Design and Evaluation of a Back Support Exoskeleton for Reducing the Risk for Back Injuries

By

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Abstract

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This thesis describes the design and development of a novel back-support exoskeleton for reducing the risk for back injury. As work tasks requiring repetitive, consistent movements become increasingly automated, the role of the human worker will shift from repetitious labor to specialized tasks. The exoskeleton discussed here is a passive, purely mechanical device that is lighter, cheaper to manufacture, and more intelligent than other current state-of-the-art passive exoskeletons, able to differentiate between walking and bending, and being able to automatically adjust sizing in response to its user’s body type.

A torque generator is selected and modified to provide a torque profile suitable for worker use. Based on feedback, a modification is added to enable the operator to toggle between standard, 30 degree engagement to support lifting, and instant engagement mode (IEM) to support postures where the operator’s torso may be upright, but manipulation of a load far from the body places a large moment load on the lumbar spine musculature. To transfer torque from the torque generator into a force that supports the weight of the upper body, a back-frame is designed. A posterior mounted frame is designed and dynamically adjusts in response to the operator’s body type and significantly reduces donning and doffing time. Additionally, four more degrees of hip abduction/adduction on the exoskeleton frame enable operators to perform a wider array of complex maneuvers that are difficult to current exoskeletons such as deep squats and high steps. Additionally, the exoskeleton is designed to be compatible with other exoskeletons for augmenting different parts of the body such as the leg or the shoulder muscles.

Lastly, an ergonomic study to evaluate the effects of wearing a back support exoskeleton on muscle fatigue are presented. The results of this study indicate that wearing a back-support exoskeleton during a lifting task reduces median and peak muscular activation of the erector spinae. Additionally, in doing a set of fixed tasks during a work session with the exoskeleton, the subjects wearing the exoskeleton were able to last 42% longer, in any secondary task, than the unassisted condition. This is corroborated by subjective rated perceived exertion, where subjects significantly rated the work session as less fatiguing when wearing backX. No changes in oxygen consumption were observed.
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Chapter 1: Introduction

1.1 Background

In 1989, the Occupational Health and Safety Administration published an article indicating that back injuries were the most prevalent workplace injury [1]. Recent studies by the U.S. Department of Labor continue to identify back injuries as the most common and costly work related injury [2]–[4]. Back injuries due to repetitive maneuvers are cited as the most common reason for absenteeism in the general workforce after the common cold [5]. According to a 2014 survey by the Bureau of Labor Statistics, back injuries affected nearly 1 in 5 American workers (18.5%) [4], significantly higher than the any other body region. Figure 1 shows the number of back injuries per year. Additionally, workers who suffer back injuries spend a median 8 days away from work recovering [4]. Cumulatively, back injuries result in an estimated 1,340,150 work days lost per year. Though injured individuals do eventually return to work, a history of low back injury puts them at higher risk for future back injuries [6][7].

The high severity of back injuries is also problematic, indicated by the high claim costs associated with back injuries. According to a 2013 report by the National Safety Council, the average cost per low back injury is $39,643 per case [8], a figure corroborated by data from Encompass Group LLC which reported the average low back claim cost to be $37,000 per case [9]. These figures account for not only direct costs associated with treatment, but indirect costs resulting from lost productivity and days away from work. Overall, back injuries cost American businesses an estimated $2.4B per year [10], [11], representing a significant financial burden.

![Number of Injuries, by Body Part, Annually (US)](image)

Figure 1: Number of injuries by body part. Back injuries constitute the majority of injuries sustained by workers. The next most common injuries are hand, knee, and shoulder injuries.
Lower back injuries occur when the applied load on the tissue exceeds the failure stress in that tissue [12]. McGill postulates that injury occurs via one of three modalities: immediate force application due to shock or impact, repetitive cyclical loading and subsequent fatigue of the tissue strength, and sustained sub-failure load coupled with tissue fatigue. Figure 3 is adapted from McGill [12] and illustrates the cyclical loading failure, wherein risk for injury can be mitigated directly by reducing the applied load on the tissue, or by reducing tissue fatigue.

Risk factors for back injuries are present in a variety of activities. Manual material handling involves considerable physical work demands and is considered as high risk for causing low back pain among workers [13]–[15]. Repetitive forward flexion during job tasks, awkward postures such as deep flexion or rotation of the trunk and heavy lifting are primary risk factors associated
with work-related musculoskeletal disorders (WMSDs) [13], [16]. Additionally, high positive associations have been found between low back pain and repetitive movement [17] or combined bending and twisting [13], [14]. Consequently, industries requiring workers to repetitively engage in maneuvers that require lifting, bending, or twisting of the lower back would be expected to sustain the highest rates of back injuries. In practice, this is reflected in industry – workers in the operations industries (transportation, warehousing, construction) and services industries (nurses, farmers) incur the large number of back injuries per year [18].

The Occupational Safety and Health Administration (OSHA) has indicated that engineering and administrative controls should be implemented wherever possible to reduce the risk for occupational injury [19]. Engineering controls are defined as physical changes to the workplace to eliminate hazards. In the context of reducing back injuries, common physical changes include lift assist cranes or palletizing gantries (Figure 4) designed to nearly completely offload the lifted weight from the human body and provide support within a specific operational footprint. However, lift-assists are typically bulky and unsuitable for a multitude of work tasks requiring operators to work in enclosed spaces or at worksites that require repetitive relocation of a job, such as sheetrock moving on a construction site. Administrative controls are defined by OSHA as procedures or training that establish efficient processes or procedures. Common administrative controls to reduce risk for back injury are worker-mandated training or workout credits for incentivizing workers to strengthen their back muscles [19]. Training programs can increase safety knowledge and improve health outcomes; however, the effectiveness of training can vary considerably due to the training style and quality [20] and in most cases be ineffective in preventing back pain or consequent disability [21]. Specifically, OSHA recommends engineering, administrative, then PPE controls be implemented in that order of preference to minimize burdens on the worker.

![Figure 4](image-url): Examples of overhead lift cranes. Overhead lift cranes can either be suspended from the ceiling (left) or constitute a large base supporting an overhead structure (right). In either case, cranes are typically effective only within a specific operational area and are unsuitable for assisting workers lifting repetitively in confined spaces.

Personal protective equipment (PPE) is recommended in worksite situations where engineering controls are impractical and often to supplement administrative controls. PPE is typically protection that is worn by the worker to reduce exposure to ergonomic risk factors [19]. Back belts are commonly used PPE to maintain a straight back when lifting and encourage proper lifting technique (Figure 5) [22]. Back belts have been shown to increase intra-abdominal pressure
and stabilizes the spine during lifting [23]. Additionally, back belts are hypothesized to protect workers from back injury by restricting posture of the torso and reducing bending of the spine during lifting, thereby reducing spinal compression [24]. However, there is no clear evidence that wearing back belts reduces back injury rates [10] and some evidence indicating increased risk for atrophy or muscle weakness of the lower back muscles [25], [26].

Figure 5: A worker using a back belt. Back belts are hypothesized to reduce injury rates by assisting wearers in maintaining a straight back when lifting; however, there is no conclusive evidence that wearing back belts reduces back injury rates.

1.2 Why Exoskeletons?

Exoskeletons are rapidly emerging as PPE devices for reducing the risk for back injury. Unlike conventional engineering lift assist interventions, exoskeletons can work in confined workspaces or at workstations where overhead space limits the practicality of using a lift assist crane. Additionally, in dynamically changing environments such as constructions sites, exoskeletons provide assistance where the worker is, versus being constrained to an operational footprint by overhead infrastructure or a large, immovable base.

A number of studies have demonstrated that wearing a back-support exoskeleton reduces the forces in the lower back muscles when bending forward. Springzback [27], HappyBack [28], Bendezy [29], Laevo [30], and PLAD [31] are all examples of wearable devices designed reduce forces acting on the tissues of the lower back and collectively referred to as “back-support exoskeletons.” A study by Barrett et al. comparing Bendezy, HappyBack, and another wearable device referred to as BNDR indicate these devices can reduce back muscle activation during lifting by up to 31% [32]. In particular, PLAD has demonstrated significant reductions in both muscle activation as well as muscle fatigue [31], [33], [34]. In general, the devices consist fundamentally of a trunk interface designed to impart supporting force onto the operator’s body, a torque generator designed to provide hip extension torque, and thigh braces coupled to the user.

Existing devices exhibit two primary characteristics that do not make them suitable for mass adoption: 1) disengagement when walking and 2) reduced range of motion when performing deep squats, one legged bends, or other complex maneuvers. All four devices mentioned above do not disengage when the user is walking, creating a situation where the worker must expend additional effort to walk, climb stairs, or perform other mobility tasks – this constitutes a potential safety hazard, as it impedes operator mobility in the event of an emergency or hazard avoidance. Additionally, current devices inhibit range of motion. This is caused by lack of alignment between the operator’s hip abduction/adduction axis and the exoskeleton abduction/adduction axis, caused
by insufficient exoskeletal degrees of freedom to match dynamic movement of the operator’s leg relative to his or her torso.

1.3 Theoretical Justification

Figure 6: Forces acting on the person. We model a person bending forward as a mass pivoting about the L5/S1 disk and calculate the muscle force $F_m$, the spinal compressive force $F_c$, and shear force $F_s$ as shown above.

A model for illustrating the stabilizing forces provided by the ES and intervertebral disc acting to support a stooped torso and a method for reducing said stabilizing forces is illustrated by Figure 6, where:

$F_g$ is the force of gravity acting on the combined mass of the object and head/arm/trunk
$F_{ex}$ is the force the back-support exoskeleton is exerting onto the person
$r_{CG}$ is the distance from L5/S1 to the combined center of mass
$r_{ex}$ is the distance along the spine axis from L5/S1 to the operator’s chest
$\theta$ is the forward bend angle
$\psi$ is the angular displacement of the combined center of mass.
$r_m$ is the distance of the erector spinae to L5/S1
$F_m$ is the force of the erector spinae
$F_c$ is compressive force on the L5/S1 intervertebral disk
$F_s$ is the shear force on the L5/S1 intervertebral disk

The main forces acting to stabilize the torso during stooping are the forces in the erector spinae ($F_M$), spinal compressive force ($F_C$), and shear force on the intervertebral disc ($F_S$). We can calculate $F_m$ by balancing the moments about the L5/S1 disk and taking into account angular acceleration $\ddot{\psi}$ as well:

$$I \ddot{\psi} = F_m r_m + F_{ex} r_{ex} - F_g r_{CG} \sin \psi$$

$$F_m = \left[ \frac{I \ddot{\psi} + F_g r_{CG} \sin \psi}{r_m} \right] - \left[ \frac{r_{ex} F_{ex}}{r_m} \right]$$

As one can see, by increasing the magnitude of the force the exoskeleton exerts onto the person $F_{ex}$, we can reduce the muscle forces $F_m$ required to stabilize the upper body. Similarly, we can solve for the compressive force at the L5/S1 disk by calculating reaction forces:
\[ \sum F_y = F_c - F_m - F_g \cos \theta = 0 \]

\[ F_c = F_m + F_g \cos \theta \]

\[ F_C = \left[ \frac{I \ddot{\psi} + F_g r_{CG} \sin \psi}{r_m} \right] + F_g \cos \theta - \left[ \frac{r_{ex}}{r_m} F_{ex} \right] \]

Again, we note that by increasing the force \( F_{ex} \) onto the person, we can reduce compressive force at the spine. This is largely due to the greatest compressive forces induced by contraction of the erector spinae in this model. Hence, by reducing \( F_m, F_c \) is reduced by consequence. Lastly, we can calculate the shear forces \( F_s \) on the spine:

\[ \sum F_x = F_g \sin \theta - F_{ex} - F_s = 0 \]

\[ F_s = F_g \sin \theta - F_{ex} \]

\[ F_s = mgsin\theta - F_{ex} \]

By increasing the force of the exoskeleton \( F_{ex} \), this reduces the spinal shear force. Furthermore, the strength of the torque as a function of forward bend angle (\( F_{ex}(\theta) \) or “torque profile”) can be adjusted to mitigate the effects of the exoskeleton on spinal shear when the user’s body is upright. For example, when \( \theta = 0 \) (i.e. the person’s torso is not inclined forward), the torque generator can reduce \( F_{ex}(\theta = 0) = 0 \) to ensure no change in spinal shear. However, when the operator is bent forward 90 degrees, \( F_{ex}(90^\circ) \) is maximized to counteract the force of gravity, thereby minimizing spinal shear.

This mathematical relationship between muscle force \( F_m \) and forward bend angle \( \theta \) form the motivation for this project. A device that imparts force \( F_{ex} \) onto the person could be deeply useful for reducing the risk for back injuries.

### 1.4 Dissertation Objective

This dissertation seeks to accomplish two design objectives:

1. Design an exoskeleton that imparts force \( F_{ex} \) onto the person and does not limit secondary tasks such as walking and is practical and easy to use.
2. Evaluate the effect of wearing a back-support exoskeleton on local and whole-body muscular fatigue.

Though these objectives may be fulfilled in a number of ways, this project builds upon a unique architecture developed by the author and the Human Engineering Lab at UC Berkeley that has been tested at various industry sites with hundreds of workers.
Chapter 2: Back Support Exoskeleton Design

To reduce back muscle forces $F_m$ and fatigue while preserving anthropomorphic range of motion, the author has developed a back-support exoskeleton called “backX” that is designed to be worn by a person. The design of backX can be separated into the following design principles:

**Torque Generator selection**

A torque generator was selected for use with backX based on the design requirements of backX. Specifically, the torque generator does not engage when the user’s upper body is vertical, but engages when the user’s body passes a predefined forward bend angle. The torque provided adjusts based on the relative angle between the operator’s trunk and thigh. During pilot testing with various user demographics and worksites, a variety of modifications were made to the torque generator to add a provision to engage the torque generator instantaneously, overriding engagement dependence on forward bend angle and adding a small magnet to reduce wearing.

**Anthropomorphic back frame**

An anthropomorphic back frame was designed to transfer hip torque from the torque generators to a supporting force onto the user’s chest to support the weight of the upper body and any held loads. This fundamentally requires the frame to be rigid in the sagittal plane, while compliant in the frontal and transverse planes. Mechanically, rotational joint axis of the frame are therefore never orthogonal to the sagittal plane. This ensures that the frame cannot freely flex or extend in the sagittal plane.

