Development of an Aerial Porter Exoskeleton and Exoskeleton Standardization Metrics

by

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ABSTRACT

As the world moves towards faster production times, quicker shipping, and overall, more demanding schedules, the humans caught in the loop are subject to physical duress causing them to physically break down and have muscular skeletal injuries. Surprisingly, with more automation in logistics houses, the remaining workers must be quicker and do more, again resulting in muscular-skeletal injuries. To help alleviate this strain, a class of robotics and wearables has arisen wherein the human is assisted by a worn mechanical device. These devices, traditionally called exoskeletons, fall into two general categories: passive and active. Passive exoskeletons employ no electronics to activate their assistance and instead typically rely on the spring-like qualities of many materials. These are generally lighter weight than their active counterparts, but also lack the assistive power and can even interfere in other routine operations. Active exoskeletons, on the other hand, aim to avoid as much interference as possible by using electronics and power to assist the wearer. Properly executed, this can deliver power at the most opportune time and disengage from interference when not needed. However, if the tuning is mismatched from the human, it can unintentionally increase loads and possibly lead to other future injuries or harm.

This dissertation investigates exoskeleton technology from two vantage points: designer and consumer. In the first, the creation of the Aerial Porter Exoskeleton (APEx) for the US Air Force (USAF). Testing of this first of its kind exoskeleton revealed 8.13% peak metabolic savings 30 N-m delivered torque about each hip. It was tested extensively in live field conditions over 8 weeks to great success. The second section is an exploration of commercially available exoskeletons and the development of a common set of standards/testing protocols is described. The results show an initial point for a set of standards to be used in a rapidly growing sector.

DEDICATION

This dissertation is dedicated to my wife, Azita, who is endlessly patient. Throughout a decade of cross-country moves, countless business trips, and the adventures of child rearing she's stuck by my side. Thank you for being the support I needed to finish this journey.

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Chapter 1

INTRODUCTION

1.1 Problem 1: Workers are injuring themselves over time performing daily tasks due to poor lifting/pushing of heavy loads

In 2018, back pain was one of the largest causes of workplace injury and lost productivity nationwide, with the Bureau of Labor Statistics finding it to be the cause of 38.5% of missed days of work (Bureau of Labor Statistics 2018). This number jumps significantly for manual laborers to 43%. The workforce is rife with repetitive lifting motions that cause injury with 14,990 cases, not including office tasks, in the US alone in 2019 (Bureau of Labor Statistics 2020). Consequently, many work centers are exploring a means to minimize this rate, and exoskeleton manufacturers are presenting an answer. These manufacturers seek to reduce back injury by supporting specific tasks completed by the intended wearer. This can include overhead work with the passive Airframe Levitate (Levitate Technologies Inc. 2020), lifting tasks with the passive Laevo exoskeleton (Laevo 2020), weapons loading with the active Sarcos Guardian XO (Sarcos 2020), and many others (Asbeck, Schmidt, and Walsh 2015; Hollander et al. 2014; Kerestes, Sugar, and Holgate 8172014; Seo, Lee, and Park 2017). Among those searching for an exoskeleton solution is the USAF.

(a) (b) (c)

Figure 1: Images of the Airframe Levitate (a); Laevo exoskeleton (b); and Sarcos Guardian XO (c)

The USAF has a varied population throughout its command. These individuals enable a global reach and rapid response. Instrumental in accomplishing this mission are aerial porters. Aerial porters complete ramp operations to palletize cargo, transport it, and load and unload cargo from airplanes. Unfortunately, a single pallet can weigh up to 10,000 lbs (Nordisk Aviation Products 2018) and aircraft are loaded with multiple pallets for maximum efficiency. Moreover, these pallets can be irregularly shaped, challenging to maneuver, and need to be maneuvered into tight spaces. These requirements make for a work environment for aerial porters that can easily cause injury leading to an early dismissal from the service due to musculo-skeletal injuries. As a part of a Rapid Innovation Fund (RIF), the USAF has contracted Arizona State University to design, test, and deliver an exoskeleton that will assist with lifting and pushing tasks and reduce metabolic costs of a typical workday.

To accomplish this, ASU investigated the benefits and limitations of passive and active exoskeleton technology. Passive exoskeletons were considered a good candidate for their simplicity and lightweight. A proper application of springs would assist in lifting tasks and provide a relatively small footprint that would make maneuvering in tight spaces less concerning. However, these devices would also be unable to assist in pushing tasks. Some passive systems are impractical to turn off after a lifting task when walking with an object as the hands are full and unable to deactivate a system easily. Powered exoskeletons suffer issues as well, often requiring a large footprint to contain electrical storage, actuating mechanisms, and control circuitry. They also suffer a complexity issue, wherein a lower-body device not properly tuned may act against the wearer, increasing the overall metabolic cost of wearing an exoskeleton (Kazerooni and Steger 2006). Unfortunately, this is frequently the case, with most powered exoskeletons designed to fit a particular use case and not robust enough to handle dynamic environments.

Nevertheless, a well-designed powered exoskeleton can provide consistent assistance, lessening the metabolic costs of prescribed activities. A very well-designed powered exoskeleton will also be robust enough to know when it is not needed and not create a hinderance on the user by causing undue braking motions in non-prescribed activities. To achieve such an exoskeleton, ASU proposed a lightweight system that could be easily donned/doffed, provide physical assistance and lower metabolic costs during lifting and pushing tasks, and not increase the metabolic costs of day-to-day activities while wearing the exoskeleton. The resulting device was tested in a lab and the field. The device was tested in controlled environments, but a more prolonged study to investigate the device's effectiveness was performed. The lab tests also included a novel system to examine the efficacy of pushing tasks.

1.2 Problem 2: No unified testing standards exist for exoskeleton technology

Ideally, a designed system would bel subject to a set of standards to and compare against similar systems. With this, the USAF, or any other entity, could quickly see how each exoskeleton ranks and might be best suited to their needs. Unfortunately, no such set of standards exist. Instead, designers rely on in-house testing and university research to back claims that their devices assist in activities as selected. In a rapidly growing sector, this creates a confusing environment for consumers, the vast majority of whom have no experience in the field. This problem has not gone unnoticed, and talks have been delivered on just such a need for standards (Schneider 3/31/2020), a committee formed in one of the largest wearable robotics associations (Wearable Robotics Association 2018), associations such as ISO and ASTM are designing standards, and mainstream publications have discussed the issue (Marinov 2019).

Complicating the development of standards are the extreme differences between applicable environments. For instance, a militarily focused exoskeleton would likely be unreasonable for an assembly line and vice versa. While both assist the wearer in some fashion, their capabilities are not necessarily tuned for the other's environment. A passive exoskeleton that excels in holding equipment overhead would be too cumbersome for a dynamic environment. An exoskeleton that assists in loading heavy munitions would likely have high power requirements to deliver torque that would far outstrip anything an assembly worker would need. These differences in requirements have stymied efforts to create unified standards that could be applied across all exoskeletons. It is for this reason that a more straightforward standard of measure has been created.

A proposed standard would focus on the sector that provides the most opportunity. Today, that sector is the warehouse/assembly line in the broad area of logistics. Both fields are similar in day-to-day tasks, requiring low dynamic movement, dedicated shift times, and highly repetitive motions. A standard developed will need to focus not only on job requirements, as so many academic papers have, but on the in-between moments as well. This includes walking, moving objects, donning/doffing, taking breaks, etc. Considering these in-between moments would allow for a more holistic view of the exoskeleton. Practically speaking, it would also give employers an idea of if the devices would provide a long-term return on investment or a device that works for one task that would likely be quickly abandoned. To assist purchasers, the standards should also be reported on a scale that everyone can understand regardless of familiarity with the field. It is proposed that a scoring system can be implemented alongside standards that would provide scores ranging from 0-10 in different categories that matter to consumers. These tests should also be relatively easy to apply to encourage adoption among exoskeleton designers and inform them of what the consuming public desires. Once created, the quantitative and qualitative measures would provide a common baseline terminology and method to improve exoskeletons as a whole.

Chapter 2

LITERATURE REVIEW

Exoskeleton creation is not easy. As with any subject, a wide range of literature advises different views and extols some ideas over others. In the literature section, the goal is to describe the most important aspects when designing a device. Below is a survey of various related literature used to design and create the Aerial Porter Exoskeleton (APEX). It is broken into four categories of varying length for ease of reading: Anatomy, Hardware Design, Control, and Testing.

2.1 Anatomy

When designing an exoskeleton for a human, perhaps the most important consideration is the human anatomy and biomechanics. Even before joints are placed and sensors are considered, human factors need to be at the front of every team member's mind. In a review of the literature, key ideas emerge in creating an exoskeleton, especially for the lower body. First: gait pattern changes need to be avoided wherever possible. For successful adoption, here defined as not making a significant negative impact on the user, the user's gait pattern must remain unchanged. By altering how a user walks, a large and difficult learning curve is introduced, increasing cognitive load and physical demands on the user (Margaria 1976, Cavanagh and Williams 1982, Donelan, Kram, and Kuo 2001, Bequette et al. 2020). Second: avoid distancing unsupported mass from the user's Center of Mass (CoM). Failing to do so introduces inertia about the body for which the user is forced to compensate. This often will result in physical injury to the body that entirely defeats the purpose of an exoskeleton (Martin 1985, Miller and Stamford 1987, ROYER and Martin 2005, Browning et al. 2007).

Next, the device should be quickly and simply understood to reduce mental load. This is not to say that a device cannot be relatively elaborate, but if it is not intuitive to how the user maneuvers typically, it will likely increase mental load significantly enough to affect productivity until the user can be trained in the new movement paradigm (Bequette et al. 2020). In an extreme case, this is seen with Furrion's "racing mech" that asks users to pilot a sizeable four-legged device with their own body as the control (Furrion 2020). This is not an ordinary movement for humans, and as such, training for the suit takes multiple days, with real proficiency coming with weeks of practice. Finally, the exoskeleton needs to handle an appropriate range of loads.

Next the purpose of the device must be understood upfront. In short, a rehabilitation robot will have different needs than an augmentation robot, and the differences need to be described. Until recently, explosive loads on the human hip, knee, and ankle were relatively poorly understood, with many forces cited. Driven by this, Cleather, Goodwin, and Bull, designed an experiment to look specifically at loads in these joints experienced while jumping and performing explosive lifts. Their work determined that loads can be up to 10 times the body weight of the individual (Cleather, Goodwin, and Bull 2013). These human factor themes can directly drive the design of robotic exoskeletons, from the hardware to the control schema.

2.2 Hardware Designs

The world of exoskeleton design is not new, but today's landscape of available exoskeletons is rather large considering the field was first explored in 1965 (General

Electric 2016). The Hardiman was the first attempt at a wearable exoskeleton, using 30 joints to match human capability. It was not as successful as hoped but did kick off a large study field still being improved upon today. For instance, the HAL exoskeleton works today to help stroke survivors in repetitive task therapy for walking (Kawamoto et al. 2003). The HAL makes use of multiple degrees of freedom (DoF) to achieve a normal walking gait. The HUMA, designed under a sponsored partnership with Hyundai, also focuses on the lower body. Instead of rehabilitation, it looks to be quicker than most other exoskeletons (Hyun et al. 2017). This active-type exoskeleton has 12 degrees of freedom with two electrically powered joints in the hip and knee that allow for powered movement in the sagittal plane. Their key innovation is in the knee joint's dual four-bar linkage that handles the knee joint's polycentric nature. Using this design and a control algorithm enabled by joint angle sensors and optic force sensors in the foot, the HUMA achieved a normal walking gait (Hyun et al. 2017).

The Laevo exoskeleton is an exoskeletal device that seeks to help alleviate lower back injuries typically experienced in warehouse or assembly line-type work. This device is passively actuated, using springs and the material properties of their design to assist users only in lifting and leaning over (Laevo 2020). The Laevo uses counterpressure and light strapping to attach itself to the user and stores energy during squatting tasks. Upon standing, the spring energy is released, assisting the user in standing upright.

Moving back to active lower-body exoskeletons, the Berkeley Lower Extremity EXoskeleton (BLEEX) was one of the first powered systems. Claiming to be "the first functional load-carrying and energetically autonomous exoskeleton" (Kazerooni and Steger 2006), the BLEEX saw great success in implementing four technologies: the novel (for the time) architecture; the control scheme (discussed below); the body

LAN; and on-board power units. The design used 14 degrees of freedom, three at the hip, one at the knee, and three at the ankle for both legs. While this design did allow for a good range of motion and could support loads, the overall design was large and heavy. It also suffered from poor control, leaving some users more exhausted than when exercising without the device. The device was later updated to be more computationally efficient by portioning legs to exist in a swing or stance phase (Kazerooni, Steger, and Huang 2006). At this time, there is a lack of in-depth results on the overall impact of this change.

Perhaps to build upon the BLEEX, a research team created the UMEx-oLEA (Sado et al. 2019). This device sought mostly to allow for typical walking motions while using a new control paradigm (discussed below). Of the 12 DoFs, only those that helped with sagittal plane motion were powered in initial experiments to validate the control architecture. Their joints are all rotational, with some compliance built into the upper leg and shank braces to prevent misalignment.

Among all these designs, the rotational joint is the common factor. This is sensible in that it most closely mimics that of the human joint and can easily be mounted closely to the human joint, provided it experiences the same rotational axis. There is also good work in the UMEx-oLEA in the creation of compliant padding to treat misalignment. This is also seen in the Lokomat from a research team in Zurich. They intentionally create compliant attachments, using springs to act as an additional sensor in their suite of control inputs (ETH Zürich 2020).

2.3 Control

Control motivations of exoskeletons can be said to fall broadly into three categories: Pre-defined, assisting, and intention-based (Sado et al. 2018). Each has its benefits and pitfalls but serves as a method to control the torque or forces of the actuators. Further within each of these motivations is the mathematical model behind them. This could range from something as simple as basic if-then-else statements to filtered algorithms (Righetti, Buchli, and Ijspeert 2006), to an Artificial Intelligence (AI) architecture (Lu and Xu 2018). Combined, the motivations and models build a powerful device that can help humans that would otherwise be trapped in their circumstance, restore a lost potential, or even do things otherwise physically impossible.

Pre-defined motion is perhaps the most simplistic of the control motivations. Here, the intent is to have the user attached to the device while the robot moves through a prescribed set of motions (Dollar and Herr 2008). There is generally little control by the user in how the robot moves, instead directing the device to an end state. This is typically used in rehab or other scenarios where autonomous control is primarily lost or unrecoverable. Kilicarslan et al. used one such robot to help people with paraplegia navigate an environment (Kilicarslan et al. 2013). Researchers used an electroencephalogram (EEG) cap to learn the brain waves of conscious control and translated that into actual control for user piloting. While their study showed high success in specifically trained scenarios, it is not necessarily suitable for daily motions in a logistics environment. As designed, the exoskeleton needs to complete pre-defined cycles before moving to another, making slight movements difficult, if not impossible.

Perhaps the most largely studied category is assisting (Marchal-Crespo and Reinkensmeyer 2009). This method allows exoskeletons to provide nudges or helping movements to allow users to complete day-to-day tasks. This is not necessarily accomplished at speed. Depending on the algorithm and the intended outcome, this could even be done quite slowly to encourage user motion. In rehabilitation cases, this type is used to help achieve the full range of motion and help prevent soft tissue stiffness (Marchal-Crespo and Reinkensmeyer 2009). This type is not to be confused with the final type: intention-based or augmenting. Here, the exoskeleton does assist with movement but augment some of the user's capability (Kawamoto et al. 2003). This is often what is envisioned when robotic exoskeletons are discussed. This motivation can be far more versatile than other methods and potentially more helpful depending on the use case, but it also requires a large amount of overhead. Properly implemented, an intention-based motivation is capable of shadow movements, following the user to appear physically invisible to the user. A famous example is Iron Man from Marvel comics. His power armor intelligently follows his movement, allowing him to wear it as a second skin while at the same time augmenting his abilities beyond that of an average human. However, while Iron Man is the myth of science fiction, many are attempting to make the control of such a suit a reality.

Of course, any type of control is impossible without input. Each motivation above and model below needs data from their environment to know how to react. In the world of robotics, this is commonly done with sensors mounted at points of rotation, along critical beams, and, in wearable robotics, electromyography (EMG) sensors. Rotation sensors can be implemented in various ways, but all seek to report rotational information back to a central monitor (Sado et al. 2019). Strain gauges also report to a central monitor but provide data on the forces it is undergoing concerning where it is placed. When married to an accurate model, both can provide critical information on the robot's orientation and position in the world. The EMG sensor is also a potential venue for input, as it can inform the robot of user intent. Properly used, the robot can then anticipate the motion and augment the user or get out of the user's way fast enough to appear invisible to the user (Kawamoto et al. 2003). Unfortunately, due to the inherently noisy nature of the EMG sensor, variation in placement among individuals, differences in skin types, and many other issues, reliable readings between usage are difficult (Sado et al. 2018).

Underneath each of these motivations lies the mathematic/programmatic model to achieve the desired result. The simplest of all of these is the "basic" model. As the name implies, this model is the simplest, most basic type of modeling and coding to get to a minimum viable execution. This is a great model for initial proofs of concept that can still accomplish impressive feats. For instance, an engineer used this methodology to control a very basic exoskeleton that allowed for degrees of rotation about the elbow. However, when implemented, it reliably lifted a 170 lb. barbell (Hacksmith 2014). This is not to say that the "basic" model needs to remain basic; indeed, relatively speaking, it can be improved. The limitation is in its hard code that leaves little room for flexibility. By implementing this model, the designer can create a consistent, relatively easy to troubleshoot robot.

Moving up the chain of models is the complex type. While there are many different underlying models, all use advanced math to have their exoskeleton respond as intended. One such example is the Sensitivity Amplification Control (SAC) implemented in the BLEEX exoskeleton. This model was chosen to fit the design paradigm of having no sensors attached to the user (Kazerooni et al., 18-22 April 2005, Kazerooni and Steger 2006). Thus, the BLEEX tries to balance itself while keeping in mind how the human inside it can move. Unfortunately, the "control method has little robustness to parameter variations" (Kazerooni and Steger 2006) and needs a highly accurate model of the exoskeleton for feedforward calculations. A later upgrade attempted to create a hybrid model that was lighter on computation by splitting motion into a stance and swing phase. This, combined with the addition of sensors worn on the human, did create a more robust exoskeleton but sacrificed an initial design requirement (Kazerooni, Steger, and Huang 2006).

Another complex control model is the Dynamic Movement Primitive (DMP) as utilized in Kimura et al. As proposed, the authors use this model to examine nonlinear dynamic systems for generating discrete and periodic movement behavior (Schaal 2006). This model is especially well-suited for locomotion since they flexibly create complex rhythmic behaviors that adapt rapidly to changes in the environment (Kimura et al. 2006). This is achieved by coordinating two different, simpler systems that consider the robot's joint space and external space. In the example given, under this model, a robot can repeat the cyclic action of moving a tennis racquet up and down to bounce a ball, but also monitor the ball to ensure the racquet stays beneath the ball (Kimura et al. 2006). This model is great for "goal-directed behavior with nonlinear systems" (Ijspeert et al. 2013), but suffers from non-oscillatory or repeating motions. Adaptive Frequency Oscillation (AFO) is another strong model that is well suited for periodic data. One of its strongest features is that it quickly adapts to oscillations; however, this is done dynamically and not "offline" (Righetti, Buchli, and Ijspeert 2006). Like the DMP model, it is not well suited to situations where quick maneuvers might be required, such as quickly and safely getting out of the way in a dangerous situation.

Another widely adopted and heavily mathematic-based model is using Kalman Filtering. The Kalman Filter uses state monitoring to make educated guesses around components that cannot be directly measured. It sees strength in identifying parameters in a “noisy” situation for a known dynamic model (Sado et al. 2018). For instance, it is using joint rotations and bend sensors to anticipate motion. This is partially used in the SAC model described above, where the sensors on the robot made determinations for the human inside based on what it knew of human anatomy (Sado et al. 2019). A team of researchers from Malaysia successfully applied an advanced Kalman Filter to their lower body exoskeleton to alleviate some muscle exertion as measured by EMG. The dual-Kalman Filter frequently updated state estimates against parameters to achieve a reliable and efficient system in their process.

Echoing this updating of state parameters is the AI control model. While there are many AI implementation types, most follow the same general idea of taking large data sets to identify patterns (Lu and Xu 2018). These can be patterns that are easy for humans to detect, such as fast vs. slow or red vs. blue, or more subtle, such as detecting a sit vs. a squat motion. It often involves an extensive library of options that directly control the robot’s response. A good example is an exoskeleton that knows when to activate given various potentially similar movements such as sitting vs. standing vs. walking vs. running vs. squatting. While this method can be extremely accurate in its modeling, it also requires a vast amount of work. The datasets the algorithm trains on need to be robust, extensive, and clearly labeled at the very least. This can be difficult to gather in a small lab, more so given a potentially rapid-iteration environment. Many researchers are developing AI algorithms as part of their control of exoskeleton devices.

2.4 Testing

When it comes to testing exoskeletons, no set measures are in place yet. Some companies are involved with testing the exoskeletons they look to employ, ones that have rated the devices they have built, and universities that also test their own devices, but there is no standardized set of tests and measures for exoskeletons. Standards are being developed at ISO and with the ASTM F48 group. Bostelman and Hong examined the National Institute of Standards and Technology (NIST) terminology used for industrial robot interaction (Bostelman and Hong 2018) and comparing it to exoskeleton use. By doing this, they were able to create a set of standard terms to bridge the process. However, while the terminology is a significant step forward in normalizing these wearables' requirements, meaningful standards need to be developed.

2.4.1 Ways to measure

It is necessary to consider the "how" of data collection to conduct testing. Designing a scenario is easy, but what needs to be physically measured to create quantifiable values? One prominent sensing modality in this category is EMG. This technology uses a pair of sensors to measure the electrical difference of an activated muscle (Hopkins Medicine 2020). As the muscle puts forth more effort, a stronger signal is registered. The opposite also holds. It therefore has great value in determining the actual workload a muscle undergoes. For instance, it has been used to quantify muscular demands during workday (Gillette and Stephenson 2019); in calculating fatigue risk value (Gillette and Stephenson 2019); and calculating fatigue index (Kiryu, Saitoh, and Ishioka 1992). More information can also be gleaned on the assistance or harm the exoskeleton provides by monitoring the muscles directly as in Gillette and Stephenson 2019, Sood, Nussbaum, and Hager 2007, and Schmalz et al. 2019, or adjacent muscles that are suspected of improperly taking on the load, as in Gillette and Stephenson 2019 and Weston et al. 2018. As with the EMG control method, though, the EMG measure can be problematic if not precisely executed. In fact, H. Iridiastadi and M. A. Nussbaum found that EMG alone “may not be enough to substantially influence measures of fatigue” (Iridiastadi and Nussbaum 2006).

A more reliable measure of fatigue might instead be the Borg scale. This subjective measure creates a user-standardized discomfort scale that allows researchers to determine how the subject feels with high-reliability (Borg 1990). This is accomplished by having users complete a small “calibration,” discussed below, and then using their recently experienced discomfort as a reference for 0-10 (modified scale) or 0-20 (original scale) values, where no unease is felt at 0, and extreme discomfort at 10. The same researchers that determined EMG might not be sufficient, H. Iridiastadi and M. A. Nussbaum, found that the Borg scale, properly calibrated, serves as a “sensitive indicator of localized muscle fatigue (Iridiastadi and Nussbaum 2006).” It has come to be so reliable, that multiple tests have involved it such as with Escalona et al. 2018, Rashedi et al. 2014, Sood, Nussbaum, and Hager 2007, and Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Jia, et al. 2018.

Of course, other sensors exist for quantifiable measures. An electroencephalogram (EEG) can detect brain patterns by using similar technology to an EMG (Mayo Clinic 2020). Measuring signals of the brain in known regions can help researchers understand cognitive load or, paired with an appropriate algorithm, the intent of the user (Kilicarslan et al. 2013). Another valuable testing metric is VO2 levels, referring to oxygen consumed through activity (Exercise Physiology Core Laboratory

2020). In essence, this can be used to see if cardiorespiratory benefits can be had with the measured population (Escalona et al. 2018). This is often conducted in conjunction with heart rate (HR) measurements. It is widely known that HR increases with activity, and monitoring HR throughout tasks can help determine which task is more demanding and how much on an individual level (Schmalz et al. 2019). Finally, motion capture provides a rich dataset to evaluate human performance within a space for human-attached measures. By having a camera team track markers strategically placed on the body, it is possible to evaluate human motion and compare results (Schmalz et al. 2019, Weston et al. 2018). Within the realm of exoskeleton testing, properly used, it can even check for poor loading conditions, an indicator of potential future injury (Weston et al. 2018).

Force plate sensors precisely calibrated to measure the amount of force being applied to them, can also detect poor loading; in some instances, even detecting the direction of said force (Bertec 2020). With these plates, it is possible to examine instantaneous forces applied, such as in jumping motions in Cleather, Goodwin, and Bull 2013, or consistent forces like drilling tasks in Sood, Nussbaum, and Hager 2007, and Weston et al. 2018. Finally, measures can be as basic as error counting and timing. When applied to a task, error counting (defined by the researcher) can be used to approximate cognitive load on an individual (Bequette et al. 2020). Timing can also be used for this (Bequette et al. 2020), or to measure productivity (Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Jia, et al. 2018), or as simple as measuring the speed of adoption of an exoskeleton through donning and doffing times (Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Alabdulkarim, et al. 2018).

In the literature, there are multiple means of applying the above metric sources to tasks. In some instances, this includes real-world tasks accomplished at the job site.

Gillette and Stephenson use workers on the production line at a manufacturing plant to test their exoskeletons in a real-world environment with experienced employees (Gillette and Stephenson 2019). Others keep their tasks more pedestrian, as with Escalona et al. In this research, they had their subjects simply walk at a self-selected pace to discover any issues (Escalona et al. 2018). Often, however, researchers craft a scenario that mimics the real world. This can be done for many reasons, but experiments conducted in the lab can be more tightly controlled, thereby more easily highlighting deviations. Concerning exoskeletons, these tests can include: drilling a height-adjusted bolt with variably weighted drills (Rashedi et al. 2014, Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Jia, et al. 2018); using a drill to tap a sequence at varying heights (Sood, Nussbaum, and Hager 2007); drilling at eye-level (Schmalz et al. 2019); directly force the tool into a force plate at prescribed heights (Weston et al. 2018); clenching the jaw until fatigue sets in (Kiryu, Saitoh, and Ishioka 1992); walking, running, and walking with weight (Hyun et al. 2017); walking on a treadmill in different configurations (Gregorczyk et al. 2010); and lifting a load, transporting it a set distance, and placing it back on the floor (Sado et al. 2018).

2.4.2 Data Preparation and Analysis

Along with the testing and measures, without proper analysis, the data cannot be compared scientifically. Data analysis uses what is collected during tests and mathematically analyzes it into a form that allows someone to glean information from it. For some measures, this can be more intensive, as with EMG filtering. For others, it falls to simple math, as with error counting. Regardless, by adequately preparing the space for data input and downstream analysis, a more effective conclusion can be reached. The first step in this is baselining. Simply put, creating a base level that can be compared against, upon which to base conclusions. This will vary between measurement types, but all are meant for the same purpose. Then smoothing and processing or reducing the effect of measurement artifacts for more rational analysis is performed. Finally comes the analysis, looking at the data based on procedures outlined to derive conclusions.

Baselining, as stated before, is merely creating a base for measurement. For EMG, this can be done by counter-intuitively gathering a ceiling. EMG already has a base value of 0 when the muscle is not in use. However, the ceiling changes for everyone and is therefore useful to know when the goal is to compare different subjects. This can be done by determining the maximum voluntary contraction (MVC). The MVC is "the single most relevant determination of fatigue" as extolled by Yousif et al. (Yousif et al. 2019). It is also useful when compared to Borg scales and long-term muscle usage. To measure usage, users are outfitted with EMG sensors placed on the researched muscles. Then, in one option, users are asked to flex the muscle and hold at maximum (Rashedi et al. 2014). If users cannot flex the muscle in isolation, they can be asked to assume the position that force will be applied in during testing. Then, apply maximum force in the same direction for a period (Sood, Nussbaum, and Hager 2007). Applying maximum force is a similar mindset in baselining VO2 levels. In one study, the base was gathered by having participants use an arm crank to determine peak HR and O2 uptake (Escalona et al. 2018). Much as in EMG, this bounded later data collection efforts.

Force plates also need a level of baselining in some cases. Like MVC, the maximum voluntary force (MVF) is gathered by having users press against the plate using the same experimental procedures to determine an upper limit. This was especially useful in Sood, Nussbaum, and Hager's tests, where the resulting data was used to detect fatigue over time (Sood, Nussbaum, and Hager 2007). Motion capture is also important to verify. This is done by placing the markers and having the user go through a prescribed series of motions to ensure the cameras work as intended. It also serves to create a base guide of what the motion looks like in a new situation. Finally, the Borg baseline also utilizes subjects in a "fresh" condition. Here, the user is first briefed on the meaning of the scale and the measures themselves. Then, the user performs a task for a length of time (Borg 1990). This task ideally is not challenging initially but needs to increase in difficulty as time goes on. Good examples include holding a plank position or conducting a wall sit. The user will be asked to call out their "Borg" level concerning the briefed scale at set intervals. This will continue until a certain level is reached (often 9-10) or fatigue makes the task no longer feasible. This will lock in the user's mind a relative scale later used to describe discomfort in other tasks (Borg 1990). For relatable results, if the discomfort is known to occur at a particular site, it is possible to conduct a Borg familiarization test on the non-dominant but similar body part (e.g., left shoulder for a right-handed individual) or even the group of muscles themselves (Gillette and Stephenson 2019).

Once the sensors have been properly baselined and the data collected, it is time to process the data. In one example, we will look specifically at EMG, but the same practices can be applied to many other of the above sensor data. Primarily, EMG data is initially band-passed filtered, though this varies between labs and experiments. In Gillette and Stephenson, the data was filtered with a 4th-order Butterworth filter between 20-250 Hz (Gillette and Stephenson 2019). Rashedi et al. filtered between 20-400 Hz (Rashedi et al. 2014), Sood, Nussbaum, and Hager from 10-500 Hz (Sood, Nussbaum, and Hager 2007), and Weston et al. from 30-450 Hz (Weston et al. 2018).

Taken together, this provides a general window of 20-400 Hz. Some also conducted a low pass filter at 10 Hz (Gillette and Stephenson 2019) and others a notch filter at 60 Hz and its aliases (Weston et al. 2018). Some normalized to the root mean square value of the entire dataset (Rashedi et al. 2014), and others to the MVC as previously discussed (Sood, Nussbaum, and Hager 2007). Some did not baseline from previous dedicated measurements at all, instead choosing to look at the control and experiment data and smoothing by RMS and then comparing to find their results (Schmalz et al. 2019). Regardless, all examined the time, frequency, or time-frequency domain to get meaningful data. This type of analysis in the different domains is echoed in Yousif et al. (Yousif et al. 2019). Finally, after processing their data, some looked at setting a baseline of activation to remove noise further. For Gillette and Stephenson, this was set at values greater than 5% (Gillette and Stephenson 2019).

When the processing is complete, there are multiple ways to evaluate the resultant data. Three well-known methods are through discovering spikes, regressions, or apparent deviations as compared to control data. Spikes are commonly used due to their (usual) immediate obviousness when graph. A spike indicates something out of the norm and is a good indicator of an area examined. This is especially true when the data has been smoothed to remove such large spikes. In some instances, this can indicate nothing more than a temporary misread, such as a slipping EMG sensor. In others, an outside disturbance. In others still, an indicator of a potential issue that can get worse in time. In all instances, the spike needs to be examined, and the cause explained.

Regressions can be used to indicate many things, usually brought about by a long-term effect. If the cause is not immediately apparent, as in experiments with multiple variables, an ANOVA can be accomplished to help isolate the source. Schmalz et al. used the linear regression discovered in their experiment to indicate fatigue (Schmalz et al. 2019). This fatigue might also have been discovered through checking for deviations against a control. As we will see below, a change in gait, highlighted by the motion capture system in Gregorczyk et al., could be found when graphed. This gait change led researchers to determine the cause and a string of downstream effects the deviation caused.

2.5 Examples

An example of synthesizing these methods to find a beneficial exoskeleton comes from the work done by Kim et al. In this experiment, researchers tasked 12 gender-balanced users to complete drilling tasks at two different heights (Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Jia, et al. 2018). Drilling was done while equipped with the exoskeleton (experiment) and without (control). Users wore EMG and motion capture sensors during the task, pressing into a force plate and calling out Borg scores at set intervals. After their testing was completed, it was discovered that the device tested decreased physical discomfort while doing the tasks by 45%. This discomfort was measured through the Borg scale, and the EMG data reinforced this finding. The users also saw a reduction of time spent on the task by an average of 20% while using the device. However, the testing also showed adverse effects. While the time spent on the task was reduced, the error rate increased. There was also a notable decrease of shoulder range of motion by 10% as measured by the motion capture system (Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Alabdulkarim, et al. 2018). A mean center of pressure increase of 12% in the anterior deltoid, a prime indicator of a future long-term pain area.

For lower body exoskeletons, researchers tested the HULC exoskeleton to examine its ability to reduce soldiers' metabolic costs during tasks (Gregorczyk et al. 2010). The team used VO2 measurements, a treadmill with an embedded force plate, and motion capture. The users completed a baseline session without the exoskeleton and then further tested with three different weights at a set speed. After analyzing their data, researchers discovered severe flaws in the exoskeleton that contributed to a significant 40% increase in VO2 consumption and significant changes in gait biomechanics (Gregorczyk et al. 2010). While this series of testing was not explicitly designed to test the design of the exoskeleton itself, it did serve the purpose of highlighting the importance of the design parameters described above and the importance of collecting useful data to get meaningful results.

2.6 Summary

There are many paths to designing a quality exoskeleton, and the target market's concerns need to be the primary consideration throughout the design process. These concerns include following overarching guidelines such as: reducing gait changes to the greatest extent possible; keep loads close to the wearer's CoM if the wearer is to support the load; keep the device as simple for the wearer; and be at minimum robust enough to handle the required loads. The design also needs to be mechanically appropriate for the task at hand. A fully powered exoskeleton would be excessive for simple pick and place operations, just as a passive exoskeleton would be insufficient in significantly augmenting motion. Controls should also be created to allow for repeatable results from the user. Controls can include unnatural motions if necessary, but they should have consistent results when executed. Finally, a competent testing plan needs to be created around the exoskeleton that adequately reflects its environment. These all combine to deliver a comprehensive plan towards an effective and productive exoskeleton.

Chapter 3

APEX DEVELOPMENT

The USAF has contracted ASU to develop a lower-body exoskeleton to assist with pushing and lifting tasks executed by their aerial porter Airmen. These service members are responsible for: “performing and managing air transportation activities; inspecting aircraft cargo to ensure proper documentation, packaging, and marking; determining the quantity and type of cargo to be loaded according to allowable aircraft cabin load; implementing necessary safety and security precautions for handling and storing dangerous materials; loading and unloading aircraft using specialized equipment; and providing the Department of Defense with the capability to move air passengers and cargo worldwide (U.S. Air Force 2020).“ The materials transported vary widely, from ammo to vehicles, to personnel, and beyond (Torres 2010). Beyond the reasons described above, the workforce available is older and aging, making them more prone to injury.

ASU has experience developing exoskeletons that assist in walking activity; primary among them is the Hip Exoskeleton for Superior Assistance (HESA). The 2.95 kg HESA assists hip flexion and extension movements and avoids interference in climbing and descending stairs (Sugar et al. 2017). Starting from the HESA, ASU will create an exoskeleton that provides more substantial assistance, more active activity recognition, and decrease weight on the human while providing back support. Metabolic improvement will be measured using the GoX Ergo Kit developed by GoX Labs. Their device has a small, wrist-mounted form factor that will eliminate the need for traditional bulky VO2 measurement devices. Aerospace company NextGen has also been included in manufacturing the final devices and creating the activity recognition algorithm. This algorithm is based on their work on Exosense, a project seeking to build a robust full-body activity recognition algorithm.

3.1 Outline

To provide a quality device, the project team has dedicated themselves to meet the following design goals in line with best practices:

- Be comfortable, lightweight, and easily donned/doffed
- Use a novel catch and release lever arm for free walking
- Allow operators to perform job duties naturally, including entering and exiting vehicles without interacting with the system
- Require little user input beyond turning on
- Accommodate a wide range of users
- Maximize efficiency by actuating only for lifting and pushing operations

The metrics for this project can be seen in table 1. The USAF has laid out a set of Contract Line Item Numbers (CLINs) to meet the metrics and requirements. ASU has developed four objectives and related subtasks to ensure on-time completion for each CLIN. The timeline for this can be seen in figure 2. Figure 2 is a description of each item. An in-depth discussion of each CLIN and objective will be discussed in related sections.

Metrics	**Threshold**	**Objective**
Total Weight	8 lbs.	6 lbs.
Battery Life	4 hours	8 hours
Donning and Doffing	2 minutes	1 minute
VO2 as measured by Ergo Kit		
- Lift Test	8% reduction	12% reduction
- Pushing Test[1]	0% reduction	12% reduction
Average hip extension torque	15 Nm	20 Nm
Exoskeleton disengaged walking on a level surface	The motor will be disengaged when walking for 20 minutes on a level surface	
Exoskeleton will allow for 90 degrees of hip flexion	90 degrees of hip flexion	

Table 1: APEx test metrics. The threshold column values are the contractual minimum requirements and the objective column values are the desired goals.

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[1] This is an additional goal to test, outside the scope of work

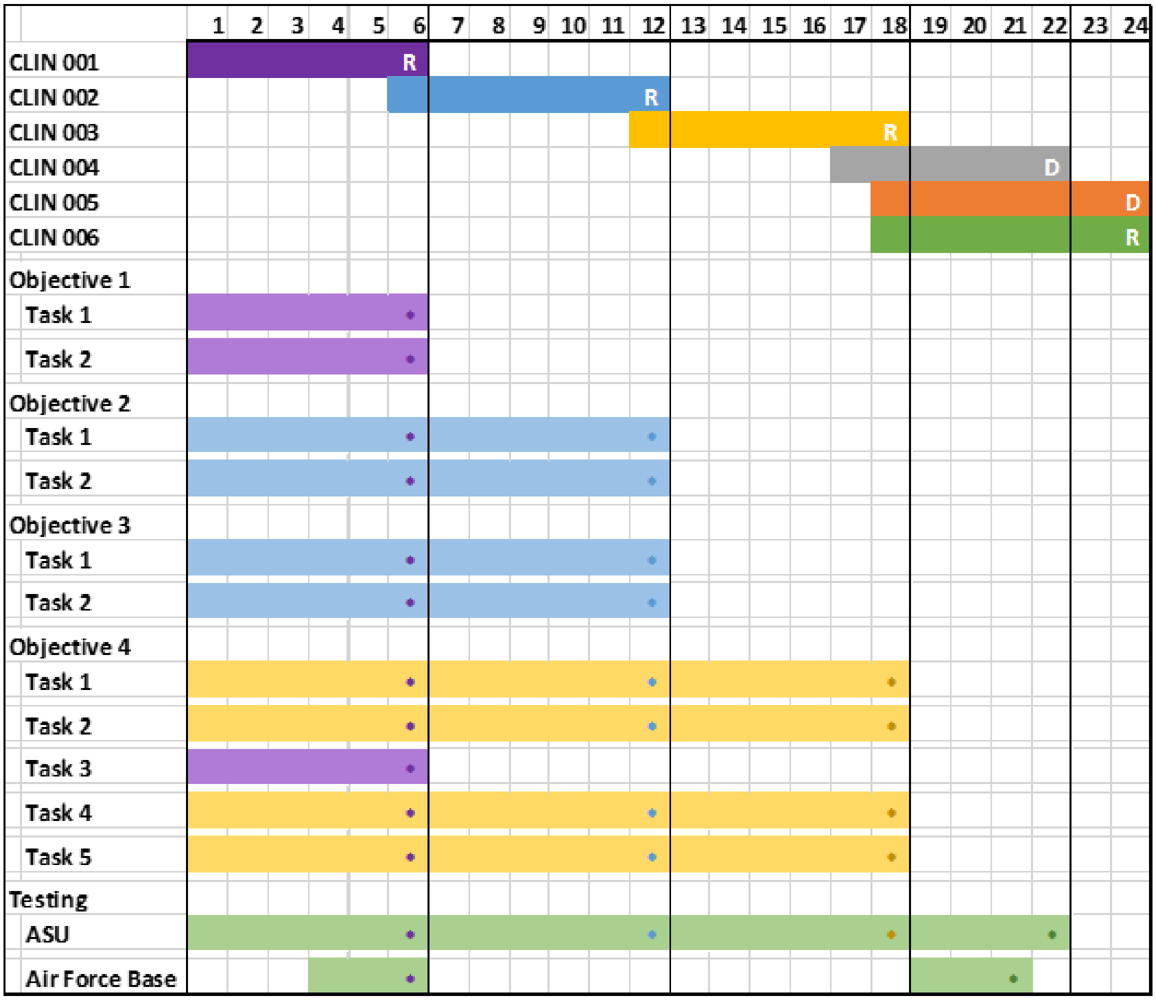


Figure 2: The timeline for the APEx project with the x-axis measured in months. The colors of objectives reference their associated CLIN. 'D' denotes a deliverable, and 'R' denotes a report. For all tasks, the colored dot relates to the CLIN report in which the update is provided. Colors that match indicate the final update for that item.

- CLIN 001: Assessments and human measurements results
- CLIN 002: Initial design report
- CLIN 003: Final design
- CLIN 004: On-site training and user manual delivery
- CLIN 005: Delivery of 6 devices

- CLIN 006: Final research and development report
- Objective 1: Assess form, force, and fatigue using the GoX Ergo Kit
  - Task 1 (O1T1): Senior Aerial Porter will be interviewed to gain valuable feedback while wearing the original device (HESA)
  - Task 2 (O1T2): The contractor will measure ten skilled technicians for a 4-6 week ergonomic study. Engineers will travel for an on-site visit for work and observation. Measurements will include worker exertion, lifting quality, and productivity
- Objective 2: Measure human motion using Inertial Measurement Units (IMUs)
  - Task 1 (O2T1): Connect the receiver with the microprocessor unit of the APEx
  - Task 2 (O2T2): Mount at least three sensors; one on each thigh and one on the pelvis
- Objective 3: Activity recognition algorithm to determine if the user is squatting, lifting, or pushing
  - Task 1 (O3T1): ExoSense algorithms will be integrated into the microprocessor unit of the Aerial Porter Exoskeleton
  - Task 2 (O3T2): Algorithm will determine worker activity (pushing, lifting, squatting, bending)
- Objective 4: Refine the APEx to reduce the lumbar forces when lifting and carrying an object
  - Task 1 (O4T1): Waist belt structure will support and protect the lower back
  - Task 2 (O4T2): Front pad will be added

  - Task 3 (O4T3): Mechanical design of lever mechanism
  - Task 4 (O4T4): Use a phase oscillator controller that is in synchronous movement with the user
  - Task 5 (O4T5): Two sizes will be developed

3.2 Completed Work

To date, CLINs 001-003 have been completed. A description of each CLIN and the related objectives follow, and plans for future work to meet upcoming CLINs. The status updates are provided as they were given at the time of the individual report. Because of this, it is possible to track the progress of research and development.

