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Design and Evaluation of a Shoulder Supporting Exoskeleton for Occupational Use

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DESIGN AND EVALUATION OF A SHOULDER SUPPORTING EXOSKELETON FOR OCCUPATIONAL USE

BY

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COMMITTEE IN CHARGE:

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PROFESSOR DAVID REMPEL
PROFESSOR GRACE O'CONNELL

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Abstract

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Doctor of Philosophy in Engineering- Mechanical Engineering

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Overexertion is a common cause of work related musculoskeletal disorder (WMSD) in the modern industry. The shoulder is one of the most susceptible joints to injury and requires the longest amount of recovery time to heal, currently accounting for about one fifth of the total cost associated with WMSD's. Exoskeleton technology has the potential to provide beneficial augmentation to workers in many industrial fields. A strategic application of support reduces the forces exerted by the operator, potentially decreasing risk of injury and increasing productivity though the added capability. Their mobility allows for application in environments where a static aid is not feasible due to constantly changing surroundings, such as in construction or shipbuilding, or due to high costs of modifying an established manufacturing line for ergonomic benefit. As the field of shoulder supporting exoskeletons begins to emerge, little is known about the effects these devices have on operator's effort and productivity.

This work introduces a novel design for a shoulder supporting exoskeleton as well as a preliminary evaluation of the device's effects during common workplace tasks. The exoskeleton builds off of the success of a trunk and a leg supporting exoskeleton developed at the UC Berkeley Human Engineering and Robotics Laboratory. A passive actuation strategy is presented to augment the torques about the shoulder due to the gravitational forces on the arm and a handheld tool for a variety of workplace tasks and individual preference. A modified iso-elastic base profile divides support into a working and non-working range of motion and can be modified in its amplitude, on/off state, and gravitational offset. A biomimetic frame design provides the support and motion necessary to apply the supporting torques across the shoulder joint for a majority of worker dimensions. Couplings at the arm, shoulders, and hip comfortably secure the frame to the body in a familiar manner that is easy to use while glenohumeral, scapulothoracic, and spinal degrees of freedom allow for relatively unrestricted mobility. A modular approach to combining the shoulder supporting exoskeleton to neck, trunk, and leg assisting devices is discussed to accommodate tasks with risk of injury to multiple joints. A combination of two, three, and four devices is presented for commonly occurring tasks, comprising what is probably the most sophisticated workplace exoskeletons that has been designed to date. A controlled study has been conducted to assess the shoulder supporting exoskeleton's effects on effort and usability for a common set of workplace tasks and tools. Results show a substantial and desirable decrease in muscle activation for all conditions.

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I'd also like to acknowledge Dr. Wayne Tung and Dr. Minerva Pillai for serving as my unofficial advisors in the Human Engineering and Robotics Lab. You both have provided invaluable guidance over the years and have looked out for me every step of the way.

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I hope someday I will be able to provide to many others what you all have done for me.

CHAPTER 1: INTRODUCTION

MOTIVATION

Work-related musculoskeletal disorders (WMSDs) of the upper extremity are an important issue in the modern workplace. In 2015, the shoulder was involved in 8% of all WMSD cases reported in the United States. [1] Injury to the shoulder is typically two times more severe than the average WMSD. The amount of missed time due to a shoulder WMSD is 23 lost workdays while the average across all body regions is 11 lost workdays. [1] These values are also likely to be underreported.

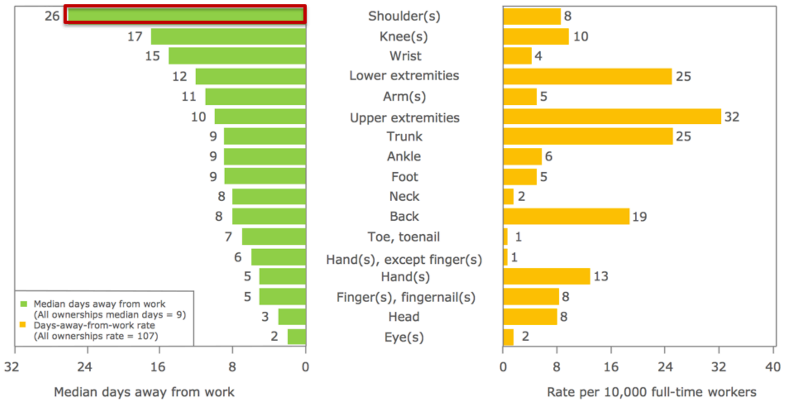


Figure 1. 2014 Lost time and incidence rate of injury by body part. [2]

Using the above information with average treatment costs [3] and assuming $30/hour for lost productivity costs the total costs of shoulder WMSD is 1.44 billion dollars annually in the United States, accounting for 18.9% of injury costs across all body regions.

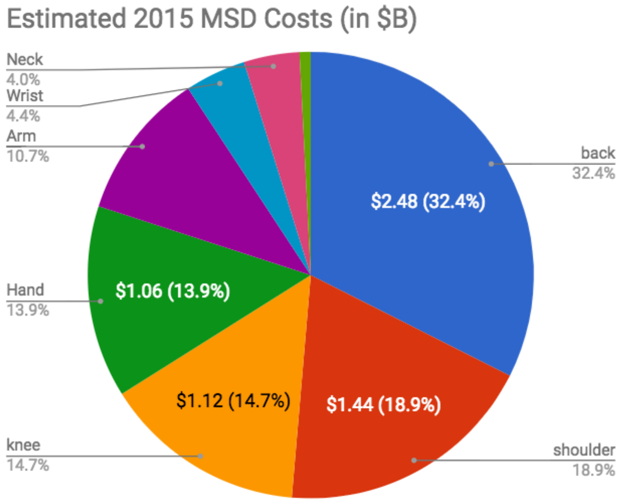


Figure 2. 2015 Injury Costs by Body Region in the United States ($B) [1] [3]

Overhead work, defined as working at or above the shoulder, has been identified as a category of tasks with especially high risk of WMSDs. Overhead work is commonly performed in construction and aircraft/automobile manufacturing. [4] Risk factors contributing to upper extremity WMSDs include repetition, force, awkward posture, and vibration. To mitigate risk of injury, shoulder load be decreased, the duration of the load reduced, or amount of rest breaks increased. [5] By reducing the force exerted by a worker, his or her task can potentially be performed with reduced risk of injury and increased productivity due to the ability to work for longer durations without rest.

Despite technological advancements in automation, human ability and expertise remains a primary source of capital for many of the largest industries. The tasks demanded of tradesman in agriculture, construction, manufacturing, and other occupations are often physically demanding and can contribute to musculoskeletal disorders if left unaddressed. Ergonomics is a field devoted to studying human's efficiency in the work environment, helping to create tools and workspaces that optimize productivity while minimizing risk of worker injury. For many trades however, environmental factors limit the effectiveness of conventional ergonomic implementations, which typically must be mounted to static features that are part of the environment. Construction workers, for example, operate within constantly changing surroundings that prevent the use of static workstations to help lift and position hand tools, such as those used in the controlled space of a manufacturing line. Even in the controlled space of manufacturing, the cost of modifying the line may outweigh any ergonomic benefits gained. For workplace tasks such as this, exoskeleton technologies offer a promising solution to reduce strains on the body without affecting the larger environment or compromising a worker's mobility.

Just as the motion of the body relies on the muscular and skeletal systems, an exoskeleton can be divided into its actuation strategy and the design of the load bearing frame structure. Figure 3a shows the basic components of an arm supporting exoskeleton consisting of a torso frame and an arm frame coupled by an actuator. The actuator creates a torque between the arm frame and torso frame, and the reaction forces and torques are distributed to the person through padded interfaces at the arms, shoulders and hips. This torque produces a force F, as shown in Figure 3b, compensating for the weight G of a person's arm and tool, theoretically reducing the muscular forces F_M that would otherwise be used to raise the arm.

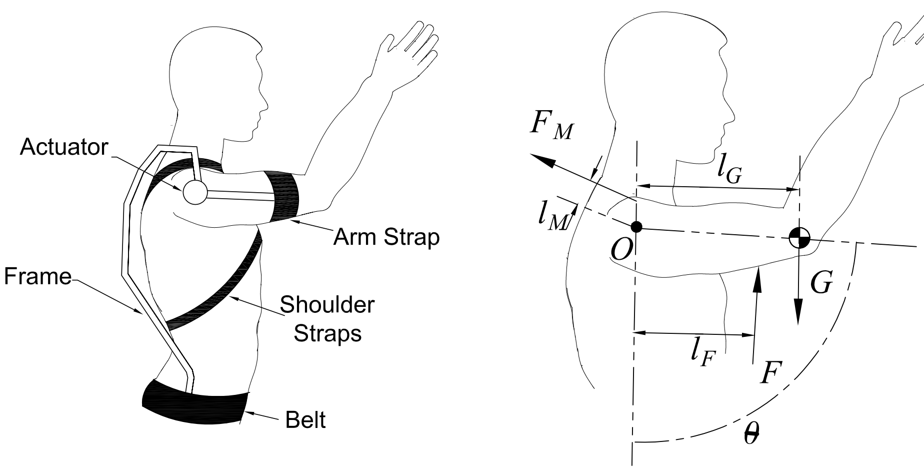


Figure 3. Basic Exoskeleton Structure (a) and Actuation Strategy (b).

PRIOR ART

Exoskeleton technologies with industrial applications are currently on the brink of proving themselves as feasible implementations to assist and protect workers operating in difficult environments. These devices can be categorized as active or passive, depending on their components and energy consumption. Active devices utilize coordination of sensors, actuators, and energy storage to provide augmentation while passive devices use intelligent placement of springs and other non energy-consuming components. Active exoskeletons allow for greater forces and dynamic features compared to their passive counterparts, but are burdened with complexity and high cost. The arm supporting exoskeletons can be categorized into active or passively actuated as well as environment and user mounted. Figure 4 shows the state of the art exoskeleton technologies as of 2015 with the target space of a passive body mounted device, a year after this project began [6].

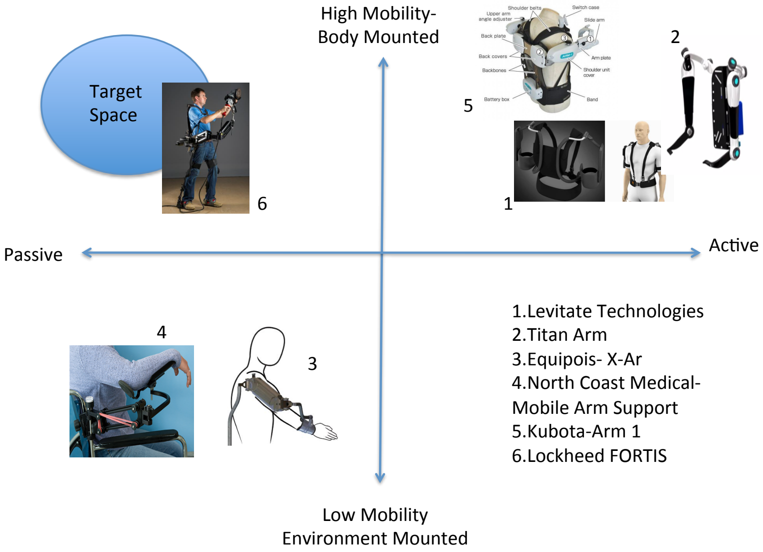


Figure 4. 2015 Upper Extremity Exoskeleton Technologies. [7] [8] [9] [10] [11] [12]

As stated in [6], "It is the author's belief that body mounted, passive devices provide the best combination of augmentation and mobility for early adoption in industrial applications." Since 2015, the target space of passive, body mounted arm supporting exoskeletons has grown rapidly. This space can currently further be divided into supernumerary configurations and parallel configurations, as shown in Figure 5. The supernumerary arm supporting exoskeletons utilize a "3rd" and "4th" arm and are most useful in supporting heavy loads, such as camera equipment. They do not rotate along the same axes as the users shoulder or elbow, and connect either directly to the tool or to the forearm so the load bypasses most of the users arm and is distributed directly to the torso. Parallel configuration arm supporting exoskeletons move along axes substantially collinear with the shoulder and most often connect to the upper arm. Parallel exoskeletons are best for supporting the shoulder complex for tasks that require low or mid-weight tools.

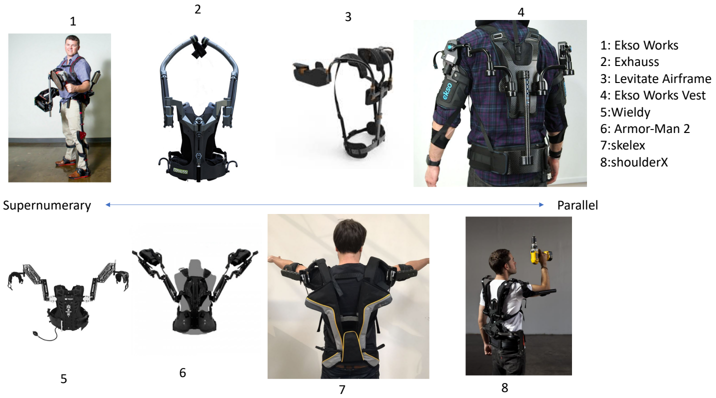


Figure 5. 2018 Passive, Body Mounted Upper Extremity Exoskeleton Technologies. [13] [14] [15] [16] [17] [18] [19] [20]

Two fundamental aspects of exoskeleton technologies are the actuator that creates a torque to support a biological joint, and the structural frame design that takes that torque and distributes it to the operator's body. Adjustability of the actuator output torque allows for the exoskeleton support to be tuned for different task motions, tool weights, and operator preferences in order to get the maximum benefit to assisted muscles. The exoskeleton frame needs to distribute that support across the operator's body comfortably without inhibiting any motions that a certain task may require. Therefore, exoskeleton frame degrees of freedom can be a good measure of the mobility a device provides the operator to complete a task as would be done unassisted. Figure 6 organizes the parallel exoskeleton technologies according the known exoskeleton frame degrees of freedom and the known actuator adjustable parameters according the specifications indicated by each respective device manufacturer or what can be observed from analyzing photographs and videos.

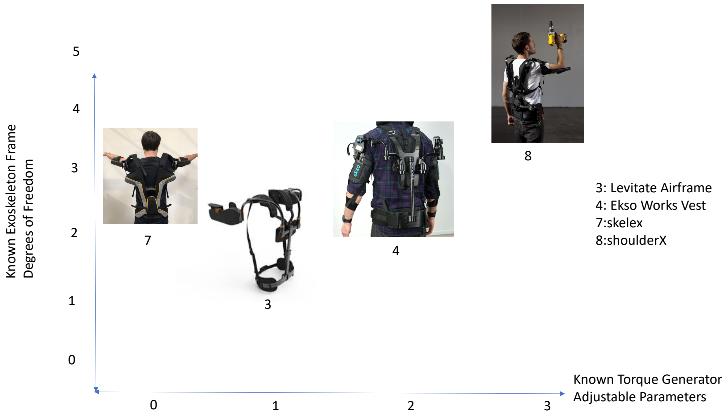


Figure 6. 2018 Passive, Body Mounted, Parallell Upper Extremity Exoskeleton Technologies by Degrees of Freedom vs Adjustable Parameters. [15] [14] [19] [20]

Prior studies have evaluated the effectiveness of upper limb exoskeletons in the automotive [21] [22] and welding/painting industries [23]. These studies have focused on joint torque effects and job simulator productivity, respectively. To date no studies have been conducted on industrial upper extremity exoskeletons that analyze muscle activation levels or patterns or the effect of changing support level or patterns.

RESEARCH OBJECTIVE AND CONTRIBUTION

The objective of this research is to develop and evaluate a novel shoulder support exoskeleton to support overhead work that is feasible to implement in the workplace. Through observation of workplace tasks across a range of industries a few insights have guided the design philosophy of the device.

1. Allowing freedom for secondary tasks is just as important, if not more so, than supporting the primary task.
2. Most tasks with awkward postures use low to mid-weight tools, tasks using heavy tools have largely been eliminated or optimized to reduce effects of the load.
3. The range of postures, preferences, and environments is vast; adjustability is important to optimize the device for each individual.
4. Passive function is desired for rough workplace environments

Over the past four years, this research project has contributed to the field both in industry and academia. The development of shoulderX has helped open world markets to industry focused exoskeletons, facilitating the expansion between Figure 4 and Figure 5 above. The device's adjustability in actuation strategy, frame design, and modularity have allowed for preliminary user trials to begin across a range of locations and industries, as shown in Figure 7. A formal laboratory study described in chapter 5 has been the first to quantify effects of the system on muscle activation during simulated work tasks, as well as the first to explore the effects of varying the level of support provided.

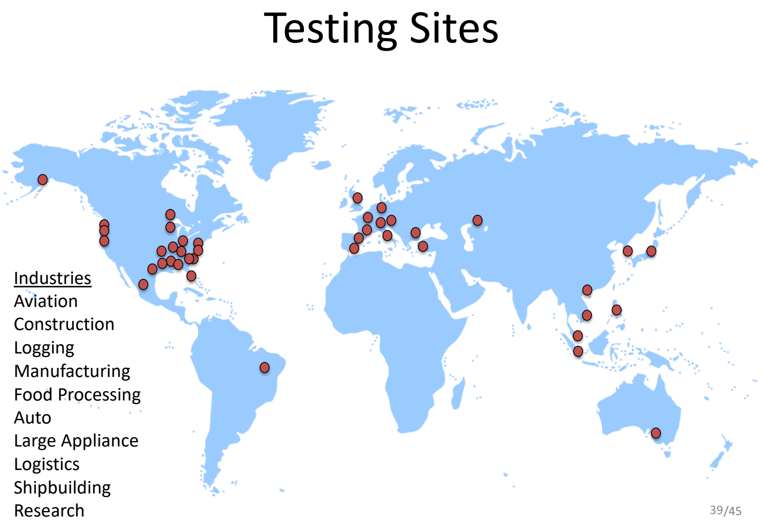


Figure 7. 2018 shoulderX testing sites and industries

To accomplish this an iterative approach was used to define specifications for range of motion, profile, support, and accessibility, and to test for adequate weight, comfort, and ease of use. Additionally, both user-based and laboratory testing was utilized to determine the feasibility of real world implementation and to quantify physiological effects of the device. Figure 8 below outlines the primary iterations and dates of the shoulder supporting exoskeleton developed throughout this research.

Figure 8. Shoulder Supporting Exoskeleton Iterations. From left to right: Case study (2014), V0 (2014), Va(2015), Vb(2016), V1(2017), V2 with scapular movement mechanism (2018).

The authors work can be categorized into the following sections:

Shoulder Supporting Actuation Strategy

The author has developed several iterations of a passive shoulder supporting torque generator with three adjustable parameters. The actuator adjusts for support amplitude, gravitational offset, and on/off states that can be tuned to optimize support for varying tasks, loads, and users. The shoulder actuator hardware embeds an angle dependent torque profile that creates a modified iso-elastic response in a range of working postures and automatically zeros in neutral postures.

Biomimetic Shoulder Frame Design

The author has developed several iterations of a structural frame designed to support the reaction forces and torques from a supportive actuator and distribute them across a wearers body. The most current frame provides 5 degrees of freedom for horizontal and vertical motions of the shoulder, scapular elevation, spinal twisting, and lateral spinal flexion.

Modularity

As many workplace tasks involve risk to multiple joints a modular framework was designed for the shoulder supporting exoskeleton to connect to a trunk supporting exoskeleton and a leg supporting exoskeleton, also designed by the UC Berkeley Human Engineering and Robotics Lab. The trunk supporting exoskeleton supports the hip during flexion while a user stoops while the leg supporting exoskeleton supports the knee in flexion during a squat. Based on user feedback, a concept for a neck supporting exoskeleton is also presented to support motions of neck extension. The neck frame utilizes the shoulder frame adjustability and provides an on-axis torque that is distributed to the back of an operator's head.

Ergonomic Evaluation of a shoulder Supporting Exoskeleton

The author has conducted a laboratory evaluation of the shoulder supporting exoskeleton to evaluate effects of support amplitude on static and dynamic overhead tasks. Electromyography recordings of fourteen subjects with a background in manufacturing and construction were taken to quantify the change in muscle activation, and surveys were used to indicate perception and usability of the device.

CHAPTER 2: SHOULDER SUPPORTING ACTUATION STRATEGY

A torque generation strategy is described to support the shoulder joint during a diverse set of overhead tasks with minimal inhibition to secondary motions a worker may perform. The basis for the actuation strategy relies on a modified iso-elastic torque profile wherein support torque equals the gravitational torque on the upper arm during the high range of shoulder elevation and remains less than the gravitational torque in the lower range of motion. For varying user and tool weights a support level adjustment mechanism varies the torque amplitude without compromising the modified iso-elastic profile. To allow for an on-off function in situations a user selectively needs support a variable mode force generator is designed to shift the torque profile between a high and a low state. Finally, to accommodate primary tasks taking place at different heights and with varying force requirements a gravitational offset adjustment mechanism shifts the torque profile relative to elevation angle. Some key challenges inherent in a shoulder actuator is that the neutral shoulder position is the state of lowest potential energy, and that the side-rear space of the shoulders where the actuator is located is often the most difficult place for users to see and reach.

MODIFIED ISO-ELASTIC PRINCIPLES

Passive gravity compensations systems utilize iso-elasticity to allow for a mass to be supported in a manner that it remains statically stable across a range of positions of the support system. These mechanisms have been utilized throughout the last century to support everything from lamp shades [24] to camera equipment [25], and more recently robotics [26] and exoskeletons [27]. Here, the design of a modified iso-elastic actuator is presented to support the unique requirements for the shoulder complex during overhead work.

A SIMPLE MODEL OF LIFTING

Consider that a person has elevated the upper arm from a vertical resting posture by θ (Figure 9). In a static scenario the torsional loading applied about the shoulder joint O can be represented by [$Gl_G \sin(\theta)$] where G is the weight of a person's arm/tool and l_G is the horizontal distance between shoulder joint, 0, and the center of mass of the persons arm. Unassisted by external forces, this torque is countered by forces generated by various shoulder muscles F_M, and the weight is transferred through the spine and the legs to the ground.

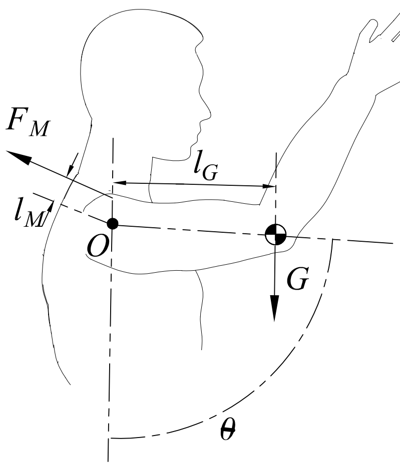
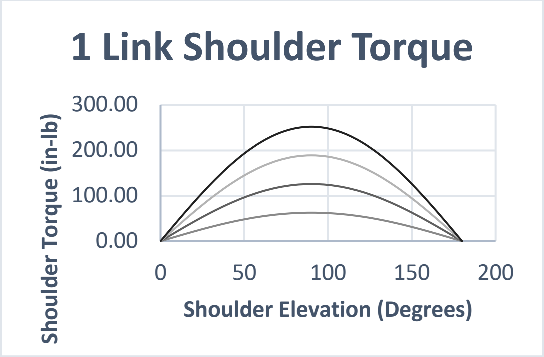


Figure 9. Kinematic Model of Lifting.

Assuming the mass of the forearm, hand, and tool to be represented as a point mass at the elbow the torque created by G can be estimated for all angles θ for any persons body weight, height, and tool using standard anthropometric proportions [28]. A profile of this torque is shown in Figure 10 for 0 to 180 degrees of shoulder elevation for a 5'8", 145lb person carrying no, 5lb, 10lb and 15lb tools. It is seen that the torque profile for all tool weights is a simple sinusoidal shape with varying amplitude.

$$M_s = .44W_1L_1\sin(\theta) + (W_2 + W_3 + W_4)L_1\sin(\theta) \qquad \text{(Equation 1)}$$



Where,

L_1= Length of the upper arm= .186*H
L_2= Length of the forearm=.146*H
L_3= Length of the hand= .108*H
W_1= Upper arm weight= .0325*BW
W_2= Forearm weight= .0187*BW
W_3= Hand weight= .0065*BW
W_4= Tool weight

Figure 10: Shoulder Torque Profile For 145lb 5"8 Human carring no, 5lb, 10lb, 15lb tool.

GRAVITY COMPENSATION MECHANISM

To reduce muscle activation, and thus risk of injury, the weight of the arm and tool as felt by the shoulder must be augmented. In a paper presented by Morita, Kuribara, Shiozawa, and Sugano titled "A Novel Mechanism Design for Gravity Compensation in Three Dimensional Space" a method of canceling gravity is presented. [29] In a static kinematic model of the mechanism shown in Figure 11a, the moment of the center of mass of the system balances with the moment created by the stretched spring. The spring constant needed to put the system in static equilibrium is solely dependent on the geometry of the system and the mass supported. The value of the spring constant, k is independent of the arm angle θ or the angle of the spring to the arm φ. Thus, the static case is viable for any angle of θ. The resultant supportive torque is equal but opposite to the simplified shoulder and elbow torque profile shown in Figure 10 above. To achieve the mechanism shown in Figure 11a, the spring must be taken off of the diagonal AC, one embodiment being shown in Figure 11b. [29]

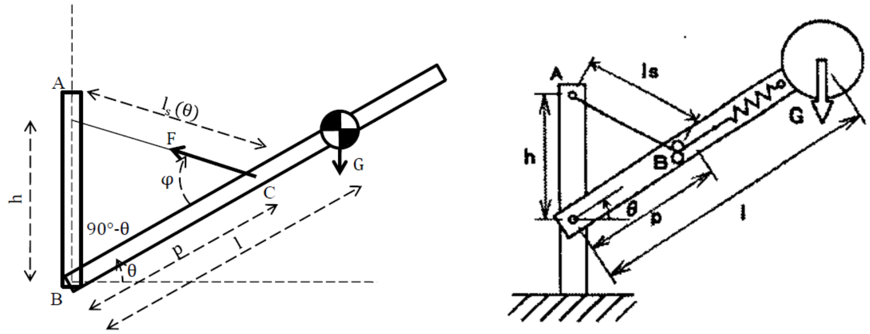


Figure 11: Gravity Cancellation Geometry (a) and proposed mechanism (b)

The exoskeleton actuator, shown in Figure 12, uses a similar configuration. The shoulder actuator 108 creates a toque 280 about a distal link 152 that is rotatably coupled to a proximal link 150 about rotation joint 151. The torque is created by a tensile force generator 178, comprising a spring 180 and flexible line 182 that is routed around a pulley 183 attached to the distal link 152. The tensile force generator 178 is attached to the proximal link 152 at point 176 and to the distal link at a flange 177. The spring is compressed by a slider 179 attached to line element 182 that translates along distal link 152.

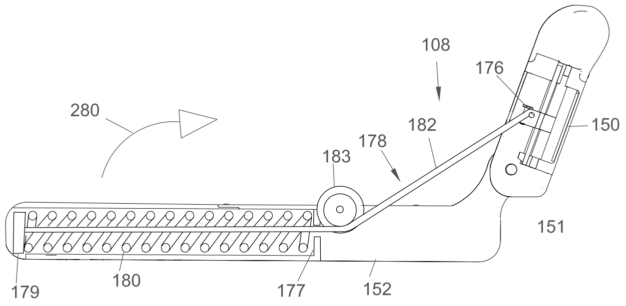


Figure 12: V1 and V2 Exoskeleton Actuator Configuration.

MODIFIED ISO-ELASTIC PRINCIPLES

Upon testing of initial versions of the device it was noted that a perfectly iso-elastic torque profile is not often desired. For most shoulder-intensive tasks a majority of the effort occurs during higher angles of shoulder elevation, while lower angles of elevation occur during secondary tasks. Thus, it is desired for the torque profile to support a user in these higher ranges of shoulder elevation and provide free movement during the lower ranges. This modification of the profile should hold true for all levels of support adjustment.

One method of modifying the torque profile begins with removing the condition from [29] that the free length of the un-stretched spring, l_{s0} is zero and applying a gravitational offset to the mechanism. Figure 13 depicts a new model similar to that of Figure 11, but with the offset parameter, ϕ, indicated, and the value of θ being indicated off of the vertical rather than horizontal.

where,

F = Force acting on spring located along AC
k = Spring constant
$l_s(\theta)$ = Length of stretched spring as f(theta)
$F0$ = Spring preload
θ = Angle BC makes with vertical
l_{s0} = Free length of the unstretched spring
G = Weight of the arm BC located at the center of gravity
l = Distance along arm BC to the center of gravity
p = Distance of spring located along BC
φ = Angle the spring along AC makes with BC

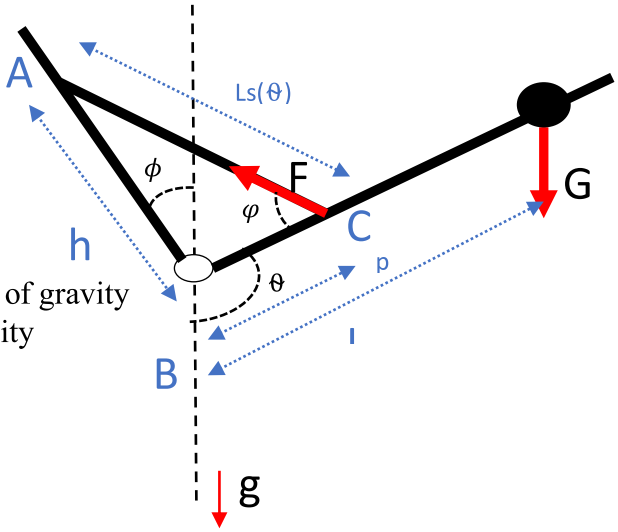


Figure 13. Modified Iso Elastic Model.

To calculate torque output of the device, τ, as a function of known variables a static equilibrium case is evaluated where the arm BC freely pivots about point B. It is assumed that an ideal linear spring acts about AC.

$$\tau = Fpsin\varphi \tag{Equation 4}$$

$$F = k\Delta l_s(\theta) = k[l_s(\theta) - l_{s0}] + F0 \tag{Equation 5}$$

Like [29], a relationship between $sin\varphi$ and θ is found using the law of sines:

$$sin\varphi = \frac{hsin(180-\theta+\emptyset)}{l_s(\theta)} \qquad \text{(Equation 6)}$$

Combining Equation 4 with Equation 5 and Equation 6 yields:

$$\tau = \frac{(k[l_s(\theta)-l_{s0}]+\mathrm{F0})\mathrm{phsin}(180-\theta+\emptyset)}{l_s(\theta)} \qquad \text{(Equation 7)}$$

With the law of cosines the term ls(θ) can be calculated as a function of arm elevation, θ, and the geometry of the mechanism.

$$l_s(\theta) = \sqrt{h^2 + p^2 - 2hpcos(180 - \theta + \emptyset)} \qquad \text{(Equation 8)}$$

Combining Equation 7 with Equation 8, the torque output of the device, τ, can be calculated as a function design input variables and angle of arm elevation. Note if values of 0 are used for the gravitational offset, φ, and un-stretched spring, l_{s0}, the resultant torque profile reduces to that of [20] shown in Figure X.

$$\tau = \frac{\left(k\left[\sqrt{h^2+p^2-2hpcos(180-\theta+\emptyset)}-l_{s0}\right]+\mathrm{F0}\right)\mathrm{phsin}\ (180-\theta+\emptyset)}{\sqrt{h^2+p^2-2hpcos(180-\theta+\emptyset)}} \qquad \text{(Equation 9)}$$

Asymmetry in the supportive torque profile can be created by removing the condition from [29] that the free length of the upstretched spring, l_{s0} equal to zero and manipulating the preload, F0, of the spring. Figure 14shows one example of a non-zero positive value being used for the un-stretched spring.

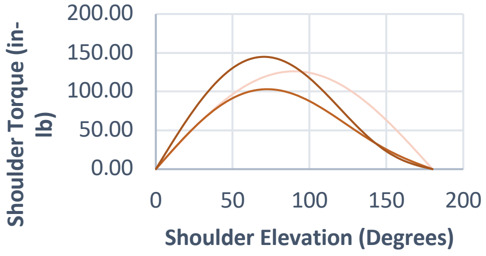


Figure 14. Skewed Supporting Torque.

At first this modification seems undesirable, as torque in the low range of elevation has been increased and torque in the high range of elevation has been decreased. To correct this a mechanism gravitational offset, ϕ, can be applied to shift the supportive torque profile left or right in the plot above. In equation 9 one may notice that for angles of shoulder elevation less than the offset value, ϕ, the resultant torque becomes negative. This is due to a togglepoint in the mechanism when ψ becomes neguative and causes F to pull the ouput link in the opposite direction. Instead of toggling, it would be desired for the mechanism to instead maintain a zero torque at angles greater than the toggle position. Using the mechanism gravitational offset, ϕ, in

Equation 9 along with the toggle modification of zero force produced past the mechanism toggle angle the following output torque profile is produced.

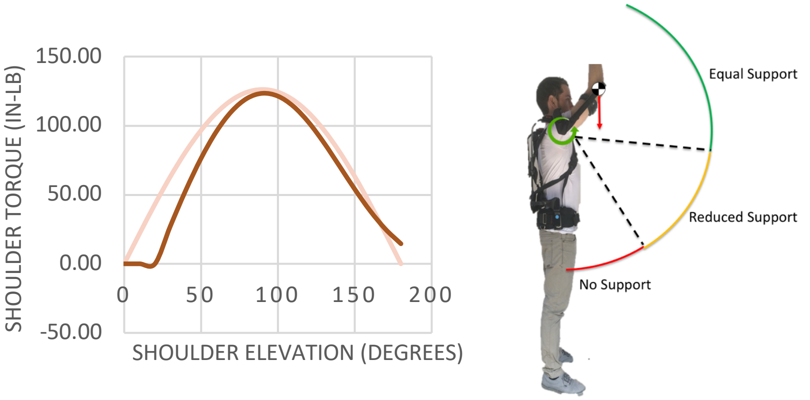


Figure 15. Modified iso-elastic torque profile (a) and resutant support characteristics (b)

The mechanism fitting the modified iso elastic criteria described above is showin in Figure 16. In Figure 16a the orientation of proximal link 150 along line 191 off of vertical is equal to the offset value, ϕ, shifting the resultant torque profile relative to θ which is based off of vertical. The mechanism toggle angle 195 is the angle of distal link 152 relative to proximal link 150 in at which the link 182 of spring element 178 crosses rotational joint 151 and the direction of generated torque 280 switches from clockwise to counterclockwise. A zoom view of is shown in Figure 16b wherein a protrusion 186 constrains line 182 and centers it about rotating joint 151 after the mechanism has passed toggle angle 195. Once centered about rotating joint 151, the moment arm acting about spring element 178 is near zero, and thus a near zero torque 280 is produced between proximal link 150 and distal link 152.

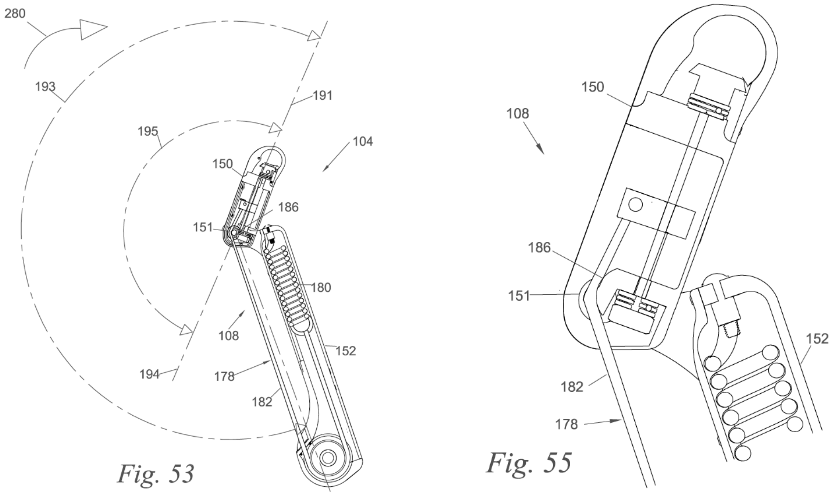


Fig. 53

Fig. 55

Figure 16. Modified Iso Elastic Mechanism toggle angle (a) and protrusion constraint (b)

The resultant modified iso-elastic support torque profile fulfills the user needs of a balanced level of support in the upper ranges of shoulder elevation while reducing support relative to gravitational shoulder torques in the lower range of elevation. This strategy optimizes support during shoulder intensive tasks, which often occur overhead, and automatically reduces inhibition of secondary tasks such as reaching for pockets or resting the arms at one’s sides.

Support Level Adjustment

The modified iso-elastic supportive torque is optimized for a single value of mass for which gravity compensation is desired. Even in the ideal case where movement of the elbow is neglected, this gravitational torque changes between user height and weight as well across a varying set of tools a user may employ during the workday. A support level adjustment mechanism allows for the amplitude of the modified iso-elastic torque profile to be adjusted to best fit these variables while maintaining the characteristics described above.

Effect of Tool weight- Determination of Torque specifications

In practice, the torque about the shoulder joint during overhead work can vary not only by angle of the workers joints, but by the weight of the workers arm and a handheld tool. Forceful motions of the upper arm have been related to shoulder fatigue and disruption of tendon circulation, especially with the addition of a hand held load. [4] Even in the most dynamic movements the glenohumeral joint and rotator cuff girdle experience loading with a static component, as these joints must be stabilized if the arm is to move properly. [4] If sustained for one hour, the onset of shoulder muscular fatigue may begin at levels as low as 5% of Maximum Voluntary Contraction (MVC). [30] Impaired circulation has been shown to result at values as low as 10-20% MVC, which further serves to increase levels of fatigue. [31]

Many ergonomic aids use muscle activation level to estimate safe working conditions, such as endurance time [32] and duty cycle [33] shown in Figure 17. It can be seen that the recommended working time or duty cycle decays non-linearly with increased effort intensity. Looking at a similar plot comparing endurance time against standardized intensity for multiple joints [34], it can be seen that the shoulder preforms the worst.

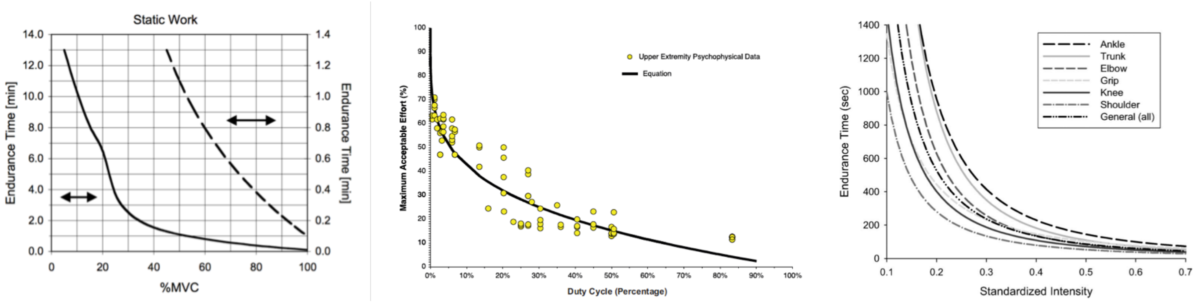


Figure 17. Plots of endurance time and duty cycle vs effort intensity [32] [33] [34]

To determine the effect of tool weight on muscle activation a pilot investigation measured the activity of the anterior deltoid muscle when supporting a load in a posture of 90 degrees shoulder flexion and 90 degrees elbow flexion. This was performed on 6 student subjects and results were normalized against maximum voluntary contraction. Results are shown in Figure 18.