**Compatibility with other exoskeletons and tools**

The torque generators and back frame are designed to be compatible with other exoskeletons and common workplace equipment, such as toolbelts or welding jackets. Though backX is designed to support workers during lifting tasks, workers commonly perform maneuvers that present musculoskeletal risks to other joints. Therefore, backX is designed as a modular platform that can connect to a leg exoskeleton or shoulder exoskeleton to further augment the operator’s capabilities. Leg exoskeletons provide a knee torque between the femur and tibia to reduce quadriceps forces when squatting. Shoulder exoskeletons provide a shoulder torque between the trunk and the operator’s humerus to reduce muscle activation during overhead working or lifting.

**2.1 Torque Generation Selection**

The torque generator was chosen to support the user while he or she is bending forward while still allowing complete freedom of movement during walking. If a device worn by a worker imposes a force that makes it difficult for the worker to walk, this significantly impedes the operator’s ability to step around tripping hazards, avoid dangerous situations, or react quickly to an emergency; thus, they should not be used in a workplace setting. For this reason, backX incorporates a torque generator that only engages when the operator’s torso is inclined forward, regardless of hip flexion [35]. This torque generator is schematically depicted by Figure 7.
The engagement mechanism (Figure 7) fundamentally comprises a pendulum (116) that can rotate relative to the upper bracket (112) and is acted upon only by gravity, an engagement bracket (118), a lower bracket (114), and a compression spring (120) connected at one end (125) to said engagement bracket (118) and connected at the other end (123) to said lower bracket (114). The mechanism is configured such that when the upper bracket (112) rotates forward beyond an engagement angle (242), the pendulum (116) engages on the engagement bracket, locking the position of the engagement bracket (Figure 7). This locks the upper end (125) of the gas spring, allowing rotation of the lower bracket (114) about the hip joint (126) to compress the compression spring and providing a resistive force on the operator. However, when the back frame does not rotate through engagement angle (242), the pendulum does not engage on the ratcheting bracket and the gas spring is free to slide. Hence, rotation of the lower bracket about the hip joint does not compress the compression spring and no resistive forces are felt by the operator. Provided that the exoskeleton is substantially coupled to the operator and does not shift significantly during operation, when the operator bends forward beyond engagement angle (242) as indicated in Figure 8, the torque generators engage and provide a resistive force between the operator’s chest and thigh to support the weight of the trunk. However, when the operator’s trunk is upright, the torque generators do not engage and the operator can move freely and unimpeded through the workplace.
The torque generator further comprises an angle adjustment mechanism to adjust engagement angle such that the engagement angle (242) can be adjusted between 30 and 45 degrees. Tuning the engagement angle enables the operator to adjust the torque generator to his or her unique gait, such that the device does not engage during walking. This mechanism is depicted in Figure 9. The angle adjustment mechanism fundamentally consists of a magnetic adjustment screw (146) with an embedded magnet (148) and the pendulum (116). Turning the screw decreases the distance between the magnet and the pendulum pawl, increasing the magnetic force acting on the pendulum pawl. When the magnetic force on the pendulum is greater than the gravitational force acting on the pendulum, the pendulum will not engage onto engagement bracket (118). This effectively reduces the engagement angle (242) by requiring the torque generator to be rotated further forward for gravity to overcome the magnetic force exerted by the embedded magnet on the pendulum and thereby engage on the engagement bracket to being compressing the gas spring.

Figure 8: Schematic view of the torque generator. Here, upper bracket (112) has rotated past the engagement angle (242). In this configuration, the pendulum (116) engages on the engagement bracket (118) and prevents sliding of the compression spring (120). This causes the compression spring (120) to provide a resistive torque between the upper bracket (112) and lower bracket (114).
Additionally, the torque generator also incorporates an override mechanism. The presence of the override mechanism is important because it enables the operator to completely disengage the device in the event of malfunction, damage, or hazard avoidance. Toggling the override switch also enables the operator to completely disengage the device and walk forward while stooped completely unimpeded. This mechanism is depicted schematically by Figure 10a and is designed to completely prevent the pendulum pawl (116) from engaging on the engagement bracket (118). The override mechanism (150) comprises an override slider (151) with an override magnet (152) which can slide relative to the upper bracket (112). The override slider can slide into a first position as depicted in Figure 10a such that the override magnet (152) exerts a magnetic force on the pendulum (116) to prevent engagement on the engagement bracket (118) regardless of whether the torque generator has rotated past the engagement angle (242). Conversely, the override slider can slide into a second position depicted in Figure 10b when the upper bracket (112) passes the engagement angle (242) such that the magnet exerts no force on the pendulum (116) and the pendulum is free to engage on the engagement bracket (118) when the torque generator rotates past the engagement angle (242).
Lastly, the torque generator features a torque adjustment mechanism depicted in Figure 11 to adjust torque output by increasing the length of the spring distance (164) from the exoskeleton joint (126). The torque adjustment mechanism comprises a prismatic joint comprising a sliding block (162) rotatably coupled to the end (122) of the compression spring (120) and a locking block (166) to lock the position of the sliding block (162) relative to the lower bracket (114). By moving the sliding block to different locations in the adjustment channel (160) then locking the position, one can adjust the moment arm (164) from the spring to the exoskeleton joint (126) and hence increase the torque acting about the joint. The torque is adjustable between approximately 180 lb-in to 140 lb-in.

Figure 10a (left): Sagittal view of the torque generator only depicting the override mechanism (150) in the first position, wherein the override magnet (152) exerts an attractive magnetic force on the pendulum (116), preventing the pendulum from engaging on the engagement bracket (118).

Figure 10b (right): Sagittal view of the torque generator depicting the override mechanism (150) in the second position, wherein the override magnet (152) exerts no force on the pendulum (116) and the pendulum can freely engage on the engagement bracket (118).
2.1.1 Instant Engagement Feature

For the torque generator to engage, the user is required to bend forward at least 30 degrees before the torque generator begins to provide a supporting torque. However, workers perform many tasks that can cause back injury even when the upper body is not inclined forward. Tasks such as manipulating a load while standing, moving boxes while twisting, or reaching forward (Figure 13) induce a bending moment on the spine due to the horizontal distance from the spine to the combined center of mass of the person and load. This bending moment is not dependent on forward bend angle and exists even when the person is not bending forward (Figure 12).
Loading of the erector spinae can be calculated by summing moments around the L5/S1 disk and therefore expressed as:

\[ F_m = \frac{r_{CG}}{r_m} F_g - \frac{r_{ex}}{r_m} F_{ex} \]

In this case, \( F_{ex} \) is nonzero if the torque generator engages before 30 degrees. Therefore, to assist users who manipulate outstretched loads while maintaining an upright posture, the torque generator must be modified to engage earlier.

To engage the torque generator for users who are reaching forward but not bending forward, an instant engagement feature was designed and incorporated into the original torque generator design. Instant engagement mode (IEM) overrides standard engagement at 30 degrees and can be toggled on or off by the user. When IEM is engaged, backX will push on the user’s legs when the user walks, rending this engagement strategy more useful for static tasks that require minimal walking.
**Early Engagement Pawl**

To engage the torque generator immediately, torque generator (108) further comprises a secondary pendulum (170). As shown in Figure 14, secondary pendulum (170) is rotatably coupled to upper bracket (112) around secondary pendulum joint (402). In operation, secondary pendulum (170) may come into contact with engagement bracket (118). This prevents engagement bracket (118) from sliding, causing compression spring (120) to be able to provide a resisting torque between upper bracket (112) and lower bracket (114).

![Figure 14: Cross section of the torque generator. Note addition of secondary pendulum (170) that locks the motion of engagement bracket (118) when secondary pendulum (170) comes into contact with engagement bracket (118). This causes compression spring (120) to provide a resistive torque to support the weight of the upper body.](image)

**Early Engagement Mechanism**

Figure 15 shows an embodiment of first torque generator (108). In this embodiment, first torque generator (108) further comprises another override mechanism (174) that prevents secondary pendulum (170) from contacting engagement bracket (118). In some embodiments of the invention, override mechanism (174) causes secondary pendulum (170) to engage onto engagement bracket (118). In some embodiments of the invention, as shown in Figure 15, secondary pendulum (170) is magnetic and override mechanism (174) comprises a secondary override slider (180) and override magnet (159).
When secondary override slider (174) is in the first position, shown in Figure 16, override magnet (159) attracts secondary pendulum (170) and prevents secondary pendulum (170) from engaging on engagement bracket (118). This occurs even if torque generator (108) is inclined forward as shown by Figure 16.
When secondary override slider (406) is in the second position, shown in Figure 17, override magnet (408) does not attract secondary pendulum (400) and allows secondary pendulum (400) to come into contact with engagement bracket (118). In some embodiments of the invention, override magnet (408) applies an attractive force on the engagement end (410) of secondary pendulum (400) and forcibly engages secondary pendulum (400) onto engagement bracket (118). This can occur even when torque generator (108) is upright.

Figure 17: cross section of torque generator (108) showing magnet (158) preventing secondary pendulum (170) from contacting engagement bracket (118).

In some embodiments of the invention, secondary override slider (174) further comprises secondary override slider (180), such that when secondary override slider (180) is in the first position, override mechanism (158) prevents pendulum (116) from contacting engagement bracket (118) and when secondary override slider (180) is in a second position, override mechanism (158) does not affect movement of pendulum (116) and allows pendulum (116) to contact engagement bracket (118) (Figure 18).
Figure 18: cross section of torque generator (108) showing magnet (158) preventing pendulum (116) from engaging on engagement bracket (118).

**User feedback**

IEM mode was evaluated at various warehouses, assembly/manufacturing plants, and construction sites. Specific workers who benefitted from using IEM performed tasks that did not require more than a 30 degree forward bend. Generally, workers performing these tasks engaged in forward reaches, were typically working at fixed workstations that did not move, and were standing. Specific tasks included table grinding, deburring tire rims at a table, or moving packages at chest height.

**2.1.2 Reducing Rail Wear**

Referring to Figure 18, when either primary pendulum (116) or secondary pendulum (170) was disengaged from engagement bracket (118), gas spring (120) did not compress. However, the movement of upper bracket (112) and lower bracket (114) caused gas spring (120) to generate a rotational moment on engagement bracket (118). This caused the leading edge of engagement bracket (118) to abrade the surface of rail (136) (Figure 19). Due to machining imperfections and striations on the surface of rail (136), engagement bracket (118) occasionally seized on rail (136), locking the motion of gas spring (120) and preventing the user from being able to perform a forward bend. This resulted in visible tilting of engagement bracket (118) relative to rail (136). To reproduce the issue, six torque generators were mounted to a test jig (Figure 20) and cycled through flexion and extension.
Figure 19: Abrasion of engagement bracket (118) against rail (136). Leading edge of engagement bracket (118) caused excessive wearing on the surface of rail (136).

Figure 20: Torque generator mounted to a test jig. Arrows indicate hip flexion and extension tests designed to replicate wearing scenario.

To reduce contact angle and prevent engagement bracket (118) and rail (136) from seizing, a 1/8” diameter, 1/8” thick neodimium magnet was added to engagement bracket (118) to provide an attractive force between engagement bracket (118) and rail (136) (Figure 21). The sliding surface of engagement bracket (118) was sufficiently flat such that no tilting of engagement bracket (118) was observed. Six new torque generators were modified the neodimium magnet, mounted onto the flexion/extension test jig, and cycled to failure if possible. Cycle data is presented in Table 1.
Figure 21: addition of the neodium magnet to reduce contact angle between the engagement bracket and rail. The installation jig features a clearance fit for the neodium magnet and is removed after pressing the neodium magnet into the engagement bracket.

Table 1: Wearing data from the test jig. Rails with the magnet modification resulted in longer performance than rails lubricated only with grease.

<table>
<thead>
<tr>
<th>Lot</th>
<th>Magnet</th>
<th>Lubricant</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/8&quot; OD x 2/10 L</td>
<td>Grease</td>
<td>355,176</td>
</tr>
<tr>
<td>2</td>
<td>None</td>
<td>Grease</td>
<td>35,370</td>
</tr>
<tr>
<td>3</td>
<td>None</td>
<td>Grease</td>
<td>35,370</td>
</tr>
<tr>
<td>4</td>
<td>1/8&quot; OD x 2/10 L</td>
<td>None</td>
<td>275,526</td>
</tr>
<tr>
<td>5</td>
<td>1/8&quot; OD x 2/10 L</td>
<td>None</td>
<td>275,526</td>
</tr>
<tr>
<td>6</td>
<td>1/8&quot; OD x 2/10 L</td>
<td>None</td>
<td>275,526</td>
</tr>
</tbody>
</table>

The modified torque generators unanimously outperformed the unmodified torque generators, lasting over 7 times longer than the control. However, some failures were observed. This may be attributed to striations on the machined rail (136), despite the machine surface finish specification being 63 Ra μ − in. Future iterations of the torque generator may replace the sliding interface between engagement bracket (118) and rail (136) with a ball bearing carriage to minimize the effect of striations and machining imperfections on disengaged torque generator operation.

2.2 Anthropomorphic Back Frame

backX is a back support exoskeleton that reduces back muscle activation and muscle fatigue when a user bends forward. backX is depicted in Figure 22 and fundamentally consists of:

A. A trunk frame (102) consisting of an upper assembly (306), spine assembly (304), and hip assembly (302) that is worn by the operator on his or her back and is configured to move with the operator’s trunk (202)

B. Two torque generators (108) coupled to the trunk frame (102) and residing on either side of the person and aligned with the operator’s hips
C. Two thigh braces (104) rotatably coupled to each torque generator (108), wherein each thigh brace (104) is coupled to the operator via thigh straps
D. A human machine interface comprising a belt, belt clips, thigh straps, shoulder straps, and a custom-designed vest configured to couple the backX to the operator’s body

The following sections focus on the development of the trunk frame of the backX.

![Figure 22: A side view of the basic architecture of backX.](image)

### 2.2.1 Workplace Postures

It is critical to ensure wearing the exoskeleton does not impede a worker from adopting postures and conducting maneuvers required by his or her worktask. In the context of an industrial warehouse or shop, workers need to be able to deep squat, deep bend, one-knee kneel, asymmetrically twist, or any combination thereof during a lifting/lowering task. Figure 23 illustrates these postures.

![Figure 23: Workers are required to perform squat lifts (left), asymmetric twisting (middle), or one knee bends (right). To ensure operators are still able to perform these maneuvers while wearing backX, an anthropomorphic back frame is designed.](image)
2.2.2 Adjustment parameters

The back frame is designed to approximately fit a range of trunk dimensions from the 5\textsuperscript{th} percentile female to a 95\textsuperscript{th} percentile male. Adjustment ranges for abdominal depth, hip width, hip to chest distance, chest width, and chest depth were determined from anthropometric data obtained by NASA [36] and The Ergonomics Center of North Carolina [37]. Table 2 tabulates these adjustment ranges and the respective adjustment range for the backX.