3.2.1 Assessments and Human Measurements

3.2.1.1 O1T1

On September 6th, 2019, an interview with senior aerial porters was conducted by Dr. Thomas Sugar (ASU) and Dr. Joseph Hitt (GoX Labs). The questions mainly centered on day-to-day activity to identify which sub-categories of the aerial porter career field would benefit from an assistive device. An appropriate test was developed from these discussions and directly informed the threshold measurements listed in table 3. The interview also left essential details that helped to inform the more demanding objective measures. Respondents indicated that moving 70 lb. bags is a common requirement versus the civilian standard of 50 lbs. There is also a highly dynamic component to the job, where, over a 4-hour cargo operations profile, a porter can be expected to spend an hour lifting cargo, another hour driving various vehicles, and 2 hours walking with some sitting. In a ramp operations profile, workers spend roughly 1 hour tying down material, often crawling and navigating tight spaces, 1.5 hours in normal lifting activities, and 1.5 hours maneuvering pallets. Finally, in this interview, respondents left recommendations that reinforced the opinions of ASU researchers. Specifically, the recommendations included that donning and doffing must be fast and straightforward, that the device must reduce fatigue, and that the exoskeleton is low profile to avoid snagging hazards. .

3.2.1.2 O1T2

An ergonomic study of aerial porters was conducted with members wearing the GoX Ergo Kit from late October to December. Data were collected across four task subgroups: bunker, cargo, passenger, and ramp. The analysis revealed that the two most demanding task groups were the cargo and ramp. While bunker and passenger groups can have an active job, the other two were more consistent in work tempo and intensity. There was also a significant injury risk variance among Airmen. There were several that were at a high risk of injury, as identified by the GoX algorithm. These injury risks included VO2 averages and peaks and HR averages and peaks. Excessive scores among these measurements indicated high exertion and would thus benefit most from an augmentation device.

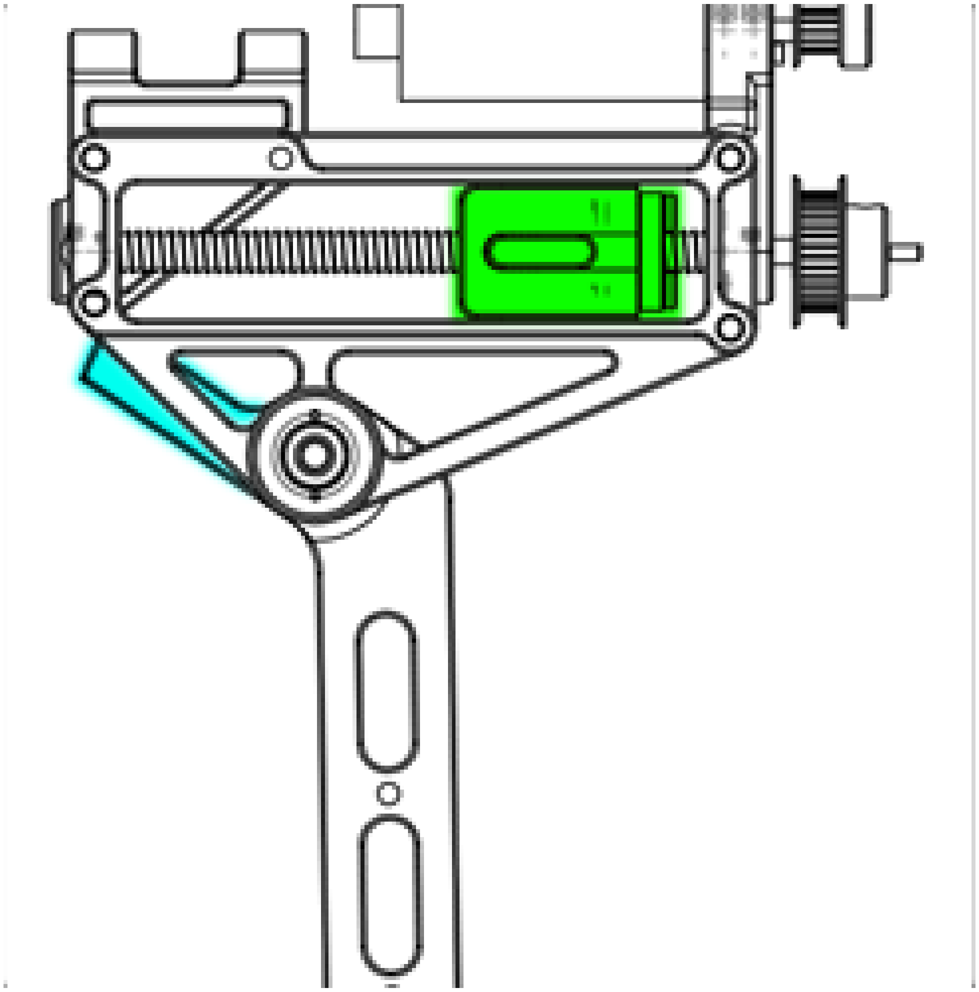


Figure 3: A side-view of the proposed alpha design.

3.2.1.3 O4T3

Finally, in this task, the mechanical design of the lever mechanism for the Alpha prototype was finalized and can be seen in figure 3. The lever mechanism that assists is configured with a push-only methodology. Under this design, the lever arm will be out of the operator's path for most movements, moving into place only when assistance is needed. Compliance will be provided using a carbon fiber arm mounted to the leg strap. This arm will slightly bend when force is placed against it to provide the needed feedback and compliance. Then, with force given, a motor on the exoskeleton's associated leg will move a pushing block (marked in green in figure 3) into position, catching the forks (marked in blue in figure 3) of the lever arm and pushing against them, translating the movement through the lever and onto the user's leg. Using this design, the unit's size and weight are decreased while maintaining a large torque potential.

The required motor and materials were determined by basing the initial design on the proportions used for the HESA and working backwards with the required output. The required input torque to the ball screw can be given by:

$$\tau_{input} = \frac{F * l_{ballscrew}}{2 * \pi * \eta} \tag{3.1}$$

Where the force is determined by:

$$F = \frac{\tau_{required}}{l_{leverarm}} \tag{3.2}$$

And the torque of the input delivered by the motor after gearing is given by:

$$\tau_{input} = \tau_{motor} * \frac{Teeth_{drivingpulley}}{Teeth_{drivenpulley}} \Leftrightarrow \tau_{motor} = \tau_{input} * \frac{Teeth_{drivenpulley}}{Teeth_{drivingpulley}} \tag{3.3}$$

Combining these equations gives:

$$\tau_{motor} = \frac{Teeth_{DrivingPulley} * l_{ballscrew} * \tau_{required}}{2 * \pi * Teeth_{DrivingGear} * \eta * l_{LeverArm}} \tag{3.4}$$

Given an output requirement of 20 Nm, a ball screw measuring 2 mm/turn, pulleys measuring 36 teeth/turn and 14 teeth/turn, and an efficiency of 96%, the following is achieved:

$$\tau_{motor} = \frac{14 * 0.002m * 20Nm}{2 * \pi * 36 * 0.96 * l_{LeverArm}} \tag{3.5}$$

	$l_{LeverArm}$	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**
τ_{motor}	**10 Nm**	0.1289	0.0645	0.0430	0.0322	0.0258
	20 Nm	0.2579	0.1289	0.0860	0.0645	0.0516
	30 Nm	0.3868	0.1934	0.1289	0.0967	0.0774
		0.06	**0.07**	**0.08**	**0.09**	**0.10**
	10 Nm	0.0215	0.0184	0.0161	0.0143	0.0129
	20 Nm	0.0430	0.0322	0.0322	0.0287	0.0258
	30 Nm	0.0645	0.0484	0.0484	0.0430	0.0387

Table 2: A table displaying the delivered torque in Nm. $l_{LeverArm}$ is measured in meters, τ_{motor} is in Newton-Meters.

Plugging this equation into a simple table, as in table 2, allows for quick and easy motor sizing, including changing the required torque.

Multiple designs were considered as the idea iterated. The design base began with the HESA exoskeleton, which uses a similar actuation method, specifically, a push block on a ball screw to translate motion. However, the HESA unit was insufficient for the task as it pushed and pulled on the leg and would be in the way when walking. This led to an iterative design that stripped the excess hardware and created a one-way push effect, the only effect that is necessary for this application. The previous system used a spring in series with the ball screw. The spring in the old version took up too much space. The lever arm itself was examined and utilized as the compliance-granting portion to make the new design smaller. This rework was resolved in the final design of the lever mechanism to be used in this project.

3.2.1.4 O2T1 & 2 Update

The system architecture has been designed on a high level, see Figure 4. The main node mounted together with the battery and a central IMU receiver from NextGen will perform the high-level control and phase oscillator algorithms. The main node contains circuitry to interface with NextGen's central receiver. Two additional processing nodes, one at the left and one at the right hip, will read hip angle via a high-resolution encoder PCB. These nodes will also communicate with the motor controllers and send all information to the main node for processing. The main node sends the final outputs (motor position, velocity, or current) to the hip nodes for motor control.

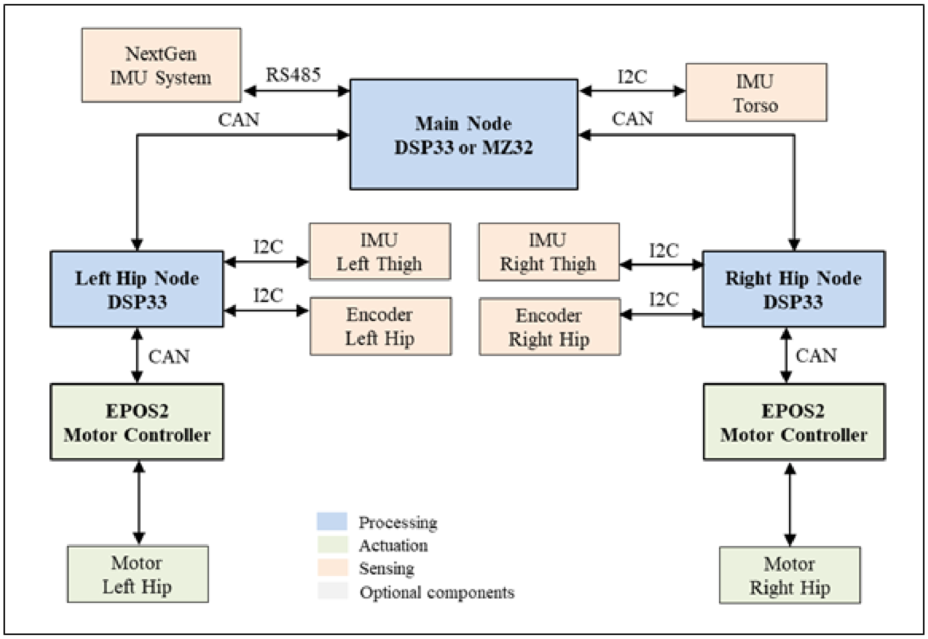


Figure 4: A high level view of the system architecture.

Second, microprocessors, IMUs, and encoders have been selected. Both main and hip nodes will use a 16-bit DSP from Microchip. NextGen's IMU system will be used to measure human motion. This system is interfaced via a central receiver over RS485 communication. The Austria Microsystems AS5048 absolute rotary magnetic encoder will be used to provide high-resolution angle information. This sensor has been used in previous projects. Finally, the hip encoder PCB design has been completed (figure 5).

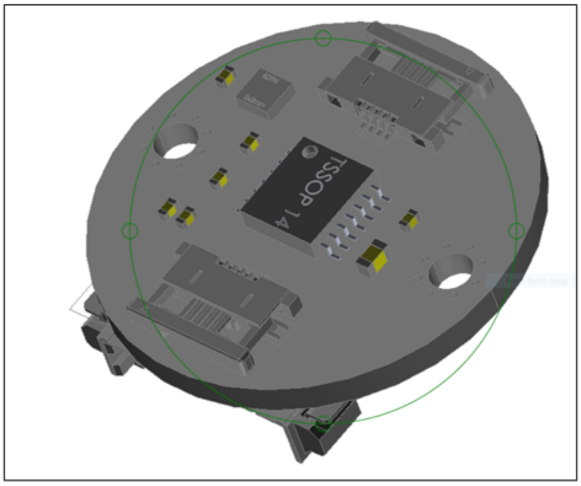


Figure 5: A 3D CAD model of the hip encoder PCB

3.2.1.5 O3T1 Update

The data collected from the IMUs will be at 1000 Hz, which provides a high sampling rate to accurately model the motions leading up to and during the activity. These data sets will be post-processed in MATLAB to determine the best method to both quickly and accurately determine the activity being performed and signal the exoskeleton to assist.

3.2.1.6 O3T2 Update

The starting point for NextGen's approach to activity classification is prior work done on the recently completed "Exosense" RIF from SOCOM. It successfully demonstrated recognition of walking, running, travel up and downstairs, using 1 to 2 IMUs.

The key to achieving high accuracy is extensive training. To this end, NextGen will first build a fully articulating model (capturing all degrees of freedom) of the

APEX hardware design. They will conduct lab tests using this model to determine the optimal IMU locations and develop the AR algorithms. The sensor locations will need to provide maximum synchronization to the body's movements and minimize complexity by placing them within the constraints of the current hardware design.

At this time, NextGen has 3D printed the exoskeleton frame and is in the process of assembly. They are working on placing three IMUs - one for each thigh and one in the center of the lower back of the exoskeleton. It is anticipated that the data from the two thigh sensors will be sufficient to perform activity recognition, and the center sensor will be used primarily as a reference for calibration. However, the design will include up to five sensors if needed (the additional sensors will be located on either side of the pelvis and would provide more accurate data in coronal and transverse planes, which potentially would enable sub-classification of the activities such as good versus bad squats, proper stance during pushing, etc.)

3.2.1.7 O4T1 Update

The waist belt structure will mostly follow previous ASU designs. The belt is designed to be placed over the porter's uniform and uses hook and loop components to ensure a tight fit. The battery will be centered in the back, where weight can be distributed appropriately and out of the way. Control mechanisms will be side-mounted and designed for simple adjustments. Final placement will be subject to testing. Though currently, the design focuses on two dials, one on each side of the device. One will have a simple switch for on/off. The second will have a stepped switch for low, medium, high settings, denoting the amount of torque the porter wishes to use. Both dials will “click“ into place to provide tactile feedback of being set into place.

3.2.1.8 O4T4 Update

The phase-based controller uses an IMU (inertial measurement unit) signal to determine the leg motion. From the IMU, the hip position and angular velocity are both determined. The phase angle is based on the arctangent of angular velocity divided by angular position. This signal is then used to determine when to supply the needed assist force.

3.2.1.9 O4T5 Update

Sizes will be based on the data provided by the US Army Natick Soldier Research, Development, and Engineering Center. This study measured over 11,000 soldiers' anthropometric data and is used as a template to predict sizing requirements for USAF personnel. Waist sizes and buttock-to-knee lengths for both men and women were taken into consideration. They will have the most significant focus as the hip (for mounting the APEX) and upper thigh (for hip-strap placement) are the two human interaction points. There are two variants on the ix devices projected for delivery. One will be designed to have a small-medium configuration, and the other a medium-large configuration. Both will be adjustable to meet an individual's sizing needs, provided they fall within the appropriate range. Table 3 reflects current projections of the sizes that will utilize the APEX.

	Small - Medium		Medium - Large	
	Minimum	Maximum	Minimum	Maximum
Waist	25 cm	35 cm	31 cm	41 cm
Thigh	53 cm	68 cm	62 cm	77 cm

Table 3: A table displaying the proposed measurements of the delivered systems.

3.2.1.10 Testing Update

Currently, the alpha jr. build of the APEX is slated for late-January completion. Once completed, the exoskeleton will be put through a series of tests designed to examine all aspects from base electronics to movement to ergonomics.

3.2.2 Initial Design

3.2.2.1 O2T1

The IMU receiver has been fully connected, and positive data read-in is confirmed. This receiver reads in the telemetry data provided, converts it into an activity and associated confidence level, and pipes it to the APEX main processing unit (AMPU). This IMU data represents an indication of the activity being performed.

3.2.2.2 O2T1

There have been a total of 5 IMUs attached to the APEX on the upper thighs, either side of the pelvis, and one on the chest. All of these have permanent, hard-mounted positions on the device to allow for consistent reading over time. The number was increased to five from three to have a more reliable activity recognition algorithm and assist in isolating legs. Having two per leg and a central unit makes it far easier to check for synchronous movement (as in squatting techniques) and identify conditions to activate. Looking forward, it is possible to identify unique split-leg cases, such as stair climbing, and allow the leg assists to activate individually.

3.2.2.3 O3T1

The AMPU is confirmed to read in IMU data from the NextGen hardware. The data received is combined with the data provided from position sensors that tell the AMPU in what configuration the APEX hardware is. Once the hardware is in a good location and the IMU data sends a positive activity request, the APEX will activate its assisting motion. It is only when the two agree that the device will activate. Moments where the device is unsure or unprepared will not activate APEX's assisting motions.

3.2.2.4 O3T2

The development of the ARA has made progress over this period by our partners at NextGen Aeronautics. Initial data were collected on six subjects using a motion capturing suit. Users performed a series of tasks, including sitting, standing, walking, jogging, lifting boxes of different sizes and weights, and pushing a car. The tasks were performed in a different order, with each set of data collected and without the subject being prepared in advance. This allowed for these activities' natural performance as requested, increasing the likelihood of collecting data that applies to real-world scenarios.

Further data on the same activities were then captured through IMUs mounted on a copy of the APEX's Alpha iteration. There were 5 IMUs used, mounted on the upper thighs, either side of the pelvis, and one on the chest. Data collected were synchronized with a recorded video of the testing session to assist with post-analysis.

On June 24th, the APEX team demonstrated the efficacy of the ARA. During this demo, NextGen was able to show a greater than 99% recognition of targeted activities. These activities were squatting (entering and exiting), walking, standing, and sitting.

Over the following months, the algorithm will continue to be refined by testing a broader range of individuals. The tests will also represent all hardware's final mounting solutions on the APEX, reflecting a complete solution.

3.2.2.5 O4T1 Update

The initial attempt used the previous belt from the HESA exoskeleton (Figure 6, (a)). This allowed for a rapid fit test and provided a baseline from which to improve. This setup did provide good initial results, assisting the wearer in recovering from a squat activity. However, the design could not provide the desired torque over the desired range since it tried to escape its hook-and-loop fastening. It rotated backward when a large torque was applied.

The second method used a stiffer brace made of hard plastic (Figure 6, (b)). The hard-mounting point provided a firm brace to minimize the "escape movement" observed with method one. This method successfully held the mechanism in place; however, the hardened belt tended to rotate into the wearer, causing uncomfortable pressure and a loss in torque delivered over time. Also, the system was heavier.

The third method, demoed at the March Zoom meeting, used this brace but added additional vertical bracing around the ribs (Figure 6, (c)). This affected the twisting observed in method two and prevented the wearer from entering a bad-form squat. Results from this method were encouraging, with better torque-to-time output and more minor discomfort.

The current design has removed the rib-hugging brace and replaced it with a more comfortable and intuitive backpack-type strapping (Figure 7). The side view shows a strong side, vertical bracing that holds the motor units in place. By replacing the hard-plastic rib case from iteration 3, a more customized fit can be achieved. The strapping also helps reduce the overall weight of the device, one of the critical design components. The backpack strapping was also added to prevent vertical shifting. This was initially achieved by tighter horizontal strapping, which caused discomfort and allowed shifting over prolonged use. Finally, a strap guide was added to the back for padding, preventing tangling, and reinforcing proper lifting form.

3.2.2.6 O4T2 Update

The original design of the thigh pad called for a printed plastic adjustable piece that was encased in carbon fiber for stability. After manufacturing, this design remained primarily unchanged for several iterations of the Alpha. However, fit became a minor issue as the APEX team tested on various individuals. The design has since been changed to be shortened but still adjustable, and the cupped pad has been integrated into the mechanism, creating a less complicated and lighter part. These changes can be observed in figure 7). There has also been a strap added to the thigh pad to hold the pad to the user consistently. This is made of an easily replaceable hook-and-loop design, allowing quick repair if damaged during work operations.

(a) (b) (c)

Figure 6: (a) Iteration 1 of belt design. (b) Iteration 2 of belt design. (c) Iteration 3 of belt design.

(a)

(b)

(c)

Figure 7: (a) Front view of APEX Alpha iteration. (b) Side view of APEX Alpha iteration. (c) Rear view of APEX Alpha iteration.

3.2.2.7 O4T4 Update

The APEX uses an underlying algorithm that can determine when to activate based on the position of the lever arm. This phase oscillator is fully integrated and provided the base level of testing in the APEX's pre-alpha stage. The system is a low-level controller that can follow the leg movement and assist from a squatting position and assist the legs when pushing a cart. It now works in tandem with the ARA to determine activation timing.

3.2.2.8 O4T5 Update

The sizes selected have remained mainly unchanged from the CLIN001 report but will be implemented differently. Earlier sizing projections relied on the hard-plastic model of the APEX. The rigid backing had notches installed to allow for precise fitting within a range with some light tooling. With the latest iteration, this backing has been removed and replaced with strapping. This allows for a wider size selection and more rapid fitting without the need for tools. The APEX will enable the two sizes by providing two sets of adjustable strapping. This will minimize the amount of leftover material to secure while allowing for the broadest range of wearers.

3.2.2.9 Testing Update

Testing has been conducted repeatedly internally as the system is refined. Externally, three demonstrations have been held over Zoom meetings with USAF representatives. The testing procedure of the APEX has been largely finalized. It is designed to capture the performance metrics specified in the Statement of Work (SOW). At this time, ASU owns the testing hardware and has begun testing the developed rubric. All tests are conducted with the APEX worn and not worn to test APEX effectiveness against a known baseline. The tests will also be conducted multiple times, in a random order, for no less than three days to get a deeper sample. Finally, all results will be baselined to the individual to account for true effect. Tests include:

- Lifting a weighted container (30 or 70 lbs) and transporting it 20 feet away, conducted 30 times over 15 minutes

- Pushing a cart loaded with 500 lbs for 100 m. One push test will be conducted at a prescribed pace, and another at a user-selected pace
- VO2 as measured by the GoX Ergo Kit will provide the metrics for the tests. This device is wrist-worn and is capable of real-time monitoring of VO2 levels

The full one-page document describing the tests is found in Appendix A.2. Images of the testing cart and containers are found in Appendix A.3.

3.2.3 Finalized Design

(a) (b)

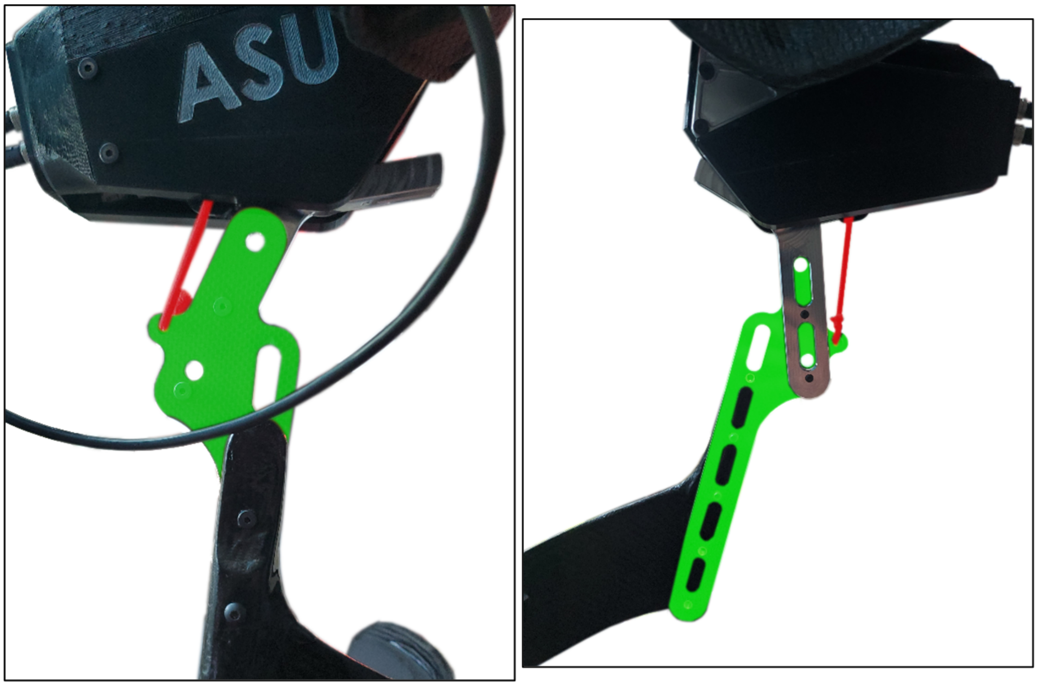
Figure 8: (a) The rear view of the APEx Beta. (b) A right side view of the APEx. Note: The final deliverable will route cabling through the vest and will not hang freely as shown on the Beta.

3.2.3.1 O4T1

A final design decision on the waist belt structure has been reached. This structure is similar to the Alpha design. The only change made has been to the vertical shaft that runs from the hip to the ribs. In the new design, it is slightly flared for greater comfort. In testing, this arrangement is highly effective. It is elaborated on in the “testing“ section below.

3.2.3.2 O4T2

The final thigh piece has also been created. Termed the “thigh paddle,” it will be created at a set size. An extension component is provided to allow for customized sizing between individuals. The paddle is held close to the leg by an elastic cord secured to the paddle and device hub. This cord is low profile and poses minimal risk to snagging hazards. It is also low tension and will put minimal pressure on the wearer. The extension component and elastic cord can be seen in figure 9.



(a) (b)

Figure 9: An updated front pad mechanism. (a) is the front view; (b) is the rear view. Green represents the modified extension bar allowing for a wider range of wear. Red is the elastic cabling holding the paddle to the leg.

3.2.3.3 O4T4

The underlying control code has improved significantly over this time. Specifically, a Basic Activity Recognition Algorithm (B-ARA) and Advanced Activity Recognition Algorithm (A-ARA) have been implemented in the Beta.

3.2.3.3.1 B-ARA

The B-ARA is the necessary underlying code within the APEx. It uses IMUs fitted in the control chip at the hip (1 on each side) and rotation sensors about the rotation axis (one on each side). Using data available from the US Army Natick Center (Joseph L Parham 2012), a basic kinematic model was created with measurements of different anthropomorphic data were normalized to thigh length. It was also assumed that the foot remained horizontal in any motion. With these measurements, the center of gravity (COG) was determined. Live tests indicated that situations requiring assistance placed the COG in front of the model's heel. This held for all tested parameters, including walking, sitting, climbing into a driver's seat, and pushing a cart downhill.

3.2.3.3.2 A-ARA

The advanced A-ARA uses a machine learning-trained model informed by IMUs placed at the top of the hip brace, the side, the lever arm, and the back. Then, motion data was captured while wearing the APEX to identify the signatures of squatting, sitting, pushing, walking, jogging, climbing stairs, and vehicle entry/exit. This was then fed into a machine learning algorithm that set parameters for the internal control board reporting. Initial tests of the AARA show a 95% success rate at identifying the activity.

The B-ARA and A-ARA work in conjunction to deliver torque as soon as it is needed. The APEx receives data initially from the B-ARA and makes its decision on if it should fire. The A-ARA is working in tandem, and while it is generally more accurate, it takes moments longer to conclude. If the A-ARA concludes differently from the B-ARA, it will take priority and discard the B-ARA input. In lab tests, it has been found that the two algorithms agree roughly 90% of the time.

3.2.3.4 O4T5

The APEx will come in two sizes, a small and a large. The small will fit a female's small shirt size to a men's medium shirt size. The large is designed to comfortably fit a men's medium shirt size to a men's XL. Throughout the vest, a strapping system makes adjusting between individuals easily accomplished by the user while wearing the APEx.

The thigh paddles will come in one standard size as currently designed. There will be an extendable plate supplied with the device to create an extended lever arm for comfort. This will not affect the device's net output regardless of length (max 30 Nm). The extendable plate can be adjusted by the wearer and does not require outside assistance.

Each device can also swap between small and large sizes, though it will take some time to reroute the strapping. This can be done by the work center and does not require outside assistance.

3.2.3.5 Testing Update

Testing will take place at ASU and Travis Air Force Base (TAFB). ASU's test will focus on the APEx's effect on pushing, and TAFB testing will examine the APEx's effects on squat quality, heart rate, and VO2 consumption.

3.2.3.5.1 ASU Testing

A preliminary test was conducted at ASU among four participants with no history of injury, neurological disease, back pain, with an unaffected natural walking gait. This was done to get a baseline expectation for the device in the Alpha configuration. The Beta is expected to improve on the Alpha.

Participants completed a modified version of the test described in previous CLIN reports. Here, subjects completed the test in two formats: wearing the APEx powered on and not wearing the APEx. Subjects were asked to begin by standing behind a weighted (40 lbs.) container. Participants would lift the box to a comfortable height and carry it 20 ft when told to start. Participants would then set the box down, walk behind it, and turn, facing the original direction to repeat the process. This task of moving a box 20 ft and then moving the box back to the original position was considered one set. Participants were given 20 seconds to complete each set, marked with an audible chime. Any time remaining within the 20 seconds after placing the box down was used as a rest period. Participants completed 40 sets in total. Once complete, participants were given 20 minutes to rest before repeating the process in the opposite format. Format order was randomized between subjects.

In a direct comparison and regardless of order, there are clear benefits to wearing the exoskeleton vs. not. The decreases in BPM and inadequate lifts indicate that the exoskeleton in its current configuration is accomplishing many of the project's goals. There are some outlying data in the results caused by hardware issues with the motor for the 4th study participant. The final test participant experienced an issue that disabled their APEx partway through the test. Their data was not used in calculating the BPM lift rates. However, their data were used in the t-test and showed that regardless of wear, BPM increased with the second test, indicating a need for a more extended rest period. However, bad lifts were decreased regardless of testing order, indicating substantial assistance by the new lumbar support system described in O4T1. Charts indicating the results of this test are available in Appendix B.1.

Future testing at ASU will focus on the effects of the APEx on pushing. This requires more specialized equipment to deliver proper measurements. The test will take place at ASU's Motion Capture Lab at the Polytechnic Campus.

In this test, subjects will be asked to press against a vertically mounted pressure sensor to both a set and undetermined force 100m while on a treadmill moving at a dedicated speed. The force pad's set condition will be 222.4 N (equal to move a 500 lb. block where coefficient of friction = 0.1). The speeds of the treadmill will be 1, 2, and 3 m/s. EMGs will be placed on the subject's legs to measure muscle activation. An Ergo Kit will be worn to measure heart rate, VO2, and bend angle. Force sensors on the treadmill and pad will measure the force output at each site. Subjects will complete the test wearing and not wearing the APEx. The sequence of wear and speeds will be generated using Latin squares, and the sequence selected by the subject chosen at random. This test will be conducted over two days with greater than 48 hours of rest between tests. Tests will be conducted at around the same time of day (±3 hrs).

3.2.3.5.2 USAF Testing

These tests will be conducted in service of the final deliverable of obtaining an 8% reduction in VO2 consumption. Tests will have two parts: a short, targeted test and a long-form test.

Targeted testing will look directly at aerial porters completing a set task within a defined timeline. This is an artificial environment intended to provide ideal conditions for the device. These tests are similar to the preliminary tests conducted at ASU. The subject audience will approach a 50 lb. weighted container. They will lift it to a comfortable height and transport it 20 feet, placing it on the floor when complete. They will have 30 seconds to accomplish this movement. This counts as one repetition. Subjects will complete 30 repetitions for one set, making 15 minutes per set. This achieves the recommended 50% duty cycle. Heart rate, VO2, and lift quality will be measured as well, using the GoX Ergo Kit consisting of a wristwatch and a small, shirt-mounted sensor. Two sets will be completed by each subject, one with and one without the exoskeleton. The order of these will be randomized. The subjects will also have greater than 24 hours of separation between the tests to rest appropriately. To eliminate variables, we will remove the resting VO2 rate, and the participants will be tested at the same time each day. This test procedure will be the priority test among those completed at TAFB.

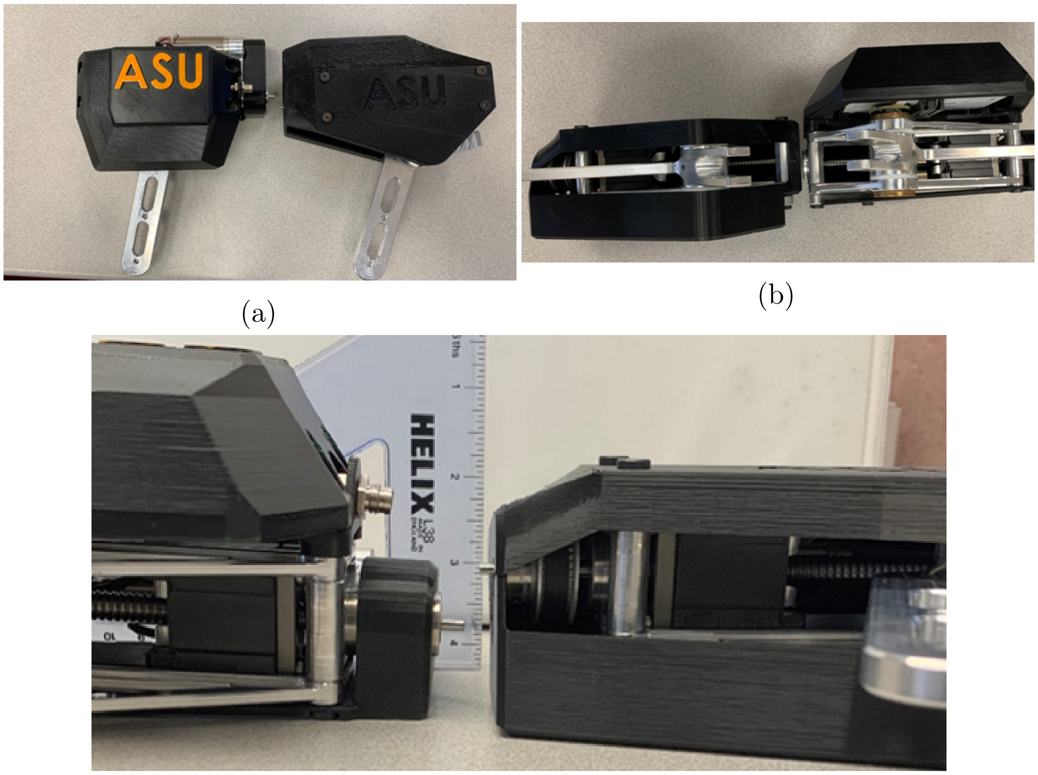
The long-form study will investigate the use of APEx in a real-world environment and take part in two phases. This is meant to measure the impact of the device on the workforce. It will also give participants time to get familiar with the device and learn to work with it to enhance effectiveness.

Subjects will be asked to complete their daily work tasks while wearing an Ergo Kit. Measurements will be taken over one week for each phase. In phase A, subjects will spend their first week wearing the exoskeleton. Phase B will have subjects complete the week without the device. Subjects will complete both phases with phase order randomized. Subjects participating in this study can, but are not required to be separate from those completing the targeted testing. These tests will determine the

VO2 reduction during lifting and pushing performance metrics described in the SOW. Additional testing will be completed at ASU to determine the other performance metrics as necessary.

3.2.3.6 Commercial Design Update

The final design for the APEx is mainly completed with minor adjustments being made. Beginning from the previous update, the Beta has moved all the strapping into a vest structure. The straps move through dedicated, closed channels to minimize snagging hazards and tangling. The battery pack and control module have also been moved into pockets on the vest.



(a)

(b)

(c)

Figure 10: (a) A side view of the old actuator casing (left) vs new actuator casing (right). (b) A bottom view of the old actuator casing (left) vs new actuator casing (right). (c) A comparison of the old actuator casing (left) vs new actuator casing (right) with a ruler in the background for easy comparison.

The actuator casing has been reduced in size to deliver a slimmer profile 10. This was achieved by reducing the control circuitry's size and moving it to rest in unused inner space between the actuator and the user's thigh. Previously the control circuitry sat outside the actuator. The commercial casing will feature a clamshell design to fit together easily. It will not be IP-rated.

Production has begun for the final six devices, focusing primarily on the actuator mechanism. Once the design is finalized, other components will enter construction. USAF and ASU test subjects will use the Beta+ models. This model is near-production ready, allowing for minor adjustments as submitted by the test group before finalization.

3.3 Center of Gravity Model

The critical component of the ARA-B is the Center of Gravity (CoG) model. Early versions of APEx control was a time-based and simple motion-based model. As the user entered a squat position, the device would track the motion and activate as the user began to rise back up. If the user stayed in the squat position for over 3 seconds without the APEx registering an upward motion, it would also activate. These controls were selected for ease of implementation and a simple assumption that remaining in a squat position for too long meant the user required help. There was, however, a flaw in this system in that sitting motions would also register a squat and could thrust a user's back into the chair, causing harm. This was mitigated somewhat by the ARA-A but suffered from timing delays. The prime issue with ARA-A was that it leaned heavily on an AI design. This approach requires a large dataset to train the algorithm to detect the necessary patterns. Further, the dataset requires a wide range of individuals. An extensive range ensures that the algorithm can make the best decision based on a wide variety of observations. Without a large and varied dataset, the algorithm often returns an incorrect result when used on someone different from those in the initial training set. Further, the algorithm requires more samples of a pattern until it returns an answer with a high degree of confidence. It is this second issue that plagued the performance of the ARA-A. The algorithm required roughly a half-second to return a value with high confidence. Such a slow return was unacceptable as the APEx is designed to help the user in the earliest stages of lifting/pushing, and a delay would result in little overall assistance. To mitigate delays, a faster system needed to be created. One that could make rapid assumptions based on the input data to provide just-in-time assistance. It was determined that a CoG model would be a good candidate for such a task. The APEx's base system provides four potential input sources, the rotary encoder, and IMU on each side. The rotary encoder measures the angle of the thigh with respect to the user's torso. The IMU measures the user's torso with respect to gravity. With these data points, it was proposed that a reasonable model could be achieved that would identify where the user was in space. Further, that the CoG of the user could be determined to decide if the user was stable enough to receive assistance, stability would be identified by locating the CoG within the user's "triangle of stability.“ Typically seen in forklift operations, this concept posits that a forklift does not tip over if the CoG remains in the triangle area illustrated in Figure 11 (Cheema and Sepehri 2002). If it falls outside this area, it is unstable and will fail. Versions of this idea are already used in the autonomous control of legged robots and have seen some successes (Messuri and Klein 1985).

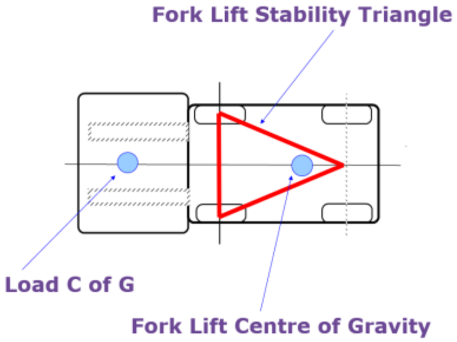


Figure 11: Forklift triangle of stability. The forklift is considered stable if the CoG is within the triangle.

3.3.1 Derivation

To develop this model for individuals, accurate measurements would be needed. Such accuracy is both unreasonable and impractical, as it would require custom profiles for each user after extensive modeling and data input. To avoid this, a survey of human anatomy was considered to make generalized measurements. Using data available in the literature, average human thigh, shank, foot, and torso measurements were taken (Dempster 1955).To make a general model, the thigh length was set as the standard unit of measure. With a generalized measurement schema, the limbs were also related to individual centers of mass with respect to known reference points (Virmavirta and Isolehto 2014). This information can be seen in Figure 12.

Assumptions and constraints based on the use case were implemented to create a robust model. The first is that the floor is level. There is no way to begin to determine if the user is standing on an un-level floor, especially in complex positions such as one foot higher on a slanted box and the other on a lower level. This pairs with the second assumption that the foot is flat and perpendicular to the floor. There is no means to measure this either, but it needed to be determined to identify the stability zone. These assumptions were further constrained by identifying locations only in the sagittal plane. Assistance is provided only in this direction, and extra calculations to determine the location in 3D space would, at this time, not be helpful. The final

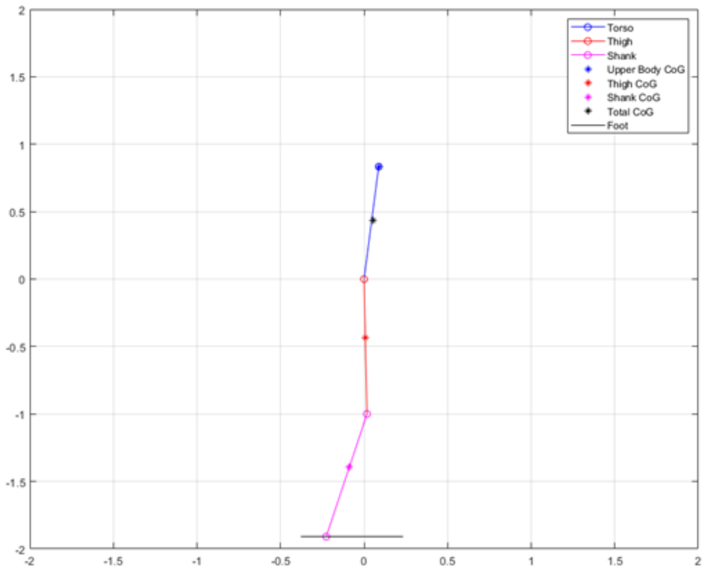


Figure 12: An example of the CoG model representation. The model uses inputs of torso angle vs. gravity and thigh angle vs. torso to create an assumed position of the human. The CoG is then determined (black asterisk).

assumption set the angle of the shank. As there are no reliable means to measure the angle of the shank based on the inputs provided, it was decided to experiment with a constant value; doing so allowed for rapid testing of the CoG model. The first three angles to test were chosen to be a factor of the torso angle. Since both are roughly vertical and change far less than the thigh, it was seen as a safe bet. The torso angle was multiplied by 0.9, 0.6, and 0.4 to dial in a value that proved most effective. After in-house tests using the different factors and assumptions, it was determined that 0.9 was the most effective. Later analysis was conducted to determine the cause of the 0.9-factor effectiveness. At the values provided, all performed moderately well and achieved a location less than 0.005 thigh units off the true value in the x-axis. The results of these factors compared to specific activities can be seen in Figures 13, 14, 16, and 17.