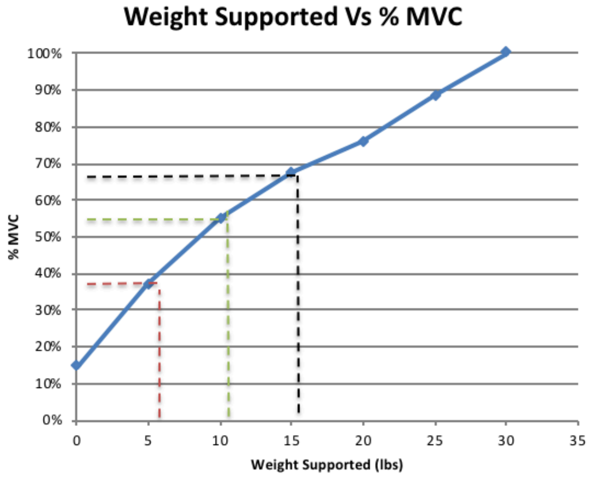


Figure 18. Muscle activation (%MVC) vs supported weight for 6 student subjects.

The force exerted at this range of contraction is very small, often less than the weight of the arm. This indicates that risk of WMSDs begins when a worker uses his arms in a raised position even without the additional load of a tool. Thus, workers carrying light, or even no tool, are good candidates for an exoskeleton to provide support to the shoulder. Additionally, workers may apply forces in addition to the weight of a tool, such as forcing a drill or grinder upwards into the ceiling. Because of the size and weight of the spring and supporting structure needed to compensate for heavy tools, it is decided that the exoskeleton should support light to moderate weight tools of 10-15lbs. Using Equation 3 above with characteristics of the 50% male [5], a peak supporting torque of approximately 200 lb-in is required. In addition to adjusting for worker and tool weights, a quickly adjustable supporting force can also accommodate varying levels of fatigue or user preference, or possibly assist a worker in a return to work program post injury.

SUPPORT ADJUSTMENT MECHANISM

Using equation 9 above, for a changing load [G], one can change values of p, k, or h to achieve a range of angle dependent support profiles. Since it is difficult to alter the spring constant, k is ruled out, leaving h and p. For purposes of this device, described later in the variable mode force generator section, the value h was chosen to adjust the amplitude of the supporting torque profile. By choosing fixed values of spring constant [k], and pulley mounting distance [p], the mechanism can be tuned to support a range of torques consistent with those needed for a particular worker population and set of common tool weights. When designing the range of torques to be produced it is important to balance this range of h with the spring parameters (k and maximum compression) and initial length of the cable across AC, ls0. Figure 19 shows the modified iso-elastic torque profile for values of h=.5:.25:1.75 with constants k=61, p=2.7, ls0=1.1 alongside the simplified shoulder moment for no, 5lb, and 10lb tools. Here it is important to note that angles at which the modified iso-elastic principles apply are relatively consistent throughout settings.

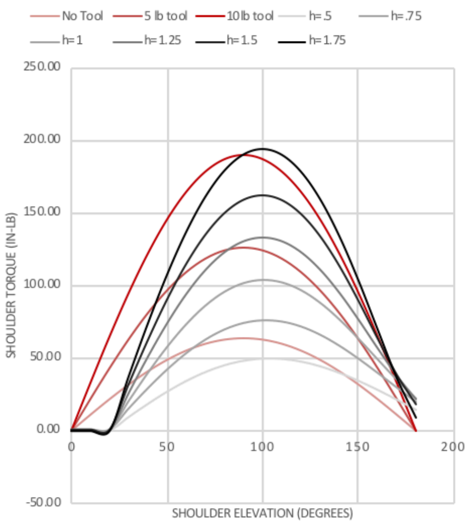


Figure 19. Adjustable modified-iso elastic support profiles vs simplified shoulder moments.

The adjustment of the h value is incorporated into the torque generator mechanism 108 as shown in Figure 20 below. The tensile force generator 178 is translationally coupled to proximal link 150 at an upper bracket 188 to vary the moment arm, h, of the tensile force generator 178 relative to the rotating joint 151. The position of upper bracket 188 is adjusted by means of a lead screw 187 that is connected to an adjustment knob (not shown). As the torque generator moves considerable force is placed on this adjustment in both directions. The lead screw provides both a mechanical advantage to the user operating the adjustment knob and prevents back drive of the mechanism due to the spring forces. Figure 20a shows the torque generator 108 in a strong setting, where the distance between upper bracket 188 and rotating joint 151, h, is large. Figure 20b shows the torque generator 108 in a weak setting, where the distance between upper bracket 188 and rotating joint 151 is small. This arrangement could also be reversed, with the pulley 183 and spring 180 located relative to the proximal link 150 and the upper bracket 188 moving the mounting point of the tensile force generator 180 along the distal link 152.

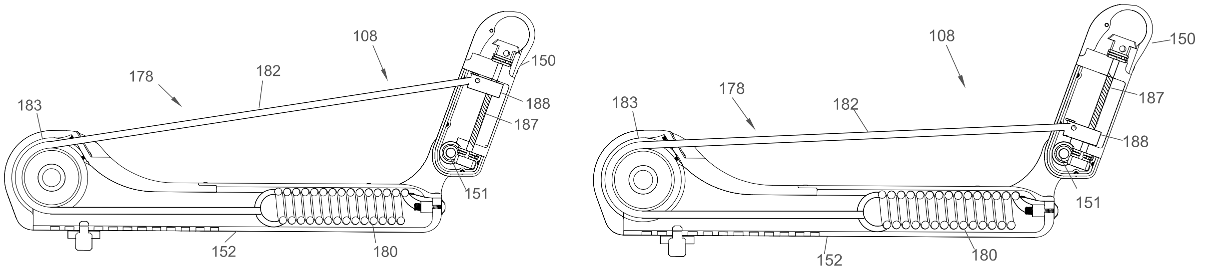


Figure 20. Support Adjustment Mechanism in (a) high and (b) low setting.

USABILITY

Implementation of the support adjustment mechanism highlights one of the key challenges in shoulder exoskeleton hardware design: the sides of the shoulders are often one of the hardest places to reach and see on the body. Figure 21 shows some various embodiments of the support adjustment mechanism in the beta, alpha, and production versions of the device. For all versions of the device the support adjustment mechanism utilized right hand threading and left-hand threading in the respective right and left arms to allow mirrored motions of operation.

Figure 21. Iterations of Support Adjustment Knob (a) Va (b) Vb (c) V1 & V2.

In the beta prototype of the device the support adjustment knob axis is parallel to the axis of motion of the upper bracket, shown in Figure 21a. This location proved difficult for operators to reach, rotate, and see. In the alpha prototype a set of miter gears is used to bring the knob axis perpendicular to the upper bracket motion and allow it to be moved medially to a position more directly above the shoulder, shown in Figure 21b. This proved easier to reach, but harder to grab, as a pinch is not possible, and less intuitive to rotate (forward-backward rather than clockwise, counterclockwise). Figure 21c shows the support adjustment interface used in V1 and V2 of the device. It likewise uses miter gears, but this time oriented orthogonal to those in Vb. While still difficult for some to reach, this has proved the best combination of access, use, and visibility.

Depending on a user's flexibility, a number of postures can be used to operate the support adjustment mechanism, as shown in Figure 22. Operationally the smoothest, but the most demanding in terms of flexibility, a user can operate the knob with the opposite arm while the arm to be adjusted is supported, Figure 22a. This requires the arm to be adjusted to be horizontally flexed across the body. If this is not possible, the arm to be adjusted can be doffed, while remaining attached to the exoskeleton torso frame as shown in Figure 22b, and either arm can be used to rotate the knob. Finally, the arm to be adjusted can be doffed and removed from the toso frame, adjusted as shown in Figure 22c, then re-attached and donned.

Figure 22. Support Adjustment Postures (a) arm donned (b) arm doffed (c) arm removed.

ON AND OFF STATES

It is often desired for the supporting torque to have an “on-off” function, especially when a handheld tool is being used. During overhead tool intensive tasks the tool is frequently set down for both long and short durations. In cases the exoskeleton operator has the support adjustment tuned for the combined weight of the arm and tool, then when the tool is set down the exoskeleton support torque would become stronger than the moment due to the arm weight alone. The overpowering of the exoskeleton could create discomfort or unwantedly increase the activation of shoulder extensor muscles. The ability to turn the device off allows tool changes or breaks to be done more comfortably, without having to constantly adjust support or doff the deivce.

VARIABLE MODE FORCE GENERATOR

To achieve the on-off functionality a variable mode force generator (VMFG) was designed. The VMFG transitions between a high and a low state by selectively engaging a set of springs. If a first spring is much weaker than a second spring, this can be equivalent to having the force turned “on” and “off”. Figure 23 shows an embodiment of the VMFG 401 configured to create a torque between a housing 406 an output link 407. Both a first spring 408 and a seocnd spring 411 are attached to a housing 406 at one end. The first spring 408 is attached to the output element 107 at it second end and the second spring 411 is selectively coupled to the first spring 408 using a constraining mechanism 414. Figure 23a shows the VMFG 401 in a first force mode where only a first spring 408 effects the motion of output link 407 relative to housing 406, creating a first force 402. Figure 23b shows the VMFG 401 in a second force mode where both a first spring 408 and a second spring 411 act in parallel to effect the motion of output link 407 relative to housing 406, creating a second force 403.

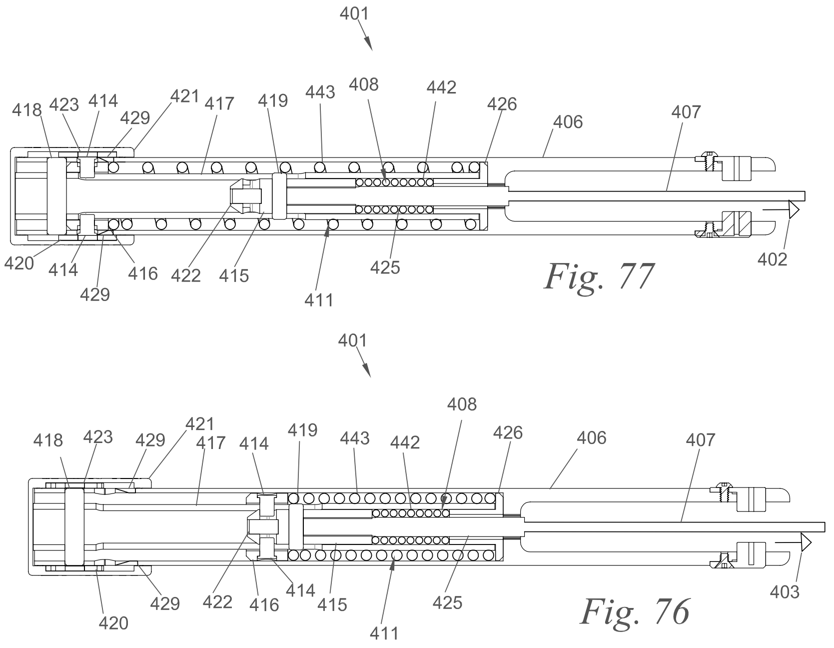


Figure 23. Variable mode force generator, (a) 1st “off” and (b) 2nd “on” modes

The variable mode force generator can be configured to create a torque about a rotating joint to function as the tensile force generator 178, or torque generator 108 from above as shown in Figure 24 below. Distal link 152 is replaceable with housing 406, line element 182 is replaceable with output link 407, proximal link 150 is replaceable with rotational base link 430, coil spring element 180 and junction 179 with first spring 408 or second spring 411, among other things. When variable mode force generator 401 is configured to create a weak first torque 404 as shown in Figure 24a, the operator may move the arm around freely without added support. When variable force generator 401 is configured to create a stronger second torque 405 as shown in Figure 24, it may similarly reduce the human shoulder forces and torques required to raise person's upper arm.

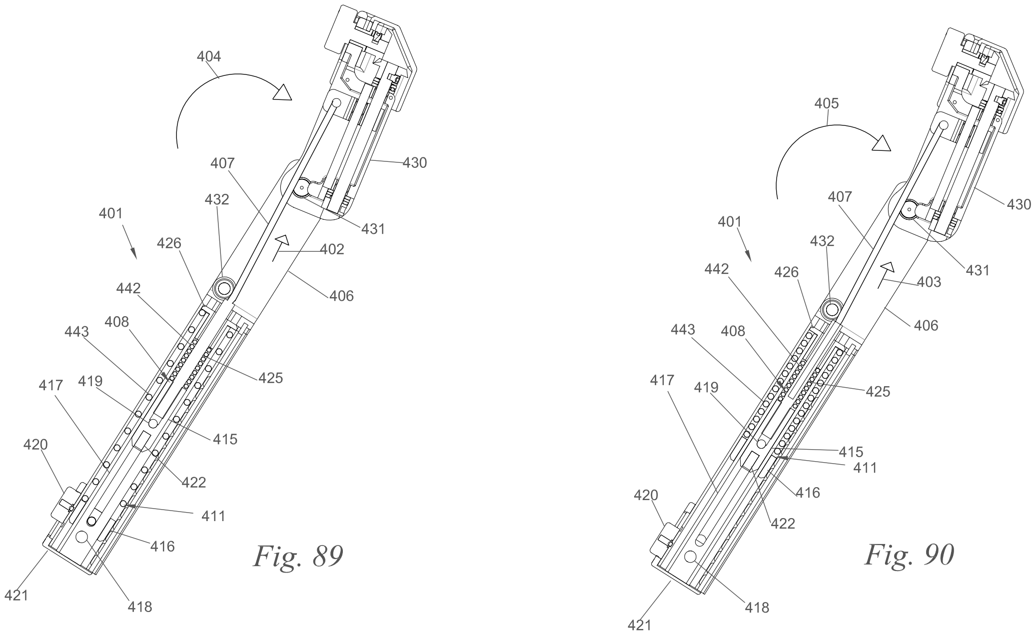


Fig. 89

Fig. 90

Figure 24. Variable force generator as exoskeleton torque generator in (a) off state (b) on state.

EFFECTIVE STATE TRANSITION

In order to transition between the first force mode and the second force mode the VMFG springs must return to an un-stretched, or a hard-stopped position. In use for the shoulder supporting torque generator, this corresponds to when the arm is in its most flexed angle. For optimal usability it is desired that the switch has the ability to be triggered at any angle of arm flexion, with the state change then occurring when the arm is flexed. Figure 25 shows the VMFG 401 at the transition position, corresponding to transition angle 427.

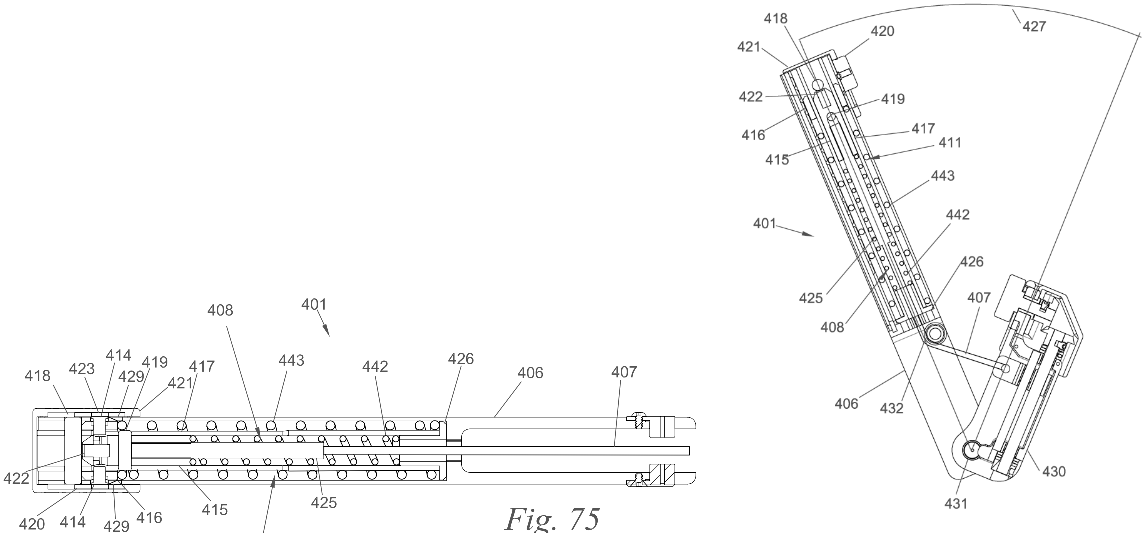


Fig. 75

Fig. 92

Figure 25. VMFG Transition Angle (a) and position (b)

At the transition state, both first spring 408 and the second spring 411 hard stop against an orientation pin 418. An orientation sleeve 415, a second orientation pin 419 and a constraining element 414 ensure that both the first spring 408 and the second spring 411 are properly oriented in the transition position. The VMFG first spring 408 further comprises a first spring element 425 and a first spring bracket 415. Likewise, the second spring 411 further comprises a second spring element 443 and a second spring bracket 416. The second spring bracket 416 houses a constraining element 414 that can selectively couple the second spring bracket 416 to the first spring bracket 415. Figure 26 shows a cross section of the VMFG with the constraining element 414 in a first and second position corresponding to the first force mode and second force mode.

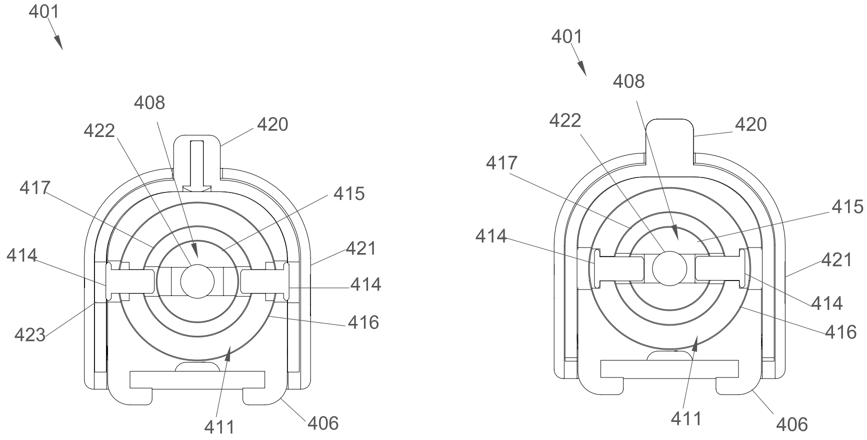


Figure 26. Constraining mechanism in (a) first and (b) second positions

The constraining element 414 is made of a magnetic steel and can be moved between its first and second positions through the use of a first magnet 422 housed in the first spring bracket 415 and a second magnet 423 housed in a switch 420 translationally coupled to the housing 406. To selectively transition between the first mode and the second mode the switch 420 can be moved from a first position where second magnet 423 influences constraining element 414 to a second position where second magnet 423 does not influence the constraining mechanism 414. When the influence of second magnet 423 is stronger than that of first magnet 422 on constraining element 414, the switch 420 can be moved to the first position at any position of output link 407 relative to housing 406 and at the transition position second magnet 423 will attract the constraining mechanism 414 and the VMFG will enter the first force state. Likewise, the switch 420 can be moved to the second position at any position of output link 407 relative to housing 406 and when the first spring bracket 415 and second spring bracket 416 return to the transition position first magnet 422 will attract constraining element 414 and the VMFG will enter the second force state.

FINDING THE OPTIMUM TRANSITION ANGLE

As the most flexed angle of the supporting torque generator the angle at which the VMFG transitions between the first force state and the second force state must be as high as possible to retain the largest ROM of support but must also be easily reachable by most operators. Additionally, the transition angle should remain unchanged across all levels of support adjustment. Configured as the supporting torque generator, the angle of the arm is represented to the variable mode force generator as the value of [$l_{s(\theta)}$]. As the transition position occurs when the hard stop removes the spring force from the constraining element, it is equivalent to the value of [l_{s0}]. It follows that increasing [l_{s0}] will increase the transition angle and decreasing [l_{s0}] will decrease the transition angle. Any added preload to the springs can prevent any shift in the force profile once engaged, as seen in Equation 9. To figure out the optimum value of [l_{s0}] and thus transition angle, [ls_0] is plotted as a function of [θ] for values of h=.75, 1.25, and 1.75 in Figure 27 with a 20 degree gravitational offset applied.

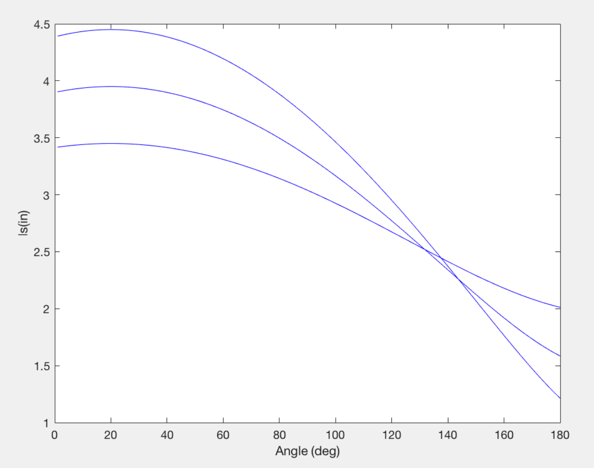


Figure 27. ls vs theta for varying values of support setting h.

From Figure 27 it can be seen the values of [l_s] converge between 135 and 145 degrees of shoulder elevation, or 115 to 125 degrees of torque generator angle without the gravitational offset applied. This occurs for values of [l_s] from 2.25in to 2.5in. When ls_0 is adjusted within this range the transition position will occur at relatively the same angle for each support setting. Figure 28 shows the supporting torque of the VMFG shoulder actuator with l_s values of 2.25 (a), 2.40 (b), 2.55 (c) all with an offset of 20 degrees and for h values of .75, 1.25, 1.75in. The resulting transition angles can be seen as the zeroing of support torque in the upper range of motion as the spring elements hard stop.

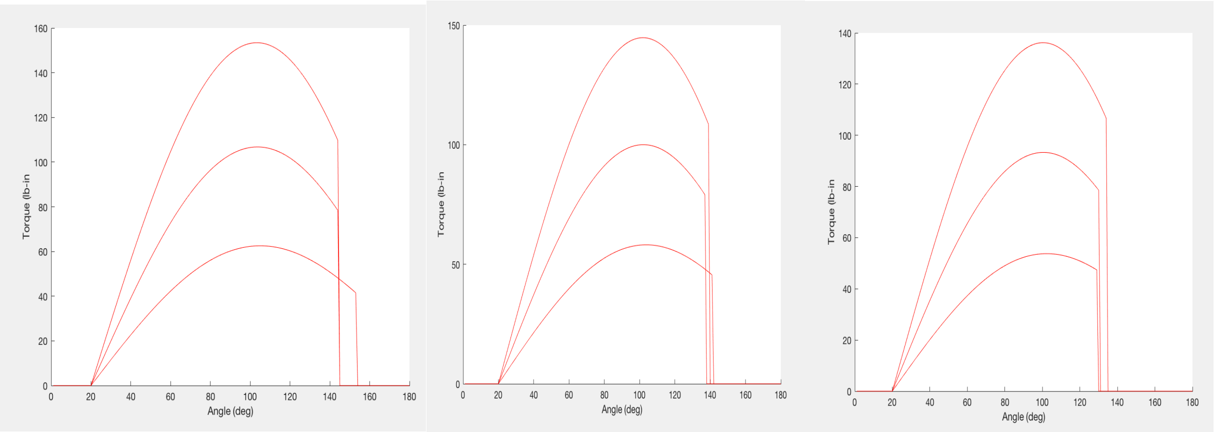


Figure 28. Transition angle values vs support level for (a) ls_0=2.25 (b) 2.40 (c) 2.55.

USABILITY

As described above, use of the on-off mechanism requires for the switch to be moved from a first position to a second position and for the mechanism to be flexed until the transition angle is reached. Because the switch can be operated at any angle, these two motions can occur separately. Figure 29 depicts use of the on-off mechanism. In Figure 29a the switch, located at the elbow for easy reach an maximum visibility, is operated as the arm is in a lowered position. In Figure 29 the user raises the arm to the transition angle, at which a “click” is heard as the mechanism changes states. For each user the transition angle can be tuned to maximize the supported range of motion.

Figure 29. On-off mechanism operation (a) switch operation and (b) transition position.

GRAVITATIONAL OFFSET ADJUSTMENT

While a majority of the observed risk-prone tasks needing support occurred in the higher ranges of motion, this is not always the case. Some tasks may require the balanced support in a lower range of motion such as table assembly procedures at waist level. Other tasks may require support that exceeds the load only after a particular angle, such as pushing a drill into a ceiling panel. As discussed earlier, the gravitational offset, ϕ, shifts the supporting torque profile relative to arm elevation angle, θ. Adjusting the offset angle likewise affects the toggle angle at which the protrusion holds the torque to near zero, and the transition angle at which the variable mode force generator changes states. Figure 30 shows the supporting force profile for offset values of -10, 0, 10, 20, and 30 degrees each for support settings h= .75, 1.25, 1.75 to achieve all permutations of the requirements described above.

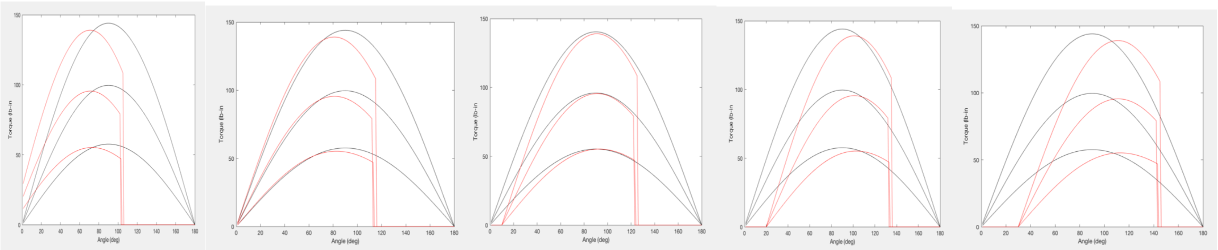


Figure 30. Arm torque vs supporting torque for offset values of -10, 0, 10, 20, 30 degrees.

GRAVITATIONAL OFFSET MECHANISM

The manifestation of the offset angle on the exoskeleton actuator hardware is shown in Figure 31. The offset angle 199 is the angle of proximal link 150, parallel to the axis about which h adjusts, relative to the vertical angle of the exoskeleton spine 208 on the torso frame 102. For all generated torque profiles, it is assumed the person is standing upright so the spine axis 208 is parallel with the force of gravity. Figure 31a shows the arm supporting exoskeleton torque generator with a low offset angle relative to the offset angle in Figure 31b.

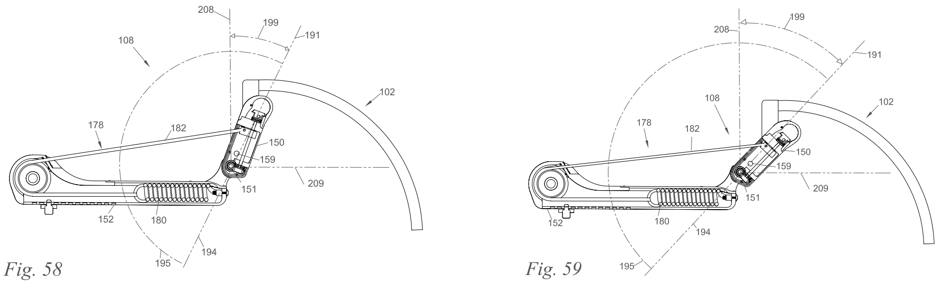


Figure 31. Offset angle effect on exoskeleton actuator for relative (a) low and (b) high offset.

The offset angle mechanism is shown in Figure 32 below. The gravitational offset angle is adjusted by means of an offset clamp 159 and screw between the actuator and the rest of an arm link mechanism 104 connected to the torso frame 102. The clamp 159 and mating component on the arm link mechanism 104 are designed so they can be secured in 5 degree intervals, allowing for the gravitational offset to be defined more precisely than shown in Figure 30 above. The mechanism is operated by loosening a screw, rotating the torque generator to the desired position, as indicated by the peak force angle, and re-tightening the screw.

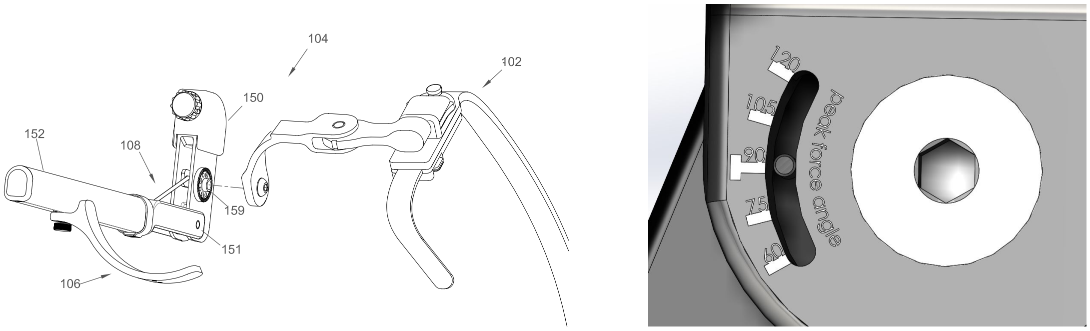


Figure 32. Offset adjustment mechanism (a) and indicator (b).

SUPPORT PROFILE CUSTOMIZATION

The gravitational offset adjustment helps to optimize the gravity-equalizing portions of the modified-iso elastic torque profile for various categories of tasks. When combined with the support adjustment mechanism, these modified profiles can not only be tuned for specific tool and arm weights, but also to alter the degree at which the support becomes equalized, increased, or reduced relative to the weight of the load. A use case and detailed graph for the offset values of -10, 0, 10, 20, and 30 degrees shown in Figure 30 above will be described. Again, 20 degrees has been identified as the value most useful in a majority of tasks and is the default setting of the device. For each of the profiles described below, the on-off mechanism can be removed to extend the support profile an additional 60 degrees in the cased the added support range outweighs the benefit of the variable mode force generator.

Figure 33shows the support and tuning charicteristers of the actuator for a -10 degree gravitational offset. This support profile exceeds the moment of the load in the lower range of motion until 50 to 90 degrees of shoulder elevation, depending on the support level adjustment. This support profile may be useful in situations where a user needs to push an object, such as a cart, while standing upright. For this force profile a torque will be applied to the users arms when standing in a neutral position, so the on-off switch can be utilized to remove any added torque during secondary tasks.

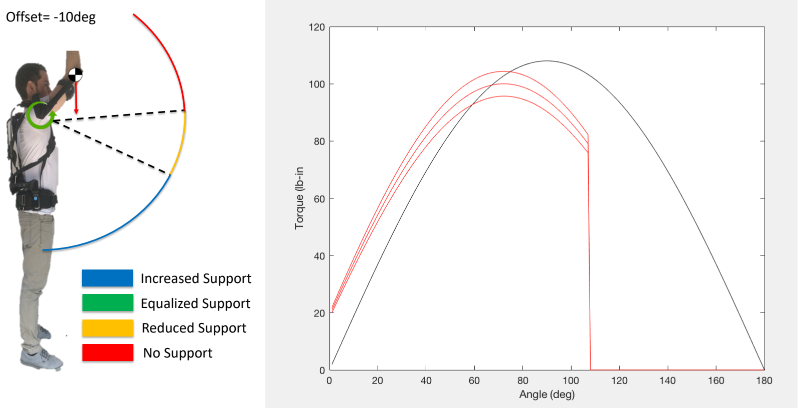


Figure 33. Support characteristics and tuning for -10 degree gravitational offset.

Figure 34 shows the support and tuning charicteristics of the actuator for a 0 degree gravitational offset. This support profile is gravitationally balanced from neutral up to 50 to 70 degrees of shoulder elevation depending on support level adjustment. After this range support continues but is reduced compared to the torque of the shoulder load. This support profile may be useful during tasks primarily taking place around waist level, such as assembly work at a table. For this force profile a torque also will be applied to the users arms when standing in a neutral position, so the on-off switch can be utilized to remove any added torque during secondary tasks.

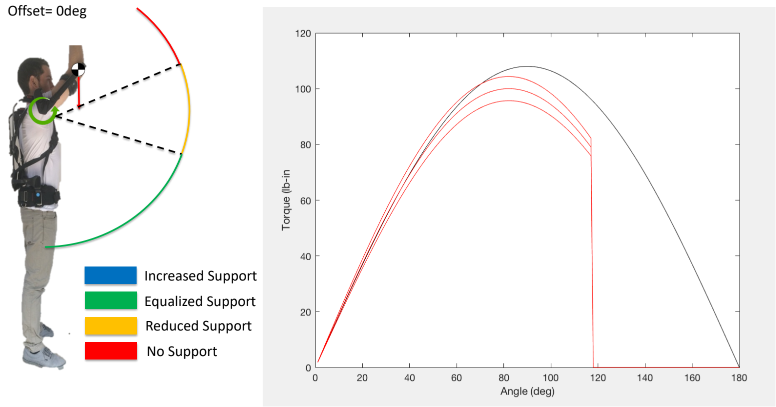


Figure 34. Support characteristics and tuning for 0 degree gravitational offset.

Figure 35 shows the support and tuning charicteristics of the actuator for a 10 degree gravitational offset. This support profile is gravitationally balanced from 60 to 120 degrees of shoulder elevation depending on support level adjustment. Before and after this range of equalized the support is reduced relative to the shoulder load. From neutral until 10 degrees of elevation the protrusion engages the tensile force generator and thus no support is generated, allowing free motion. This profile is most useful for sustained waist to eye-level tasks, common in many construction and manufacturing environments.

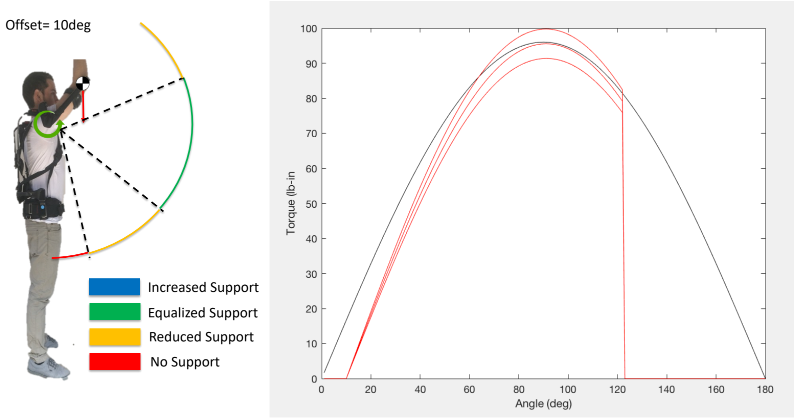


Figure 35. Support characteristics and tuning for 10 degree gravitational offset.

Figure 36 shows the support and tuning charicteristers of the actuator for a 20 degree gravitational offset. This support profile is gravitationally balanced after 100 to 120 degrees of shoulder elevation depending on support level adjustment. Before this range of equalized the support is reduced relative to the shoulder load and until 20 degrees of elevation the protrusion engages the tensile force generator and thus no support is generated. This profile is most useful for sustained shoulder to ceiling level tasks, common in many construction and manufacturing environments.

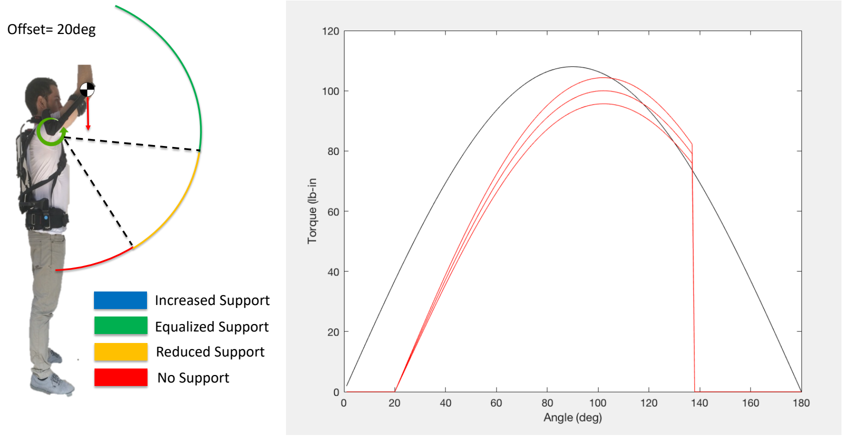


Figure 36. Support characteristics and tuning for 20 degree gravitational offset.

Finally, Figure 37 shows the support and tuning charicteristers of the actuator for a 30 degree gravitational offset. This support profile exceeds the gravitational load after 100 to 120 degrees of shoulder elevation depending on support level adjustment. Before this range of equalized the support is reduced relative to the shoulder load and until 30 degrees of elevation the protrusion engages the tensile force generator and thus no support is generated. This profile is most useful for tasks requireing a forceful exertion at a particular level of elevation- such as drilling into a ceiling panel.

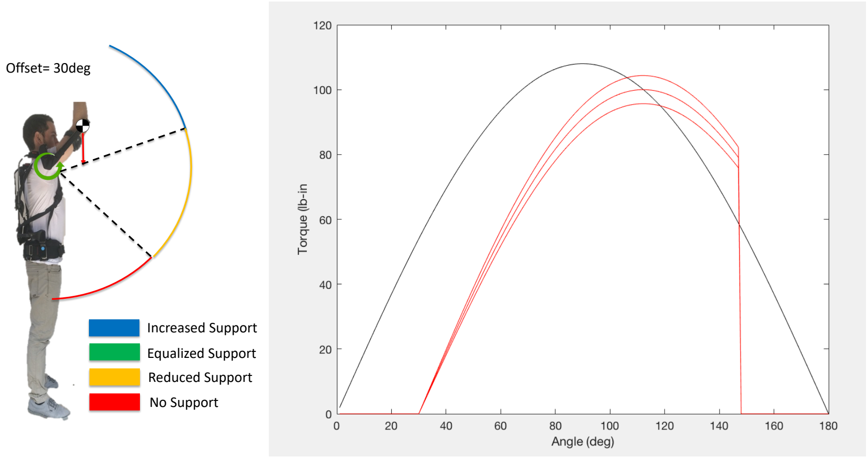


Figure 37. Support characteristics and tuning for 30 degree gravitational offset.

CHAPTER 3: BIOMIMETIC FRAME DESIGN

Just as with the human skeleton, the purpose of the exoskeleton frame is to provide a means for support and motion. To apply the designed supporting torque, the frame serves to comfortably distribute the reaction forces and torques to the user's body. The design likewise mimics the biomechanics of the shoulder complex and spine to center the actuator about the glenohumeral joint for a wide range of postures. Just as with the actuator, two primary objectives of frame design, in addition to supporting the primary task, involve reducing inhibition of secondary work activities and maximizing ease of use. Some general challenges then are to maximize range of motion, minimize profile, and create an intuitive user interface.