Table 2: Anthropometric body dimensions and respective backX adjustment range. backX adjustment range was designed to approximately accommodate the 5th percentile woman up to the 95th percentile man.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>5\textsuperscript{th} percentile female</th>
<th>95\textsuperscript{th} percentile male</th>
<th>backX adjustment range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdominal depth</td>
<td>8.7”</td>
<td>13”</td>
<td>9” – 12”</td>
</tr>
<tr>
<td>Hip width</td>
<td>12”</td>
<td>15.4”</td>
<td>13” – 17”</td>
</tr>
<tr>
<td>Hip to Chest distance</td>
<td>8”</td>
<td>10”</td>
<td>8” – 13”</td>
</tr>
<tr>
<td>Chest width</td>
<td>9.7”</td>
<td>14.4”</td>
<td>10” – 14”</td>
</tr>
<tr>
<td>Chest depth</td>
<td>6.8”</td>
<td>11.1”</td>
<td>4.5” – 13”</td>
</tr>
</tbody>
</table>

2.2.3 Spine Degrees of Freedom

To enable a user to perform these maneuvers while wearing the backX, the trunk frame is comprised of a hip assembly, a spine assembly, and an upper assembly. The hip frame is rotatably coupled to the spine frame approximately posterior to the user’s L5/S1 disc to allow for lateral rotation of the spine in the frontal plane. The spine frame is also rotatably coupled to the upper frame, allowing the upper frame to rotate about the long axis of the spine. This allows the backX to biomechanically mimic the lumbar spine degrees of freedom, enabling all manner of twisting, side-bending, and flexion/extension maneuvers.

Twisting

Twisting is defined as rotation of the trunk in the transverse plane and is typically present in job tasks that require the operator to move objects laterally. Notably, the rotational axis of the spine is substantially misaligned from rotational twisting axis of the person (Figure 24). Consequently, to allow free rotation of the trunk without impeding the operator, spinal twisting is accommodated by lateral flexion/extension (310) and axial twisting (314) of the exoskeleton spine. While this does not completely eliminate relative motion between the operator’s trunk and exoskeleton frame, the human-machine interface is sufficiently compliant to allow the operator to twist comfortably.
Lateral Flexion and Extension

Workers engage in many tasks requiring lateral flexion and extension of the spine. Common tasks include picking up paint cans on either side of the body or palletizing. The author also notes that the lateral rotational degrees of freedom could be obtained using a plurality of joints extending up the length of the spine – however, motion of the spine can be largely described by the rotary ranges of motion of the T12 to L4 vertebrae, which exhibit both the largest rotational range of motion as well as the most caudal location [38]. Therefore, because T12 to L4 is a relatively small localized area and has the greatest rotational range of motion, we represent the lateral rotation of the spine as a single pivot joint. This also reduces the manufacturing cost of the backX supporting trunk by requiring fewer components to account for lateral spinal rotation.

2.2.3 Hip Alignment

Misalignment between the hip joint of the exoskeleton and the operator’s biological hip joint can cause relative movement between the exoskeleton and operator’s body. This substantially restricts the movement of the operator, preventing him or her from performing tasks critical for job completion or creating a hazard to the worker. Consequently, it is critical that the backX hip joint axis of rotation is aligned as closely as possible with the biological hip axis of rotation to prevent relative motion.

Figure 25 illustrates forces acting on the exoskeleton when the torque generators are engaged. If not secured to the operator’s body, the exoskeleton moves upward relative to the person. When the operator’s legs are not abducted, effects are constrained to small contact forces that may cause the operator’s pants to “bunch up.” However, when upward movement is not constrained and the operator’s legs are abducted beyond 45 degrees, forces against the thigh braces
do not produce adequate torque to keep the torque generator flexed, causing immediate extension of torque generator and severely limiting the operator’s range of motion.

Figure 25: Forces acting on backX when the operator is bent forward. If the seat strap is not tightened, $F_p$ is very small and the exoskeleton can move forward and upward on the person, resulting in misalignment of the hip joints with the operator's biological hip joints.

To maintain joint alignment between the exoskeleton and the operator, a seat strap is attached to the lower bracket of each torque generator, above the hip abduction joint. The seat strap is designed to be cinched below the coccyx in the pelvic bone region and is adjustable between 14” and 26” to accommodate various body sizes. When the operator bends forward, the seat strap tightens and prevents upward movement to prevent joint misalignment. When the operator is not bending forward, a belt connected to each torque generator supports the weight of backX and prevents vertical joint misalignment.

2.2.4 Evaluation with different workplace tasks

Multiple tests were conducted at various baggage handling, materials warehouses, and manufacturing sites to evaluate backX usefulness for worker tasks and collect worker feedback. Workers were observed, photographed, and video recorded by researchers during their shifts wearing the backX. Feedback was collected from both facility managers and verbally from workers by requesting:

1. General feedback on the usefulness of the device
2. Comfort: identifying comfort of the backX on body segments such as the thigh, hip, waist, pectorals, shoulders, and lower back
3. Usability: identifying whether the device was easy to put on and take off, bulk, weight, and whether it prevented the operator from performing his or her task normally.
4. Effectiveness: workers were asked whether they would be comfortable using the device every day and if they perceived that it would be useful for that specific task.

Overall, worker reception of the device was positive – the majority of workers felt the device reduced strain on their lower back. Contact pressure was comfortable for most users, although 21% indicated that they felt the device was “too hot” and trapped too much heat. Additionally, 15% of feedback indicated that the frame protruded too far from the body, causing contact with moving arms during the work task. The backX was too complicated for workers to learn how to adjust and don for the first time, so adjusting and donning the backX was performed by the researchers in all cases. Workers who were consistently lifting from ground to waist-height, lowering boxes, or sustaining a forward bend unsupported by the hands found the device useful for their tasks.

2.2.5 Palletizing Case Study

Palletizing requires workers to lower a load from a conveyor belt, typically waist height, down to the ground onto a pallet. As the pallet is stacked higher, lifting posture changes from a stooped or squat lift to an overhead reach, where more experienced workers typically exhibit less lumbar flexion and greater knee flexion during lifting \[15\]. Regardless of whether a worker is executing a stooped or squat lift, adopting these postures results in an increase of muscle loading at the lumbar spine \[39\]. Figure 26 illustrates workers palletizing using the backX. Use of the backX was evaluated at the warehouse of a shipping company.

![Figure 26: Palletizing task at a warehouse. The worker lifts a package from a full pallet and lowers it to ground. As the full pallet height lowers, lifting changes from an overhead-to-ground lift to stoop/squat lift.](image)

Use of the backX was well received by palletizing workers. 1 male and 1 female wore the backX for a palletizing task and both indicated the device reduced loading on their lower back muscles. Both workers reported that their elbows contacted the top of the torque generators during the lifting process, causing minor changes to their lifting techniques. Additionally, the male indicated that wearing the exoskeleton made him feel “too hot,” specifically at the lower back area. However, despite these drawbacks, both workers indicated that they would wear the device again for their palletizing task.
2.2.6 Packaging Operations (Sustained forward bend)

backX was evaluated to assess usefulness for workers performing packaging operations. A large object to be wrapped in shrink-wrap was placed on a rotating table, which began. Packing operations required the operator to shift from a kneeling, forward bending position to a stooped forward bend to wrap the rotating object in shrinkwrap (Figure 27). The operator was not required to move his or her feet or change location relative to the object.

Figure 27: A worker performing packaging operations. Worker is required to shift from a kneeled forward bend to a stooped bend while wrapping.

backX was evaluated by 6 males and 1 female warehouse worker. All workers reported that the device supported their lower back muscles. 2 workers indicated that they felt some mild discomfort under the arm area caused by the strap connecting the chestplate to the back frame. One of the workers also indicated that he felt “too hot” in the exoskeleton and that transverse twisting was impeded.

2.2.7 Design Feedback Summary

Overall, all users felt that the backX provided support and reduced forces in the lower back muscles. However, there were a number of feedback items necessitating improvement to make adoption viable. In both operations, operators indicated an increase in heat. Inherently, this may be caused by sub-optimal ventilation properties of the backX padding. There is no consistent path for airflow from the user’s clothes to the exterior of the padding – this could be rectified by cutting ventilation holes through the foam to improve air circulation.

Operators at the packaging warehouse indicated that the backX torque generators contacted their elbows during lifting operations, requiring them to slightly alter their lifting mechanics. This is caused by the height of the torque generators, which is largely due to the length of the gas spring. Reduction in torque generator profile could be accomplished by repositioning the gas spring horizontally to reduce the height of the torque generator. Alternatively, the gas spring could be located behind the user and actuated remotely by a control cable linked to a pulley at the hip.

Donning was performed in all cases by the researcher, as the donning process was too complicated for a first-time user to perform independently. The backX includes 8 separate straps to attach to the operator: two shoulder straps, a chest strap, a belt, two leg straps, and two thigh straps. This is in addition to the hip, spine, and torso adjustment required before putting on the
suit. Performing these procedures substantially increases the time required to put the backX on. Some operators indicated that they would wear the device intermittently throughout the day and that don/doff speed is important for incorporating the device into their work routine. To reduce the number of adjustments and don/doff speed, an “automatic adjust” feature could be introduced into the frame, enabling compliance in the frontal plane for adjustment and spinal range of motion, but rigidity in the sagittal plane. Additionally, it was observed that minimal torso width adjustment was required across users – therefore, it may be sufficient to create an upper torso structure that does not require adjustment. To reduce the number of straps, the shoulder straps and chest straps can be combined, as well as both leg straps. Overall, this would reduce the number of straps by 37% and the number of adjustments by 25%, likely resulting in significantly faster and more intuitive don/doffing operations.

2.3 Second Generation Auto-adjusting Frame Design

Fitting a back-support exoskeleton to a user is a critical, but time-consuming task. The exoskeleton must be adjusted properly to fit a user’s torso width and height – if not, the exoskeleton may not function properly or induce severe discomfort. Many back-support exoskeletons, such as Laevo and backX V2, employ lockable adjustment mechanisms, consisting of a rigid metal frame that is adjusted to discrete width or height settings, and then these settings are locked for the duration of use [40]. While useful for approximating the user’s width, these fail to account for two fundamental fitting issues:

1. The joints of the exoskeleton are not aligned coaxially with the rotation axis of the user’s joints because the exoskeleton exists outside of the user’s body. Consequently, as the user flexes/extends his or her limbs, the exoskeleton must expand or contract to maintain joint alignment and comfort. This is not possible with Locked Adjustment because once the exoskeleton is adjusted, it cannot expand or contract.

2. Adjustment of rigid metal components induces an additional mental and time burden when putting on the device. Feedback from industry users indicates the time and mental burden to putting on and adjusting the exoskeleton constitutes a practical barrier to adopting exoskeletons in the workplace.
Table 3 tabulates this feedback. Consequently, a new frame design is required to maintain joint and alignment and comfort, as well as reduce the time it takes to put on and adjust the backX.

Table 3: Worker feedback related to fitting. Feedback largely centered on the time to put the device on and difficulty of adjustment.

<table>
<thead>
<tr>
<th>Source</th>
<th>Region</th>
<th>Industry</th>
<th>Workplace tasks</th>
<th>Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worker</td>
<td>United States</td>
<td>Warehousing</td>
<td>Palletizing, lifting, reaching</td>
<td>Would not wear because takes too long to put on.</td>
</tr>
<tr>
<td>Worker</td>
<td>Brazil</td>
<td>Warehousing</td>
<td>Palletizing, lifting</td>
<td>Uncomfortable, but wasn’t adjusted properly</td>
</tr>
<tr>
<td>Electronics installation</td>
<td>United States</td>
<td>Aircraft manufacturing</td>
<td>Sustained kneeling forward bending</td>
<td>Will not wear because too confusing</td>
</tr>
<tr>
<td>Inventory worker</td>
<td>United States</td>
<td>Auto manufacturing</td>
<td>Lifting from ground level</td>
<td>Can’t put on quickly enough to get on shift</td>
</tr>
</tbody>
</table>

### 2.3.1 Design Description

The torque transfer frame of the backX V3 automatically adjusts with the user to maintain joint alignment with the user’s hip and spine joints and is referred to as the second-generation back frame (100). The second-generation back frame is comprised of a hip assembly (200), spine assembly (300), and upper assembly (400) (Figure 28).

Figure 28: posterior three-quarters view of backX V3 being worn by a person.
The hip assembly (200) is adjustably coupled to the spine assembly (300) and comprises a width adjustment mechanism (202) enabling the width (206) of the hip assembly (200) to freely increase or decrease (Figure 29). In this embodiment, the width adjustment mechanism (202) is comprised of at least one right adjustment link (208) and at least one left adjustment link (210). The right adjustment links (208) are rotatably coupled to an attachment block (212) and the right curved link (214). As seen in Figure 28, the right curved link (214) wraps around the user’s back (502) and is also prismatically coupled to the right torque generator 600. The left adjustment link (210) is rotatably coupled to an attachment block (212) and the left curved link (216). The left curved link (216) wraps around the user’s back (502) as seen in Figure 28 and is prismatically coupled to the left torque generator (602). In some embodiments, the rotational coupling of the right adjustment link (208) and left adjustment link (210) relative to the attachment block (212) are mechanically linked by a gear transmission (218) as seen in Figure 29. This can be useful for mechanically constraining the width of the lower frame to expand or contract symmetrically.

Referring to Figure 28, the depth (220) of the hip assembly can be adjusted with a depth adjustment mechanism (222). In this embodiment, depth adjustment mechanism (222) comprises a hip frame mount (224) with a cylindrical protrusion (226), a button plunger (228) set inside cylindrical protrusion (226), and the right curved link (214) or left curved link (216) configured such that cylindrical protrusion (226) can slide freely inside the curved link (Figure 30). Hip frame mount (224) is attached to the right torque generator (600) or left torque generator (602). The position of the hip frame mount (224) relative to the curved link is locked into place when button plunger (228) engages into holes (230) in the curved link, enabling lockable adjustment of hip assembly depth (222). Figure 30 shows an exploded view of the left side depth adjustment mechanism (222). Button plunger (228) is spring-loaded and can snap into one of the holes (230) to lock depth adjustment mechanism (222) (Figure 31).
The spine assembly (300) is rotatably coupled to the hip assembly (200) at at least one point and is aligned substantially with the axis of the user’s spine (504) as seen in Figure 32. The length of the spine (312) is adjustable using a height adjustment mechanism (302). In some embodiments, the spine assembly (300) comprises an upper tube (304), a lower tube (306), and said height adjustment mechanism (302). This configuration is depicted by Figure 33. In this configuration, the lower tube (306) connects to the attachment block (210) of the hip assembly (200) and the upper tube (304) connects to the upper assembly (400). The height adjustment mechanism (302) is comprised of a button plunger (308) that is set inside the upper tube (304), wherein button plunger (308) engages into holes (310) in said lower tube (306) to adjust the length.
(312) of the spine assembly (300). Button plunger (308) is spring loaded to snap into the holes (310) in the lower tube (306). Figure 34 shows a cross section of height adjustment mechanism (302).