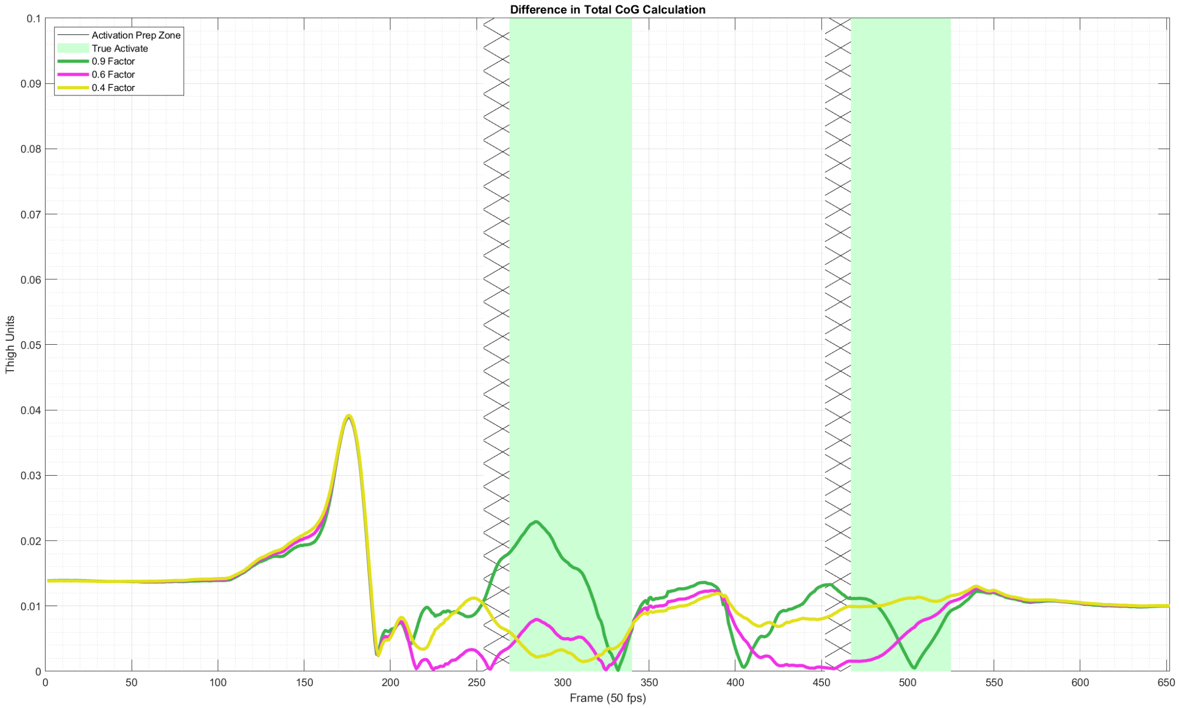


Figure 13: Graphs of the squat lift task using different shank angle constants. The hashed zone represents critical preparation areas, and the green zone an approximation of when the robot should activate based on the thigh angle reversing direction. Approximations were determined from video review. (Top) When conditions are met for activation, the associated value registers as 1. (Bottom) The difference in Total CoG location calculated with different factors (lines) vs. true (y=0).

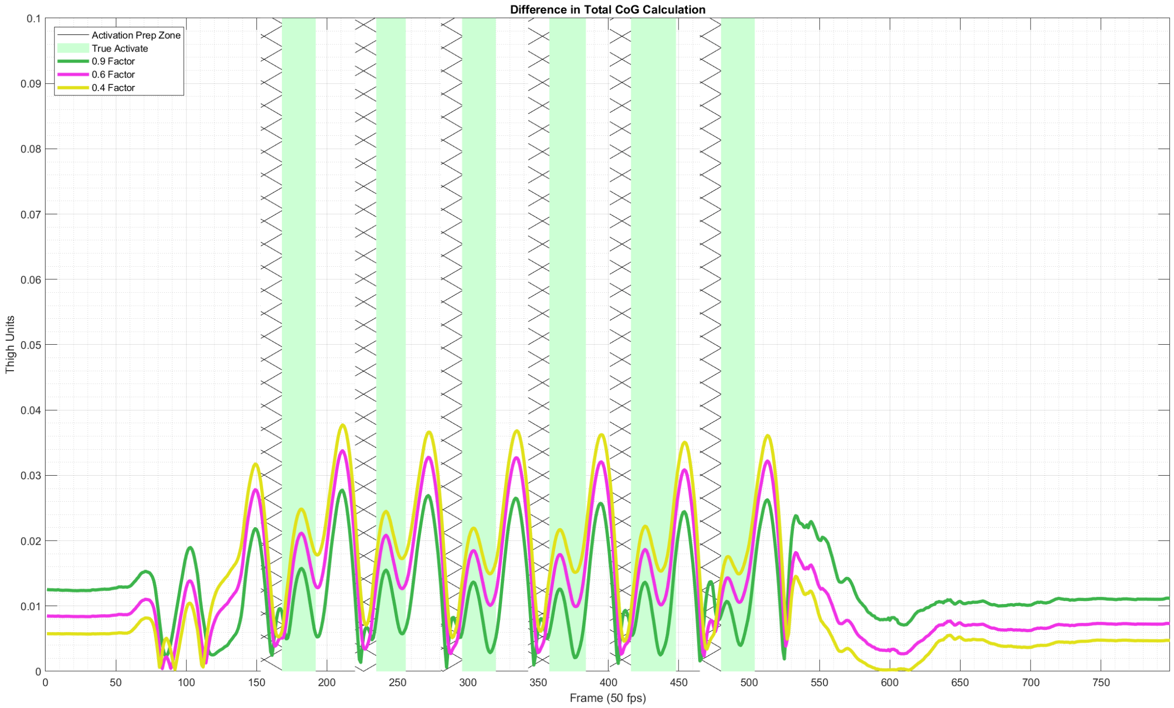


Figure 14: Graphs of the push task using different shank angle constants. The hashed zone represents critical preparation areas, and the green zone an approximation of when the robot should activate based on the thigh angle reversing direction. Approximations were determined from video review. (Top) When conditions are met for activation, the associated value registers as 1. (Bottom) The difference in Total CoG location calculated with different factors (lines) vs. true (y=0).

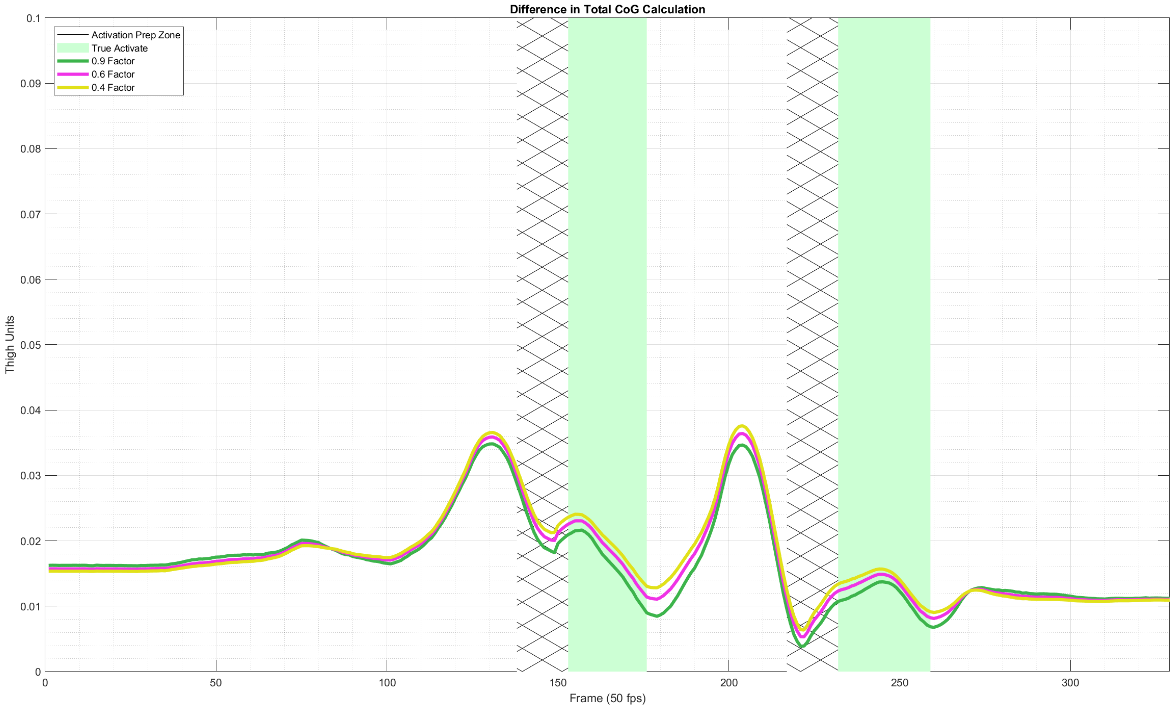


Figure 15: Graphs of the ascend stairs task using different shank angle constants. The hashed zone represents critical preparation areas, and the green zone an approximation of when the robot should activate based on the thigh angle reversing direction. Approximations were determined from video review. (Top) When conditions are met for activation, the associated value registers as 1. (Bottom) The difference in Total CoG location calculated with different factors (lines) vs. true (y=0).

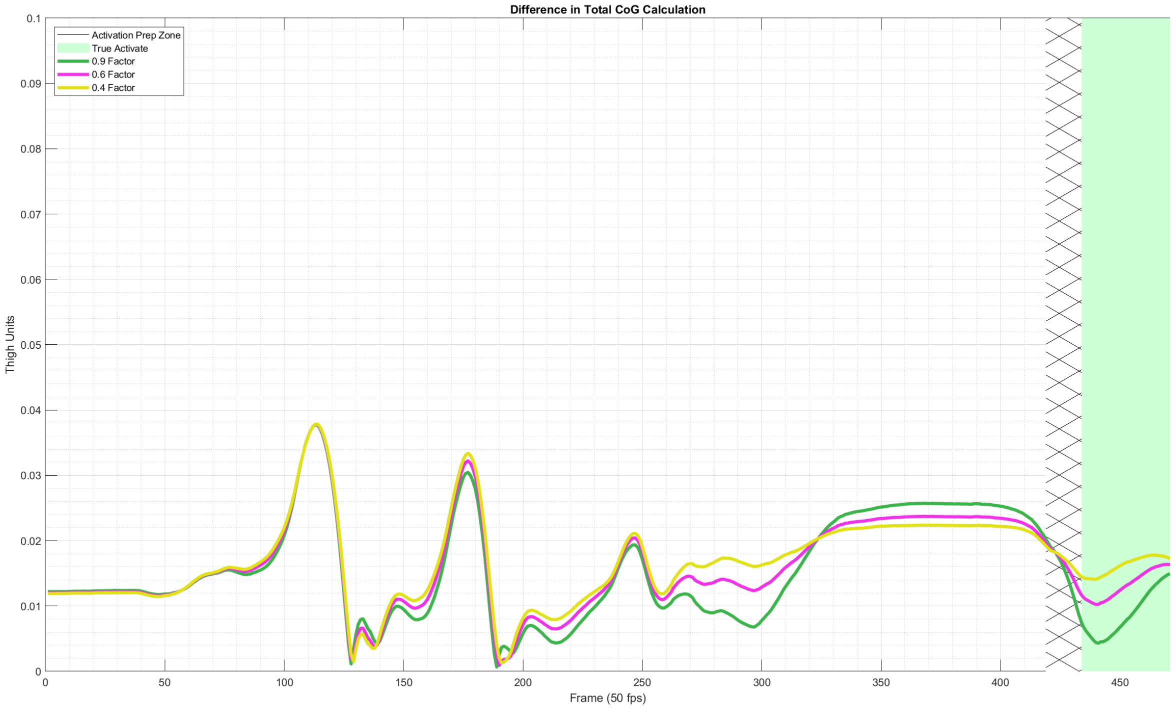


Figure 16: Graphs of the sitting when approached from the left task using different shank angle constants. The hashed zone represents critical preparation areas, and the green zone an approximation of when the robot should activate based on the thigh angle reversing direction. Approximations were determined from video review. (Top) When conditions are met for activation, the associated value registers as 1. (Bottom) The difference in Total CoG location calculated with different factors (lines) vs. true (y=0).

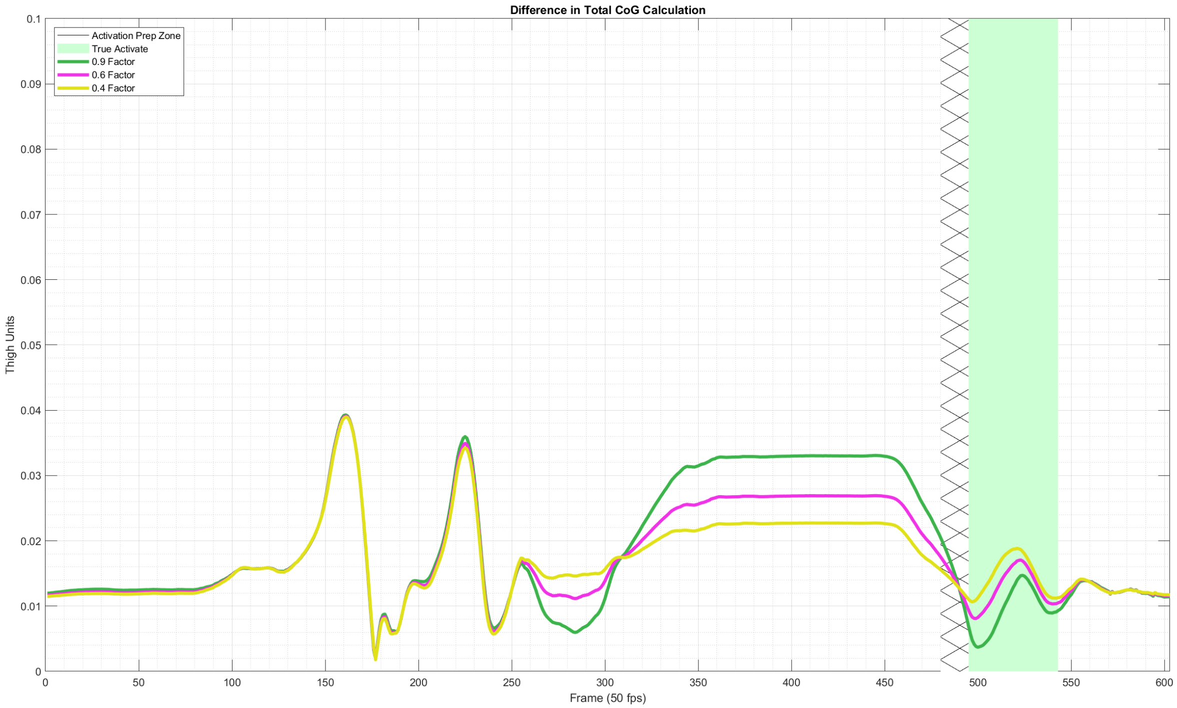


Figure 17: Graphs of the sitting when approached from the right task using different shank angle constants. The hashed zone represents critical preparation areas, and the green zone an approximation of when the robot should activate based on the thigh angle reversing direction. Approximations were determined from video review. The difference in Total CoG location calculated with different factors (lines) vs. true (y=0).

The 0.9 factor had a strange interaction, where, in squat lift tasks, it was more incorrect than the other values during the activation period. However, it was more accurate in other tasks (pushing, sitting, and stair climbing) throughout. Using the 0.9 factor, pushing performed admirably, activating when at critical moments where others might not. It also erred on the side of safety, delivering a Type II error when users were on the edge of stability. Based on their geometry, others would be less sensitive and could activate in undesirable situations. Because of its overall accuracy and performance, the factor of 0.9 was chosen to model the shank CoG.

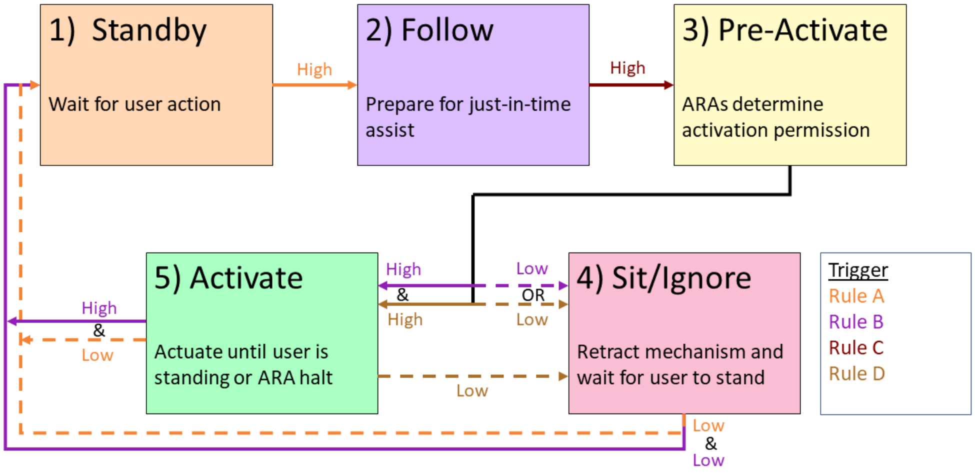


Figure 18: The state space digram of the B-ARA.

With an acceptable means of calculating the CoG of the body, a state controller was designed to handle the resultant calculations. This controller would decide when the use of the device was within safe parameters and act accordingly. The states are split into five distinct components with four trigger rules governing them at their most basic.

- States
    1. Standby
    2. Follow
    3. Pre-Activate
    4. Sit/Ignore
    5. Activate
- Rules
    - Equation 3.6: Boolean equation monitoring the thigh angle against the trunk. Returns 1 where true.

$$50^\circ <= \theta_{thigh} <= 120^\circ \tag{3.6}$$

    - Equation 3.7: Boolean equation monitoring the torso angle against gravity. Returns 1 where true.

$$0^\circ <= \theta_{torso} <= 70^\circ \tag{3.7}$$

    - Equation 3.8: Boolean equation monitoring the change in thigh angle over the last two time periods. Returns 1 where true.

$$(\theta_{thigh}(t) < \theta_{thigh}(t-1)) and (\theta_{thigh}(t) < \theta_{thigh}(t-1)) \tag{3.8}$$

    - Equation 3.9: Boolean equation monitoring the location of the X value of the Total CoG. Returns 1 where true.

$$0 <= TotalCoG_x \tag{3.9}$$

Rule A monitors the thigh and determines if it is in a range where the APEx can assist. If it is determined to be so (Equation 3.6), it returns a high value. Rule B monitors the torso for lean and returns a high value if it is within the appropriate range (Equation 3.7). Rule C checks for user intent to return to a standing position by taking the change in thigh angle over time. If the previous three values are progressively smaller, the rule returns true (Equation 3.8). Finally, rule D uses the above CoG location calculations by verifying if the x value of the total CoG is ahead of the user's heel. The value of 0.15 was selected as it roughly keeps the CoG from going behind the heel. Rule D returns a high value where true (Equation 3.9). Each state monitors some combination of these 4 rules to determine appropriate activation times. In the first state, standby, the unit reads in data from the torso and thigh. The actuation mechanism is in the stored position, awaiting instructions. Once rule 1 is true, the system progresses to state 2, follow. Here, the push block moves up to the fork and follows it back, staying close by and ready to apply force when needed. It stays in this follow mode until rule C is high. Returning high indicates the user is ready to begin their upward motion. If true, the system proceeds to state 3, pre-activation. In pre-activate, the APEx makes a safety decision by monitoring rules B and D. If either returns a low value, the system enters into the sit profile. This profile is because either the user is in an assumed crawl position or the CoG is in a hazardous location. It remains in state 4 until the user is standing upright, characterized by having the torso in a good location and the thigh straightened. When standing it detected, the system returns to state 1. If instead rules B and D return high values, the system moves to state 5. State 5 is responsible for activating the unit and applies torque until the user is standing again. If rule D returns a low value during state 5 activity, the system immediately moves to state 4. Physically this retracts the actuation mechanism to a non-interfering position. This action proved to be essential in protecting against corner-case seating, where a user entered what appeared to be a squat before shifting back into a seated position. Without moving from state 5 to 4, the unit would throw the user into the chair. Testing then began in earnest to identify effectiveness. Different users wore the device and found that the model's view of the world was practical, resulting in few false activations. These could be attributed to the generalized model of the human created before. By taking an average, there were opportunities for users to be in a poor position, regardless of the model. This positioning issue was solved by adjusting the area of stability 0.2 thigh units ahead of the heel, leaving the toes in the same position. While this shrank the range of firing opportunities, it improved reliability, reducing false activations to a near-zero occurrence.

Figure 19 is an example of this state diagram and accompanying rules in action. The user was instructed to approach a container, squat lift it, and place it back down. The APEx starts in state 1, waiting for the user to begin a downward motion. Rule A (orange) can be seen going high when this is true. Once started, the APEx shifts to state 2, following the user down. Once rule C is true (magenta, high), indicating a changing direction, the APEx moves to state 3 for one frame. It makes the determination that the CoG is safe (Rule D, brown, high) and the torso is in an appropriate location (Rule B, purple, high) and moves into state 5. It stays there until the user stands upright (Rule A, orange, low; Rule B, purple, high) and resets to state 1.

Figure 20 represents the results of a sitting activity. The user moves through states 1-3 in the same manner as in the lifting example. However, at the time of the decision, the CoG is evaluated as false (Rule D, brown, low) and moves into state 4. It stays in this condition until the user is standing again (Rule A, orange, low; Rule B, purple, high). Then it returns to state 1.

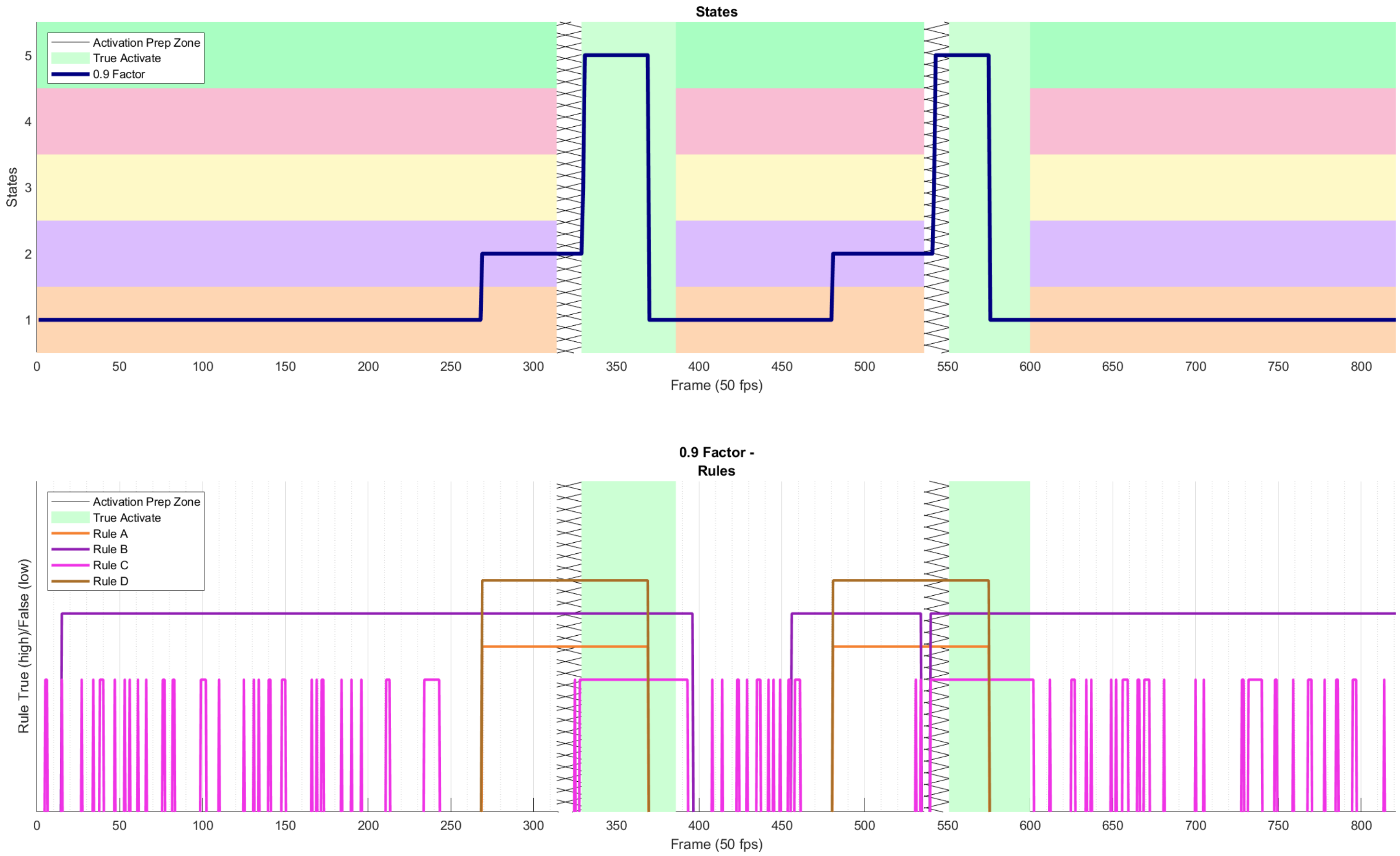


Figure 19: An example of the state diagram process in a lifting task.

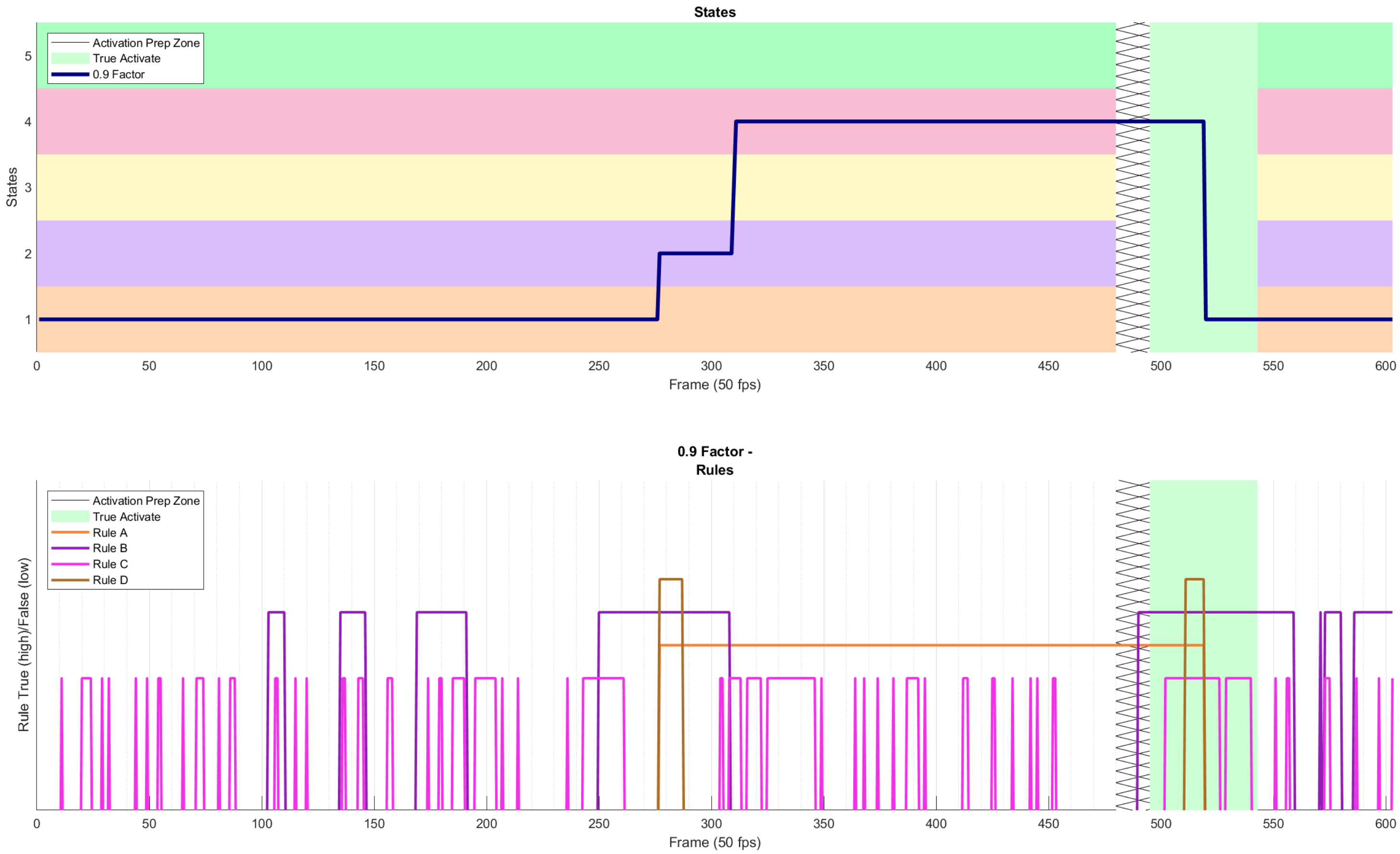


Figure 20: An example of the state diagram process in a sitting task.

3.3.2 Updated Derivations

This was the ARA-B model implemented for testing, but there was still work to be done on the model for refinement. This problem was looked at as having different solutions:

1. Using brute force programming, is it possible to identify a better constant for a range of valid positions?
2. Humans are dynamic but repeatable. Can captures be generated from different activities to identify patterns?
3. Can these patterns be formed into an equation for better refinement?

A brute force algorithm was created to measure the different CoG positions given the useable range of lower leg motion to answer the first question. Three constraints were placed on the model to reduce processing time and make the resulting data more relevant. The goal was to determine if a more relevant factor than 0.9 existed. If not one factor, then if a pattern emerged that identified clear regions in which to use different factors. First, the total CoG had to be within the zone of stability: before the heel and behind the toes. This condition ensures that the user is fully stable and is at the least likely risk of falling. However, it doesn't consider a carried load that could shift the CoG in the real world but not in the model. The mischaracterization would result in a device that doesn't activate even though it's needed. Second, the Y position of the knee could not be below the Y position of the heel. Similarly, the third constraint prevented the Y position of the hip from being below the Y position of the heel. These rules helped to eliminate "impossible" situations where the limbs would extend into the ground. The angles tested were also constrained to roughly the range of motion for each limb: the torso from 0 degrees to 90 with respect to the vertical;

the thigh from 70 to 200 degrees with respect to the torso; the knee from 50 to 170 degrees with respect to the thigh. All tests were run with a step size of 1 degree to capture a significant number of combinations.

- Equation 3.10: Test constraint 1, requiring the x component of the CoG to remain over the feet.

$$0.15Units_{thigh} <= TotalCoG_x <= 0.15Units_{thigh} \tag{3.10}$$

- Equation 3.11: Test constraint 2, requiring the x component of the CoG to remain in front of the heel.

$$0.15Units_{thigh} <= TotalCoG_x \tag{3.11}$$

- Equation 3.12: Test constraint 3, requiring the torso angle to be between 0 and 70 degrees.

$$0^\circ <= \theta_{torso} <= 70^\circ \tag{3.12}$$

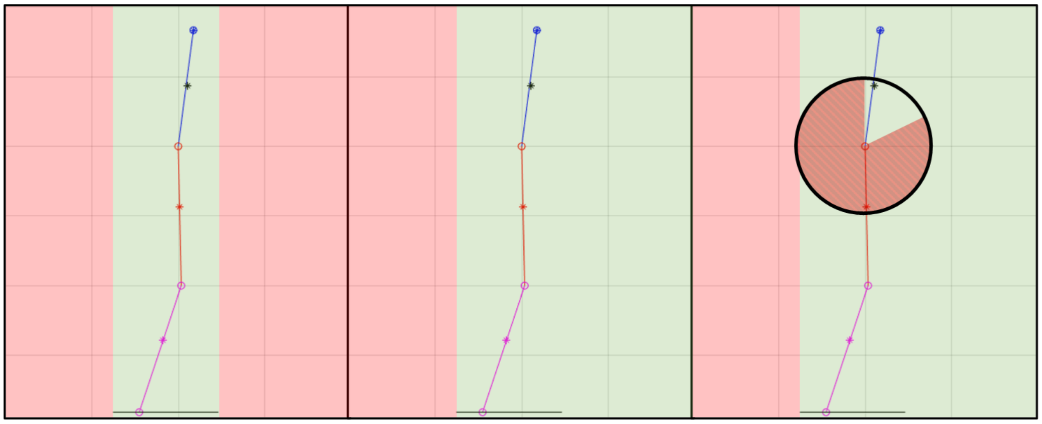


Figure 21: A graphical representation of the 3 conditions analyzed with the brute force method. (Left) Condition 1, (Center) Condition 2, (Right) Condition 3. Red vertical bars indicate invalid locations for the CoG. Green indicates valid positions. The circle in the right image indicates angles from the vertical that are valid and invalid. The dark red section is invalid.

Two additional tests were run, one adjusted the zone of stability to be any point beyond the heel plus 0.2 thigh units, and the other added a constraint to have the torso at less than 70 degrees lean. Adjusting the acceptable CoG location allowed the APEx to activate in the carried load situation described above. It assumes that the user can recover if the CoG is off with a minor adjustment of footing. However, it allows for any condition, so long as the CoG is before the heel to activate, including crawling. Naturally, this is undesirable, so the lean condition was implemented. This angle was chosen as observational tests did not see the user going beyond 50 in desired activation conditions. By implementing this, a user could crawl without worrying about losing stability. Although, it also removed the possibility of pushing items close to the ground. The figures below show the 3D and 2D comparisons. A histogram was also created that evaluated the ratio of the angle of the torso to the angle of the shank for all three conditions.

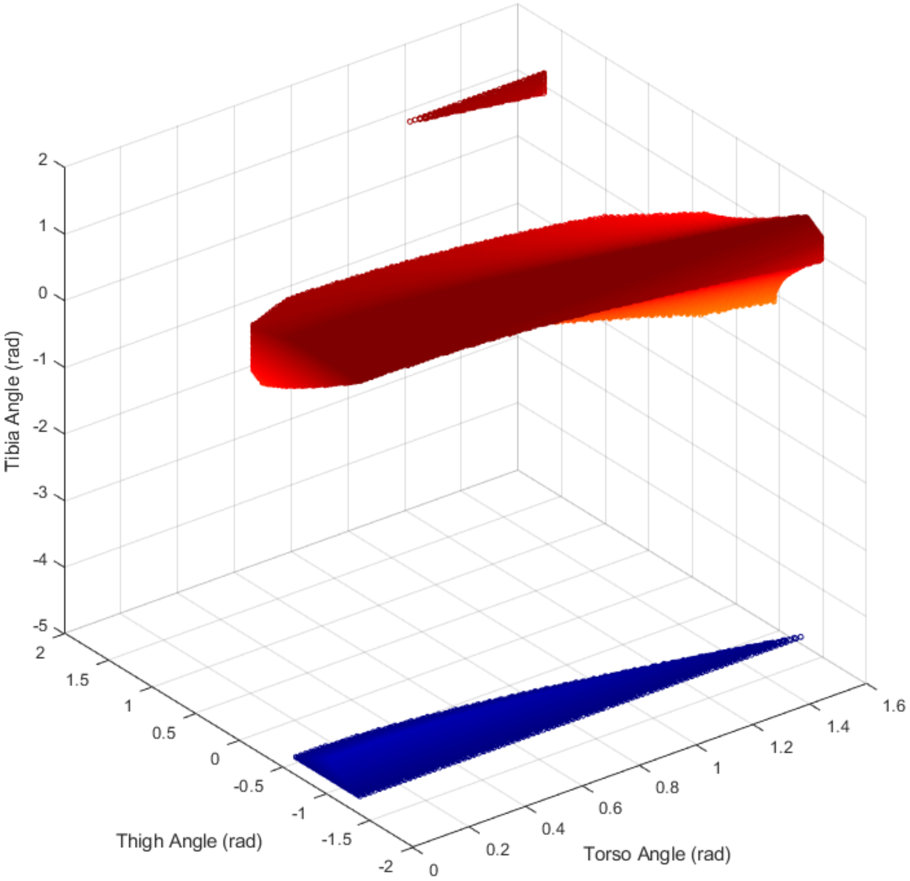


Figure 22: 3D graph of the leg angles leading to a stable stance for condition 1. Condition 1's requirement is to have the CoG in front of the heel and behind the toes.

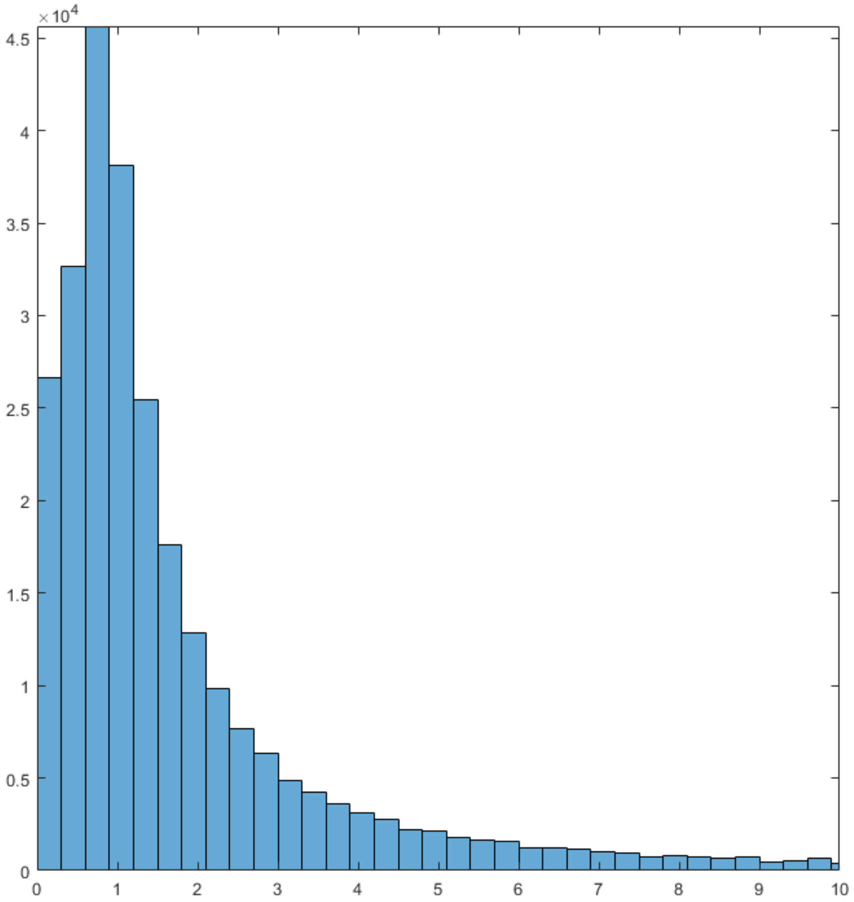


Figure 23: Histogram of associated Tibia (shank) versus torso angles for condition 1.

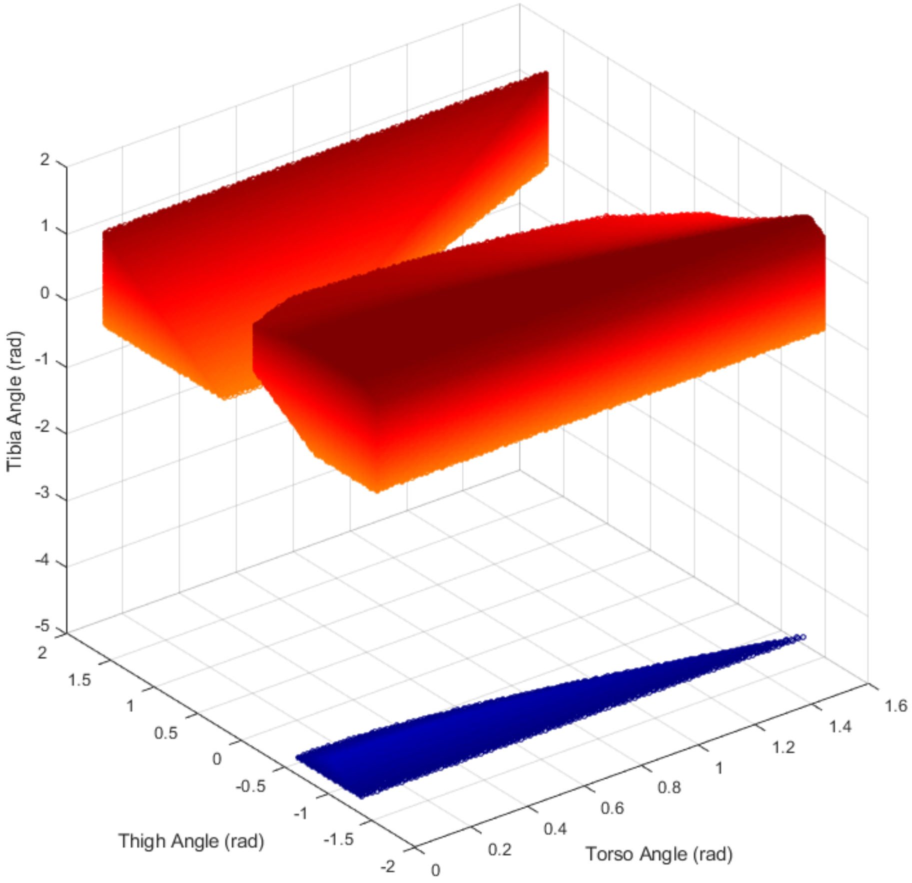


Figure 24: 3D graph of the leg angles leading to a stable stance for condition 2. Condition 2's requirement is to have the CoG in front of the heel and behind the toes.

