.

Table 1. Device Component Parameters

Component	Moment of inertia about COM (kg*m^2)	Mass (kg)	Moment arm from pitch axis (m)	Moment of inertia about pitch axis (kg*m^2)
counter weights	0.86	42.00	1.14	55.44
head	0.83	11.23	1.88	40.52
sheet	2.62	22.68	1.98	91.53
arm	0.01	7.70	0.30	0.70
	Total mass	83.61	Total moment of inertia about pitch axis	188.20

Table 2. DH Parameters for Proposed Device

Link	a_i (m)	d_i (m)	theta$_i$ (rad)	alpha$_i$ (rad)
1	0	1.3	Base yaw axis	π/2
2	1.88	0	Base pitch angle	0
3	0	0	Head pitch angle	-π/2
4	0	0	Head yaw angle	0

CHAPTER 4

TESTING

While some previous studies have attempted to build models (Yuan, Buccholz, Punnett, & Kriebel, 2007) or assess sampled positions during installation (Pan & Chiou, 1999) to estimate or predict the loading on the user's back, to our knowledge, no one has actually measured muscle activation during drywall installation. In addition, the use of tools has not been evaluated against this lifting baseline.

Experiment Setup

Pan and Chiou (1999) estimated that a user lifting a 60-lb sheet using the lower lift described above would experience a back compressive load of 915 lbs. The NIOSH (1981) recommended working level for the spine is 770 lbs (Waters, Putz-Anderson, Garg, & Fine, 1993). Our analysis indicates that a 15% reduction of stress in the user’s back would place the stress well below the recommended spinal compression force. We hypothesize that the use of a passive, counterbalanced, assisted lifting device will reduce the stress on the user’s back by at least this amount. The goal of the experiment was to evaluate this hypothesis. This objective was accomplished by observing and comparing the EMG muscle activation during unassisted and assisted lifting. While the EMG signal magnitudes are not a direct measurement of the spinal disk compreesion force, they do have a strong correlation (Hughes & Chaffin, 1995).

Biomechanical Basis

A well-established and widely accepted model of the compressive loads on the back was developed by Schultz (Schultz & Andersson, 1981; Schultz, Andersson, Ortengren, Haderspeck, & Nachemson, 1982). In this model, the compressive force on the L5/S1 disk is found by calculating Equation 6:

$$F_c = F_Z - F_A + F_M + A + V_L + V_R \tag{6}$$

where

F_c = compressive force on the L5/S1 disk,

F_z = external forces in the vertical direction,

F_a = abdominal wall force,

F_m = erector spinae muscle force,

A = rectus abdominus force,

V_l = left oblique muscle force, and

V_r = right oblique muscle force.

To solve the entire set of equations for this model, assumptions must be made about the antagonistic muscle during a certain motion. In the case of lifting an object, the moment about the pitch axis of the back is less than zero; therefore, the rectus abdominus muscle plays no role in the back compressive load. Some models for lifting use only the erector spinae muscle force, body weight, and load weight to predict disk compressive loads.

Although the muscle forces cannot be measured directly, their values can be predicted using EMG sensors (Liu, Herzog, & Savelberg, 1999). Each muscle must be analyzed to find the relationship between the signal and force. Knowing this relationship, we can demonstrate that a decrease in the relative magnitude of the EMG signal in a muscle will result in the relative muscle force having been decreased by the same amount. If we can demonstrate that the EMG signal for all muscles that contribute to the spinal compressive load has decreased, then we can safely assume that the actual compressive load on the spine has been reduced by a similar amount.

Participants

A convenience study of participants was solicited from the local area to complete this study. It was desirable for the participants to have had some experience installing drywall, but it was not a discriminating factor, given that the device is intended to be used by both professionals and novices. Participants were required to be men between the ages of 18 and 45 with no history of back injuries. Table 4 is a summary of the demographics of the participants.

Tasks

Two motions were observed during this experiment. The first involved lifting a sheet of drywall from the floor to an erect carrying position (approximately 0.75 m). This motion is the lift most commonly observed in the residential market (Pan & Chiou, 1999). During the unassisted lift, the erect carrying position (see Figure 24) is achieved when the legs are in a full standing position, one arm is in a dead hang holding the bottom of the sheet, and the other hand is holding the top of the sheet.

During the assisted lift, the user was not required to squat down to grab the bottom of the sheet before lifting (see Figure 25). Because the device supported a majority of the load, the participant was only required to grab the machine or the sheet in a manner that was comfortable for him. This lift typically involved the user remaining standing and guiding the sheet up, with one hand on the device arm and another on the sheet to maintain orientation.

The second lift was begun in the lifted position previously described. The user then lifted the sheet so that the top of the sheet reached 8 ft (see Figure 26), which is the typical height of a residential ceiling. This lift was repeated as an assisted lift (see Figure 27). With two lower motions and two upper motions, both assisted and unassisted, there were a total of four lifting sequences. Each of these lifts sequences was repeated four times, resulting in a total of 16 lifts being conducted for the entire experiment (see Table 5). Each user was assigned a user number and a random order was followed for each of the four lift sequences. This approach was to applied ensure that the experiment was not biased toward any lift because of training or fatigue. These lifting motions were chosen because they are the most common positions and most likely to cause injury (Pan & Chiou, 1999).

Sensors

Eight Bagnoli surface electrodes by Delsys were affixed to each user (see Figure 28) on the muscles listed in Table 6. The purpose was to measure muscle activity during the lift. These muscles were chosen for the major contributions they make during the lifting cycle, as previously discussed. The sensors were attached by an experienced technician according to several texts (Kramer et al., 2010; Konrad, 2006; Merletti & di Torino, 1999) used as a guide. Double-sided adhesive tape as well as coflex wrap was used to hold the surface electrodes in place. A grounding probe was also placed on the bony mound of the shoulder.

All of the sensors and probes were attached to a connector block, National Instruments Model BNC-2111, and from which lines fed the data into the computer via a data acquisition system, National Instruments Model NI 6210. The signal was sampled at a rate of 10kHz. These signals were then recorded on the computer using a Matlab script and a graphical user interface. The data were processed in the following order to prepare them for comparison and analysis.

1. Low pass filtered at 450 Hz.
2. Bias removed to baseline signal to zero.
3. Full wave rectification.
4. Time shifted so that all lifts started at time ($t = 0$).
5. Averaged left and right muscles.
6. Averaged all lifts for a user of the same type (i.e., upper lift unassisted).
7. Extract data (peak, mean, standard deviation, total effort).

In addition to the EMG sensors, the user was fitted with infrared (IR) markers to allow for the capture of 3D motion by motion capture cameras installed in the lab. Although these motion capture data were not factored into this study, they could be used at a later date for more thorough analysis.

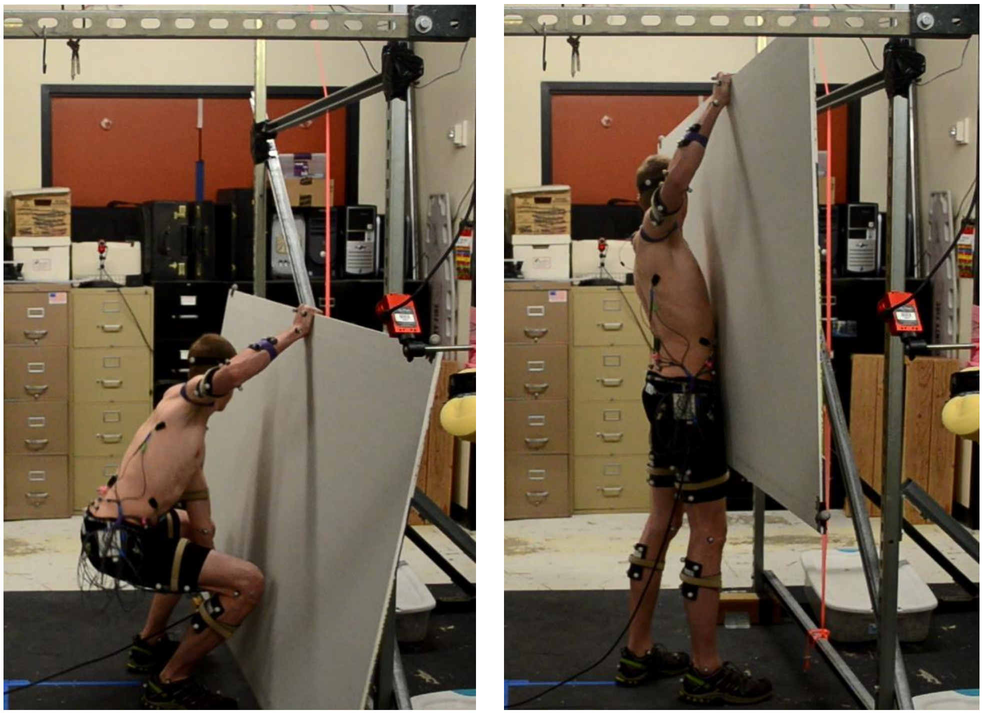

Figure 24. Unassisted lifting from the ground.