Figure 32: posterior three-quarters view of spine assembly (300).

Figure 33: Sagittal view of spine assembly (300).
The upper assembly (400) is coupled to the spine assembly (300) and attaches to the user’s torso (506), as seen in Figure 35. In some embodiments, the upper assembly (400) comprises an upper attachment block (402) and a pair of shoulder straps (404). The upper attachment block (402) is rotatably coupled to the spine assembly (300). The shoulder straps (404) are configured to wrap around the user’s shoulders (508) and attach to the hip assembly (200), upper assembly (400), spine assembly (300), or any combination thereof. In Figure 35, shoulder straps (404) are connected to the hip assembly (200). The shoulder straps (404) can be adjusted in length (406).
In some embodiments, the torque transfer frame (200) may additionally include a suspension hammock (102), a spine pad (104), or both (Figure 36). Suspension hammock (102) is a textile part in between the person’s lower back (502) or upper back (510) and the spine assembly (300) that creates a physical space (106) between the person’s lower back (502) or upper back (510) and the spine assembly (300) as depicted in Figure 37. Spine pad (104) can be attached to the suspension hammock (102), hip frame (200), spine frame (300), or upper frame (400). Spine pad (104) is designed to provide additional padded support if the user’s lower back (502) or upper back (510) contacts the spine frame (300).

Figure 36: Second generation back frame (100) with attached suspension hammock (102) and spine pad (104).

Figure 37: Sagittal view of second generation back frame (100) with suspension hammock (102) and spine pad (104).
2.3.2 Don/Doff Procedure

The operator first dons backX by inserting his or her arms through the shoulder straps and buckling the waist belt. The leg straps are then buckled and tightened until snug. Lastly, the sternum strap is buckled and tightened. The tension of the shoulder straps can be adjusted to the operator’s comfort, but must be snug tight to transfer the hip torque from the torque generators into a force onto the operator’s torso to support the weight of the upper body and any attached loads.

The second generation auto-adjusting back frame significantly reduced the number of adjustments required prior to donning backX. Required adjustments was reduced from six adjustable parameters (chest width, torso depth, torso width, spine height, hip width, hip depth) in the first generation backX to three adjustable parameters (torso, spine height, hip depth) in the second generation backX. However, reduction in the number of torso adjustment parameters resulted in greater protrusion off of the user’s back compared to the first generation back frame (Figure 38). This was attributed to the longer length of the second generation back frame spine. The first generation back frame is designed to extend up to the user’s mid-thoracic (T8-T10) spine and uses two straps passing under the arms at the level of the operator’s 5th and 7th ribs to transfer supporting force onto the operator. When the operator bends forward, protrusion of the exoskeleton is minimal and caused by minor angular displacement between the exoskeleton spine and user’s lumbar spine. The second generation back frame rigidly extends up to the level of the operator’s acromion and does not include any sagittal flexion/extension degree of freedom. Consequently, when the operator bends forward, flexion of the operator’s cervical and thoracic spine is not replicated by the exoskeleton, causing the exoskeleton to protrude significantly more from the operator’s thoracic and cervical spine.

Figure 38: Protrusion of the first generation back frame (left) is less than the protrusion of the second generation back frame (right). However, many tasks in the workplace do not require the user to bend forward in areas with low vertical clearance. Consequently, while the second generation back frame has increased protrusion, this has minimal effect on job tasks for many workers.
The first and second-generation back frames were tested with 8 individuals to assess changes in don/doff time between the first- and second-generation back frame. The back frame was first adjusted to fit each user, then placed facing the user at waist height on a bench. The times for each subject between lifting the backX off of the bench and buckling the last buckle (don time) and the times between Disconnecting the first buckle and placing backX on the bench (doff time) were recorded for each subject. Don and doff times between first generation and second generation backX were compared. Don and doff time was reduced by an average of 50% (10.8%) and 58% (9.1%) for all users, with all users unanimously indicating that they felt it was more intuitive. Table 4 illustrates don/doff time reductions, average intuitiveness score, and maximum protrusion from the user’s back.

Notably, greater protrusion from the operator’s back was observed with the second generation back frame. The average distance between the operator’s back and the device increased by 2 inches (SD = 0.7”) across all subjects. This reduces practicality of the back frame for tasks that require working in tight spaces with minimal vertical clearance, such as inside of a ship or airplane. However, for the majority of warehouse or materials handling tasks, protrusion from the thoracic or cervical level while performing a 90 degree forward bend has a negligible effect on worker performance. These two different work environments are depicted by Figure 39.

Table 4: Don/doff times (sec) for first generation (G1) and second generation (G2), changes in don/doff time, intuitiveness (1 = most intuitive, 5 = very difficult), and maximum protrusion off the operators back (in)

<table>
<thead>
<tr>
<th>Subject</th>
<th>G1: $t_{don}$</th>
<th>G1: $t_{doff}$</th>
<th>G2: $t_{don}$</th>
<th>G2: $t_{doff}$</th>
<th>$\Delta t_{don}$</th>
<th>$\Delta t_{doff}$</th>
<th>$I_1$</th>
<th>$I_2$</th>
<th>$d_1$</th>
<th>$d_2$</th>
<th>$\Delta d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39</td>
<td>12</td>
<td>19</td>
<td>6</td>
<td>-51%</td>
<td>-50%</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>4.25</td>
<td>42%</td>
</tr>
<tr>
<td>2</td>
<td>41</td>
<td>13</td>
<td>24</td>
<td>6</td>
<td>-41%</td>
<td>-54%</td>
<td>3</td>
<td>1</td>
<td>2.5</td>
<td>3.5</td>
<td>40%</td>
</tr>
<tr>
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<td>30</td>
<td>8</td>
<td>20</td>
<td>3</td>
<td>-33%</td>
<td>-63%</td>
<td>3</td>
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<td>2.5</td>
<td>4</td>
<td>60%</td>
</tr>
<tr>
<td>4</td>
<td>79</td>
<td>30</td>
<td>29</td>
<td>8</td>
<td>-63%</td>
<td>-73%</td>
<td>3</td>
<td>2</td>
<td>2.5</td>
<td>4.5</td>
<td>80%</td>
</tr>
<tr>
<td>5</td>
<td>38</td>
<td>11</td>
<td>23</td>
<td>5</td>
<td>-39%</td>
<td>-55%</td>
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<td>3</td>
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<td>45</td>
<td>22</td>
<td>19</td>
<td>9</td>
<td>-58%</td>
<td>-59%</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>5.5</td>
<td>83%</td>
</tr>
<tr>
<td>7</td>
<td>59</td>
<td>19</td>
<td>23</td>
<td>7</td>
<td>-61%</td>
<td>-63%</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>67%</td>
</tr>
<tr>
<td>8</td>
<td>52</td>
<td>16</td>
<td>26</td>
<td>9</td>
<td>-50%</td>
<td>-44%</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>33%</td>
</tr>
<tr>
<td>AVG</td>
<td>47.9</td>
<td>16.4</td>
<td>22.9</td>
<td>6.6</td>
<td>-50%</td>
<td>-58%</td>
<td>3.4</td>
<td>2.0</td>
<td>2.8</td>
<td>4.5</td>
<td>66%</td>
</tr>
<tr>
<td>SD</td>
<td>15.4</td>
<td>7.1</td>
<td>3.5</td>
<td>2.1</td>
<td>10.8%</td>
<td>9.1%</td>
<td>0.5</td>
<td>0.8</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Figure 39: the larger protrusion of the second-generation back frame would be less suitable for workers who are working in environments with low vertical clearance (left). However, many warehouses have ample vertical clearance where rearward protrusion has minimal effect on job performance or worker adoption.

2.3.3 Range of motion

The position of the operator’s trunk is largely determined by lateral flexion and twisting of the spine. Lateral flexion can be largely accounted for by lateral flexion of the lumbar spine. Unlike other body joints, the spine consists of a multi-segmented column of vertebrae, each with its own degree of lateral flexibility (Figure 40). Lateral movement of the torso is attributed to lateral flexion at each level of vertebrae, while twisting in the transverse plane is attributed to relative rotation between each vertebrae. Torques in the sagittal plane (forward flexion or extension torques) are translated into forward movement of the torso by flexion/extension at each vertebral level – however, for the exoskeleton to transfer torque to the operator’s body, the spine cannot be allowed to freely flex in the sagittal plane. Because of this, forward flexion and extension of the spine are not replicated by the back-frame.

Figure 40: Range of motion at each vertebral disk of the spine. Adapted from [38].
The second-generation back frame features 5 degrees of freedom; 4 hip abduction/adduction joints and twisting of the spine in the frontal plane (Figure 41). The plurality of hip joints allow for both lateral flexion of the trunk and also freely adjusting the width of the frame without misaligning the hip joint. This allows the operator to perform complex maneuvers such as deep squats, low lateral shuffling, or stepping up onto a high step that were not possible with the first-generation frame. The degree of twisting freedom is preserved from the first-generation frame and is critical for enabling the operator to reach to either side and isolate transverse rotation of the trunk from movement of the hips.

![Figure 41: Twisting and lateral flexion degrees of freedom of the second-generation back frame. There is 1 twisting degree of freedom and 4 ab/adduction axes of rotation.](image)

2.3.4 Loading

The torque produced by the torque generators reaches a maximum of 180 in-lb of torque per generator, resulting in a total of 360 in-lb of bending moment on the frame from the torque generators (Figure 42). This places a significant bending moment at the base of the lumbar spine and the attachment mounts that couple the torque generator to the back frame. Consequently, the torque generator mount, spine joint, and abduction links must be designed to withstand these loading conditions. Stress concentrations were simulated using Solidworks (Dassault Systemes, France) and generated using worse-case loading scenarios where, referring to Figure 42, $d$ was assumed to be 15”, the largest configuration possible for the back frame, and $F_{ex}$ was applied at the end of $d$. 

36
Figure 42: Bending moment $T_{ex}$ on the back frame. Areas with high stress concentrations are circled in red. Specifically, these regions are (left to right): the torque generator mount, spine pivot, and abduction links.

The torque generator mount (224) couples the back frame to the torque generator and is depicted in Figure 43, along with the calculated stress concentrations. The torque generator mount (224) slides prismatically within the back frame tube (216) and is locked by a button plunger (228). Torsional loading of 360 in-lb was applied using a simulated test fixture, while the base of the torque generator mount (224) was fixed to simulate worst-case loading. A rolling fixture constraint was applied to the button plunger hole (230) to simulate the button plunger locking relative motion between the back frame tube (216) and the torque generator mount (224). Maximum stresses were determined to be $\sigma = 25.1 \text{ ksi}$, located at the bottom of the tube frame. Consequently, the material chosen for the torque generator tube was 7075-T6 aluminum ($\sigma_y = 70 \text{ ksi}$), giving the component a factor of safety of 2.8.

Spine pivot (212) connects the spine frame (300) to the abduction links (208) and (210) and is depicted by Figure 44. Two custom 0.375” diameter bolts are used to couple spine pivot (212) to each abduction link (208) and (210). A 0.0625” thick thrust washer sits between the flat interfaces of the spine pivot (212) and abduction links (208) and (210). For this loading scenario,
a roller fixture was applied to the bolt holes and washer surfaces, and the spine assembly hole in spine pivot (212) was subjected to 360 in-lb of flexion torque as indicated. A 200 lb upward force was applied to simulate tension in the spine rod due to elongation of the spine during forward bending; a 15 lb anterior facing, sagittal force was applied to simulate forces from the operator’s torso pulling on the shoulder straps; and a 360 in-lb bending moment was applied. Maximum stresses were determined to be $\sigma = 27.3 \text{ ksi}$, and therefore the spine pivot was manufactured using 7075-T6 aluminum as well to yield a factor of safety of 2.6.

![Diagram of spine pivot and loading results](image)

Figure 44: Loading results on the spine pivot (212). Largest stress was 27.3 ksi, located at the bottom of the “spine frame hole” in spine pivot (212).

The abduction links (208) and (210) couple the spine pivot (212) to the back frame tubes (214) and (216) and are thin, lightweight, and designed for low cost manufacturing. Each link can be laser cut from a flat sheet of 0.125” 17-4PH with relatively low (+/- 0.010) tolerances. The holes can be bored using a 0.375” reaming operation. There are four abduction links total, which were subjected to a bending moment of 360 in-lb (collectively). A 15 lb horizontal force was also applied to simulate forces from the operator’s torso pulling on the shoulder straps. A roller fixture constraint was placed around each hole to simulate thrust washers. A maximum stress of $\sigma = 50.0 \text{ ksi}$ was found, yielding a factor of safety of 2.4, and is depicted by Figure 45.
The largest stresses were found on the insight of the bolt holes and was 50.0 ksi, yielding a factor of safety of 2.4.