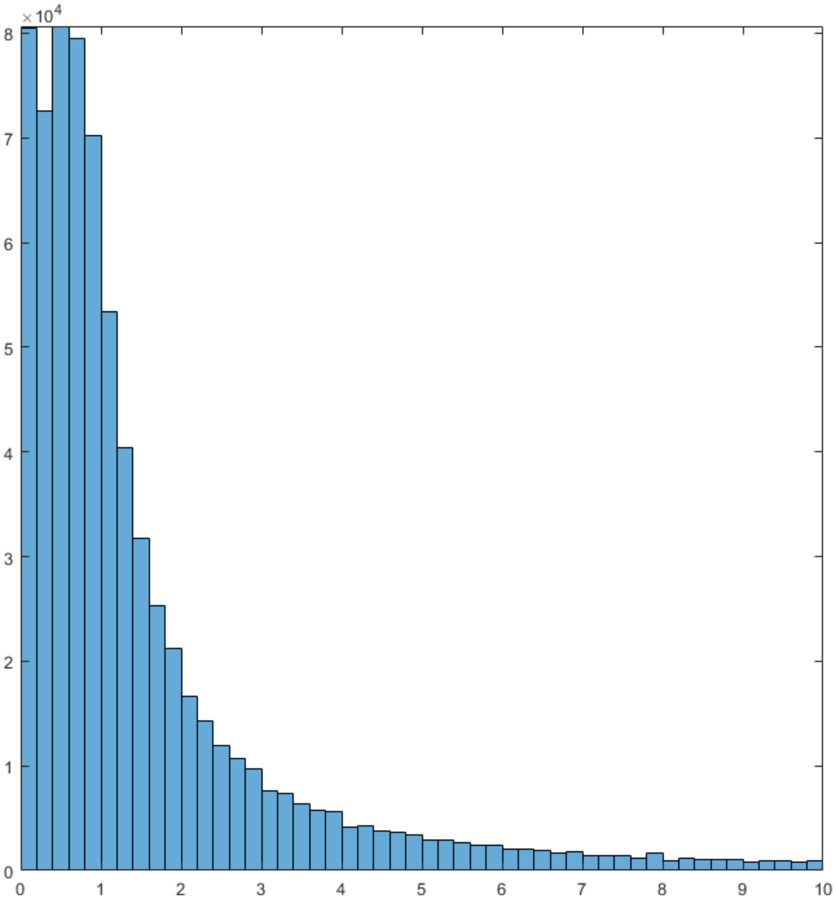


Figure 25: Histogram of associated Tibia (shank) versus torso angles for condition 2.

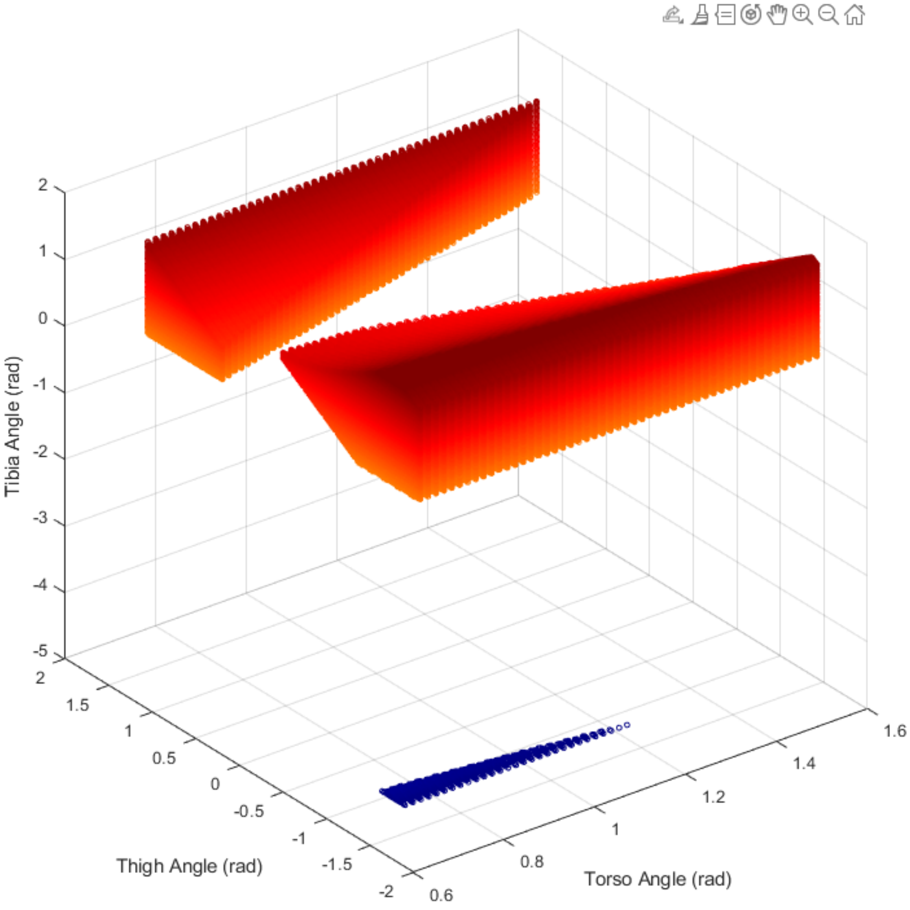


Figure 26: 3D graph of the leg angles leading to a stable stance for condition 3. Condition 3's requirement is to have the CoG in front of the heel and behind the toes.

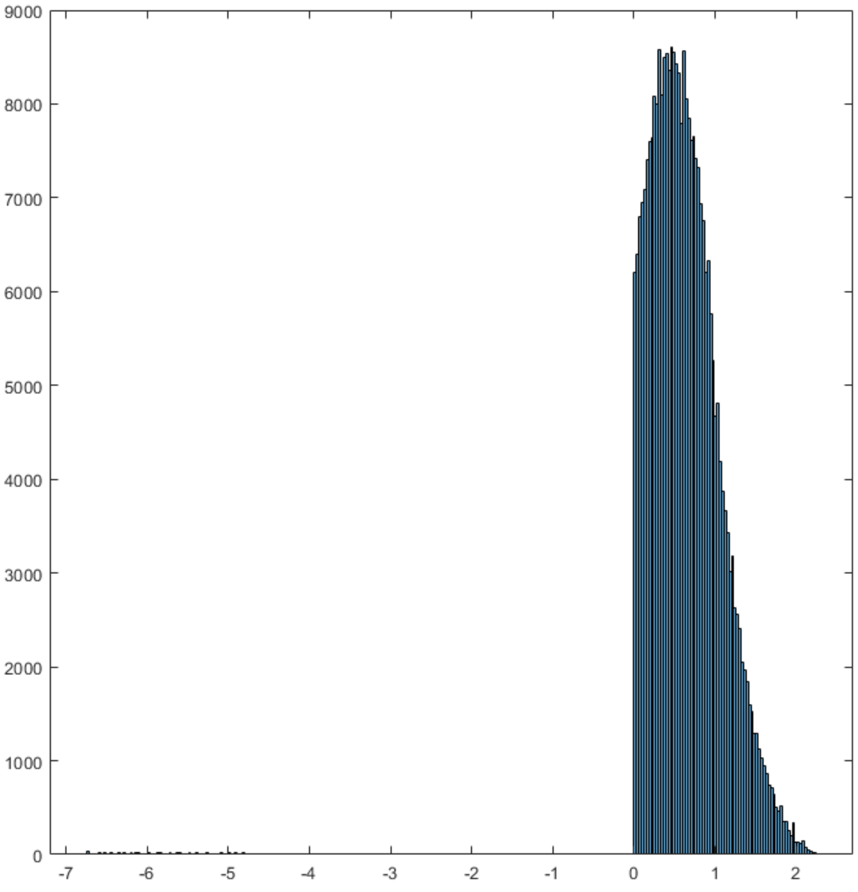


Figure 27: Histogram of associated Tibia (shank) versus torso angles for condition 3.

Condition 1 was characterized by requiring the CoG to be between the x-values of the toe and heel to be considered valid. Using a step size of 1 over the previously identified angles, 26.4% (278,783/1,055,241) were found to be valid. Condition 2 was characterized by requiring the CoG to be in front of the x-value of the heel to be considered valid. Using a step size of 1 over the previously identified angles, 71.5% (754,391/1,055,241) were found to be valid. Condition 3 was characterized by requiring the CoG to be in front of the x-value of the heel and the torso angle (measured from the vertical) to be less than 50 degrees to be considered valid. Using a step size of 1 over the previously identified angles, 29.2% (308,211/1,055,241) were found to be valid. In reviewing the histogram data for all three conditions, there are clear highs at a factor of 0.4 for conditions 2 and 3, but a high at 0.9 for condition 1. This is sensible as condition 1 leaves a smaller room for acceptable points, in general forcing a more upright position. Conditions 2 and 3 allow for the CoG to be forward of the toes, creating a far more extensive field of valid locations. These conditions were allowed as it assumes the user will either use outside assistance to support the imbalance (as in pushing activities) or will step forward to recover.

3.3.2.0.1 Dynamic Model Development

The dynamic nature of human motion was also investigated with an aim to identify patterns. This was done using a motion capture system while using the exoskeleton and completing various tasks. These were: approach, squat lift, and set down a container; approach a chair from the left/right, sit, and stand; ascend/descend stairs; push. The model was then solved to return angles of the torso, thigh, and shank to identify a ratio, much as the brute force investigation. This method allowed for investigating changes in sagittal plane angle as the body moved through 3D space and yielded some interesting results. The first step was to put the data together in one image to identify any immediate trends (Figure 28). Unfortunately, while there appears to be defined branches, there is no clear pattern to be determined. To parse out more information, the data was color-coded according to activity: standing, walking, squatting, climbing or descending stairs, pushing, and sitting (Figure 29). Almost immediately, patterns arise, showing motion profiles in unique spaces from other activities. Going a step further, the direction of motion in terms of theta dot was also separated, adding additional insight into the motion pattern (Figure 30). Walking and standing points were then removed as they are not motions intended to be assisted (Figure 31). This cleared representation implied that all the motions had a central node but also had local patterns and extrema that might be used in later activity recognition endeavors.

With the cleared data in hand, a modified histogram was made to identify how difficult it might be to create a generalized factor for torso vs. shank angle (Figures 32, 33). This was done by binning the data in n = 100 (10x10) and n=2500 (50x50) boxes and taking the min, max, average, and range of the shank angle given the associated hip and torso measurements. Unfortunately, the resultant plot showed that there was a wide range of potential at the start of movements, with fewer options at the fringes of the motion space. To provide additional context, these bar graphs were added to the colored point clouds (Figures 34, 35).

These binned averages were then mapped to a surface to identify areas of rapid change that would make defining a position difficult. Very quickly, at n=100 (Figure 36), the central node identified itself as the area of steepest ascent/descent, with smoothing at the fringes. At n=2500 (Figure 37), the initial glance shows a chaotic field but relatively the same results. The n=100 mesh (Figure 38) was then overlaid to the point cloud to get context, where it became rapidly apparent that the stair activity was the cause of this rapid change. Raising the sample to n=2500 (Figure 39) helped differentiate slightly. The mesh data was then fed into MATLAB's scattered interpolant function to create a pseudo lookup table to create a means to determine shank angle dependent on the torso and hip angles.

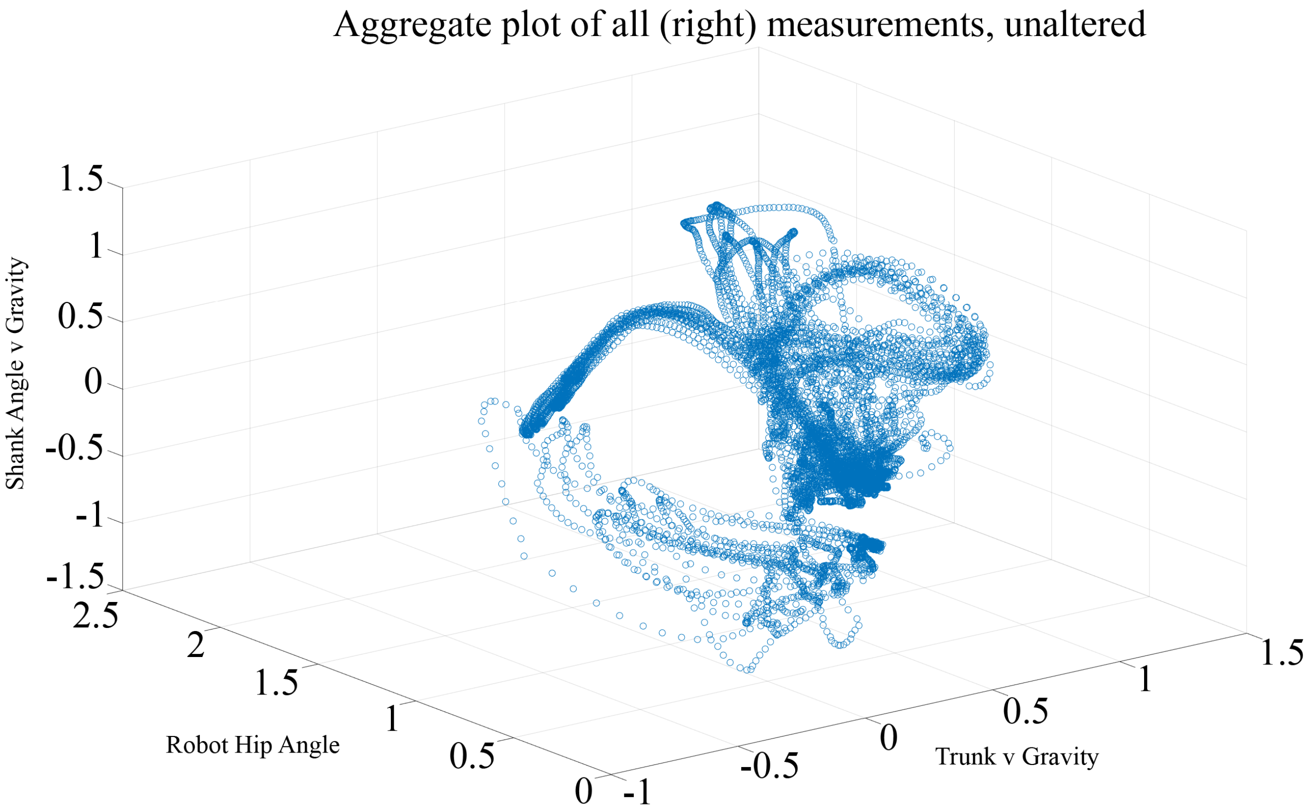


Figure 28: Aggregate plot of all right leg measurements.

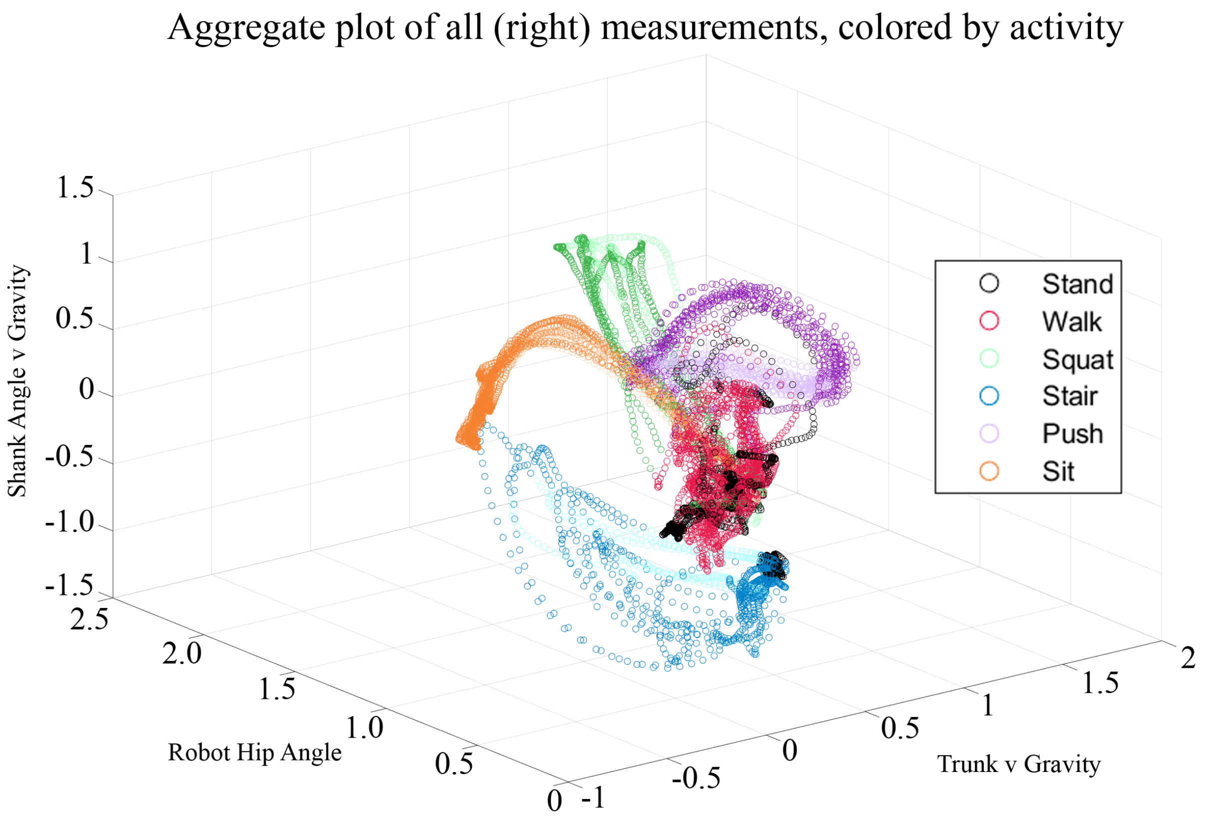


Figure 29: Aggregate plot of all right leg measurements, colored by activity.

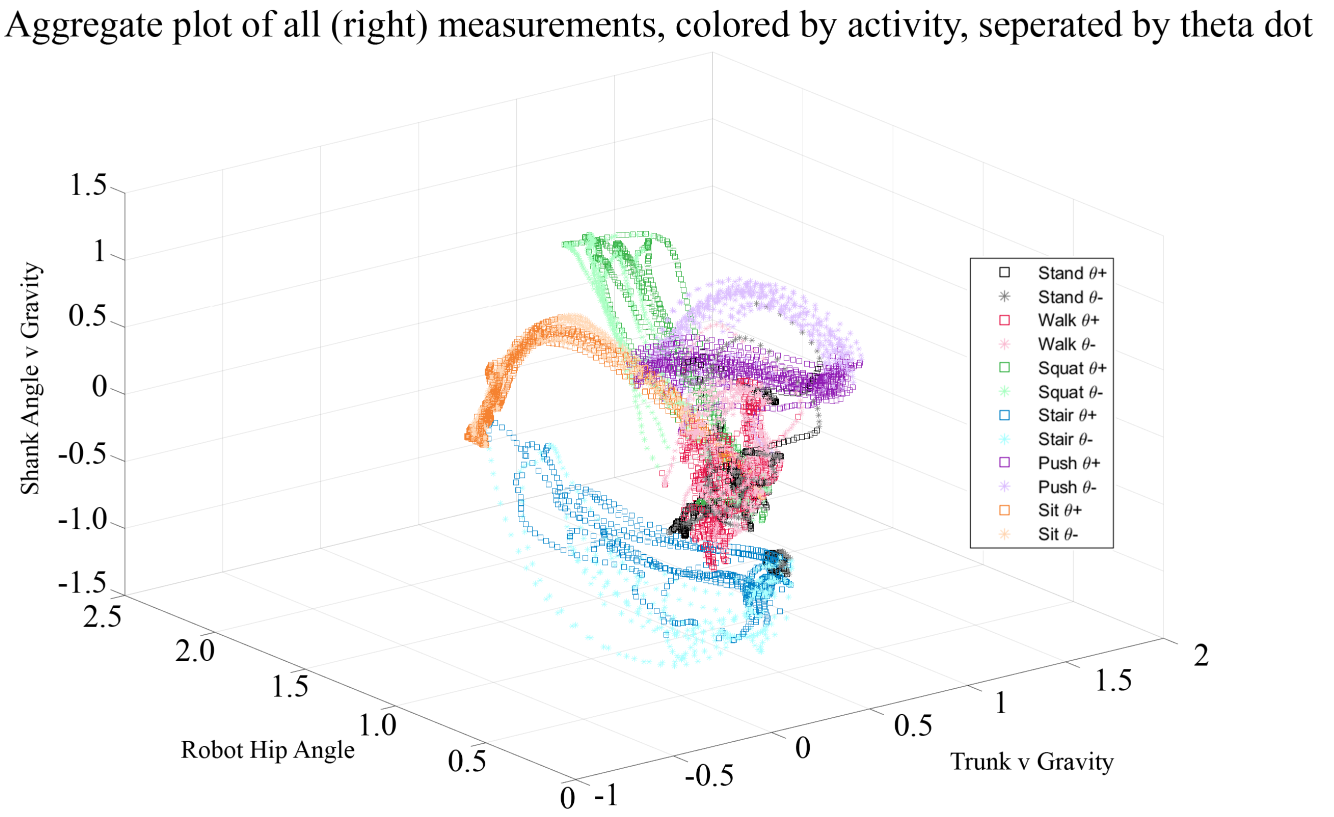


Figure 30: Aggregate plot of all right leg measurements, colored by activity, separated by theta dot.

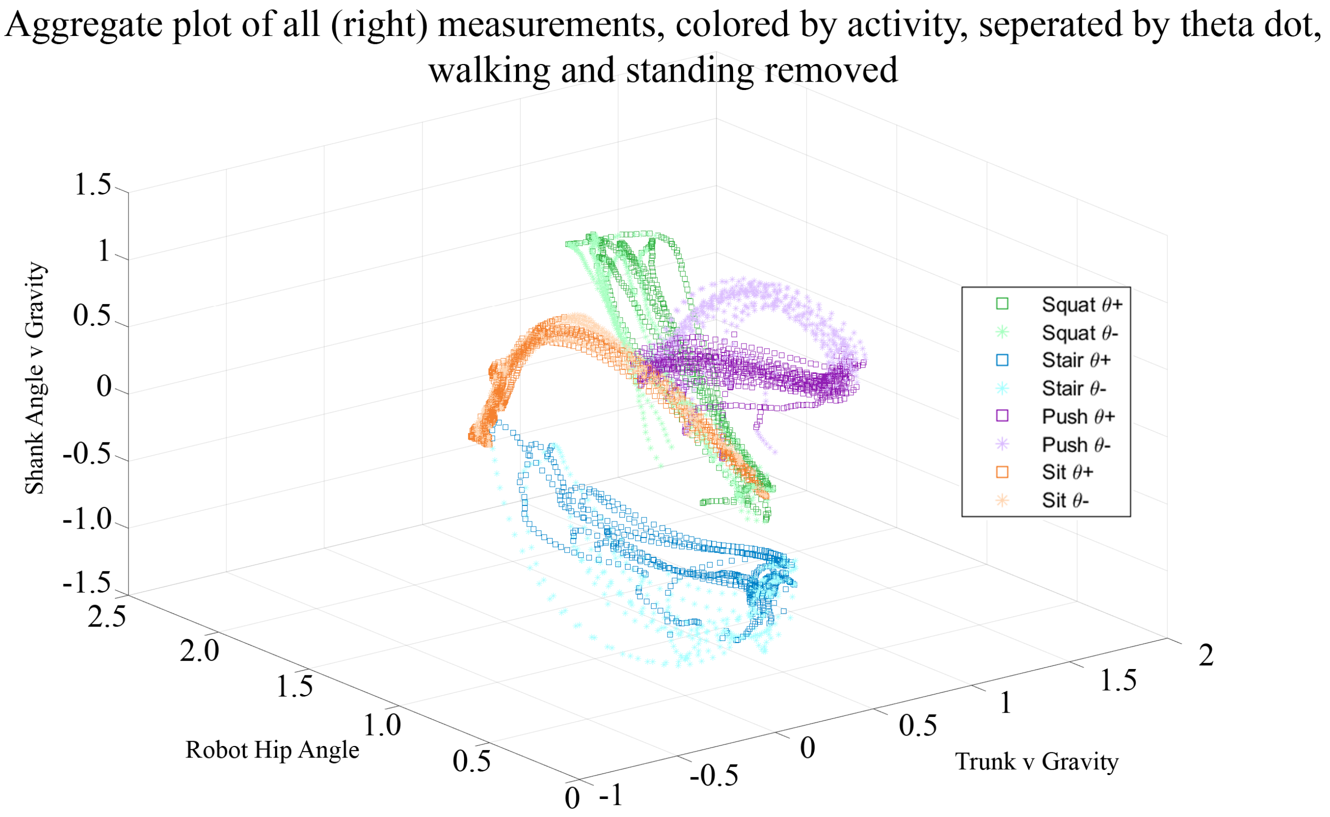


Figure 31: Aggregate plot of all right leg measurements, colored by activity, separated by theta dot, walking and standing removed.

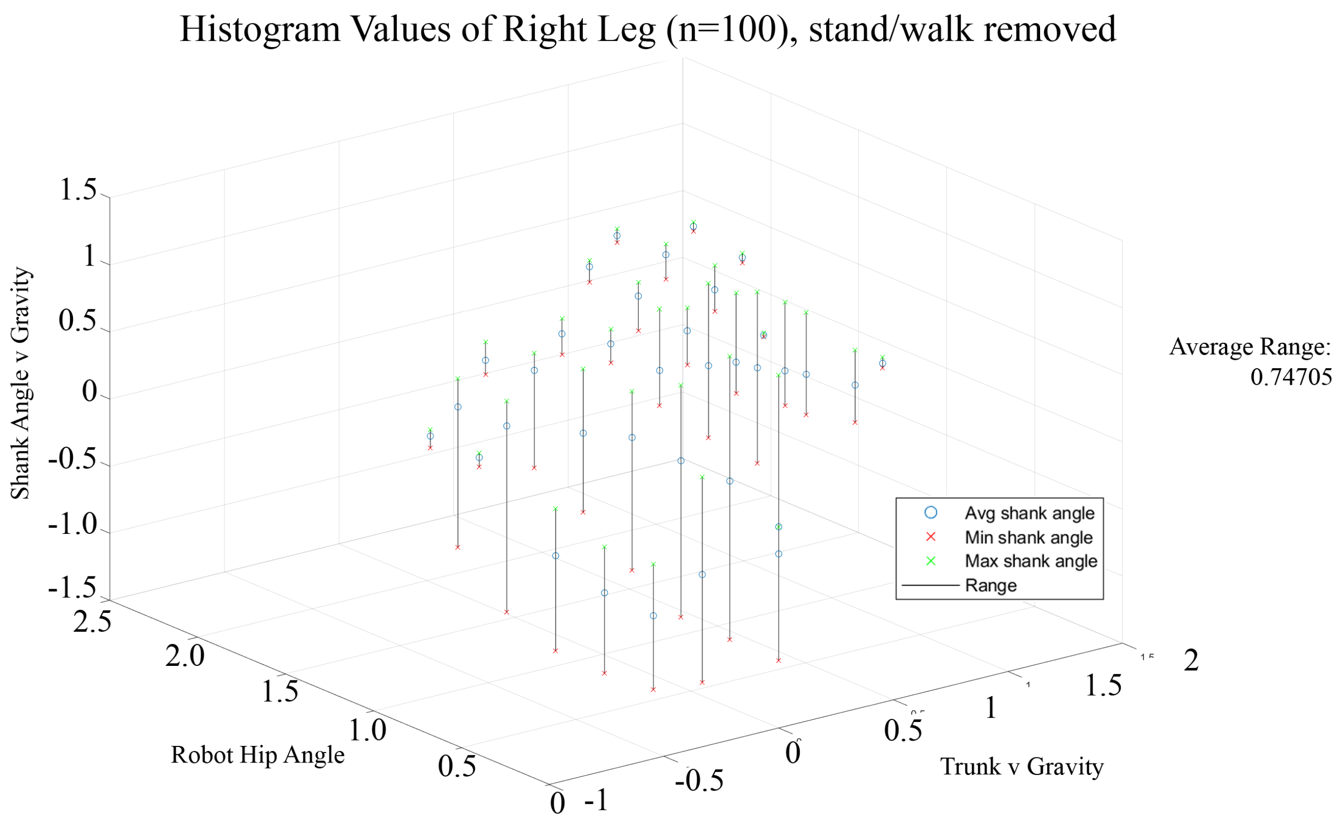


Figure 32: Histogram values of the right leg at n=100, standing and walking removed.

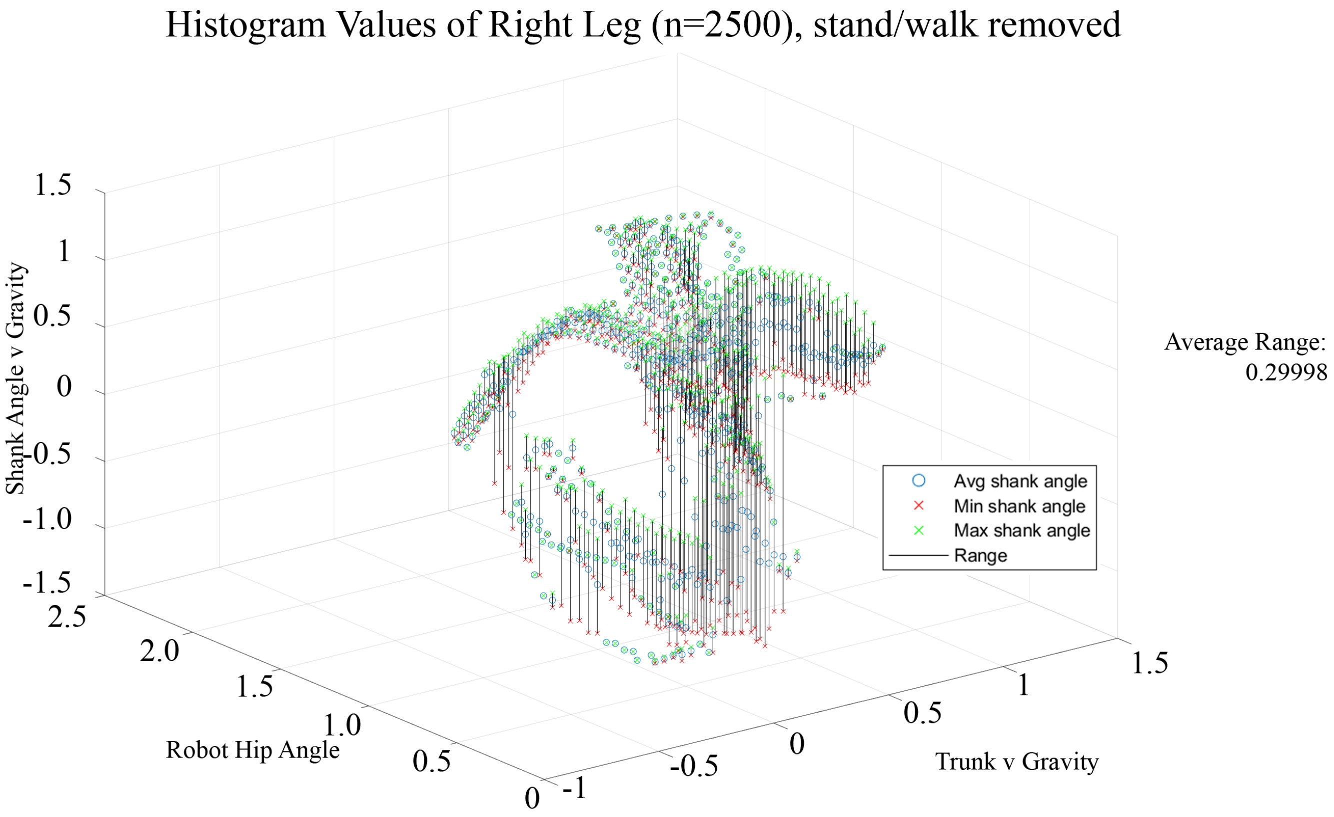


Figure 33: Histogram values of the right leg at n=2500, standing and walking removed.

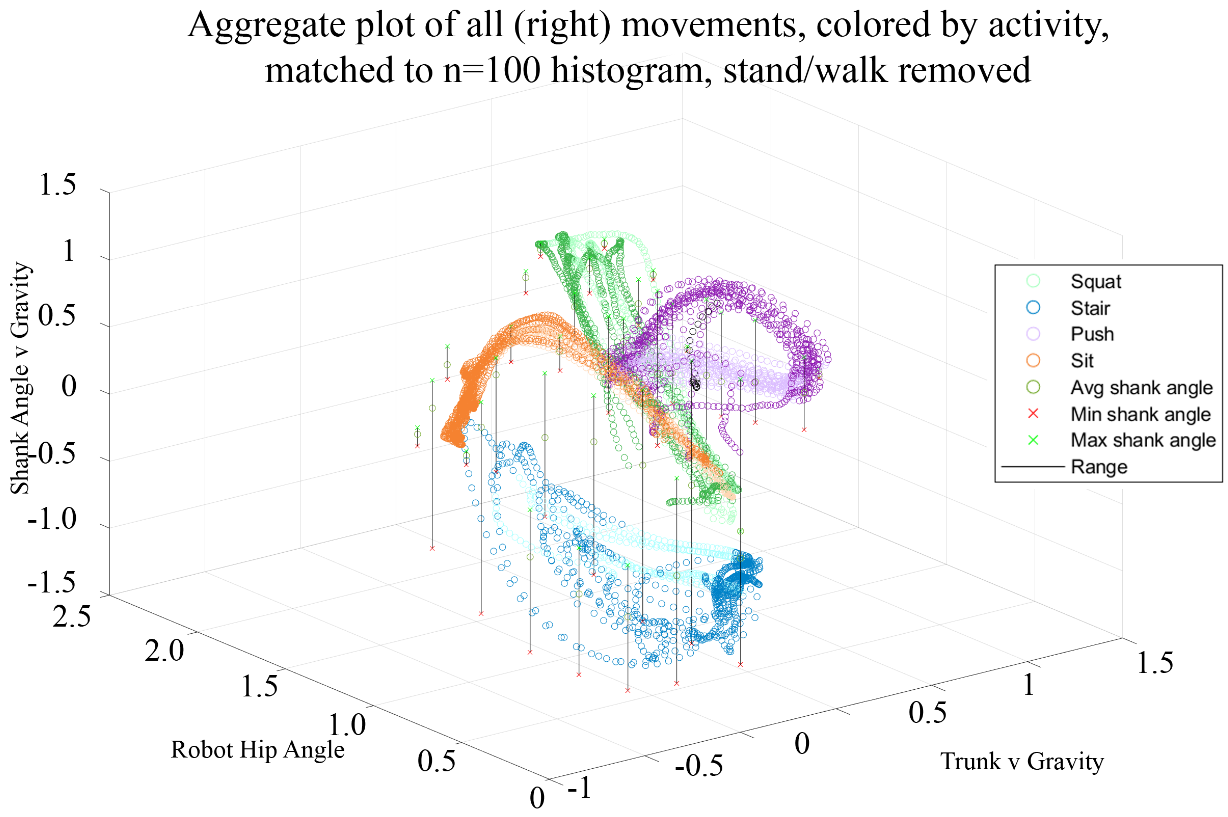


Figure 34: Aggregate plot of all right leg measurements, colored by activity, matched to n=100 histogram.

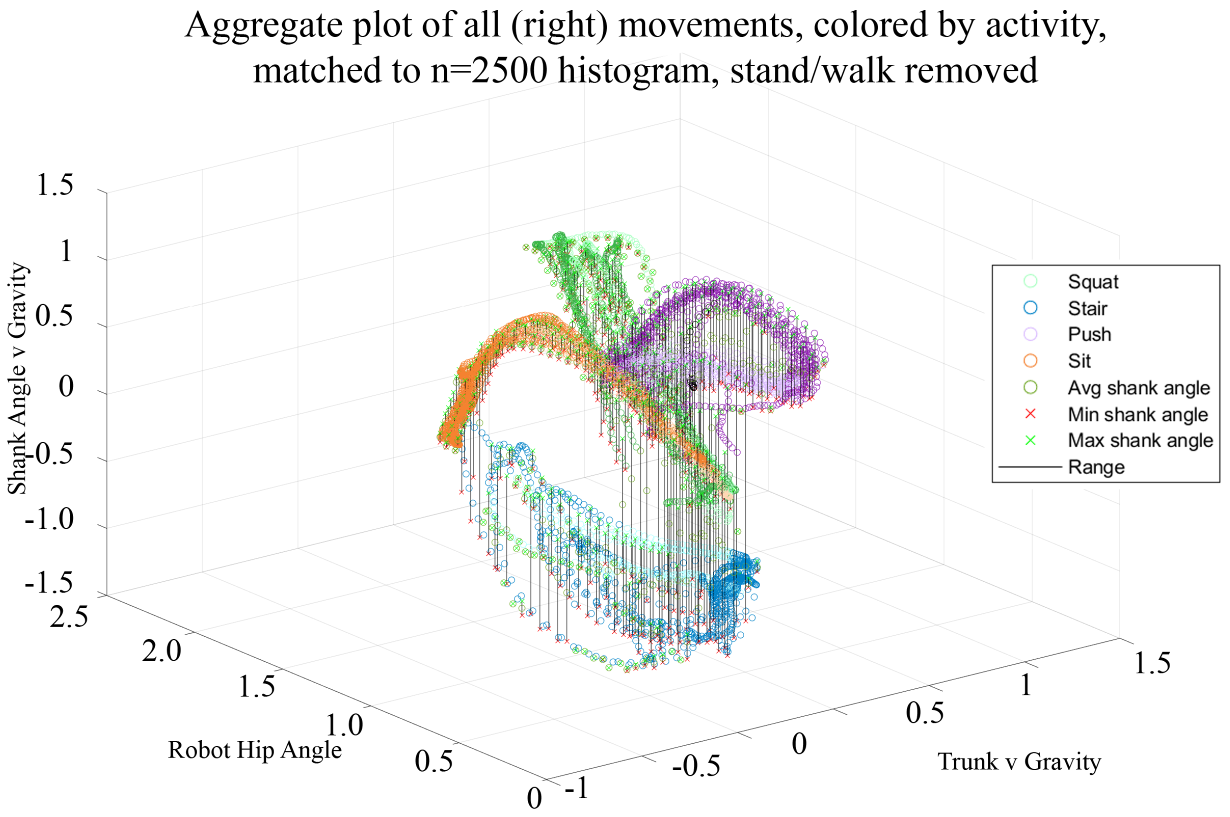


Figure 35: Aggregate plot of all right leg measurements, colored by activity, matched to n=2500 histogram.

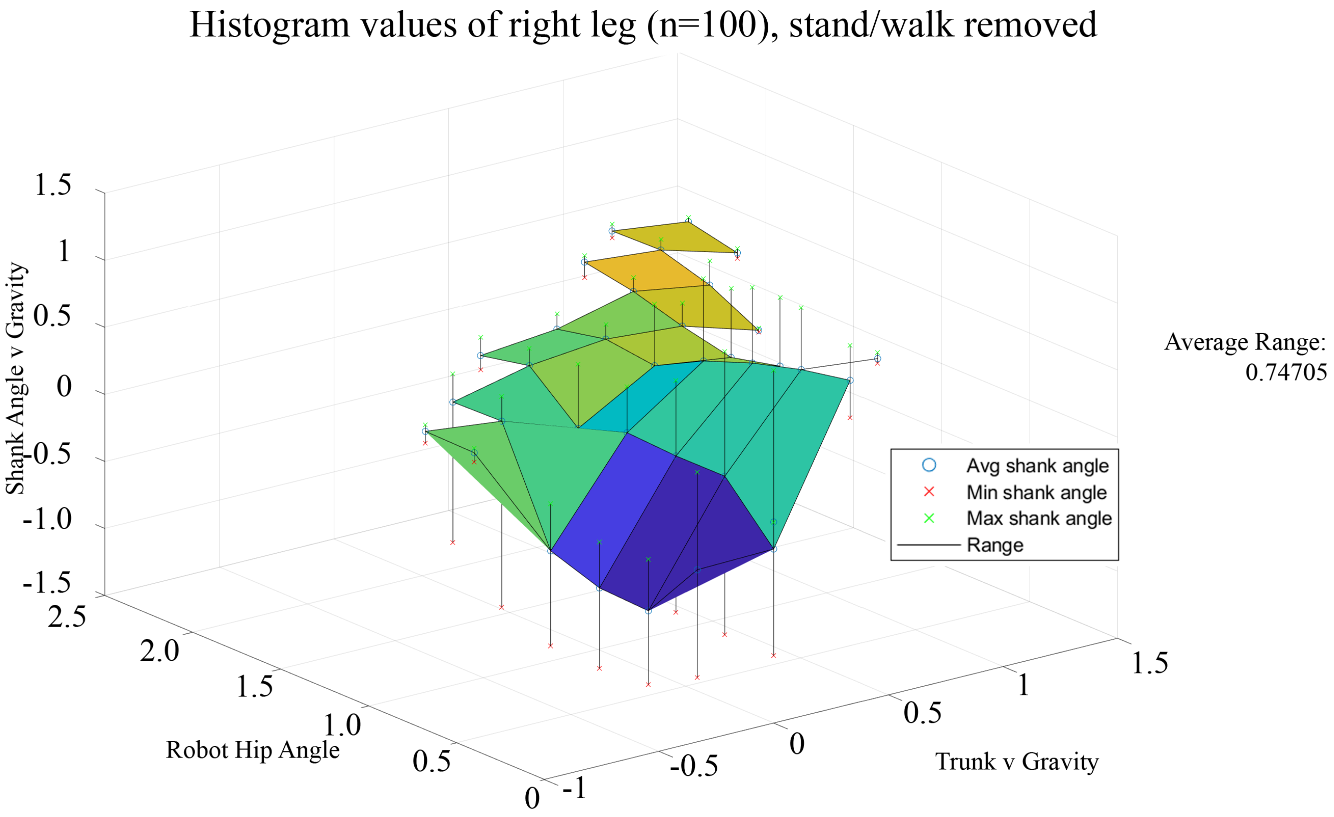


Figure 36: Histogram values of the right leg with mesh overlay at n = 100.