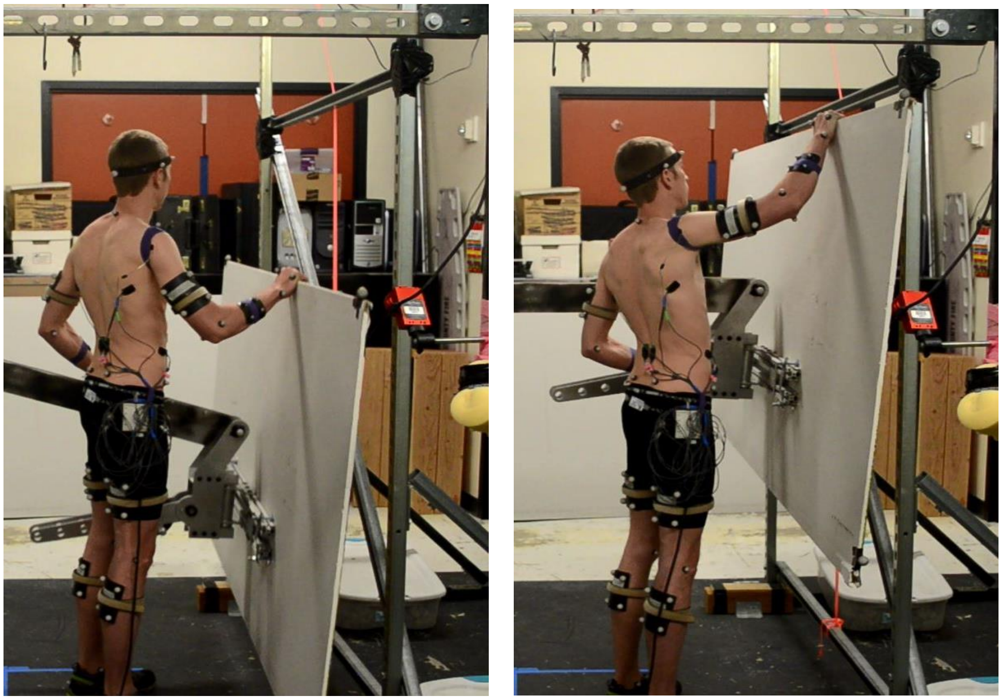

Figure 25. Assisted lift from the ground.

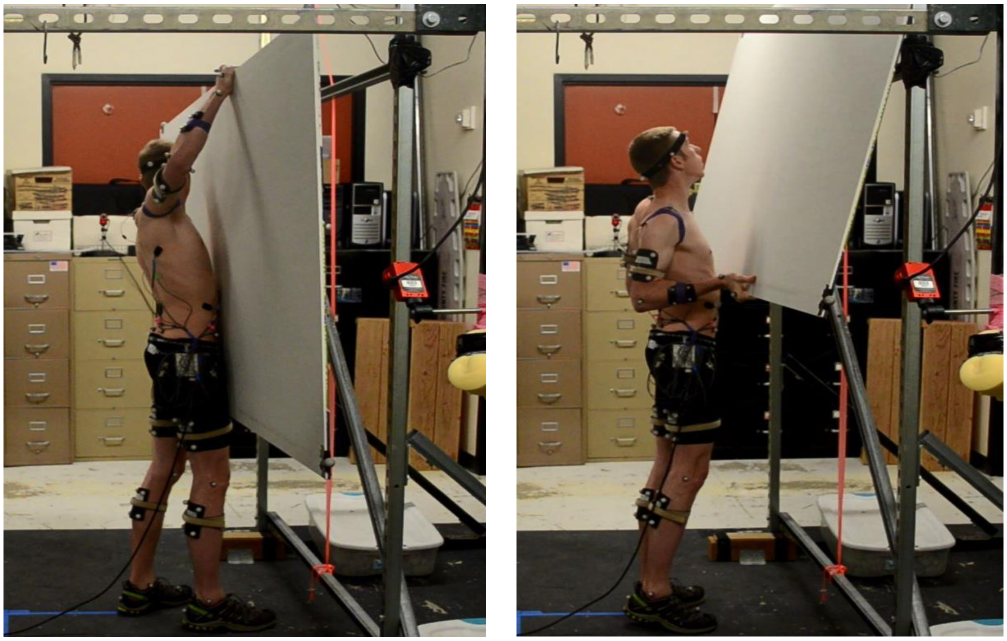

Figure 26. Unassisted lift to the ceiling.

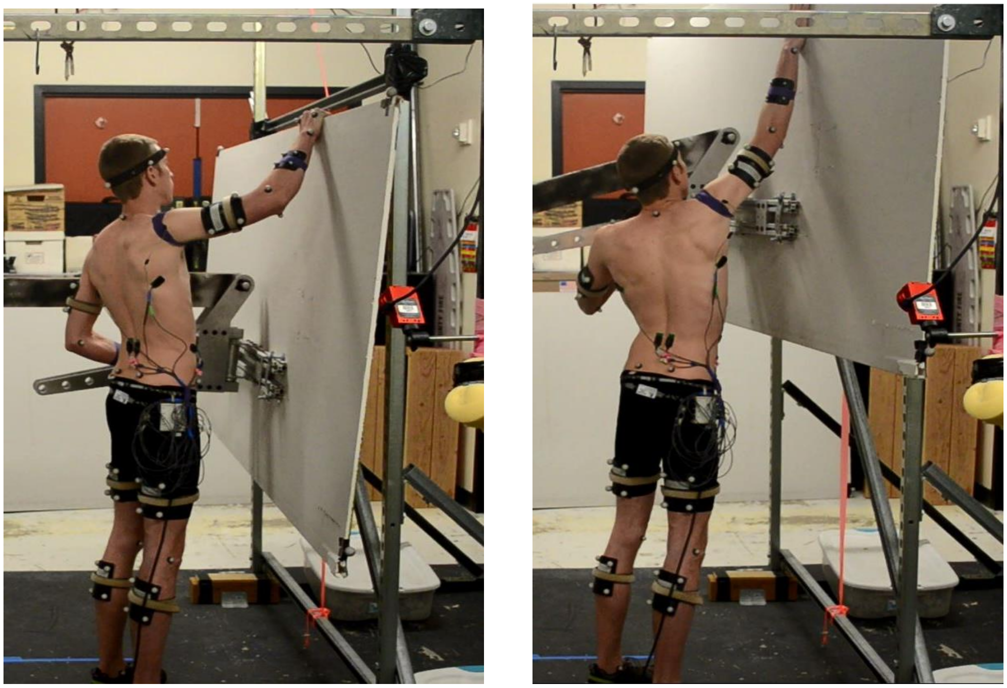

Figure 27. Assisted lift to the ceiling.

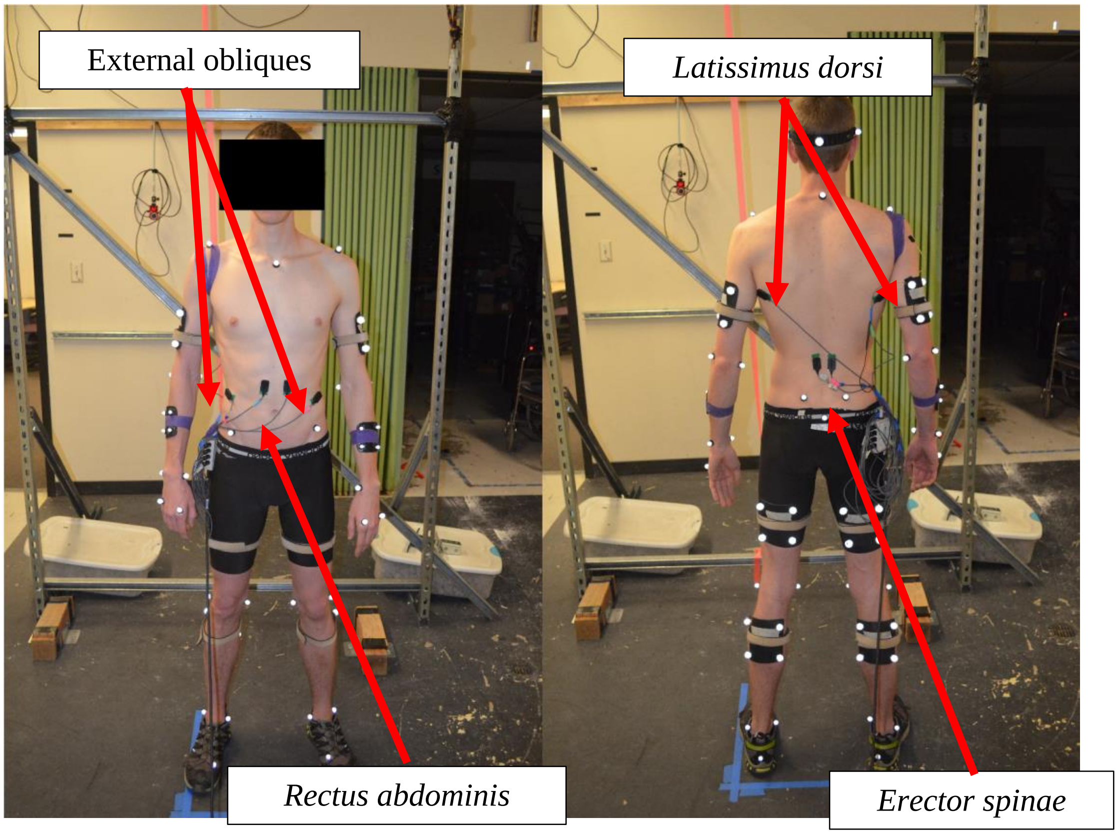
[redacted]

Figure 28. Sensor placement on test subjects.