2.3.5 Usability Testing and Feedback

The second-generation back frame was tested with 8 individuals to assess comfort, perceived weight, fit, and preference to determine whether the second-generation frame constituted an improvement over the first-generation frame. Changes in subjective comfort values are summarized by Table 5. Overall, subjects ranked the second-generation frame as less comfortable at the front of the shoulder (AVG: -0.6, SD: 1.1) and the ribs (AVG: -0.4, SD: 1.1) and more comfortable on the pectorals (AVG: +0.3, SD: 1.5) and hips (AVG: +0.5, SD: 0.9). Slightly less shoulder and rib comfort was expected, as the auto-adjusting frame transfers torque to the operator via two shoulder straps which place additional pressure over the anterior deltoids and lower ribs; in contrast, the first generation frame used a rigid, adjustable chestplate which distributed the load across the pectorals and did not load the shoulders. However, this slight reduction in shoulder comfort is offset by the average comfort ranking of the subjects which indicates a higher degree of comfort than discomfort as well as the faster don/doff time afforded by the second generation back frame’s shoulder straps. Also noteworthy is the increase in hip comfort ratings. This was expected because the operator’s single hip abduction axis is mirrored by two exoskeleton abduction joints, forming a three-bar linkage that enables the torque generator hip flexion/extension joint to faithfully remain aligned in the frontal plane with the biological hip flexion/extension joint. This allows the exoskeleton to flex laterally in response to the user abducting and adducting his or her hip. This ability to flex laterally in the frontal plane was not present in the first generation back frame. Consequently, this led to reports of discomfort when operators were required abduct their legs for a long period of time and the back frame did not expand laterally, creating uncomfortable hip pressure, which is reflected by the data presented by Table 5.
Table 5: Subjective changes in comfort rating. Subjects were asked to rank comfort on a 1-5 scale (1 was very uncomfortable, 5 was very comfortable). This table summarizes changes in ranking. Positive values indicate subjects felt the 2nd generation device was more comfortable than the 1st generation device, and negative values indicate the contrary. Average scores for both the 1st generation and 2nd generation device are summarized at the bottom.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Top of shoulder</th>
<th>Front of shoulder</th>
<th>Pectorals</th>
<th>Ribs</th>
<th>Waist</th>
<th>Hips</th>
<th>Thigh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>-2</td>
<td>1</td>
<td>0</td>
<td>-2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>-1</td>
<td>2</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>-1</td>
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<td>0</td>
</tr>
<tr>
<td>7</td>
<td>-1</td>
<td>-2</td>
<td>-3</td>
<td>-2</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>AVG</td>
<td>0.0</td>
<td>-0.6</td>
<td>0.3</td>
<td>-0.4</td>
<td>0.0</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>SD</td>
<td>1.3</td>
<td>1.1</td>
<td>1.5</td>
<td>1.1</td>
<td>1.2</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td>AVG 1st Gen score</td>
<td>4.3</td>
<td>4.5</td>
<td>3.6</td>
<td>3.9</td>
<td>4.1</td>
<td>3.6</td>
<td>4.3</td>
</tr>
<tr>
<td>SD 1st Gen</td>
<td>0.9</td>
<td>0.5</td>
<td>1.2</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>AVG 2nd Gen score</td>
<td>4.3</td>
<td>3.9</td>
<td>3.9</td>
<td>3.5</td>
<td>4.1</td>
<td>4.1</td>
<td>4.4</td>
</tr>
<tr>
<td>SD 2nd Gen</td>
<td>0.9</td>
<td>1.2</td>
<td>1.4</td>
<td>0.9</td>
<td>0.8</td>
<td>1.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Subjects were also asked to rank the perceived weight and range of motion while performing a deep squat, deep bend, 45 degree trunk twisting, and 30 degree side bending. Subjective changes in rank and average scores for the first and second generation device are presented by Table 6. There was an overall reduction in perceived weight. Despite that the first and second generation back frames both weigh approximately 3 lb, users perceived the second generation frame as being lighter. This was not expected, but may be due to a simplified donning procedure in which users are physically hold the exoskeleton for a shorter period of time and thereby expend less energy during donning, hence an overall reduction in perceived weight. There were minimal changes to range of motion, with the exception that operators overall felt greater range of motion while performing a deep squat. This is due to the additional abduction degrees of freedom mentioned before, which enable the second generation frame to freely expand and contract in the frontal plane without impeding the operator’s biological hip abduction.
Table 6: Changes in subjective ranking of perceived weight and range of motion during selected maneuvers. Subjects were asked to rank perceived weight and range of motion as indicated. Positive values indicate improvement over the 1st generation back frame, while negative values indicate lower performance of the 2nd generation back frame.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Weight (1 = too heavy, 5 = like wearing nothing)</th>
<th>ROM - Deep squat</th>
<th>ROM - Deep bend</th>
<th>ROM - Twisting</th>
<th>ROM - Side Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>-2</td>
<td>-1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>-1</td>
<td>-2</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>AVG</td>
<td>0.8</td>
<td>0.5</td>
<td>0.0</td>
<td>-0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>SD</td>
<td>0.7</td>
<td>1.8</td>
<td>1.2</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>AVG 1st Gen score</td>
<td>3.0</td>
<td>2.8</td>
<td>3.8</td>
<td>4.1</td>
<td>4.4</td>
</tr>
<tr>
<td>SD 1st Gen</td>
<td>0.9</td>
<td>1.3</td>
<td>1.3</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>AVG 2nd Gen score</td>
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<td>3.3</td>
<td>3.8</td>
<td>4.0</td>
<td>4.5</td>
</tr>
<tr>
<td>SD 2nd Gen</td>
<td>0.7</td>
<td>1.4</td>
<td>1.0</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Overall, 75% of subjects preferred the second generation frame to the first generation frame when asked which unit they would prefer to wear all-day for a lifting task.

2.4 Modularity

Workers at various industry facilities such as warehouses or packaging centers conduct many maneuvers in addition to bending, such as overhead reaching, lowering from overhead bins to conveyor belts, performing squat lifts, or sustaining a squat position while bending forward. These maneuvers can place additional force requirements at the user’s shoulder or leg muscles, in addition to the lower back muscles, increasing the risk for injury. Therefore, two connective systems are designed into backX to connect a leg support exoskeleton and/or a shoulder support exoskeleton to reduces forces in the leg and shoulder muscles, respectively, during these additional maneuvers.

2.4.1 Knee Exoskeleton Modularity

Many workers in the materials handling and warehousing industries perform both stoop and squat lifts. There is evidence that squat lifts can reduce bending moment about the lumbar spine [39], [41]. However, lifting using a squat lift technique incurs a higher metabolic cost than
stooped lifting [42]. Consequently, some workers may exhibit a higher propensity towards stoop lifting, despite the higher risk for back injury.

A knee-support exoskeleton called legX has been designed by suitX in Emeryville, CA, USA to reduce the risk for knee injury by reducing quadriceps muscle forces when squatting [43]. Figure 46 depicts the legX [44].

Figure 46: legX developed by suitX (legX, suitX, Emeryville, CA, USA). legX is a robotic exoskeleton designed to reduce quadricep muscle activation when squatting.

legX (100) fundamentally comprises a thigh link (104) designed to move in unison with the user’s thigh (204), a shank link (102) configured to move in unison with the user’s shank (206), a seat strap (640) to couple knee flexion of the user to knee flexion of the exoskeleton (100), and a shank attachment (642). Additionally, legX (100) may also include a foot mechanism (183), comprising an angle joint (180) and a foot connector (184) which may be configured to be attached to a user’s shoe (212). Seat strap (640) is designed to sit just below the user’s coccyx and pass behind the legs.

When the user performs a two-legged squat, legX (100) imposes a torque between thigh link (104) and shank link (102) to assist knee extension (118). Knee extension is defined as an increase in angle (122) between thigh link (104) and shank link (102). This generates a supporting force just below the user’s coccyx to support the weight of the upper body, where the supporting force $F_{ex}$ is transferred to the user by seat strap (640) (Figure 47). legX is also configured to electronically recognize the difference between walking and squatting, and only engage the supporting torque when the user is squatting.
Figure 47: Forces imposed on the operator by legX. $F_{ex}$ is a supporting force to support the weight of the upper body. $F_s$ and $F_g$ are reaction forces transferred to the user’s shank and foot, respectively.

legX also incorporates a “lock mode” that locks the exoskeleton knee joint against flexion, allowing legX to transfer all of the reaction forces from the operator’s weight to the ground. In this configuration, legX performs like a wearable chair.

**Coupling to backX**

Referring to Figure 48, the backX torque generator (108) features a removable thigh link. To remove thigh brace (106), the user pulls out abduction pin (700), located on the lower bracket (114) of torque generator (108). This allows thigh brace (106) to be removed. Abduction pin (700) cannot be separated from torque generator lower bracket (114). Once removed, torque generator (108) can be attached to the proximal end of legX thigh link (702) by aligning backX abduction hole (706) with legX abduction hole (704), then pressing abduction pin (700) through both assemblies by hand. This operation also disconnects the backX thigh straps from the exoskeleton. When backX is connected to legX, the leg straps are redundant as upward relative movement between the operator and the exoskeleton is prevented due to rigid attachment between the legX foot mechanism (Figure 46, 183) and the operator’s shoe.
Figure 48: Attachment procedure for attaching legX to backX. (a) push out abduction pin (700). (b) remove backX thigh link 106. (c) insert legX thigh link (702) and push abduction pin (700) back in. (d) procedure complete.

To wear the backX-legX combination, the operator first dons backX, then dons legX as shown by Figure 49.

Figure 49: Donning procedure for backX-legX combination. Operator first dons backX, then attaches legX.

**Task Evaluation and Use Cases**

When worn together, backX and legX impose functionally separate forces onto the operators body to reduce back muscle and quadricep muscle activation. As mentioned before, backX provides a supporting force onto the operator’s chest to support the weight of the trunk when the operator’s trunk passes a predefined angle from vertical. Furthermore, backX only engages when the operator is bending forward, and does not engage when he or she is walking.
legX provides a supporting force onto the operator’s buttocks region, just below the coccyx to support the weight of the upper body when two conditions are met: 1) the operator’s knee flexion reaches a predefined angle and 2) both knees are undergoing flexion. Consequently, the backX-legX combination is useful for reducing muscle activity during tasks that either require repetitive alternation between trunk flexion and squatting or sustained flexion of both the trunk and both knees.

Repetitive alternation between trunk flexion and squatting is characteristic of many warehouses and materials handling sites. In these cases, workers transition between receiving assistance from backX and legX depending on the type of lift and these transitions occur too quickly or unpredictably to make donning and doffing a separate exoskeleton for each lift practical. Figure 50 depicts an operator who frequently transfers from a stoop to squat posture while grinding. When the operator is lifting with a stooped posture, backX imposes a force on the operator’s chest to support the weight of the trunk and legX imposes negligible forces onto the operator’s body due to little to no knee flexion. When squat lifting, legX imposes an upward force onto the operator’s buttocks to support the weight of the upper body due to flexion of the knee and backX does not impose significant forces onto the operator’s upper body due to low inclination of the torso. The author does note that squat lifting often incorporates a forward bend, where the operator leans forward to improve the grip on the lifted object. In these cases, backX does engage due to forward inclination of the torso and supports the weight of the upper body.

Sustaining combined hip and knee flexion is common in many manufacturing plants that require a worker to manipulate a tool, grind, or weld at slightly below waist level (Figure 51). In these cases, backX and legX provide simultaneous assistance to the hip and knee joints, respectively. When both backX and legX torque generators are engaged, this does limit the mobility of the operator as both hip and knee flexion are required for walking. For workers engaging in sustained forward bending and squatting, this does limit the backX-legX combination to job tasks that require minimal forward or lateral movement of the legs.
Figure 51: A worker performing a sustained forward bend and knee flexion while wearing a backX-legX combination. In this configuration, the worker’s forward and lateral leg mobility is impeded by engagement of both torque generators, minimizing the benefit for tasks requiring the worker to walk around the workpiece.

The backX-legX combination has the added benefit of transferring the reaction forces and torques of any load attached to backX to the ground. This offloads the weight of the exoskeleton when the operator is not moving his or her feet. However, this requires legX is not flexed or in “lock mode.”

2.4.2 Arm Exoskeleton Modularity

Lifting objects from overhead to ground results in muscle loading of the anterior deltoids as height of the carried load increases [45]. However, the backX is only designed to provide a restorative hip torque to reduce muscle forces in the erector spinae. In a practical workplace setting where a user may not be exclusively bending forward but also reaching forward and overhead, it is useful to provide augmentative torques at the shoulder, in addition to the hip, to reduce muscle activity of both the anterior deltoid and erector spinae, respectively.

The backX V3 is designed to provide a hip flexion torque with an optional attachment for connecting a device to provide shoulder flexion torque. This is referred to as shoulderX and is depicted in Figure 52.

Figure 52: posterior view of shoulderX. shoulderX comprises a torso frame (102), proximal link (150), and distal link (152). In this case, torso frame (102) can be connected to backX.
shoulderX comprises a torso frame (102), proximal link (150), and distal link (152). When engaged, shoulderX provides an upward force under the operator’s arm via arm cuff (106). The forces the person imparts onto shoulderX are shown in Figure 53. When the user lifts their arm, shoulderX imparts for F onto the user to support the weight of the arm and any held loads. Supporting force F can be toggled on or off by the user when wearing shoulderX, but does not disengage automatically. Specifically, shoulderX has 2 degrees of freedom at the glenohumeral joint, allowing for extension/flexion of the shoulder, as well as abduction/adduction. The arm cuff (106) is also adjustable along the length of the humerus link to accommodate users of varying arm lengths.

![Figure 53: sagittal view of shoulderX worn by a person. shoulderX imposes a force F under the operator’s arm to support the weight of the arm and held loads](image)

**Coupling to backX**

Attaching shoulderX to backX does not require modification of backX. The attachment procedure is illustrated by Figure 54. The operator first depresses switch (700) on the upper frame (400), and slides the shoulderX torso frame (102) into the mounting slot of backX upper frame 702. shoulderX torso frame (102) includes indexing slots (704) which lock lateral adjustment upon insertion into upper frame (400). The height of spine frame (314) is then adjusted such that the distance (704) between the top of shoulderX torso frame and the operator’s shoulder is approximately one inch. This allows for a small degree of scapular protraction before the operator’s shoulder contacts the shoulderX torso frame.
To wear the backX-shoulderX combination, the operator first connects backX to shoulderX, as shown in Figure 55. Then, the operator can put on the exoskeleton system using the backX shoulder straps. Average donning time of the full system is approximately equal to time to put on backX, as the donning process is very similar.

**Task Evaluation and Use Cases**

backX and shoulderX impose functionally separate forces onto the user’s body. Fundamentally, the backX torque generation strategy requires the operator’s torso be inclined forward beyond a predetermined angle, and generates a torque profile that maximizes when the operator’s forward flexion angle reaches 90 degrees. By contrast, the shoulderX torque profile is continuously engaged and generates a torque profile that maximizes when the operator’s arm reaches 90 degrees of sagittal flexion relative to the spine and is not dependent on forward inclination of the torso. Therefore, the backX-shoulderX combination is useful for tasks that require lifting/lower operations from overhead to below-chest level work, repetitive below-chest
to above-chest work level changes, or work requiring operators to perform a horizontal push while stooped forward.