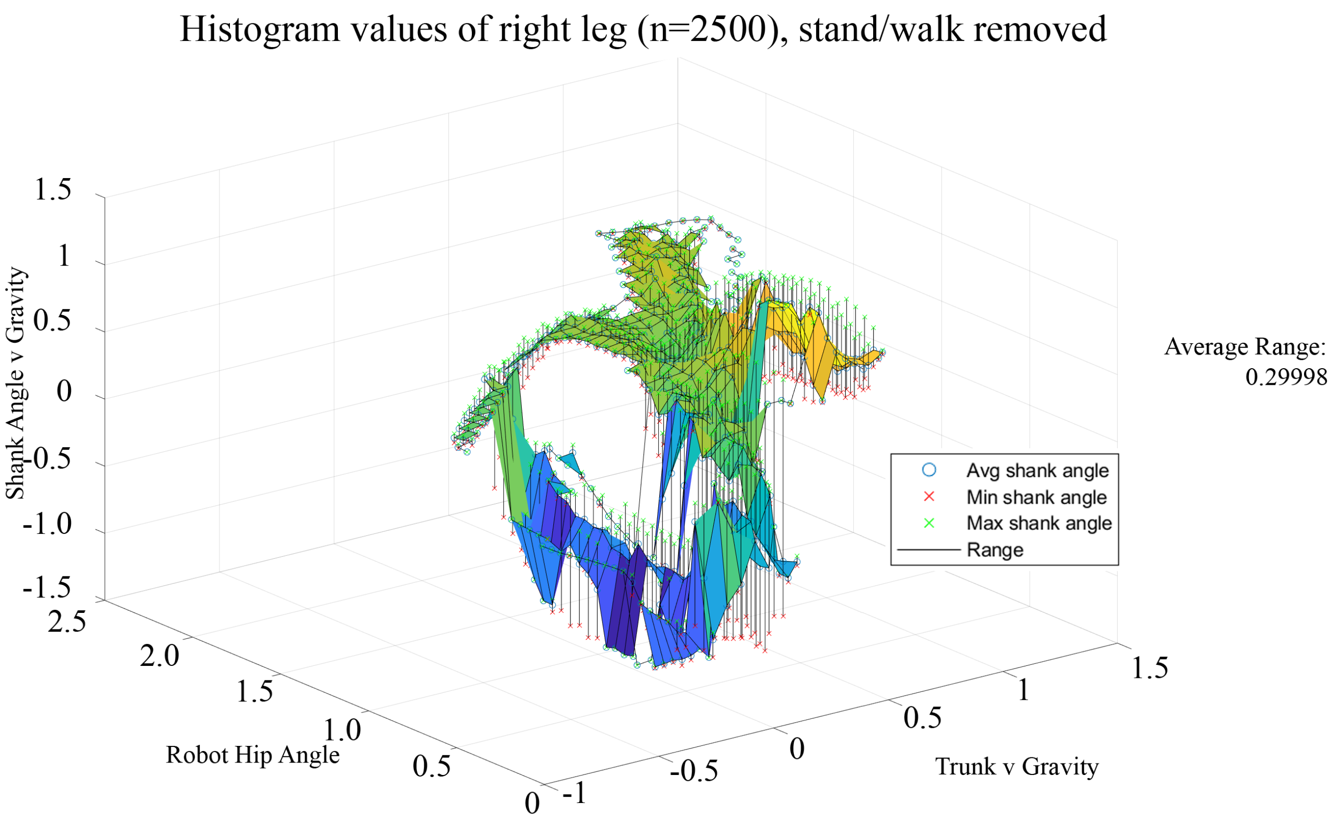


Figure 37: Histogram values of the right leg with mesh overlay at n = 2500.

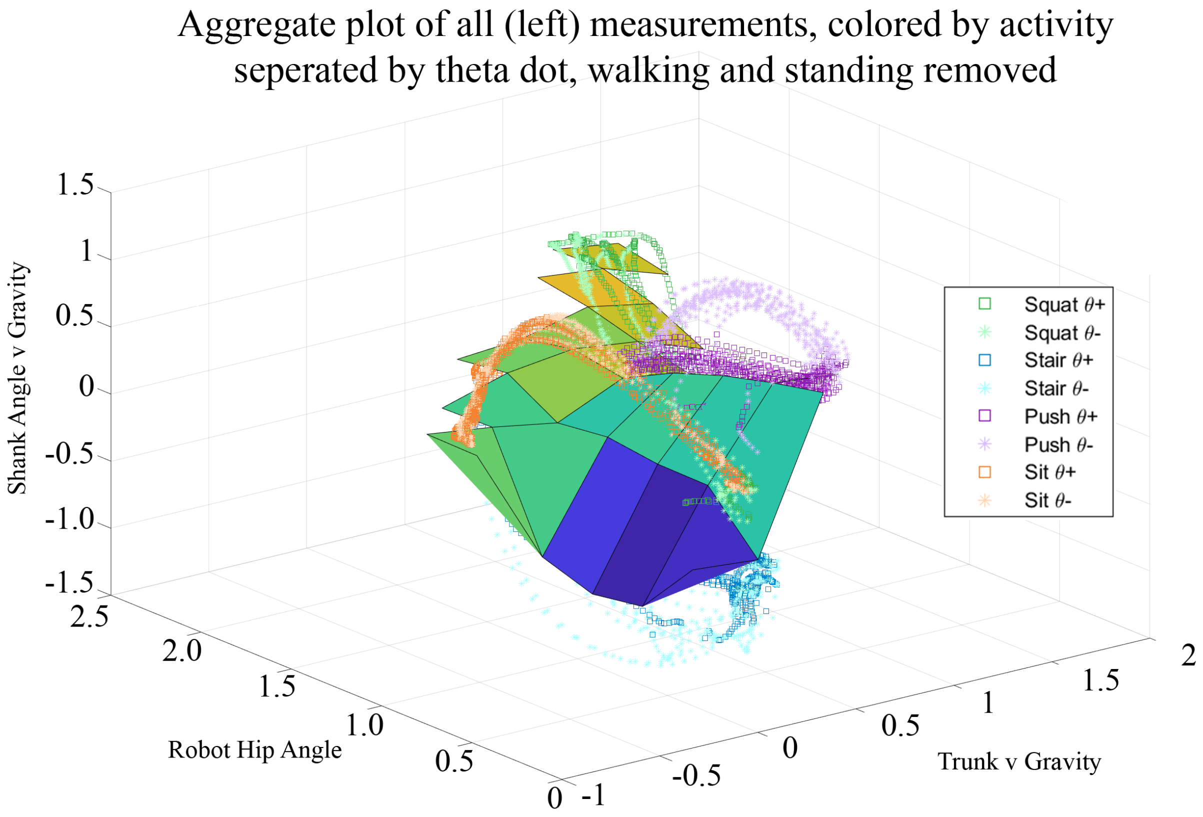


Figure 38: Aggregate plot of all left leg measurements, colored by activity, separated by theta dot, overlaid on the mesh at n=100.

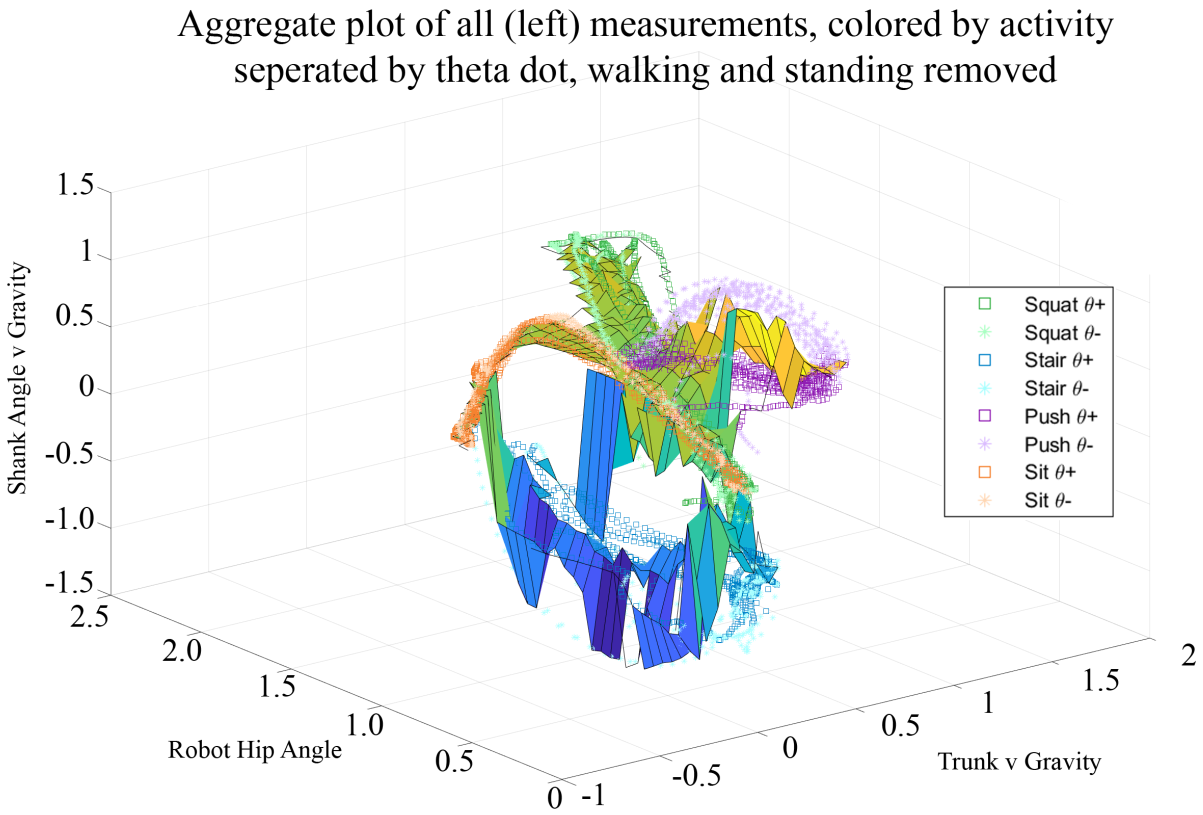


Figure 39: Aggregate plot of all left leg measurements, colored by activity, separated by theta dot, overlaid on the mesh at n=2500.

3.3.2.0.2 Stable Model Development

A second set of motion capture was also taken, this time focused on remaining stable in extreme positions while the feet are firmly planted on a level surface. This was chosen to create conditions that served two purposes. The first: to mimic constraints placed on the original model, specifically the requirement that feet were always flat. The second: to create a well-defined model of stability. It was assumed that points reached outside of this model would be unstable and therefore likely inappropriate for APEx activation. These results were processed in the same way as the more dynamic tests to create a separate lookup model.

3.3.3 Results/Analysis

The various algorithms were then compared using motion capture data gathered during the above modeling phase. The first algorithm, the current CoG model, is used, identifying the shank angle as 90% of the torso angle and then determining position and activating permission. The second algorithm was the lookup table based on the dynamic model generated from the multi-activity capture. It was considered that this would bias the results to be artificially accurate, but a general comparison of the idea wanted to be made first without involving multiple research subjects. Finally, the third algorithm utilized data captured for the stable model. The same considerations for this algorithm were made as for algorithm 2. Finally, the algorithms' predicted angle was compared to determine the accuracy of the various models. In the following graphs, this can be seen in the bottom half. The upper half is the actuation recommendation with respect to time.

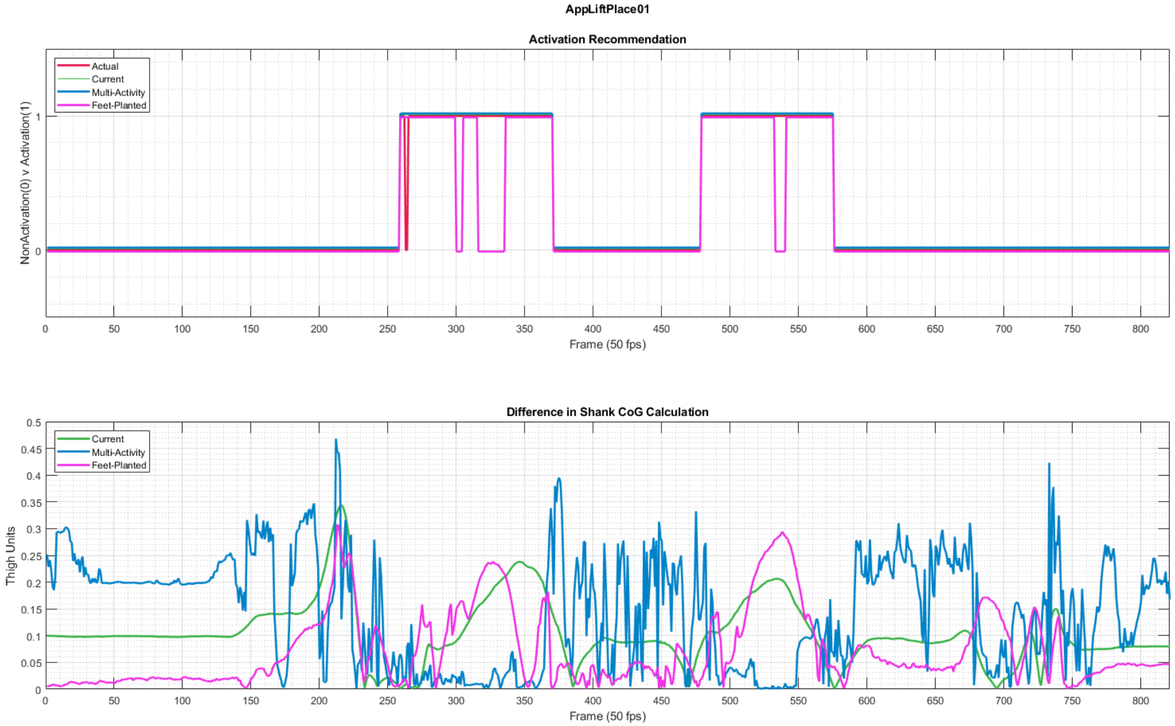


Figure 40: Difference in angle from true angle based on different algorithms. This activity involved approaching a box, squat, lifting it, placing it back down, and walking forward.

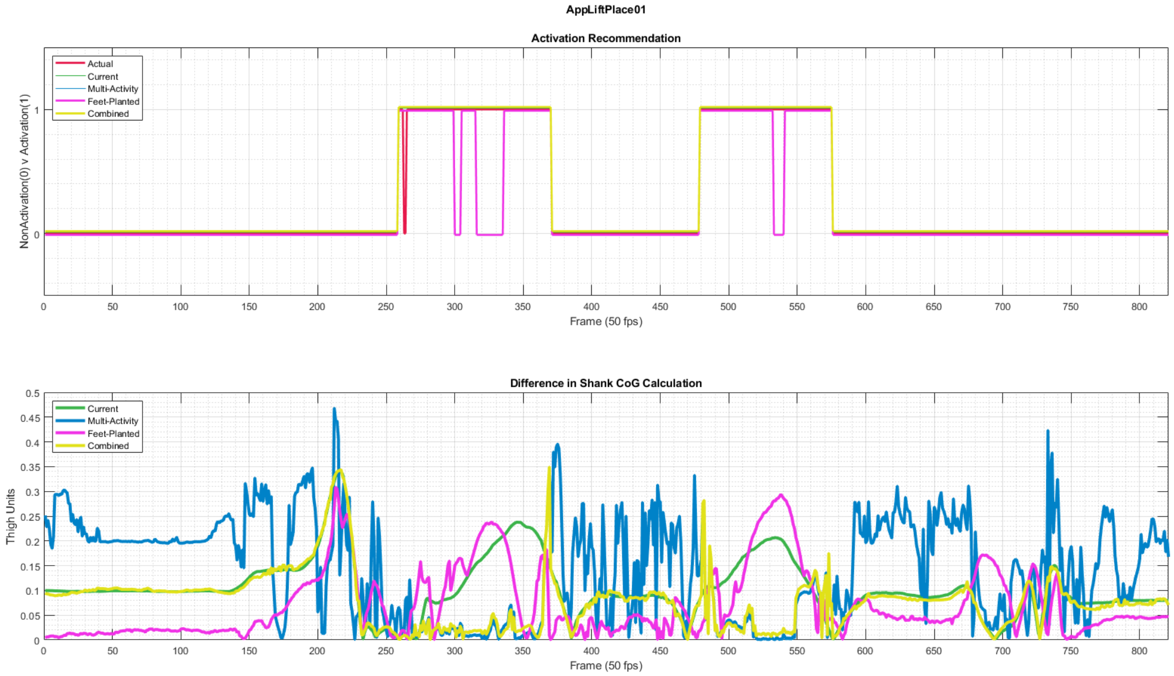


Figure 41: Difference in angle from true angle based on different algorithms. This activity involved approaching a box, squat, lifting it, placing it back down, and walking forward.

A few exciting items arise upon viewing these charts. The first is the smooth nature of the current algorithm in comparison to the others. This is due to the constant factor instead of a lookup table. However, there are few moments where the error is less than 0.1 thigh units. This contrasts with the multi-activity algorithm. While it is far more varied, there are several moments where it is achieving an accuracy of < 0.1 thigh units. The third algorithm performs the worst in these activities. While it hits some valid points, it is almost always wrong with several moments of being entirely outside the graphing area. This is primarily due to not having enough information on extreme positions the body might be put into, forcing an assumption of values with no factual basis. A combined method was created to take advantage of the differences in accuracy. This can be observed in Figure 41. The 0.9 factor was used where the hip angle was less than or equal to 50 degrees. The multi-activity algorithm was used for all other angles. An angle of 50 degrees was chosen as it mimicked the crawl angle detection and inspection of the second model (multi-activity) revealed it as the rough area where it outperformed the first model (generic 0.9 factor). This significantly decreased the error and would be a good candidate for future implementation.

3.3.4 Way Ahead

Future work can be done further to improve the activity recognition capabilities of the APEx. One of the easiest would be to take advantage of an IMU at the nape of the neck, where the proposed location for the updated unit will sit. This will allow for a better understanding of the location of the back (e.g., in stoop lifts) to determine how the body is positioned. Creatively done, it might be possible to refine activities such as crawling or stair climbing. An additional update would be to increase accuracy by adding wireless foot pods that attach to the wearer's boot. This would be a unique attachment for the Air Force, given their uniform requirements, but the data yielded from an attachment would be priceless. They would allow for real-time tracking of shank position, allowing the CoG model to identify the location of the user far more accurately. Further, it could be an optional accessory, provided the user is comfortable in the operation of the APEx in an older mode instead of a more advanced one.

3.4 Final Deliverables

3.4.1 User Manual & Device Delivery

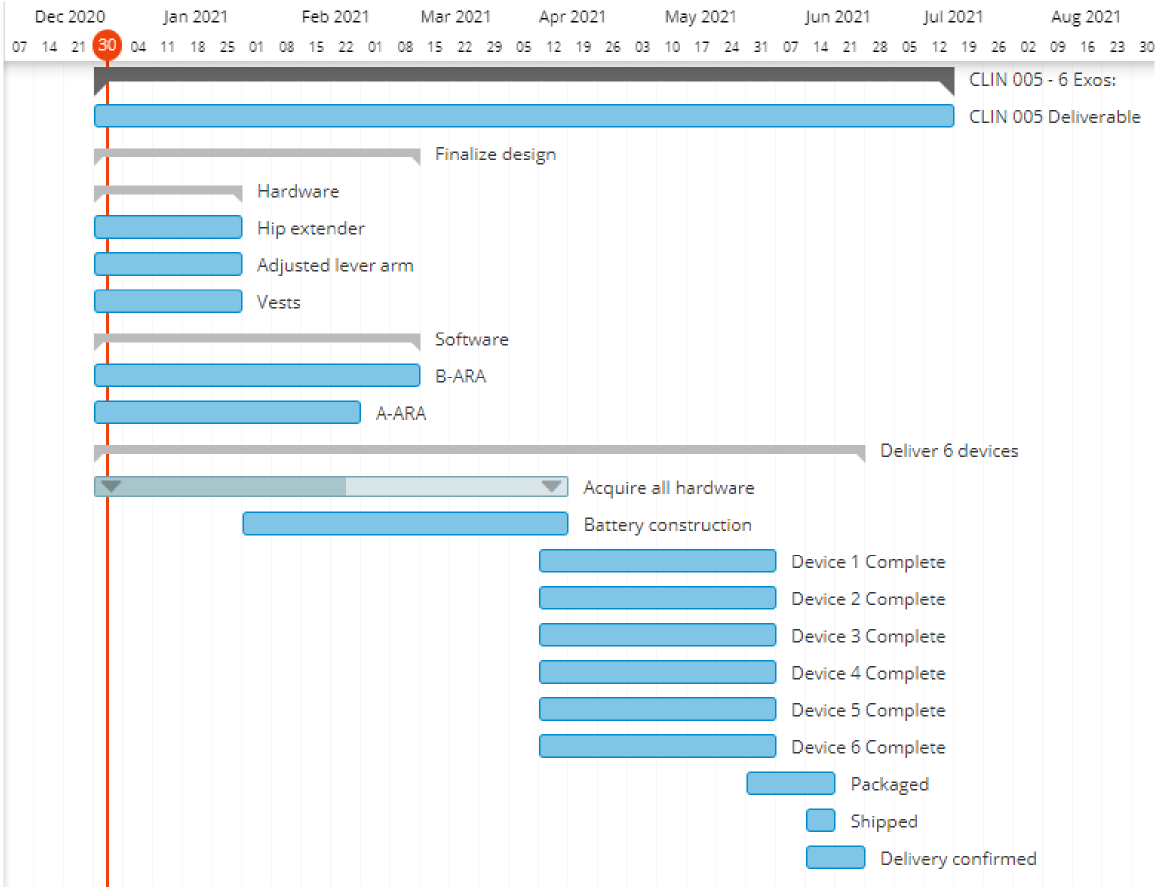


Figure 42: The timeline for accomplishing CLIN 005 of the APEx project.

The user manual has been completed and can be seen in its entirety in Appendix C. It covers recommended use cases, wear of the system, basic operation, battery care, troubleshooting, and a manufacturing plan. It was compiled while at TAFB using input from Airmen to create a more meaningful document. Device construction and delivery is currently in progress and is due to be completed following Figure 42. Final delivery is to be made to Wright-Patterson AFB, under the care of AMC.

3.4.2 Testing Results

Figure 43: An Airman wearing the APEx device as used in testing at 60th APS.

Demonstrations and testing were conducted at Travis AFB with the 60th Aerial Porter Squadron from April 19th to June 9th. During this time, 17 individuals wore the device and completed real-world and simulated testing. An additional 8 individuals wore the device to demo. Data was collected measuring lift quality, heart rate (HR), and VO2 consumption using the GoX Ergonomic Kit. Users were trained in donning and doffing the devices IAW the User Manual. Data was collected under ASU IRB # STUDY00013619 and holds an active registration with OHRP under IRB Number IRB00005065. Complete documentation can be found in Appendix D.

3.4.2.1 Testing Methodologies

Figure 44: 60th APS Airmen pushing a load onto an aircraft. The user of the APEx is highlighted.

3.4.2.1.1 Real World Tasks

Real-world activities as executed by the 60th APS Ramp office were monitored for exoskeleton effectiveness. Before stepping to aircraft, Airmen were paired with a testing partner and fitted for GoX Ergo kits and APEx devices. Both components of the GoX Ergo Kit were classified as having a quick release and posing no risk to flightline Airmen. Because of this, no additional clearances for the kit were required. One of each pair was equipped with the APEx device at a time. Each pair were instructed to complete tasks together where possible to provide a near-direct comparison with similar tasks. Nominally, after completing a flight's worth of work, the pairs would switch configurations and move onto the next flight. During the testing period, a total of eight flights were observed with eight participants. A chart indicating their treatment (green yes, Table 4) or non-treatment (blue no, Table 4) configurations can be seen in Table 4. These flights included a mix of upload and download activities, and times of active load vs. passive moments were logged for comparison. Each flight provided an average of 3 distinct active moments for direct comparison.

	1103.3	**1104.3**	**1152.3**	**1258.0**	**1292.1**	**1303.0**	**1312.3**	**1315.3**
Flight A	No		No				Yes	Yes
Flight B	Yes		Yes				No	No
Flight C		No		Yes		Yes	No	
Flight D		Yes		No		No	Yes	
Flight E					Yes			Yes
Flight F					Yes		Yes	No
Flight G					No		Yes	Yes
Flight H					Yes		No	Yes

Table 4: Testing of deidentified Airmen on flights. 'Yes' indicates APEx wear, 'No' indicates no wear.

Figure 45: Four Airmen are awaiting the beginning of the lift test. Two are equipped (back), and two are unequipped (fore).

3.4.2.1.2 Lifting Test

The lift test was executed as described in the CLIN003 report, with some slight modifications. It had the intention of creating a relatively ideal testing condition to focus directly on the effect of the APEx. Participants were fitted with an APEx device and given brief training with the device. Please see the User's Manual in Appendix C for the fitting procedure. Training included an introductory discussion of the device's actuation algorithm, with examples provided during the talk. This served to allow the participant to anticipate the device and allow for easier adoption. Participants were also encouraged to explore use cases for themselves, including lifting containers, walking, jogging, and low-reaching. During these cases, participants were advised to place the device in standby mode when assistance was not actively needed. After fitting and training were complete, participants were invited to participate in one of three lift tests, with the goal of completing all three by the end of the eight-week testing period. All tests included the lifting component, where users lifted a 50 lb. box, transported it forward 20 ft, and set it down within 30 seconds. The remaining time was used as a rest, giving an average 1/3 duty cycle. This was repeated over 15 minutes to make one set. Test A saw users completing only one set in an equipped or unequipped configuration. Test A in the inverse configuration was completed 3+ days after the initial test. Test BA users completed a set first unequipped, then equipped, with a 30-minute rest in between. During the rest, participants were given a sports drink to replenish lost fluids and electrolytes. Finally, Test BB had users completing a set first equipped, then unequipped, with a 30-minute rest in between. A GoX Ergo Kit was worn during all tests, measuring HR, VO2, and lift quality. Talking during the test was forbidden to minimize variables. At the end of testing, the Rate of Perceived Effort (RPE) was collected as a scale from 0-20 to qualitatively determine if users felt the APEx assisted in their tasks or not. A score of zero indicated no effort exerted in the task, and a score of 20 indicated maximum possible effort. Participants were told to relate a score of 0 to “lying on a couch“ and 20 to “trying to get the last rep in a bench press at the moment just before you realize it won’t be completed.”

3.4.2.2 Processing the Data

To first create a frame of reference for the tasks, graphs of each testing period were generated. This included real-world tasks and lifting tasks. Real-world tasks were graphed between the periods of first stepping onto the aircraft and exiting the aircraft. Periods of activity, defined by actively loading or unloading the aircraft, were logged. Inactivity was characterized as between moments of heavy activity. For instance, while waiting for a transport vehicle to deliver the next load. Lift tests were graphed between the time “go“ was announced and after 15 minutes from that point. Both VO2 and HR were plotted. These plots quickly identified significant issues with the collection environment. During flightline tests, participants were frequently in and out of positive cellular coverage. At the time of testing, the collection hardware was limited to reporting a valid value only when it had a strong signal. If no signal existed at the expected report time, the collection service defaulted to the last known good. This had the effect of creating extensive periods of “flat lined” collections. While some participants were less affected than others, the issues were prevalent enough that meaningful comparisons could not be made. An example of this issue can be seen in Figure 46.

Data collected during the HR tests proved more fruitful. While there were a good handful of tests that were deemed invalid, fifteen were considered sufficient. This determination was made by finding a test with at least 2 minutes of good collection in the final third of the 15-minute test. These two minutes needed to have a pair set at the same time for both configurations. Further, both captures needed to be representative of a steady-state. This meant that data could not vary wildly nor be part of the ramp-up period typically seen at the beginning of the activity. A prime example of these criteria can be seen in Figure 47.

Initially, baselines for HR and VO2 were set with popular generic formulas. For HR, the baseline was set with $MaxHeartRate = 220\breve{\ }age$. The baseline for VO2 was set with $VO2Max = 15.3 * \frac{MaxHR}{RestingHR}$, where Resting HR was set at 70 BPM. However, it was quickly determined that while these work well for approximations, they are insufficient for the task. Instead, new baselines were created based on the 2

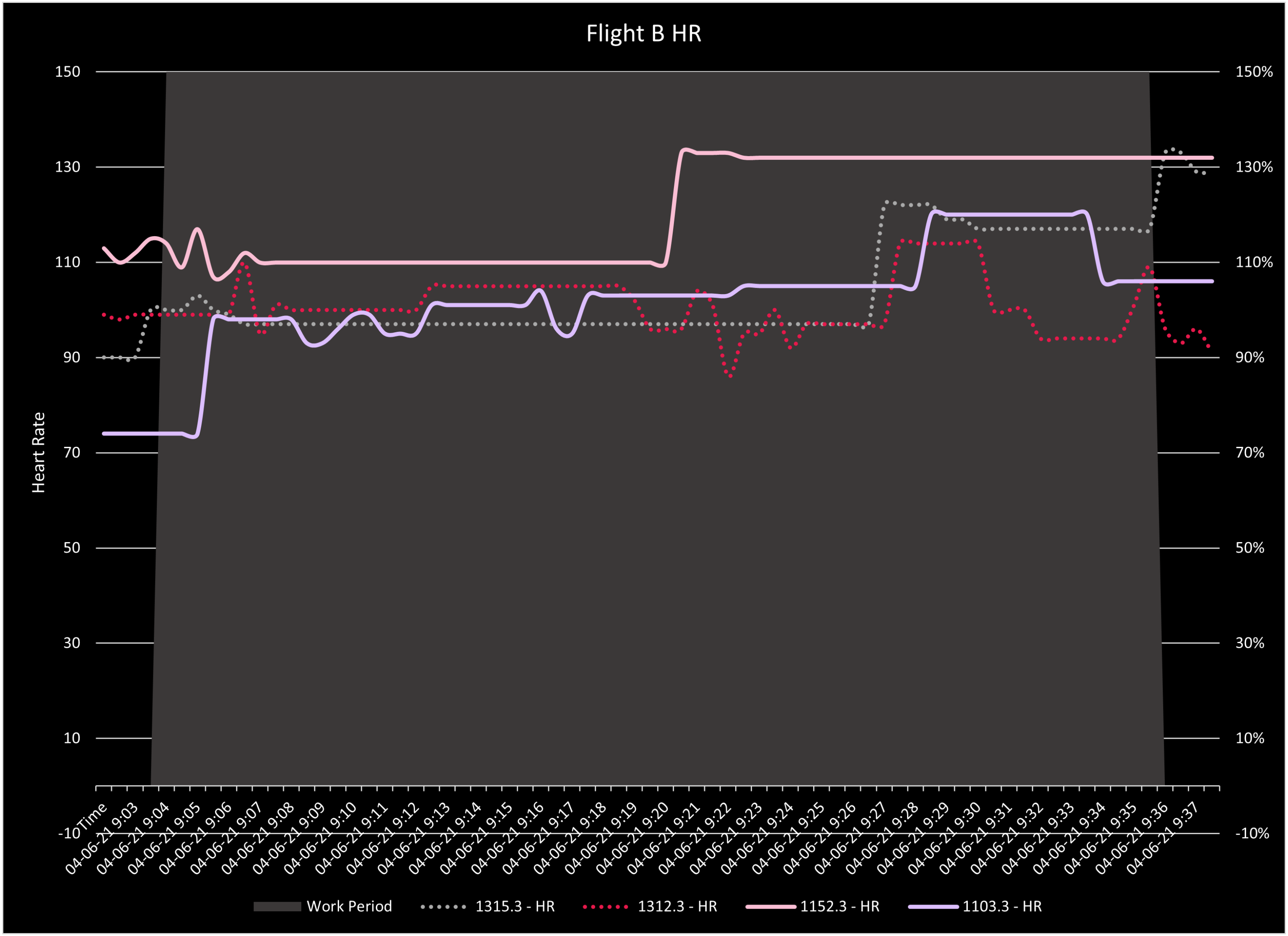


Figure 46: The plotted heart rates of experiment participants on Flight B. Solid lines indicate an equipped participant, and dashed lines indicate an unequipped participant. The grey section marks a period of activity. Of focus are the long periods across all four users of flat-lined results, notably towards the end, where the effects of the activity are most felt.

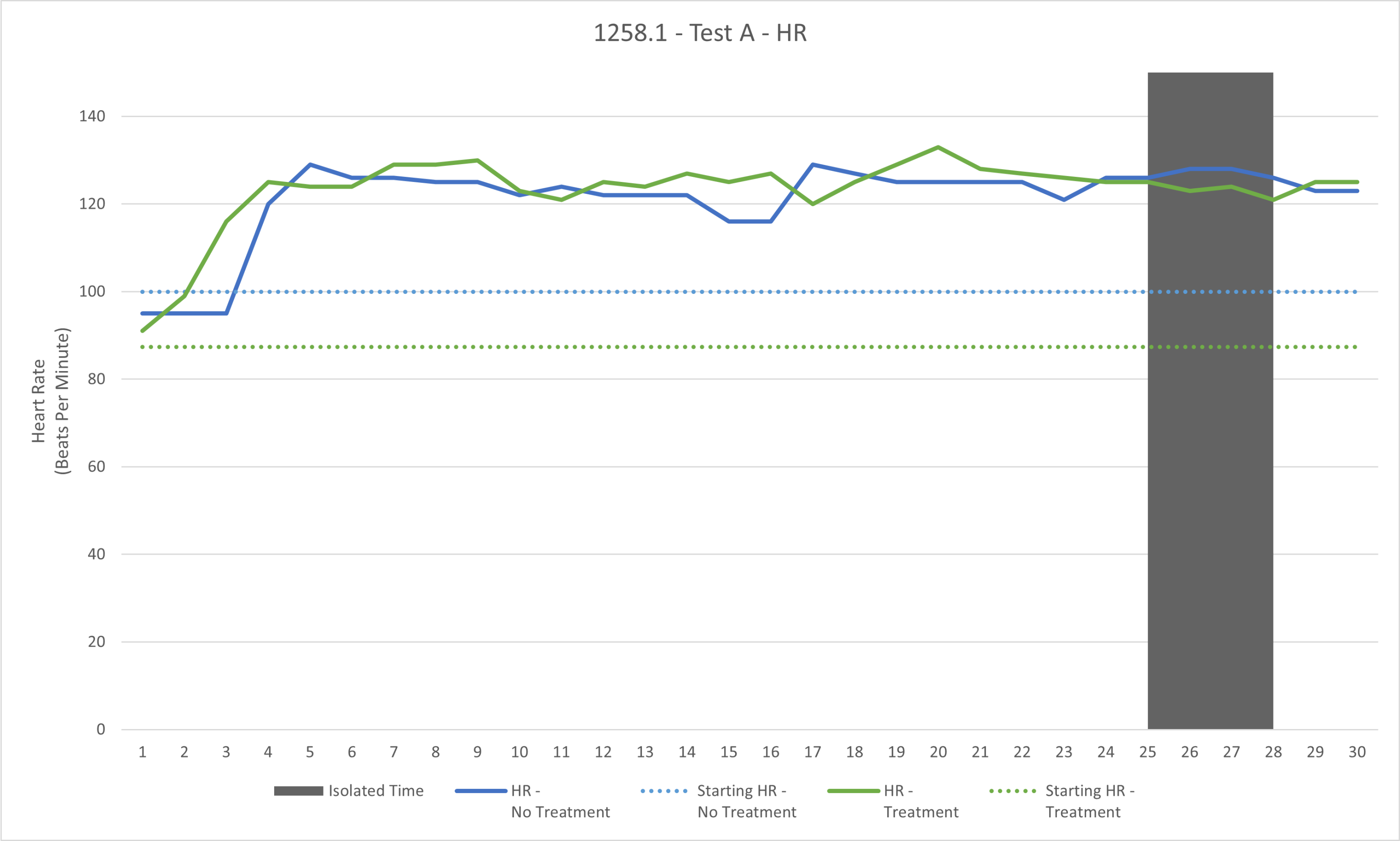


Figure 47: Plotted data collected during Test A of participant 1258.1. A blue line indicates no treatment; green indicates treatment. The dashed lines represent the baselines for their respective configurations based on the 2 minutes immediately before the test. The grey bar indicates the selected 2-minute period. Here the final two minutes were not selected due to the flat line at periods 29 and 30.

minutes preceding the lift test. Then, the collected values were divided against their corresponding baseline number to determine a Percent of Starting HR (PSHR) and Percent of Starting VO2 (PSVO2). All 15 datasets were processed in this manner.

After processing, the resulting graphs were reviewed to confirm quality. Two were more closely examined for being exaggerated outliers and were summarily eliminated from the set. The first, 1258.1, Test BB, returned values highly favorable of the APEx but far higher (54% improvement) than other tests. Investigation revealed that the participant began their test at 160 BPM, and their HR dropped during the resting periods of the test itself. Because of this, any comparison data would be unreliable, so the test itself was removed. An example of the effect can be seen in Figure 48.

The second individual also returned values well outside the norms, though this time in favor of no APEx. This was suspicious since the participant reported enjoying the APEx and rated it favorably in their RPE score. A review of the data revealed that the wrong times were isolated as a testing period. This was due to two separate tests conducted on that day. User 1315.0 was using their watch while the other test was going on, and the processing program captured it as a testing period. Unfortunately, the collection device did not correctly report the user's test either, and so the test as a whole was eliminated. The remaining 13 tests were reviewed by hand to ensure this timing error did not apply and were found to be correct.

Finally, the percentage averages were taken to determine the average change from the baseline. A percent change value was determined with Percent Change = $\frac{(\text{New Value } - \text{ Old Value})}{\text{Old Value}}$, treating the non-treatment value as the base value and the treatment value as the new. The result was multiplied by -1 to place positive values favoring the APEx and negative values against the APEx.

Two ANOVA tests (single factor, $\alpha = 0.5$, $H_0 = 0$) were conducted on the results

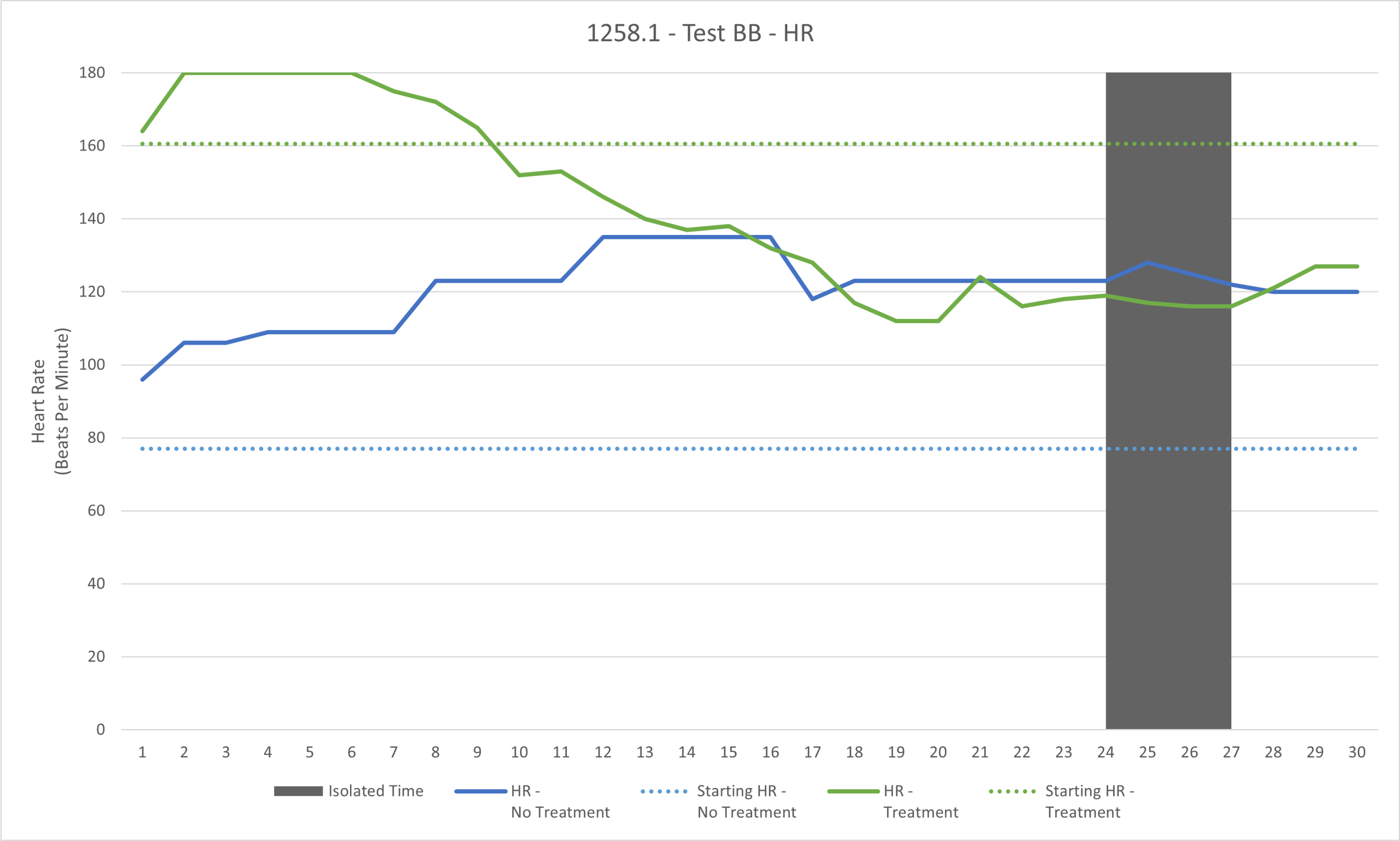


Figure 48: Plotted data collected during Test BB of participant 1258.1. A blue line indicates no treatment; green indicates treatment. The dashed lines represent the baselines for their respective configurations based on the 2 minutes immediately before the test. The grey bar indicates the selected 2-minute period. Note the high starting HR. While the participant did reach a steady-state, the high initial start makes comparisons worthless.

to determine the effects of testing order on PSHR and PSVO2. Tables of the values used can be seen in Tables 5 and 6. T-tests were conducted (paired two sample for means, $\alpha = 0.5$, $H_0 = 0$) comparing the equipped and unequipped pairs for RPE, HR, and VO2 values. Values for RPE, PSHR, and VO2 can be seen in Tables 7, 8, and 9 respectively.

Test A - PSHR - Percent Change	22.61%	6.09%	-11.12%	-1.30%	16.95%
Test BA - PSHR - Percent Change	5.99%	15.63%	0.72%	-1.22%	
Test BB - PSHR - Percent Change	31.19%	5.99%	5.07%	27.66%	

Table 5: Percent change of Percent of Starting HR values grouped by test. Positive values indicate changes in favor of the APEx.

Test A - PSVO2 - Percent Change	8.32%	0.36%	-2.29%	-2.43%	5.84%
Test BA - PSVO2 - Percent Change	-1.88%	4.59%	-1.49%	0.25%	
Test BB - PSVO2 - Percent Change	7.89%	2.40%	3.92%	8.18%	

Table 6: Percent change of Percent of Starting VO2 values grouped by test. Positive values indicate changes in favor of the APEx.