Table 3. Participant Demographics

Variables	Mean	*SD*	Range
Age	32.3	5.8	24–43
Height (in.)	71.2	2.1	68–75
Weight (lbs)	173.5	23.5	134–210

Table 4. Lifting Test Quantities

Lift type	Assisted	Unassisted
Lower lift	4	4
Upper lift	4	4

Table 5. EMG Muscle Groups

Right and left *erector spinae*
Right and left *latissimus dorsi*
Right and left *rectus abdominis*
Right and left external oblique

CHAPTER 5

EXPERIMENTAL RESULTS

Figure 29 is an example of the output data for a single lift. This particular data set is for the lower lift performed by User 2. The data set was used to generate a plot for each of the muscle groups to indicate the assisted (red) and unassisted (green) signal. The signal indicated in the plot is the average of the left and right muscles, as well as the four repeats of the lift. This plot is characteristic of the signals generated by all users and for all lifts. During the unassisted lift, there is almost always a spike in muscle exertion at the start of the lift, likely due to the acceleration of the drywall. This spike is followed by a reduction in exertion that never fully dissipates. Conversely, for the assisted lift, there are very few spikes in the signal: the signal maintains a fairly low level.

Averaged Percent Reduction

Mean EMG Signal

Across all muscle groups in both the upper and lower lifts, there was an average 69% reduction in mean EMG signal during the lifting cycle. Average reductions were greater for the lower lift than for the upper lift (78% versus 68%), which is to be expected, given the significant posture change during the lower lift. See Figure 30 for details.

Peak EMG Signal

Across all muscle groups in both the upper and lower lifts, there was an average 78% reduction in peak EMG signal during the lifting cycle. Average reductions were greater for the lower lift than for the upper lift (86% versus 78%). See Figure 31 for details.

Effort

In the context of this research, effort is the area under the EMG curve. In a traditional sense, effort would be the force exerted over time; however, the present definition is analogous. While a certain lift might require a higher peak effort, it might cause less fatigue because of its short duration. This information is important because effort correlates to total fatigue throughout the day. If the effort is reduced for each lift, then the user could conceivably work longer.

Across all muscle groups in both the upper and lower lifts, there was an average 75% reduction in effort during the lifting cycle. Average reductions were greater for the lower lift than for the upper lift (80% versus 69%). See Figure 32 for details.

Across all lifts and all muscle groups, the average reduction in EMG signal was 74%, which is close to what was predicted for reduction in the hand loads. Factors such as posture, location of the load, and EMG-to-muscle force ratios all play a role in the correlation. However, there is a strong correlation between them and there was a sufficiently significant reduction in the EMG signals that we can safely draw the conclusion that the assisted lifting device does significantly reduce the back compressive loads and effort required by the user during the lifting cycle. This evidence is reinforced by feedback from and observations of the users during the testing.

Muscle Group Comparison

Data collected for this study were reorganized to facilitate analysis of the variation in effort reduction by muscle group. Figure 33 shows the percent reduction for mean, peak, and effort by lift (lower/upper). All signals are grouped by muscle for easy comparison. On the first figure above the erector label on the horizontal axis are 10 bars. Each bar represents a user in the study.

Although there appears to be a significant variation in the reduction among the users, the reductions overall are quite large across the board. It would be useful to do further research into those users whose lifts resulted in a large or small reduction, as compared to the other users. It would be beneficial to understand whether this variation is due to some underlying effect or just erroneous data.

Correlation to Subject Demographics

Another area of interest was whether a correlation exists between subject demographics such as age, weight, and height to the percent reduction. Each of these demographic factors were compared against percent reductions for mean, peak, and effort data on the upper and lower lift. The subject demographic variables appear to have little or no effect in any of these scenarios. Figure 34 is an example of one of the plots generated.

Statistical Significance

Each of the muscle data values were plotted to demonstrate whether a relationship between the left and right muscles was present, as well as to represent the significance of the reduction in signal due to the machine. The chart in Figure 35 shows the mean EMG values for the *erector spinae* muscles during the lower lift by User 1. It is representative of a majority of the signals obtained. There are two common characteristics among all participants. First, because the body is not symmetric during the lift, one of the muscles exerts more effort than another. Second, the values for the unassisted lift are higher than those of the assisted lift, with two standard deviations rarely overlapping. By inspecting these results, it is apparent the device has had a significant positive effect on muscle exertion. Figure 36 shows these data for all 10 study participants.

A *t* test (95% confidence) was performed to compare the mean, peak, and EMG values for both the left and right muscle signals individually. For example, the mean values for User 1’s right *erector spinae* during the lower unassisted lift (four data points) were compared to those of User 1's assisted lift (four data points). In a majority of the cases (see Figure 37), the test showed a significant decrease in muscle activation. The distribution cannot be determined as being normal because there were only four data points. Consequently, this uncertainty regarding normality will limit the reliability of the test.

Effort made by the *erector spinae* muscle was significantly reduced in 100% of the cases. Effort made by the *rectus abdominus* muscle revealed the least quantifiable reduction, with an average of 72% cases. This disparity was expected because the lifting motion mostly uses the *erector spinae*, *latissimus dorsi*, and oblique muscles due to asymmetry. These data validate the expected results as well as the observations made during actual testing.

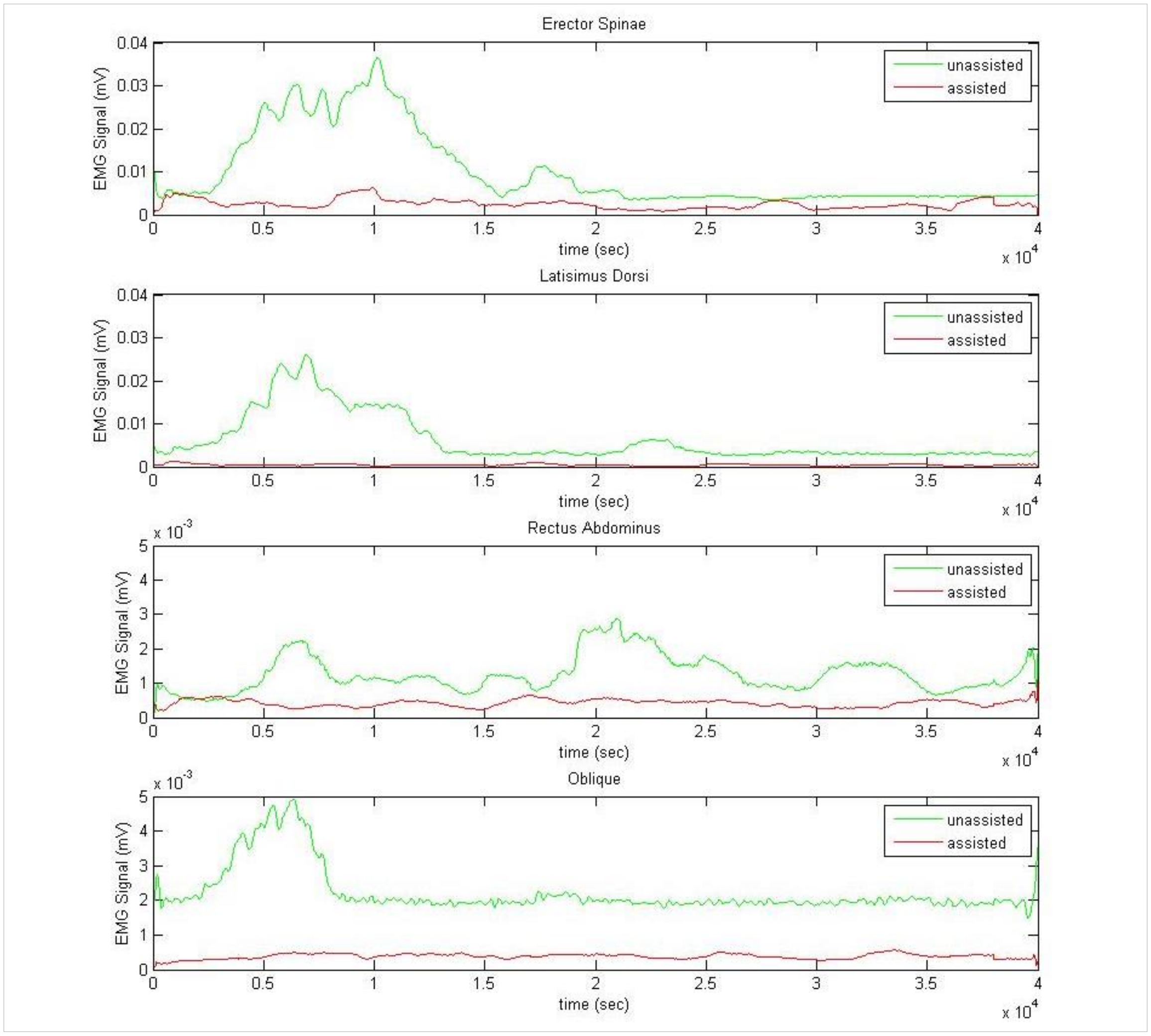

Figure 29. Sample output data.