Lifting or lowering from an above-chest to below-chest work height is common at some plants where workers were required to palletize (Figure 56). Palletizing requires a worker to lift objects, usually from a waist-height conveyor belt, and stack these objects on an industrial 4x4 foot pallet – common examples may be automobile tire plants or delivery warehouses. The worker’s lifting posture changes as the pallet is stacked higher from a waist-to-ground lift performed either by bending at the knees or bending forward, to an overhead reach where the user’s back is relatively straight but the load is supported overhead and outstretched. In addition to generating forces in the posterior deltoid, the outstretched load additionally generates forces in the erector spinae to stabilize the resulting moment load. The backX+shoulderX combination generates restorative counter-torques to noticeably reduce posterior deltoid and erector spinae forces, resulting in worker relief and preference for using this combination.

![Figure 56: Worker performing a palletizing operation with the backX+shoulderX combination. Tasks requiring this combination typically require the operator to transfer shoulder-height loads to or from below-chest height.](image)

Repetitive below-chest to above-chest work level changes are common in some manufacturing plants wherein work height changes dynamically or rapidly enough such that donning a different exoskeleton for each task height is impractical. A common example is in construction sites, where workers may be required to install screws at various height levels (Figure 57). In this case, the backX provides assistance when the user stoops or works at a lower level, while shoulderX provides a supporting underarm torque during overhead installation. It is also useful to note that even while the operator’s torso is upright, there is a net moment at the lumbar spine caused by the weight of the tool being manipulated in the worker’s frontal workspace. In this case, backX may be shifted to Instant Engagement Mode to counteract the bending moment at the spine.
Stooped work where the operator is performing a horizontal push can be observed at construction sites and some manufacturing plants. When the user bends forward, backX supports the weight of the upper body and the load being held (Figure 58). In this case, shoulderX does not provide gravity compensation to offset the shoulder moment from holding the load, but rather exerts a flexion torque that maximizes when the arm is perpendicular to the spine and imposing a supporting force under the arm that pushes the arm forward.

2.4.3 Combined Knee/Arm Modularity

Workers are often required to perform tasks that place strains across the leg, back, and shoulder joints either simultaneously or unpredictably such that donning and doffing a separate exoskeleton for each job task is impractical. When configured in this way, despite being
interconnected, the backX, shoulderX, and legX are functionally independent and locally assist their respective joints. In other words, the backX supports the lower back muscles, shoulderX supports the shoulder complex, and legX supports the quadriceps, with no device assisting an unassociated muscle.

**Coupling to backX**

For the full suit combination, legX and shoulderX are coupled to backX as shown in sections 2.4.1 and 2.4.2. First, the backX thigh braces are removed, as shown in section 2.4.1. shoulderX is then attached to backX while the user is not wearing backX as shown previously in Figure 55. This allows the operator to don the backX-shoulderX combination using the shoulder straps. Next, legX is donned as previously shown by Figure 49.

**Use Cases**

The full system combination is useful for tasks that either require constant switching between leg, back, and shoulder muscle groups, or tasks that require the operator to squat, reach forward, and work overhead simultaneously. Repetitive tasks are commonly found at work sites that require workers to perform a dynamic array of tasks, such as a construction site. On a construction site, workers may be required to perform overhead tasks such as welding or drilling and various stoop or squat lifts such as drywall moving. However, in these cases, often the single benefit of one of the exoskeletons is offset by the added burden stemming from the combined weight of the exoskeleton. Hence, for workers required to perform a variety of tasks that may engage the back, shoulder, and leg muscles periodically throughout the day, workers should choose the exoskeleton that matches the posture and muscle loading that occurs most often during their work shifts. As exoskeletons become lighter and lower profile, the feasibility of a full suit exoskeleton with multi-joint augmentation will substantially increase as the metabolic cost of wearing a full suit will be reduced.

Tasks that require the operator to squat, reach forward, and work overhead simultaneously may include installation of electrical wiring or welding (Figure 59). In this configuration, the weight of the exoskeleton can be transferred directly to ground by placing legX in “lock mode.” This is useful for static tasks that do not require the operator to walk.

![Figure 59](image)

Figure 59: a worker wearing the full backX-legX-shoulderX system combination. In this configuration, legX can be locked against knee flexion, transferring the weight of backX and shoulderX to the ground so the operator is not impeded by the weight of these systems as long as both feet are on the ground.
Chapter 3: Ergonomic Evaluation for Repetitive Lifting

3.1 Introduction

Back-support exoskeletons have been shown to reduce back muscle activity while lifting [27]–[31]. Abdoli-Eramaki et al. demonstrated that wearing a back-support exoskeleton can reduce lumbar and thoracic erector spinae activation by 14.4% and 27.6%, respectively [46]. Wearing a back support exoskeleton while lifting a 30 lb package can result in a 54% reduction in erector spinae muscle activity [47]. Furthermore, Ulrey et al. demonstrated that wearing a back-support exoskeleton called “BNDR” reduced bicep femoris activation by 17% when bending forward [48]. Wearing a back-support exoskeleton also significantly reduced thoracic and lumbar erector spinae activation when the user was sustaining a static forward bend and not lifting, and did not significantly increase rectus abdominus activity [49].

The effect of back-support exoskeletons on reducing erector spinae activation is well documented – however, there is limited work available to characterize the effects of wearing a back-support exoskeleton on fatigue and whole-body metabolic cost. In one study, Whitfield et al. demonstrates no significant changes in oxygen consumption while wearing a back-support exoskeleton to perform a lifting task [50]. In another study, Lotz et al. indicated significant decreases in EMG MNF after 5 minutes of repetitive lifting of a ~17 kg box at 6 lifts/lowers per minute [34]. However, studies by both Whitfield and Lotz are limited to a non-commercially available device called “PLAD” that generates a spinal extension torque by imparting a force substantially parallel to the axis of the user’s spine [51]. This is fundamentally different than many commercially available back-support exoskeletons that impart a force sagittally perpendicular to the user’s spine when the user bends forward, thus supporting the weight of the upper body without exerting downward pressure on the user’s shoulders (Figure 60).

![Diagram](image)

Figure 60: (Left) Forces acting on a person wearing PLAD. (Right) Forces acting on a person wearing backX. Note that $F_{ex}$ and $F_{leg}$ are parallel to the longitudinal axis of the person’s body when wearing PLAD. This results in a downward compressive force on the shoulders. In contrast, wearing backX exerts a force perpendicular to the longitudinal axis, minimizing contribution to spinal compression.
As shown in Figure 60, backX fundamentally differentiates itself from PLAD by imparting a force onto the user’s chest rather than onto the user’s shoulders in a manner similar to BNDR, Springzback, and Laevo. For back-support exoskeletons that function similarly to backX, there is little literature that describes how wearing such an exoskeleton affects user fatigue and whole-body metabolic cost. Therefore, the purpose of this study was to evaluate the impact of wearing backX on muscle fatigue, metabolic cost, worker perception, and preference.

3.1.1 Study Objectives

The amount of time a person can maintain a specific level of muscle activity until exhaustion (endurance time) decreases after performing a fatiguing task [52], [53]. The objective of this study was to evaluate the effect of wearing backX on muscle fatigue during repetitive lifting and lowering by assessing whether wearing backX increases endurance time. Additionally, a common industry concern is whether workers will incur higher oxygen demands while wearing an exoskeleton due to its weight [54]. Thus, a secondary objective was to evaluate how wearing backX affects whole-body metabolic output during repetitive lifting tasks by measuring oxygen demand and rated perceived exertion.

3.2 Methods

3.2.1 Orientation

Eleven male subjects with an average age of 33.2 years (SD = 10.7) participated in this within-subjects laboratory study. Individuals with medical history including back injury or any surgery were excluded. After providing informed consent, participants completed a baseline survey and electromyographic (EMG) electrodes (Noraxon, Scottsdale, Arizona) were attached over the right and left lumbar erector spinae (RLES, LLES), thoracic erector spinae (RTES, LTES), and biceps femoris (RBF, LBF). backX was then adjusted to fit the subject’s body dimensions.

To measure maximum voluntary contraction EMG activity (MVC) for each muscle group, subjects were instructed to incline their upper body to horizontal while in the Roman chair with their feet secured, grasp a floor-mounted strap, then extend their back with maximum effort for 3 seconds. This procedure was repeated three times. The MVC for each muscle was recorded as the maximum EMG signal measured in that muscle over the course of these three trials. Subjects did not wear backX while eliciting MVC measurements.

3.2.2 Experimental Protocol

Subjects first performed an endurance test where each subject was in a prone position on a Roman chair with their feet secured, then held their upper body at a 45° angle while holding a 5 kg weight until they could no longer hold their body at the 45° angle (test posture, Figure 61a). The duration that the subject could hold the test posture prior to performing any work was measured before (pre-work endurance time) and after (post-work endurance time) each work session. The work session consisted of lifting and lowering an 18 kg load at 7 lifts/minute for 4 minutes (Figure 61b). After each post-work endurance session, the subject was required to take a 30 minute break to minimize the cumulative effects of fatigue. These endurance tests and work
session were repeated for each subject with and without backX in a randomized order. Figure 62 diagrams the experimental procedure.

Figure 61a (Left): Subject performing test posture for the endurance test. Figure 14b (Right): Subject lifting and lowering weight tray while wearing the exoskeleton.

Figure 62: Experimental procedure. The procedure consisted of a calibration session for fitting and instrumenting the subject, as well as collecting the subject’s MVC, followed by a pre-work endurance session, a work session, a post-work endurance session, and a survey/break. The endurance and work sessions were repeated upon changing the independent variable. A final survey was administered at the end.

EMG data was collected at 1500 Hz continuously during work and endurance tests and normalized to the subject’s MVC. Summary measures of EMG amplitude probability distribution functions for 50 (APDF50) and 90 (APDF90) percent of the work session were estimated and normalized against MVC for each muscle group to quantify mean and peak muscle activation levels. Metabolic changes were quantified by oxygen consumption (Metamax, Leipzig, Germany).
Subjects rated their perceived exertion every 30 seconds on the BORG 1-10 scale during each endurance and work session. After completing the post-work endurance test, subjects were requested to fill out a survey to assess thermal buildup while wearing backX, propensity for wearing the device and gather condition-specific feedback. Lastly, upon completion of the experiment both with and without backX, subjects completed a final survey to directly compare task difficulty with and without backX, overall device usefulness, and gather practical feedback.

3.2.3 Electromyography setup

EMG data was recorded using a remote system (TeleMyo, Clinical DTS, Noraxon MyoMuscle, Scottsdale, AZ) and sampled at 1500 Hz continuously throughout the experimental session. Pairs of Ag/AgCl electrodes (1 cm diameter, 2 cm inter-electrode distance) were attached bilaterally along the long axis of the lumbar erector spinae, thoracic erector spinae, and biceps femoris [55], [56]. If necessary, participant skin was shaved before adhering the electrodes to minimize signal interference due to hair between the user’s skin and electrode surface. Thin elastic bands were then wrapped around the user’s quadriceps, lumbar torso segment and thoracic torso segment as an additional measure to prevent electrode movement during the experiment. Data was captured by Noraxon MR3.10 software and rectified, smoothed (RMS 100ms window), and normalized against each subject’s MVC. Median and peak muscle activity was summarized by calculating muscle activity that each user was at or below for 50% (APDF 50) and 90% (APDF 90) of the work session [57], respectively, using Matlab (Matlab, The Mathworks, Inc.).

3.2.4 Endurance Tests

Endurance tests are commonly used to evaluate changes in local muscle fatigue after performing work. The general sequence of performing an endurance test is as follows:

1. **Pre-work endurance test**: the subject maintains a posture designed to activate the primary muscles to be studied and holds this posture until exhaustion. Exhaustion is defined as the time at which the subject can no longer hold this posture. In this study, maintaining a 45 degree posture (Figure 61a) activated the lumbar and thoracic erector spinae. Exhaustion could therefore be attributed to erector spinae muscle fatigue. Subjects held this posture until exhaustion. The time until the subject became exhausted was labelled “pre-work endurance time.”

2. **Work session**: the subject performs a work session designed to fatigue, but not exhaust the user. In this study, workers were asked to lift an 18 kg load at 7 lifts/minute for 4 minutes.

3. **Post-work endurance test**: the subject maintains the same posture as the pre-work endurance test and held this posture to exhaustion. The time until the subject became exhausted was labelled “post-work endurance time.”

4. **Work session (n+1…)**: the work session can be repeated as part of the experimental protocol. This study only required one work session with backX and one work session without backX.

5. **Post-work endurance test (n+1)**: After each work session, a post-work endurance test was performed to assess muscle fatigue.

As subjects performed more work sessions, post-work endurance time will decrease relative to pre-work endurance time [34], [52], [58]. The reduction in endurance time is reflective
of cumulative muscle fatigue, and not necessarily dependent on load lifted, lifting rate, or duration of work. The same post-work endurance time may be observed after lifting a light load for a lengthy period of time versus a heavy load for a short period of time. Potvin et al. indicate no significant difference in maximum extensor moment or exhaustion time due to muscle fatigue after subjects undergo a fatiguing work session consisting of repetitive lifting at 8 lifts/lowers per minute for 20 minutes with a 19 kg load or 6 lifts/lowers per minute for 120 minutes with a 17 kg load [52]. Subjects demonstrated no significant changes in maximum extensor moment or exhaustion time, indicating equal amounts of fatigue after both the 20 minute and 120 minute work session. These results imply that equal amounts of fatigue can be induced both by short, high load, high rate work sessions and long, lower load, lower rate work sessions.

Therefore, to reduce the time required for each subject to participate in this experiment, a lifting protocol similar to the short 20 minute procedure from Potvin et al.[52] and Lotz et al. [34] was developed. Subjects were asked to lift and lower an 18 kg load at 7 lifts/lowers per minute for 4 minutes and perform an endurance test before and after the work session to determine the rate of fatigue [34], [52]. To determine the duration of the experiment, we observe that Lotz et al. indicated significant decreases in EMG MNF after 5 minutes of repetitive lifting of a ~17 kg box at 6 lifts/lowers per minute [34]. A pilot protocol was established using a slightly shorter 4 minutes of lifting at a faster lifting rate of 7 lifts/lowers per minute, and also resulted in an MNF shift to lower frequencies.

### 3.2.5 Oxygen Consumption

Metabolic cost of exercise was measured by oxygen consumption, which increases during exercise or strenuous activity [59]. Perceived exertion was measured by having subjects rate perceived intensity of effort (RPE) on the BORG scale, which is significantly and strongly correlated to blood lactate and heart rate during exercise and is independent of age, gender, medical history, level of physical activity, and type of exercise [60].