SUPPORT: LOAD TRANSFER, COUPLING, ADJUSTABILITY

The primary purpose of the exoskeleton frame is to position the actuator alongside the users shoulder joint and to distribute the generated support torque across the arm and torso. To provide the torque profiles as described above, the distal link of the actuator is designed to rotate in parallel with the operators arm while the proximal link remains stationary with respect to the torso in the direction of gravitational forces. A structural frame applies the actuator torque as a supporting force to the person's arm and distributes reaction forces and torques across the torso. A set of coupling mechanisms at the arms, shoulders, and hips comfortably applies these forces to the human body while securing the structural frame relative to the operator. To accommodate users of varying stature, both the structural frame and human machine interface adjust along numerous key dimensions. Figure 38shows the basic supporting structure of the shoulder supporting exoskeleton frame.

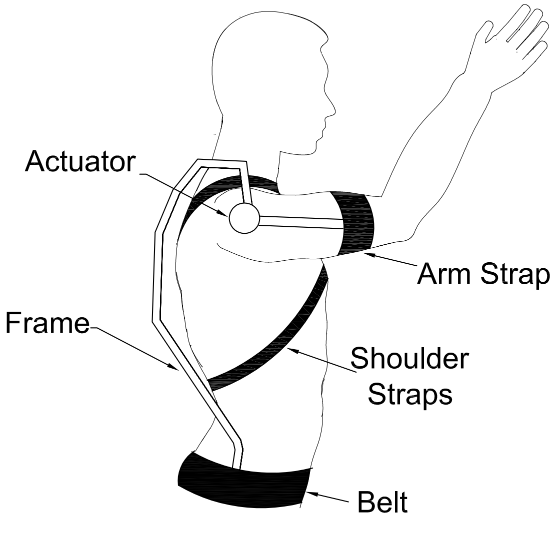


Figure 38. Shoulder supporting exoskeleton frame.

ARM COUPLER

To support the torques about the shoulder due to arm/tool loads, the torque generated by the actuator is applied to the users arm as the force [F] from the model of Figure 3b above. The arm coupler force can be found by dividing the actuator torque output by the distance between the actuator axis of rotation and the location of the arm coupler [$F=\tau/l_F$]. For effective operation the arm coupler must comfortably transfer the support force, securely couple to the persons arm, adjust for varying user sizes, and maintain a useable interface.

Load transfer

Distal to the torque generator, the arm supporting exoskeleton arm coupler acts to apply the support torque to the upper arm of the operator. Throughout the range of shoulder elevation, this force remains perpendicular to the upper arm and changes proportionally with the generated torque profile. Figure 39 shows an arm link mechanism utilizing the shoulder supporting actuator with an arm coupler configured to provide the gravity-compensating force to a user's upper arm. Arm link mechanism 104 comprises torque generator 108 described above with the addition of the arm coupler 106. The arm coupler 106 applies force 212 to persons upper arm, equivalent to the force F in Figure 3b. Contact area and collinearity of the arm coupler are two key aspects of a comfortable application of force 212.

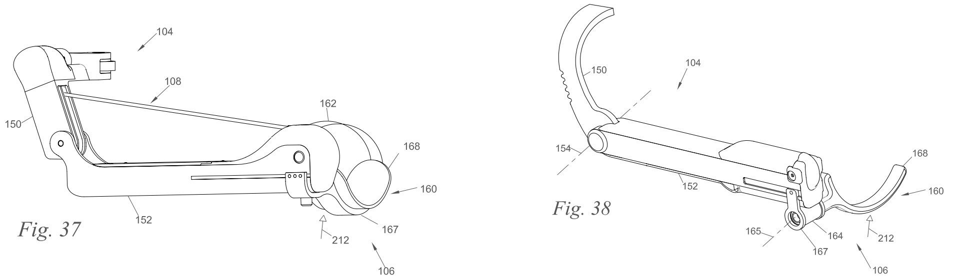


Figure 39. Arm supporting exoskeleton arm coupler (a) with rotational DOF (b).

In Figure 39a, the arm coupler 106 further comprises an arm support link 167 to transmit the actuator torque to the axis of the upper arm and an arm cuff 168 to disperse the load to the operator's body. The larger arm cuff 168 becomes, the lower the pressure on persons arm due to force 212. However, a larger surface area of arm cuff 168 also results in edge contact with persons arm in the event distal link is not parallel with persons upper arm.

To ensure the arm cuff contact remains normal with the persons upper arm, either the actuator must be accurately placed about the shoulder joint, the coupler must be made compliant, or kinematic redundancy added to the system. [35] The torque profile of the actuator is designed as a response to the persons arm elevation angle, thus to properly provide the designed forces the arm coupler must not allow the distal link to become skew relative to the persons upper arm. In Figure 39b a degree of freedom allows arm cuff 168 to rotate relative to the distal link 152 about axis 165, parallel to actuator axis 154 to eliminate edge contact. This however allows the distal link 152 to become skew with respect to the persons upper arm, creating an unpredictable shift in torque profile. A compliant arm coupler 106 would result in a similar outcome. Eliminating axis 165 and compliancy ensures the arm cuff, and thus the distal link, will remain parallel with the persons upper arm. Any edge contact will be feedback to the user that the actuator joint is not properly aligned. With this assumption it is only a matter of finding the arm cuff surface area to balance distributed force transfer with the sensitivity to misalignment before edge contact does occur.

Coupling

The arm cuff is almost always being forced into the operator’s upper arm by the actuator, except in the zero-torque zone below the gravitational offset angle. Even in the off position, a low spring force counters of the weight of the exoskeleton distal to the torque generator. An arm pad attached to cuff 168 serves to interface with the persons upper arm throughout the support zone to best distribute the forces from the arm cuff. An arm strap 162 serves to ensure persons arm does not separate from the arm coupler within the zero torque zone due to sudden accelerations of the operators upper arm. Figure 40 below shows the arm coupling system of the arm pad and arm strap. The arm strap can be tightened to ensure a tight fit with the operator’s arm.

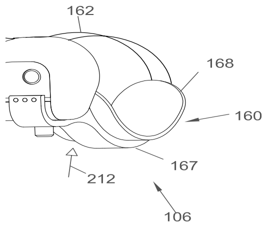


Figure 40. Arm coupler coupling mechanism.

Adjustability

For optimum comfort, the arm coupler is adjustable to accommodate user arm length and circumference. Figure 41a shows the arm link mechanism 104 where arm coupler 106 can be adjusted along the axis of distal link 152, shown by arrows 243. It is important to note for purposes of both comfort and finite element analysis, that for a constant actuator torque, support force 212 changes as a function of the arm coupler length setting 243. When decreasing the distance between arm coupler 106 and actuator axis 151 the applied force 212 will increase. Figure 41b shows a perspective view of the arm length adjustment mechanism that includes a locking tab to secure the arm length setting. Locking in a person’s arm length setting prevents axial motion of arm coupler 106 relative to persons arm, a possible result of misalignment of actuator joint 151. While allowing free axial adjustment would prevent relative-motion-induced forces at the upper arm in the event of actuator misalignment, it can cause unintended forces at the users and torques about user’s shoulder. While unpleasant, this discomfort caused by a fixed axial position can quickly identify an error in actuator placement and elicit a prompt adjustment.

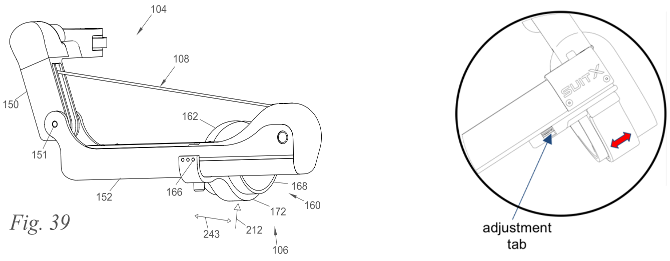


Figure 41. Arm length adjustment (a) direction and (b) interface

To get a range of exoskeleton arm length values to accommodate a majority of the working population, anthropometry values from a 50/50 male/female US population [36] are used for 5-95% range. Translating these values to the device hardware however requires a few modifications. For optimum comfort the arm length setting should be as long as possible to reduce the forces applied through the cuff, while also minimizing contact with the bony landmarks and nerves near the elbow. Through feedback and observation, the most comfortable spot for the arm coupler is approximately 2-3 inches behind the user’s elbow. Additionally, while the upper arm is measured from the back of the shoulder, the exoskeleton frame value is best defined from the actuator axis of rotation. Table 1 below shows the anthropometric values for arm length of and how they are translated to hardware specifications.

	5-95% US (in)	Modifier	Specification(in)
Upper Arm Length	12.9-15.5	-3”: arm rest placement behind elbow -2”: measure from GH center	7”-10” actuator joint to center of arm rest

Table 1. Anthropometric [36] and hardware specifications for arm length

A mismatch of exoskeleton arm cuff circumference with that of the operator’s arm can result in pinch points, in the even the cuff is too small, to an inability of the arm strap to secure the users arm in place when the cuff is too large. Figure 42 shows an adjustable diameter arm cuff 168 made of a semi-rigid material attached to a rigid arm support 167. Arm strap 162 is likewise made of a flexible or semi-rigid material and is configured to wrap from a first end of arm cuff 168 fixed to arm support 167 and around a second end of arm cuff 168. When arm strap 162 is tightened, both arm strap 162 and arm cuff 168 conform to the diameter of persons arm. The semi-rigid material of arm cuff 168 allows for this motion while still comfortably distributing force from arm support 167.

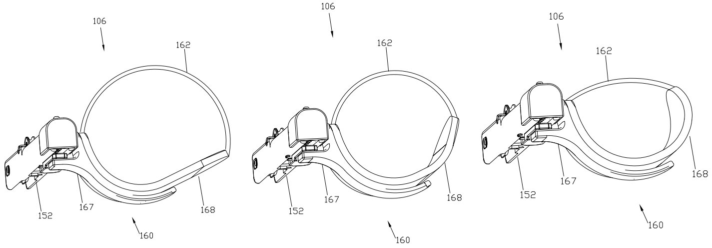


Figure 42. Upper arm circumference adjustment (a) large (b) medium (c) small.

Usability

Use of the arm coupler consists of adjustment, donning, and doffing. The adjustment process is relatively simple: a user can measure his or her arm to get the proper setting, or more likely adjust iteratively while wearing the device. Donning of the arm coupler is shown in Figure 43. It requires the torque generator to be extended with the contralateral arm so that the arm to be supported can be placed within the arm cuff, Figure 43a. Once placed, the arm-cuff interface keeps the actuator flexed so the contralateral arm is free to let go and secure the arm strap, Figure 43b. The arm strap is simply fed through a loop in the arm cuff and secured back to itself with a hook and loop closure. Alternatively, the arm coupler can be donned with the actuator in an off position allowing the process to be done in a more neutral posture, but for some the lack of torque forcing the cuff into the arm makes securing the arm strap more difficult. Doffing the arm coupler is simply the reverse of the donning process.

Figure 43. Donning the arm coupler (a) arm cuff and (b) arm strap.

TORSO FRAME

Located proximal to the actuator, the torso frame is responsible for distributing the reaction forces and torques from the arm coupler interface comfortably across the users hips and shoulders. As the persons arms move throughout their range of motion the actuator torque and angle of force applied to the user's upper arms are constantly shifting. Individual variances in fit and anthropometry also affect how the frame interacts with the body. It is important that the differences in load transfer and coupling be understood to optimize the frame to distribute the necessary forces and adequately couple the device to the user's torso. Additionally, the frame needs to adjust in the dimensions necessary to allow access to a majority of the working population and maintain an intuitive user interface.

Load transfer

The exoskeleton frame and human machine coupling is designed to apply loads to the hips and shoulders to counteract the forces and moments created by the supporting force being applied to the persons upper arm. As the persons arm raises, lowers, or moves side to side the forces distributed by the frame, and the manner in which it applies those forces, is similarly in flux. As stated [37] even with low loads the limiting factor of load carriage is skin pressure on the shoulders if no waist belt is present to relieve reaction forces. Due to the loads in question only a hip-shoulder frame will be considered.

Figure 44 shows the torso frame load transfer. The torso frame load bearing structure 112 takes the reaction force 214 and torque 215 from the arm support of torque generator and distributes to them to the shoulders 225 and to the hips 221 via a back frame 130 and hip belt 131. As this is a gravity compensation device, the largest support forces occur in the vertical plane. The most extreme loading cases therefore are when the persons arm is at 90 degrees in either pure flexion or abduction.

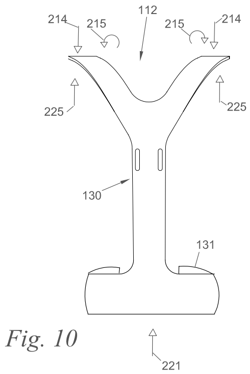


Figure 44. Torso Frame Load Transfer.

Figure 45 shows torso load distribution responses the person due to the arm supporting force [F] at 90 degrees of shoulder flexion, the worst case loading in the sagittal plane. Depending on the fit of the frame, the origin, or primary superior reaction force and the point 0 at which the frame rotates relative to the torso, can shift between the shoulders and hips. Various combination of coupling mechanisms can provide the stabilizing forces at the hips [F_h] and shoulders [F_s] in superior (s), inferior (i), posterior (p), anterior (a) or lateral (l) directions with a slight variance in moment arm or angle of applied force.

Figure 45a depicts a first sagittal distribution mode where the origin is located at the shoulders. Here [Fs_s] along the top of the shoulder is roughly equivalent of the vertical force [F] supporting the upper arm. Just as in the unassisted scenario, this force is then transferred down the spine and legs to the ground. The posterior force [Fh_p] in plane of the belt counters the moment created by the actuator support. If no belt is present the force [Fh_p] can be applied by a horizontal chest strap- although with a much smaller moment arm. This first sagittal distribution mode is limited in the applied supporting force [F], due to the nature of load on the shoulder and spine relative to the hip as well as the discomfort of a horizontal force on the stomach.

Figure 45b and Figure 45c show two examples of a second sagittal distribution mode where the origin is located at the hips. In Figure 45b this point is located at the rear of the hips. The vertical load [Fh_s] is applied here and the moment balancing forces [Fs_p] and [Fs_s] are applied horizontally by the upper thoracic portion of the frame leaning against the back and vertically across the shoulders due to rotation and flex of the frame. Depending on the rigidity of the belt and the location of its connection with the frame this origin can also be shifted forward, such as depicted in Figure 45c. While the location of forces remains the same, the relative moment arms shift, creating some differences in comfort. The exoskeleton uses the arrangement in Figure 45c, as the iliac crest of the hip is shaped best for effective vertical load transfer.

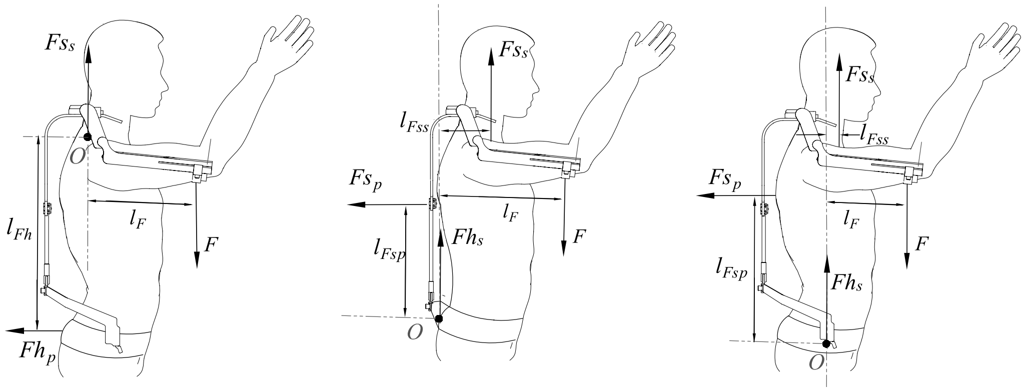


Figure 45. Worst case sagittal exoskeleton frame loading modes pivoting about (a) shoulder (b) rear hip (c) mid hip.

Figure 46 shows a similar range of exoskeleton frame load distribution responses for 90 degrees of shoulder abduction in the coronal plane. Unlike the sagittal loading, where each arm loads the frame in the same direction, coronal loading is opposite between the right and left actuators. Again, the coupling mechanism configuration slightly alters the moment arm and magnitude of the reaction forces.

Figure 46a shows the first coronal distribution mode when the origin is at the left shoulder strap. Here the vertical reaction forces are taken up along the top of the left shoulder while the moment cancelling forces occur horizontally at the belt and both vertically and/or horizontally at the contralateral shoulder coupling, depending on its type. This mode is similarly limited in the amount of supporting force F that can be applied before the manifestation of discomfort at the shoulders.

Figure 46b and Figure 46c show two examples of the second coronal distribution mode where the loading origin is at various locations along the user's hips. When the primary vertical reaction force is located at the center of the hips as in Figure 46b, vertical reaction forces at both shoulder couplings and a horizontal force in the contralateral shoulder coupling stabilize the moment. When located at the side of the hip of the supported arm as in Figure 46c, all moment stabilizing reaction forces occur at the contralateral shoulder coupling. As mentioned above, the case in Figure 46c is preferred due to the shape of the human hips.

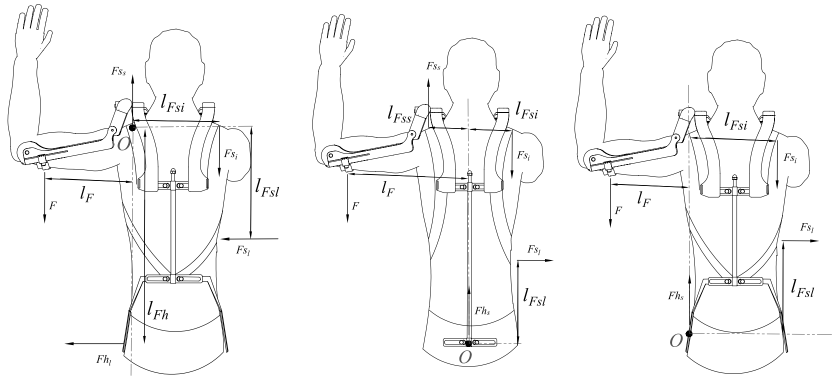


Figure 46. Worst case coronal exoskeleton frame loading modes pivoting about (a) shoulders (b) rear hip (c) side hip.

While the horizontal component of arm supporting force generally has less influence than the vertical component, it has potential to cause discomfort of the exoskeleton frame in certain postures. In both the sagittal and coronal planes, the direction of horizontal reaction force changes as the arm crosses 90 degrees of elevation. If the frames center of location is at the shoulders, this will not affect the direction of the moment applied to the frame. With the center of rotation at the hips the arms position will cause the shoulder portion of the frame to rotate towards or away from the body. Again, the figures shown are for only one arm, one simply has to add the effects of both arms at their specific positions together to understand the effect of the combined forces on the frame.

Figure 47a and Figure 47b show the forces on the shoulder origin exoskeleton frame due to the horizontal component of arm supporting force when the arm is both above and below the horizontal line. For both positions the primary force countering the arms moment is [Fh_a] at the belt or a chest strap (not shown). Force [Fs_s] may be also be created due to the rotation of the frame to contact the shoulder- although the short moment arm may cause discomfort. Figure 47c and Figure 47d show equivalent position of the arm about a hip origin. When the arm is below horizontal the frame rotates backward with the force of the shoulder coupling [Fs_a] countering it along a long moment arm. When the arm is above the horizontal the back of the frame contacts the users thoracic creating countering force [Fs_p]. Depending on frame flex or rotation force [Fs_s] may also help stabilize the device.

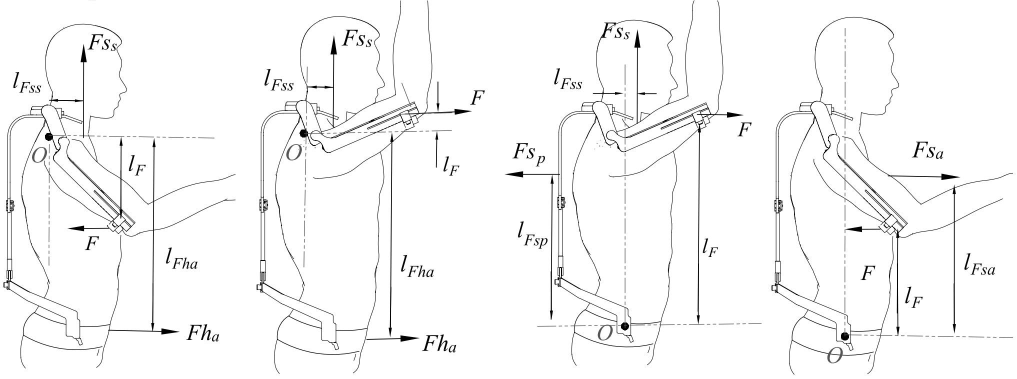


Figure 47. Horizontal support component effects on frame loading in the saggittal plane.

Figure 48 shows equivalent examples of arm position and center of frame location in the saggital plane. The result is equivlent, but with the added influcence of the shoulder strap of the contralateral side- which acts about a moment arm substantial enough for comfortable moment-stabilizing use.

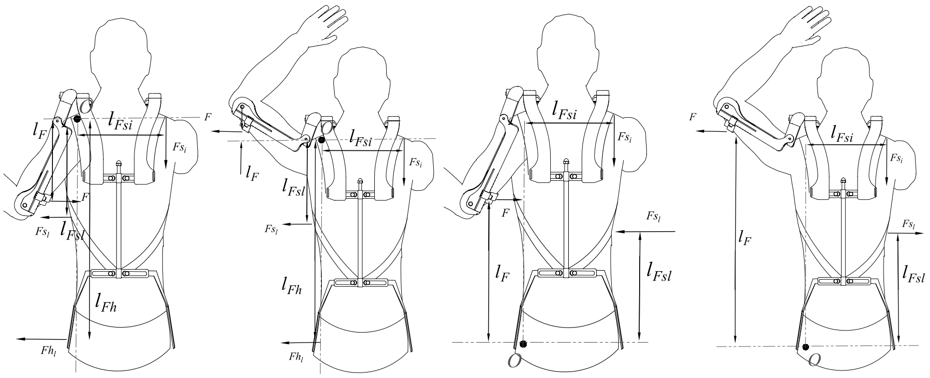


Figure 48. Horizontal support component effects on frame loading in the coronal plane.

For all loading cases the ideal load transfer occurs when the frame center of rotation, and thus largest v of vertical reaction forces- occurs at the hips. In this situation a majority of the arms load bypasses the spine- potentially alleviating the strain of the back in addition to the shoulder. [37] In another embodiment of the device the load may be further transferred from the hips to the ground with the addition of a leg supporting exoskeleton, as discussed in Chapter 5.

Coupling

To comfortably counter the reaction forces and moments described above, the torso frame coupling mechanisms at the hip and shoulders need to properly conform to each user's body and provide stiffness in the direction of needed forces. The coupling mechanisms are key to the donning and doffing of the exoskeleton so it is important that they be intuitive in operation and adjustment. As they are the point of contact with the human body, hygiene is also a consideration.

For the optimal load distribution, proper fitting of the hip belt is perhaps the most important coupling of the torso frame. The frame geometry and belt stiffness must be designed to apply the exoskeleton load to the iliac crest of the hips, at the sides of the body. Loading at the sacrum or abdomen is likely to cause discomfort. Operators with larger abdomens that prevent the ability to apply forces to the hips are forced to rely on the shoulder loading mode operation or loading of non-bony structures at the hips. To keep this point of loading from twisting or translating it is important that the belt have circumferential contact around the entire waist.

Figure 49 shows three embodiments of a hip coupling system. In Figure 49a the frame (hatched) terminates behind the body and the semi-rigid/load bearing padded part of the hip coupling mechanism (solid) wraps around the back and both sides of the operator. The coupling mechanism is adjusted along a strap A that conforms to the body. As the load bearing portion often needs to be padded, the version in Figure 49a is likely to generate excess heat around the lower back. Furthermore, this is less adjustable as the two sides of the padded portion may contact each other anterior to the body on smaller individuals, preventing proper tightening of A, or become so short as to not fully wrap around the iliac crest for larger individuals. In Figure 49b two padded portions are located along a rigid frame at both sides of the hips. These are connected anteriorly and posteriorly by adjustable straps A and B. For this configuration the frame must also be adjustable to properly position the side pads of the coupler. A third option in

Figure 49c shows a semi-rigid frame located posterior to the person that is adjustably coupled to two load bearing pads of a hip coupler at C and D. An anterior strap couples everything together and adjusts at A. In this configuration the frame must be able to flex in the transverse plane but remain stiff in the load bearing direction normal to the page. Currently the exoskeleton utilizes the approach in Figure 49b, but future versions may employ Figure 49c.

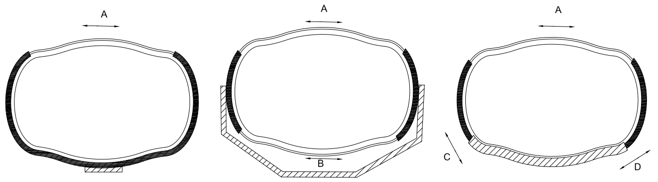


Figure 49. Hip Coupling Mechanism Configurations (a) single adjust (b) dual adjust (c) triple adjust.

After the hip coupling takes a majority of the load off of the system, the next priority is that the shoulder coupling counter any moments while minimize the pressure applied to the operator. Even small pressures on skin over muscle have shown to reduce circulation of the underlying tissue [38], while the hips are less sensitive by a factor of three [39]. These high pressures can lead to arm muscle weakness [37], possibly countering the beneficial effects of the device. To reduce contact pressure, it is important therefore that the shoulder coupling remain compliant enough to conform to the users body. Figure 50 shows two methods of pressure limiting load transfer to the shoulder. In Figure 50a a conventional shoulder strap is used that wraps around the entirety of the shoulder. Note that the load bearing frame can only be connected at one point in this system, creating some instability between the coupler and the frame. The shoulder pads are tightened along strap E, just as in a backpack. In Figure 50b an adjustable hammock strap F is formed between two padded ends of a rigid frame structure. Again, the frame structure must adjust or flex to properly position each padded end for a range of operator sizes. It similarly secures to the shoulder along strap E. A third option of a custom molded rigid/padded frame is not discussed.

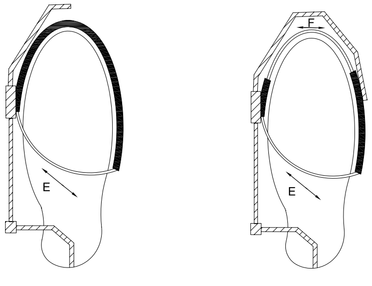


Figure 50. Shoulder Coupling Mechanism Configurations (a) shoulder strap (b) shoulder hammock.

To counter the moments about the exoskeleton frame the shoulder coupling mechanism must be able to transmit forces anteriorly-posteriorly, superiorly-inferiorly, and laterally. The anterior-posterior forces prevent tilt in the sagittal plane or a twist in the transverse plane, lateral forces to prevent tilt in the coronal plane, and the superior-inferior forces preventing tilt in the sagittal or coronal planes as well as providing limited load transfer. Figure 51 shows three general strap configurations that can be used alone or in combination to provide the shoulder coupling reaction forces. Figure 51a shows a chest strap 118 wrapping around persons torso 202 in the transverse plane- providing forces both posterior-anteriorly and laterally. Figure 51b shows suspender straps 126, often the type found in a safety harness- providing anterior-inferior forces with small components of the other directions between the belt 116 and top of the load bearing frame 112. Figure 51c depicts shoulder straps 120, sometimes connected by a sternum strap 122, providing forces in all directions- the proportions of which depending on the strap mounting points. Currently shoulder straps are the method of choice due to similarities with a standard backpack that facilitate more intuitive donning.

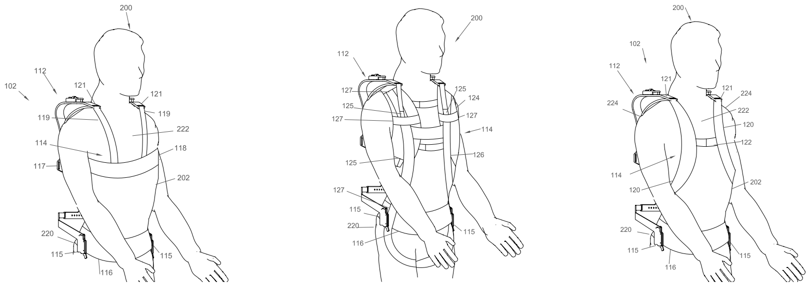


Figure 51. Torso Frame Shoulder coupling configurations (a) chest strap (b) suspender (c) shoulder straps

Adjustability and Fitting

The torso frame is adjustable to accommodate a majority of users and body types for a proper fit. All coupling mechanisms are likewise adjustable in length to provide consistent pressure around the respective contact areas. Figure 52 shows the V1 and V2 iteration of the torso frame adjusting in hip width (1), hip depth (2), torso height (3), shoulder width (4) and shoulder depth (5). The arm length adjustment (6) discussed earlier is also shown. Additionally, the blue circles indicate textile adjustments of rear belt length (A) front belt length (B) R&L shoulder hammock length (C) and R&L shoulder strap length (D), with previously discussed arm strap length (E). As the hips are the most crucial element of the frame, we will start with hip frame adjustments and move superiorly.

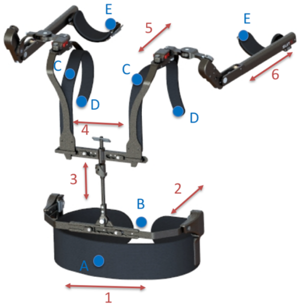


Figure 52. V1/2 shoulder frame adjustable parameters.

The combination of hip frame and coupler adjustments allow for the reaction loads to be placed at the sides of the hip and for the belt to securely engage around the persons waist. With a rigid frame routed laterally and flexible belt this necessitates the hip width (1) and hip depth (2) frame adjustments and rear belt length (A) and front belt length (B) adjustments. With a rigid posterior frame and belt this can be achieved with a single adjustment of front belt length (B) and padding that can be adjusted in position as done in commercial backpacks. The hip adjustments should be made so that the bones of the hip prevent the frame from falling but without uncomfortable restriction. If the frame is too tight the pressure may become uncomfortable, if the frame is too loose the belt may sag or tilt- resulting in more load being transferred to the shoulders. Figure 53 below shows how each parameter is adjusted, and setting indicated on the V2 exoskeleton frame. Table 2 gives the relevant anthropometric values for the 5-95% US population and how they translate to hardware specifications.

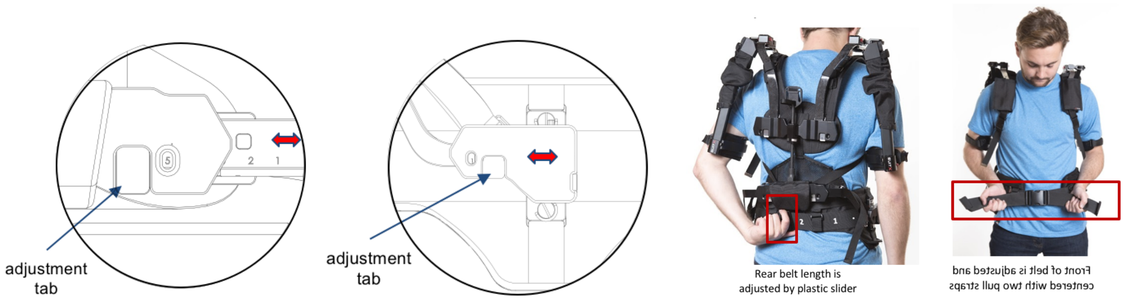


Figure 53. Adjustments to hip frame width (a) depth (b) and coupling mechanism rear (c) and front (d).

	5-95% US (in)	Modifier	Specification (in)
Hip Width	12.8-16.3	N/A	12.8-16.3 Between medial side edges of hip frame
Hip Depth	7.1-10.2	/2 for midpoint of hip + 2" avoid anterior contact	5.5-7.1 Between medial back edge and hip joint

Table 2. Anthropometric [36] and hardware specification for hip frame.

With a load bearing connection established at the hips, an adjustable spine frame serves to properly position the actuator vertically with respect to the biological shoulder joint. In the event the minimum spine height is too tall to accommodate a user the shoulder straps or hammock can be tightened, although this results in a vertically misaligned actuator. When the maximum spine height is too short, the belt can be worn higher on the waist, negatively impacting load transfer to the hips. The height of the spine will also influence the moment arm of the shoulder coupling about the hips. Figure 54 shows the torso height adjustment mechanism and indicators. Table 3 gives the anthropometric values and hardware specifications regarding torso height.

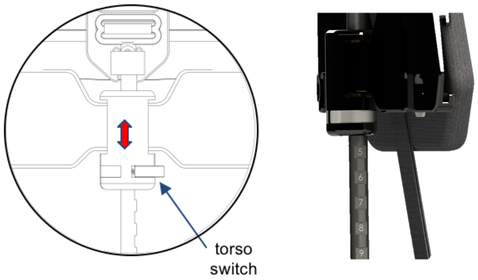


Figure 54. Spine Frame adjustments (a) and indicator (b)

	5-95% US (in)	Modifier	Specification (in)
Waist height	37.4-44.7		12-16" Belt to inferior face of shoulder frame
Shoulder height	48.4-59.7	+1" avoid superior contact	

Table 3. Anthropometric [36] and hardware specifications for spine frame dimensions.

The shoulder frame adjusts horizontally to position the actuator alongside the shoulders and optimize load transfer to the operator. A shoulder width adjustment alters the horizontal location of the actuator relative to the shoulder joint. Both the shoulder width and shoulder depth adjustments serve to position the rigid ends of the shoulder hammock comfortably relative to the upper torso, the hammock length adjusting to accommodate the frame depth. If the shoulder width is set too narrow, the frame may put uncomfortable pressure on the neck. When the frame is too wide pressure over the acromion may prevent movement. A misalignment either way and arm coupler motion relative to the operator’s arm will indicate actuator misplacement. Figure 55 shows the shoulder adjustment mechanism and indicators. Table 4 gives the anthropometric values and hardware specifications regarding shoulder width and depth.

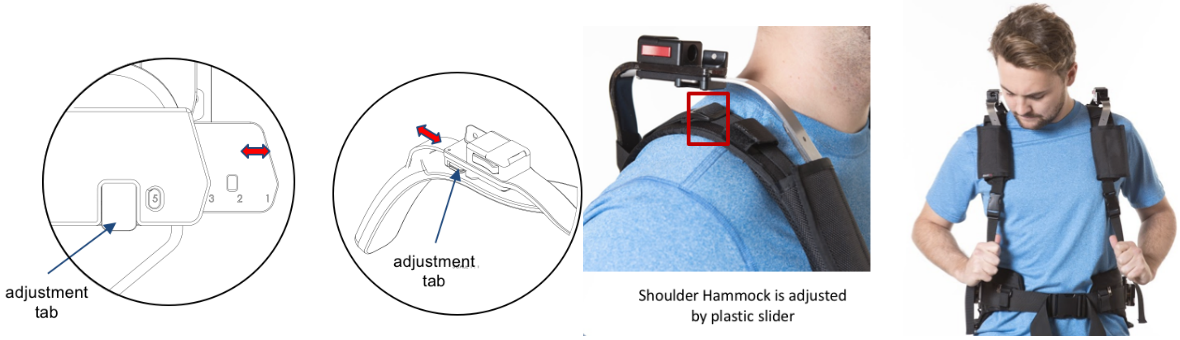


Figure 55. Shoulder Frame adjustments in hardware (a) width (b) depth and Coupling (a) hammock (b) shoulder straps.

	5-95% [US?]	Modifier	Specification
Shoulder Width	14.3-18.8	-1” from GH joint center	13.3-17.8”
Forward reach including body depth	27.2-35.0	Combine for shoulder depth	4.6”-5.7”
Forward reach to acromial process	22.6-29.3		

Table 4. Anthropometric [36] and hardware specifications for shoulder frame dimensions.

Usability

Just as with the arm coupler, use of the torso frame entails adjusting, donning, and doffing. Once properly fit to an operator’s body, a series of indicators for each of the above adjustments allows any frame to quickly be customized for optimum support. It also allows for the development of a recommended fitting guide- shortening the learning period necessary for training on fitting procedure and correction. Identical mechanisms to the arm length adjustment are likewise used for the shoulder width, shoulder depth, hip width, and hip depth frame adjustments for simple recognition and operation. Finally, all points of adjustment- including actuator parameters- are being transitioned to the only red parts for better visibility.

When donning the device, the shoulder straps and hip belt serve as a familiar interface similar to a backcountry back pack. Figure 56 depicts the donning process of the V2 shoulder frame. The first step, shown in Figure 56a, is to put the shoulder frame around the body. This can be done with either one or both shoulder straps disconnected, donning with both connected requires a high degree of flexibility as the rigid shoulder frame inhibits the ability to bend the upper portion of shoulder strap. Next, the belt is tightened around the waist to establish a good hip coupling, depicted in Figure 56b. Clipping and tightening the shoulder straps, as in Figure 56c and Figure 56d respectively, secures the shoulder frame to the rib cage of the body. While wearing the frame, the hip belt and shoulder straps can be adjusted to alter the load transfer pattern of the frame as described above. Doffing the system is equivalent to the reverse of the donning process.

Figure 56. Torso Frame Donning Process.

ARM SUPPORTING EXOSKELETON

Once combined, the arm unit and the torso frame serve to establish the basis needed for torque to be comfortably transferred between the actuator and the operator to support the shoulder during overhead tasks. To accommodate the largest range of needs and facilitate ease of donning, the arm unit can be detached or stowed relative to the torso frame. Each allows for the arm supporting exoskeleton to support one arm only- for short periods using the stow, or for longer periods by disconnecting the contralateral arm unit. The configurations likewise allow for the system to be put on and taken of in separate pieces, or in one rigid piece.

Arm Detachment

Both the right and left arm units can be quickly attached and detached from the torso frame. Figure X shows a view of the Vb device in each configuration. To attach the two, an insert link on the arm unit 104 mate with a shoulder bracket 153 mounted to the torso frame 102. As the arm unit is brought to the shoulder frame, a magnetic insert guide attracts insert link of the arm unit 104 and orients it medially/laterally while the shoulder frame orients it superiorly/inferiorly. The insert guide further ensures that the left arm unit 104 cannot be inserted into the right shoulder bracket and vice versa. A circular profile with a round-entry key slot allows the insert link to be inserted into the shoulder bracket at a range of angles and then forces into a proper rotational orientation. When the insert link has moved far enough axially into the shoulder bracket 153 a nose spring is compressed, and a set of locking pins secure the two in place. To decouple the two, a set of switches are depressed to release locking pins. The nose spring then pushes the insert pin far enough out of the shoulder bracket, so the locking pins don’t automatically re-engage when the switches are released.

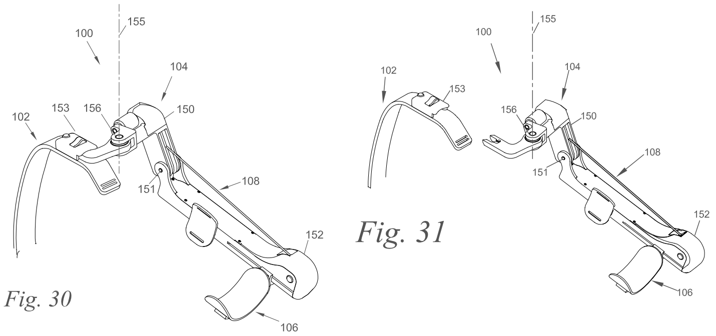


Figure 57. Arm unit and torso frame (a) attached (b) detached.