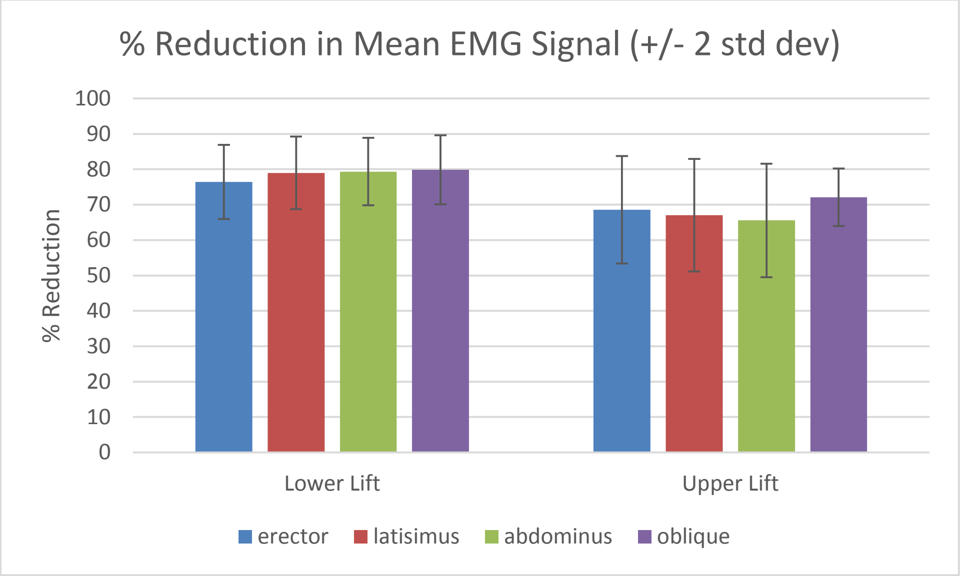

Figure 30. Percent reduction in mean EMG value.

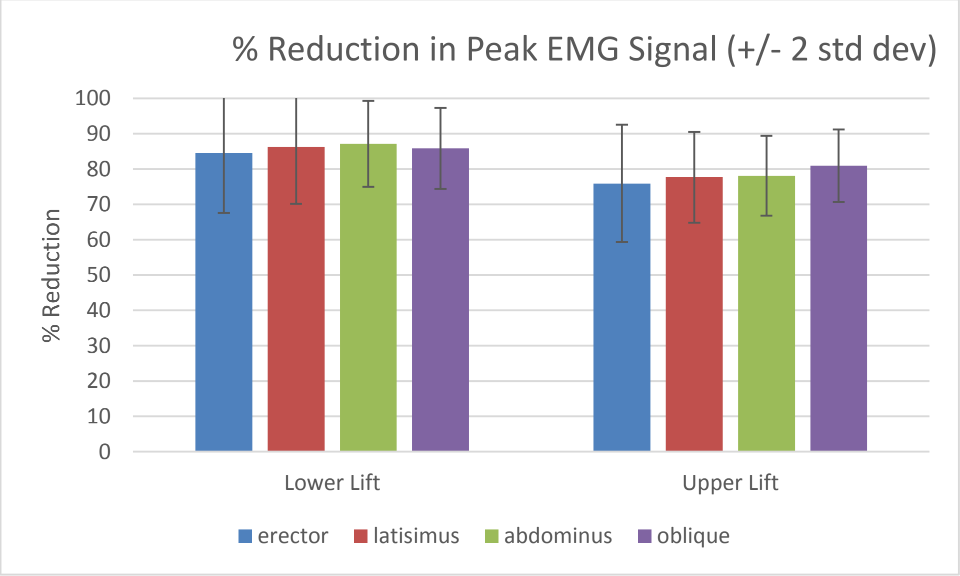

Figure 31. Percent reduction in peak EMG value.

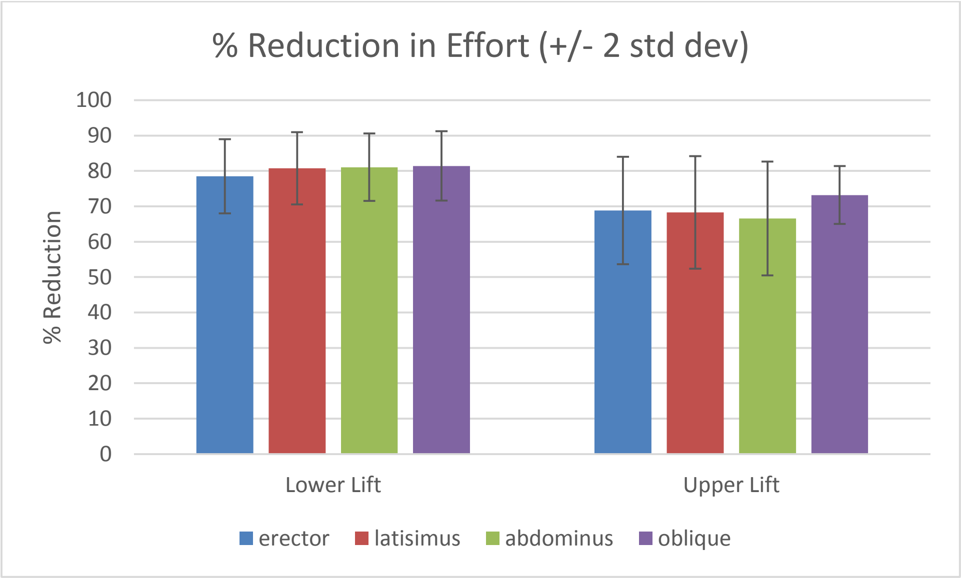

Figure 32. Percent reduction in effort.