Metabolic changes were measured using a teleoperated Metamax 3B system (Metamax 3B, Cortex Biophysik Gmbh, Leipzig, Germany) and sampled during the work session only. Maximum oxygen uptake was calculated using the Wasserman weight algorithm [61]. Volume of inhaled O$_2$ (V$_{O_2}$) consumption rate was captured using Metasoft Studio and normalized to subject body mass [34]. For both the unassisted and assisted experimental condition, oxygen consumption across all subjects for each percent completion of the work session was averaged, then plotted to summarize oxygen consumption rate as a function of percent completion of the work session [50].

### 3.2.6 Qualitative Measurement

Subjects were asked to verbally rate perceived exertion on the BORG CR10 scale (1 = low exertion, 10 = extremely high exertion) every 30 seconds during the endurance tests and work sessions to assess RPE. Post-experiment qualitative measures of perceived exertion, task difficulty, heat buildup, and device performance were captured using a Qualtrics survey (Qualtrics, Provo, UT) after both experimental sessions with and without backX. Subjects were asked to rate exertion (1 = no exertion, 10 = exhausted) in their lower back, upper back, abdominals, quadriceps, hamstrings, and shoulders to assess perceived muscular load. Subjects were then asked to indicate on heat maps areas of body heat buildup during the work session. Changes in exertion and heat scores were then collated across unassisted and assisted conditions to assess how wearing backX affected perceived exertion and heat buildup. A final survey was administered via Qualtrics at the
end of the experiment to garner general feedback about backX and whether it would be useful for everyday use.

3.3 Results

3.3.1 Peak and Median Muscle Activity

Compared to the unassisted condition, use of backX during the repetitive lifting task reduced median and peak thoracic and lumbar erector spinae muscle activity, as seen in Figure 63 and Figure 64. For 50% of the work session, median RLES and LLES activation was at or below 24.3% and 23.3% of MVC when wearing backX, compared to 29.2% and 27.3% of MVC when not wearing backX (Figure 63). Reduction of peak muscle activation for RLES and LLES was statistically significant (p < 0.05). This was expected since using backX during a lifting task induces a torque about the hip joint to support the weight of the upper body, thereby reducing erector spinae activation throughout the entire work session.

RLES and LLES EMG activation when wearing the backX were at or below 62.6% and 57.4% of MVC for 90% of the work session, respectively, compared to 75.0% and 73.4% of MVC when not wearing backX.

![Figure 63: Summary measures of APDF 50. *indicates statistically significant result.](image1)

![Figure 64: Summary measures of APDF 90. *indicates statistically significant result](image2)

3.3.2 Endurance Time

Comparing endurance times with and without backX show that the work session was less fatiguing when performed wearing backX. This is depicted graphically by Figure 65 and Figure 66. Referencing Figure 65, 

\[ T_{fBX} = 0.71 T_{fBX} \]

\[ T_{fNO} = 0.50 T_{fNO} \]
Additionally, it is noted that $T_{fBX} \approx T_{fNO}$ as there was no significant difference between $T_{fBX}$ and $T_{fNO}$. Equating these two terms, we can relate post-work endurance time after using backX $T_{fBX}$ to post-work endurance time after not using backX $T_{fNO}$ as follows:

$$T_{fBX} = 1.42 T_{fNO}$$

In other words, if the pre-work endurance time for a subject was measured to be $T$, the post-work endurance time was 50% of $T$ when no backX was used, compared to 71% of $T$ when backX was used. This means in doing a set of fixed tasks during a work session with backX, the subjects wearing backX were able to last 42% longer, in any secondary task, than when not wearing backX.

![Diagram showing the comparison between pre-work and post-work endurance times with and without backX](image)

Figure 65: Results for endurance times. Note that post-work endurance time after wearing backX was generally longer than post-work endurance time not wearing backX.

![Bar chart showing post-work endurance time comparison](image)

Figure 66: Post-work endurance time normalized against pre-work endurance time. Higher value indicates subjects were able to hold the post-work endurance posture for a longer period of time.

### 3.3.3 Oxygen Consumption

Wearing the backX resulted in no significant increase in VO$_2$ oxygen consumption rate. The oxygen consumption rate per kg of body mass while wearing backX was 14.7 mL/kg/min after 2 minutes of lifting and 15.2 mL/kg/min after 4 minutes of lifting. VO$_2$ consumption rate while lifting without backX was 14.4 mL/kg/min after 2 minutes and 15.7 mL/kg/min after 4 minutes of lifting. After 50% of the work session was completed (2 minutes), oxygen consumption
rate stabilized and no significant differences were found. Oxygen consumption data is presented in Figure 67.

![O2 consumption rate graph](image_url)

Figure 67: Oxygen consumption vs % work session completion. After approximately 2 minutes (50% completion), no significant differences in oxygen consumption rate.

Perceived exertion was generally significantly lower (p < 0.05) during each 20 second interval when wearing backX vs. when not wearing backX (Figure 68). Minimum/maximum perceived exertion across all subjects when wearing backX was 2 and 10, respectively, compared to 4 and 9 when not wearing backX. Median perceived exertion was rated at a 3 when wearing backX, compared with 5 when not wearing backX.

![Rated Perceived Exertion (BORG 1-10) graph](image_url)

Figure 68: Average rated perceived exertion across all subjects during the work session. *indicate statistically significant negative changes.
Overall, lower peak and median muscle activation was recorded for workers using backX during the work session than workers not wearing backX. Furthermore, changes in endurance time indicate that in doing a set of fixed tasks during a work session with backX, subjects wearing backX were able to last 42% longer, in any secondary task, than when not wearing backX, with no changes in VO$_2$ consumption rate. In all cases, workers perceived the work session as less tiring when wearing backX; though the magnitude of the change in perceived exertion was not statistically significant, RPE scores during the assisted condition were significantly lower relative to the unassisted condition.

3.4 Discussion

3.4.1 Muscle Activity

The results of this study indicate that wearing backX during a lifting task reduces muscular activation of the erector spinae. Peak muscle activation for RLES and LLES was reduced by 16.5% and 21.8%, respectively, when wearing backX ($p < 0.05$). This reduction in peak and median muscle activation for RLES, LLES, RTES, and LTES is consistent with various studies showing reduction of back muscle activation while wearing a back support exoskeleton to perform a lifting task [31], [34], [50], [58]. Smaller changes in peak thoracic erector spinae activation versus median activation levels can be attributed to the lumbar erector spinae supplying the majority of extension torque when the user is lifting and therefore benefitting the most from the supporting torque provided by backX.

The implications of reduced back muscle activity include reducing the risk for back injury. As mentioned by McGill, back injuries can occur in one of three modalities – an instantaneous load that exceeds the failure strength of the tissue, sustained cyclical loading causing a reduction in tissue failure strength, and sustained loading also causing a reduction in tissue failure strength [12]. A significant reduction in muscle activity can reduce muscle loading below the tissue failure strength for all three cases, thereby indicating a mechanism by which wearing back support exoskeleton reduces risk for back injury.

3.4.2 Fatigue

General overall reduction of endurance time was expected as the work session was designed to fatigue the user and not completely exhaust them (Figure 66). The 50% reduction in endurance time is slightly less than the 57% reduction in endurance time reported by Lotz et al. [34]. However, it should be noted that the lifting rate was 16% faster in this experiment but conducted over a shorter period of time. Psychological effects may have played a role in subjects adjusting their efforts knowing that they would be lifting for a shorter period of time, and thereby conspicuously increasing muscle force as the work session was short.

The post-work endurance time increased by 52% after performing the repetitive lifting task with backX. Increased post-work endurance time and reduced muscle activation is congruent with reduced muscle fatigue after repetitive lifting [33], [34], [52]. Reduction in muscle activity increases post-work endurance time [53], hence the observed increase in post-work endurance time after wearing backX is likely attributed to the reduction in erector spinae muscle activity from wearing backX to perform the lifting task.

All subjects subjectively perceived exerting less during the work session while wearing backX, with the exception of one subject who indicated that he may have been deliberately pushing
into the device to engage the support, rather than leaning into the device and allowing gravity to instigate forward motion. This misunderstanding of how to use the device highlights the importance of training on the proper usage of backX. Users must understand and trust backX to support a portion of the weight of their upper body; otherwise, users may feel that wearing backX increases exertion.

### 3.4.3 Metabolic Changes

Consistent with findings from Whitfield et al. [50], wearing the backX had no negative effects on oxygen consumption rate. Differences in oxygen consumption rate with backX (SD = 1.2 mL/kg/min) and without backX (SD = 1.8 mL/kg/min) across all subjects were due to how the subjects used the backX. Some subjects lean forward into the device and allow gravity to instigate forward movement of the trunk, rather than pushing deliberately into the device to force forward bending of the trunk, the latter of which requires more effort.

O2 consumption rate begins to stabilize after about 2 minutes of work. This is consistent with Whitfield et al. [50], though the average 14.7 mL/kg/min in this study is slightly lower than the 17.8 mL/kg/min reported by Whitfield et al. This was to be expected as the work session was designed to maintain O2 consumption below the anaerobic threshold (AT). AT is defined as the transition from aerobic to anaerobic metabolism and is characterized by an increase in ventilatory rate, which occurs after prolonged exertion [62]. Generally, AT is characteristic of prolonged, heavy exertion typically encountered when running marathons or long distances and is a level of exercise that is not required for palletizing operations at a warehouse. Consequently, as this study was meant to approximately emulate package weight and lift rates characteristic of warehouse palletizing, subjects were not expected to reach AT and exhibit a sharp increase in oxygen consumption rate.

Data is subject to high variations between subjects due to inadequate recovery time for some subjects between performing the protocol assisted versus unassisted. Consequently, the initial large variability between O2 may be due to the rest period between conditions being inadequate to allow full muscle recovery after the fatiguing work session.

### 3.4.4 Subjective Feedback

Table 7 tabulates selected subjective feedback on backX comfort, usefulness, and practicality.

#### Muscle Groups

Subjects consistently indicated reduced muscular exertion in lower back, upper back, and shoulder muscle groups when wearing backX. Reduced exertion in the back muscles is consistent with literature showing a reduction in back muscle strain when using a back-support exoskeleton to lift a load [34], [58], [63]. These findings are corroborated by reductions in erectors spinae muscle activity, and indicate that wearing a back support exoskeleton reduces muscle activity. Additionally, this may also carry some implications for use in the workplace – if workers perceive less strain in the lower back region, this may cause some workers to overexert or lift loads that are substantially heavier than their normal lifting loads. This is potentially dangerous, as backX is only designed to reduce lower back muscle forces and does not impact loading of other joints or muscles. Therefore, even though backX may reduce lower back muscle activation to safe levels, a worker perceiving that he or she can lift more may injure a different muscle group. It is therefore
recommended that backX not be used to lift loads heavier than the operator would normally lift during his or her work shift.

**Thermal Discomfort**

There were no significant differences in heat buildup location when wearing backX. Subjects indicated the lower back as the primary area of heat buildup both when wearing backX and not wearing backX. Although backX covers more area when worn, the heat trapped by wearing backX is negligible. This may be due to the short duration of the work session – if multiple work sessions were performed by each subject, a more pronounced difference in heat buildup between with and without backX may be observed. The results of this study indicate that thermal buildup will occur first at the lower lumbar region; this could be addressed by either integrating cooling packs into the back frame or maximizing ventilation around the lumbar spine region for future backX iterations.

**Exertion**

The majority of users (n = 10) indicated that they felt using the device would reduce the exertion required for a repetitive lifting task. The remaining subject indicated he would expect no change in exertion. Changes in preference are likely due to the perceived strength of the device – even though the subject who indicated no change in exertion was not the heaviest nor the most muscular subject, he commented “I could see more effect with the assist being stronger,” and indicated that it would have been easier to let gravity charge the spring if the spring was stronger. In these cases, it is important to note that this was the first time all operators had worn an exoskeleton, and perceived exertion has been observed to change in the field after operators become more accustomed and trained to backX. The assistive torque provided by backX is also constrained by form factor of the mechanical gas springs – stronger assistive springs are larger and heavier and would increase protrusion of the torque generator into the user’s workspace, in the current configuration of torque generator. A method of reducing the size of the torque generator is discussed in Section 4.2.1 Powered Actuation. In this case, it would be possible to use a heavier gas spring to provide more assistance.

**Posture**

9 subjects indicated that wearing backX would be useful for bending forward, holding a bend while standing, and lifting from a stooped position. However, many users did not feel it would be useful when kneeling. One user commented “One knee is difficult because [there is] more pressure on one side.” This is attributed to the torque generators providing different torques based on different hip flexion angles at each hip. During field testing of devices, this also manifested as backX rotating in the transverse plane when users adopted a one-knee kneeling posture while bending forward. This could be addressed by either changing the torque profiles of the torque generator such that it provides the same torque at every flexion angle or linking the two torque generators with a differential such that they always provide equal torque, regardless of flexion angle.
Table 7: Selected subjective feedback on usefulness, comparison to other devices, and practicality.

<table>
<thead>
<tr>
<th>Subject</th>
<th>What are a few things you like about the device?</th>
<th>How does this device compare to other devices you have used in the past to prevent back injuries?</th>
<th>Compatibility: What features would prevent you from using this device during the work day?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>It did help my lower back with the repetitive motion of lifting</td>
<td>Better than the lifting belt</td>
<td>I need to fluidity and wide range of motion when I am taping and mudding. This would limit that</td>
</tr>
<tr>
<td>2</td>
<td>support</td>
<td>I would wear one to work</td>
<td>climbing ladders and scaffolding</td>
</tr>
<tr>
<td>3</td>
<td>I like how for this test I was able to bounce back and forth allowing the springs to push me back.</td>
<td>This device is designed for people who lift with their back, so it would be for someone who doesn't regularly lift heavy objects</td>
<td>The stiffness and diminished utility while sitting down.</td>
</tr>
<tr>
<td>4</td>
<td>substantially easier to lift objects from floor to waist level</td>
<td>far superior to an old-school back brace</td>
<td>having to repeatedly put the device on and take it off</td>
</tr>
<tr>
<td>5</td>
<td>Its simple, helps with lifting, looks like a cool backpack</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>takes away strain</td>
<td>I only used gloves and a backstrap once</td>
<td>A lot of twisting of body</td>
</tr>
<tr>
<td>7</td>
<td>Very simple, Comfortable</td>
<td>No previous devices used</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>support overall</td>
<td>100% increase compared to back brace</td>
<td>how bulky it is</td>
</tr>
<tr>
<td>9</td>
<td>Ease of use</td>
<td>Actually assists your motion</td>
<td>Items may get caught on device</td>
</tr>
<tr>
<td>10</td>
<td>Great stability and back support when lowering items.</td>
<td>Much more support provided. Feels more stable in the lifting range of motion.</td>
<td>Pieces that interfere or block normal motions involved with typing on a computer at a sitting or standing desk.</td>
</tr>
<tr>
<td>11</td>
<td>It seems like it helps spring back into place when lifting weight and would help maintain proper posture.</td>
<td>It forces a spring when lifting up to support the lower back.</td>
<td>While it would help with posture, I don't think I would use it because it's bulky and not super comfortable or stylish.</td>
</tr>
</tbody>
</table>

3.5 Limitations

One of the key limitations of this study is duty cycle, weight, and lifting posture were held constant throughout the work session. This is not necessarily reflective of specific tasks where muscle fatigue would occur at a slower rate over the course of a work shift. Professional material-handlers in warehouses or delivery stations handle a variety of packages of differing sizes and
weights, and work rates vary widely across facilities and industries. These variations were controlled for in this study by isolating the subject from psychological and social factors in a laboratory setting, and having the subject perform a well-defined, repetitive task. A more comprehensive study would assess muscular fatigue under a variety of lifting conditions and weights to minimize confounding bias.