Figure 58 shows an operator donning the arm unit after having previously donned the toso frame. The donning process requires a familiarity with the coupling/decoupling mechanism as it is difficult to see just above the shoulder. The motions of inserting the arm further require some practice until muscle memory is achieved. Whether the actuator is on or off during the donning process is a matter of personal preference. To don the arm units, the user first orients them relative to the torso frame until the insert link meets the insert guide, shown in Figure 58a. Next, the user axially pushes the insert link into the shoulder bracket until the click of the locking mechanism is heard. The locking switches can be checked flush with the shoulder bracket to ensure both locking pins fully engaged, as in Figure 58b. Donning the exoskeleton finishes with that of the arm coupler shown above. For doffing the exoskeleton, the reverse order can be applied.

Figure 58. Donning of the arm unit (a) aligning & inserting (b) checking/releasing.

Rather than being between the arm unit and the torso frame, the point of detachment may also be located within the arm unit itself. Figure 59 shows the arm unit 104 with a detachment mechanism 535 between horizontal rotation joint 156 and torque generator 108. This allows the attachment posture to be located in front of the person rather than over the shoulder, facilitaing ease of use. The mechanism comprises a detachment bracket 536, insert link 537, and release button 538. The detachment bracket 536 is attached to torque generator 108 and the insert link 537 is attached to the remaining portion of arm supporting exoskeleton 100 attached to persons trunk 202, which may comprise some of shoulder base 102 and some of arm link mechanism 104. Insert link 537 houses a spring-loaded release button 538 that locks insert link 537 into detachment bracket 536 when they are coupled. To detach the torque generator 108, release button 538 is compressed allowing insert link 537 to be removed from detachment bracket 536. Detachment bracket 536 and insert link 537 may be located anywhere between torque generator 108 and torso base 102. Similarly, insert link 537 may be coupled to torque generator 108 and detachment bracket 536 to the other portion of the device. Other capture and release mechanisms may also be possible.

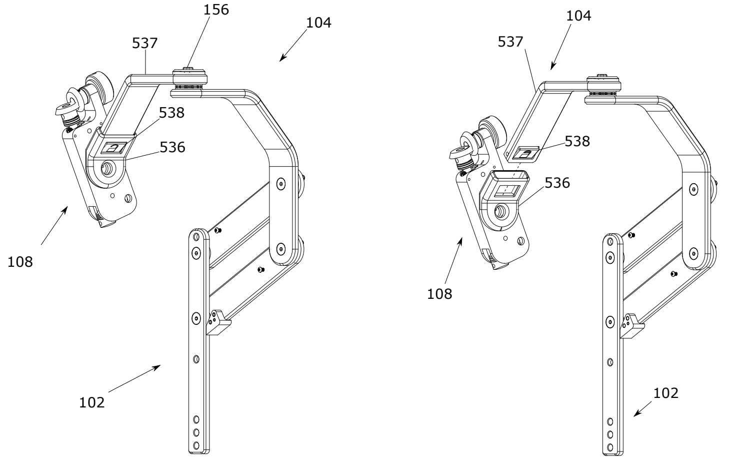


Figure 59. Seperable Arm Unit (a) attached (b) detached.

Arm Stow

For shorter duration breaks, as an alternative to turning the actuator off, on or both arm units can be stowed relative to the torso frame out of the persons workspace. Stowing the arms here further allows the entire exoskeleton to be donned or doffed as one rigid piece, shaped to allow best access to the coupling mechanisms. Figure 60 shows the arm unit 104 stowed behind shoulder frame 102 out of the persons workspace 230 as well as the stow mechanism under the in-use and stowed configurations. While attached to the arm unit 104, the shoulder bracket 153 rotates relative to the torso frame 102 until the arm unit 104 is positioned behind the torso frame 102. A locking pin 156 ensures that the mechanism does not unwantedly switch between configurations. When stowed, the actuator further serves to constrain the arm unit by flexing the distal link 152 about elevation joint 154 until it hard stops against the proximal link 150.

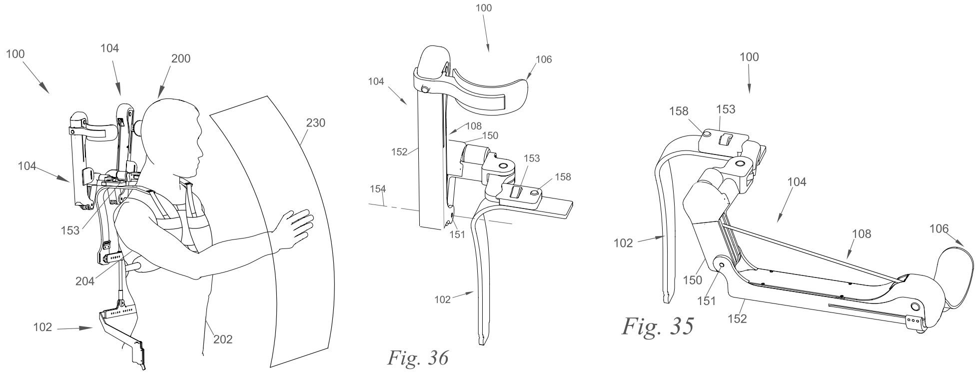


Figure 60. Arm unit stwed postion (a) on person (b) hardware (c) hardware in use position.

Motion

To effectively augment the force of the shoulder complex without inhibiting its motion requires an understanding of the joint anatomy and kinematics. The function of the shoulder complex, in coordination with the spine and distal joints of the upper limb, is to allow the hand to be accurately placed and controlled within the anterior workspace. [40] The shoulder is one of the most complex joints in the human body consisting of four articulating mechanisms: the glenohumeral, acromioclavicular, and sternoclavicular joints, as well as the scapulothroacic gliding mechanism. When the movement of the humerus relative to the axial skeleton is the object of interest, as is most often the case, the humerus is an end link of the following kinematic chain: trunk (sternum), sternoclavicular joint, clavicle, acromioclavicular joint, scapula, glenohumeral joint, humerus. [41] Figure 2 shows the anatomical positions of the four joint mechanisms comprising the Shoulder Complex and the joint mechanisms of the shoulder supporting exoskeleton frame. As this is an anthropomorphic design, it is important these joints are properly aligned to reduce relative movement between the operator and the frame and minimize improper internal or interface forces. [42] We start with the primary motion to be supported and move upstream, progressively expanding the range of accommodated postures.

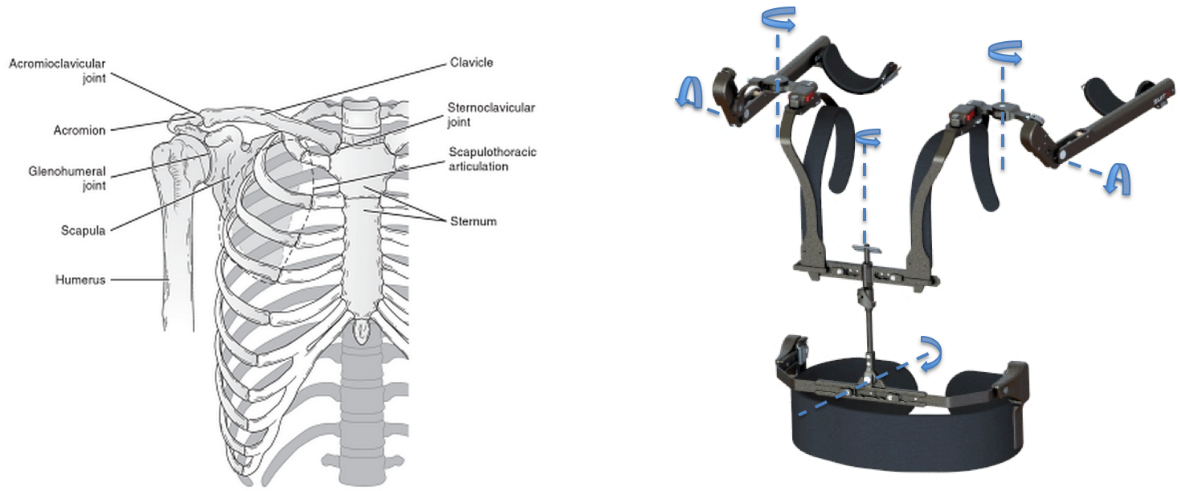
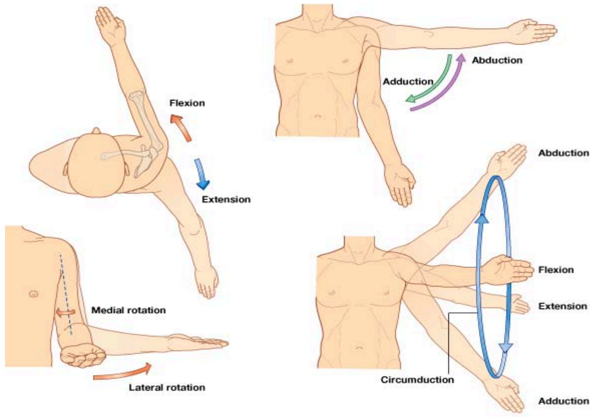


Figure 61. Human (a) and Exoskeleton V2 (b) Joints

Glenohumeral Degrees of Freedom

The shoulder complex is most often modeled as a three degree of freedom (DOF) system consisting of flexion/extension, abduction/adduction, and internal/external rotation of the upper extremity. Elevation refers to the raising of the upper arm, and contains both elements of abduction, in the plane of the torso, and flexion, out of plane of the torso. Horizontal flexion/extension refers to movements of the upper arm in the horizontal plane after elevation has occurred. The shoulder joint can also move vertically (e.g. shrug) and anterior/posteriorly but these motions are usually not considered in simple models. [41] The following figure and table gives the average range of motion of shoulder complex. [36]



Shoulder ROM	
Abduction	180 Degrees
Adduction	75 Degrees
Flexion	180 Degrees
Extension	60 Degrees
Horizontal Flexion	130 Degrees
Horizontal Extension	150 Degrees

Figure 62. Motions of the shoulder complex and Range [11]

Vertical Motion: gravity support

As this is primarily a gravitational support exoskeleton, the actuated joint is focused on the motions of shoulder elevation. In simple models, the functional rotation axis of flexion/extension or abduction/adduction is located at the humeral head [43]. Considering this, it can be concluded that the frame should center the axis of actuator rotation roughly about the operators glenohumeral joint. This can be done as described above through the various shoulder frame anthropometric adjustments.

Figure 63 shows the V0 arm supporting exoskeleton actuator alignment with the persons humeral head in both sagittal and coronal elevation postures. With proper settings of the torso frame 102 as described above the actuator rotating joint 151, and thus the actuator rotational axis 154, is roughly aligned with the persons glenohumeral joint 218. With proper alignment the actuator output link and the persons upper arm will remain parallel, ensuring that the proper torque is applied to the upper arm at any given angle of elevation. Furthermore, this joint alignment ensures that the arm coupler does not rotate or translate relative to the persons upper arm during vertical motion, an important aspect of comfort.

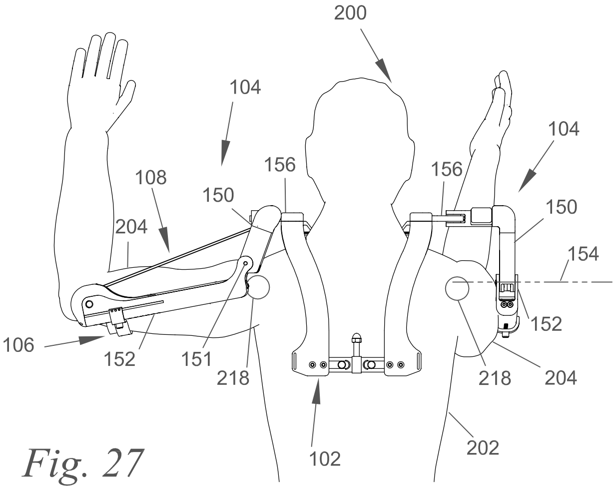


Figure 63. Actuator alignment with the glenohumeral joint.

Horizontal Motion

To allow gravity support at all ranges of shoulder elevation between the sagittal and the coronal planes the exoskeleton must also provide a degree of freedom for horizontal motion. During motions of horizontal flexion, the center of rotation is located roughly at the glenohumeral joint, this is not true for horizontal extension [44] but due to the rare nature of the posture this is not considered. To keep the actuator axis of rotation properly centered about the glenohumeral joint it is important that the horizontal movement mechanism either manually adjust for a centered axis of rotation, utilize a compliant mechanism, or contain kinematic redundancy [35]. As the actuator is passive and dependent on an axis of rotation perpendicular to the gravity line, a horizontal rotation axis parallel to the gravity line is needed. This eliminates a change in actuator angle as the arm moves in horizontal flexion and extension- creating a more uniform torque response. While a centered axis of rotation requires manual adjustment for proper functioning it is simpler and lower profile than many of the compliant or redundant options. As the torso frame adjusts in multiple dimensions, a centered axis of rotation is chosen for horizontal motion of the shoulder. To align this axis with the glenohumeral joint the joint must be located above the shoulder as in [45] [46] [47]. Similar active exoskeletons can offset the joints to eliminate toggle points [48] [49].

Figure 64 shows the arm supporting exoskeleton wherein the arm link mechanism 104 rotates about a second axis 155. This second axis is perpendicular to the torque generation axis 154 and also centered about the persons glenohumeral joint 218. The shoulder width setting can be used to center the second axis 155. Figure 64b shows a perspective view of the arm link mechanism 104 showing the actuator joint 151 rotating in the vertical plane about axis 154 and the horizontal joint 156 rotating in the horizontal plan about axis 155.

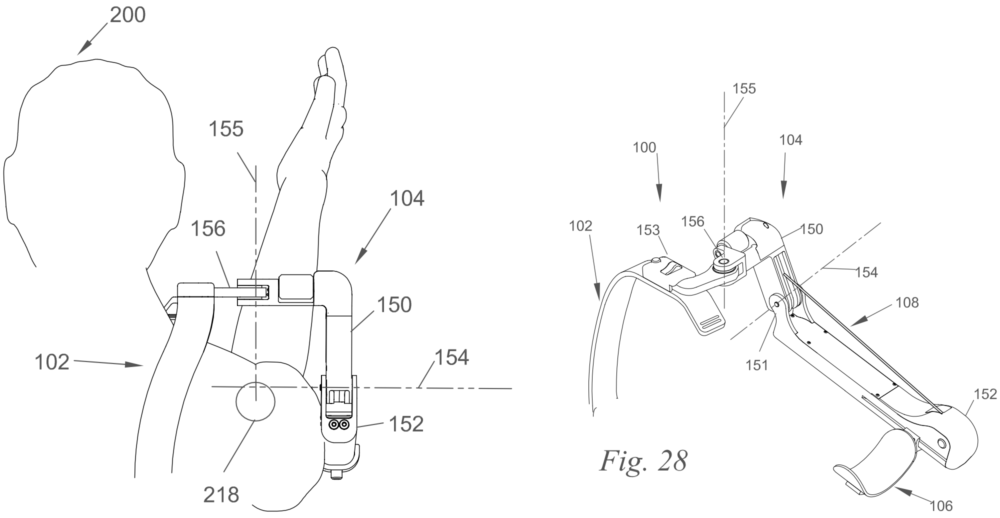


Figure 64. Exoskeleton Horizontal Flexion/Extension Joint

The horizontal rotation joint can also serve as an arm unit stow mechanism as described above via a selective locking of the joint. Figure 65 shows a horizontal rotation joint locking mechanism that locks the arms in the stowed position of Figure 60. For ideal functioning, it is desired that this mechanism automatically locks in the proper position once the switch is set to lock. Additionally, once unlocked the switch should not have to possibility of unwantedly relocking. Figure 65a (top and bottom left) and Figure 65b (top and bottom right) detail the horizontal joint locking mechanism 550 transitioning rotation between an acromial link 504 fixed to the shoulder base and a rotating shoulder link 551 between a locked and unlocked state. The mechanism contains a switch 552 and a locking pin 553 that fits into a groove of rotating shoulder link 551. The locking pin is pushed away from the switch 552 by means of a spring. When unlocked, as in Figure 65b, the switch moves the locking pin into a position where it cannot interface with the groove in the shoulder link. The switched can be moved to the locked position, as in Figure 65a, for any location of shoulder link 551 relative to acromial link 504. The spring will compress as the locking pin 553 is forced against shoulder link 551 until the proper shoulder link orientation is reached and the spring forces the locking pin into the groove of shoulder link.

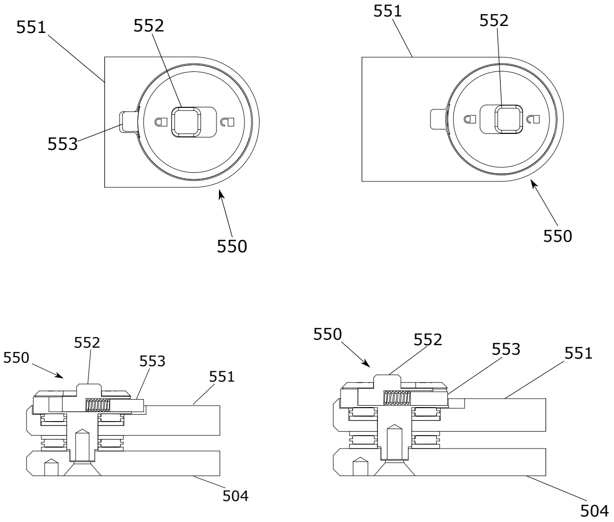


Figure 65. Horizontal Joint Locking Mechanism (a) locked (b) unlocked.

Rotational motion

The final degree of freedom of the glenohumeral joint is internal-external rotation, acting to transition the arm between flexion and abduction. As the spectrum of elevation motions between these all require equal degrees of gravitational support it is therefore best for the accommodating exoskeleton mechanism to not affect the output of the torque generator. To achieve this then the internal external rotation mechanism must be located distal to the exoskeleton actuator. In terms of gravity compensation this movement is used to counter the moment influenced by an elevated upper arm and flexed elbow as deviation from a neutral posture increases.

With no exoskeleton forearm it is near impossible to apply a supporting moment, thus the degree of freedom must also remain free. With even a relatively tight arm cuff and strap, the relative motion between the operators skin, bicep/triceps muscles, and bone allows for internal and external shoulder rotations with no discomfort. Thus the arm supporting exoskeleton only needs to ensure a proper arm coupling the allow the third rotational degree of freedom.

Figure 66 shows an embodiment of the arm coupler 106 where the arm cuff 168 translates with respect to the arm support link 167 about a center of rotation 173 roughly aligned with the center of the operators glenohumeral joint. This configuration is useful if planning for an addition of an elbow joint and forearm to the arm cuff 168. The joint can accommodate later additions of actuation mechanisms.

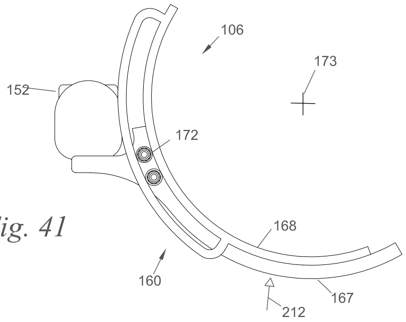


Figure 66. Shoulder internal/external rotation mechanism for use with an elbow joint.

Glenohumeral Motion Results

With the glenohumeral movement mechanisms the exoskeleton range of motion encompasses a majority of the operator's workspace. Table 5 lists the limits of the human shoulder motions biologically as well as when interfaced with the exoskeleton. The device provides a majority of vertical flexion/extension except for the upper 40-60 degrees. This is due to the operator's upper arm contacting the horizontal joint that sits above the shoulder. Abduction is similarly limited. In a majority of shoulder-intensive tasks these extreme angles have been eliminated rendering these upper range limits acceptable. For horizontal motions, extension is hard stops at zero degrees. This is a rare posture and the limitation has also been deemed acceptable for a majority of tasks.

	Human ROM	V2 Exo ROM
Flexion/Extension	180/-60	130/-60
Abduction/Adduction	180/-75	120/0
Horizontal Flexion/Extension	130/-50	130/0

Table 5. Range of motion of human [36] [28], and human wearing V2 Exoskeleton frame.

While it has been found that a majority of tasks do not require the uppermost range of elevation, an increase in profile can be sacrificed to achieve greater mobility. A higher range of flexion can be achieved if the spine is artificially raised to lift the horizontal joint higher, but this results in vertical misalignment of the actuator. The V2 hardware is built on a balance of this vertical distance between the horizontal joint and the torque generation axis and the added above shoulder profile. Alternately, a kinematically redundant mechanism can be used behind the shoulder for horizontal rotation but this too has an overbearing cost on profile.

SCAPULAR MOVEMENT MECHANISM

While the glenohumeral joint solely influences rotation, flexion/extension and abduction/ adduction are a result of more complex interactions of glenohumeral joint movement assisted by motions of the scapula via the sternoclavicular and acromioclavicular joints. The scapulohumeral rhythm has been defined the ratio of movement between the glenohumeral and scapulothroacic motion, with estimates ranging from 1.25:1 to 2.4:1. [50] [51] [52] This rhythm affects the functional center of rotation of the shoulder complex, and is primarily affected by the motion of scapular elevation and upward rotation. [53].Figure Xa depicts this motion for three positions of the arm. Although the ratio varies, most authors agree that the contribution of scapular motion occurs late in the elevation range of motion. [54] In addition to the primary vertical movements of elevation/depression and upward/downward rotation we will also consider horizontal movements of protraction and retraction. Figure Xb shows these movements terms the sternoclavicular joint.

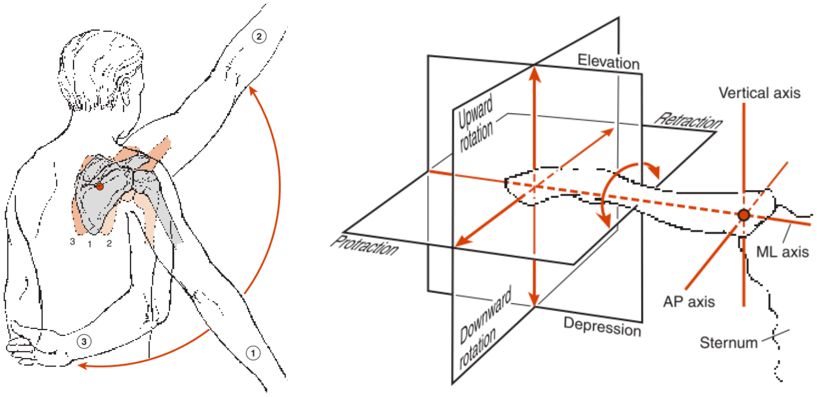


Figure 67. Scapular rotation about anterior poster axis during arm elevation (a) and axes of motion of the sternoclavicular joint (b) [54]

Mechanism overview

The purpose of the scapular movement mechanism is to allow full flexion and abduction of a person's upper arm and to best maintain alignment between the actuator and the shoulder complex axis of rotation. When a person's arm elevates to the point scapulothroacic motion begins, the scapular movement mechanism moves the arm link mechanism in a superior-medial direction relative to the persons torso to reduce contact forces between the persons shoulder and the exoskeleton frame. As the gravity compensation torques are calculated for and applied across the shoulder complex, not the individual glenohumeral and scapulothroacic joints, it is crucial that the scapular movement and torque is considered in supporting torque profile applied to the persons arm.

The scapular movement mechanism 500 sits between the torso frame 102 and the arm link mechanism 104, as shown in Figure 68. Due to this position, all reaction forces and torques from arm link mechanism 104 are transferred through the scapular movement mechanism 500 to the torso frame 102. The mechanism reacts to the angle of elevation 251 of persons upper arm 204, assuming the spine is perpendicular to a gravity line 208. When the angle of persons upper arm 204 rises above a first threshold angle 252, the scapular movement mechanism 500 begins moving the arm link mechanism 104 superiorly-medially and allows persons arm 204 to continue elevation unimpeded. At a second threshold angle 253 the scapular movement mechanism 500 ceases superior-medial movement of the arm link mechanism 104 as to not make contact with the persons head 201 or neck 203. This range of movement between the first threshold angle 252 and the second threshold angle 253 is the scapular equilibrium range. Below threshold angle 252 the scapular movement mechanism ceases further inferior-lateral movement and directly transfers reaction forces and torques between the actuator and the torso frame.

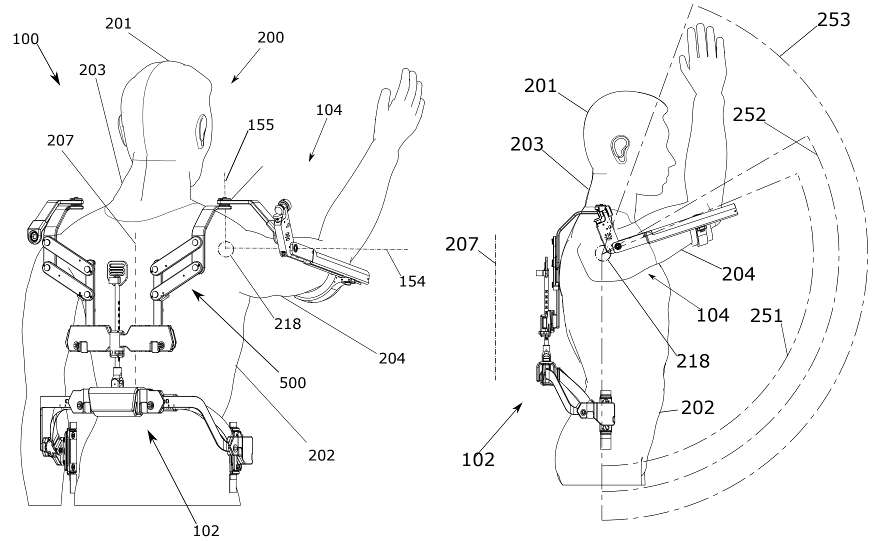


Figure 68. Scapular Movement Mechanism Overview.

Scapular Elevation

The scapular movement mechanism 500 is attached to a base link 501 parallel to gravity line 208. The base link 501 may be part of the torso frame 102. The device, shown in Figure 69a, further comprises a bottom cross link 502 and a top cross link 503, each rotatably coupled to the base link 501 and an acromial link 504. The angle of between the base link 501 and the bottom cross link 592 is defined as the scapular angle 505. The link lengths define a parallelogram-type four bar mechanism that keeps the acromial link 504 parallel to base link 501, and thus gravity line 208, for all values of scapular angle 505 between first scapular angle 506 and second scapular angle 507. As the acromial link 504 is attached to the arm link mechanism 104, this motion may 1) reduce contact between the persons arm or shoulder and the arm link mechanism 2) move the actuator's first rotational axis upwards to best align with the glenohumeral joint and 3) maintain a horizontal first rotational axis to provide consistent gravity compensation torque. At first scapular angle 506, a first hard stop 510 prevents scapular angle 505 from decreasing, shown in Figure 69b. This is equivalent to previously discussed levels of arm elevation and support, where persons upper arm does not contact the arm link mechanism 104 and the glenohumeral joint is relatively static. Here first hard stop 510 is coupled to base link 501 and contacts bottom cross link 502 at first scapular angle- but any combination or integration of coupling and contacting to or with various links is possible. Figure 69c shows second scapular angle 507 where a second hard stop 511 prevent a further increase in scapular angle 505. This prevents acromial link 504 from contacting the persons head or neck. Here second hard stop 511 is formed when bottom cross link 502 and top cross link 503 contact each other but other combinations of links may also be used. First scapular angle 506 or second scapular angle 507 may be adjusted by means of a change in shape or position of first hard stop 510 or second hard stop 511.

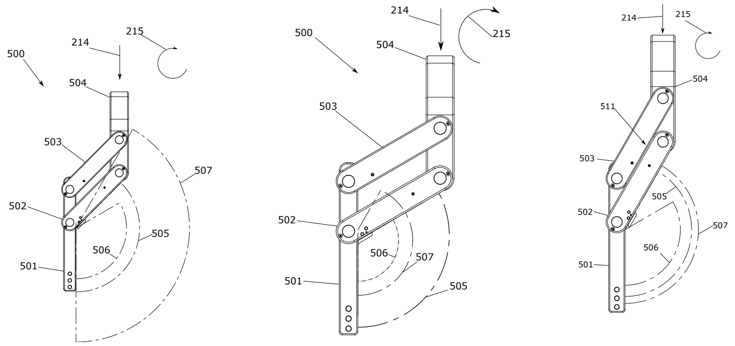


Figure 69. Scapular Movement Mechanism Motion.

Motion may also be achieved through a translation joint 560 between base link 501 and acromial link 504 as in Figure 70a moving the acromial link 504 in the superior inferior direction 561. Alternatively, the scapular movement mechanism 501 may comprise just one cross link 562 as in Figure 70b rotating relative to the base link 501 and acromial link 504. These designs are limited though in that they do not maintain orientation of torque generator 108 (Figure 70b) or move the arm link mechanism medially to get of the way of persons arm (Figure 70a).

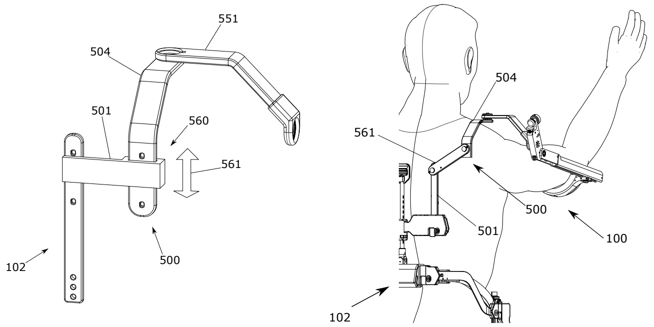


Figure 70. Alternate Scapular Movemet mechanism (a) translation (b) single base link.

In Use

The mechanism is positioned on the body with link lengths and first and second scapular angles defined to mimic the motion of the acromion about the sternoclavicular and acromioclavicular joints. A change in scapular angle 505 moves the arm link mechanism 104 relative to the torso frame 102 along a scapular mechanism path. This is similar to the glenohumeral path of caused by scapular elevation/depression and or upward/downward rotation motion moving the persons glenohumeral joint relative to the torso. Proper joint alignment allows scapular mechanism path to closely approximate persons glenohumeral path.

Figure 71 shows the progression of motion accommodated by the scapular movement mechanism. In Figure 71a arm elevation angle 251 is below a first threshold angle 252 and scapular movement mechanism 500 is hard-stopped at first scapular angle 506. Here the arm receives gravitational support forces from the actuator as it moves about the first rotational axis 154 and or second rotational axis 155 and reaction forces are transferred through scapular movement mechanism 500 to torso frame 102. Figure 71b shows persons arm elevation angle 251 reaching first threshold angle 252, where the scapular angle 505 begins to increase, and scapular movement mechanism 500 begins rotating the arm link mechanism 104 superiorly-medially. Scapular angle 505 increases with arm elevation angle 251, as in Figure 71c, moving the arm link mechanism out of the way of persons raised shoulder profile 256 as it raises from a neutral shoulder profile 255 and maintains a horizontal first rotational axis 154 centered about glenohumeral joint 218. Figure 71d shows persons arm at second threshold angle 253, where scapular angle 505 is prevented from increasing to prevent contact between the device and the persons head 201. Past second threshold angle 253 the person has the space to more fully elevate the upper arm 204 if it has not done so. Between the first threshold angle and the second threshold angle, the scapular angle changes so that the forces and torques from the arm link mechanism acting to decrease the scapular angle balance with the forces from a scapular torque generator 520 and or shoulder contact forces acting to increase scapular angle. The first and second threshold angles can thus be tuned through modifications of actuator torque, shoulder contact force, and any added torque to the scapular movement mechanism.

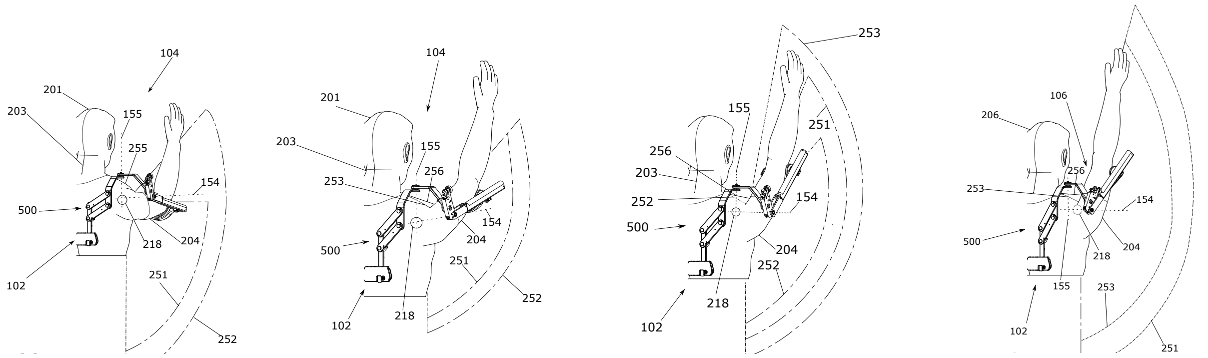


Figure 71. SMM motion with operator (a) below first threshold (b) at first threshold (c) between first/second threshold (d) at second threshold.

Scapular Retraction-Protraction

The scapular movement mechanism may also accommodate scapular motion in addition to elevation/depression and upward/downward rotation. Figure 72 shows a protraction-retraction joint 515 of the scapular movement mechanism 500. This joint moves the arm link mechanism 104 relative to the torso frame 102 about a scapular retraction protraction axis 516 parallel to gravity line 208. To trigger movement in this degree of freedom, the shoulder coupling 114 or the horizontal reaction forces of the actuator may be used. As the protraction-retraction axis of rotation 516 is perpendicular to the actuator axis of rotation 154 it will not affect the actuator torque profile, but rather the horizontal alignment of the arm link mechanism 104. In Figure 72a the scapular movement mechanism is protracted by an angle 517. This movement may be initiated by the arm coupler horizontal reaction force when the arm is raised above 90 degrees and stopped through contact with the rear of the persons shoulder. Additionally, a horizontal force between the persons shoulder and the shoulder coupling as the persons scapula protracts will initiate movement. For scapular retraction in Figure 72b the opposite is true, the arm coupler reaction force triggering motion below horizontal levels of elevation with the anterior portion of the shoulder coupling controlling the motion. Movement of the protraction/retraction joint 515 may further be spring loaded, limited by hard stops built into the hardware, or locked in discreet increments to provide an adjustment to the location of rotational axes of the exoskeleton with respect to the operator.

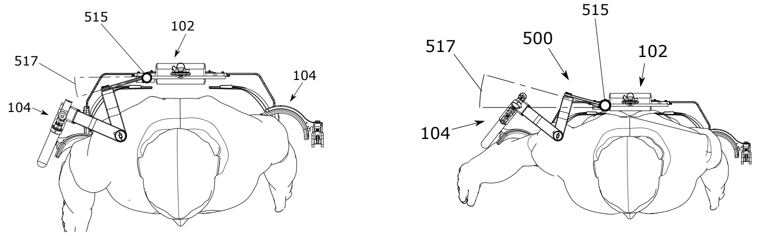


Figure 72. Scapular protraction (a) and retraction (b) movements

Scapular Torque Generation

Vertical movement of the scapular movement mechanism depends on mechanism hard stops, reaction forces and torques from the shoulder torque generator, contact with persons shoulder, and any added torque from a scapular torque generator. Absent of a scapular torque generator, scapular mechanism motion would be defined by the contact forces with the persons shoulder relative to the reaction forces from the shoulder supporting torque and mechanism weight, potentially causing discomfort. For ideal functioning of the scapular movement mechanism, a scapular torque generator defines the first threshold angle just before the top of the shoulder makes contact with the horizontal joint and the second threshold angle just as the arm is fully vertical. This results in the properly timed initiation of movement and it equipoises the reaction forces to smoothly increase scapular angle until the arm is fully overhead. Likewise, when lowering the arm, movement should initiate as the arm deviates from vertical and smoothly transition to the hard stop at the first threshold angle. The scapular torque generation strategy varies based on the configuration of the shoulder supporting primary actuator.

The scapular movement mechanism may contain a scapular torque generator 520 acting to increase scapular angle 505 by means of a spring element 523 acting between any two of the scapular movement mechanism links, as shown in Figure 73a. Between first scapular angle and second scapular angle, the scapular torque 521 created by the scapular torque generator supports the reaction forces and torques form the arm link mechanism, distributing them to the torso frame. Within the scapular equilibrium range the system acts with the two torque generators in series, further biased by any contact with the shoulder profile. The scapular torque generator may comprise a torsion, leaf, compression, or extension spring acting across one of the rotatable couplings of the scapular movement mechanism. The torque profile of the scapular torque generator 520 can similarly be modified as described for the shoulder supporting torque generator by changing the position 524 or angle 525 of the spring element 523 attachment as in Figure 73b with a spring translational bracket 527 or spring rotational bracket 538, or by changing the spring constant or linear position 526 to adjust preload as in Figure 73c with a spring preload bracket 529. The spring element 523 may also include a cable and pulley, or a leaf spring, to apply forces through the scapular movement mechanism.

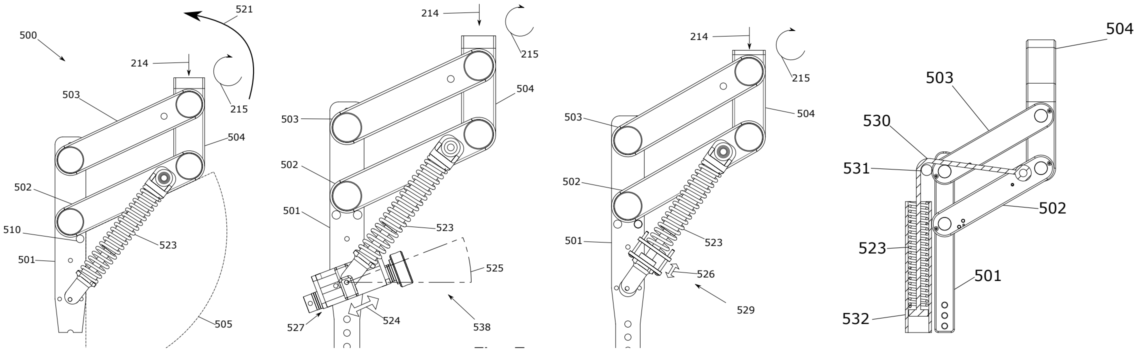


Figure 73. Scapular Torque Generator (a) postion adjustment (b) preload adjusment (c) cable and pulley (d).

The first scapular torque generation strategy applies when the shoulder supporting actuator is configured to transition to a zero-torque mode after first threshold angle. This may be done by hard stopping the standard tensile force generator or by using the variable mode force generator, wherein the support from the shoulder elevation actuator cuts out after the mechanism transition angle. As shown above, this angle is between 130 and 140 degrees of shoulder elevation with a twenty-degree gravitational offset, conveniently near the angle at which contact between the persons shoulder profile and the horizontal link begins. Thus, at first threshold angle a substantially small torque is being applied to the persons arm by the arm coupler for all actuator and frame settings, minimizing reaction forces and torques to be supported by the scapular movement mechanism. The scapular torque generator therefore must only support the weight of the exoskeleton distal to the base link. With this configuration the operator will not receive support past the first threshold angle but will also not be inhibited during a fully vertical reach. This has been deemed acceptable, as the fully vertical reach is a seldom used posture for most tasks, and as the arm reaches the upper range of elevation the exoskeleton actuator must bring support to a near zero torque anyway to prevent pushing the arm past the biological range of motion.