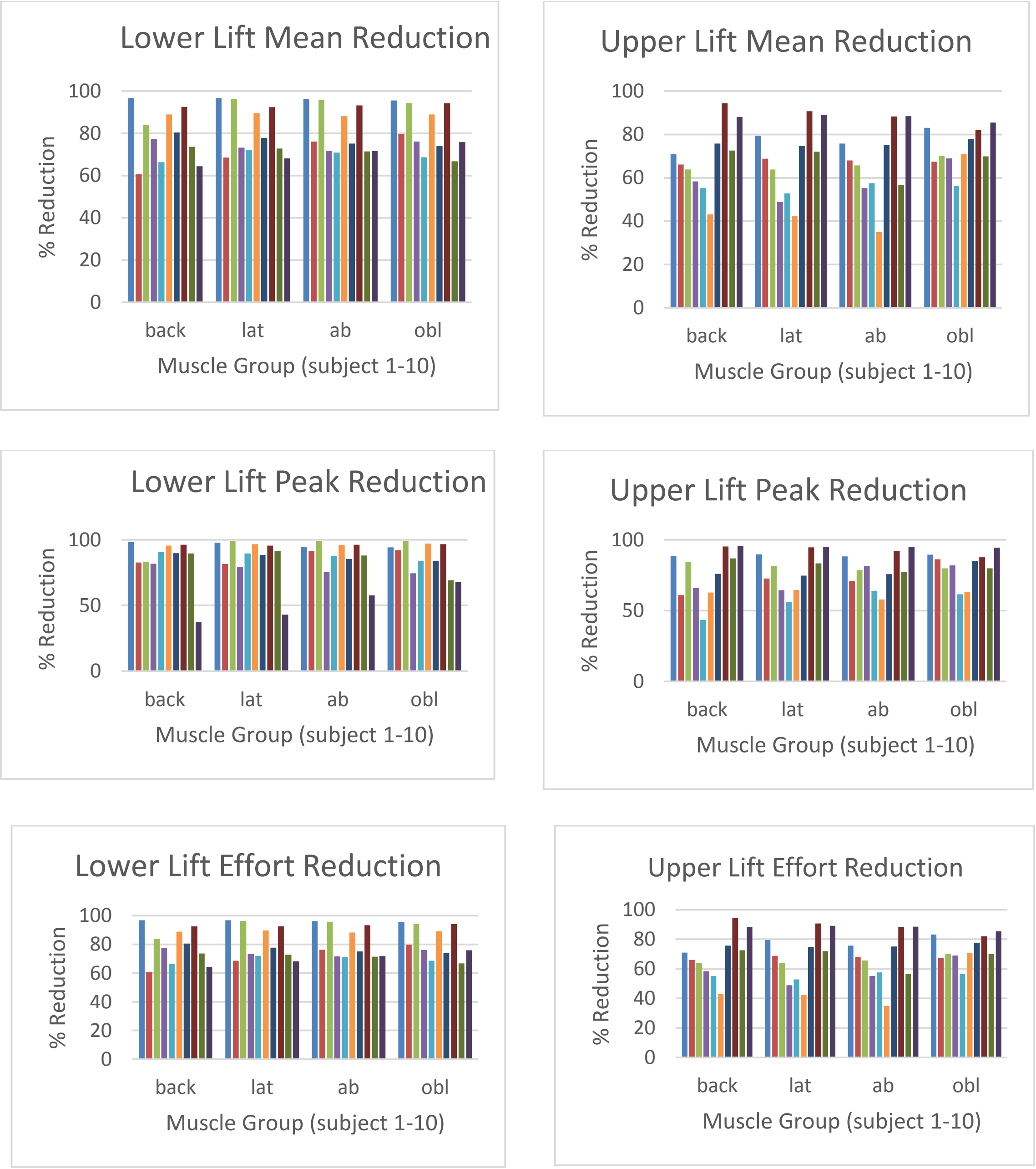

Figure 33. Percent reduction by muscle group.

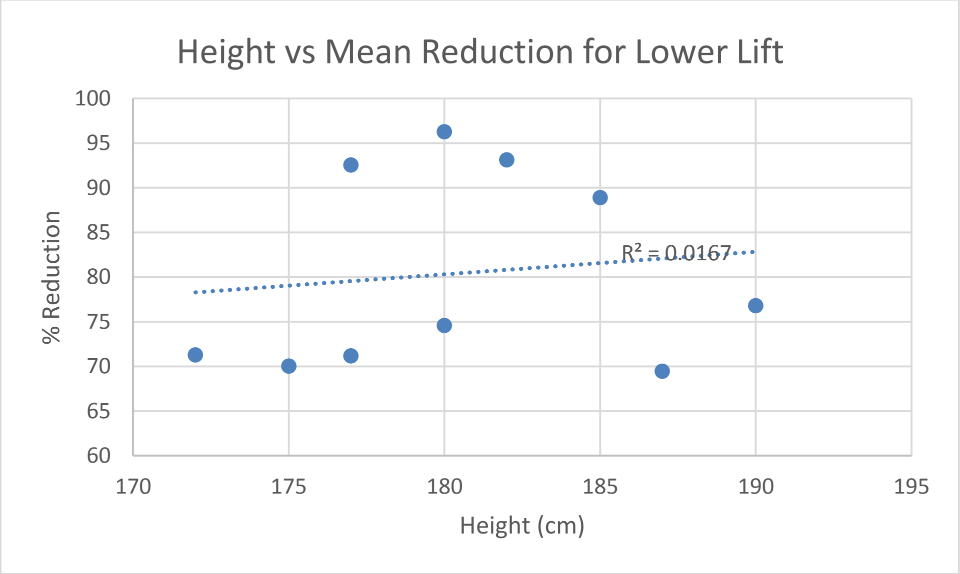

Figure 34. Correlation of height and mean reduction.

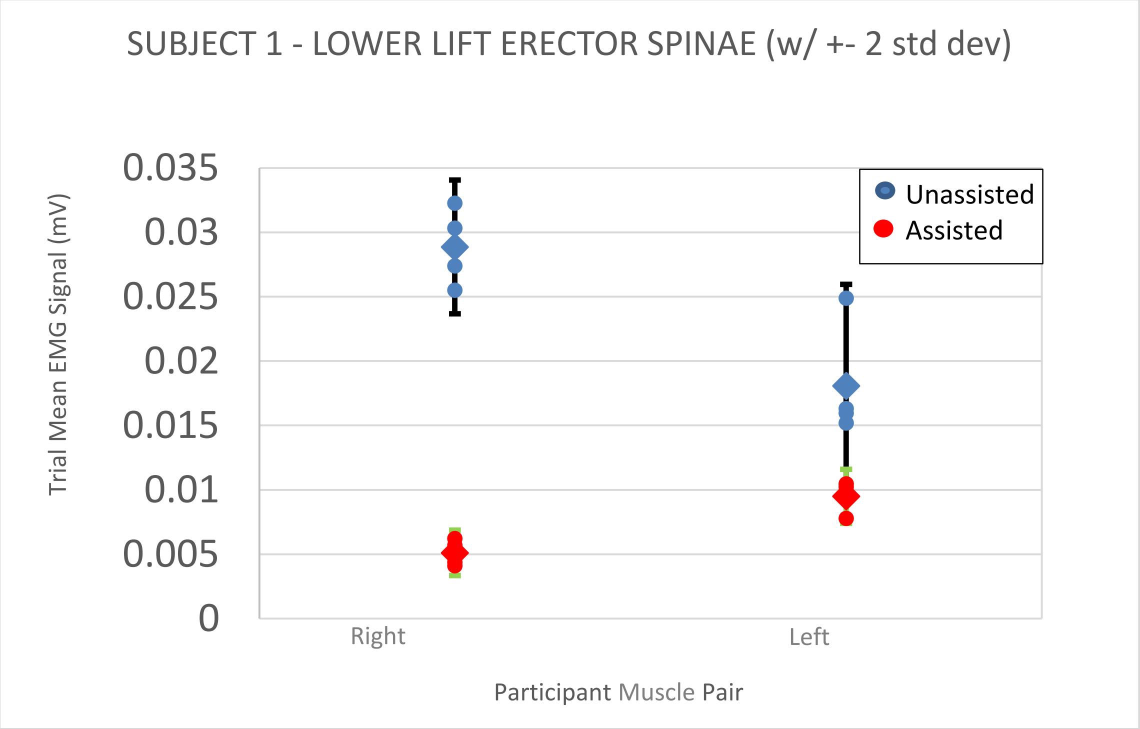

Figure 35. Subject 1 data spread comparison.

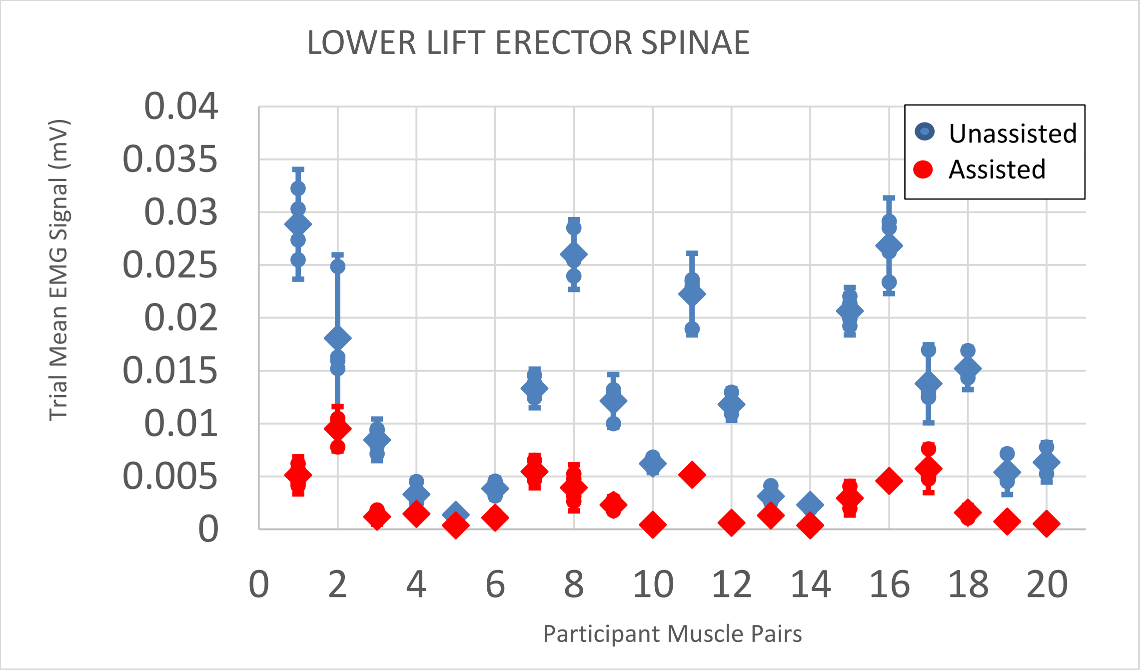

Figure 36. Data spread comparison.