Another limitation of this study is the number of lifting trials performed by the subjects. Prior to conducting the study, researchers determined 20 minutes was required for each subject to recover sufficiently to minimize buildup of muscle fatigue by testing the experimental procedure in a pilot study, calculating rest allowance via Rohmert’s method [64], and applying a Factor of Safety of 2. To ensure subject experimentation fit within a 3-hour block, subjects performed one 4-minute lift with and without the exoskeleton. Future studies would extend the time allocated for the experimental procedure and increase the number of work sessions to increase statistical significance between measuring muscle fatigue in assisted and unassisted conditions.

Lastly, the study cohort was limited to men with a materials handling background. This potentially biases the results towards more muscular, physically fit individuals with larger body types. A more comprehensive study should include a broader sample population to achieve a more generalized result – however, caution should be taken to ensure the sample population is representative of the end-user population.

3.6 Conclusions

This study confirms that wearing a backX reduces muscle activation in the lower back for this specific dynamic lifting task. Additionally, we find that wearing a backX may reduce the risk of low back injuries by reducing muscle activity and increasing endurance time to fatigue.
Chapter 4: Concluding Remarks

4.1 Thesis Summary

This thesis describes the design and development of a novel back-support exoskeleton for reducing the risk for back injury. As work tasks requiring repetitive, consistent movements become increasingly automated, the role of the human worker will shift from repetitious labor to specialized tasks. The material in this dissertation represents a step forward in preserving the flexibility of the human workforce in an age of automation. The exoskeleton discussed here is a passive, purely mechanical device that is lighter, cheaper to manufacture, and more intelligent than other current state-of-the-art passive exoskeletons, able to differentiate between walking and bending, and being able to automatically adjust sizing in response to its user’s body type.

A torque generator is selected and modified to provide a torque profile suitable for worker use. Before modification, the torque generator differentiates between walking and bending, engages when the user bends forward 30 degrees, and occasionally seizes due to wearing of an internal component. Based on customer feedback, a modification was added to enable the operator to toggle between standard, 30 degree engagement to support lifting, and instant engagement mode (IEM) to support postures where the operator’s torso may be upright, but manipulation of a load far from the body places a large moment load on the lumbar spine musculature. Additionally, abrasion between two sliding parts was identified as the primary cause behind torque generator seizure and hence, a small magnet and grease was added to minimize abrasion between the two sliding parts. The resulting torque generator was over 7 times more robust and was well received by operators who reported back pain from table work, grinding, or manipulating heavy loads during tire manufacturing.

To transfer torque from the torque generator into a force that supports the weight of the upper body, a back-frame is designed. Both a first- and second-generation back frame are described in this dissertation. The first-generation frame is adjustable by locking mechanism for hip width, hip depth, spine height, torso width, and chest width and fits the 5th percentile female to the 95th percentile male. The first-generation frame was tested extensively in warehouses, manufacturing plants, and materials handling work sites and is responsible for generating feedback that drove the design of the second-generation frame. The second-generation frame is dynamically adjustable in response to the operator’s body type and significantly reduces donning and doffing time. Additionally, 2 more degrees of hip abduction/adduction on the second-generation frame enable operators to perform a wider array of complex maneuvers that are difficult to perform in the first-generation frame such as deep squats and high steps.

Additionally, the backX is designed to be compatible with other exoskeletons for augmenting different parts of the body such as the leg or the shoulder muscle complex. This gives backX unparalleled flexibility to remain suitable for any job task requiring prolonged squatting or working overhead. Once connected, all exoskeleton devices are functionally independent and do not impede the function of each other. Quick connection mechanisms are designed to rapidly attach a leg exoskeleton or shoulder exoskeleton.
Lastly, an ergonomic study to evaluate the effects of wearing a back support exoskeleton on muscle fatigue are presented. The results of this study indicate that wearing a backX during a lifting task reduces median and peak muscular activation of the erector spinae. Additionally, comparing endurance times with and without backX suggests that the work session was less fatiguing when performed wearing backX. The increase in post-work endurance time is likely attributed to the reduction in erector spinae muscle activity when using backX. Specifically, this means in doing a set of fixed tasks during a work session with backX, the subjects wearing backX were able to last 42% longer, in any secondary task, than when not wearing backX. This is corroborated by subjective rated perceived exertion, where subjects significantly rated the work session as less fatiguing when wearing backX. No changes in oxygen consumption were observed.

4.2 Future Work

Despite recent advances in exoskeletons to reduce weight, improve range of motion, and increase practicality, the field of exoskeleton development will see continued, rapid progress over the coming years. Specifically, these changes can be categorized into three main trends: reduction in profile and weight, powered actuation, and practicality in the workplace.

4.2.1 Remote Actuation

A promising strategy for reducing profile and weight while still retaining a passive system is to employ a remote actuation strategy. In such a strategy, the power generating components can be housed on the exoskeleton on the operator’s back and transfer force to the operator’s hip via pulleys at the hip. Figure 69 depicts one iteration of this design when it is worn by an operator.

![Figure 69: Remote actuation prototype where a spring subassembly (300) is mounted to the back frame, then connected to two bilateral pulleys (100) over each hip by Bowden cables (200).](image)

In this iteration, a subassembly housing the springs can be mounted to the back-frame and connected to a set of bilaterally mounted hip pulleys mounted on each hip. Figure 70 shows a cutaway illustrating the internals of each pulley (100). A pawl (124), enclosure (102), carriage (110), thigh link (104), and hip frame adaptor (106) are rotatably coupled to each other about main pin (128). Thigh link (104) has a contour (126) designed to engage with pawl (124) and is rotatably
coupled to thigh brace (108). Hip frame (106) is rigidly coupled to a back frame that encircles the operator’s trunk. In some embodiments, pawl (124) may move under the influence of gravity. Operation is such that if pawl (124) engages onto the contours (126) of thigh link (104), the motion of thigh link (104) is coupled to rotation of enclosure (102) and they move together relative to hip frame (106). When pawl (124) does not contact contours (126), thigh link (104) rotates freely relative to hip frame (106). When the operator’s torso is upright, the pawl does not engage onto the thigh link and the torque generators do not engage. When the operator bends forward, the pawl engages onto the thigh link and pulls the cable to tension the Bowden cable and compress the springs. Figure 71 illustrates this mechanism in action.

Furthermore, referring to Figure 71, enclosure (102) is attached to a cam (118), a cable (112). A sheath (202) is attached to carriage (110). In some iterations, Bowden cable assembly (200) is comprised of this sheath (202) and cable (112). In some iterations, a switch (116) may be used to forcibly engage or disengage pawl (124) with thigh link (104). When pawl (124) is not engaged onto thigh link (104), thigh link (104) rotates freely and enclosure (102) does not pull cable (204). When pawl (124) is engaged onto thigh link (104), enclosure (102) rotates with thigh link (104). This rotation (122) pulls cable (204) around cam (118), creating a tension (120) in cable (204) and a compressive force in sheath (202). The resulting hip torque can be expressed as

\[ T = F_{\text{cable}} r(\theta) \]

where \( F_{\text{cable}} \) is the tension in the cable generated by the spring assembly and \( r(\theta) \) describes the radius of the cam as a function of rotation (122) angle \( \theta \).
Figure 71: cutaway of hip pulley (100) showing operation of the pulley mechanism.

The torque profile as a function of rotation angle (122) can be changed by redesigning the radius of cam (118). Figure 72 illustrates how different cam profiles can be obtained by varying cam radius as a function of rotation angle (122).

![Hip Torque for various bend angles](image)

Figure 72: various hip torque profiles can be obtained by changing r as a function of $\theta$.

Additionally, a new torque generator triggering strategy is proposed. During backX operation, it is critical that backX does not engage when the user is walking. Observing the forward walking gait cycle, the operator’s hips are either both in extension or one in flexion and one in extension (Figure 73) [65]. They are rarely, if ever, both in flexion during forward walking.
However, in the event of accidental torque generator engagement when the operator is walking, the operator should feel minimal impediment to walking. To minimize the force the operator feels and to prevent asymmetric forces (i.e. force on one leg being greater than the other), one can connect the cables (204) of each hip pulley (100) via a differential mechanism (302). This is presented schematically in Figure 74. Fundamentally, spring subassembly (300) would comprise this differential mechanism (302), a spring (306), and a pulley wheel (304). Spring subassembly (300) is configured such that cable sheath (202) enters and is mounted to the enclosure of spring subassembly (300). Cable (204) continues through subassembly (300) and wraps over the top of pulley wheel (304), then enters the cable sheath on the contralateral side and continues to the other contralateral hip pulley (400). In this iteration, contralateral hip pulley (400) and ipsilateral hip pulley (100) are mirror assemblies of each other.

![Figure 74: Schematic depiction of remote actuation system with differential mechanism with the operator’s hips are not flexed or extended.](image)

When the operator bends forward, the contralateral hip pulley (400) and ipsilateral hip pulley (100) engage. Tension is produced in cable (204) and compressive forces are noted in cable sheath (202). Because each hip pulley is creating tension, this results in a compression force (308) on both sides of the spring (306) (Figure 75). Consequently, this compresses the spring (306) and generates a hip extension torque at each hip pulley.
However, when the user takes a step with the torque generator engaged, one hip pulley flexes while the other hip pulley extends. For example, when the user takes a step as shown in Figure 76, the ipsilateral hip pulley (100) extends while the contralateral hip pulley (400) flexes. Consequently, ipsilateral hip pulley (100) is releasing cable (204) while contralateral hip pulley (400) is taking up cable (202). This results in cable (204) travel across the wheel (304), resulting in net movement of the cable (310). This causes no or minimal movement of the spring (306) and maintains equal tension at both hip pulleys to prevent asymmetric loading.

Figure 76: Schematic diagram of remote actuation method with differential mechanism (302). When one hip is flexing, the other hip is extending, resulting in travel across the wheel 304 and no compression of spring (306). However, tension is distributed equally between both hips.

Figure 77 illustrates this spring subassembly (300). Enclosure (314) is designed to house the and mount spring subassembly (300) to the exoskeleton frame. Long coil springs (312) are designed to maintain cable tension for cables (204). Placement of pulley wheel (304), spring (306), cable (204), and sheath (202) is indicated within spring assembly (300) and comprise the differential mechanism (302). Note that wheel (304) rotates freely within enclosure (314).
4.2.2 Powered Actuation

In some embodiments of the invention, it is possible to replace spring subassembly (300) with a powered mechanism (500) to induce tension in cable (204) and thereby generate a hip extension torque in both hip pulleys. In one iteration, it is possible to replace the springs (306) depicted in Figure 77 with powered actuator. In another iteration, it is possible to not use any differential mechanism and instead couple the cable (506) from each hip pulley to a separate actuator (502) (Figure 78). In this case, the actuator (502) is rigidly attached to the casing (314), which is rigidly attached to the cable sheath (202). Cable (506) is allowed to slide freely inside sheath (202) and within casing (314). An elastic member (504) may be added in series in between the actuator (502) and cable (506) to maintain tension on cable (506).
This configuration has the added benefit of not requiring the operator to engage his or her abdominal muscles to compress the spring and constitutes a transition from the passive device described in this dissertation to a powered device.

4.2.4 Future study topics

Further studies can be categorized largely into three groups: 1) large meta-studies investigating the effect of wearing back-support exoskeletons on worker injury rates, 2) assess the effect of wearing a back-support exoskeleton across a variety of tasks, postures, manipulated weights, duty cycles, and demographics, and 3) study changes in worker productivity due to wearing a back-support exoskeleton.

Lack of industry knowledge constitutes one of the largest barriers to adoption in the exoskeleton industry. A broad spectrum of studies must be undertaken to analyze the effect of wearing back support exoskeletons over time to assess if wearing an exoskeleton significantly reduces risk for injury. If results positively support this conclusion, this may result in an increase in worker wellbeing and facilitate exoskeletons into becoming more of a consumer-facing good. If results do not support this conclusion or are inconclusive, this data is nevertheless valuable in designing the next generation of exoskeleton suits for improving worker health.

As mentioned before, this dissertation examines the effect of wearing a back support exoskeleton on user fatigue for a predefined weight, lifting rate, and posture. For the industry to develop a more informed perspective on the potential benefits of exoskeletons on worker health and productivity, a series of studies investigating the effect of back-support exoskeletons on fatigue based on varying work conditions such as task, posture, weight, duty cycle, worksite, even climate should be undertaken. Naturally, it is very difficult to simulate every working environment possible – however, quantifying the effects of a back support exoskeleton on fatigue for common tasks such as palletizing or static table work is valuable and provides a scalable datapoint that can be referenced across multiple industries.

Lastly, changes in worker productivity provide the basis for corporate adoption of exoskeletons. In addition to reducing risk for injury, exoskeletons have the potential to improve worker productivity by making previously difficult tasks substantially easier. Similar to measuring the effects on fatigue over a broad variety of tasks, measuring productivity may be substantially more effective when evaluated for common tasks such as palletizing that are common across multiple industries. Specific metrics to consider are time-on-task, produced units, and frequency and duration of micro-breaks.

4.3 Concluding Remarks

The exoskeleton field is a rapidly growing industry and holds significant potential for improving quality of life for individuals across the world. Though there are a number of hurdles to reach adoption, the exoskeleton presented in this dissertation constitutes a clear advance in the state of the art. The conclusions reached in this dissertation imply a promising future in which mechanical human augmentation provides significant benefits to workers performing manual labor and using exoskeletons will profoundly improve quality of life.
References