The second scapular torque generation strategy applies to get support in the full range of arm elevation. There the variable mode force generator must be removed from the primary exoskeleton actuator or set to have a much smaller transition angle. In this case the torque applied to the scapular movement mechanism is dependent on the elevation of the persons arm as well as settings of gravitational offset, support adjustment, and arm length. Proper scapular movement and support thus requires a careful tuning of the scapular torque generator according to the settings of the shoulder elevation torque generator. The accommodating torque generation and adjustment of the scapular movement mechanism may be created by mechanism geometry spring element position 524, spring element angle 525, and or spring element preload 526 similar to the strategy used in the arm supporting exoskeleton.

Pop Up & Indicating Neutral Posture

With increasing levels of scapular torque generator output, an issue arises as the arm moves to a neutral position and the primary shoulder actuator transitions to the zero force state. If the scapular torque is too great, the mechanism will pop up due to the lack of reaction forces from the arm cuff as shown in Figure 74. This results in the actuator axis of rotation 154 rising relative to persons glenohumeral joint 218, and an increase in profile superior to the shoulder. As the persons shoulder re-elevates and the actuator resumes torque generation the scapular movement mechanism will again lower for to the proper position. For higher levels of scapular torque generation of the second strategy the mechanism must therefore differentiate between a neutral and a raised arm position. At lower levels of scapular torque of the first strategy above this issue does not severely manifest due to friction within the mechanism and between the human machine interface.

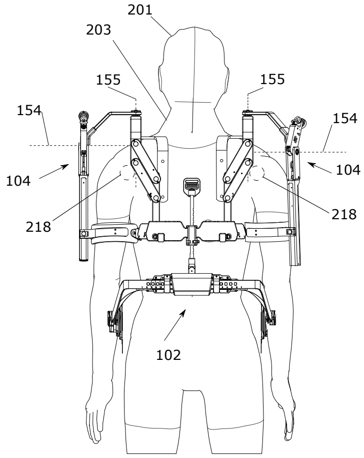


Figure 74. Scapular Pop up manifestation

A few methods are proposed in Figure 75 to identify a neutral position of the persons upper arm and lock out the scapular angle from increasing before popup occurs. One method includes the use of a contact force sensor 541 and scapular locking element 543. In Figure 75a a contact force sensor 541 above persons shoulder 224 measures the contact force between the exoskeleton and the person. At a neutral posture the persons scapula remains depressed and the sensor does not trigger locking of the scapular movement mechanism. At an elevated posture the persons shoulder profile elevates, triggering the contact force sensor 541 which causes scapular locking element 543 to unlock the scapular movement mechanism 500 and begin superior-medial elevation of the arm link mechanism 104. In the embodiment of Figure 75a the contact force sensor 541 comprises a contact force spring 542 connected to a control element 544 that triggers the scapular locking element 543. The contact force sensor 541 may similarly be electronic, pneumatic, or hydraulic. The control element may comprise a rigid or simi-rigid linkage or a flexible cable. In Figure 75b a retraction/protraction joint 515 of scapular movement mechanism 500 reacts to the horizontal forces between the persons arm and the arm coupler. At low angles of elevation this reaction force moves the joint 515 posteriorly by retraction angle 517, triggering scapular locking element 543 just before neutral position. As the persons arm is elevated the horizontal reaction forces shift to an anterior direction- retraction angle 517 is decreased the scapular movement mechanism unlocks just as movement is needed. Figure 75c shows a third embodiment where a routed control element 544 measures the angle between the two links of the shoulder supporting torque generator, directly triggering a locking mechanism 543 at a specified value. For each of these neutral angle reaction strategies a number of strategies may be used for the locking mechanism such as a ratchet/pawl, clutch, brake, or moveable hard stop.

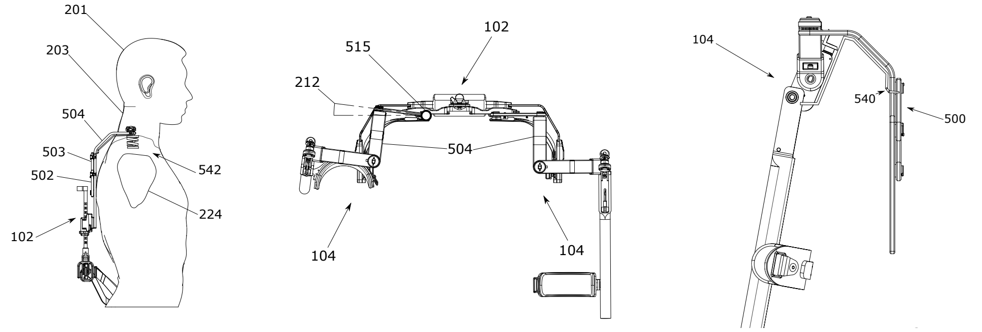


Figure 75. Methods of Neutral Position Identification by (a) vertical force (b) horizontal force (c) actuator angle.

An alternate popup solution lies in an alternating state hard stop mechanism shown in Figure 76. The alternating state hard stop 545 limits an increase in scapular angle 505 to either the second scapular angle 507 previously described at a first state or a third scapular angle 508 at a second state. Third scapular angle 508 is substantially close to first scapular angle 506, limiting the angle of pop up. The mechanism alternates between the first state and the second state each time the first scapular angle 506 is reached. In use, the first state corresponds to raising of the arm, as the scapular movement mechanism 500 is allowed to fully elevate the arm link mechanism 104 to second scapular angle 507. The second state corresponds to the arm in a neutral position where the forces of the scapular torque generator 520 unwantedly increase scapular angle 505. In the second state however scapular angle 505 can only increase to third scapular angle 508, minimizing the impact of popup. Figure 75a and Figure 75b show the alternating state hard stop 545 at the first state and second state respectively.

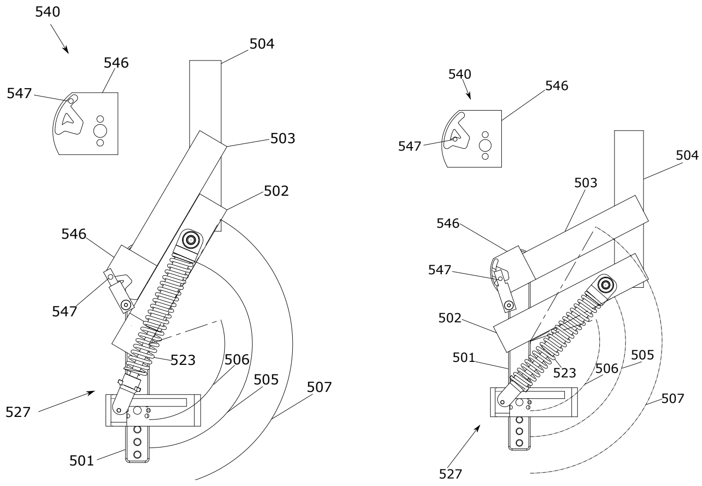
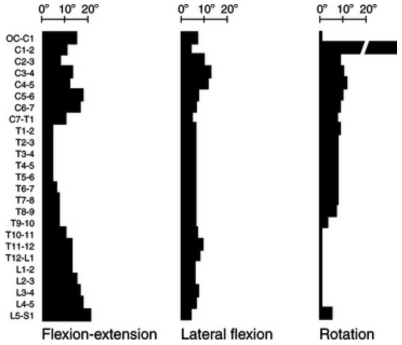


Figure 76. Alternating State Scapular Hard Stop (a) first state (b) second state.

The alternating state hard stop 545 may comprise a profile 546 and a follower 547 acting between too links of the scapular movement mechanism 500. In the first hard stop state follower 547 is at a first position 548 along profile 546, where an increase in scapular angle 505 is prevented. This corresponds to second scapular angle 507. At the second state follower 547 is at second position 549 along profile 546 that also prevents an increase in scapular angle 505, now corresponding to third scapular angle 508. The design of profile 546 in one or more dimensions may be set to influence the motion of follower between the first state and the second state. The follower 547 may likewise be given rotational or translational degrees of freedom relative to its attachment to scapular movement mechanism 500 to influence its motion along profile 546. This motion may also be biased by a follower spring.

SPINAL DEGREES OF FREEDOM

In addition to the four component joints discussed above, shoulder complex motion is enhanced by thoracic and lumbar spine movements that situate the torso to optimize positioning of the upper extremities. [55] The spine positions the shoulders in the sagittal plane through flexion/extension, in the coronal plane through lateral flexion, and in the transverse plane through rotation. There is no definitive axis of rotation, as overall spinal movements comprise many separate rotations between individual vertebrae as shown in Figure 77. When adding spinal degrees of freedom to the exoskeleton hardware it is important to ensure that load transfer is not compromised.



Torso ROM	
Side Bending	35 Degrees
Rotation	45 Degrees
Flexion	80 Degrees
Extension	20-30 Degrees

Figure 77. Range of motion at different levels of the spine [55] and over all Torso ROM [36]

If properly designed the torso frame can provide motion and supporting stabilization to the persons back. The exoskeleton frame provides for both lateral flexion and rotation degrees of freedom. Flexion/Extension is influenced too heavily by the reaction forces at the arm coupler, causing discomfort and improper actuator location and orientation. Figure 78 shows the V0 exoskeleton frame and its spinal degrees of freedom. Movement of the torso frame 130 is defined by rotations of the shoulder frame 136 relative to the hip frame 138, equivalent of movement of the rib cage relative to the hips. Lateral flexion occurs at the coupling of spine 134 and hip frame 138 in the direction 260. Twisting occurs between the shoulder frame 136 and spine 134 along the spinal axis 135.

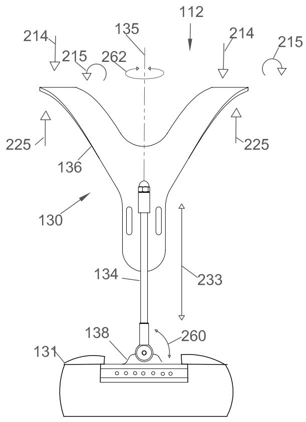


Figure 78. Torso frame with spinal degrees of freedom

Lateral Flexion

Providing a degree of lateral spinal flexion in the torso frame has shown to assist operators in key ranges of motion, with the drawback of requiring a more secure shoulder coupling. This range of motion assists most to help decouple the hip movement while walking from affecting the shoulder frame of the device. Lateral flexion is also useful when navigating tight spaces, such as ducking under low beams, inspecting a workspace, or entering lifts. Under load of the arm supporting exoskeleton, especially in abduction, the shoulder coupling must counter the moment about this joint to prevent excessive shoulder contact forces.

Figure 79 shows a free body diagram of the forces about the lateral rotation joint in the worst case loading of 90 degrees shoulder elevation in the coronal plane. Before transferring the primary vertical reaction forces to the hips as in Figure 46 above, the shoulder coupling forces must first counter the moment about the joint center O. The moment arms of each reaction force are modified based on the vertical height of the lateral flexion joint as well as the strap configuration. Other than the reaction forces from the opposite exoskeleton actuator, the primary stabilization forces are the horizontal force F4 vertical force F3 from the contralateral shoulder coupling. With an asymmetrical actuator load the contralateral shoulder strap must often be tightened. The reaction force F2 on top of the supported shoulder should be minimized due to avoid discomfort. In future research a torque may be applied about this joint to help counter the moment as well as to provide spinal support.

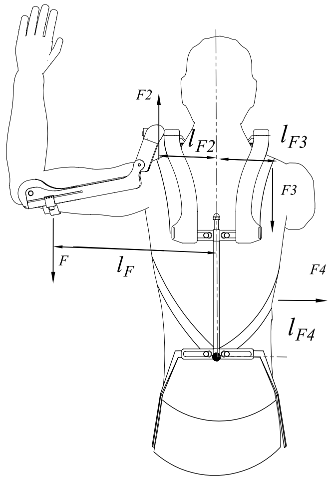


Figure 79. FBD of worst case shoulder reaction forces about the lateral spinal flexion joint.

Joint location is important to most comfortably accommodate this motion with minimum relative motion between the operator's shoulder and the shoulder frame. The optimum lateral flexion angle has been experientially determined to be at approximately the L3 vertebrae. If placed to low as in figure Xa contact will occur with the shoulder frame and the persons neck towards the location of the bend. If placed too high this may occur on the contralateral side. Figure Xb shows an operator in lateral flexion with an optimal joint placement.

Figure 80. Effects of lateral spinal flexion joint vertical location (a) Va (b) V0.

Twisting

Spinal twisting of the exoskeleton frame is provided but rarely used as the axis of rotation is behind the user’s body, and much of the twisting during overhead work can be provided at the hips. In future work mechanism providing an axis of rotation along the spine similar to the design of the arm coupler may be designed.

Flexion/Extension

To date all designed exoskeleton torso frames have not provided a spinal flexion or extension motion. This is due to the excessive moment that would be created about the joint when both arms are flexed in the sagittal plane. Additionally, feedback has been given that the rigidity of the spine in this plane helps to support the back and maintain a straight posture. If the user slouches in the device this will result in an uncomfortable tightening of the shoulder coupling. When bending over, such as to grab and object from the ground, sufficient flexion motion is provided by the operator’s hips- which are unobstructed by the exoskeleton. In future versions of the exoskeleton frame, a degree of spinal extension may be permitted, as shown in Figure 81 as users often lean backwards to access the workspace. It must be determined what angle 155 of extension should be permitted and if this creates more of less stress in the back during overhead work. This may also assist scapular movement mechanism elevation and may be spring-loaded or limited by hard stops to control motion.

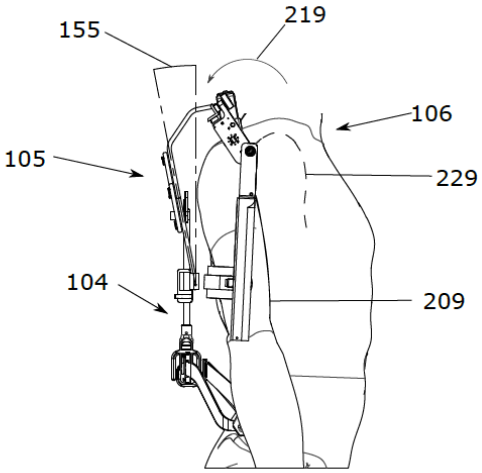


Figure 81. Spinal extension of the exoskeleton frame

CHAPTER 4: MODULARITY

Many occupations and workplace tasks are exposed to injury risk factors to multiple joints within the body. In addition to the shoulders, the back and the knees make up the top 3 locations of injury. [2] [1] During overhead tasks, the neck is similarly at risk as the operator often must look up to see the workspace. It is therefore desirable for an exoskeleton to have a modular architecture that can selectively support a range of joints for a specific job or task. A modular system allows for both expanded assistance for complex tasks as well as minimal hardware for single-joint risk tasks. The primary cost of the modular system is the added complexity of attachment points and weight for a frame designed to withstand multiple loading conditions.

NECK SUPPORTING EXOSKELETON

Neck support devices are commonly utilized in medical and safety related applications, such as braces for automotive use to protect users from rear end collisions. A few, such as [56] may be used for recreational or industrial applications but are limited in that it does not provide freedom of motion or a supporting torque. In many industrial settings a worker is required to perform tasks in a position that places strain on the persons neck. Neck extension results in an increase in upper trapezius and sternocleidomastoid activation, especially when both arms are elevated for tasks such as painting. [57] For these tasks it would be beneficial to have a device that provides a supportive force at the head, thus a torque about the neck, that compensates for the forces and torques imposed on the head and neck due to gravity. Ideally, the neck supporting exoskeleton compensates for the gravitational forces on the head during these risk prone postures with minimal restriction of movement in other postures. Furthermore, the neck supporting exoskeleton should be configured to fit a range of human dimensions and may be adjustable to provide varying levels of torque about different axes of rotation.

Figure 82 depicts a neck supporting exoskeleton 600 alone and used with arm supporting exoskeleton 100. The exoskeleton comprises a torso frame 102 coupled to a person’s torso 202 and a neck link mechanism 603 that applies a supporting force to persons head 201. The neck linkage 603 couples to the torso frame 103 at base coupler 630 and to the persons head 201 at head contact element 620. At least one neck actuator 615 generates a torque 613 between head contact element 620 and base coupler 630 about neck rotational axis 608 to support persons head 201 from the forces of gravity. Here it is assumed that the vertical axis of torso frame 102 is parallel to the gravity line 208.

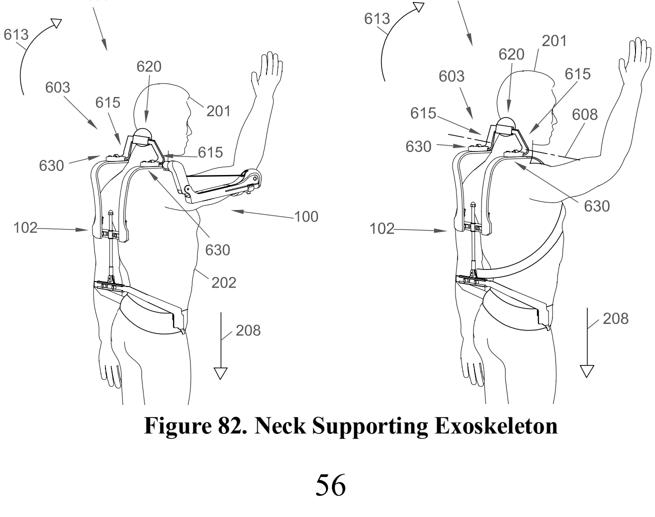


Figure 82. Neck Supporting Exoskeleton

NECK SUPPORTING ACTUATION

The neck supporting exoskeleton applies a gravity compensating torque to the persons head as it deviates from a neutral position. To prevent inhibition of the user the exoskeleton provides no support when the neck is substantially straight. The current exoskeleton assumes the person is standing straight with the spine orientation parallel with the direction of gravity, thus the applied forces will be incorrect if a person is in a bent posture.

Figure 83shows the neck supporting exoskeleton operational principle. When persons neck is substantially strait, the moment about the neck due to the weight of the head is minimal. Here no support is needed. When persons neck undergoes extension motions, a torque is created about the neck due to the mass of persons head [$M_h g$] and the distance [l_M] between the head's center of gravity and an estimated rotational center of the spine [O]. During this extension motion, a neck supporting force [F] to persons head counters the torque due gravity. While the motion of extension is shown, similar forces can be applied for motions of flexion or lateral flexion through a simple rearrangement of the described configuration of the neck linkage and actuator.

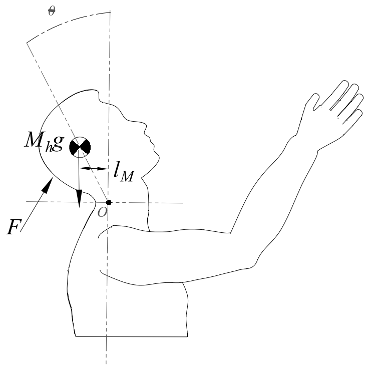


Figure 83. Neck supporting exoskeleton principle of operation for neck extension.

Actuator Placement

The neck supporting actuator relies on an actuator axis of rotation that is centered about the neck rather than using a compliant or kinematically redundant approach, keeping with the design philosophy of the shoulder supporting exoskeleton. During extension motions each of the cervical vertebra rotate relative to each other about horizontal axes that shift posteriorly as extension increases. [58] To best support neck extension motions about a single axis, it is therefore important that the neck supporting exoskeleton actuator be centered about the spine in the sagittal plane.

Figure 84 shows the neck supporting exoskeleton 600 where neck rotational axis 608 is approximately centered about the rotational center of the spine [O], or more generally any part of the spine itself. The placement of neck actuator rotational axis 608 results in the neck torque generator angle changing in proportion to the angle of persons neck extension. This reduces relative motion between head contact element 620 and persons head 601 throughout the flexion/extension range.

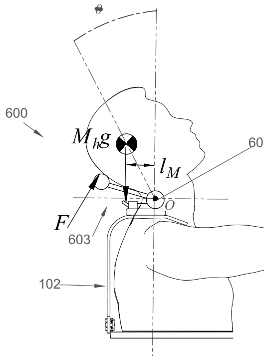


Figure 84. Neck actuator placement.

Neck Engagement Angle

The neck supporting exoskeleton applies a gravity compensating force to the back of the operator's head after a certain angle of deviation from a neutral posture. With increasing engagement angle, the operators free range of motion expands but the level of support received is reduced. A balance of neck engagement angle must be obtained to allow for minimal inhibition with maximum support. In the following figures neck extension angle is defined as the angle between the center of rotation of the persons spine to the back of persons head.

Figure 85 shows the neck supporting exoskeleton torque generation range. When the angle of neck extension 254 is greater than engagement angle 611, as in Figure 85a, neck supporting exoskeleton generates a supporting force 612 applied to persons head 201 at head contact element 620. At neck extension levels 254 less than engagement angle 611, shown in Figure 85b, neck supporting exoskeleton motion ceases for further levels of flexion- resulting in free movement of persons head 201 or separation between persons head 201 and head contact element 620. This neck extension engagement angle 611 can be defined by a hard stop or zero torque state of the neck actuator 615.

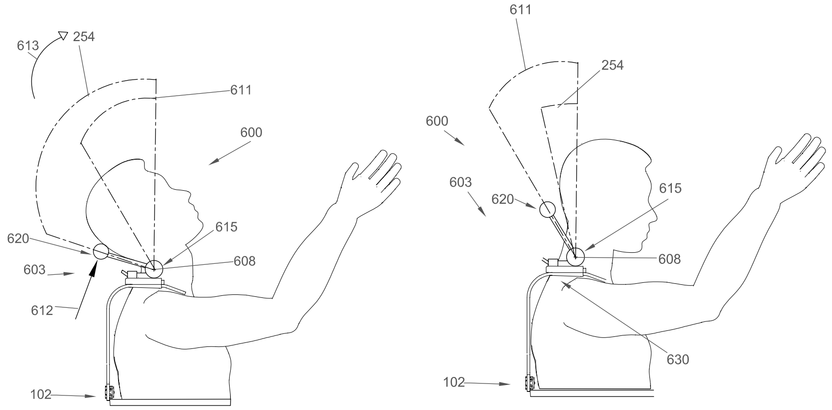


Figure 85. Neck actuator (a) greater than engagment angle (b) less than engagement angle.

Below the engagement angle the head contact element may either separate from the persons head entirely or follow the persons movement without an applied torque, provided a proper coupling. Figure 86a shows a configuration where a superior link 605 connects the head contact element 620 to the neck linkage 603 about neck rotational axis 608. For neck flexion angle 254 less than engagement angle 611 superior link 505 loses contact with neck actuator output link 607 and allows head coupler 620 to freely track the head. Maintaining tracking of the head coupler 620 through the necks neutral position may be useful if the neck supporting exoskeleton is configured to support the head for more than one motion. In Figure 86b the neck actuator output is the superior link 605, and after the neck engagement angle persons head 201 loses contact with head contact element 620.

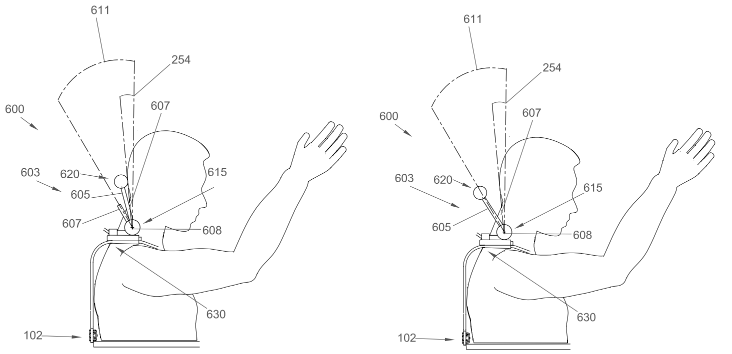


Figure 86. During free range (a) Head contact (b) head separation.

Torque Generation

Once engaged, the neck actuator generates a torque about the neck rotation axis that increases with increasing level of extension. The torque profile of the head relative to the torso about the single extension axis is a curve defined by the sine of deviation from the neutral vertical posture. The amplitude of this torque varies based on the mass of the persons head and any helmets or other head-mounted devices. Maximum neck torque occurs when the neck is at its greatest level of flexion, the range of neck motion is not great enough for a decrease in moment arm past the horizontal. The ideal neck support torque therefore is equal and opposite to the torque due to the head across the neck's range of motion.

Figure 87 shows a few methods of neck actuator 516 torque generation about neck rotational axis 608 between an inferior link 604 secured to base coupler 630 and an superior link 605 secured to head contact element 620. In Figure 87a a neck spring 616 is a leaf spring used create a neck supporting torque 613. Here the leaf spring acts both as the mechanical joint allowing the extension motion, a portion of the neck linkage structural frame as well as the neck actuator. In Figure 87b neck spring 616 is a torsion spring that creates a torque between an inferior link 604 and a superior link 605. Figure 87c shows a third embodiment where a neck spring 616 is a compression used to create a torque between the inferior link 604 and superior link 605. Other spring configurations not shown may be possible through the use of control cables.

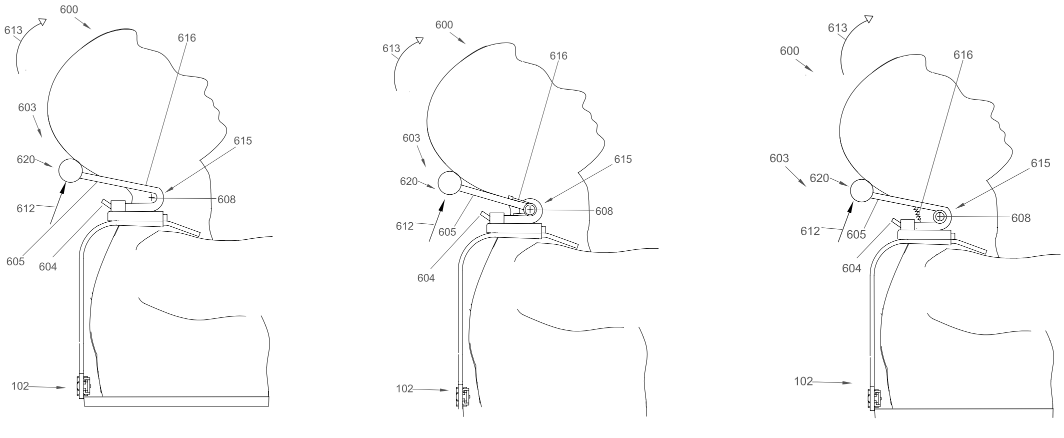


Figure 87. Neck torque generation strategies (a) leaf spring (b) torsion spring (c) compression spring.

The neck supporting torque profile generation and modification requirements are much simpler than for the shoulder supporting exoskeleton. Because the necks range of motion cannot exceed the horizontal the generated torque does not have to create an increasing-decreasing pattern. Additionally, the weight of the head does not vary as much as the arm and tool combination, removing the need for drastic changes in output amplitude. Neck actuator torque profile may be adjusted by preloading the actuator against a hard stop or by modifying the location of spring attachment points for the linear spring torque generation method.

NECK SUPPORTING FRAME

The neck supporting frame facilitates load transfer, coupling, adjustment, and movement of the persons head relative to the torso. A head contact element transfers the torque from the actuator to the back of the operator's head as force F and a torso frame coupler distributes the reaction forces and torques to a torso frame. A coupling mechanism secures the persons head to the head contact element to comfortably distribute the neck supporting forces. Finally, a neck link mechanism allows for movement of the persons head and adjusts to fit a majority of the workforce.

Load transfer

The head contact element is designed to transfer the neck supporting force to the person's head throughout the range of motion of the neck supporting exoskeleton. For optimum comfort the supporting force should be applied to the base of the skull and avoid any upper cervical vertebrae. As the neck does not rotate about a single axis, relative motion between the head and the head contact element is difficult to avoid, especially if the actuator is misaligned. For optimum load transfer the head contact element should therefore minimize relative rotation or translation between the neck supporting exoskeleton and the persons head.

Figure 88 shows a few embodiments of the head contact element 620. In Figure 88a the head contact element 620 comprises a contoured head pad 621 that allows for rolling contact with the persons head 201 as neck extension occurs. The pad may be made of a smooth material to minimize any friction if persons head translates relative to the device. In the configuration of Figure 88a the neck supporting force is always normal to the head pad 621 at the center of contact with persons head 201. In Figure 88b the head contact element 620 pivots relative to superior link 605 about joint 622 along an axis parallel to the neck actuator axis of rotation 608 in order to maintain normal contact between persons head 201 and head pad 621. Figure 88c the head contact element 620 translates relative to superior link 605 along direction 624 to eliminate any relative motion between persons head and the device. To keep the device as simple as possible the current device uses the configuration of Figure 88a.

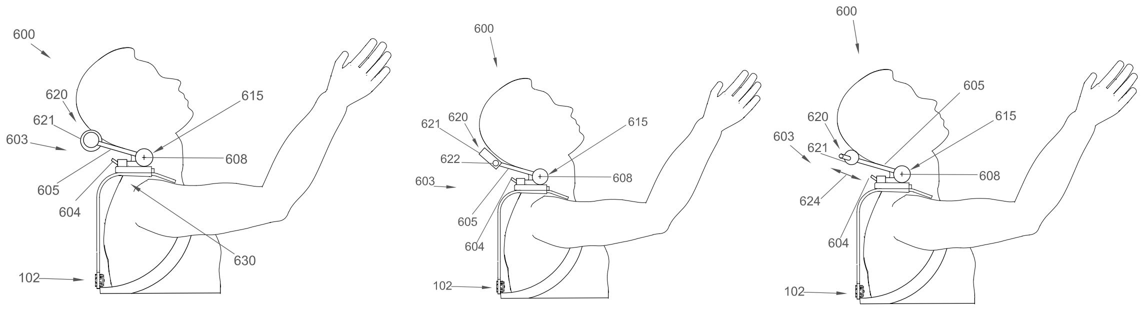


Figure 88. Head Contact Element Load Transfer (a) rolling contact (b) pivoting (c) translating.

Inferior to the actuator the neck supporting exoskeleton selectively couples to and transfers reaction forces and torques to a torso frame. Compared to the shoulder supporting exoskeleton, these loads are relatively small. The primary reaction forces are directed anteriorly and inferiorly to the persons head. Rotating about a shoulder pivot the resulting moment is countered by posterior contact with the spine or hip frame. Rotating about a hip pivot the resulting moment is countered by anterior contact with a shoulder coupling chest strap or shoulder straps. The vertical component of the support is taken by either the shoulder straps or the hip belt. Depending on the configuration of the torso frame 102 the base coupler 630 of neck supporting exoskeleton 600 can couple to the exoskeleton spine 134, the shoulder frame 146, or the shoulder straps 120, as shown in Figure 89a, Figure 89b, and Figure 89c. The neck supporting exoskeleton may also be connected to shoulder straps 120 of a backpack 312, as shown in Figure 89d.

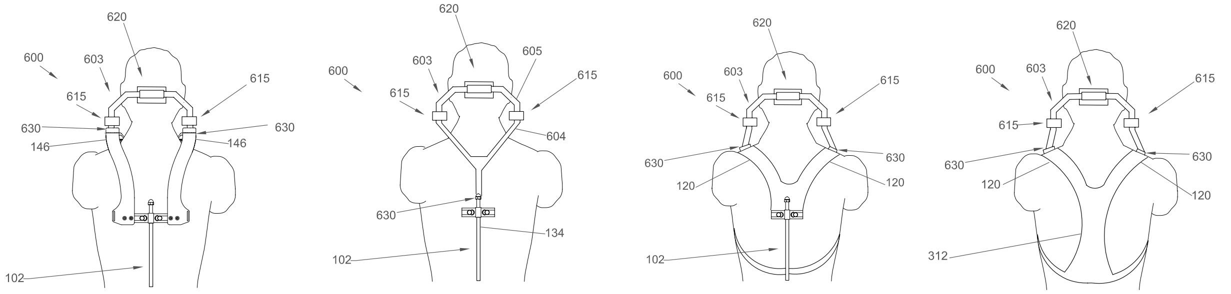


Figure 89. Neck supporting exoskeleton mounting (a) shoulder frame (b) spine frame (c) shoulder straps (d) backpack.

Coupling

The neck supporting exoskeleton couples to the persons head through a head coupling mechanism and to a torso frame through a torso frame coupling mechanism. Depending on the supported motions the head coupling mechanism may or not be needed. When only supporting extension motions of the persons neck, it may be desired for the persons head to separate from the device for extension angles below the neck engagement angle. Supporting the neck during extension is more important than flexion due to the weaker anterior neck muscles. In this configuration no head coupling mechanism is needed, as the nature of the supporting torque maintains contact between the head contact element and the persons head. If it is desired for the device to also support neck flexion or maintain coupling between the device and the person throughout range of motion, head contact element 620 may further comprise a head strap 626 as shown in Figure 90a. The head strap can be configured to apply a neck supporting force 612 anterior to the head to support flexion. The head strap 626 can be made of a non-flexible material to transfer force directly from the neck actuator 615 or of a flexible material to generate a supporting force of its own. The head contact element 620 may also include a head brace 626 made of a rigid or semi-rigid material partially encircling persons head 201, as in Figure 90b. The head brace can be configured to provide a supporting force laterally to persons head or restrict the persons range of motion.

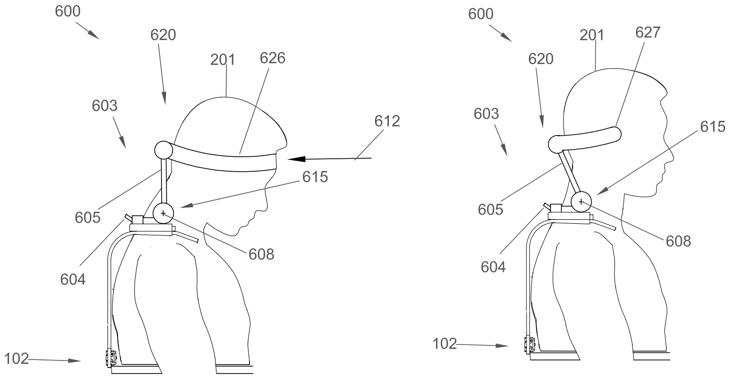


Figure 90. Head coupling mechanisms (a) strap (b) brace.

A selective coupling to a torso frame allows the modular connection to a shoulder supporting exoskeleton. The neck supporting exoskeleton may be remain attached to the torso frame and donned as one unit, with or without the arm link mechanisms. Alternatively, the neck supporting exoskeleton may be quickly attached or removed from the torso frame while it is being worn by the operator to optimize support for a shifting task. For usability purposes a tool should not be needed to attach or detach the neck supporting exoskeleton to the torso frame.

Figure 91 shows an embodiment of the neck supporting exoskeleton base coupler 630 comprising a locking insert 631 on neck link mechanism 603 and a locking slot 632 attached to the torso frame 102. The locking insert 631 is inserted into the locking slot 632 which constrains the locking insert in two dimensions. Once fully inserted the locking insert 631 is fixed in place in the third dimension by a first profile 633 in the locking slot 632 that interfaces with a second profile 634 in the locking insert 631. The first profile 633 or second profile 634 may be spring loaded to ensure automatic engagement. Here the locking insert 631 is made of a leaf spring material. A contoured surface 635 is used to compress the spring as the locking insert 631 is inserted. A flange on the locking insert may further serve to constrain the connection in the third dimension. Once engaged the torso frame coupler transmits the reaction forces and torques from the neck exoskeleton head supporting force to the torso frame. Figure 91a shows the base coupler connecting the neck link mechanism 603 to torso frame 102, and Figure 91b shows them disconnected. Other methods of coupling to the torso frame (not shown) may utilize buckles or hook and loop fasteners.

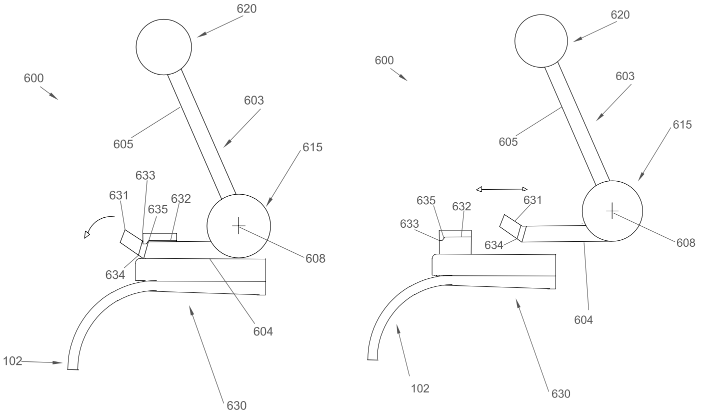


Figure 91. Neck supporting exoskeleton torso frame coupler (a) engaged (b) disengaged.

Adjustment

To accommodate users of varying dimensions and to best align the neck actuator axis of rotation the neck supporting exoskeleton may adjust in dimensions of width, height, or depth.

The primary adjustment is in width, which allows for the torso frame shoulder couplings to be properly spaced for optimum comfort- similar in function to the shoulder width adjustment described above. Head breadth changes little between individuals so the head contact element can be dimensioned to facilitate all users. [36] To avoid unnecessary complexity, it is therefore ideal for the neck width adjustment to automatically lengthen or shorten as the shoulder width setting is changed. Figure 92 shows the neck link mechanism 603 further comprising a width bracket 641, a first width bar 642 and a second width bar 643. Width bracket 641 is coupled to head contact element and translationally coupled to first width bar 642 and second width bar 643. At least one of the first width bar 642 and second width bar 643 are free sliding within width bracket 641 and automatically adjust in position as their mounting locations to the torso frame adjust in the shoulder width dimension. A slot within one or both width bars interfaces with a width locking element 644 of width bracket 641 to hard stop adjustment at a maximum and minimum position, or to prevent free sliding of the mechanism. If both first width bar 642 and second width bar 643 are free moving relative to width bracket 641 the head contact element may properly remain centered for the entire range of width adjustment, as well as facilitate motion of the persons neck. Figure 92a shows the neck link mechanism in a small and large width setting, and Figure 92b shows the direction of neck width adjustment 244 on person 200. Figure 92c shows a free floating width bracket for constant setting of neck linkage width that may be further used to facilitate movement about a second or third rotational axis as described later.

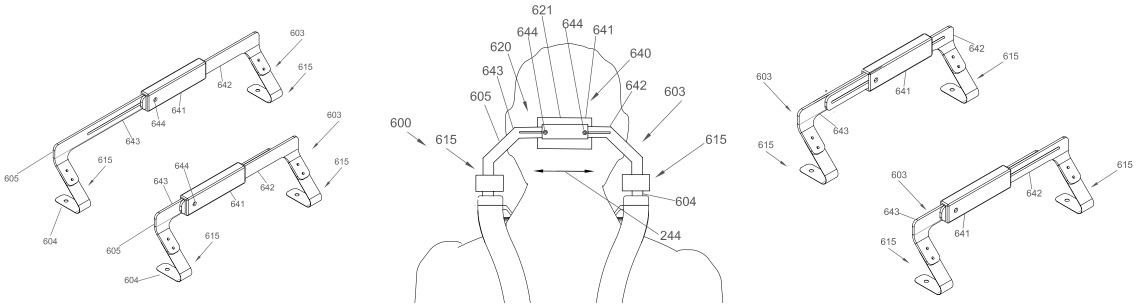


Figure 92. Neck supporting exoskeleton width adjustment (a) mechanism (b) on body (c) floating head couper.