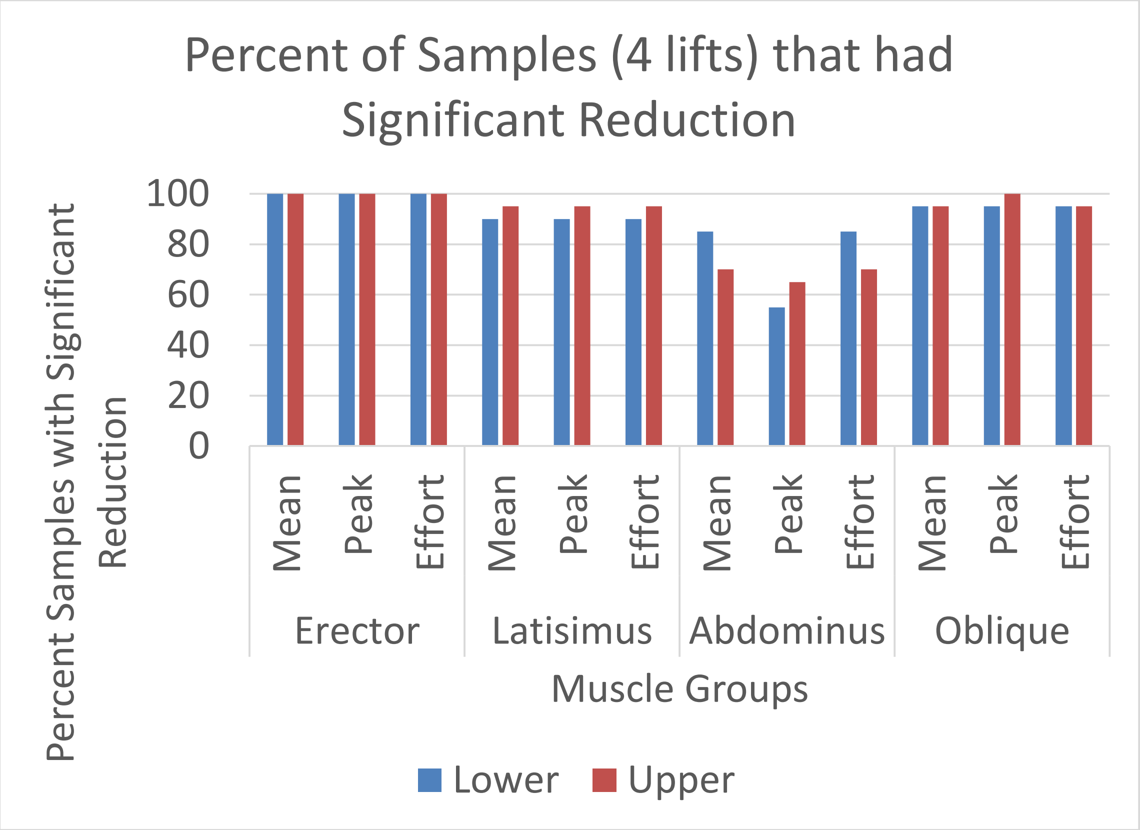

Figure 37. Percent of samples (four lifts) with significant reduction in EMG signal.

CHAPTER 6

CONCLUSION

This study serves to demonstrate that methods and tools can be adapted to reduce worker injuries in a relatively hazardous industry. Using an unpowered lifting device similar to those found in other industries can reduce the muscle activity levels in an drywall installer's back by 69%. Such reductions have the potential to transform the rate of drywall industry injuries and prolong worker longevity and productivity. An unpowered lifting device has the potential to decrease costs for government agencies and companies associated with the industry as well as increase profits. Although considerable development is needed before this device can be successfully deployed in the construction environment, this device, as demonstrated, is a first step in addressing a universal hazard.

CHAPTER 7

FUTURE WORK

The scope of this project was limited by time and budgetary constraints. It is the goal of the researcher to continue studying in this industry. Two major areas of work are projected. The first area focuses on quantifying the benefits of the device and the second area is adding functionality to the device.

Testing

Although measurement of the muscle activation of the *erector spinae* muscles has a high correlation to spinal compressive forces, it is not an exact correlation. Future work will take advantage of 3D motion data captured during the experiments and combine those data with models developed to better predict the spinal compressive forces.

Development

The device, as currently configured, is only practical for use in large, open rooms to allow for rotation of the arm, and on smooth floors to allow the device to traverse across the floor. In most residential and commercial construction settings, these requirements are not practical. Rooms can be small and floors rough. To overcome these environmental obstacles, the researcher plans to add the following functionality to future iterations of the device:

- telescoping arm to increase the work envelope and limit the need for the device to traverse on wheels during operation;
- moveable counterbalance weights to adjust for the telescoping arm and different size sheets of drywall;
- feedback control on the counterbalance to actively provide balancing and user effort during lifting;
- suction cups to attach drywall to the device quickly;
- brake on pitch axis lock position during detaching of suction cups (before counterbalance has had time to adjust); and
- add more degrees of freedom to the head mechanism to allow installation on ceiling or in a vertical orientation, as well as picking up sheets from a horizontal stack.

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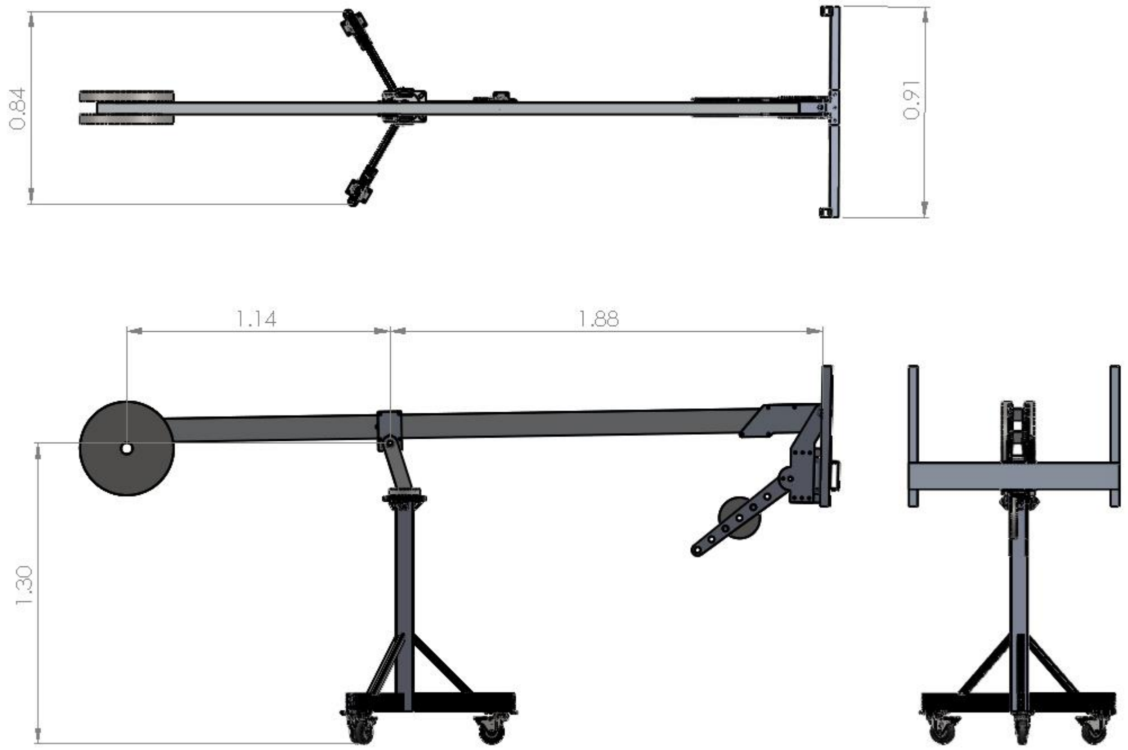
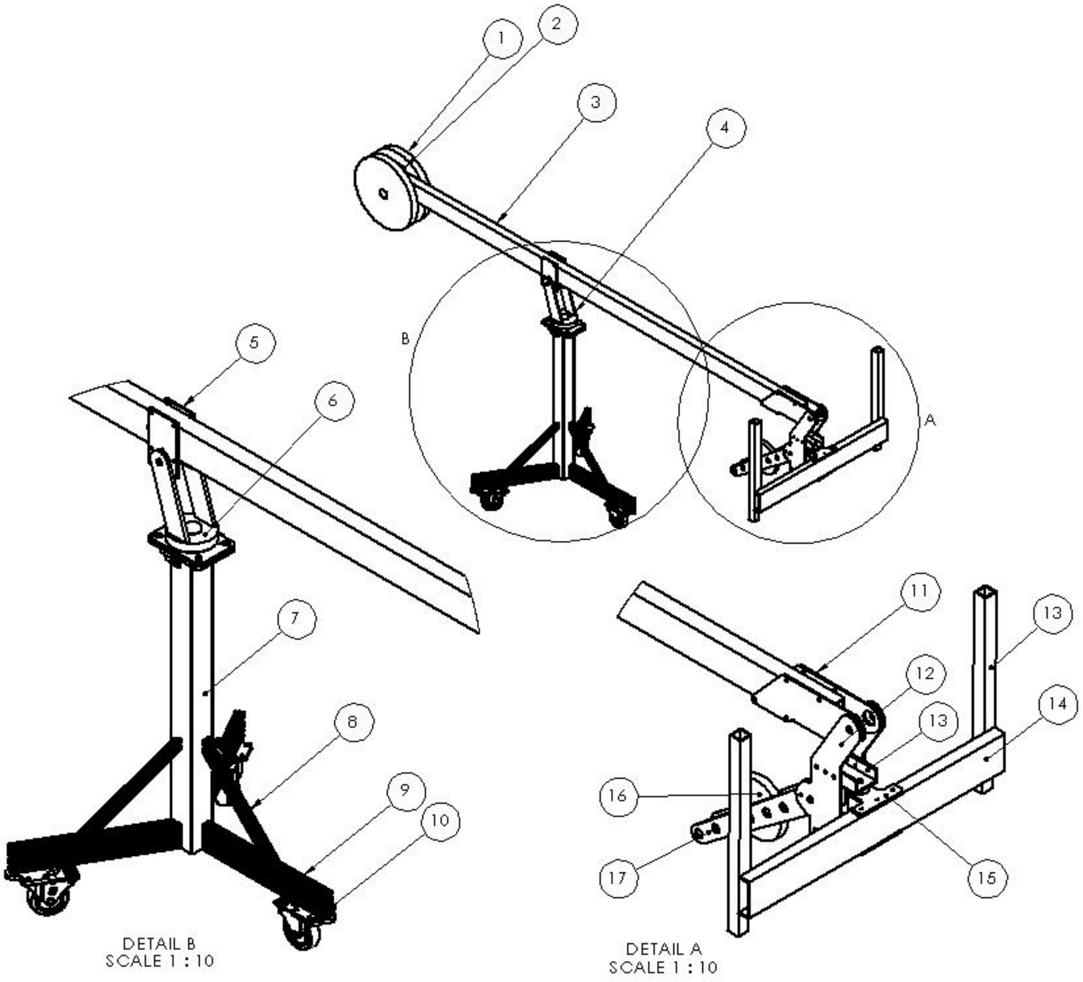
APPENDIX