	AA	**AB**	**BA**	**BA**	**BB**	**BB**
1059.0	12	11				
1103.1					10	9
1152.1			14	12		
1204.0	10	10	12	10	14	10
1204.1			12	11		
1258.1	10	11	10	9	11	14
1292.0			10	6		
1301.0	16	16	14	14	14	12
1303.0	14	11				
1312.1			16	12		
1315.0	12	12				
1315.1					12	10

Table 7: Reported RPE values groupd by users (vertical) and test type (horizontal). Blue indicates reports with the APEx unequipped. Green indicates reports with the APEx equipped.

3.4.2.3 Results and Discussion

3.4.2.3.1 ANOVA

The ANOVAs showed a p-value of 0.33 for PSHR (Table 10) and 0.19 for PSVO2 (Table 11). Since both were well above $\alpha = 0.5$, the null hypothesis was accepted; the

	1059	**1103.1**	**1152.1**	**1204**	**1204.1**	**1258.1**	**1292**	**1301**	**1301**	**1301**	**1303**	**1312.1**	**1315.1**
PSHR - No Treatment	180.22%	116.07%	137.37%	120.56%	166.85%	127.00%	178.18%	130.48%	123.81%	162.18%	146.95%	155.25%	172.70%
PSHR - Treatment	139.48%	79.87%	129.15%	113.21%	156.86%	141.13%	150.33%	132.18%	122.92%	153.95%	122.04%	157.14%	124.94%
PSHR - Percent Change	22.61%	31.19%	5.99%	6.09%	5.99%	-11.12%	15.63%	-1.30%	0.72%	5.07%	16.95%	-1.22%	27.66%

Table 8: Average values of Percent Starting HR of each user during two minutes of steady state activity. Blue indicates reports with the APEx unequipped. Green indicates reports with the APEx equipped. White indicates the percent change between the two for each user.

	1059	**1103.1**	**1152.1**	**1204**	**1204.1**	**1258.1**	**1292**
PSVO2 - No Treatment	119.19%	106.77%	108.02%	107.04%	121.24%	105.35%	117.40%
PSVO2 - Treatment	109.28%	98.34%	110.05%	106.65%	118.32%	107.76%	112.00%
PSVO2 - Percent Change	8.32%	7.89%	-1.88%	0.36%	2.40%	-2.29%	4.59%
	1301	**1301**	**1301**	**1303**	**1312.1**	**1315.1**	
PSVO2 - No Treatment	110.10%	103.88%	119.14%	111.73%	117.32%	116.41%	
PSVO2 - Treatment	112.78%	105.43%	114.47%	105.20%	117.02%	106.89%	
PSVO2 - Percent Change	-2.43%	-1.49%	3.92%	5.84%	0.25%	8.18%	

Table 9: Average values of Percent Starting VO2 of each user during two minutes of steady state activity. Blue indicates reports with the APEx unequipped. Green indicates reports with the APEx equipped. White indicates the percent change between the two for each user.

differences between the means are not statistically significant. This indicated that the testing order did not matter, and direct comparisons would be appropriate.

3.4.2.3.2 Heart Rate

Overall, HR saw an average 14.9% difference while wearing the exoskeleton and a 9.6% decrease in the same. This was found to be statistically significant, with a p-value of 0.01 (Table 12). This result indicates that most users see a substantial improvement of the APEx. The most significant outlier, user 1258.1, saw the most significant negative percent change of -11.1%. Following a discussion with the user, it was discovered they were poorly fit due to being physically outside the intended band of wearers (90th percentile). The discomfort of this fit is also reflected in the user's reported RPE values. Other negative values (1301, 1312.1) are so small to be negligible. These results indicate that the APEx can take up a portion of the workload significant enough to ease the efforts of Aerial Porters. As stated in earlier documents, this does not mean that porters can push or lift larger masses. Instead, it helps decrease the effort exerted over time, allowing users to finish their shift with more energy than otherwise.

3.4.2.3.3 VO2

Vo2 saw an average 3% difference while wearing an exoskeleton and a 2.59% decrease. This was found to be statistically significant, with a p-value of 0.04 (Table 13). The top three improvements were 8.3%, 8.2%, and 7.8%. The bottom three saw

Anova: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Test A - PSHR - Percent Change	5	0.33221	0.066442	0.018503		
Test BA - PSHR - Percent Change	4	0.211245	0.052811	0.00569		
Test BB - PSHR - Percent Change	4	0.699012	0.174753	0.01925		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.036635	2	0.018318	1.23074	0.332776	4.102821
Within Groups	0.148834	10	0.014883			
Total	0.185469	12				

Table 10: Results of PSHR ANOVA analysis.

Anova: Single Factor						
SUMMARY						
Groups	Count	Sum	Average	Variance		
Test A - PSVO2 - Percent Change	5	0.098017	0.019603	0.002387		
Test BA - PSVO2 - Percent Change	4	0.014734	0.003684	0.00088		
Test BB - PSVO2 - Percent Change	4	0.223982	0.055995	0.000832		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.005795	2	0.002898	1.973502	0.189494	4.102821
Within Groups	0.014683	10	0.001468			
Total	0.020479	12				

Table 11: Results of PSVO2 ANOVA analysis.

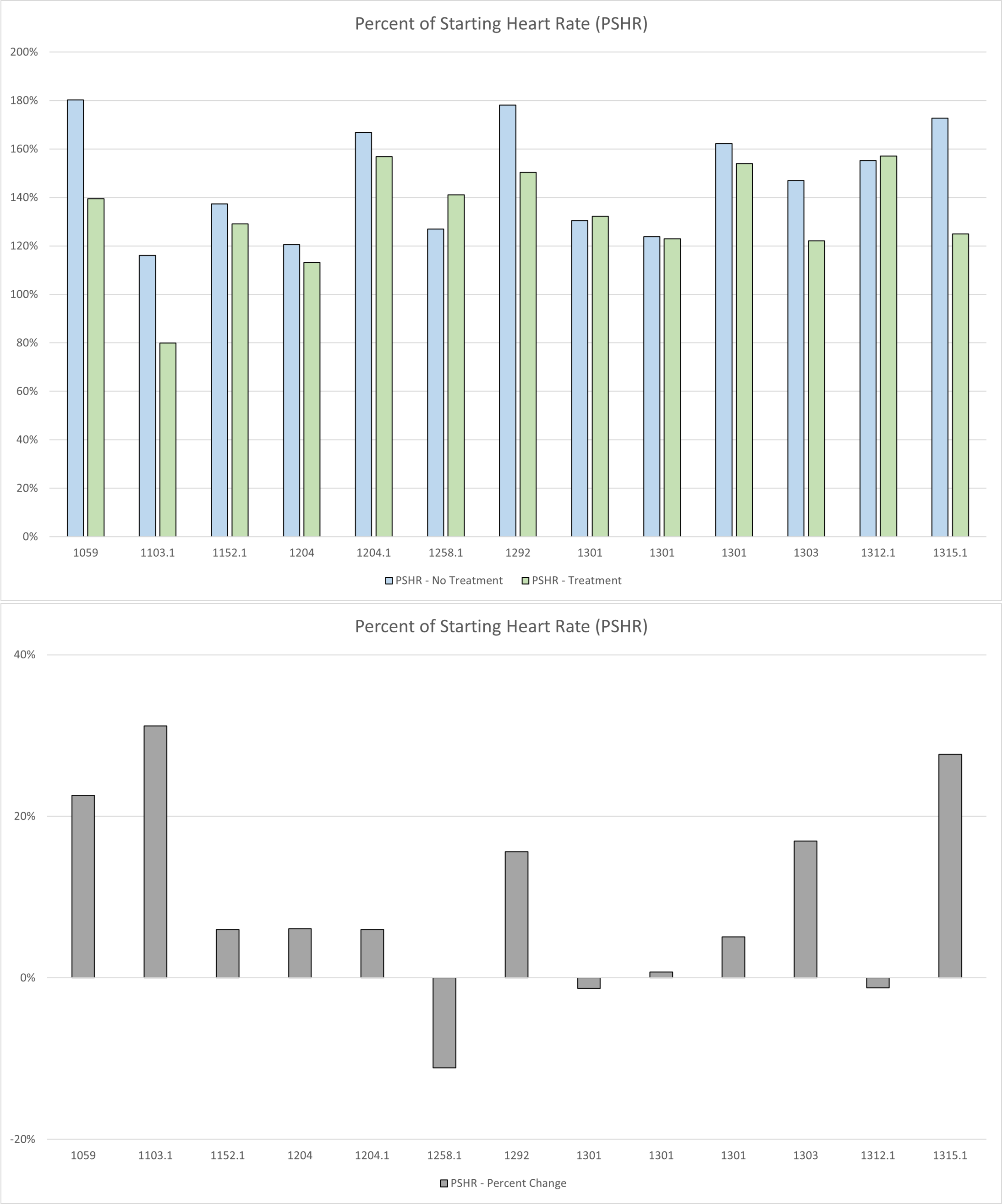


Figure 49: (Top) Results of HRs adjusted as a percentage of the starting HR. Blue bars indicate no APEx; green indicates APEx equipped. (Bottom) Percent change between the PSHR values.

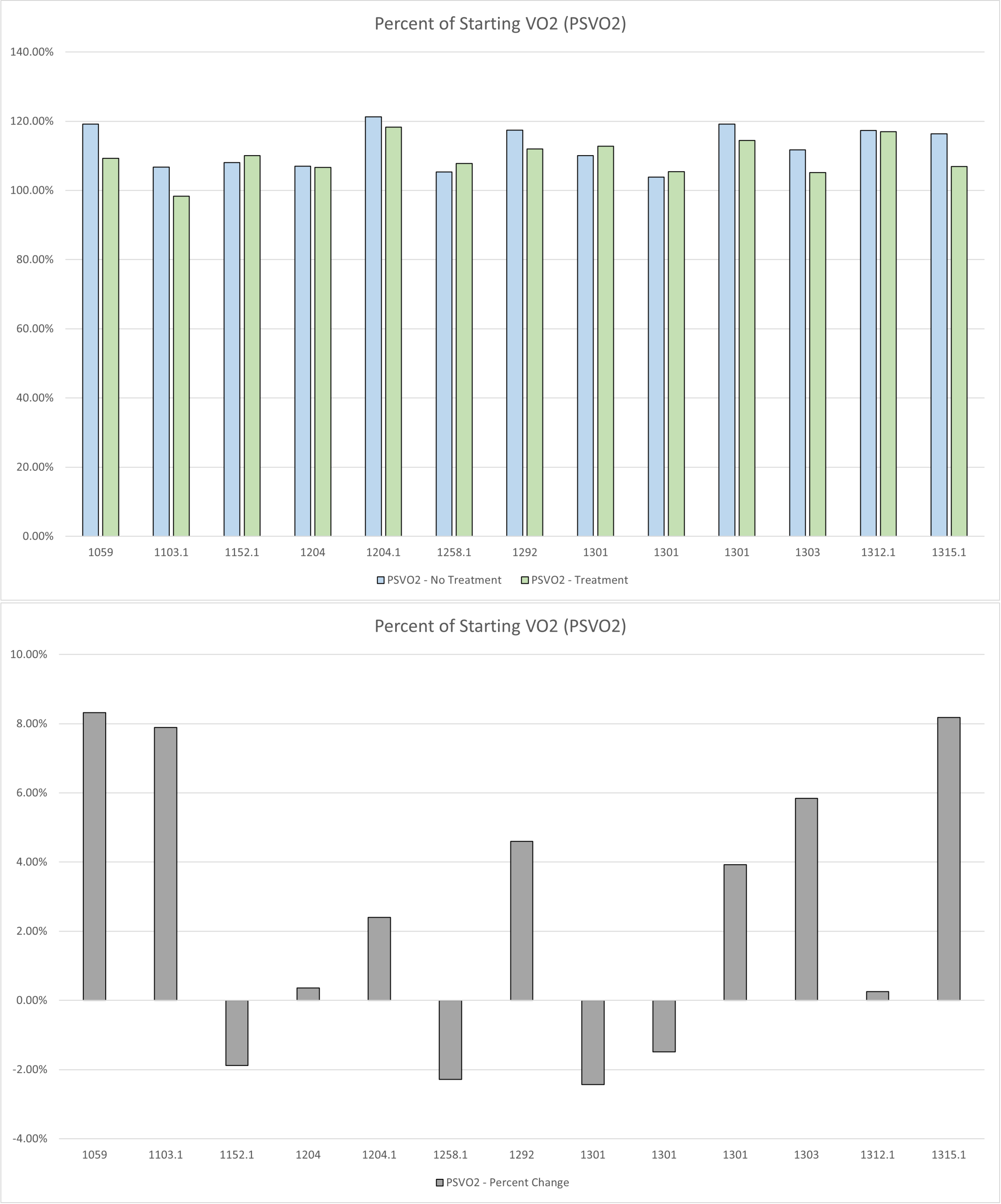


Figure 50: (Top) Results of VO2 adjusted as a percentage of the starting VO2. Blue bars indicate no APEx; green indicates APEx equipped. (Bottom) Percent Change between the PSVO2 values.

a hindrance of -2.4%, -1.9%, and -1.5%. These results indicate considerable benefits in using the device, with relatively small hindrances in those it does not help. Notably, top performers included a mix of those with extensive training with the device (1059, 1303) and less than an hour of experience (1103.1, 1315.1). This implies that benefits can be had near-immediately when the device is used in its intended use. Training would be used to handle day-to-day activities to ease the transition into daily life.

3.4.2.3.4 RPE

Perhaps most convincing were the RPE scores given by the participants. Largely speaking, most users indicated a clear difference in perception in how hard their work was as a whole when using the exoskeleton versus unequipped. An average effort score of 12.4 was given for non-equipped, and 11.1 while equipped; a 10% change in perceived effort. This preference reached a statistically significant p-value of 0.009. The one instance of a preference for no exoskeleton was the same user who reported a poor fit. The two earliest instances of a tied value occurred on the multi-day test 'A,' potentially creating a situation where a reference value was not clear in their mind. The final tied value is also relatively high. The report in question (User 1301) was given after a Test BA day, indicating their discomfort with the robot was the same as not using the robot just 30 minutes prior. This keeps with the results observed above.

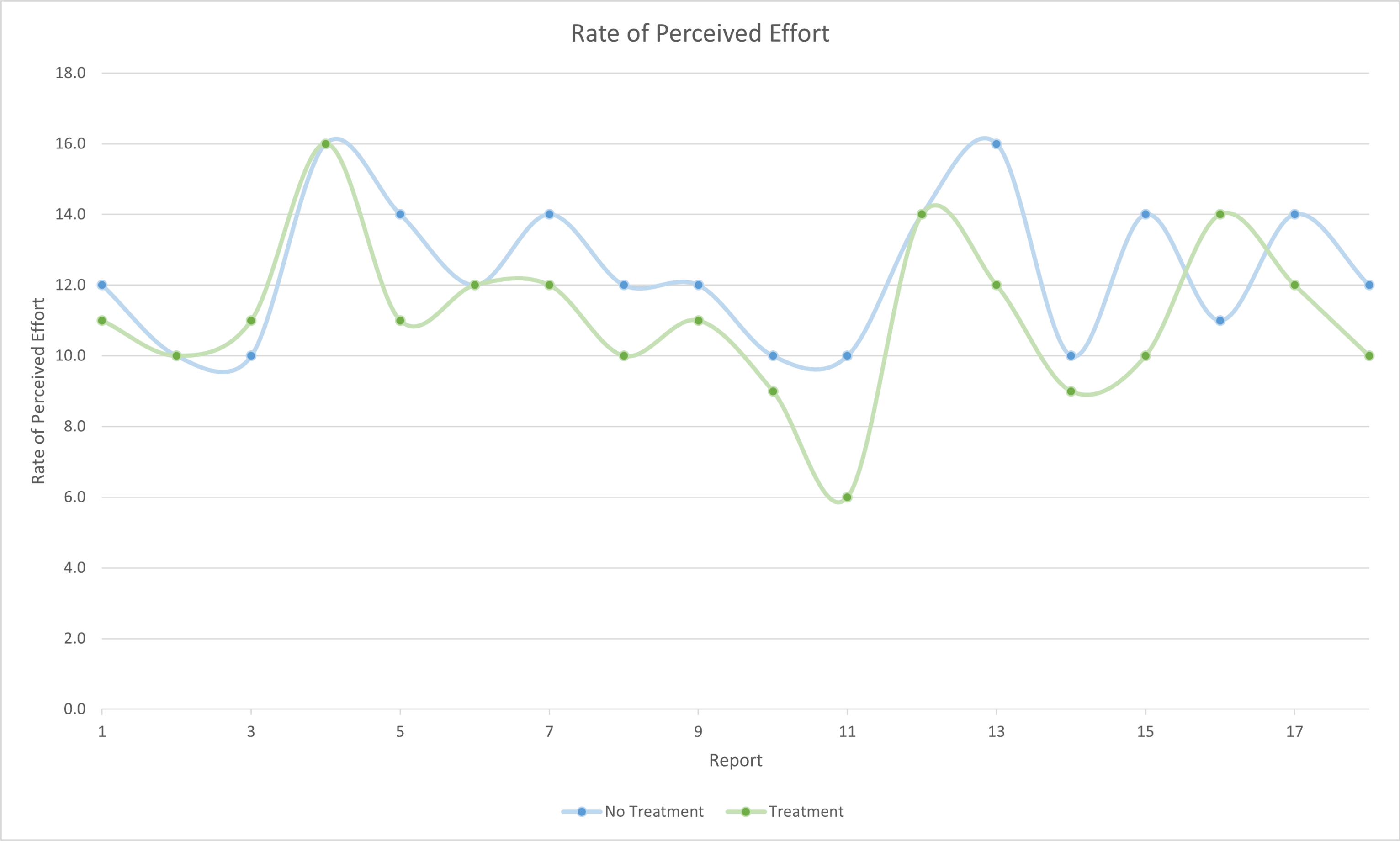


Figure 51: RPE as reported by users. Reports are from 18 tests across 12 users. A low score indicates low perceived effort, and a high score indicates a high perceived effort. Blue indicates no exoskeleton was worn, green indicates the APEx was worn. There are more pairs here than in the HR and VO2 since the values do not require instrumentation.

t-Test: Paired Two Sample for Means

	PSHR - No Treatment	*PSHR - Treatment*
Mean	1.475086822	1.325530699
Variance	0.053206748	0.045944059
Observations	13	13
Pearson Correlation	0.645725659	
Hypothesized Mean Difference	0	
df	12	
t Stat	2.870101681	
P(T<=t) one-tail	0.007043573	
t Critical one-tail	1.782287556	
P(T<=t) two-tail	0.014087145	
t Critical two-tail	2.17881283	

Table 12: Results of the t-Test conducted on PSHR.

t-Test: Paired Two Sample for Means

	PSVO2 - No Treatment	*PSVO2 - Treatment*
Mean	1.125830658	1.095534466
Variance	0.003683834	0.002948684
Observations	13	13
Pearson Correlation	0.674238168	
Hypothesized Mean Difference	0	
df	12	
t Stat	2.335170399	
P(T<=t) one-tail	0.018857435	
t Critical one-tail	1.782287556	
P(T<=t) two-tail	0.03771487	
t Critical two-tail	2.17881283	

Table 13: Results of the t-Test conducted on PSVO2.

3.4.2.4 Observations/Airmen Input

Multiple observations were made of the Airmen during testing activities. It became apparent that different Airmen preferred different methods of controlling the robot. This was especially apparent in tasks that would typically require the Airman to place the device on standby. The given instructions were to dial the torque level to zero when assistance is not needed. This advice was followed for long gaps in activity but was considered cumbersome by some. Instead, different use patterns were adopted. Some moved the thigh paddles to rest behind the leg, where they would be out of the way. Others adjusted their gait after having become familiar with the robot to avoid activation. One chose to enter a modified squat that appeared as a sit to the robot, allowing it to deactivate before moving onto the intended task. While some did use the product as intended, it was valuable and encouraging to see users adapting to the robot for synergistic activities. Over the period, many ideas and comments were also given by the Airmen. Some were new design ideas, some of which are planned implementations for a V2 of the APEx. Others were direct complaints unique to their situations. These include creating a more adjustable leg length, interchangeable leg paddles, and padding inclusion. Overwhelmingly though, Airmen were excited to use the device. There was more than one instance of an Airman requesting the device though it was outside their assigned date. Finally, towards the end of testing and during a high ops tempo, supervision requested their Airmen wear the device as often as possible to prevent long-term injury while they could. These inputs provided a solid validation of the device and the help it could provide.

3.5 Future Work

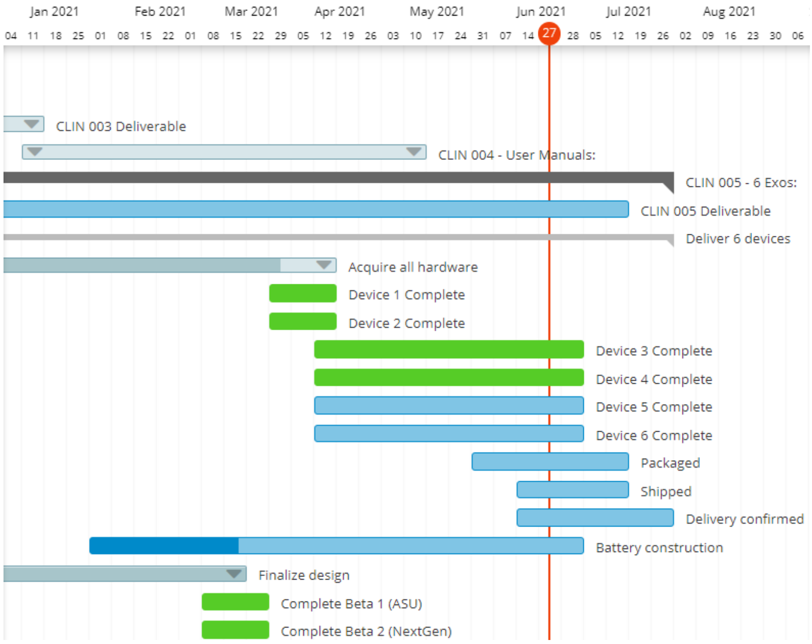


Figure 52: The timeline for accomplishing CLINs 4-6 of the APEx project.

Now that the design and testing phases are complete, all that remains is submitting the user's manual in completion of CLIN004 (Appendix C), the final 6 exoskeletons for CLIN005 (on track IAW figure 52), and the final report for CLIN006. These are the final contractual obligations. However, they are not in themselves the end of work that can be applied to this project. Moving forward with the project, either through a continuation of funding, an independent business venture, or personal curiosity, roughly four categories of improvement exist: wear, internal programming, battery solution, and cabling. Additionally, experiments focused on pushing assistance, and lower back support would help shed light on the device.

3.5.1 Updates to the Device

3.5.1.0.1 Updates to Device Wear

The everyday wear of the system has many drawbacks that need to be updated in future revisions. First, the straps that make up the fitting mechanisms need to be shortened and moved to the inside of the device where possible to avoid snagging hazards. The Airmen observed were consistently moving in a dynamic environment surrounded by heavy machinery. While tied down through the course of the experiment, a large number of straps are at constant risk of catching on a piece of equipment, hindering the motion of the user, or risking them to injury. Moving adjustment straps to the device's interior and providing a means of restraining them so they don't slip out can help to alleviate this issue. This could potentially be accomplished by creating a two-layer vest system, where belts are sandwiched between the fabric. A channel system would help keep belts in place and enable a safer device.

Second, a zipper system to provide an initial fit should be utilized to ensure proper wear and prevent an uncomfortable appearance. When fitted, female air complained about the front-upper strap creating a brassiere effect. This effect didn't affect the physical comfort of the wear but did cause them to be self-conscious and uncomfortable around their peers. Other Airmen had difficulty keeping the shoulder straps where intended, especially if they had a longer torso. For both, a zipper-based solution could help to alleviate issues. Using a zipper from the base to roughly the upper chest assists in maintaining fit and preventing the pronounced brassiere effect.

Third, the twist-lock mechanism proved to be a favorite among participants. An updated design would take advantage of this quick system to allow for a quick-adjusting system that doesn't require long times to re-fit. Ideally, this would work in tandem with the updated strapping and zipper systems. The cords would sit outside the vest and hook into place opposite side the zipper once secured. A simple twist would then provide the final secure fit. This has the added benefit of allowing for a quick easing of the system if users sit but don't take off the device. It was observed while waiting for flights that Airmen would adjust the top buckle when sitting for extended periods.

Fourth, the thigh paddle system needs an additional size to accommodate larger members. This would expand the usability envelope greater than the 90th percentile. One user in particular found extreme discomfort while using the device due to ill-fitting paddles. Given their size, they would become dislodged in most assistance activities or constrict the leg when they did remain in place. This was fixed when the user was fit with paddles with a less aggressive curvature, but time constraints prevented testing with the better fitting device.

Fifth, the hip brace likely needs to be modified to handle deeper squats and different body types. A handful of Airmen complained that the lower edge of the brace dug into their upper thigh, causing mild discomfort. Not extensive enough to end the test, but enough to be noticeable. A simple curved notch cut into the base could quickly alleviate this. Other users suggested a brace stem that curved along the upper body more efficiently. The current design has a flare out to avoid digging into the user but at the cost of a conforming fit. A system similar to a rigid belt could allow a conforming fit along the user's side but remain rigid in the sagittal plane.

Finally, a design that allows for easy cleaning would also benefit the long term. This could include a simple system to remove hardware from the vest and removable pads from the hardpoints from the device. A user brought this request forward after a day of strenuous work in 100+ degrees Fahrenheit work. Test periods with the device were short and infrequent enough not to be a problem, but most users prefer working without their blouse and typically complete their work in just a T-shirt. This is especially true in deployed locations. Enabling ease of sanitation helps prevent adverse health effects.

3.5.1.0.2 Updates to Internal Programming

Programming could be updated to both ease future fittings and identify more activities. By zeroing the device whenever powered on, the device wouldn't need to rely on precise fitting or tricks to take full advantage of the robot. The device could reset its zero after recovering from a squat to ensure that it operates with the most relevant data to remove slippage as a concern. Further, as described in the CoG model section above, many activities showed isolated patterns. A more robust system could potentially track these to identify activities. An additional sensor placed at the base of the neck would also provide an additional point of measure to refine the CoG model, though new captures would need to occur with the new sensor in place to create a meaningful dataset.

3.5.1.0.3 Updates to the Battery Solution

The battery solution is currently acceptable for this advanced prototype device but is unlikely suitable for long-term use, particularly in environments with high tempos, such as a deployed environment. The 36V batteries are slow to charge, last only roughly 4 hours, and are not particularly hardy. An updated system would need to correct all of these issues. This can be accomplished by designing an all-new system or adapting a COTS battery pack, such as those used in drills. This second option has the added benefit of making the device more robust in austere locations, enhancing overall usability.

3.5.1.0.4 Updates to Cabling

Finally, rerouting the cabling of the device would create a more streamlined and straightforward approach to the device. Currently a proposal, a battery pack would connect to a central unit where the only human input area exists. The input would be situated in an easy-to-reach area with intuitive controls for quick manipulation. The battery would also have quick detach capabilities in case of an emergency. Connection points on the actuators would be adjusted to handle the challenging aerial porter environment. Finally, the wiring would, where able, be moved to be internal to the vest, minimizing snagging hazards.

3.5.2 Future Experiments

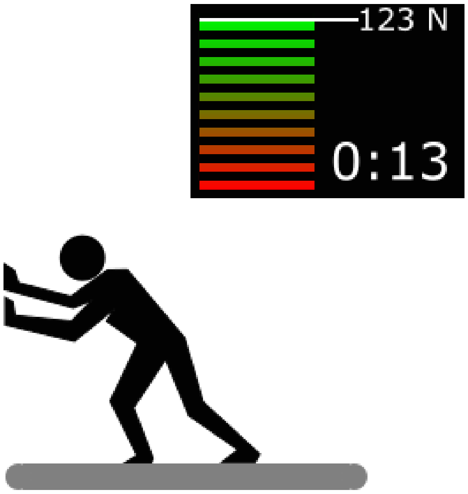


Figure 53: A simple visual description of the push test. The upper right is a sample representation of the screen available to users. The bottom shows a user pushing against a mounted plate while standing on a force-sensing treadmill.

3.5.2.1 Pushing Experiment

A pushing experiment as described in the previously submitted prospectus was cut due to time constraints. However, it remains a reasonable method to test how the device assists in pushing activities. The original parameter in the SOW called for a 500 lb cart to be pushed at a travel rate of 1 m/s over 100 m assuming a friction coefficient of 0.1. This has been adjusted to more tightly control the test and provide cleaner results. The tests are completed in two periods, separated by >72 hours. The order of the four tests will be randomized, and participants will not be compensated.

3.5.2.1.1 Hypothesis

Two hypotheses will be examined after this study. The first: maximum force output will increase by a statistically significant amount while wearing the APEx in the Varied Pushing mode. If true, this will show that the APEx is effective at enhancing the output of the user. The second: the force generated in the Controlled Pushing procedure will be equal while either wearing or not wearing the APEx, but the maximum muscle activation measured by EMGs will be smaller while wearing the APEx. If true, this will show that the APEx effectively reduces the muscular strain on subjects to achieve similar results, increasing time to fatigue.

3.5.2.1.2 Experiment Design

The pushing experiment will use the Bertec Force-Sensing Treadmill and EMG sensors located in the Motion Capture lab at ASU. A force-sensing plate will also be used, mounted to a height-adjustable vertical surface in front of the treadmill. Data reported by the treadmill will be sent to the lab's computer, while a Raspberry Pi will collect data from the vertical plate. There will also be a live display above the plate, indicating the push's force and the desired force (if needed). A graphical representation is shown in Figure 53. EMG sensors will be placed on the Rectus Femoris, Quadricep, and Lumbar region of the user. The EMGs will all be baselined to individual Maximum Voluntary Contractions (MVCs). The sequence of wear and speeds will be generated using Latin squares, and the sequence selected for the subject will be chosen at random. Tests will be conducted at around the same time of day (±3 hrs).

3.5.2.1.2.1 Controlled Pushing

Controlled pushing will cover the test as described in the SOW. After completing MVC exercises, users will begin on the treadmill in front of the vertical plate, with hands-on the plate. The height of the plate will be set to 75% of the height of the user. On “go,“ users will push against the plate while the treadmill moves at one m/s for 100 m. The force readout will show a live numeric and graphic indication of force. Users will be asked to push against the plate until the force equals 222.4 N (equal to move a 500 lb. block where coefficient of friction = 0.1). Once the treadmill has traveled 100 m, the experiment will stop, and the user will rest.

3.5.2.1.2.2 Varied Pushing

This test will be similar to the controlled test but remove the set level requirement. Users will be encouraged to push against the plate at maximum strength for the 100 m push duration. The graphical display will show a live readout of their input force and indicate the maximum achieved for that test. This is to encourage users to push harder continually and increase their force. Users will push against the plate at treadmill speeds of 1, 2, and 3 m/s. The 1 m/s category is for direct comparison to the controlled pushing test. The other two are to determine rough trends.

3.5.2.2 Back Support Experiment

Testing at TAFB intended to make use of the GoX Ergo Kit to measure good vs. bad lifts. This was accomplished but was insufficient in predicting long-term effects on the back during a range of activities. It is proposed that additional testing be accomplished to measure this effect.

3.5.2.2.1 Hypothesis

. Maximum muscle activation measured by EMGs in the lumbar region will be smaller by a statistically significant amount when wearing the device than not while completing activities. Additionally, associated regions will see the same effect. If true, the device, when worn, can be assumed to assist the lower back, requiring lower activation from the lumbar region and not exacerbate issues in other regions.

3.5.2.2.2 Experiment Design

The back support experiment can be conducted in tandem with previously described experiments. EMG sensors are placed on the lower back, quadriceps, upper back, and abdominals for both pushing and lifting tests. The EMGs will all be baselined to individual Maximum Voluntary Contractions (MVCs). The sequence of wear and speeds will be generated using Latin squares, and the sequence selected for the subject will be chosen at random. Tests will be conducted at around the same time of day (±3 hrs).

3.6 Summary

The APEx has been an excellent foray into the world of wearable robotics for demanding career fields. ASU developed a device that weighed eight lbs. and provided

30 N-m of force about each hip: a world first. The device in its prototype form has proven robust and reliable, with few issues during real-world testing. Perhaps most importantly, it stayed out of the way of the user in day-to-day operations while providing back support throughout. From the user's perspective, the device helped many, with a peak of 8.3% metabolic reduction, allowing users to last longer throughout the day and likely reducing their risk of long-term injury. While follow on research is necessary to understand the long-term benefits of the device fully, it is a significant first step in delivering practical robotics for our nation's Airmen.

Chapter 4

EXOSKELETON TESTING STANDARDS DEVELOPMENT

4.1 Outline

As reviewed above, currently, there are no widely or minimally accepted forms of standardized testing for exoskeletons. Standard organizations such as the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) are developing standards for industrial and medical exoskeletons but are just developing standards such as ISO 13482 and the work at ASTM F48. Because of this, the exoskeleton market is bursting with marketing buzzwords and internal testing that third parties cannot reliably verify. They also cannot be compared in a meaningful manner. The lack of comparison methods leaves companies aiming to implement exoskeletons in their workforce to rely on marketing teams, narrow academic testing, or costly exploratory programs to determine if an exoskeleton would be a good fit for their work center. It also leaves exoskeleton manufacturers without a sense of what companies are looking for and prioritizing outside of their ownresearch. Developing and testing a set of standards/protocols allows consumers intending to use exoskeletons to make an informed decision on which device to use and select an exoskeleton based on parameters pertinent to them.

4.2 Status of Project

4.2.1 Procedure Creation

The body of academic work was examined before drafting tests and standards. This involved tests conducted across a range of devices, including (non-exhaustively) on commercial exoskeletons, as with Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Jia, et al. 2018 and Gillette and Stephenson 2019, internally designed devices like the lower body exoskeletons by Sado et al. 2019, and Kazerooni, Steger, and Huang 2006, and tests conducted in a live environment as with Butler and Gillette 2019. A review of these research efforts is outlined above in the literature review.

Following this investigation, a basic outline was created. The tests and standards isolate lower and upper body exoskeletons to their specialized tasks in one portion and perform the same tasks in the other. Separating into the two methods identifies how specifically the exoskeletons help during their intended use and fill the picture on the rest of the day between work tasks. This second set of testing, referred to as usability testing, is vital in predicting if the devices are readily adopted by a workforce or used begrudgingly, if at all. Testing also needs to take place over one day for the initial rollout. Doing so allows for an investigation of multiple procedures without the risk of subjects not returning for another round. It did, however, limit the executable time of the tests to minimize fatigue skewing the results.

Finally, initial tests were built out for the exoskeletons. Five tests were developed for the lower body and three for the upper. Both sets were completed twice, one with and the other without the exoskeleton. These tests are referred to as work tests. In the usability procedures, eleven tests were created. These are also completed once with and once without the exoskeleton. The order of wear was selected using Latin squares.

4.2.1.1 Lower Body Work Tests

The lower body tests are similar to tests conducted for the APEx. Testing on lower body exoskeletons often has subjects standing in place and completing squat lifting tasks. These are valuable in isolating the muscles used to lift but do not reflect a traditional work environment. As this project aims to do this, the tests were designed to focus on transporting a load, not solely lifting it. Finally, the tests themselves are completed at the chosen pace of the subject, not within a specific time limit.

4.2.1.1.1 Testing Rig

The tests require two tables, both with an adjustable lower shelf, a set of weighted containers, a pushcart, and a tray of tools. Tests can be completed within one adequately sized room.

4.2.1.1.2 Test 1 - Lifting A Load From Floor Height

This task makes use of the lower body testing equipment. Users approach a 10 kg box placed on the floor from 5m and pickup to a comfortable height. Then walk a further 5m before setting it down at the prescribed height (randomly selected: floor, low shelf, or table). Users rest by returning to the starting position. This cycle is repeated five times, followed by a 30-second rest. This is considered 1 set. Users complete three sets.

4.2.1.1.3 Test 2 - Lifting A Load From A Low Shelf

This task makes use of the lower body testing equipment. Users approach a 10 kg box placed on a low shelf 15 cm above the ground from 5m and pickup to a comfortable height. Then walk a further 5m before setting it down at the prescribed height (randomly selected: floor, low shelf, or table). Users rest by returning to the starting position. This cycle is repeated five times, followed by a 30-second rest. This is considered 1 set. Users complete three sets.

4.2.1.1.4 Test 3 - Lifting A Load From Table Height

This task makes use of the lower body testing equipment. Users approach a 10 kg box placed on a table 86 cm above the ground from 5m and pickup to a comfortable height. Then walk a further 5m before setting it down at the prescribed height (randomly selected: floor, low shelf, or table). Users rest by returning to the starting position. This cycle is repeated five times, followed by a 30-second rest. This is considered 1 set. Users complete three sets.

4.2.1.1.5 Test 4 - Pushing A Loaded Cart

This task makes use of the lower body testing equipment. Users approach a cart loaded with 45 kg from 5m and push a distance of 15 meters at a rate of over one m/s. Users then disengage and walk a further 5m. Users rest by returning to the starting position. This cycle is repeated five times, followed by a 30-second rest. This is considered 1 set. Users complete three sets.

4.2.1.1.6 Test 5 - Performing Twisting Tasks

This task makes use of the lower body testing equipment. Users stand before a 10 kg container set at table height and then pick it up to a comfortable height. Users then place the loaded container on a table situated 1.5 m behind them. Users then rest by returning to the starting position and making marks for 5 seconds on a form on the starting table. This cycle is repeated five times, followed by a 30-second rest. This is considered 1 set. Users complete three sets.

4.2.1.2 Upper Body Work Tests

Upper body tests are completed at prescribed intervals and pacing. This is to test the idea of set guidelines and their ability to make post-processing easier. It was chosen to have set guidelines for this test as walking movement is not common in tasks that require upper body assistance. These guidelines make the required time more predictable than with the walking tasks of the lower-body exoskeleton.

4.2.1.2.1 Testing Rig

Tests require a keyboard mounted on a vertical wall. The rig also needs an adjustable overhead component to place a keyboard on at individualized heights.

Finally, a metronome, nut and bolt, piece of paper, and pen are needed. All tests can be completed within one large room. “Light manual labor” is defined as screwing and unscrewing a bolt, making a tick mark on the paper for each screw/unscrew set completed.

4.2.1.2.2 Test 1 - Repetitive Motion at Waist Height

This task makes use of the upper body testing rig. With the testing rig set to a height equal to the elbow’s height at 90° flexion, use a weighted drill to tap out a specified sequence for 30 seconds at 75 BPM. This is followed by light manual labor for 30 seconds. This cycle is repeated three times and followed by a 5-minute rest.

4.2.1.2.3 Test 2 - Repetitive Motion at Shoulder Height

This task makes use of the upper body testing rig. With the testing rig set to a height equal to the user’s shoulder height, use a weighted drill to tap out a specified sequence for 30 seconds at 75 BPM. This is followed by light manual labor for 30 seconds. This cycle is repeated three times.

4.2.1.2.4 Test 3 - Repetitive Motion at Overhead Height

This task makes use of the upper body testing rig. The testing rig is set to position the hand at a height equal to the median height between the shoulder and the hand at full overhead reach (shoulders remaining parallel to the ground). The tester then uses a weighted drill to tap out a specified sequence for 30 seconds at 75 BPM. This is followed by light manual labor for 30 seconds. This cycle is repeated three times.

4.2.1.3 Usability Tests

These tests are designed to catch the in-between moments of a typical workday. Regardless of the job task, these specific tasks might be accomplished while wearing an exoskeleton. A device that inhibits these motions makes it less likely to be adopted by the workforce.

4.2.1.3.1 Testing Equipment

These tests make use of the weighted containers, tables, tool kit, and cart from the lower body tests. A treadmill and staircase are also necessary.

4.2.1.3.2 Test 1 – Don the Exoskeleton

Beginning with the Exo in its stored configuration, the user don the Exo per manufacturer standards. This timed test occurs at the end of the study when users are most familiar with the Exo wear.

4.2.1.3.3 Test 2 – Walking

Beginning in a standing position, users walk 5 minutes at 5 km/hr. This is intended to test basic job requirements. This is performed once with the Exo worn and once without.

4.2.1.3.4 Test 3 - Jogging

Beginning in a standing position, users jog for 1 minute at 8 km/hr. This is intended to test the ability to maneuver away from danger quickly. This is performed once with the Exo worn and once without.

4.2.1.3.5 Test 4 – Climbing Stairs

Beginning in a standing position, users ascend and descend a flight of stairs at a self-selected pace. This is intended to test basic mobility requirements. This is performed once with the Exo worn and once without.

4.2.1.3.6 Test 5 - Kneeling

Beginning in a standing position, users kneel and reach under a table for a 5 kg object. The user then switches legs and repeat. This is intended to test basic job requirements. This is performed once with the Exo worn and once without.

4.2.1.3.7 Test 6 – Crawling

Beginning in a crawling position, users crawl 2.5 m at a self-selected pace. This is intended to test basic job requirements. This is performed once with the Exo worn and once without.

4.2.1.3.8 Test 7 – Lateral Stepping

Beginning in a standing position, users sidestep 5 meters in each direction at a self-selected pace. This is intended to test basic job requirements. This is performed once with the Exo worn and once without.

4.2.1.3.9 Test 8 – Arrange Tools

This task uses the tool kit test equipment. Beginning with an empty tray, users transfer various tools from a populated tray to the designated position in the empty one at their desired pace. This is intended to test micro manipulation abilities. This is performed once with the Exo worn and once without.

4.2.1.3.10 Test 9 - Load A Work Cart

This task makes use of lower body testing equipment. Beginning with an empty work cart, users transfer containers of varying mass from a table height onto a work cart at their desired pace. This is intended to test macro manipulation abilities. This is performed once with the Exo worn and once without.

4.2.1.3.11 Test 10 - Push A Work Cart

This task makes use of lower body testing equipment. Beginning with the loaded work cart from 1.d.U2, users push the cart 15 meters at their desired pace. This is intended to test day-to-day Jobsite preparation activities. This is performed once with the Exo worn and once without.