A neck supporting exoskeleton height adjustment may be used to ensure proper placement of the head contact element vertically on persons skull. Table 6 shows the dimensions of shoulder height and eye height for 5-95% of the US male/female population [36], the range between the two being the vertical dimension of the neck supporting exoskeleton. It can be seen that there is little variance in shoulder to eye distance across the population. The fit of the torso frame on the person may be more influential for proper vertical positioning of the head contact element than the physical size of the operator. Adjusting the torso frame fit therefore may take the place of a vertical height adjustment of the neck supporting exoskeleton.

	5-95% US (in)	Modifier	Specification (in)
Shoulder height	48.4-59.7	+1” for frame gap	7.1-7.4”
Eye Height	56.8-67.8	N/A	

Table 6. Anthropometric data [36] and hardware specification for neck height.

If it is desired, a height adjustment mechanism similar to the width adjustment may also be designed into the neck supporting exoskeleton as shown in Figure 93. The neck linkage 603 further comprises a height bracket 646 transitionally coupled to a first height bar 647 between the head contact element 620 and neck actuator 615. Alternatively, height adjustment may occur between the actuator 615 and base coupler 630 with a right and left mechanism, both affecting actuator alignment and head contact element position. The height bar 647 and height bracket 646 can be locked in place with height lock 648 to retain the vertical height setting. Figure 93 shows the height adjustment mechanism adjusting in the direction of persons head height 246.

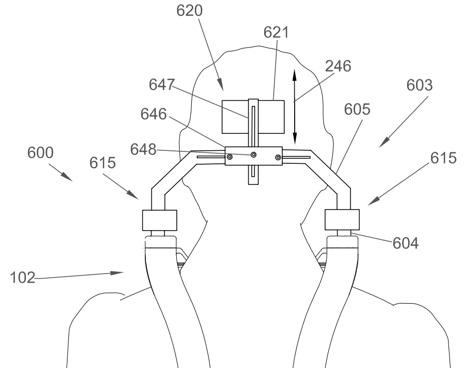


Figure 93. Neck supporting exoskeleton height adjustment

Finally, a depth adjustment of the neck supporting exoskeleton may serve to position the actuator axis in the anterior-posterior dimension or to ensure the proper angle of engagement with the head contact element. Depth adjustment may be facilitated through the location of the coupling with torso frame to affect both properties or by means of an adjustable mechanism within the neck linkage superior to the torque generator to affect only the engagement angle with persons head. Figure 94a shows an embodiment of neck supporting exoskeleton 600 wherein the position of coupling with torso frame 102 as described above can be adjusted in the anterior-posterior direction 248. This affects the alignment of actuator axis 608 with persons spine and the angle of contact between head contact element 620 with persons head 201. Figure 94b shows an alternative arrangement where neck linkage 603 contains a depth bracket 649 and a depth bar 650 that translationally adjust to affect both actuator placement and head contact if inferior to the actuator, or head contact only if superior to the actuator as shown. Depending on the angle of depth bracket 649 and depth bar 650 this mechanism may facilitate a combination of depth and height adjustment along dimension 249.

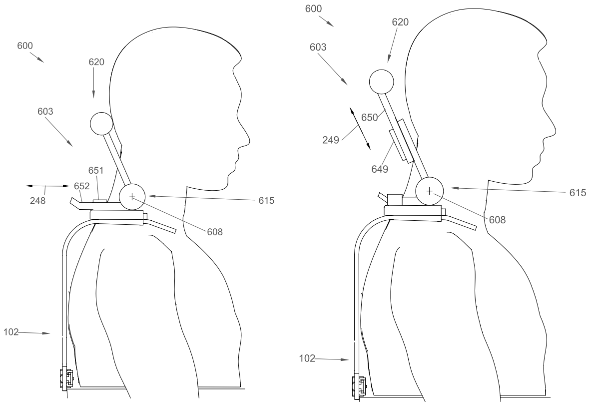


Figure 94. Neck supporting exoskeleton depth adjustment (a) base coupler (b) depth bracket.

Movement

As the primary purpose of the exoskeleton is to support extension, and sometimes flexion, movements the actuator axis of rotation includes the neck linkage degree of freedom in the sagittal plane. To accommodate twisting and lateral flexion of the neck alternative degrees of freedom may be added to the neck linkage. Alternatively, these motions will be uninhibited if the neck is in a neutral position in the sagittal plane and contact has not yet occurred between the persons head and the head contact element. During neck extension when the head is in contact with the neck supporting exoskeleton, additional degrees of freedom for lateral flexion and twisting will minimize rubbing between the device and the persons head. Because these degrees of freedom are orthogonal to the axis of torque generation they may be added with no influence to flexion-extension support torque. The range of motion of persons neck to be accommodated by the neck supporting exoskeleton is shown in Table 7 below. [36]

Motion	Range (degrees)
Flexion/Extension	45/45
Lateral Flexion	45/45
Rotation	60/60

Table 7. Range of motion of the cervical spine. [36]

Motion of the neck supporting exoskeleton may be limited by a hard stop to prevent persons neck from entering dangerous postures or to provide full support of persons head at a specific angle. Figure 95 shows neck supporting exoskeleton 600 further comprising a hard stop 606 between inferior link 604 and superior link 605 preventing further rotation about neck rotational axis 608. The position of hard stop 606 may be adjusted to alter the angle at witch movement ceases. Figure 95a shows the hard stop 606 in a first position allowing a greater range of motion and Figure 95b shows the hard stop 606 in a second position allowing a lesser range of motion.

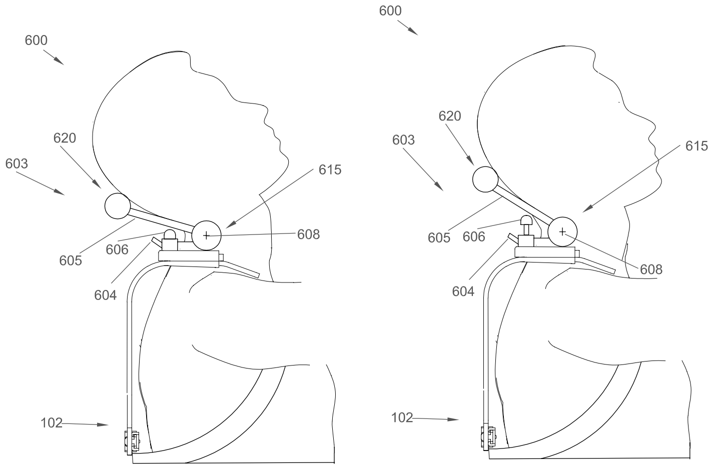


Figure 95. Neck linkage hard stop in (a) first position (b) second position.

Additional degrees of freedom may also be provided to expand the allowed neck postures. Figure 96a shows an embodiment of the neck supporting exoskeleton 600 further comprising a lateral flexion joint 655 between the actuator 615 and the head contact element 630. The lateral flexion joint 655 axis of rotation 609 is roughly centered about persons spine in the coronal plane and is orthogonal to gravity line 208 and first neck rotational axis 608. This joint may be free, lockable, or spring loaded and used in conjunction with the lateral brace to provide additional support to the persons head during lateral flexion motions. A twisting degree of freedom in the transverse plane may likewise be included in the neck supporting exoskeleton. Ideal rotation occurs about an axis through the spine but this is often difficult to achieve without a complex mechanism. Figure 96b shows transverse rotation axis 610 added to neck supporting exoskeleton 600 that is parallel to gravity line208. Figure 96c shows a perspective view of neck supporting exoskeleton 600 comprising a first 608 second 609 and third 610 neck rotational axes. Twisting or lateral flexion of the head may also be provided by a free-floating width bracket as described above.

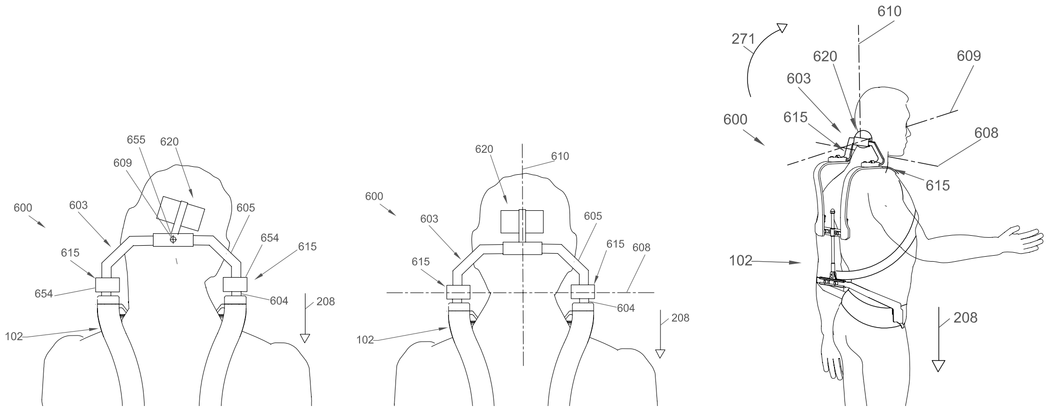


Figure 96. Additional Degrees of Freedom (a) lateral flexion (b) twisting (c) all axes.

Use and Benefit

A majority of the overhead tasks in which the shoulder supporting exoskeleton is used may likewise benefit from the neck supporting exoskeleton- as the workspace is often above eye level. As both the neck supporting exoskeleton and arm supporting linkage are quickly connected and disconnected from the torso frame the two devices may be used separately or together with no modification to torso frame donning procedure as described above.

A pilot trial was conducted to estimate the benefit to the sternocleidomastoid muscle during neck extension at varying degrees with and without the neck supporting exoskeleton. A subject was asked to stand in the same position and look at three markers at increasing heights along a wall. Levels of neck extension were approximately 15, 30 and 45 degrees. For all conditions the neck supporting exoskeleton reduced both right and left sternocleidomastoid muscle activation with increasing effects at higher angles of extension. Table 8 shows muscle activation as %MVC for each level of flexion.

Extension	SCM no exo (R/L) % MVC	SCM exo (R/L) % MVC
15 degrees	1.61/ 1.51	1.13/1.04
30 degrees	4.45/2.49	0.86/1.01
45 degrees	5.89/4.62	.99/1.04

Table 8. Neck Support Pilot Results (1 subject).

TRUNK SUPPORTING EXOSKELETON

Some occupations require a diverse range of postures that puts both the shoulders and lower back at risk of strain or injury. In addition to the overhead work described above, repetitive or prolonged stopping is a common workplace posture posing a risk of injury, even with relatively light loads. [59] [60] For some tasks it is desirable to have support provided at both the back and the shoulders. Figure 97 shows a trunk supporting exoskeleton also developed in the Human Engineering and Robotics Lab to support the lower back during sustained or repetitive stooping. [61] Two versions of this device distribute a counter moment to the hips via an anterior and a posterior frame. Due to the ability to connect the device to the shoulder supporting exoskeleton only the posterior frame will be discussed.

The trunk supporting exoskeleton comprises a torso frame 102 configured to be coupled to persons trunk and a set of thigh links 104 106 coupled to each of persons thighs. A set of hip torque generators 108 and 110 generate a torque between the torso frame 102 and thigh links 104 106 that is applied as a supporting force 230 to persons chest 218. Reaction forces are applied to the persons hips and thighs.

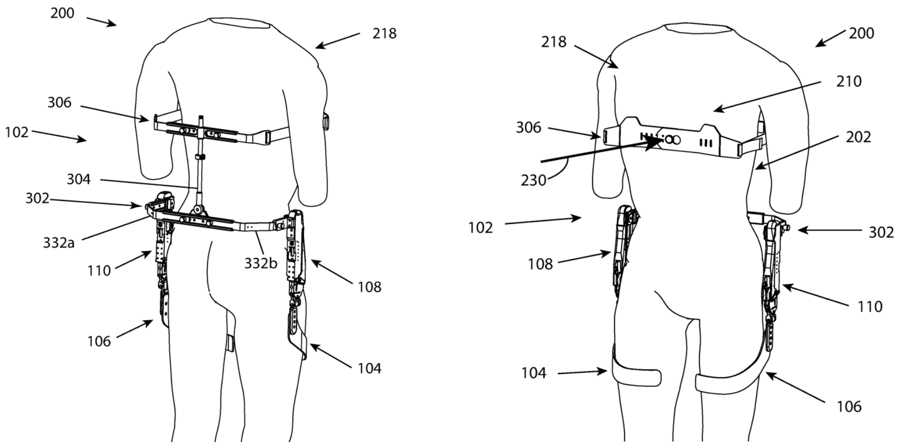


Figure 97. Trunk Suppoting Exoskeleton Configuration. [61]

TRUNK TORQUE GENERATION

The trunk supporting exoskeleton generates a torque that counters the mass of the upper body about the hip joint while in a bent posture. As shown in Figure 98, a moment is created about the hips during flexion by angle α due to the center of mass of the upper body M_{BG} as well as any hand held load M_{pg}. This moment is countered by the exoskeleton supporting force F applied a distance L from the hip joint. If the center of gravity location is held constant this torque follows a sinusoidal torque profile as the moment arm increases and then decreases with increasing values of α. As the mass of the upper body is quite large, the trunk supporting exoskeleton generates a substantial supporting force F to adequately relieve the lower back. Just as with the other devices it is important that the hip torque generator axis of rotation be closely aligned with the biological axis of persons hip. The details of the trunk support torque are explained further in [61].

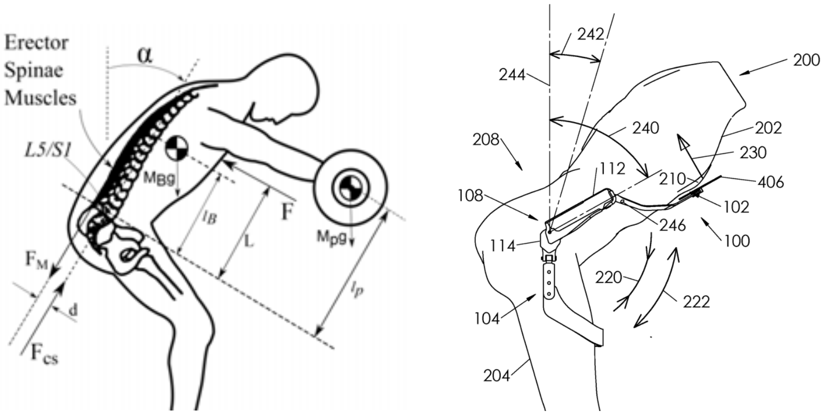


Figure 98. Trunk Supporting Exoskeleton Supporting Force. [61]

TRUNK SUPPORTING FRAME

The trunk supporting frame facilitates similar requirements of load transfer, coupling, adjustability and movement described in the shoulder supporting exoskeleton torso frame, as each are located at similar points on the body. The main differences are that the trunk supporting torso frame must withstand the substantial hip supporting torque in the sagittal plane and maintain alignment of the hip torque generator. For the torso frame to work for both the shoulder supporting exoskeleton and the trunk supporting exoskeleton the properties of each must be taken into consideration.

Load transfer

Rather than support a vertical load and changing moment as with the shoulder support exoskeleton, the primary purpose of the trunk supporting frame is to apply a constant supporting force to the operator's chest. The maximum loading condition occurs when the persons torso is parallel to the ground, and thus has the greatest moment about the hips. The only vertical loads to be supported are due to the weight of the exoskeleton when the person is standing upright. To properly transmit this load between the hip and the chest the exoskeleton spine must be made substantially more rigid in the sagittal plane than when considering the shoulder supporting exoskeleton alone. Thigh links inferior to the hip torque generator must also be added to transfer reaction forces from the chest support to the user's thighs.

Coupling

The trunk supporting exoskeleton coupling mechanisms also have a few key differences when compared to the shoulder supporting exoskeleton due to the load transfer requirements and actuator alignment. Figure 99a shows a trunk supporting exoskeleton coupling mechanism 500. Because the supporting force is oriented perpendicular to the chest a strong anterior-posterior coupling is needed. While this can also be achieved with a shoulder strap, a chest strap 506 provides the optimal force vector. To maintain proper torque generation vertical alignment of the hip torque generator must also be maintained. A set of suspender straps 504 are used to prevent lowering of the hip actuator and thigh straps 508 to prevent motion in the upward direction. This strap configuration of suspender straps and chest strap is roughly equivalent to the shoulder straps, as described above, and each configuration may be used for either the shoulder supporting or trunk supporting exoskeleton shoulder coupling. Figure 99b shows the back-supporting exoskeleton 302 and shoulder supporting exoskeleton 100 combination with associated coupling mechanisms of thigh straps 119, belt 116, shoulder straps 120.

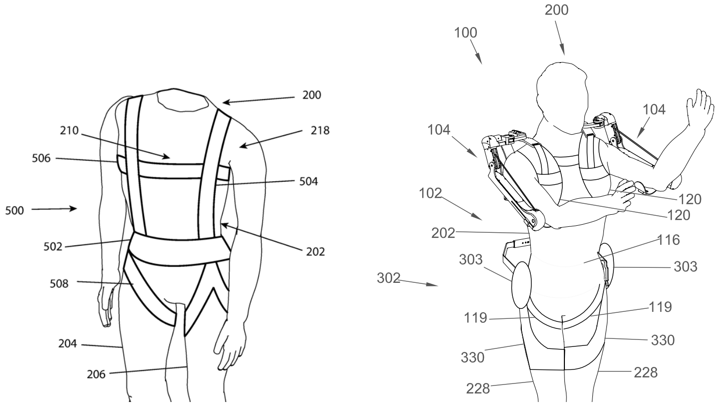


Figure 99. Trunk Supporting Exoskeleton Coupling Mechanism alone [61] (a) with shoulder exoskeleton (b).

Movement and Adjustment

Motions of lateral spinal flexion and twisting are equivalent to those of the shoulder supporting exoskeleton torso frame as described above. Similarly, adjustment for torso dimensions are equivalent, with the only addition being the length of the thigh link to accommodate leg length of the user.

As the trunk supporting exoskeleton crosses the hip and attaches to the thigh, movements associated with the hip must be accommodated for in the device hardware. The hip flexion/extension axis 331 is supported by the hip actuator and must be aligned both vertically and horizontally in the sagittal plane for proper torque generation and elimination of relative movement between the frame and the persons torso and thighs. A free joint provides ab/adduction of the hip, the axis of rotation 332 located laterally to the biological hip. Finally, internal/external rotation is allowed via relative movement between the thigh and thigh link, just as with internal/external rotation of the shoulder in the arm supporting exoskeleton.

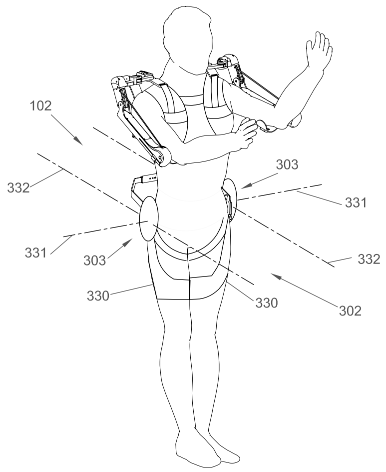


Figure 100. Back supporting exoskeleton axes of rotation.

Attachment and donning

Due to the similarity of the torso frame requirements between the shoulder supporting exoskeleton and the trunk supporting exoskeleton, the construction between the hips and shoulder frame can be identical provided the load transfer requirements are met for each. Figure 101 shows four methods of combining the trunk support and shoulder support exoskeletons. For all, the function of shoulder straps and combination of the chest strap and suspender straps are interchangeable. In Figure 101a a portion of the shoulder supporting exoskeleton torso frame 102 is added to an already worn rear frame trunk supporting exoskeleton 302 at shoulder mounting point 334. The arm link mechanisms can then be added to complete the assembly. Figure 101b shows an alternate attachment method that starts with the donned shoulder supporting exoskeleton 100. A set of hip torque generators 303, thigh links 330, and thigh straps are added to the shoulder supporting torso frame 102 at hip actuator mounting point 333. Once combined, either of the two configurations may be donned similar to the shoulder supporting torso frame as shown in Figure 101c. For Figure 101a-c the back frame functions to support the load from both the shoulder and back supporting exoskeleton. Finally, a front frame trunk supporting exoskeleton 302 may be attached to the shoulder supporting exoskeleton 100 at hip actuator mounting points 333 on torso frame 102, as shown in Figure 101d. Here each exoskeleton frame may be specific to the loads of its respective device. Hip actuator mounting points 333 may also be located on belt 116.

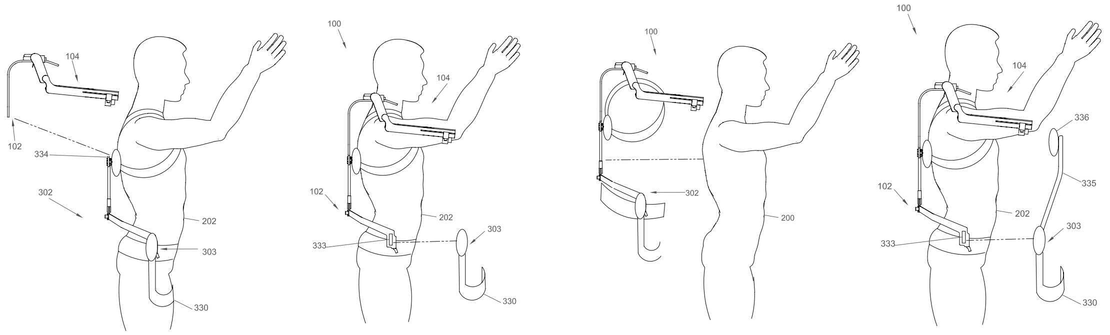


Figure 101. Attachment methods between trunk and shoulder supporting exoskeletons.

USE AND BENEFIT

Use of the shoulder-trunk exoskeleton combination is not as straightforward as that of the neck-shoulder. The torque generation strategy of the shoulder supporting exoskeleton relies on a vertical spine, while the trunk support exoskeleton generates torque only when the spine is bent. Therefore primary two use cases of the combination are when A) repeated stooping and shoulder elevation are interspersed for a task or when B) a maintained stooped posture is required with the addition of a horizontal push.

In the case of interspersed shoulder elevation and stooping the shoulder and hip torque generator benefits are alternating. A common example is moving an object from a low elevation to a high one, or visa versa, as shown in Figure 102. As a worker bends down to get a box from the floor, as shown in Figure 102a, back support is given by the back supporting exoskeleton, with the added benefit of the shoulder frames preventing excessive spinal flexion or shoulder protraction. When the back is stooped the spine deviates from horizontal and the shoulder actuator pushes the arms forward rather than up. For stooped lifts the operator's arms must either fight the shoulder torque generator or the shoulder supporting exoskeleton must be turned off. As the user straightens and begins to lift the box above hip level the shoulder support exoskeleton begins applying assistive forces to the upper arm throughout the remainder of the lift, as in Figure 102b. Many tasks involve this interspersed motion, common in construction, manufacturing and logistics.

Figure 102. Low to High back-shoulder use case

The second use case of the trunk-shoulder support combination occurs when a worker is stooping and applying a horizontal force with the arms. Figure 103 shows an operator using a saw near ground level. The sustained forward bending is supported by the back support exoskeleton and the shoulder supporting torque, rather than supporting gravitational forces, are used to push the arms horizontally into the cut. Other examples of this posture can be found in drilling, painting, and welding.

Figure 103. Sustained Stoop With Horizontal Push back-shoulder use case

LEG SUPPORTING EXOSKELETON

As mentioned, the knee is a primary location of occupational injury [1] [62] and often associated with squatting and general floor level work [63]. Many occupations involve postures that create risk of injury both at the shoulders and the knees. Using the shoulder supporting exoskeleton with a leg supporting exoskeleton can serve to both accommodate a greater range of postures and transport the reaction forces and torques from the arms all the way to the ground. Figure 104 shows a leg supporting exoskeleton also developed in the Human Engineering and Robotics Lab to support the lower back during sustained or repetitive stooping. [64]

The Leg supporting exoskeleton 100 has a first link 102, rotating about a second link 104 at a knee joint 106. First link 102 is coupled to persons thigh 204 at with brace 100, and second link 104 to persons shank 206. A force generator 108 creates a torque between about knee joint 106 in a motion of extension. Reaction forces are applied by braces 110 at persons thigh 204 and shank 206. A foot mechanism 183 comprising an ankle link 180 and foot connector 184 may also be connected to the leg supporting exoskeleton 100 to transfer the weight of the system and reaction forces to the ground.

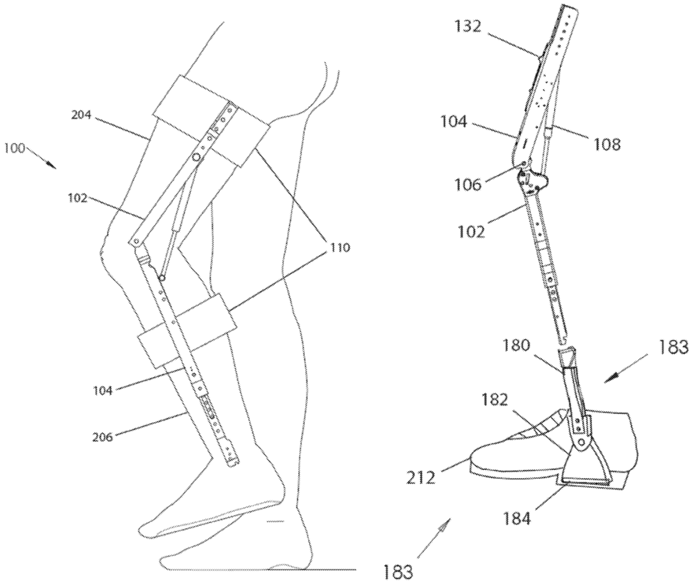


Figure 104. Leg supporting exoskeleton construction. [64]

KNEE TORQUE GENERATION

The leg supporting exoskeleton generates a torque that counters the mass of the upper body about the knee joint while in a squatting posture. As shown in Figure 105, a moment is created about the knees as the ankle, knee, and hip joints flex and the body's center of mass is lowered. Shifting ones weight and adjusting posture can shift a substantial torque between the leg's. The leg supporting exoskeleton creates a supporting force F at the thighs with reaction forces F1 and F2 applied to the shank and the ground. Furthermore, the device is designed to recognize the differences between squatting and similar leg motions involved in walking, ascending and descending stairs, to only apply torque when needed. The leg supporting exoskeleton torque profile and method of generation are similar to the trunk support exoskeleton above and are described in more detail in [64].

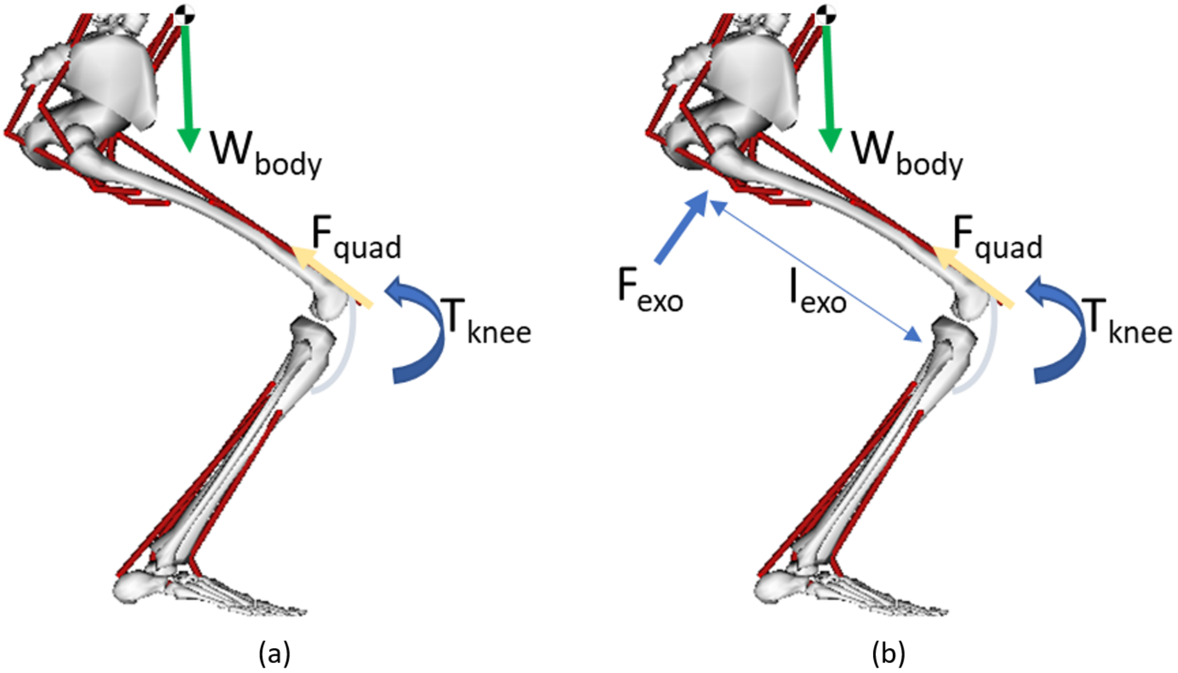


Figure 105. Leg Exoskeleton Operational Priciniple.

KNEE EXOSKELETON FRAME

As the leg supporting exoskeleton hardware is located inferior to the hips and the shoulder supporting exoskeleton superior their respective frames share little in common. In terms of load no structural similarity between the devices exists but they do share a coupling mechanism at the hips and shoulders. To transfer reaction forces and torques between the two an adapter must be used to add a hip rotational degree of freedom, the hip supporting torque generator may also serve as this adapter. Adjustment, attachment, and use all vary slightly depending whether or not or the adapter is present.

Load transfer

The leg supporting exoskeleton creates a “chair” under the operator as it applies supportive torque to the thigh link. With the addition of a hip adapter load can be transferred between the shoulder exoskeleton hip belt to the proximal end of the thigh link. However, the leg support exoskeleton is only designed to transfer load between the thigh and the shank during squatting, allowing free motion at all other times to prevent inhibition of movement. Because of this the vertical load from the arm supporting exoskeleton may only be brought to the ground either when the legs are straight, or the knee actuators are active. Figure X shows a figure of reaction forces 214 and torques 215 from the arm supporting exoskeleton 100 being transferred through the leg supporting exoskeleton 304, resulting in ground reaction forces 311. Here the shoulder frame pivots about the hip joint in the sagittal plane, with reaction forces at the rear of the spine frame comfortably countering the moment. Connection with the leg supporting exoskeleton does not effect loading conditions on the shoulder frame- as it reflects the hip centered loading case described in chapter 2. During walking an unsupported squatting, the shoulder supporting exoskeleton loads the hips and shoulders as described above.

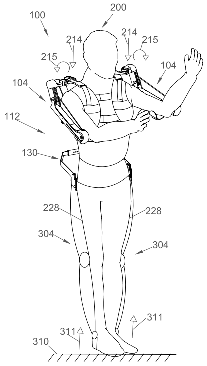


Figure 106. Load transfer between Shoulder ang Leg Exoskeleton.

Coupling

The leg coupling mechanisms act to keep the leg supporting exoskeleton aligned with the persons thigh and shank during load transfer and motion. A connection to the ground orients the height and location of the ankle joint, about which the rotation of the shank is tied to the lower link with a shin coupling brace. A thigh brace or a butt strap similarly constrains the thigh link to the upper leg. To prevent the leg supporting exoskeleton from sagging on the person a belt or suspender straps may be used. When connecting the leg supporting exoskeleton to the shoulder supporting exoskeleton, the former can replace these straps to prevent the device from sagging. Figure 107 shows the leg supporting exoskeleton human coupling with and without the shoulder supporting exoskeleton. In Figure 107a the leg supporting exoskeleton is worn alone. A thigh coupler 345 shank coupler 346 and foot coupler 348 attach thigh link 340, shank link 341, and ground link 342 to persons thigh 228, shank 229, and foot respectively. Too keep the exoskeleton from falling on the person a belt 116 and suspender straps 115 may also be worn, with a support strap 347 attaching thigh link 340 to belt 116. Figure 107b shows a soft coupling between shoulder supporting exoskeleton 100 and leg supporting exoskeleton 304, in which reaction forces from the arm support are not transferred to the ground. Here, belt 116 and suspender straps 115 are replaced with the belt 116 and shoulder straps 120 from arm supporting exoskeleton 100. Figure 107c shows the arm supporting exoskeleton and leg supporting exoskeleton combined with a mechanical adapter 370, allowing reaction forces to be transferred to the ground. With adapter 370 leg support strap 347 is no longer needed.

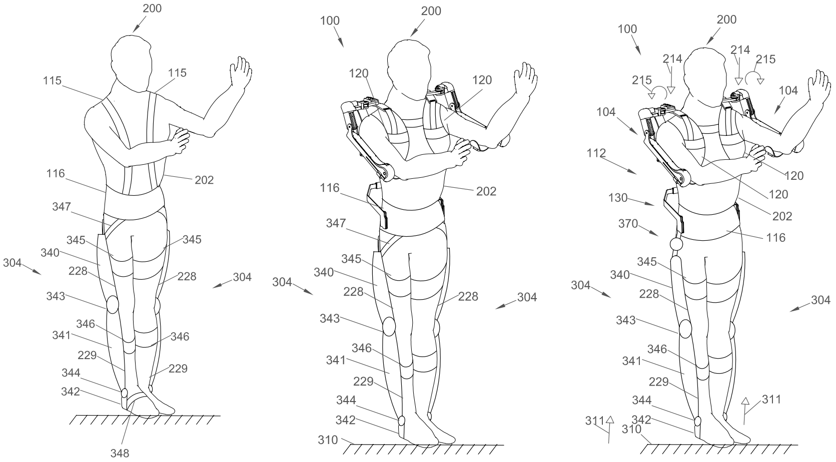


Figure 107. Coupling mechanisms of (a) leg exoskeleton only (b) leg-shoulder soft (c) leg shoulder mechanical.

Movement & adjustment

As the two devices share no hardware, there is little interaction of movement and adjustment between the devices. When the hip adapter is not present, the textile interface between the shoulder and leg exoskeletons allows free motion between the two for all hip degrees of freedom. The shoulder supporting exoskeleton adjusts as described in chapter 2 while the legs adjust in shank and thigh length to best center the knee joint. With the adapter present the femur length and spine height must be tuned to also align the hip joint in the flexion/extension and abduction axis similar to the method of the trunk supporting exoskeleton. The adapter additionally contains an internal/external rotation axis located lateral to the biological hip. Regardless of if the hip adapter is present, the tibia of the leg supporting exoskeleton must be adjusted to vertically align the knee in the sagittal plane.

Figure 108 shows the knee and hip axes of rotation of the leg-shoulder exoskeleton as a whole and the hip degrees of freedom within the adapter. In Figure 108a, the knee rotational axis 305 of leg supporting exoskeleton 304 is roughly aligned with the persons knee. Adapter first rotational axis 371 provides for flexion/extension of the hip and is aligned in the sagittal plane. Adapter second rotational axis 372 allows for abduction/adduction and is located laterally to the persons hip in the coronal plane. Adapter third rotational axis 373 is in line with the thigh link 340 of leg supporting exoskeleton 304 and allows for internal external rotation of the leg. Figure 108b shows these axes of rotation on adapter 370 between first link 375 coupled to torso frame 102 and second link 376 coupled to thigh link 340. Adapter further comprises a third link 377 and a fourth link 378 to provide proper motion and may contain an additional firth link to provide a translational degree of freedom 374 to accommodate for the misalignment of second rotational axis with persons hip. In the current hardware second link 376 and fourth link 178 are part of the leg exoskeleton to facilitate the leg-back exoskeleton combination. In this case the pin that forms adaptor second rotational axis forms as the connection point between the adapter and the leg supporting exoskeleton. While it is most efficient for the shoulder-leg adapter to remove as many components of the standalone systems as possible, any of the adapter axes of rotation or links may be incorporated into the shoulder or leg exoskeleton standard hardware. If fully integrated the function of the adapter can be integrated into the shoulder or leg exoskeletons, or a combination of each. Additionally, the rotational or translational directions of adapter 370 may be spring loaded or hard stopped to provide assistance to or limit certain motions.

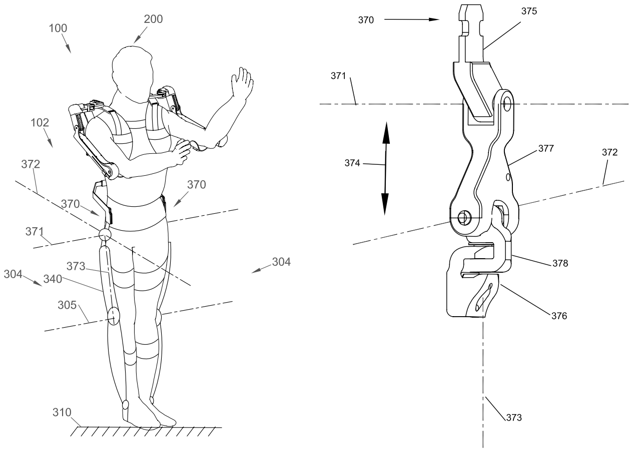


Figure 108. Axes of rotation for shoulder-leg system (a) and adapter (b).

Attachment and Donning

The hardware configuration and coupling requirements allows the shoulder-leg exoskeleton system to be truly modular in attachment. The system is similarly donned without the adapter 370 as in Figure 109 above and with the adapter as in Figure 110 below. Either the legs 304 can be attached to a donned shoulder 100 system, the shoulders attached to a donned leg system, or the whole suit put on at once. For the leg to shoulder coupling without the adapter, the leg coupling point 349 on support straps 247 is added to the belt 116 first. For the shoulder to leg coupling, shoulder attachment points 339 may first be put on the belt 116 of the leg supporting system. With the adapter 370, the leg to shoulder coupling no longer needs the support straps 347, as their function is equivalent aside from the added load transfer of the adapter and are joined at an adapter-shoulder coupling point 380. To couple the shoulders and adapter to leg system two connections are needed at the adapter-leg coupling point 381 as well as the shoulder attachment point 339 on belt 116. The adapter can finally be added to a previously donned shoulder-leg soft connection system through adapter-shoulder coupling 380 and adapter leg coupling 381.