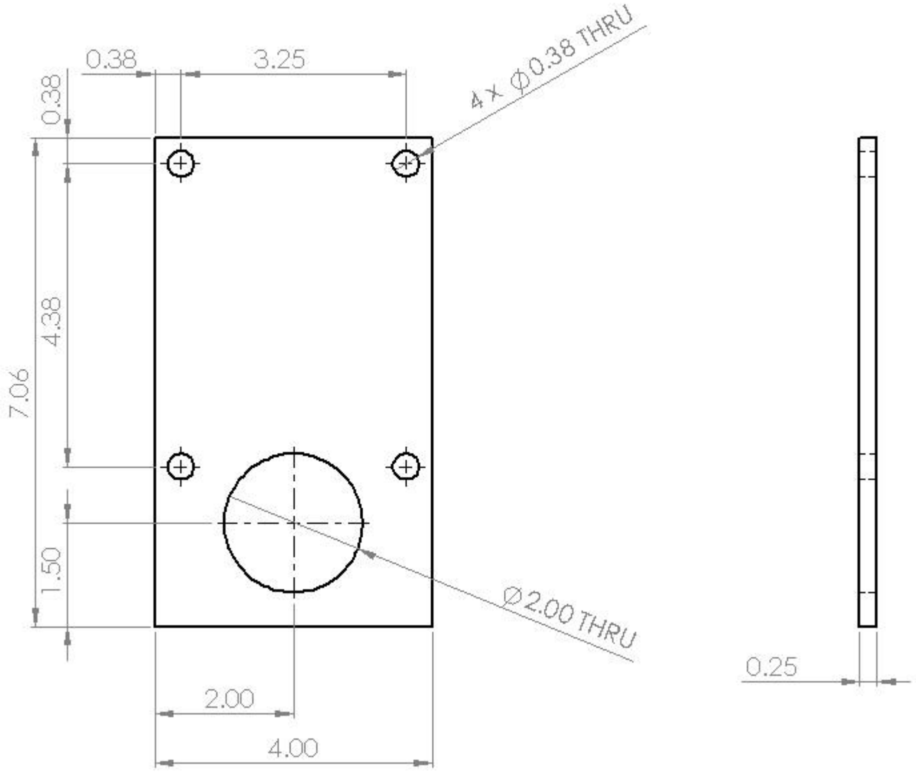
CAD DRAWINGS OF DEVICE



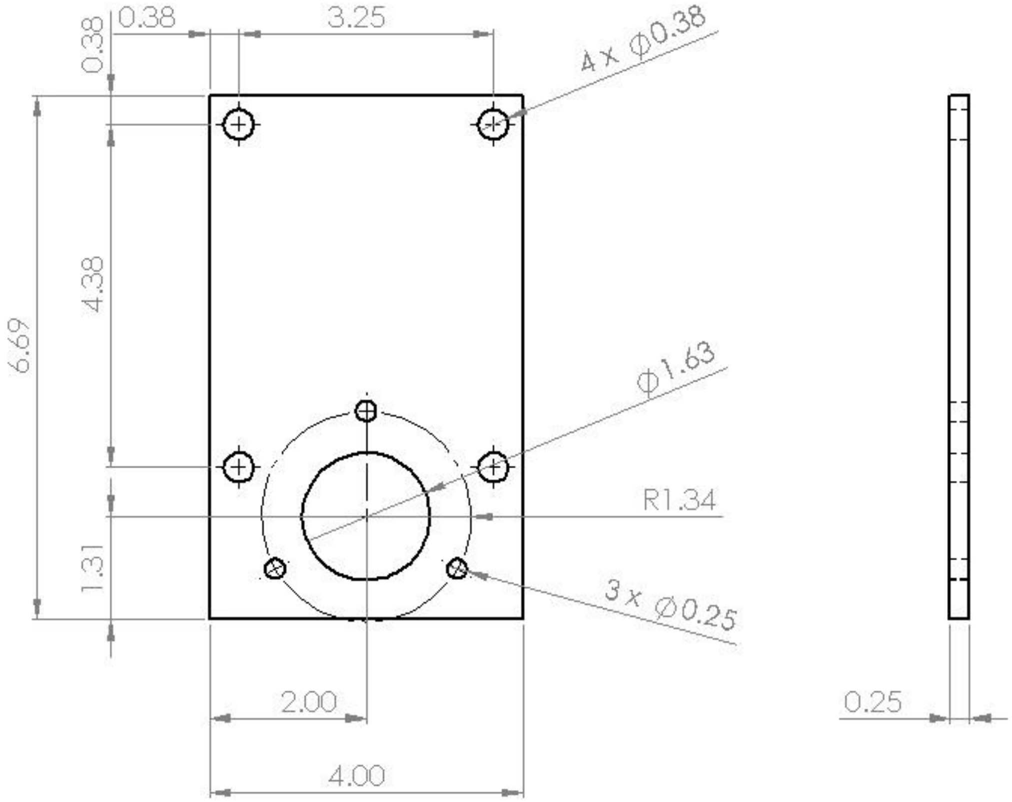
Standard View



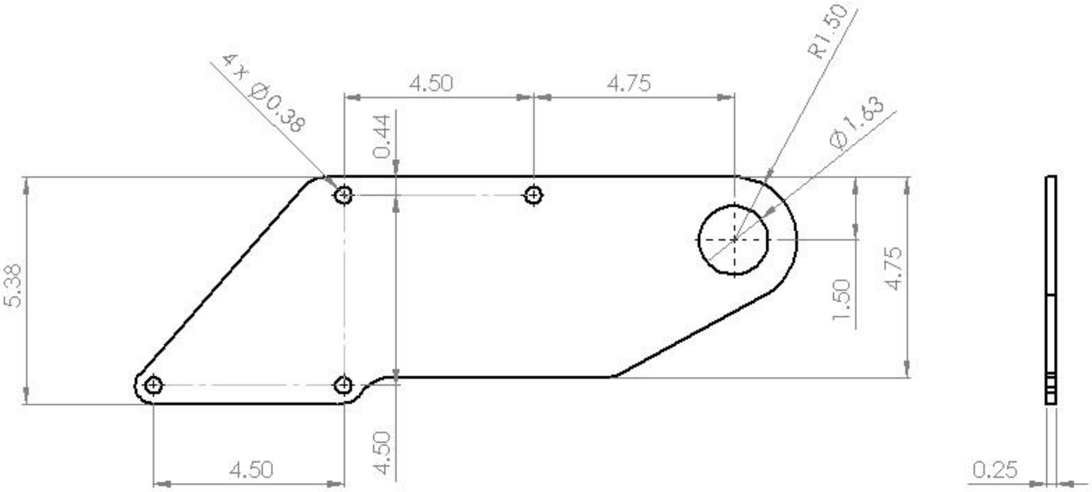
Isometric View



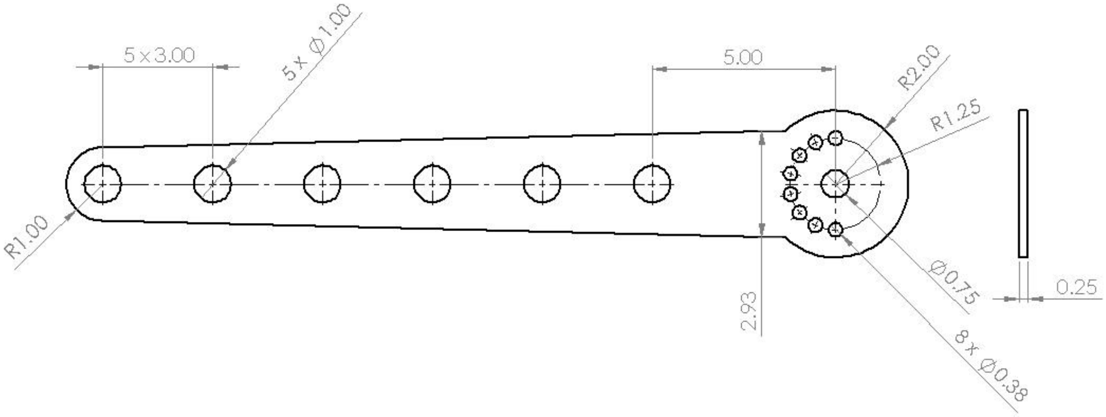
Weight Plate



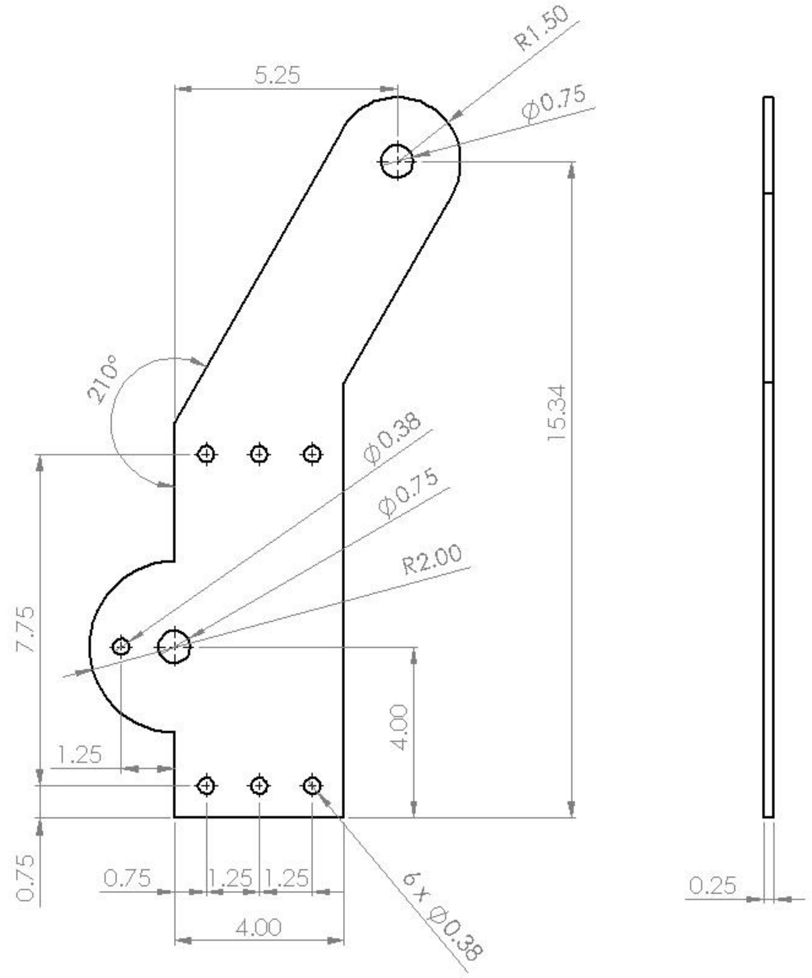