4.2.1.3.12 Test 11 – Doff the Exoskeleton

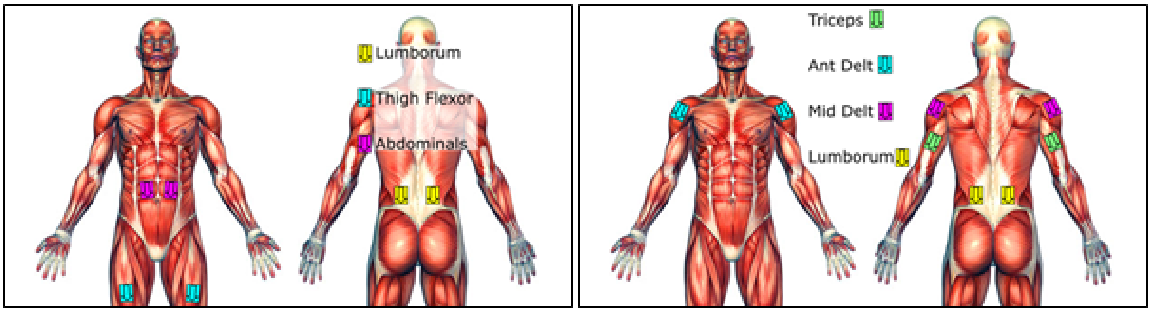
Beginning with the Exo in its worn configuration, the user doffs the Exo and returns it to its stored position per manufacturer standards. This timed test occurs at the end of the study when users are most familiar with the Exo wear.

4.2.1.4 Additional tests

Beyond the human subject testing, additional parameters were identified for testing. These include duration, ergonomics, latency, back-drivability, and portability and are discussed in depth in this report's “Scoring Algorithm“ portion.

4.2.1.5 Measurements and tools

Five parameters are measured during testing of both devices: EMG, IMU, HR, VO2, and Borg scale. All are valuable in the data they provide and highlight different aspects of the exoskeleton. EMG is a direct measurement of muscle activation and is the most often used in testing exoskeletons. A device that causes a smaller EMG reading when used versus when not worn indicates a muscularly helpful device. IMUs are used to measure the maximum G forces each attached limb undergoes during testing. G-force levels are one indicator of a device that causes the user to execute unsafe movements. Heart Rate is a standard measure of the level of effort an individual is putting into the exercise. VO2 is another of these measures indispensable in determining the metabolic cost of an activity. In both, a lower measure while wearing the exoskeleton versus not worn indicates a more assistive device. Finally, Borg scores are used as a subjective measure of the comfortability of the device. While subjective, this scale is an effective predictor of fatigue and is used herein similarly.



(a) Lower body (b) Upper body

Figure 54: Placement EMG/IMU devices for the lower and upper body.

Placement of EMG and IMU devices for the lower body tests focus on the Triceps Brachii (elbow flexion) and Anterior and Middle Deltoids (shoulder motion). The Iliocostalis lumborum pars lumborum is also measured to detect load shifting. The upper body tests are monitored through the Triceps Brachii (elbow flexion) and Anterior and Middle Deltoids (shoulder motion). The Iliocostalis lumborum pars lumborum is also measured to detect load shifting.

4.2.1.6 Baselining

All equipment and measures to be used are baselined before testing. After gathering height and weight for the GoX algorithm, a resting HR is discovered by having the subject sit for 5 minutes. Users are not allowed to speak or look at their phones. The lowest value obtained during this time frame is considered the resting HR (RHR). Next, the EMG/IMU devices are placed on their required muscle sites. These sites are cleaned with alcohol wipes and lightly abraded. Then the connections are verified, and impedance levels are measured. Once read is confirmed, subjects perform reference contractions to determine MVC values. These movements include maximum contraction (MC) for the lower body during leg extensions, MC during held V-ups, and MC in prone spinal extension. The upper body utilizes unweighted position holding; maximum contraction (MC) at 90° shoulder abduction; MC in standing elbow flexion; and MC in prone spinal extension. Finally, subjects complete familiarization with the Borg scale for comfortability rating. For the lower body, the users sit in a “wall squat” position with their back on the wall and knees bent to 90°. The user then reports their discomfort level every 5 seconds. The calibration period is complete when a level of 10 is reached, or the position can no longer be held. They are asked to hold a 0.5 kg mass in their non-dominant hand at a 90° shoulder abduction for the upper body. The user then reports their discomfort level every 5 seconds. The calibration period is complete when a level of 10 is reached, or the mass can no longer be held. Once baseline development is complete, the subject is ready to complete the above tests.

4.2.2 Scoring Algorithm

After determining the subject-required tests and designing a base experiment, a scoring algorithm was created. This score is the final consumer-facing measure and thus needed to be intuitive to the average person. For this reason, a linear, 0-10 scoring system was created. A score of zero indicates very low performance, and a ten a high level of performance. The proposed scoring system comprises five categories: Assistance, Comfort, Human Hazard, Movement Restriction, and Space Consideration. Each category is further broken into sub-categories. These are broken down and described below.

4.2.2.1 Assistance

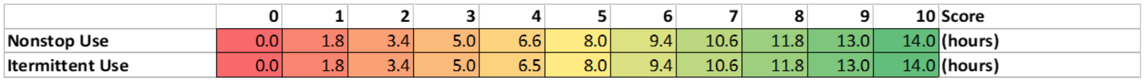
Assistance is the primary measure requiring direct human subject testing. This measure reflects the effect of the device on the human in assisting in prescribed tasks.

4.2.2.1.1 Effective Duration

This test is for powered exoskeletons only. This category is measured in two forms: non-stop use and intermittent use. Non-stop use is measured as the time between power-on from a full charge and battery depletion with the Exo in motion throughout. Worksite use is measured as the time between power-on from a full charge and battery depletion with work interspersed with breaks. To measure non-stop usage, the Exo is attached to a rigid structure and an automated actuation device. This device simulates constant use, counting cycles, and measuring time in motion. Intermittent use is measured by attached the Exo to the same testing rig. The testing robot actuates continuously for 10 minutes, pauses for 5 minutes, and repeats until battery depletion.

The final score is taken as the average score between the two metrics: Nonstop use and intermittent use. Eight hours was selected as the mid-point to meet average shift requirements, with an emphasis on slightly longer times to deal with donning/doffing considerations. A top score of 14 hours accepts a 12-hour shift, with extra time for donning/doffing considerations. Equation(s) follow:

$$score = -\frac{5}{2} * (\sqrt{81 - 4 * hours} - 9) \tag{4.1}$$



	0	1	2	3	4	5	6	7	8	9	10	Score
Nonstop Use	0.0	1.8	3.4	5.0	6.6	8.0	9.4	10.6	11.8	13.0	14.0	**(hours)**
Itermittent Use	0.0	1.8	3.4	5.0	6.5	8.0	9.4	10.6	11.8	13.0	14.0	**(hours)**

Figure 55: Effective duration range of scores

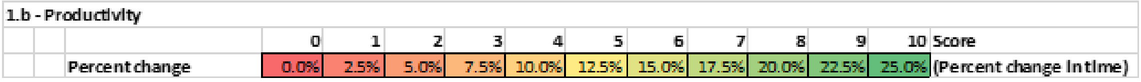
4.2.2.1.2 Productivity

Productivity is the ability of the Exo to extend work time, complete tasks more quickly, or delay fatigue. These tests are completed in conjunction with the 1.c series of tests. Following the prescribed test, users are asked to complete a task at their own pace chosen for comfort. Results from the chosen pace tests are compared to measure the potential for productivity improvements.

The final score is taken as a factor of the percent change in time taken to complete a task. Percent change is calculated using the self-selected pace of the non-equipped and equipped exercises. Equation(s) follow:

$$PercentChange = \frac{\sum IndividualPercentChanges}{NumberOfTests}$$

$$score = \frac{PercentChange}{0.025}$$



1.b - Productivity														
			0	1	2	3	4	5	6	7	8	9	10	Score
		Percent change	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change in time)

Figure 56: Productivity range of scores

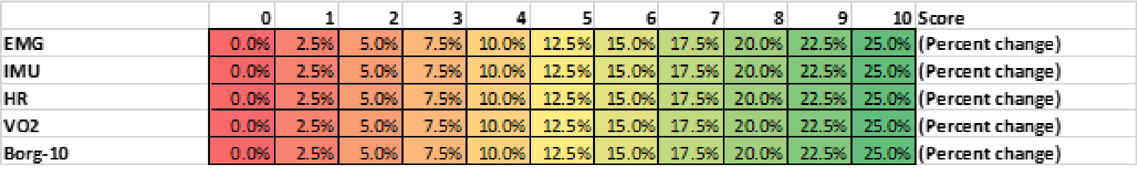
4.2.2.1.3 Work

As described above, work is measured as the assistance provided in various work tasks. These tasks vary between the upper and lower body, seen below. All tests take metrics through EMG, IMUs, a heart rate monitor, a VO2 monitor, and the Borg CR-10 scale.

The final score is given as an average of the scores for each category: EMG; IMU; heart rate; VO2; and Borg-10 score. All these categories is scored as a factor of percent change, where a percent change favoring the exoskeleton gives a positive score. Equation(s) follow:

$$PercentChange = \frac{\sum IndividualPercentChanges}{NumberOfTests}$$

$$score = \frac{PercentChange}{0.025}$$



	0	1	2	3	4	5	6	7	8	9	10	Score
EMG	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
IMU	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
HR	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
VO2	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
Borg-10	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)

Figure 57: Work range of scores

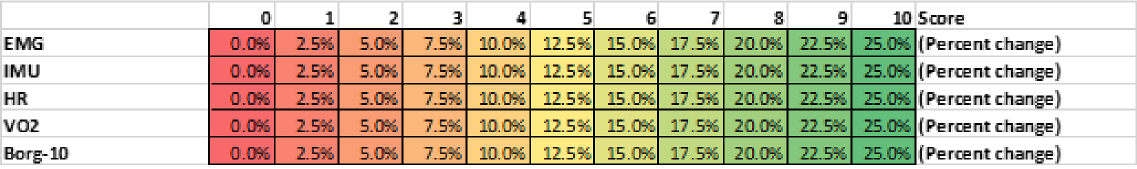
4.2.2.1.4 Usability

As described above, usability is measured as the ability to perform standard non-work tasks within the Exo compared to without. These tasks vary between the upper and lower body, seen below. All tests take metrics through EMG, IMUs, a heart rate monitor, a VO2 monitor, and the Borg CR-10 scale.

The final score is given as an average of the scores for each category: EMG; IMU; heart rate; VO2; and Borg-10 score. All these categories is scored as a factor of percent change, where a percent change favoring the exoskeleton gives a positive score. Equation(s) follow:

$$PercentChange = \frac{\sum IndividualPercentChanges}{NumberOfTests}$$

$$score = \frac{PercentChange}{0.025}$$



	0	1	2	3	4	5	6	7	8	9	10	Score
EMG	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
IMU	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
HR	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
VO2	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
Borg-10	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)

Figure 58: Usability range of scores

4.2.2.2 Comfort

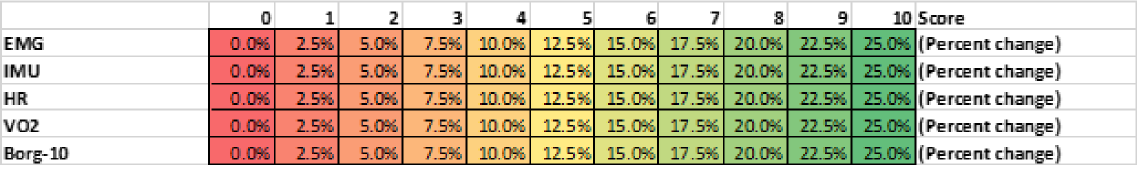
The ability of the Exo to input body measurements and translate them to action.

4.2.2.2.1 Ergonomics

Ergonomics is a measure of (dis)comfort and posture while wearing the exoskeleton. Comfort is measured using the Borg CR-10 scale during each of the tests conducted throughout the study. Posture is also measured through the tests using IMUs. Additionally, displacement from robot-human attach sites is measured as the difference between initial fitted placement and final location post-activities.

The final score is given as an average of the scores for each category: Borg-10 score, posture difference, and pad displacement. The Borg-10 score is calculated as the average of the scores during tests with the exoskeleton (powered on if applicable). Posture difference is measured as the percent change between unequipped motion and equipped motion (powered on if applicable). Finally, pad displacement is measured as the position of the pad at the end of the tests vs at the start. Equation(s) follow:

$$\begin{aligned}
score_{borg} &= \frac{\sum IndividualBorgScores}{NumberOfMeasures} \\
score_{posture} &= \frac{\sum IndividualPercentChanges}{NumberOfTests} \\
score_{displacement} &= measured \\
score_{final} &= \frac{\sum scores}{3}
\end{aligned}$$



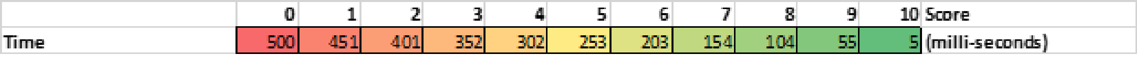
	0	1	2	3	4	5	6	7	8	9	10	Score
EMG	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
IMU	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
HR	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
VO2	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
Borg-10	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)

Figure 59: Ergonomics range of scores

4.2.2.2.2 Latency

This is for powered exoskeletons only. Latency is a measure of the time difference between an input signal and the output action. This measure uses a rigid mount and an adjustable linear actuator with a force sensor. In this manner, it is possible to test the devices without access to the internal software, protecting proprietary code and preventing circumvention methods. The final score is the result of an average of 3 tests. The measure is in milliseconds. Equation(s) follow:

$$score = -49.5 * time + 500$$



	0	1	2	3	4	5	6	7	8	9	10	Score
Time	500	451	401	352	302	253	203	154	104	55	5	(milli-seconds)

Figure 60: Latency range of scores

4.2.2.2.2.1 Direct force application

No users are required for this test. The Exo is mounted on the rig to hold the base rigid. The linear actuator is placed perpendicular to the force-sensing surface of the Exo. The actuator then applies a known constant force directly to the surface. The timer starts when contact is made and ends when the Exo moves in response to the action. The tests are repeated for each of the Exo's force-sensing surfaces.

4.2.2.2.2.2 Oblique force application

No users are required for this test. The Exo is mounted on the rig to hold the base rigid. The linear actuator is placed at a prescribed angle to the force-sensing surface of the Exo. The actuator then applies a known constant force directly to the surface. The timer start when contact is made and ends when the Exo moves in response to the action. The tests repeat at differing vectors to get an approximation of the range of acceptable angles. The tests are repeated for each of the Exo's force-sensing surfaces.

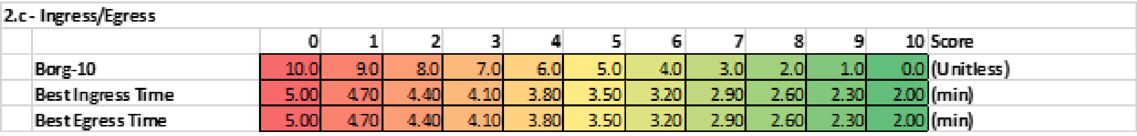
4.2.2.2.3 Ingress/Egress

Both Ingress and egress are the ability to don and doff the Exo. This category is measured using the Borg CR-10 scale, and a stopwatch factors in the assistance required to complete the tasks.

The final score is given as an average of the scores for each category: Borg-10; Best ingress time; Best egress time. The Borg-10 score is calculated as the average Borg-10 score given during the donning/doffing activities. The ingress and egress time scores is calculated using the best time from both activities, measured in minutes.

Equation(s) follow:

$$score_{borg} = \frac{\sum IndividualBorgScores}{NumberOfMeasures}$$
$$score_{time} = -\frac{time - 5}{0.3}$$
$$score_{final} = \frac{\sum scores}{3}$$



2.c- Ingress/Egress												
	0	1	2	3	4	5	6	7	8	9	10	Score
Borg-10	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0	2.0	1.0	0.0	(Unitless)
Best Ingress Time	5.00	4.70	4.40	4.10	3.80	3.50	3.20	2.90	2.60	2.30	2.00	(min)
Best Egress Time	5.00	4.70	4.40	4.10	3.80	3.50	3.20	2.90	2.60	2.30	2.00	(min)

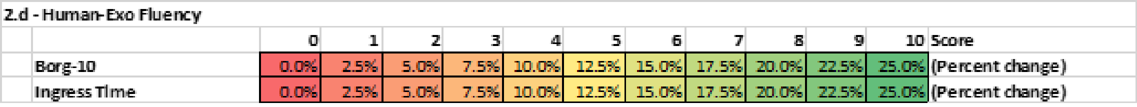
Figure 61: Ingress/Egress range of scores

4.2.2.2.4 Human-Exo Fluency

Human-Exo fluency is a measure of how long it takes for the human to become accustomed to the exoskeleton. This category is measured through two vectors. The first is the rate of change in donning/doffing time over the test sessions. The second is through the Borg-10 scale via the change in task completion comfortability while equipped with the exoskeleton. For both measures, as the user becomes more familiar with the device, their interactions become more fluid, which is essential in maximizing productivity.

The final score is given as an average of the scores for each category: Borg-10; Best ingress time. The scores is calculated as the percent change over testing days activities. Equation(s) follow:

$$score = \frac{PercentChange}{0.025}$$



2.d - Human-Exo Fluency

	0	1	2	3	4	5	6	7	8	9	10	Score
Borg-10	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)
Ingress Time	0.0%	2.5%	5.0%	7.5%	10.0%	12.5%	15.0%	17.5%	20.0%	22.5%	25.0%	(Percent change)

Figure 62: Human-Exo Fluency range of scores

4.2.2.3 Human Hazard

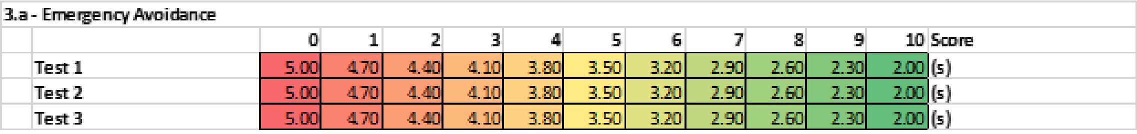
Ability to recover from hazards and complications

4.2.2.3.1 Emergency Avoidance

Obstacle avoidance is a measure of how quickly the Exo can react to an emergency. Tests for the upper body include a flashing light and buzzer signaling users to stop their task immediately. The lower body tests have obstructions enter the field of operations suddenly (e.g., opening doors or wandering tester). These tests are conducted for three randomly selected tests in the work series.

The final score is given as an average of the scores for each test of avoidance. The scores is calculated as the time in seconds taken to react to the given emergency. Equation(s) follow:

$$score = \frac{time - 5}{0.3}$$



3.a - Emergency Avoidance

	0	1	2	3	4	5	6	7	8	9	10	Score
Test 1	5.00	4.70	4.40	4.10	3.80	3.50	3.20	2.90	2.60	2.30	2.00	(s)
Test 2	5.00	4.70	4.40	4.10	3.80	3.50	3.20	2.90	2.60	2.30	2.00	(s)
Test 3	5.00	4.70	4.40	4.10	3.80	3.50	3.20	2.90	2.60	2.30	2.00	(s)

Figure 63: Emergency Avoidance range of scores

4.2.2.3.2 Back-drivability

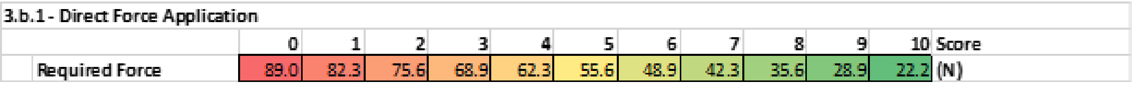
Back-drivability is a measure of the force required to move the exam in a no power condition. This measure uses a rigid mount and an adjustable linear actuator with a force sensor. In this manner, it is possible to test the devices without access to the internal software, protecting proprietary code and preventing circumvention methods.

4.2.2.3.2.1 Direct force application

No users are required for this test. The Exo is mounted on the rig to hold the base rigid, and the linear actuator is placed perpendicular to the force-sensing surface of the Exo. The actuator then applies a known constant force directly to the surface. The timer starts when contact is made and ends when the Exo moves in response to the action. After resetting to initial positions, the test actuator decrements the known force and repeats. Tests continue decrementing known force until the Exo no longer responds. The tests are repeated for each of the Exo's force-sensing surfaces.

The final score is derived from the force used in the test. The scores is calculated as the force in newtons taken to provoke a response. Equation(s) follow:

$$score = -\frac{Newtons - 88.96}{6.672}$$



3.b.1 - Direct Force Application

	0	1	2	3	4	5	6	7	8	9	10	Score
Required Force	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)

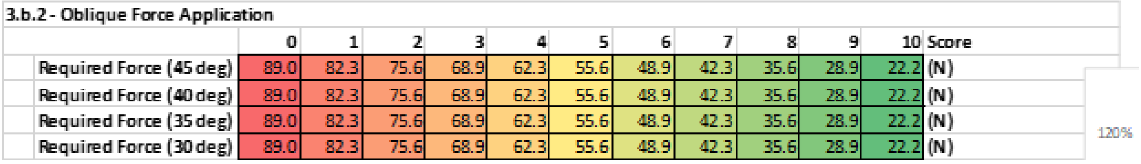
Figure 64: Direct Force Application range of scores

4.2.2.3.2.2 Oblique force application

No users are required for this test. The Exo is mounted rigidly on the rig. The linear actuator is placed at a prescribed angle to the force-sensing surface of the Exo. The actuator then applies a known constant force directly to the surface. The timer starts when contact is made and ends when the Exo moves in response to the action. After resetting to initial positions, the test actuator decrements the known force and repeat. Tests continue decrementing known force until the Exo no longer responds. The tests repeat at differing vectors to get an approximation of the range of acceptable angles. The tests are repeated for each of the Exo's force-sensing surfaces.

The final score is the average of the results of test scores derived from the force used in the different tests. The scores is calculated as the force in newtons taken to provoke a response. Equation(s) follow:

$$score_{angle} = -\frac{Newtons - 88.96}{6.672}$$



3.b.2 - Oblique Force Application

	0	1	2	3	4	5	6	7	8	9	10	Score
Required Force (45 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)
Required Force (40 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)
Required Force (35 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)
Required Force (30 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)

Figure 65: Oblique Force Application range of scores

4.2.2.3.3 Control Force

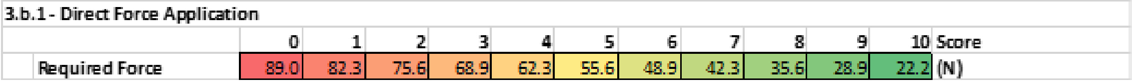
This is for powered exoskeletons only. Control force is a measure of the force required to move the exam in a powered-on condition. This measure uses a rigid mount and an adjustable linear actuator with a force sensor. In this manner, it tests the devices without access to the internal software. Without this access, the proprietary code is protected, and circumvention methods are prevented.

4.2.2.3.3.1 Direct force application

No users are required for this test. The Exo is mounted rigidly on the rig. The linear actuator is placed perpendicular to the force-sensing surface of the Exo. The actuator then applies a known constant force directly to the surface. The timer starts when contact is made and ends when the Exo moves in response to the action. After resetting to initial positions, the test actuator decrements the known force and repeat. Tests continue decrementing known force until the Exo no longer responds. The tests are repeated for each of the Exo's force-sensing surfaces.

The final score is derived from the force used in the test. The scores is calculated as the force in newtons taken to provoke a response. Equation(s) follow:

$$score = -\frac{Newtons - 88.96}{6.672}$$



3.b.1 - Direct Force Application

	0	1	2	3	4	5	6	7	8	9	10	Score
Required Force	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)

Figure 66: Direct Force Application range of scores

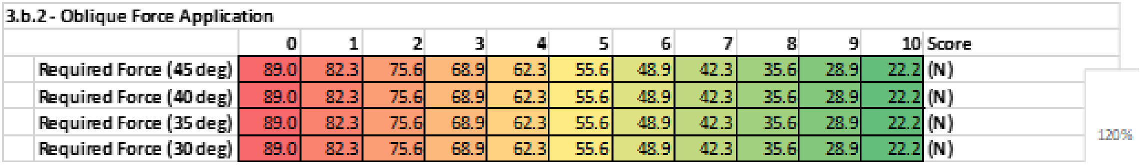
4.2.2.3.3.2 Oblique force application

No users are required for this test. The Exo is mounted on the rig to hold the base rigid. The linear actuator is placed at a prescribed angle to the force-sensing surface of the Exo. The actuator then applies a known constant force directly to the surface.

The timer starts when contact is made and ends when the Exo moves in response to the action. After resetting to initial positions, the test actuator decrements the known force and repeat. Tests continue decrementing known force until the Exo no longer responds. The tests repeat at differing vectors to get an approximation of the range of acceptable angles. The tests are repeated for each of the Exo's force-sensing surfaces.

The final score is the average of the results of test scores derived from the force used in the different tests. The scores is calculated as the force in newtons taken to provoke a response. Equation(s) follow:

$$score_{angle} = -\frac{Newtons - 88.96}{6.672}$$



3.b.2 - Oblique Force Application

	0	1	2	3	4	5	6	7	8	9	10	Score
Required Force (45 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)
Required Force (40 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)
Required Force (35 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)
Required Force (30 deg)	89.0	82.3	75.6	68.9	62.3	55.6	48.9	42.3	35.6	28.9	22.2	(N)

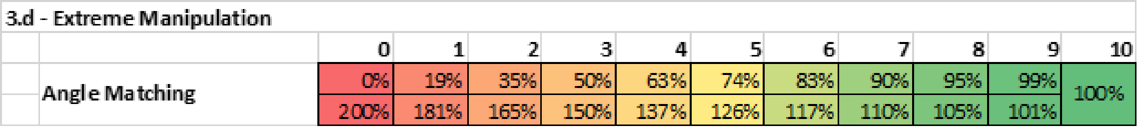
Figure 67: Oblique Force Application range of scores

4.2.2.3.4 Extreme Manipulation

Extreme manipulation tests the extreme angles achievable by powered motion. A non-actuated joint is not counted against the score. The tests measure the most extreme points achievable and compare them to the human-associated range of motion. An example of a high-scoring Exo would have the means to stay within the range of human motion to prevent injury.

The final score is the average of the results of test scores derived from the force used in the different tests. The scores is calculated as the force in newtons taken to provoke a response. Equation(s) follow:

$$score = \begin{cases} percent \leq 100\% & 10.2737 - 52.6316\sqrt{0.038103 - 0.038 * percent} \\ percent > 100\% & 10.2737 - 52.6316\sqrt{0.038 * percent - 0.037897} \end{cases}$$



3.d - Extreme Manipulation

	0	1	2	3	4	5	6	7	8	9	10
Angle Matching	0%	19%	35%	50%	63%	74%	83%	90%	95%	99%	100%
	200%	181%	165%	150%	137%	126%	117%	110%	105%	101%	

Figure 68: Extreme Manipulation range of scores

4.2.2.4 Movement Restriction

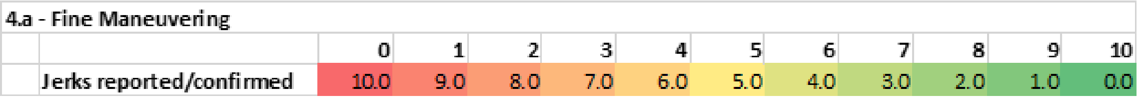
The ability of the Exo to move appropriately for the task.

4.2.2.4.1 Fine Manipulation

Fine Maneuvering is the ability to accurately and repeatably achieve a pose angle. This category is tested during all tests that the exoskeleton is worn. Scores are measured based on the Exo's reactions. For example, a low-scoring Exo jerks the user as they aim for slight movements within the normal operable range and are repeated throughout the test.

The final score is derived from the number of jerks reported and confirmed. Equation(s) follow:

$$score_{angle} = 10 - jerks$$



4.a - Fine Maneuvering

	0	1	2	3	4	5	6	7	8	9	10
Jerks reported/confirmed	10.0	9.0	8.0	7.0	6.0	5.0	4.0	3.0	2.0	1.0	0.0

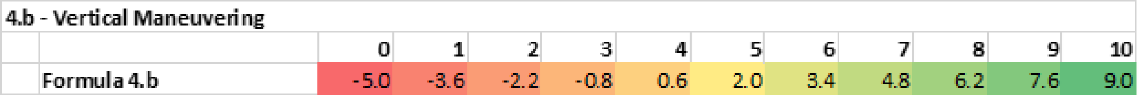
Figure 69: Fine Manipulation range of scores

4.2.2.4.2 Vertical Maneuvering

Vertical maneuvering is the ability to navigate inclines of lift loads for lower or upper body Exos, respectively. Observations for this category are conducted during the 1.c and 1.d series of tests. Measures are made using IMUs and user feedback. For example, a low-scoring Exo has IMUs indicating trouble in the assigned task or users reporting active resistance to the task.

The final score is derived from the percentage of matched motion from equipped vs unequipped motion and the Borg-10 average throughout the same exercise. Equation(s) follow:

$$score = PercentIMUMatch * 100 - \frac{Borg_{Avg}}{2}$$



4.b - Vertical Maneuvering

	0	1	2	3	4	5	6	7	8	9	10
Formula 4.b	-5.0	-3.6	-2.2	-0.8	0.6	2.0	3.4	4.8	6.2	7.6	9.0

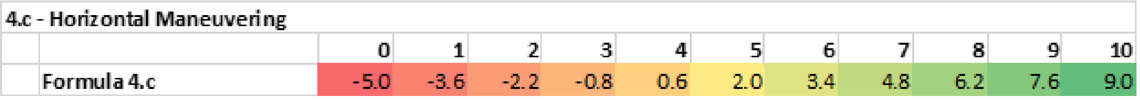
Figure 70: Vertical Maneuvering range of scores

4.2.2.4.3 Horizontal Maneuvering

Horizontal maneuvering is the ability to move forwards/backward or translate loads for lower or upper body Exos, respectively. Observations for this category are conducted during the 1.c and 1.d series of tests. Measures are made using IMUs and user feedback. For example, a low-scoring Exo has IMUs indicating trouble in the assigned task or users reporting active resistance to the task.

The final score is derived from the percentage of matched motion from equipped vs unequipped motion and the Borg-10 average throughout the same exercise. Equation(s) follow:

$$score = PercentIMUMatch * 100 - \frac{Borg_{Avg}}{2}$$



4.c - Horizontal Maneuvering

		0	1	2	3	4	5	6	7	8	9	10
	Formula 4.c	-5.0	-3.6	-2.2	-0.8	0.6	2.0	3.4	4.8	6.2	7.6	9.0

Figure 71: Horizontal Maneuvering range of scores

4.2.3 Space Consideration

Metrics related to the space required for the unit(s)

4.2.3.0.1 Portability

Portability is the ability to move the system from one site to another. Testing this category involves a full construction and deconstruction of the system. Factors considered are the tools, time, and transport required. An example low-scoring system requires a wide range of tools used over an extensive period (e.g.,$>$ 12 hours) and a large transport system.

The final score is derived from the use of heavy equipment, the number of unique tools required to complete a transport task, and the time to disassemble and assemble to palatable components (measured in hours). Equation(s) follow:

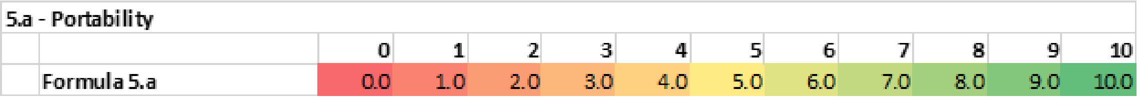
$$value_{HeavyEquipment} = \begin{cases} -5 & RequiredHeavyEquipment \geq 1 \\ 0 & RequiredHeavyEquipment < 1 \end{cases}$$

$$value_{tools} = \begin{cases} 10 - NumberTools & NumberTools > 0 \\ 0 & NumberTools = 0 \end{cases}$$

$$value_{time} = \begin{cases} time - 1 & time \geq 1 \\ 0 & time < 1 \end{cases}$$

$$\sum values = value_{HeavyEquipment} - value_{tools} - value_{time}$$

$$score = \begin{cases} \sum values & \sum values > 0 \\ 0 & \sum values \leq 0 \end{cases}$$



5.a - Portability

		0	1	2	3	4	5	6	7	8	9	10
	Formula 5.a	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0

Figure 72: Portability range of scores

4.2.3.0.2 Range of Use

This test is for powered exoskeletons only. Range of use is the Exo's ability to be used at a distance from a set location. For battery-operated/actuated exos, this location is the charging station. This location is the connection site for otherwise powered/actuated exos (e.g., hydraulic pump or power supply). An example low-scoring Exo requires a constant plugin to a non-movable object via a short supply line.

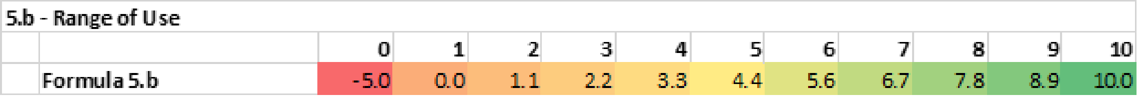
The final score is derived from the need for a constant “umbilical” attachment and the operable distance from a central node (measured in meters). Equation(s) follow:

$$value_{plug} = \begin{cases} -5 & umbilicalrequired = yes \\ 0 & umbilicalrequired = no \end{cases}$$

$$value_{range} = \frac{range - 6.096}{8.5344}$$

$$\sum values = value_{plug} + value_{range}$$

$$score = \begin{cases} \sum values & \sum values > 0 \\ 0 & \sum values \leq 0 \end{cases}$$



5.b - Range of Use

		0	1	2	3	4	5	6	7	8	9	10
	Formula 5.b	-5.0	0.0	1.1	2.2	3.3	4.4	5.6	6.7	7.8	8.9	10.0

Figure 73: Range of Use range of scores

4.2.3.0.3 Weight

Weight is the effective weight on the user. Weight is measured through force sensors placed between the user and the contact points with the robot. Data is collected during the 1.c and 1.d series of tests. An example of a low-scoring Exo is heavy (e.g.,>10 kg) and is not self-supporting.

4.2.4 Partnership Buy-In

The completed initial testing document was then sent to partners worldwide. Seeking stakeholder input was vital in not only closing blind spots but in getting buy-in. Partners were selected from industry and academia, at home and abroad. Partners in the industry at Lean Steps Consulting and GoX Labs helped identify everyday tasks personnel might be asked to complete and practical tests. Mr. Butler of Lean Steps Consulting has experience in implementing exoskeletons as PPE on an assembly line. The CEO of GoX Labs, Dr. Joseph Hitt, is also the Wearable Robotics Association (WearRA) executive director. WearRA is the worlds leading trade organization for wearable robotics, and their insight into the state of the industry and connections to key players is instrumental in wide adoption. Academia partners include Dr. Thomas Sugar of Arizona State University and Dr. Jason Gillette from Iowa State University. Both have designed and tested their exoskeletons and are well aware of current trends in the community. Finally, internationally are Dr. Urs Schneider, Dr. Urban Daub, and Ms. Verena Kopp from the Fraunhofer Institute in Stuttgart, Germany. Fraunhofer is globally recognized as a leader in researching exoskeletons and their effects on the human body. Additionally, their backing helps gain the trust of the European community, helping for adoption. After some back and forth with the partners, the initial design was finalized, thus clearing the way for human testing. Not mentioned as a partner are the two exoskeleton developers that provided their devices for initial testing. Their specific names have been anonymized to shield them from adverse results that may not yet be ready for publication.

4.2.5 Early Proof Of Concept Testing

Before entering live trials, dry runs were completed with researchers acting as subjects. Early on, issues with EMG/IMU adherence were identified. An early test for lifting sheared two abdominal sensors off, removing any chance at redundancy.

Athletic tape was applied over the devices to hold them in place to fix the shearing issue. This fix proved a helpful measure, and no further issues were encountered. Most of the other tests for both skeletons failed to show practical issues, but some tests and equipment needed to be adjusted before going live. The stairs task was stymied by a lack of reliable access to the testing center's stairwell. A small, 4-step flight of stairs was brought in for the tests, but a more traditional staircase should be used in future tests. The lifting tasks determined that varying the height that subjects needed to return containers introduced too many variables. Instead, subjects placed boxes at a table height, regardless of the height from which they were collected. Finally, early tests on the upper body testing rig showed that it was set at far too high a level. Early subjects were required to step on a stool to reach their required height setting, causing them to focus more on balance than on the task at hand. The bars holding the overhead components were adjusted, and subsequent tests worked well.

After all early adjustments were made, the participant testing began. These tests aimed at no less than eight healthy male and female participants. This number was selected to isolate any gender disparities while providing a pool large enough to give meaningful results. IRB protocols were approved by Argus IRB Inc. with testing conducted at the WearTech facility.

4.2.6 Initial Data Analysis

Upon completion of the tests, the collected data were run through post-processing algorithms. EMG and IMU data were smoothed using a Bandpass Filter, and baseline activities are normalized per individual. From each period, aberrant data +/- 3 SD from the mean is removed. The RMS per session was then determined and used in

Figure 74: Two subjects completing the lower and upper exoskeleton test. Transporting a load (left) was critical to the lower body tests. Tapping a sequence (right) for a set period made up the majority of upper body tests. Control tests are pictured here to maintain anonymity of exoskeletons tested.

future comparisons. Heart rate information was placed in a readable CSV format for later use. Finally, Borg scores were placed into a spreadsheet for processing.

4.2.6.0.1 EMG

After early post-processing, the data were ready to be evaluated. Results were imported on a per-subject basis using a MATLAB script. The script split the combined EMG/IMU data into separate files for an independent analysis. At this time, only EMG data has been thoroughly analyzed. After import, the script calculated the MVCs for each EMG device. Then, the last two seconds of work and usability data were truncated. Truncation was done to remove transitions from the end of the exercise. Finally, the data were compared with their respective MVCs and converted into percent MVC. The top 5 values were extracted and averaged for both the unequipped and equipped movements with properly conditioned data. The percent difference between the two was found and printed. This result was used for scoring.

4.2.6.0.2 HR/VO2

HR and VO2 processing were based on similar scripts. The initial CSV containing HR and VO2 at set time intervals was downloaded and imported on a per-user basis. The first five minutes were isolated, and the RHR was determined. This determination was possible since the HR collection only begun when the user was seated and ready to begin the collection. From there, the data were further split according to the time notation taken during testing. The times were verified against the timestep on the EMG data, which only started when testing began. After splitting, averages for each portion were taken and compared to the RHR to determine an effort percentage. Finally, the percent differences were found and output for scoring.

4.2.7 Initial Results/Reporting

Testing the developed protocols was conducted on one lower-body exoskeleton (Exo 1) and an upper-body exoskeleton (Exo 2) for two months. Tests were conducted at the WearTech facility using volunteers sourced from ASU, social media, and word of mouth. The five male and four female participants for Exo 1 had an average age of 23.1 (SD 4.91), height of 67.6“ (3.7”), and weight of 146.25 lbs (38.48 lbs). The five male and four female participants for Exo 2 had an average age of 25.1 (4.7), height of 68.1“ (3.9”), and weight of 155.4 lbs (41.4 lbs).

4.2.7.1 Lower Body Tests

The lower body exoskeleton was the first to start testing. Because of this, several issues were initially encountered that were not with the upper body testing. Primary among these is an issue with the EMG/IMU sensors. While reporting good connections in early testing, the devices initially used were not stress tested beyond 10 minutes. When applied to particpants, it was discovered that many of the devices did not hold an active charge longer than 20 minutes. For a 4-hour test, this was unacceptable and new devices needed to be sourced. After obtaining and testing new devices, scheduling began again.

Beyond the initial issues, the use of the EMG proved to be complicated. Following the testing procedure, after placing the devices, an MVC was taken to develop a ceiling for the muscle activated. The procedure to gather the MVC as designed initially failed to give quality results. Because of this, early participants were asked to complete various movements that would give better results. The updated movements became held V-Ups for the abdominals and lying back extensions for the lumbar.

The work tests themselves had issues with the irregular testing period, making direct comparisons difficult. The irregular periods were later used as a measure of productivity, but a more reliable time-scale would benefit the testing procedure as a whole. The burst of activity followed by lengthy breaks also made collection difficult and is an inaccurate representation of a workday. Future tests likely need to be longer and more controlled to provide more significant value. Regardless, the tests themselves provided an exciting insight into exoskeleton efficacy that other studies have not shown; primarily, the exoskeleton did not help in the extensive manner others observed. More analysis is needed to be completed to make a definitive statement, but early results are compelling.

4.2.7.2 Upper Body Tests

These tests benefitted mainly from being the second set of tests. Early issues with MVC were identified before live testing, and subjects were able to give significant results. There was, however, a change made to the placement of EMG based on a limitation of the EMG/IMU attendant software. One of the deltoid sensors was instead moved to the trapezius muscle. Changing the sensor location helped identify any issues in the “shrug“ motion required to lift arms overhead.

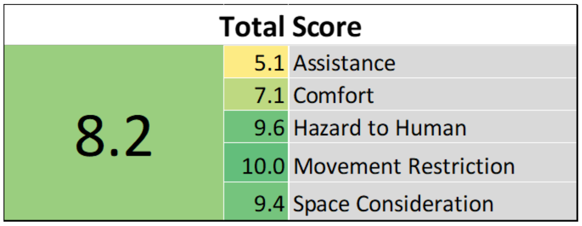
The tests themselves proved to be initially overwhelming for subjects but manageable with practice. Subsequent studies should allow for either a practice session to familiarize subjects or an extended overall test to negate the initial confusion. Once familiar, subjects proved to be more than capable of tapping out the required sequence while avoiding the obstacles. Using a keyboard also proved an effective means to measure productivity. Future tests should examine subjects’ foot placement, placing them in positions where a fully extended arm is necessary. While uncommon based on our research, it is a possibility and remains an intriguing study.

4.2.7.3 Usability Tests

The usability tests showed themselves to be an acceptable broad view of day-to-day tasks limited only by the limited-time nature of some tests. The tests conducted were unique for exoskeleton testing but provided a holistic view of how the devices impact users' everyday activities. It also provided subjects with a second glance at the device where they were more familiar with the device and attuned to its quirks. While jogging and walking tests were sufficient in time, the remaining were extremely short, with some not captured by the 30s-interval that the HR monitor operated on. Future tests should include more lengthy procedures of a similar type or be introduced to work tests to provide a more meaningful view into their effect.

4.2.7.4 Scoring Procedure

Following post-processing, the data collected was manipulated into a format that the scoring procedure could use. While the original document suggested an aggregated set of scores on an even playing field, the reality was a skewed system that favored some results. Coupled with issues in the data collection itself described above, the system showed itself not to be as robust as intended. However, as a first-of-its-kind test, it resulted in a valuable baseline to compare reconfiguration attempts. Below are the results of the tests with the scoring procedure applied.