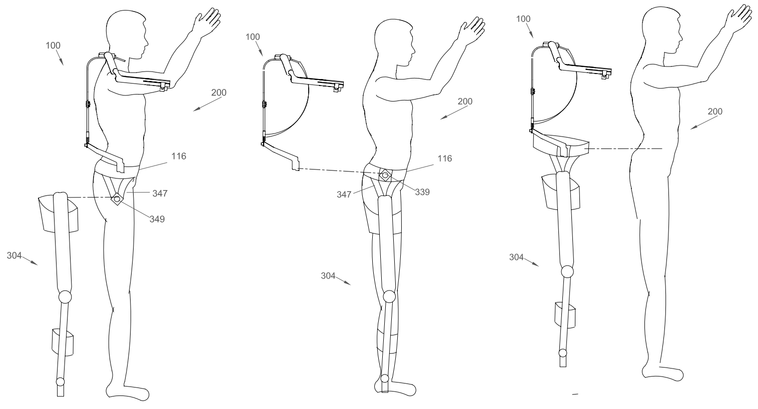


Figure 109. Shoulder Exoskeleton- Leg Exoskeleton soft coupling combinations

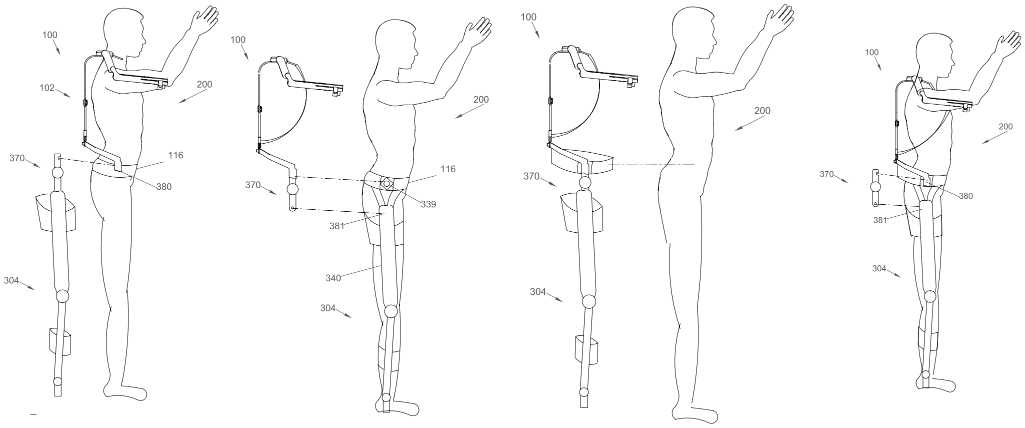


Figure 110. Shoulder exoskeleton- leg exoskeleton adapter coupling combinations.

Use Cases

Situations occur when a worker needs to squat and elevate the arms, such as working under low ceilings, torso level tasks that require eye-level visual feedback, table level assembly tasks where a stool or chair is not feasible, or when load transfer from the arms to the ground during normal shoulder support use are desired.

Many common ceiling-level tasks also occur for low hanging ceilings, requiring the operator to both squat to fit in the give space as well as then work overhead. Examples of this are in shipbuilding, aviation construction, hydraulic press jig replacement, and large appliance manufacture. Here the operator squats to get to the proper high to fit in the workspace and is supported by the leg supporting exoskeleton. Overhead work can then be conducted normally in accordance with normal shoulder exoskeleton support. At some levels the operator may have to lean forward slightly to maintain the center of mass over the base of support, deviating the spine from vertical. In these cases the shoulder gravitational offset can be adjusted to properly support the task.

Figure 111. Low Ceiling Work with shoulder-leg system.

A parallel to standard chest to head level work's strain on the shoulders when standing upright is low to mid-level tasks that require the operator to squat for visual observation. Many assembly tasks, electrical panel work, and precision welds require this posture. Again, the proper task height is set by the supported squat of the leg supporting exoskeleton. The arms are then offset according to the average tilt of the spine and work continued as normal.

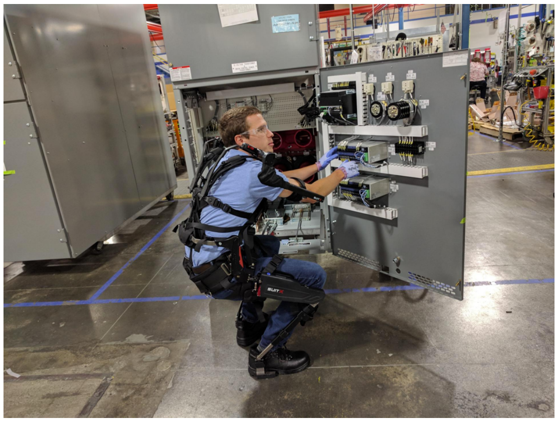


Figure 112. Squatted Eye Level work with shoulder-leg system.

For each of the above task types the leg supporting exoskeleton is engaged and thus some of the reaction forces and torques from the arm supporting exoskeleton travel through the frame, when the adapter is attached, and to the ground. For a third category of tasks the leg supporting exoskeleton can be worn solely to support these reaction forces and torques while standing straight. This category of tasks are the same as discussed for the shoulder supporting exoskeleton. A key point here is that the legs must be straight to transfer force to the ground, or else the knee joint will simply collapse, and the hip belt will be loaded instead.

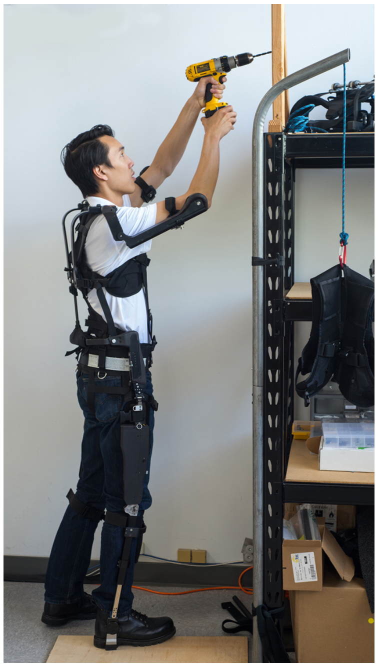


Figure 113. General load transfer during overhead work with shoulder-leg system.

FULL SYSTEM COMBINATIONS

In some situations support is desired from 3 or more of the exoskeleton modules. The neck and back can be attached to the shoulder as described above, and the leg can be attached to the back in place of the thigh links though a mechanism equivalent to the leg-adapter connection. The resultant system comprises supported flexion of the knee, hips, and shoulders, and supported extension or flexion of the neck. A total of 2 DOF at the ankle, 1 at the knee, 3 at the hips, 2 at the spine, 3 at the shoulder, and 1 at the neck provided minimum inhibition of common workplace postures while providing the needed support. Figure 114, Figure 115, and Figure 116 shows the combinations of the shoulder-back-leg exoskeleton system. The neck system requires the shoulder and is attached in the same manner as above in each instance.

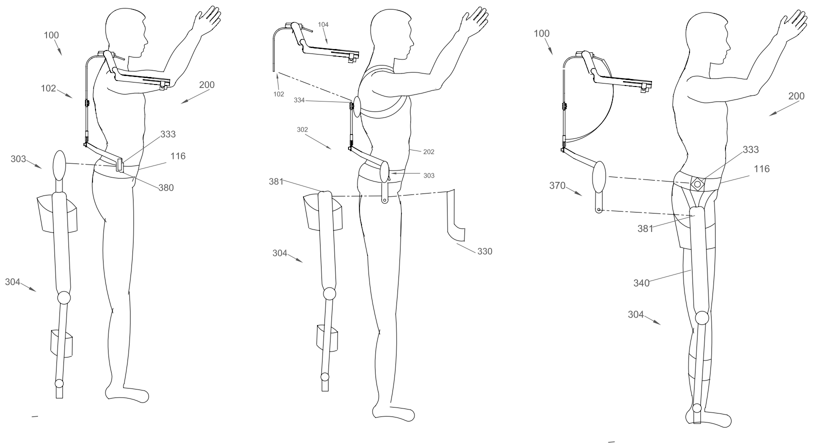


Figure 114. Shoulder-torso-leg system combination if single system donned.

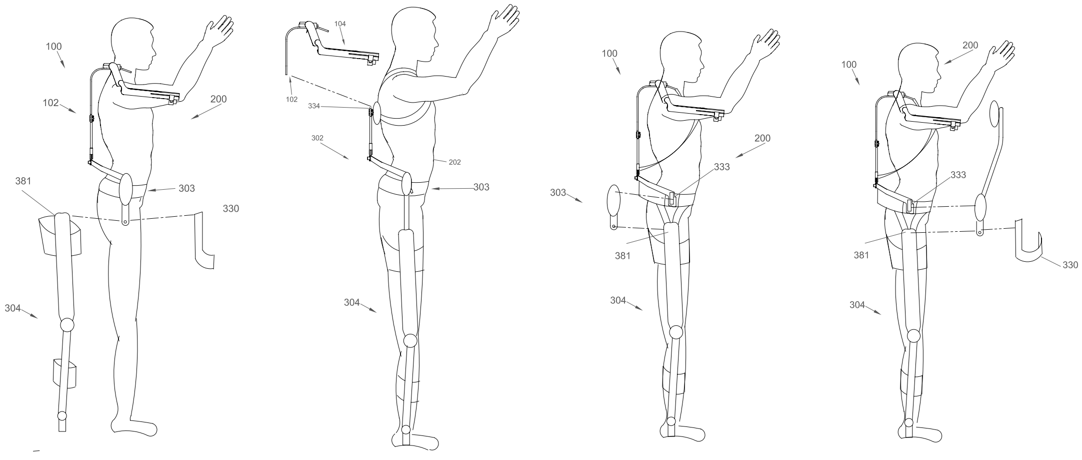


Figure 115. Shoulder-torso-leg system combination- adding 3rd device if two donned.

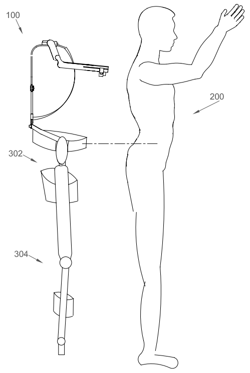


Figure 116. shoulder-torso-leg system combination.

Few single tasks require all modes of support to be provided at once. The most valuable use for all four modules instead are varied tasks with individual components that require support from at least one of the devices in repetitive succession. Use cases for 3 module combinations include extreme cases of those previously described. The neck-shoulder-leg combination may be used for low ceiling work where the neck is extended. The shoulder-back-leg combination may be used for visually driven work at very low levels as described in the leg section or floor level work as described in the back section. The shoulder-back-leg combination may also be useful in material handling where low-mid and high-level reaches are repetitively done.

Figure 117. Shoulder-Trunk-Leg Exoskeleton System.

CHAPTER 5: ERGONOMIC EVALUATION

Many tasks increase the risk of work related musculoskeletal disorders (WMSDs) to industrial workers. Exoskeleton technology has the potential to reduce exposure to heavy exertion forces from overhead work thereby reducing risk of WMSDs. **Methods:** An arm supporting exoskeleton with adjustable, angle dependent torque was evaluated on bilateral muscle activation (upper trapezius, anterior deltoid, posterior deltoid, biceps, triceps, flexor digitorum, latissimus dorsi, and infraspinatus) during static and dynamic overhead tasks (N=14) while using light (1 lb) and medium (5 lb) weight tools to understand the effect of varying exoskeleton support levels (0, 75, 115, 177lb-in peak torque). Muscle activity was measured using surface electromyography and normalized to maximum voluntary contraction (MVC). Self reported feedback was gathered on exertion, preference, comfort, and usability. **Results:** During static and dynamic tasks with heavy and light tools, muscle activity of bilateral UT, AD were reduced with increasing amounts of arm support from the exoskeleton ($p<0.05$). Muscle activity of PD, B, IF were reduced significantly for some settings of the exoskeleton. Activity of the triceps increased significantly for only the highest support setting and no significant changes were found in the FD and LD. Subjects unanimously preferred use of the exoskeleton, although individual preference between support settings varied. **Conclusion:** Arm support exoskeletons can reduce muscle activity in overhead static and dynamic work having important implications for the possible reduction of risk for shoulder WMSDs.

BACKGROUND

In 2011, the shoulder was involved in 13% of all work related musculoskeletal disorder (WMSD) cases reported in the United States and the average amount of missed time due to a shoulder WMSD was 23 lost workdays [62]. Risk factors contributing to upper extremity WMSDs include repetition, force, awkward posture, and vibration. Overhead work, defined as working at or above the shoulder, has been identified as a category of tasks with especially high risk of WMSDs [4]. If sustained for one hour, the onset of shoulder muscular fatigue may begin at EMG levels as low as 5% of maximum voluntary contraction (MVC) [30]. It has been shown that impaired circulation occurs at 10-20% MVC, which further serves to increase fatigue [31]. To mitigate risk of injury, the load lifted must be reduced, the duration of the task reduced, and/or the amount of rest breaks increased [36].

The shoulder contains a network of muscles responsible for both articulating and stabilizing the joint. In part, the shoulder's wide range of motion is due to the fact that there are no bony hard-stops to impede movement, all actions of the shoulder are limited by muscular and ligamentous structures. [13] The muscles of the shoulder complex must continually work in an agonist-antagonist configuration to stabilize the joint and ensure that no dislocation occurs as a result of the desired movements. Given intricacy of shoulder complex, muscles may span many joints and depending on position of the upper extremity, its relationship with regard to any one articulation may change thus altering its effect on that joint and the resultant forces or moments produced. [55]

Exoskeleton technology has the potential to reduce exposure to heavy exertion forces thereby reducing risk of WMSDs. Prior studies have evaluated the torque effects of upper limb exoskeletons in the automotive industry [21] [22] and the productivity impact from a shoulder support exoskeleton in the welding/painting industries [23].

However, many questions about the application of shoulder exoskeletons remain. For example, although the assistive torque effect has been studied, the effect on antagonist muscles has not been widely studied. Additionally, differences in the application of arm supporting exoskeletons to different types of tasks, such as static overhead versus dynamic overhead tasks, is not known. Finally, the amount of torque assistance that is optimal for varying sized workers and tasks is not well understood.

To address this gap, an arm supporting exoskeleton device was developed to support the shoulder muscles during tasks that require repetitive or sustained arm elevation. The exoskeleton provides an adjustable, angle dependent torque to the operator's upper arm to counteract the forces of gravity due to the weight of the arm and tool. The purpose of this study is to evaluate the impact of various assistive support (torque) settings of the exoskeleton on muscle activation for both static and dynamic tasks with light and medium weight

METHODS

PARTICIPANTS

Fourteen male subjects with past experience in construction or manufacturing industries were recruited for participation in this within subject intervention study of cross over design. All subjects were right handed with average age 37(13) yrs. average weight 179(32) lbs. and average height 72(3) in. Subjects reported an average of 11 (10) hours of overhead work a week with post-work soreness occurring 44 (23) percent of the time at the shoulders 30 (18) percent of the time at the neck and 35 (22) percent of the time at the back. The subjects provided informed consent, approved by the investigational review boards of the University of California, Berkeley.

MEASURES

Procedures

Fourteen subjects were studied while performing overhead tasks. The task height was set according to subject height so that while performing the task each subject's dominant arm was at 90 degrees of shoulder flexion and 90 degrees of elbow flexion. A static task consisted of tracing a series of lines with a tool, and a dynamic task consisted of inserting and removing a series of screws with a drill. For each task type, subjects used both a light weight (1 lb.) tool and a medium weight (5 lb.) tool. Subjects completed two 30 second trials for each combination of task type and tool weight under conditions of no support, low support (75 lb-in peak torque), medium support (115 lb-in peak torque) and high support (177 lb-in peak torque) provided by the arm supporting exoskeleton for a total of 16 conditions. Task type and support level were randomized, the light tool always being used first to minimize fatigue. For the no support setting subjects continued to wear the exoskeleton torso frame with the shoulder supporting arms removed. For the static task subjects were instructed to try and keep the forearm vertical to reduce moments about the shoulder in internal external rotation. For the dynamic task no instruction was given.

Figure 118. Experimental setup.

Outcome Variables

Subjects were instrumented with Noraxon mini DTS electrodes sampling at 1500Hz to record muscle activation of the upper trapezius (UT), anterior deltoid (AD), poster deltoid (PD), biceps (B), triceps (T), flexor digitorum (FD), infraspinatus (IF), and latissimus dorsi (LD) bilaterally. The EMG elecrodes were attached according to [65]. Prior to recording subjects completed standardized maximum voluntary contractions (MVCs) to normalize signals measured during the trials. The MVC testing procedure performed is described by [66].

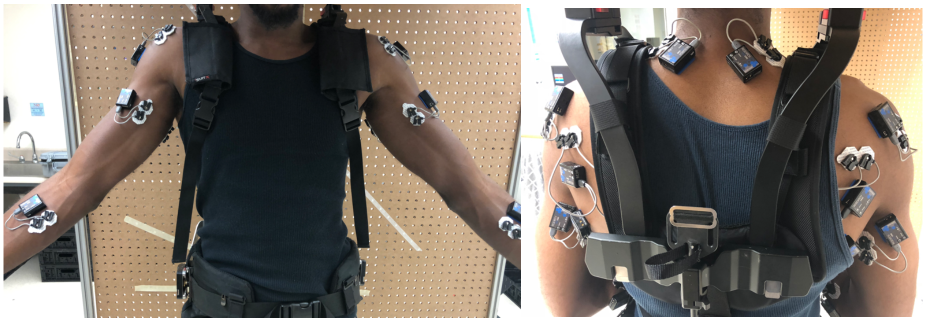


Figure 119. EMG electrode placements.

After each experimental condition subjects self-reported exertion (Borg CR 10) at the neck, back, front musculature of the shoulder, back musculature of the shoulder, and arm bilaterally.

After each set of task-tool combinations subjects reported their order of preference between no device, low support setting, medium support setting, and high support setting. They additionally rated their perceived comfort of the device contact points under the arms, across the shoulders, and along the hips.

After each task type subjects completed a usability survey to assess their views of the device and its practicality in the workplace with both numerically rated and short answer questions.

Data Analysis

Electromyography data was rectified, smoothed with a root mean square algorithm with a 100ms window, and normalized as a percentage of each subject's maximum voluntary contraction (MVC). Summary measures of each muscle were calculated for each trial and averaged across conditions. ADPF50 and ADPF90 force data was calculated to summarize the mean and peak forces each muscle was at or below 50% and 90% of the time. Summary measurements were compared between conditions by using repeated measures analysis of variance (Stata, College Station, TX) and the Tukey post-hoc test.

RESULTS

Data was analyzed to determine effects on outcome variables for support setting, task type, and load. Results are summarized for muscle activation, perceived exertion, preference, and usability.

MUSCLE ACTIVATION

Mean and peak muscle activity vs support level are shown in Figure 120 for each combination of task and tool type. Values are given for 13 of the subjects due to poor electrode adhesion for one subject. Generally, the trapezius and anterior deltoid are the most active muscles and the posterior deltoid, bicep, and triceps the least active. This is to be expected given the task posture places a moment primarily about the shoulder joint in the moment of extension for both dominant and non-dominant arms. Additionally, activation is increased in flexors for the dominant arm, as it is the one supporting the load. It should be noted that in use the exoskeleton right and left arms can be adjusted independently.

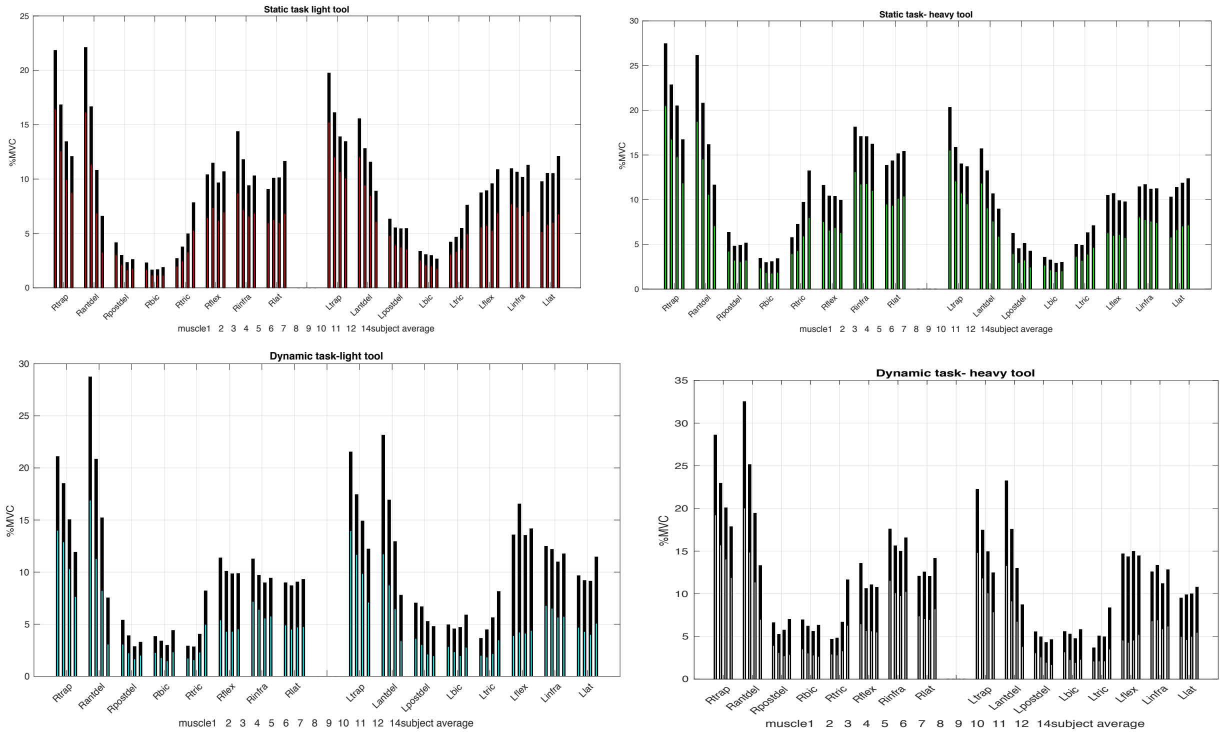


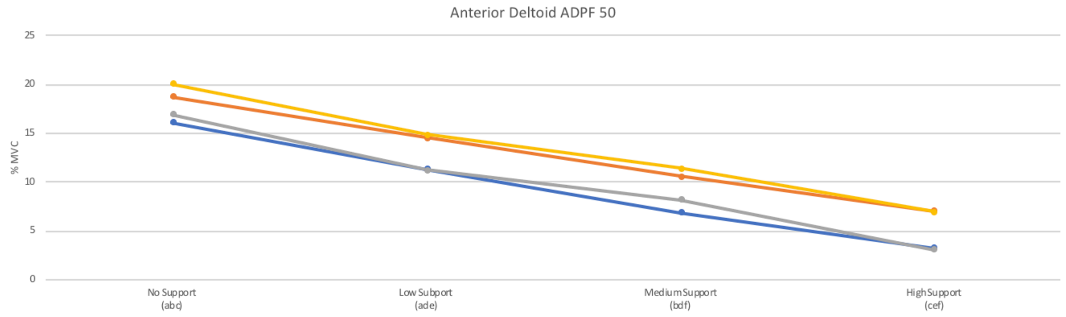
Figure 120. Average Mean (color) and Peak (black) Muscle activity by Task-Load.

Table 9 below shows the significant differences as indicated by the Tukey Post-Hoc test, the direction of the effect being represented in Figure 120. AD ant UT muscle activation is significantly different between each support condition bilaterally, with the exception of L UT peak activation between medium and high support settings. Significant differences in support setting are also found at the right and left posterior deltoid, biceps, triceps, and infraspinatus, and the left latissimus dorsi. No differences were found in the flexor digitorum. Task and tool type also affected muscle activation, indicating that the conditions were significantly different. The only interaction effect between support and task or tool occurred for peak anterior deltoid activation of the left arm between support and task.

P<0.05		Support 1=no 2=low 3=medium 4=high						task	tool	Interaction	
		2 vs 1	3 vs 1	4 vs 1	3 vs 2	4 vs 2	4 vs 3	2 vs 1	2 vs 1	support x task	support x tool
Right Arm	UT 50	x	x	x	x	x	x		x		
	UT 90	x	x	x	x	x	x		x		
	AD 50	x	x	x	x	x	x		x		
	AD 90	x	x	x	x	x	x	x	x		
	PD 50	x	x	x					x		
	PD 90	x	x	x				x	x		
	B 50	x	x	x				x	x		
	B 90							x	x		
	T 50			x		x	x	x	x		
	T 90		x	x		x	x	x	x		
	FD 50							x			
	FD 90										
	IF 50		x	x				x	x		
	IF 90		x						x		
	LD 50							x	x		
	LD 90							x	x		
Left Arm	UT 50	x	x	x	x	x	x	x			
	UT 90	x	x	x	x	x					
	AD 50	x	x	x	x	x	x				
	AD 90	x	x	x	x	x	x	x		x	
	PD 50		x	x				x	x		
	PD 90			x					x		
	B 50	x	x	x				x			
	B 90							x			
	T 50			x		x	x	x			
	T 90			x		x	x				
	FD 50							x			
	FD 90							x			
	IF 50		x					x			
	IF 90										
	LD 50			x				x	x		
	LD 90			x		x	x	x			

Table 9. Tukey Post-Hoc Signifiance Results.

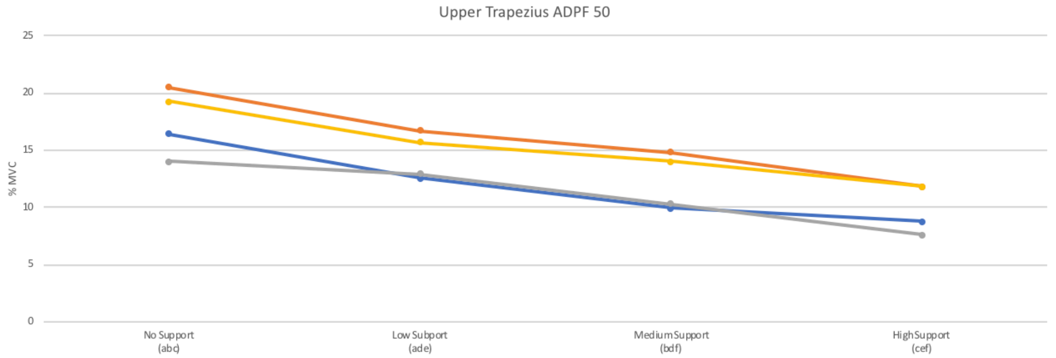
Across all conditions it can be seen that the most substantial effect for increasing support lies in anterior deltoid reduction. This effect occurs bilaterally, with the larger difference occurring in the right arm that is supporting the load of the tool. This is to be expected as the AD muscle is the primary shoulder flexor, the motion that is supported by the exoskeleton. Compared to the unsupported condition the right AD muscle decreases a substantial percentage under each condition as described in Figure 121 below. The activation pattern changes between the light and heavy tools, but not significantly between the static and dynamic tasks. A similar, although less substantial pattern can be seen for the non-dominant arm. For the static task the non-dominant arm was flexed at a greater angle of elevation to hold the tracing in palace, supporting only the load of the clipboard and paper. Subjects likely pushed the clipboard into the ceiling to some degree, although this was not measured. For the dynamic task the non-dominant arm was flexed to the same degree as the dominant arm to feed and retrieve screws from the ceiling, as well as to aid in drill placement.



Anterior Deltoid	% MVC no support	% reduction low support 75 lb-in	% reduction medium support 125 lb-in	% reduction high support 175 lb-in
Static Task- Light Tool	16.14	30%	57%	79%
Static Task- Heavy Tool	18.74	22%	43%	62%
Dynamic Task-Light Tool	16.90	33%	51%	81%
Dynamic Task-Heavy Tool	20.03	25%	43%	65%

Figure 121. Percent Reduction in Dominant Anterior Deltoid Activation Across Trials.

The second largest effect occurred at the upper trapezius muscle, responsible for elevating the scapula and is shown for the right arm in Figure 122. The upper trapezius activation reduced bilaterally for increasing levels of exoskeleton support and again is significant between all support conditions. The reduction is generally greater for the light verses the heavy tool as well as for the static compared to the dynamic task.



Anterior Deltoid	% MVC no support	% reduction low support 75lb-in	% reduction medium support 125 lb-in	% reduction high support 175 lb-in
Static Task- Light Tool	16.42	23%	39%	46%
Static Task- Heavy Tool	20.49	18%	27%	42%
Dynamic Task-Light Tool	14.01	8%	26%	45%
Dynamic Task-Heavy Tool	19.24	18%	27%	38%

Figure 122. Percent Reduction in Dominant Upper Trapezius Activation Across Trials.

Other effects occurred at the triceps and infraspinatus muscles as shown in Figure 123. An increasing pattern is shown in the triceps, with the high setting being significantly different from the no, low, and medium support condition. As an antagonist muscle, an increase in triceps activation may indicate that the support level is too high and the subject is actively fighting the device. Activation seems to be affected by both task type and tool weight. The infraspinatus activation may be an indicator of shoulder stabilization muscle activation. It decreases significantly between the no support and medium/high settings. For all except the static task-heavy tool, infraspinatus activation is least during the medium support setting, possibly indicating an ideal balance between agonist and antagonist muscle activation.

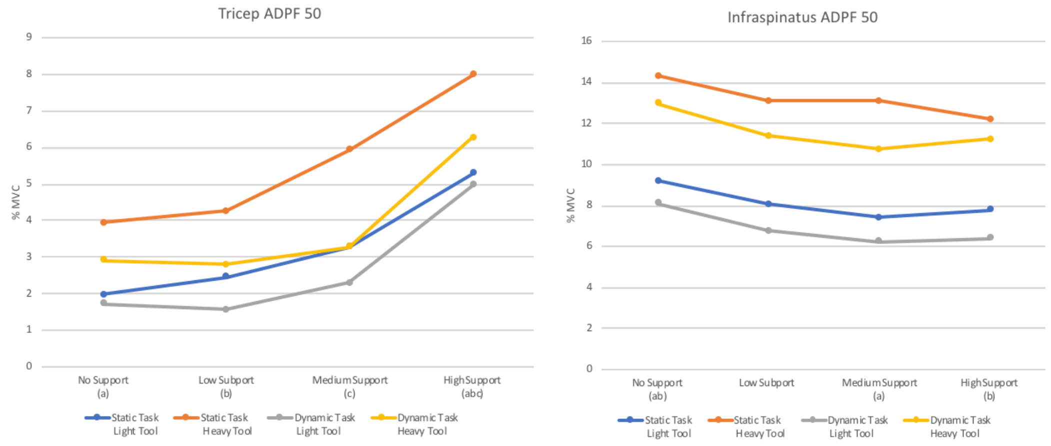


Figure 123. Dominant triceps (a) and infraspinatus (b) muscle actiation vs support setting.

PERCEIVED EXERTION

Subjects rating of perceived exertion after each condition is shown in Figure 124. Ratings are for seven subjects, due to data loss of the first seven. In general, subjects reported less fatigue for all exoskeleton support conditions relative to the no support condition. There was not much difference between exoskeleton support conditions. Subjects likely did not have enough strain to accurately report perceived exertion due to the short duration of each trial and the relatively light weights supported. The maximum exertion level was a 2 for the light weight and a 2/5 for the heavy weight. The greatest differences in perceived exertion occurred at the back, and the greatest overall differences were reported for the static task. The dynamic task was likely less fatiguing due to the repetitive movement facilitating greater blood flow.

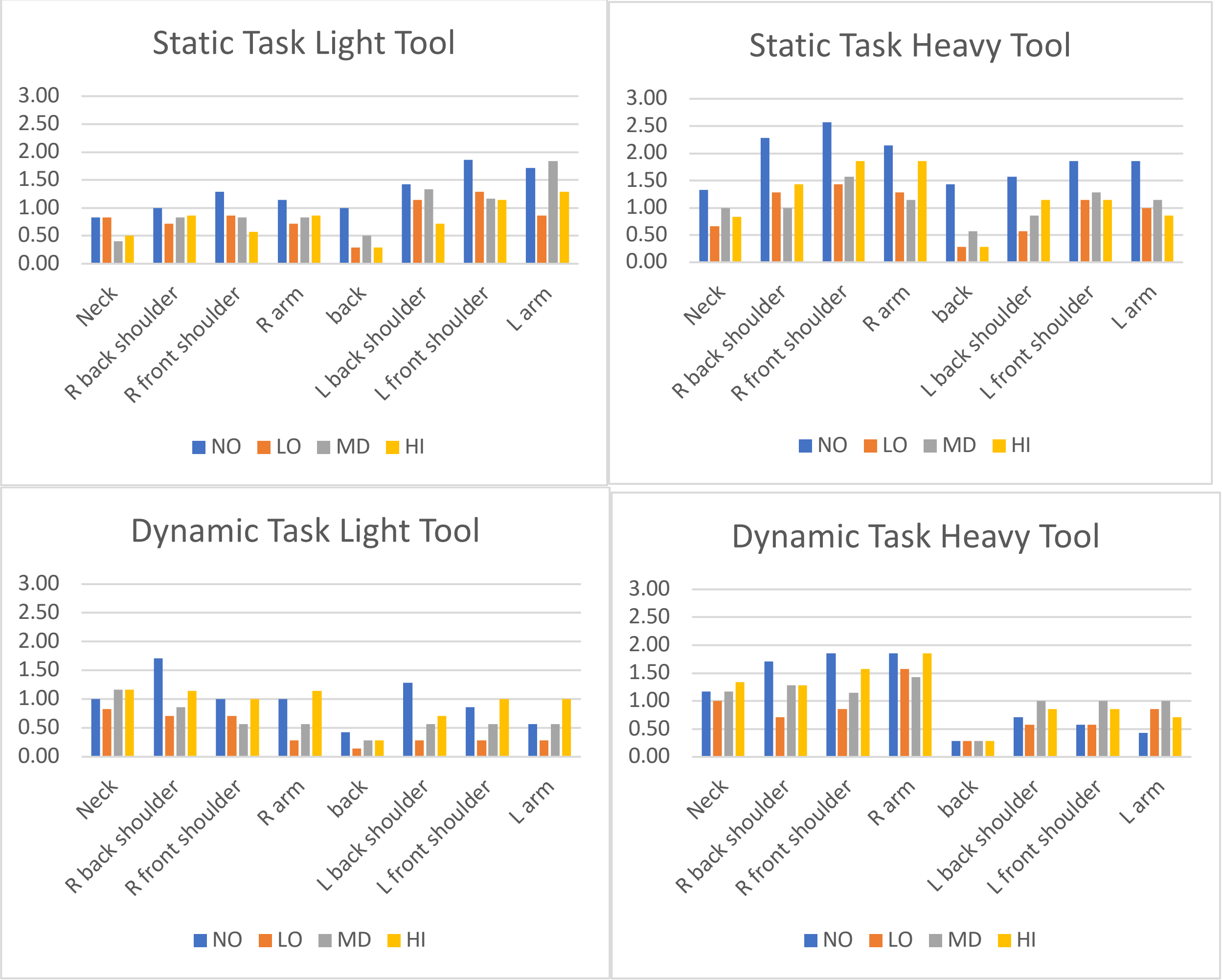


Figure 124. Perceived exertion ratings, Borg (CR-10), across all conditions.

PREFERENCE

After completing a set of support conditions for each tool and task, subjects identified their 1st, 2nd, 3rd, and 4th support preference between no device, low, medium, and high. A total of 31 preference surveys were recorded for 14 subjects, the results summarized in Table 10. Across all subjects and conditions the no support setting was the least preferred and medium setting most preferred. Low and high support fell in the upper and lower ranges of preference respectively.

TOTAL	No	Low	Medium	High
# 1st	0	6	21	4
# 2nd	7	17	3	4
# 3rd	9	8	6	8
# 4th	15	0	1	15

Table 10. Total Support Preference Results.

To examine differences between task and tool type the preference data is further broken down in Table 11. Between the static and dynamic tasks subjects prefer a higher support setting for the static condition. Similarly, a higher support setting is preferred for the heavy tool.

Static	No	Low	Medium	High
# 1st	0	3	12	3
# 2nd	4	10	1	3
# 3rd	6	5	4	3
# 4th	8	0	1	9

Dynamic	No	Low	Medium	High
# 1st	0	3	9	1
# 2nd	3	7	2	1
# 3rd	3	3	2	5
# 4th	7	0	0	6

Light	No	Low	Medium	High
# 1st	0	3	9	0
# 2nd	4	5	1	2
# 3rd	4	4	2	2
# 4th	4	0	0	8

Heavy	No	Low	Medium	High
# 1st	0	3	12	4
# 2nd	3	12	2	2
# 3rd	5	4	4	6
# 4th	11	0	1	7

Table 11. Preference Results by Task and Tool

Between individuals there was a high variance in preference, shown in Figure 125. Variance between individuals may affected by differences in fit, and be reduced given further exposure to the device.

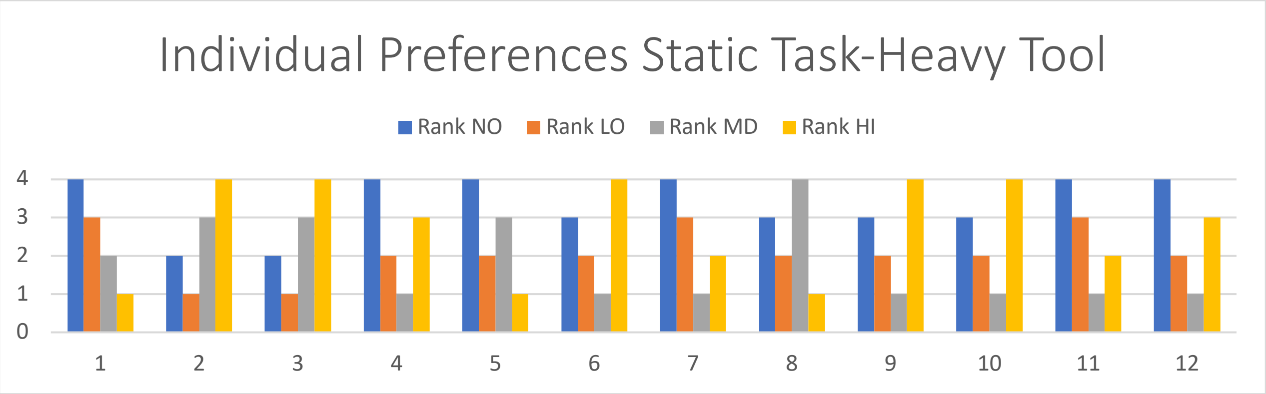


Figure 125. Individual Preferences (lower value= higher preference) for Static Task Heavy Tool Condition.

USABILITY

A usability survey was given after each task to assess the perception of the device and training it would require, its effectiveness for various subtasks and overall workmanship, and generally how it would be utilized in the workplace.

The overall perception of the exoskeleton and its ease of use are summarized in Figure 126 and Figure 127. Subjects were asked to rate the support, range of motion, ease of use, comfort, durability, and looks of the device on a 0-5 scale with 0 being poor, 3 neutral, and 5 excellent. Overall ratings were positive averaging between a 3 and 4. Subjects were also asked how much training they perceived would be needed for proper donning, sizing, adjusting support, performing the task, and doffing on a similar scale of 0 none to 5 extensive. Overall ratings were between a 1 and 2, with doffing being perceived as easiest at 1.1 and adjusting the size for a proper fit a most difficult at a 2.3.