Pitch Axis Plate



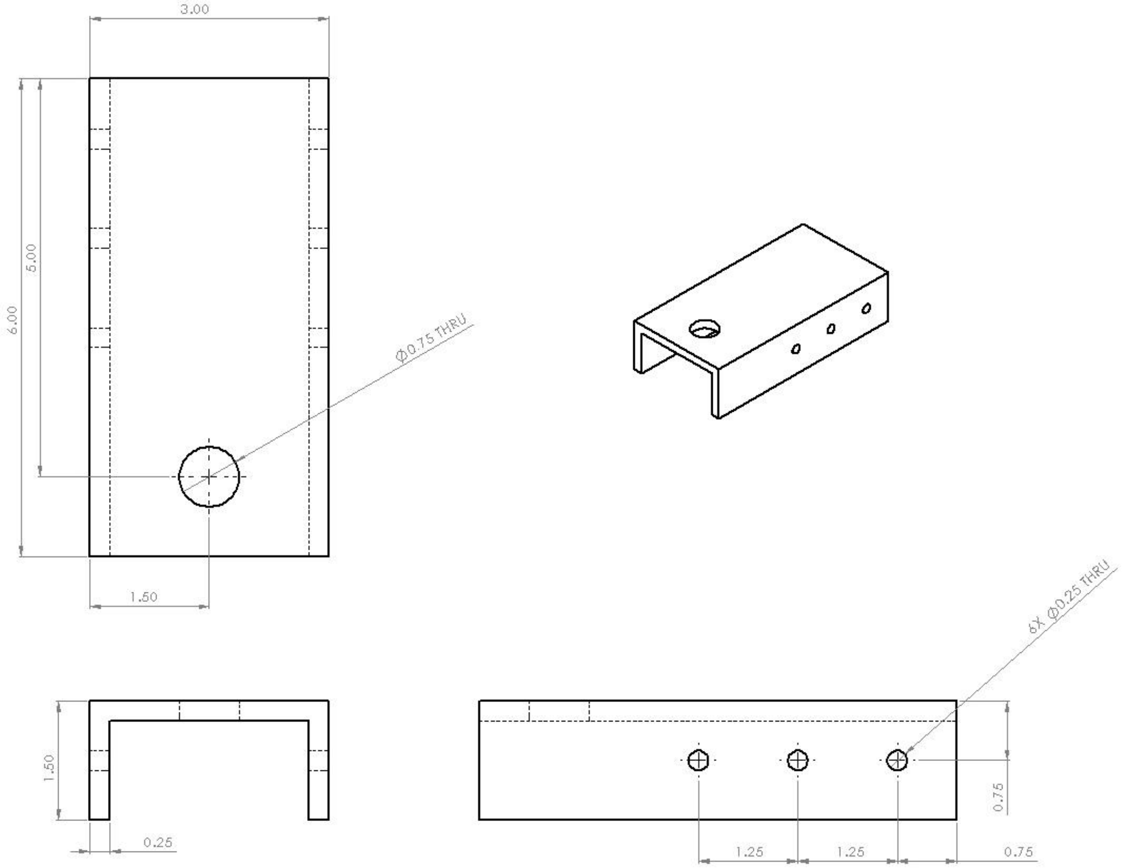
Arm Plate



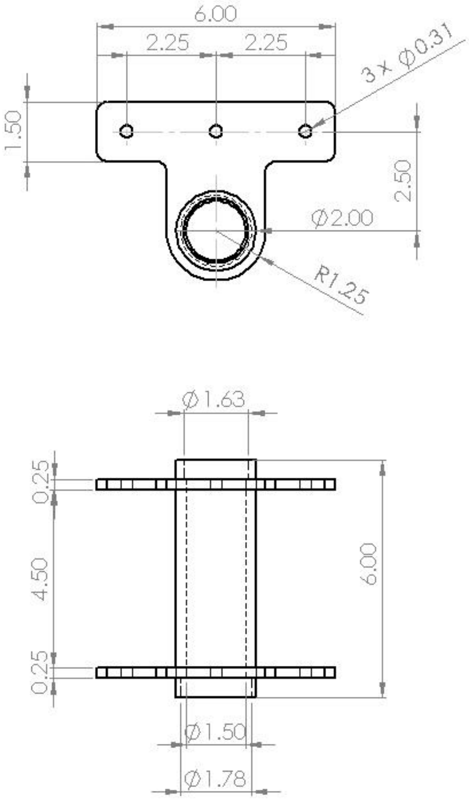
Counterbalance Plate


R1.50
5.25
Ø0.75
210°
Ø0.38
Ø0.75
R2.00
15.34
7.75
4.00
1.25
0.75
0.75
1.25
1.25
4.00
6x Ø0.38
0.25

Head Plate



Yaw Hinge Channel



Yaw Hinge Assembly