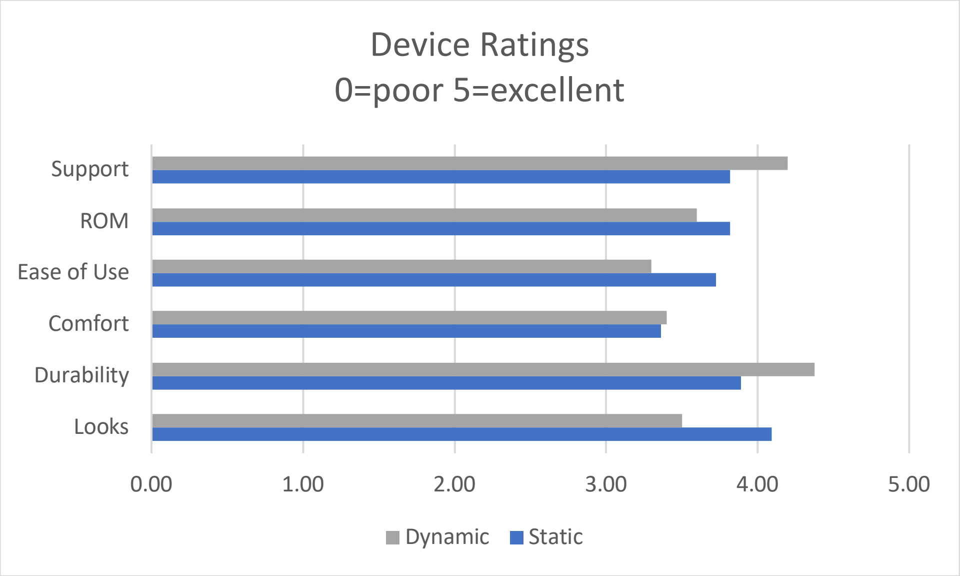


Figure 126. Overall Device Perception.

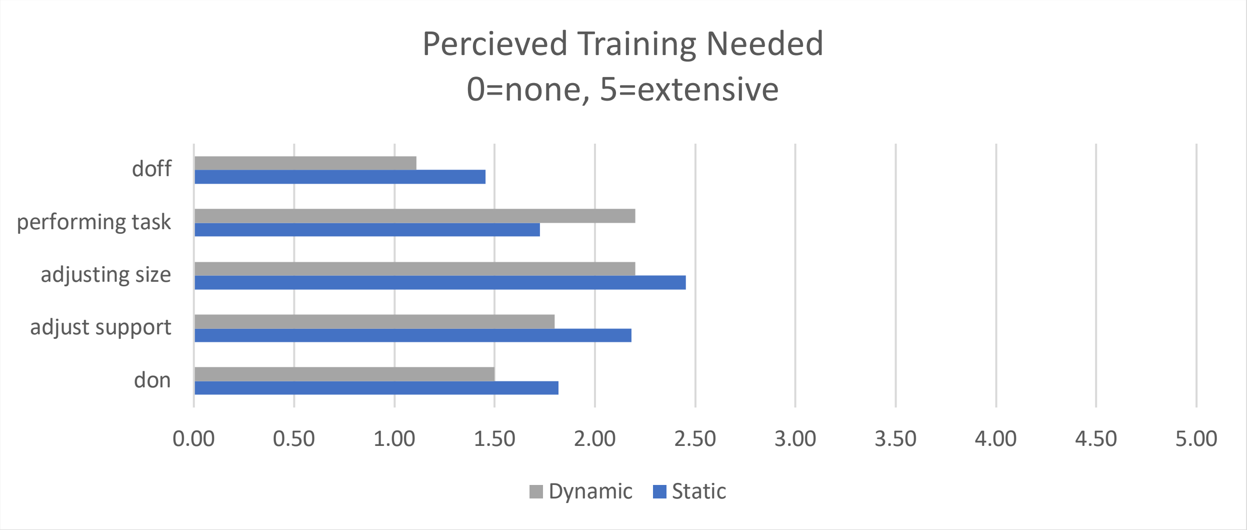


Figure 127. Percieved Training Needed.

Subjects were next asked to rate the effectiveness of the device for their work compared to the no support condition, as shown in Figure 128 and Figure 129. Effectiveness of the device on subtasks of dominant/non-dominant arm work, lowering the arm, repetitive movement, fine movement, holding the arm raised, raising the arm, and resting was rated on a 0 to 5 scale with 0 being poor, 3 neutral and 5 excellent. In general ratings were slightly better for the static task with the exception of non-dominant arm work. The device was perceived as best for raising the arm at 4.5 and holding the arm in a raised position at 4.4, and worst for fine movements at 2.5. In Figure 129 subjects rated how the device affected the duration, speed, and accuracy with which they could work compared to the no support condition 0 being worse, 3 the same, and 5 better. For both static and dynamic tasks subjects indicated an increase in the duration with no change in accuracy or speed. In the short answer section many subjects noted that after given time to get used to the device ratings would increase.

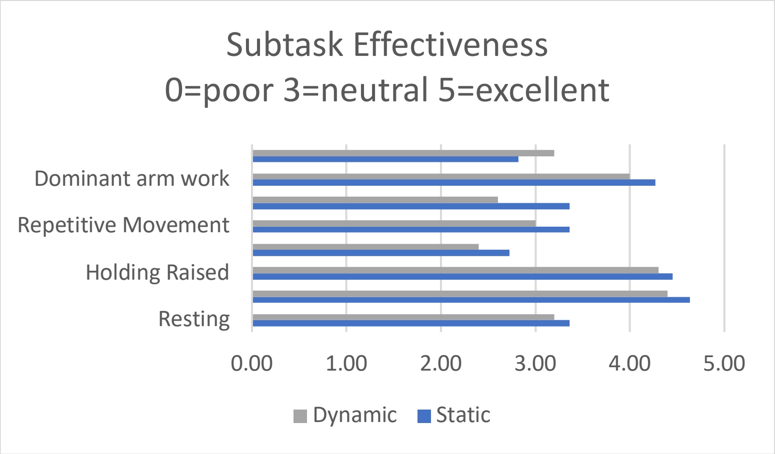


Figure 128. Subtask Effectiveness Ratings.

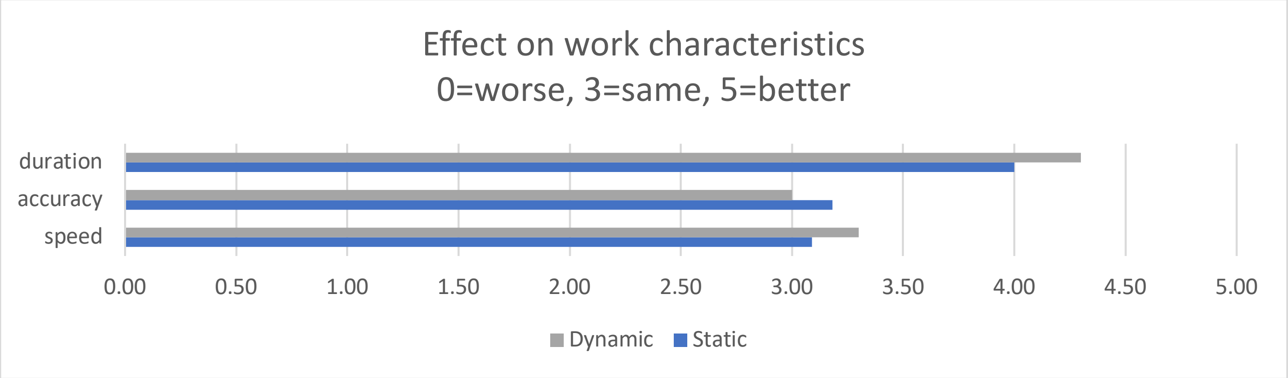


Figure 129. Perceived Effectiveness of the device on task characteristics.

Finally, subjects were asked how helpful the device would be at work, the percentage of time they would wear it at work, and if they would recommend it to a friend. Again, a majority of the subjects were construction laborers thus this feedback is specific to that field. Results were fairly consistent between static and dynamic tasks. Overall, subjects rated the device to be 67/100 or very helpful at work and would wear the device 51% of their workday. 95% of subjects would recommend the device to a friend.

DISCUSSION

A clear benefit was shown for all subjects regarding the anterior deltoid shoulder flexor, the primary muscle used in the designed task. Two response types were identified for the upper trapezius, possibly indicating two modes of device load transfer. For the extensors and rotator cuff muscles 3 response types were observed- beneficial, neutral, and adverse- which are thought to be linked to a subject's inherent familiarity with the added support. As far as the flexor digitorum and biceps activation there is no clear pattern across support levels, and it can be concluded that these muscles are not affected by the exoskeleton. Not addressed in this study is the ability to adjust the right and left arms to different settings to optimize for dominant and non-dominant arm tasks.

SHOULDER FLEXORS

For all subjects there was a reduction in anterior deltoid muscle activation for increasing levels of exoskeleton support. As a primary shoulder flexor, the R Anterior Deltoid was the primary outcome of interest. In the no support condition this was the muscle with the highest level of activation for all tasks and tools, and thus likely the most prone to strain. In the high support condition AD muscle activation was reduced by 80% for the 1lb tool and 63% for the 5lb tool. This reduction has the possibility to substantially reduce risk of injury or increase an operator's functional capacity.

The L AD activation was similarly reduced for the dynamic task but to a lesser degree for the static task. This is likely due to the increase in flexion of the L arm in the static task, an angle of about 130 degrees rather than 90 degrees. The setting of the arm supporting exoskeleton for the experiment provides less support to the upper arm after 90 degrees, but this may be changed in future studies or in a similar operational use case.

LOAD TRANSFER

The upper trapezius muscle activation was also heavily influenced by the shoulder supporting exoskeleton, with average reduction of up to 45% with the light tool and about 40% with the heavy tool. However, unlike the anterior deltoid, the response of the upper trapezius muscle was not consistent across subjects. Figure 130 shows two observed patterns of UT activation, Figure 130a showing a reduction for increasing levels of support, and Figure 130b showing little to no change.

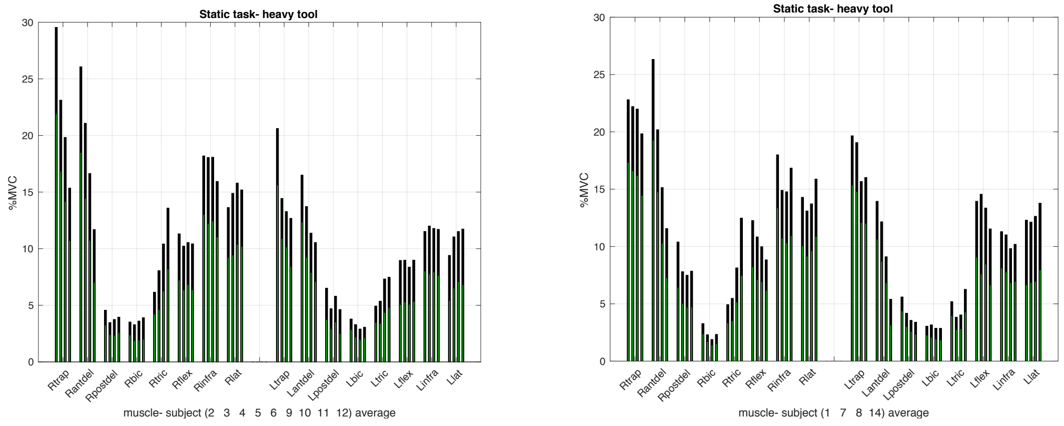


Figure 130. Inter subject difference in UT response to increasing exoskeleton support.

It is hypothesized that the UT activation in this study is indicative of the load transfer between the shoulders and the spine, rather than support of the arm in shoulder flexion. The UT is responsible for elevation of the scapula and along with the sternomastoid and levitator scapulae supports the shoulder girdle from which the upper arm is suspended. [40] Studies have shown that UT activation increases from an increasing single-handheld load, at both the side of the load as well as the contralateral muscle. [67] Additional studies have similarly indicated an increase in UT activation due to a load placed at the back and distributed to the shoulders via standard backpack straps [68] [69] that can be reduced if the backpack transfers a majority of the load from the shoulders to the hips [37]. Unassisted, vertical reaction forces of a hand held load must travel from the load, through the arm, scapula, spine, and eventually to the ground. The shoulder supporting exoskeleton supports this load about the shoulder joint and distributes the reaction forces via the torso frame to the shoulders and hips, depending on the quality of coupling to the human body. It is hypothesized that Figure 130a depicts a fit where a majority of the load is applied to the hips, the torso frame relieves the reaction forces in the direction of depression applied to the scapula, thus reducing the needed activation of the upper trapezius. If this is the case it can be concluded that this load also bypasses the user's spine. Figure 130b may depict a case where the hip coupling is poor and the reaction forces form the supported arm are applied to the users shoulders along the torso frame shoulder straps, only bypassing the glenohumeral joint. Here there is no effect to UT activation, and thus spinal loading. Further study is needed to investigate and confirm the effect of the device on spinal loading.

SHOULDER EXTENSORS

For increasing levels of support, it was noted by some subjects that the exoskeleton would become too strong- thus greater than normal effort in extension was needed. This result is likely influenced by the weight of the tool, the task, and the subject's inherent familiarity with the device.

In Table 10 above the user preference results clearly indicate a bias toward the higher support settings for the heavier tool. The near constant increase in triceps activation between the light and heavy tool weight is likely due to the increase in moment about the elbow during performance of the task, as evidenced by the baseline increase of the no support setting. The percentage difference between the no-support and support settings however is also better for the heavy tool when compared to the light tool across both tasks. This indicates that a portion of the triceps increase is due to the long head of the muscle acting to extend the shoulder and counter the supporting force of the exoskeleton.

From the EMG results it can also be observed that there is a different pattern of triceps activation between the static and dynamic tasks. In general, there was more activation for the static task compared to the dynamic, likely due to fine movements of the tool about the elbow while tracing the line. Looking at the pattern of activation, the static task activation increases more or less steadily with increasing support level- starting with the low support. Meanwhile for the dynamic task there is a benefit to the triceps at low support, small increase at medium support, and then a large increase at the high support setting. This is also supported to some degree by the increase in preference of the high setting for static compared to dynamic.

The final, and perhaps least understood impact on triceps, or general extensor activation, may be the subject's inherent familiarity with the added support of the exoskeleton. While all subjects were new to the device and had equivalent periods of wearing it before testing began, some may have been more comfortable relaxing the arm into the device while others fought the support to an unnecessary degree. In Figure 131 the EMG results for the static task are divided into three groups, subjects with a neutral triceps response, those with an adverse response at higher support settings, and those with an adverse response at all support settings. This response pattern holds across both varying task and tool conditions (Figure 132, Figure 133, Figure 134) but does not seem to correlate strongly with differences in other extensor muscles of the posterior deltoid and latissimus dorsi or overall rotator cuff activation indicated by the infraspinatus. It may likely be that increasing training with the device will transition all subjects into a more beneficial category of triceps activation. Until then a lower support setting can be used to maximize the benefit of support while minimizing any discomfort.

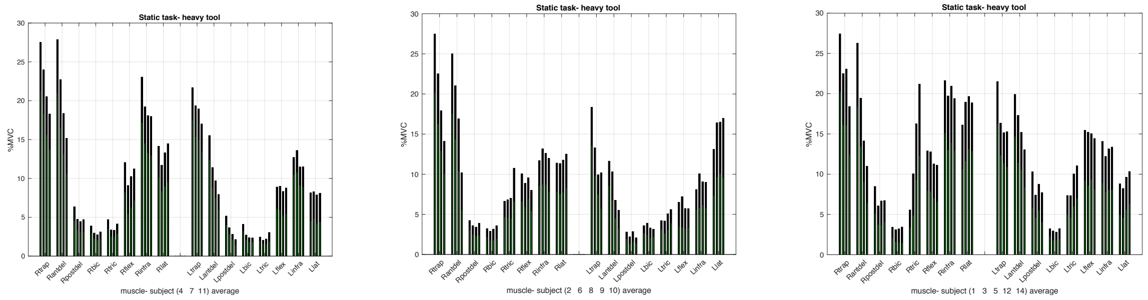


Figure 131. Static-Heavy EMG results by tricep activation pattern (a) neutral (b) slightly adverse (c) adverse.

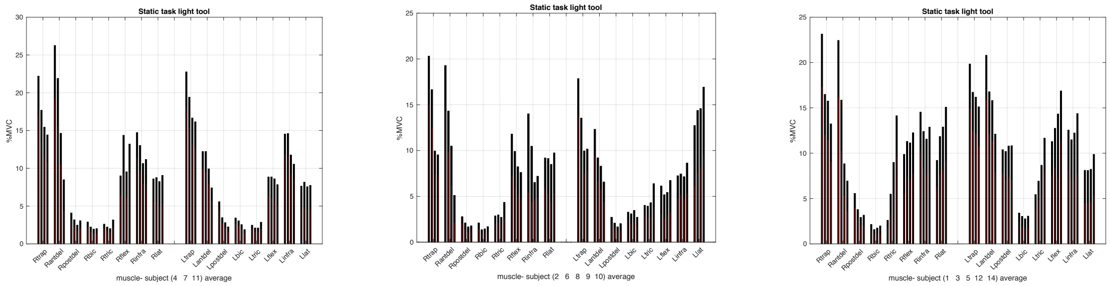


Figure 132. EMG results by Static Heavy tricep activation pattern for Static-Light.

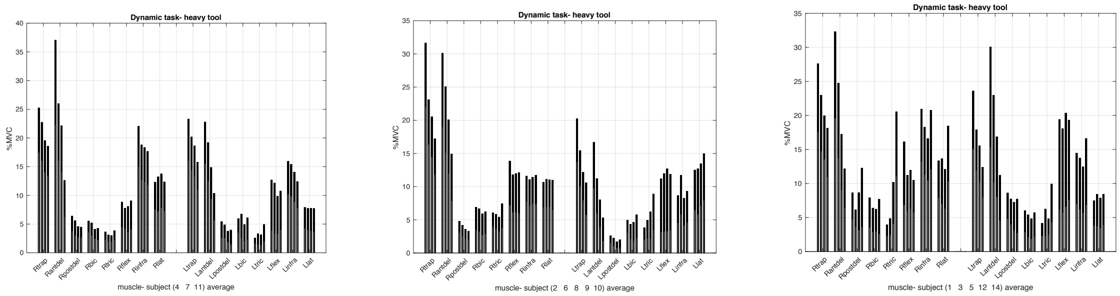


Figure 133. EMG results by Static Heavy tricep activation pattern for Dynamic-Heavy.

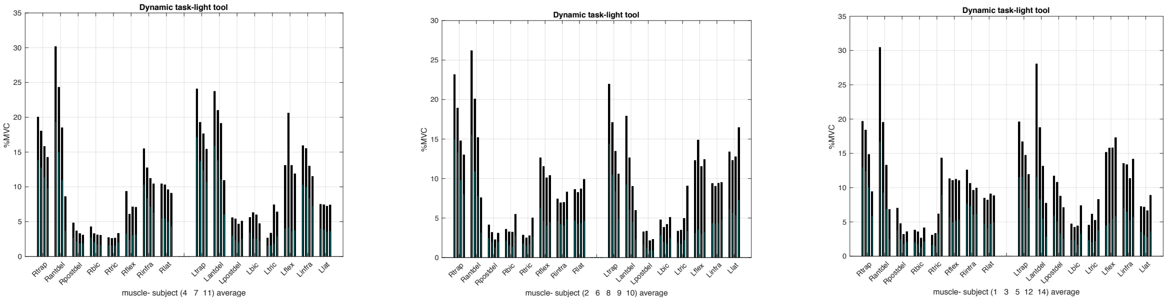


Figure 134. EMG results by Static Heavy tricep activation pattern for Dynamic-Light.

Similar to the triceps the posterior deltoid and latissimus dorsi can also be divided by subject into groupings of benefitial effect, neutral effect, and adverse effect of support levels, as showin in Figure 135 and Figure 136 respectively. Each of the resulting plots does have a relation to tricep activation, but not to eachother. This may futher exemplify the differences between individual's inherent familarity with the device support and may similarly transition to a benefical pattern given additional training.

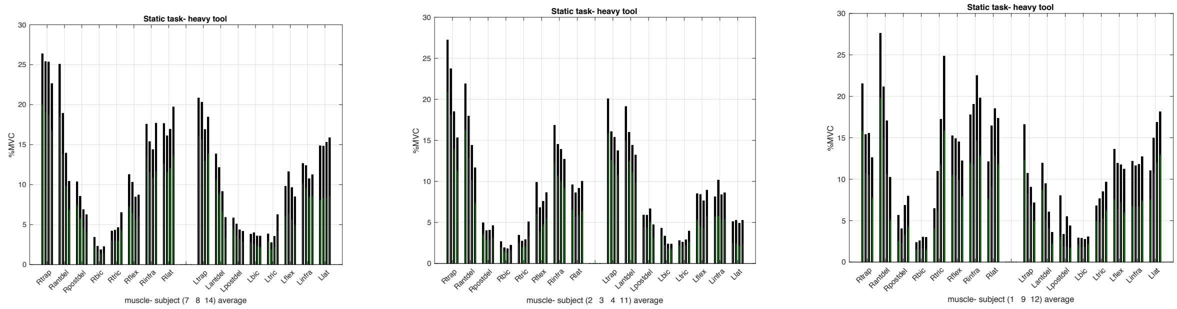


Figure 135. EMG results divided by posterior deltoid activation pattern.

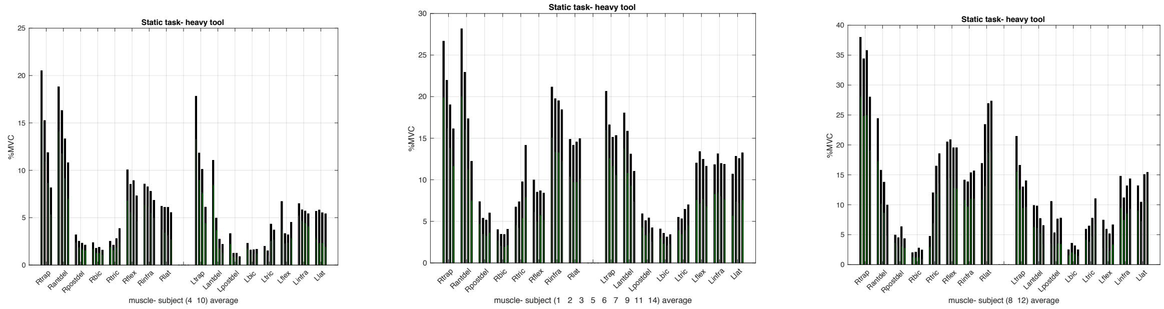


Figure 136. EMG results divided by latissimus dorsi activation pattern.

ROTATOR CUFF- SHOULDER STABILITY

Measurement of the infraspinatus can indicate the rotator cuff forces needed to maintain proper coupling of the glenohumeral joint during elevation of the upper limb. [40] A reduction of rotator cuff activation may signify that less load is being applied across the glenohumeral joint. This stabilizing load-response activation is influenced both by forces from the shoulder flexor and extensor activation for the studied tasks. Overall activation of the infraspinatus decreased significantly for the static task- light tool condition with a non-significant decrease in the other conditions. However, infraspinatus activation can further be segmented by subject for a beneficial, neutral, and adverse effect for increasing support, shown in Figure 137. For the same subjects this segmentation holds across all tasks and tool weights. Again, it can be seen that there is a strong relationship with triceps activation and somewhat for posterior deltoid and latissimus dorsi activation. This indicates that to reduce rotator cuff activation it is necessary to find a support level that optimizes shoulder flexor support with minimization of extensor activation. With increasing training familiarity subjects may adapt to allow more beneficial effects of higher support at the rotator cuff.

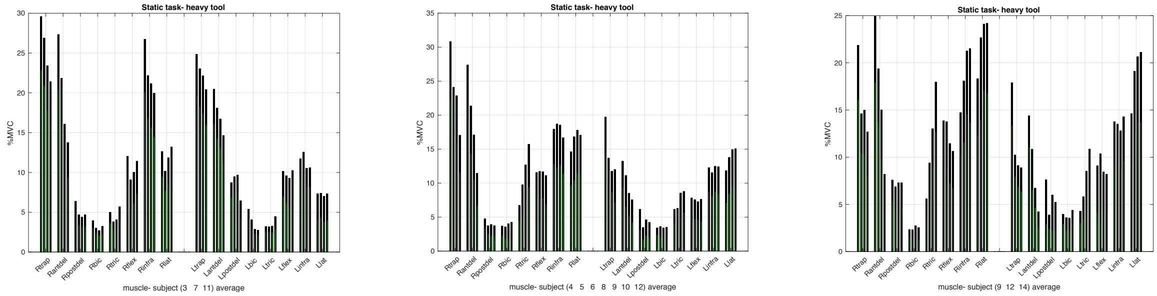


Figure 137. EMG results divided by infraspinatus activation pattern.

SUBJECTIVE FEEDBACK

Overall subjects unanimously preferred using the exoskeleton compared to no support for all tools and tasks. Differentiating preference between exoskeletons support settings depends on both task and tool, as well as personal differences likely due to familiarity with the device as described above. An increase in prior training or the longevity of the performed tasks may likely create a more consistent pattern in subjective exertion and preference results.

For both the static and dynamic tasks the device was perceived as effective and easy to use. Subjects reported the most substantial effect of wearing the device being the longevity with which they could perform a task without taking a break. On average it was stated that no effect to speed or accuracy of the work was present, although some subjects noted these aspects of the work would also benefit from the device. Some subjects noted difficulty with lowering of the arm, repetitive, and fine movements because the added support altered their normal movement patterns, but with practice may likely be overcome.

Specific to subject's background in construction labor, it was indicated that the device would be best for occasional use during the most overhead intensive tasks. The device would not be used for tasks that require little shoulder activation and thus ease of don/doff was emphasized. Overall subjects estimated that the device would be beneficial for about half of the time spent working each day and all but one would recommend the device to a friend for all task types. These results may likely differ in other work environments, such as manufacturing, where the diversity of daily tasks is comparatively less.

In the short answer section subjects indicated that the primary feature of the device they disliked was fighting the device during extension at the highest support setting. They had suggestions for features such as additional support to other body joints and attachments to mount pockets and tools. The primary aspects of work that would prevent use of the device possibly would include fitting into cramped spaces, added heat during the summer, and potential cost. Some notable quotes to what was most valued in the device include:

- "It made me feel like I was using muscles in a more healthy and controlled manner, almost like a work-out instead of actual work."
- "ability to prevent fatigue from repetitive tasks, and possibly prevent injury "
- "posture improvement"
- "it helps relieve stress on back"
- "wearing it doesn't strain your back, all weight is primarily carried on your hips."
- "it helps make work easier"

LIMITATIONS

The primary limitation of this study is the short duration of each condition. This did not allow sufficient time for subjects to accurately assess their level of exertion or comfort of the device throughout an entire shift. A longer duration study will also be needed to determine how the device affects worker fatigue throughout the work day, week, or career. Additionally, while the designed tasks attempted to best represent workplace conditions, it remains a simulated environment. The most applicable results will come from additional experiments taking place in the factories or constructions sites in which the exoskeleton will be used.

CONCLUSIONS

It is clear from the results above that the shoulder supporting exoskeleton provides a desirable reduction in shoulder flexor muscle strain during both static and dynamic overhead tasks and for light to medium weight tools. It also appears that the adjustable support level may alter the muscle synergies of overhead work and is important to optimize the device to each operator's personal preferences. User feedback indicates that while there are areas of improvement to be made, the shoulder supporting exoskeleton is ready for workplace implementation- at least at the preliminary trial level.

FUTURE WORK

Further research can be done to quantify the effects of the exoskeleton on other joints of the body, for additional workplace tasks, and with specific worker population. One key limitation of the current study is the short duration the device was tested under each condition. This results in reduced user familiarity with the device and limited time to accurately assess the benefit and comfort. For future tests the number of conditions should be narrowed, and the length expanded to better assess subjective feedback in addition to fatigue and productivity. Longer duration studies may also be able to determine effects of training and how a self-selected support level optimizes agonist-antagonist muscle synergies.

Subjective feedback indicated that subjects felt the device helped exertion of the back. Further investigation is needed to determine the exact effect of the exoskeleton on the spine. This may include spinal muscle activation or loading effects based on how well the exoskeleton distributes load to the hips.

Finally, the scope of studied tasks and populations for which the exoskeleton may be used must be expanded. Modifications of the task can be made to tool weight, workplace height, tool type, task characteristics, and complexity may be made to better assess how well the exoskeleton may benefit other occupations. Additional variables of exoskeleton support such as gravitational offset must also be studied to determine how all torque profile modifications can be fine tuned to optimize the support. Finally, the effects on specialized populations, such as the aging workforce and programs for return to work post injury, can be studied to determine if there are extra benefits for specific groups of users.

CHAPTER 6: CONCLUDING REMARKS

This dissertation has described the design and evaluation of a novel approach to supporting the shoulder during overhead work wile minimizing inhibition of all other task types. Throughout the past four years the arm supporting exoskeleton has evolved from an initial self-machined concept to a durable product distributed on a global scale. The development of this device has helped to create and define the market for industrial exoskeletons, paving the way for a new class of ergonomic aids to benefit workers across a range of industries.

A shoulder supporting actuator is described that can be tuned to create a range of torque profiles to best support the upper arm for a variety of workplace tasks. The modified iso-elastic base profile allows for support to be provided in the working range of motion with minimum inhibition during neutral postures. An adjustable torque profile amplitude alters the amount of support to accommodate different user sizes, tool weights, and individual preferences. The variable mode torque generator allows an operator to essentially turn the device on and off, giving free motion throughout the range of motion when desired. Finally, a gravitational offset is described to shift the torque profile for various types of task.

This dissertation further describes a biomimetic frame design that allows for the structural support and motion necessary to comfortably apply the actuator torque to operators along a majority of the anthropometric spectrum. The frame transfers load from the arm to the hips, not only bypassing the shoulder joint but also the scapula and spine. Couplings at the arm, shoulders, and hip comfortably secure the frame to the body in a familiar manner that is easy to don and doff. Both the rigid structure and textile couplings adjust along multiple dimensions to create a secure and comfortably fit for a majority of the working population. Glenohumeral, scapulothroacic, and spinal degrees of freedom allow the actuator support to be applied across the widest range of working postures.

For more complex tasks with risk factors at multiple joints this paper discusses a modular approach to combining the shoulder supporting exoskeleton to neck, trunk, and leg assisting devices. The design of a neck supporting exoskeleton is described to assist neck extension that commonly occurs alongside overhead work. Modular attachments to a trunk and a leg supporting exoskeleton developed by other members of the human engineering robotics lab is discussed to address the major three locations of workplace injury. A combination of all four devices is presented, comprising what is probably the most sophisticated workplace exoskeletons that has been designed to date.

Lastly, a controlled study has been conducted to assess the shoulder supporting exoskeleton for a common set of workplace tasks and tools on a population of construction laborers. Results show a substantial decrease in shoulder flexor activation, the primary muscle group utilized during overhead work. Across all workers and conditions not one would choose to work without the exoskeleton. The range of desired support varied across individuals, highlighting the benefit of the actuator adjustability. Investigating patterns of patterns of activation highlighted future areas of investigation to quantify reduction of spinal loads an impacts of device training on muscular synergies.

FUTURE WORK

As the field of industrial exoskeletons continues to progress, work must continue both to solidify the device's utility for identified applications and to expand the capabilities of the hardware to accommodate currently unmet needs. To address the former, research must be continued to more fully understand the short and long-term impacts of exoskeleton use in the workplace- not just at the supported joint but across the entire body. On the design side devices must be optimized for ease of use across a global population. Furthermore, the function of industrial exoskeletons must be expanded both in functionality of the current scope of the hardware as well as the support of additional joints across the body.

EVALUATION

Ergonomic evaluation of industrial exoskeletons must continue to expand the scope of understanding of how these devices affect the body as a whole over a range of working conditions. Eventually standardization of testing procedures must occur to be able to compare similar exoskeletons and align compatibility of results across testing sites. Further studies must be conducted to assess how these devices affect the entire body over longer durations of use. It is recommended that further work be done to investigate effects on fatigue, muscle synergies, posture, dynamic movement, and spinal loading- both during short and long term use. Additionally, specialized populations must be investigated, specifically the aging workers and return to work post injury. With a comprehensive understanding of the exoskeleton's effects its use may eventually be incorporated as a factor in standard ergonomic risk assessment tools.

EASE OF USE

Refinement of the device to reduce mass and complexity will further its reach into the industrial workforce. While currently deemed acceptable by many working populations there is always room for improvement. Reducing the weight and profile of the device though novel materials or optimized structure will minimize operator interference and possibly also heat. A reduction in complexity, either of hardware or textile adjustments, should allow for faster donning and a simplified process of properly fitting the frame to each operator. Both sizing and frame adjustments may be further refined to allow for more intuitive use through higher visibility, uniform mechanisms, or the postures needed to reach them.

Support Adjustment Tuning

Currently one of most difficult aspects of the shoulder exoskeleton in terms of usability is accessing the support adjustment knob. Support may also be adjusted, although in a much more limited range, by altering the position of pulley 183 along distal link 152, as shown in Figure 138a, resulting in a modified force profile, as shown in Figure 138b. Altering this distance affects the length [ls] and angle [φ] of the cable acting across the mechanism as well as the preload [F0] on the due to the length change. Adjusted along path 181, the pulley 183 contact with cable 182 remains concentric with spring 180. This secondary support adjustment may be used to fine tune a primary support adjustment setting through an easier to access interface location and angle of adjustment, as the pulley is located on the distal link and is best adjusted when the mechanism is at the toggle position as the pulley moves parallel to the cable. In the graph of Figure 138b the blue line corresponds to a larger p value created by the pulley, thus a shorter distance 181. The red line corresponds to a smaller p values as the pulley moves closer to the rotating joint 151.

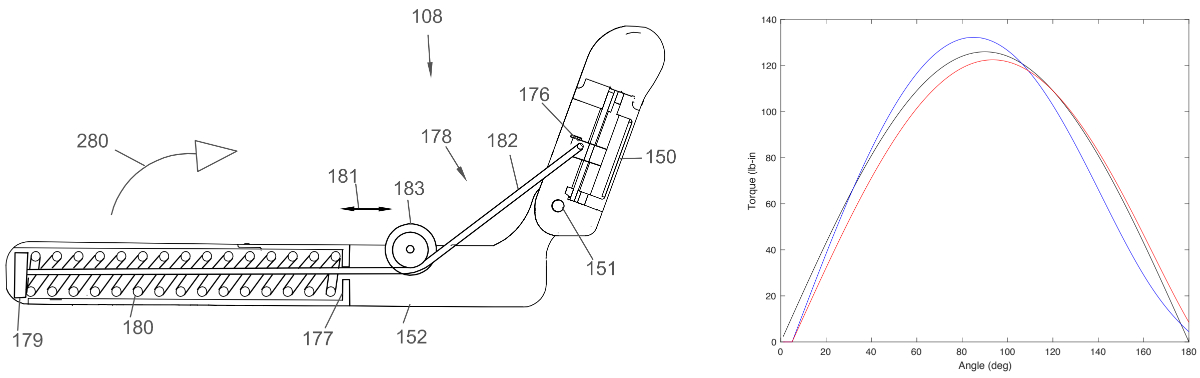


Figure 138. Secondary Support Adjustment (a) and Torque Profile Effect (b).

Alternate Torque Generator Configuration

A second approach may also be explored to move the support adjustment knob to the distal link to facilitate ease of reach. The configuration of the torque generator 108 may be reversed with respect to the proximal link 150 and distal link 152. Figure 139 shows spring 180 and pulley 183 fixed relative to proximal link 150 and the lower bracket 190 adjusting along distal link 152 serving to provide support adjustment equivalent to the upper bracket and proximal link of the previously discussed configuration. The added profile of proximal link 150 due to spring 180 may further be reduced through a remote spring housing 395 and control cable 398. Control cable 398 comprises first fixed end 396 attached to proximal link 150 and a second fixed end 397 attached to remote spring housing 395 to transmit forces from spring 180 to first tensile end 176. Depending on the length and bend of the routing of control cable 398 the remote spring housing 395 may be placed on the torso frame or more proximally on the arm link mechanism.

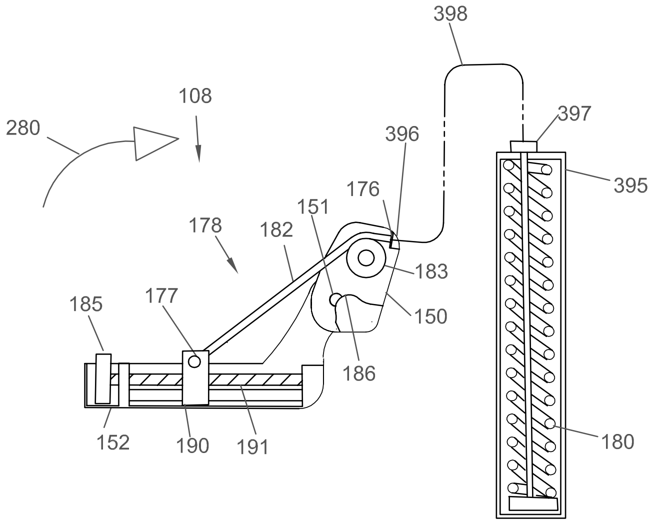


Figure 139. Reversed and remote spring configuration.

Motorized Support Adjustment

A third approach to simplifying the support adjustment posture is by adding an active element to the system. Figure 140 shows a motor 360 and transmission 361 attached to the upper bracket screw 187. The motor 360 then can adjust the position of upper bracket 188 and thus the support level of the torque generator 180. The motor can be controlled remotely with a user interface located at an easy to reach place on the persons arm or torso.

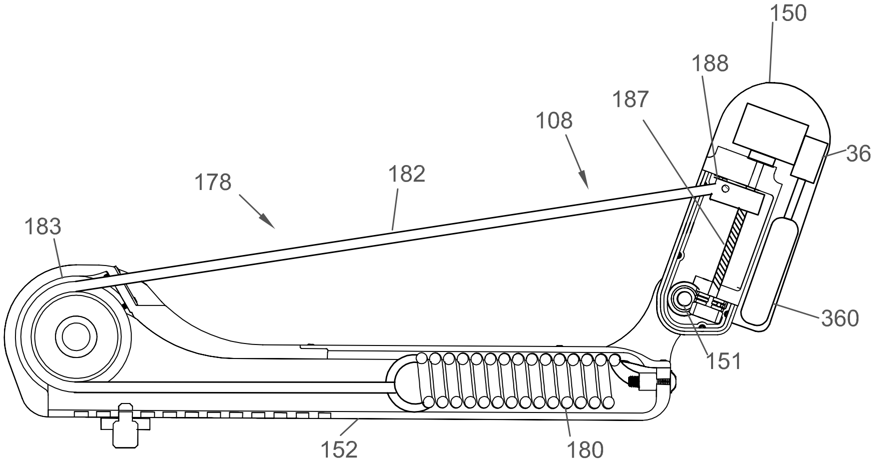


Figure 140. Motorized Support Adjustment.

CAPABILITY EXPANSION

While the current device has successfully been shown to augment the shoulders for many workplace tasks there remains plenty of room for additional capabilities- both in support of the shoulders as well as related joints.

Notice of Conflict of Interest:
Logan Van Engelhoven has a financial interest in US Bionics, the company that will manufacture the exoskeleton device as well as in the exoskeleton device. Logan Van Engelhoven is a paid contractor to US Bionics and has stock options. Logan Van Engelhoven invented the device being studied and may benefit financially from sales of the device if it is marketed.

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