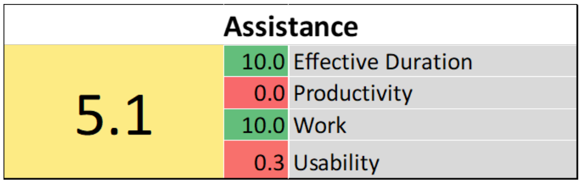


Total Score		
8.2	5.1	Assistance
	7.1	Comfort
	9.6	Hazard to Human
	10.0	Movement Restriction
	9.4	Space Consideration

Figure 75: Lower Total Score scores

4.2.7.4.1 Lower Body

Under the protocols tested, Exo 1 saw the clearest differences from other studies on the same device in the academic literature. Those tests often marked Exo 1 as high performing in their controlled tests, but ours highlighted clear procedural issues that could affect the device's adoption. High scores in the final three categories helped it score higher, but some assistance issues were tested under our protocol.

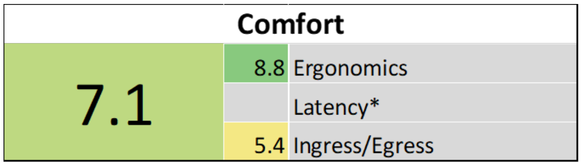


Assistance		
5.1	10.0	Effective Duration
	0.0	Productivity
	10.0	Work
	0.3	Usability

Figure 76: Lower Assistance scores

4.2.7.4.1.1 Assistance

Effective duration of Exo 1 was given a full 10 out of 10 as it is a passive system. Work was also given a full 10 of 10 in part for high EMG scores to calculate the score. Productivity saw a score of 0, where only 2 of the nine tested saw an improvement in the time taken to complete their tasks. Usability also scored low, with all components (EMG, IMU, HR, VO2, and Borg) showing worse performance in the related tasks.

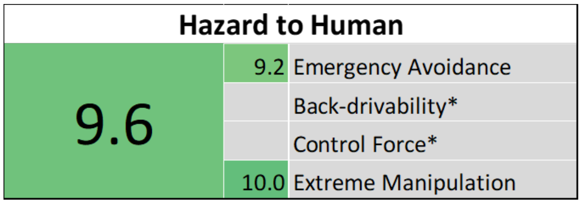


Comfort		
7.1	8.8	Ergonomics
		Latency*
	5.4	Ingress/Egress

Figure 77: Lower Comfort scores

4.2.7.4.1.2 Comfort

Ergonomics was the highest scoring component in the comfort category. Largely the device was found to stay stationary when properly fit. Ingress/Egress suffered not for time, where it scored well, but for Borg. In that category, some users found the device to be difficult or cumbersome to put on.



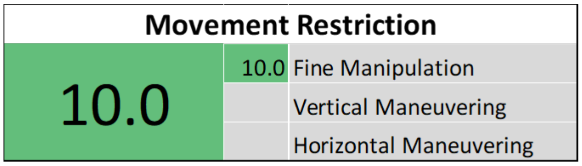
Hazard to Human		
9.6	9.2	Emergency Avoidance
		Back-drivability*
		Control Force*
	10.0	Extreme Manipulation

Figure 78: Lower Hazard To Human scores

4.2.7.4.1.3 Hazard to Human

Hazard to human scored well with only two components measured. Back-drivability and control forces were not measured in these tests as Exo 1 is unpowered. Users did well in emergency avoidance tasks, with reactions largely related to user vs. Exo 1.

Extreme manipulation also scored well, with Exo 1 placing the subject in no damaging positions.

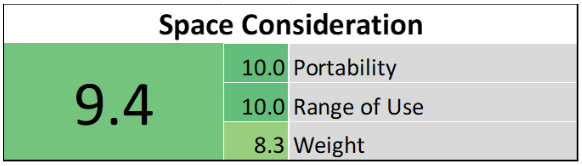


Movement Restriction		
10.0	10.0	Fine Manipulation
		Vertical Maneuvering
		Horizontal Maneuvering

Figure 79: Lower Movement Restriction scores

4.2.7.4.1.4 Movement Restriction

Movement restriction scored a perfect 10 with only 1 category measured. Vertical and horizontal maneuvering were not measured due to issues with IMU measurement and analysis. Fine manipulation saw no issues as subjects reported no undue motion in their work.

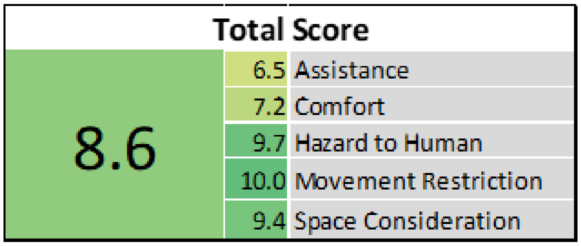


Space Consideration		
9.4	10.0	Portability
	10.0	Range of Use
	8.3	Weight

Figure 80: Lower Space Consideration scores

4.2.7.4.1.5 Space Consideration

Space consideration scored highly in all three categories. Exo 1 was highly portable with all components contained to a 1m x .3m x .25m container. Exo 1 also had an infinite range of use with no power requirements. The weight on the user was non-negligible, but the device's center of gravity was held close to the center of gravity of the subjects.

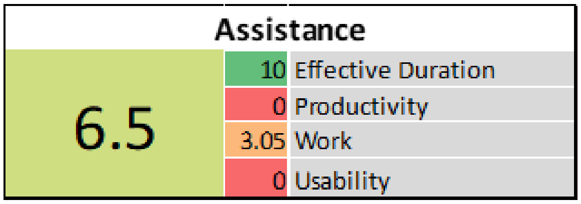


Total Score		
8.6	6.5	Assistance
	7.2	Comfort
	9.7	Hazard to Human
	10.0	Movement Restriction
	9.4	Space Consideration

Figure 81: Upper Total scores

4.2.7.4.2 Upper Body

Under the protocols tested, Exo 2 saw slight differences from other studies on the same device in the academic literature. These studies showed a device that reduced metabolic costs, and our tests showed a more nuanced result. High scores in the final three categories helped it score higher, but there were some issues with assistance and comfort when tested under our protocol.

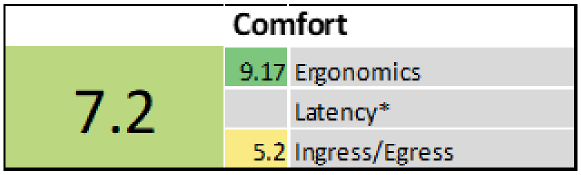


Assistance		
6.5	10	Effective Duration
	0	Productivity
	3.05	Work
	0	Usability

Figure 82: Upper Assistance scores

4.2.7.4.2.1 Assistance

Effective duration of Exo 2 was given a full 10 out of 10 as it is a passive system. Productivity saw a score of 0, where only 1 of the seven tested saw an improvement in their tasks' execution. Work scored low but above 0, indicating some overall assistance in work tasks. Usability also scored low, with all components (EMG, IMU, HR, VO2, and Borg) showing worse performance in the associated tasks.

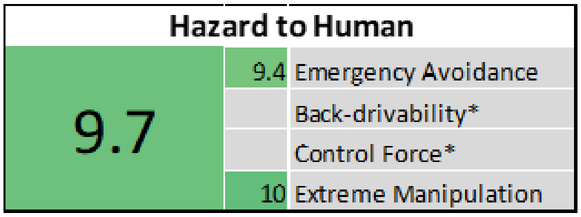


Comfort		
7.2	9.17	Ergonomics
		Latency*
	5.2	Ingress/Egress

Figure 83: Upper Comfort scores

4.2.7.4.2.2 Comfort

Ergonomics was the highest scoring component in the comfort category. Largely the device was found to stay within 1 cm when properly fit. Like Exo 1, Ingress/Egress suffered in Borg scores. Some users found the device hard to deactivate and difficult or cumbersome to put on in that category. After fitting, the average time to don the exoskeleton was 1.5 minutes.

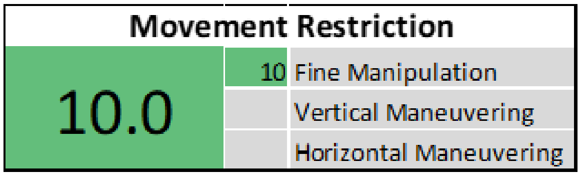


Hazard to Human		
9.7	9.4	Emergency Avoidance
		Back-drivability*
		Control Force*
	10	Extreme Manipulation

Figure 84: Upper Hazard to Human scores

4.2.7.4.2.3 Hazard to Human

Hazard to human scored well with only two components measured. Back-drivability and control forces were not measured in these tests as Exo 2 is unpowered. Users did well in emergency avoidance tasks, with reactions largely related to user vs. complications with Exo 2. Extreme manipulation also scored well, with Exo 2 forcibly placing the subject in no damaging positions

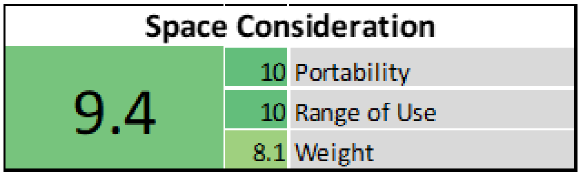


Movement Restriction		
10.0	10	Fine Manipulation
		Vertical Maneuvering
		Horizontal Maneuvering

Figure 85: Upper Movement Restriction scores

4.2.7.4.2.4 Movement Restriction

Movement restriction scored a perfect 10 with only 1 category measured. Vertical and horizontal maneuvering were not measured due to issues with IMU measurement and analysis. Fine manipulation saw no issues as subjects reported no exacerbating motion in their work.



Space Consideration		
9.4	10	Portability
	10	Range of Use
	8.1	Weight

Figure 86: Upper Space Consideration scores

4.2.7.4.2.5 Space Consideration

Space consideration scored highly in all three categories. Exo 2 was found to be highly portable with all components contained to a 1m x .5m x .25m container. Exo 2 also had an infinite range of use with no power requirements. The weight on the user was non-negligible, but the center of gravity of the device was held close to the center of gravity of the subjects.

4.2.8 Recommendations

There are several changes to the protocol that need to be implemented to create a more robust system. The first is changing the tests themselves to flow into each other more fluidly. This benefit was seen in the upper body tests, where rest and work periods were all in the same data capture, allowing for more straightforward data analysis later. It also limited rest time resulting in more meaningful results. Future tests should follow the same but longer structure. These would include triggers to automatically mark points in time for even more helpful data processing automation.

The test itself for both arrangements also needs to change. For the lower body, this is recommended to be a more typical, dynamic warehouse situation. Here, workers would interact with a standing rack and remove boxes, placing them on another rack on a set shelf some distance away. This updated method would allow for an extended-form test and repeatability that makes valid comparisons readily available. For the upper body, extending the time spent doing one activity is recommended. Doing so would allow for more meaningful results while pushing the subject closer to a fatigued state. It would also enhance simplicity in the test, removing artifacts of confusion from the results. Both tests would undergo similar usability measures as an orientation. This orientation would be short but allow users to get familiar with the device before beginning tests in earnest.

There are also changes in hardware and software that need to be made in future iterations. The first is utilizing better EMGs that are more reliable, less invasive, and more customizable. Upgraded devices would allow for better placement of devices, generating more meaningful data overall. It would also allow flexibility around exoskeletons of different types as each anchors its hardware in different locations. The addition of motion capture technology would also assist in better analysis. With this technology, a pipeline could highlight points of stress and isolate anomalies in the subject. It also unlocks the ability to place markers on the exoskeleton itself, creating a unique method of tracking the device as it goes through motions and identifying problematic motions. Finally, a battery of load cells would help identify the effects of the exoskeleton on the human at anchor points. Such devices would highlight shifts in the device that could cause safety or health issues down the line. It also is necessary for testing powered devices and identifying musculoskeletal hazards.

4.3 Work to be done

The final report on this project has been submitted to stakeholders, though there remains work to close the project altogether. Without creating a new testing facility, this includes a more thorough analysis of the collected data. First, a re-evaluation of the script code should be completed to streamline analysis. Streamlining would include better data storage, efficient function calls, and automatic output in a friendly format. Second, the IMU data needs to be evaluated and run through the scoring procedure. This was not done for the submitted report given time constraints and issues with the EMGs' software. Analysis of the IMU data would closely follow the EMG analysis process but requires several alterations to handle the IMU's 3-degree nature. Finally, several ANOVA analyses need to be conducted to highlight any factors that might have an undue influence on the test. Factors include sex, testing order, height, weight, and age. It is hypothesized that testing order affects the testing results and requires an alteration of the scoring parameter to reflect as much.

Chapter 5

CONCLUSION

This dissertation covers creating and evaluating an APEx for the USAF and complimentary research to create a set of standards to be used by the exoskeleton community. USAF aerial porters are currently left to complete back-breaking labor, which is rapidly damaging their available workforce. Other exoskeletons are potentially available, passive, and active, but none explicitly created for the aerial porter community. The device created is lightweight, robust device focused on pushing and lifting. To date, Alpha and Beta prototypes have been created and tested with a final goal of delivery of 6 devices to the USAF. Testing of this exoskeleton revealed a peak metabolic savings of 8.13%. Regarding standards, a proposed testing procedure has been presented. The proposal covers the initial concept, a review of the body of work, and finalized testing methods.

Overall, in completing this dissertation, multiple guidelines were discovered for future exoskeleton design. These are universally applicable. Some are basic, such as a need to minimally hinder movement, be lightweight, and be easy to interact with in don/doff/operation. However, others require more intent, such as designing compliance at interaction points for less wear on the user. Remaining stable on the user is also a must. Perhaps the most important is a reliable device. One can surmise that the APEx was successful because it stayed where it was initially fit, and it acted the same way every time. Once users understood how it would react in different situations, it became a second-nature device, allowing them to focus on the task at hand. Everyone tested developed their style of using the device that, while similar, allowed the robot and user to move as one. An unpredictable device will likely never reach the required level of comfort to gain wide adoption.

Moving forward, the APEx will need to be further refined and tested. These include potential upgrades to the ARA systems, a streamlined fitting method, and quality of life adjustments. There is also potential for quasi-active and entirely passive designs that could assist at a reduced price point. Finally, testing for the efficacy of the device in pushing activities should be completed. Successful completion could create a baseline for future improvements.

Future work on the standards project will involve more robust data analysis. As it stands, the software and scripting used to evaluate the data are clunky and time-consuming. A streamlined system will make the process faster for future tests; it will also highlight any issues with calculations that might have been missed in the initial scripting. There is also a large amount of data that has been unprocessed for the IMUs. While time-consuming, the resultant data could reveal issues that the other tests missed. Finally, after all the primary analysis is complete, several ANOVA analyses must be completed to identify any causes of skewed data. An updated test overall will also be needed to allow for a broader range of testing devices with their limitations.

5.1 Contributions

Contributions to this project included but are not limited to the following:

5.1.0.0.1 Designed a robot that did not have any hindrance when walking, running, jogging, and crawling

Where most robots choose to assist in a majority of motions, we chose to limit interaction to one direction of the sagittal plane. By limiting in this way, we were able to create a wholly disengaged robot from the user's path until necessary. Further, in a power loss situation, the hardware would allow for recovery and resumption of day-to-day activity. This exact situation was tested live in the field when a crimped wire caused such a situation. The right paddle was limited in motion because of where the pushing block was located at the time of power loss. By applying slightly greater force on the paddle, the block was slid back, and the remainder of the event was unremarkable.

5.1.0.0.2 Designed a novel back brace

A patent-pending back brace was created to comfortably lock onto the user without resting on the lower back. By resting on the hips, the APEx avoids the pitfall common with most back braces where the heat center in the lower back is smothered, causing the wearer to overheat and become uncomfortable.

5.1.0.0.3 Designed a record-setting device

At 8 lbs and 30 N-m of torsional force about each hip, the APEx is lighter and more powerful than most commercially available devices.

5.1.0.0.4 Designed a pushing focused robot

A review of the literature showed an apparent lack of robots designed to help in pushing tasks specifically. Work is in progress now to test subjects and measure the efficacy of this device designed for pushing.

5.1.0.0.5 Designed a lifting-focused robot that allowed for walking while transporting a load

Commercially available exoskeletons typically only help in the lift motion itself. The follow on moving to another location with the load is largely ignored, including in testing, and the user may suffer for it. By designing a low-profile robot and limiting accessories to the sides of the user instead of the front, we prioritize object transportation.

5.1.0.0.6 Developed, analyzed, and expanded a CoG control model

To accompany the unique push-only nature of the APEx, a CoG model was created. An initial constant value was used, but follow-on work was done to create a more refined model that combined real-world captures with in-lab assumptions leading to an overall more accurate method.

5.1.0.0.7 Developed test methods for upper and lower body exoskeletons

In order to create a more cohesive environment where direct comparisons are available, a draft set of tests and scoring algorithms were created. While other entities are attempting such a comparison, it does not appear that they have been actively tested.

5.1.0.0.8 Performed an eight-week real-world test

In a University first, we tested 4 APEx devices in the field at an active Air Force base daily for eight weeks. The devices could withstand the rigors of the demanding aerial porter environment and performed flawlessly at two high-profile events. Over 25 individuals were fitted with the devices, and they were also used in mission-critical activities.

NOTES

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APPENDIX A

CLIN 002 DOCUMENTS

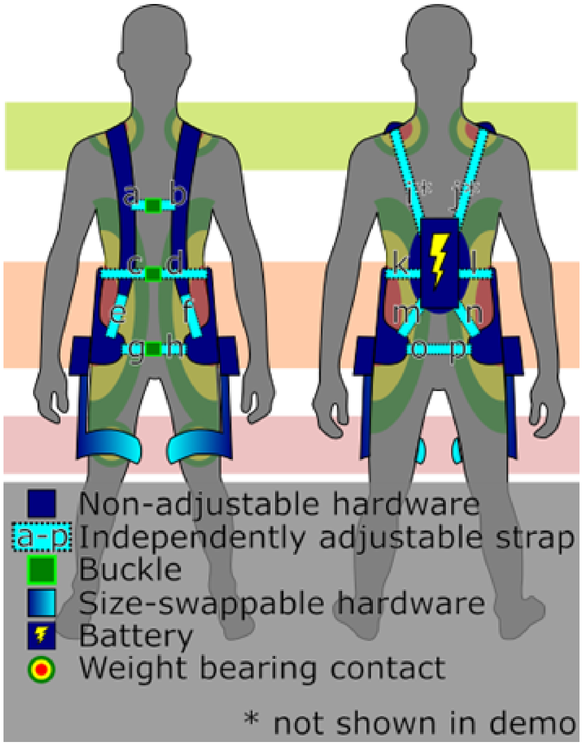
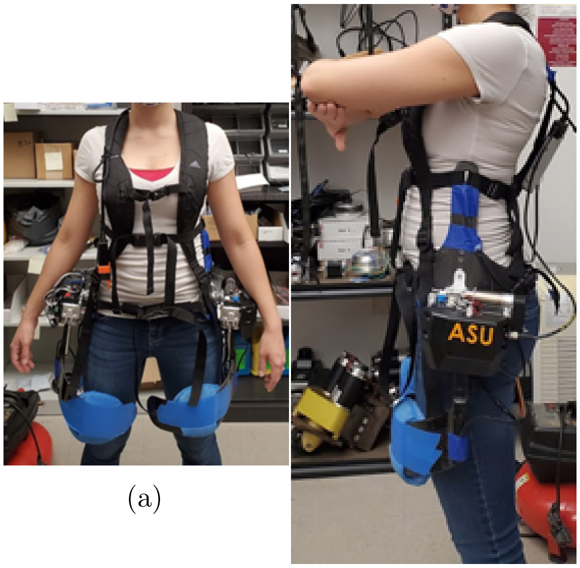


Figure 87: The APEX's effects on a user. Shaded bands indicate weight bearing regions. 'Targets' indicate contact points. See the legend for further detals.



(a)

(b)

Figure 88: Placement of EMG/IMU devices for the lower and upper body.

Strapping			**Hardware**	
Fig 3 Reference	**Minimum**	**Maximum**	**Name**	**Length**
a	2”	11.5”	Backpack Strap	20”
b	1.5”		Hip	8”
c, d	3”	14.5”		
e, f	1.5”	14”		
g, h	2”	16.5”		
i, j	12”			
k, l	2”	11”		
m, n	5”			
o, p	5”	13”		

Table 14: Measurement chart for APEX Alpha. Beta will include adjustable sections for i, j, m, and n for maximum fit and comfort. Note: ■Hip■ measurement refers to length of section in contact with user and effecting circumference of fit.

A.1 CLIN 002 Testing Photographs

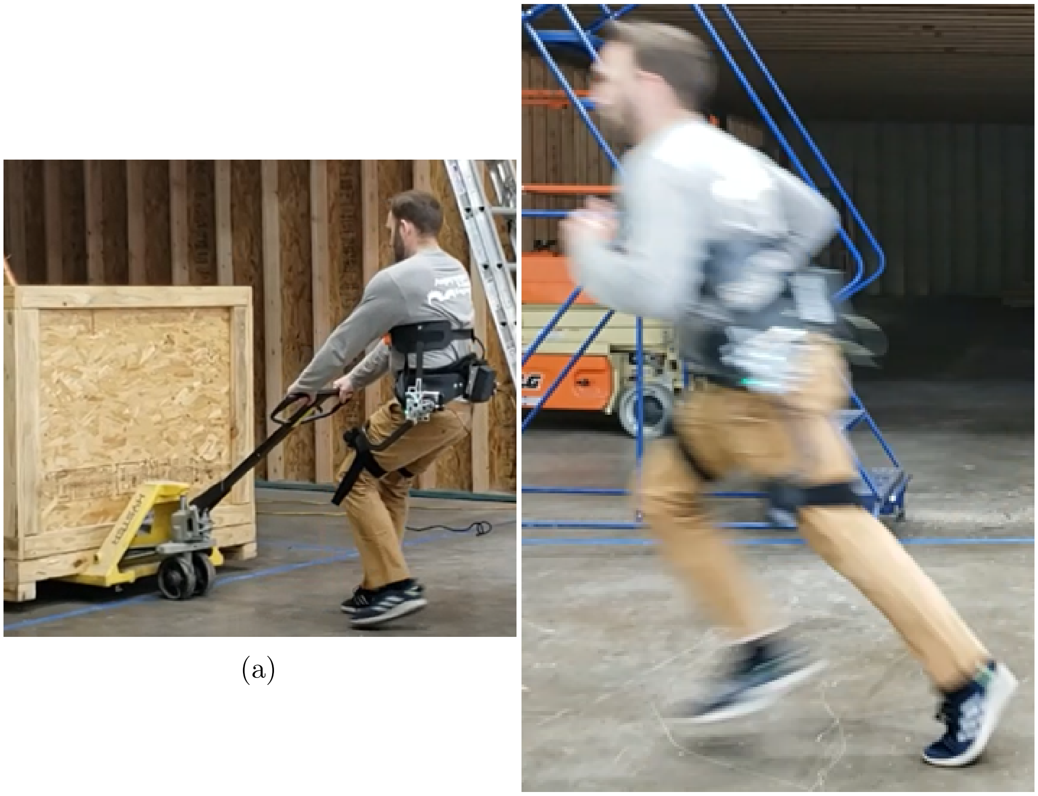
A.1.1 Active Mode Tests

(a)

(b)

Figure 89: (a) Lifting while powered on. (b) Stair climbing/descending while powered on.

Figure 90: Pushing while powered on.

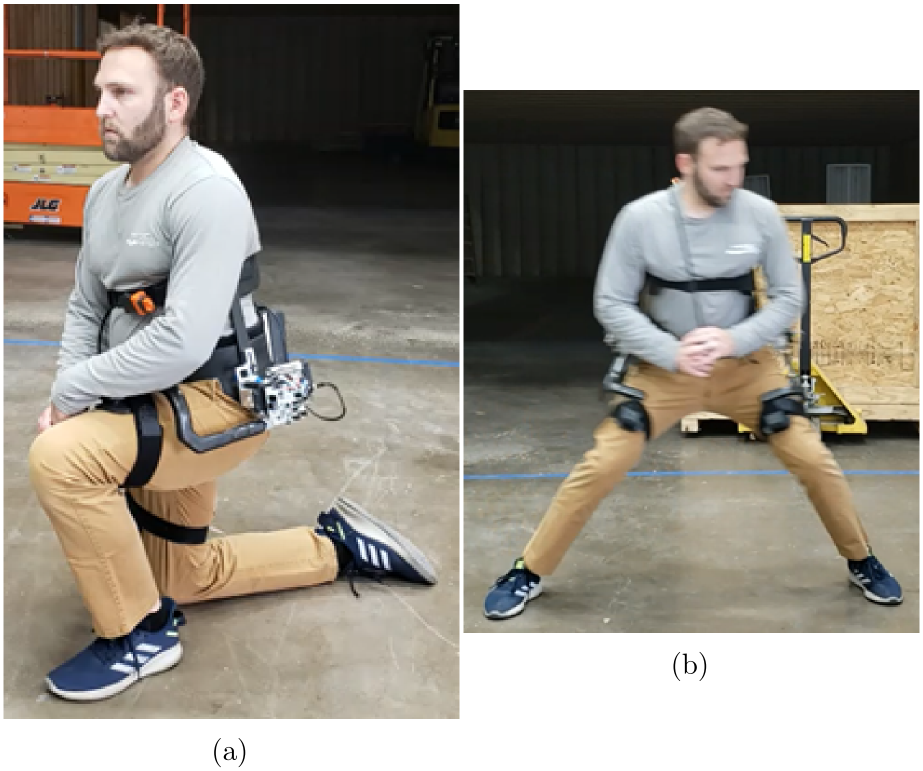


(a)

(b)

Figure 91: (a) Pulling a pallet loader while powered on. (b) Running while powered on.

A.1.2 Passive Mode Tests


(a)

(b)

Figure 92: (a) Kneeling while powered off. (b) Wide-stepping while powered off.

(a) (b) (c)

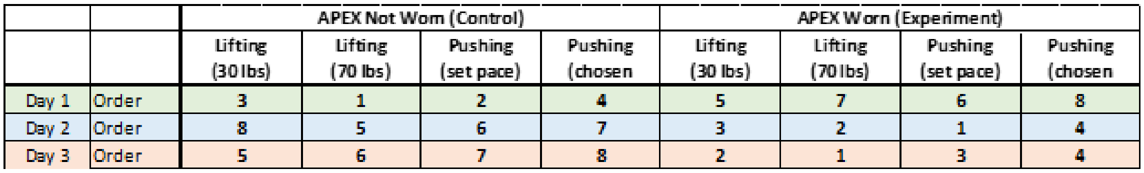
Figure 93: (a) Cross stepping while powered off. (b) Hip-flexor rotations while powered off. (c) Crawling while powered off.

A.2 CLIN 002 Testing Plan

APEX Testing Plan

- All tests will be conducted with the APEX worn and not worn to test APEX effectiveness
- All tests will be conducted multiple times in a randomly selected order
- All tests will have rest times between all exercises to decrease effect of fatigue
- All results will be baselined to the individual users
- Lifting
  - Users will start standing in front of a weighted container (30 lbs or 70 lbs)
  - On “go”, users will pickup container and place it 20 feet away
  - Users will then return to the starting position. This is one set
  - Sets will be conducted 50 times over a period of 15 minutes
- Pushing
  - Users will start standing in front of a loaded pushcart (500 lbs)

  - On “go”, users will push the cart 100 m (109 yards)
  - Users will push at a set pace (1 m/s) and chosen pace



		APEX Not Worn (Control)				APEX Worn (Experiment)			
		Lifting (30 lbs)	Lifting (70 lbs)	Pushing (set pace)	Pushing (chosen	Lifting (30 lbs)	Lifting (70 lbs)	Pushing (set pace)	Pushing (chosen
Day 1	Order	3	1	2	4	5	7	6	8
Day 2	Order	8	5	6	7	3	2	1	4
Day 3	Order	5	6	7	8	2	1	3	4

Figure 94: An example testing schedule with randomized order

- Torque
  - The APEX will be attached to a rigid structure
  - The APEX will actuate into a load cell at the thigh pad, measuring torque
- Walking
  - This test will be independent of the above testing schedule
  - This test will be conducted a maximum of 1 time per user
  - Users will walk 20 minutes on a level surface while wearing the APEX
  - Users will indicate verbally when the APEX actuates over the testing period

A.3 CLIN 002 Testing Equipment

Figure 95: Testing equipment used for pushing. Five hundred pounds loaded on a cart. Future iteration will include a vertical wall for pushing against, as well as a containment system to contain errant weight material.

Figure 96: Container used for lifting tests. Stabilized weights will be placed inside IAW testing procedure.

Figure 97: GoX Ergo Kit used in VO2 and HR measurement. This is a similar device to what was used to test Airmen at Travis AFB in late 2019.

APPENDIX B

CLIN 003 DOCUMENTS

B.1 CLIN 003 Test Results

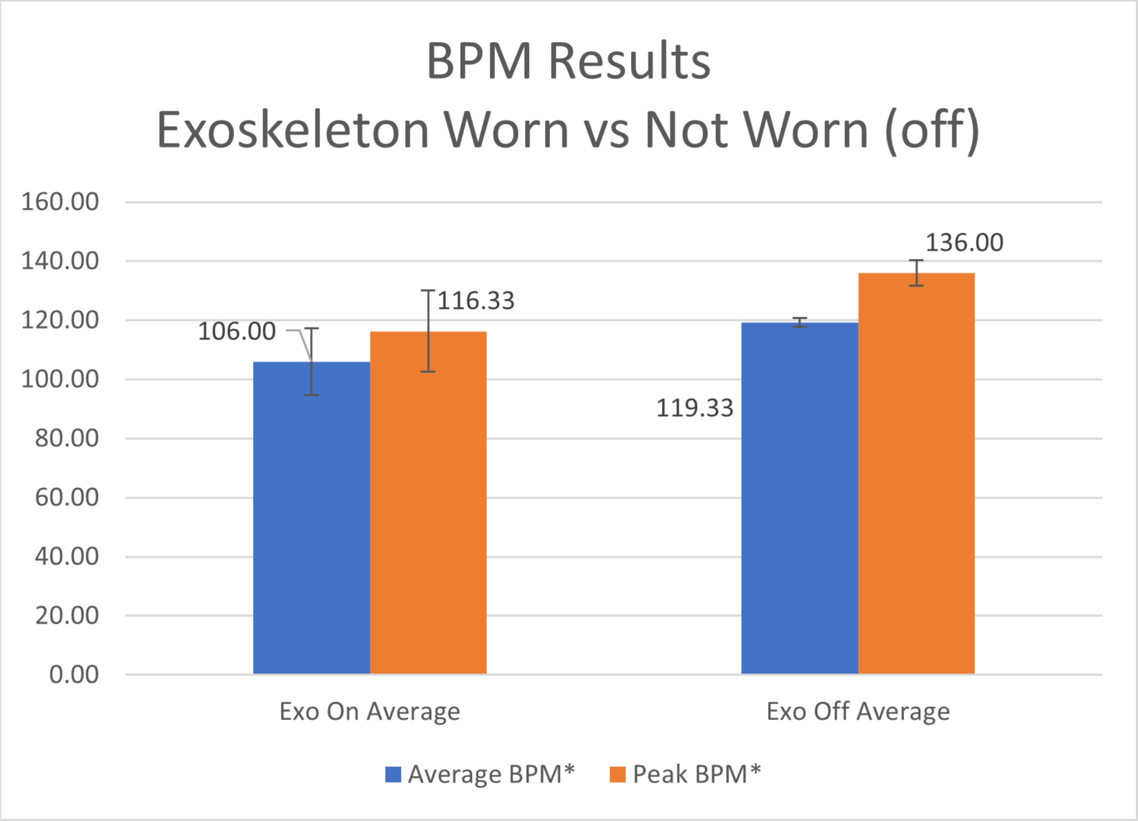


Figure 98: BPM results of tests

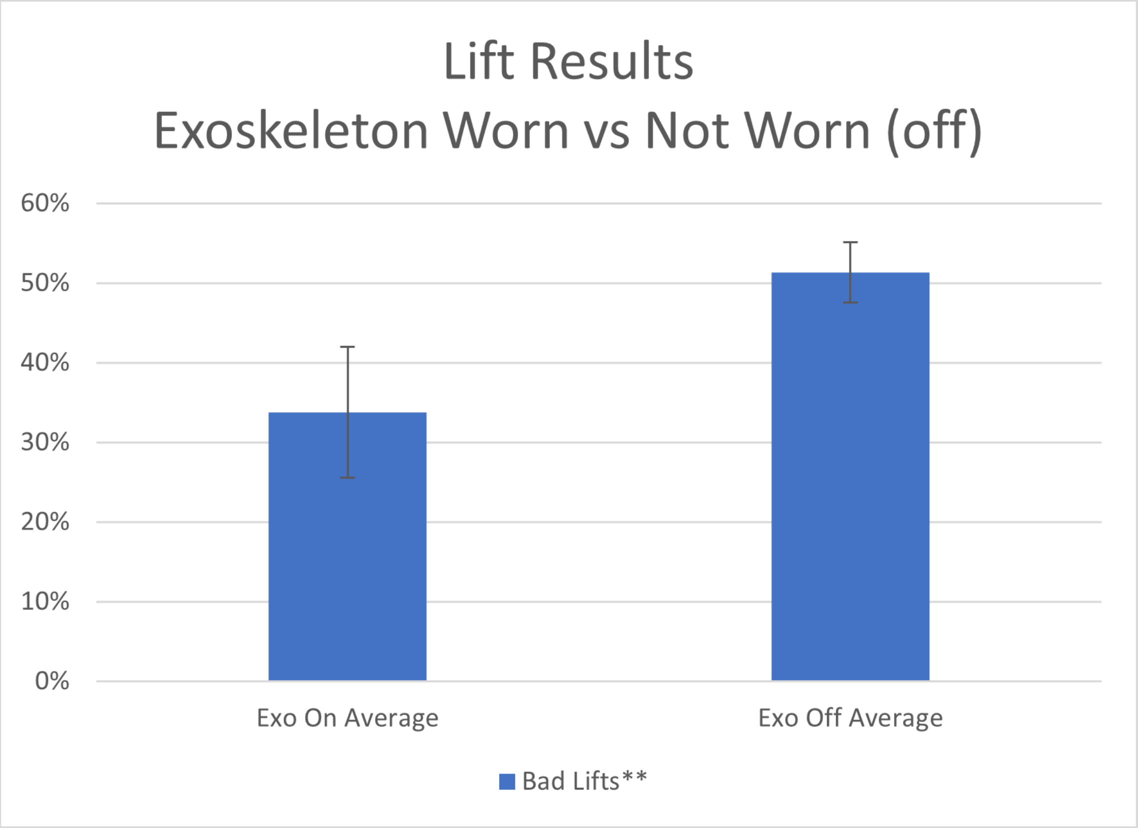
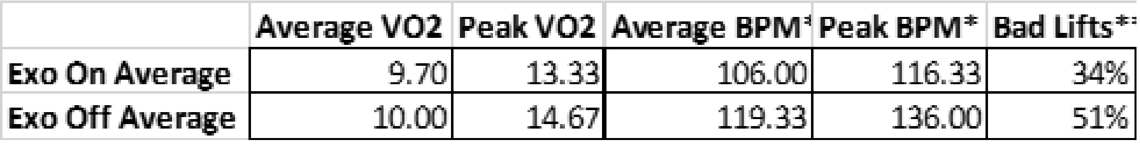


Figure 99: Lift results of tests

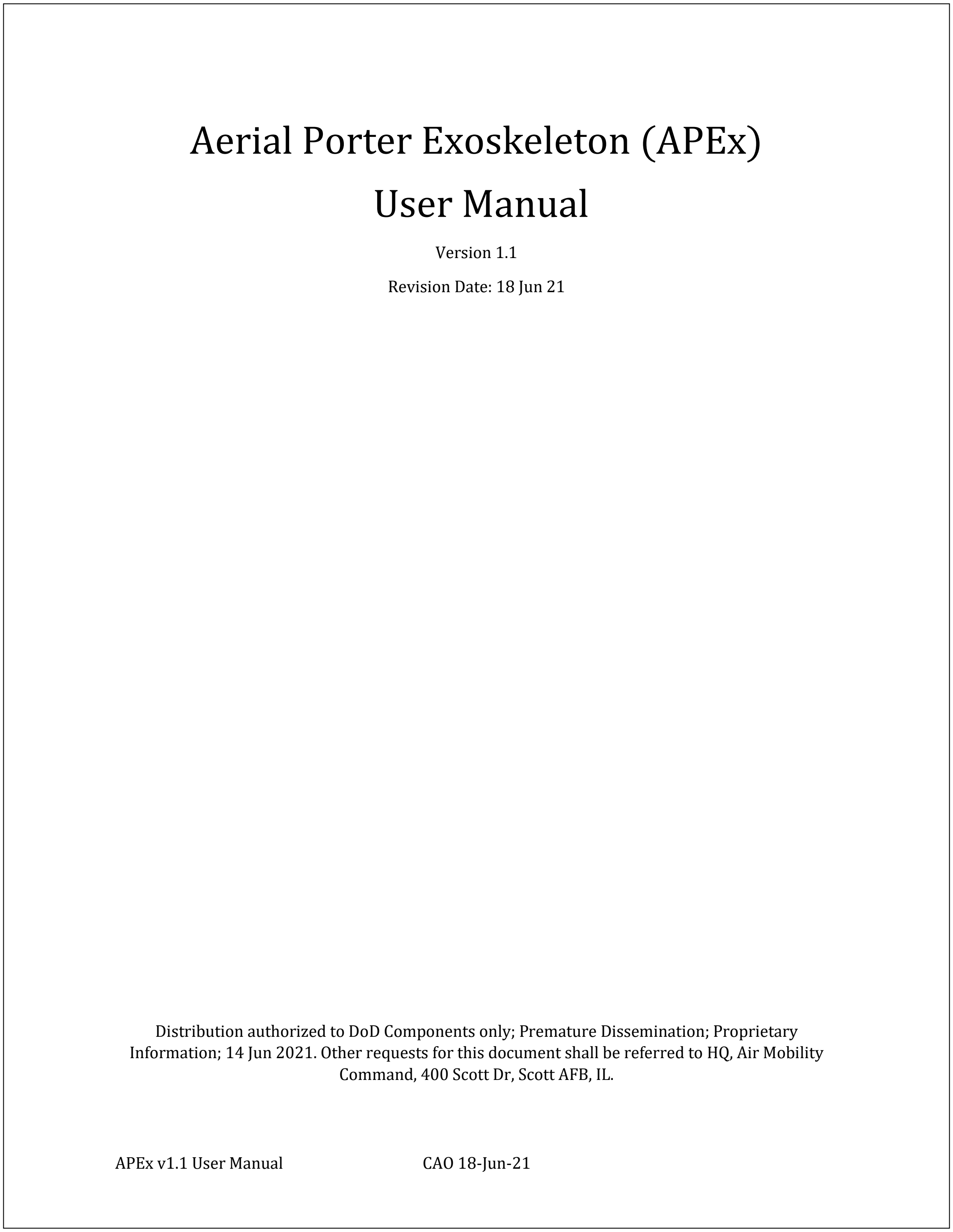


	Average VO2	Peak VO2	Average BPM	Peak BPM*	Bad Lifts*
Exo On Average	9.70	13.33	106.00	116.33	34%
Exo Off Average	10.00	14.67	119.33	136.00	51%

Figure 100: Quantitative results of tests

APPENDIX C

CLIN 004: USER MANUAL



Aerial Porter Exoskeleton (APEx) User Manual

Version 1.1

Revision Date: 18 Jun 21

Distribution authorized to DoD Components only; Premature Dissemination; Proprietary Information; 14 Jun 2021. Other requests for this document shall be referred to HQ, Air Mobility Command, 400 Scott Dr, Scott AFB, IL.

Overview

The Aerial Porter Exoskeleton APEx is designed for assistance with lifting and pushing activities. It works by anchoring at the hips and pressing the upper thigh through the standing motion, applying up to 30 N-m of assistive torque about the hip joint per leg. The APEx has a secondary function of bracing the lower back to encourage proper lifting, decreasing the risk for future back pain.

This device is made to fit a wide variety of sizes and provide a user-selected amount of assistance. When not in use, the device's actuating mechanism remains out of the way, allowing for freedom of motion without the need to remove the device. Finally, it features some level of activity recognition, enabling it to activate *only* when a squat or push is detected. For safety purposes, if the device is unsure of the movement, it does not activate.

Recommended use cases

It is recommended that this device is used in pushing and lifting activities. Lifts are assisted only if the user is completing a proper lift to incentivize good form and injury mitigation. The device works by helping to rotate the hip joint, and activities that do not involve this movement do not see a benefit. When not completing these activities, the device is to be in power off or inactive condition or removed entirely.

Disclaimer

While this device is designed to minimize injury to the greatest extent possible, the chance for injury exists. Improper handling of the battery pack (sudden hard impact, puncture, excessive heat, etc.) may cause injury through combustion reactions. Please visit www.osha.gov[1] for more information. Additional hazards exist within the device; the casing should not be removed. There should also not be any debris or items placed into the device before, during, or after operation.

This device is not to be used while operating machinery.

This device is not to be used in rain or wet environments.

This device is not to be used near live munitions.

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[1] https://www.osha.gov/dts/shib/shib011819.html

Contents

Wear of System

This section reviews the proper wear, adjusting, and storage of the APEx. To check which device arrangement is correct for the user, refer to the sizing chart (table 1) below. **NOTE:** This device is only to be used for pushing and squat lifting activities. During other activities, the device should be powered off, adjusted to inactive mode, or removed.

Donning

To prepare the APEx for wear, remove the battery from the charging deck. Place it in the left or right pocket with the wire at the upper rear. Then, connect the plug to the nearest actuation mechanism in the associated plug. Next, place the torque control device in the remaining pocket with the wire facing the upper rear. Then, connect the plug to the nearest actuation mechanism in the associated plug. Ensure a connection is made between the two actuation devices with the connection wire running across the rear. Finally, ensure all plugs have a solid connection by twisting the plugs to a locked position.

To don the APEx, open the vest and place arms through the holes. Then, holding the hip actuators, maneuver the braces onto the hip bone. To ensure good placement, practice one or two squats while holding the device in place. A proper fit results in minimal movement during these activities. Next, cinch the device down using straps 3 and 4 in the front and 5 and 6 in the rear. The straps should encourage a slight forward lean of braces, evidenced by the stem leaning toward the front of the user. In addition, the device should not move when struck. Next, adjust shoulder straps 1 and 2 to ensure a proper vertical fit.

A good fit prevents the device from slipping down throughout the day but should not cause shoulder discomfort. After the vest is secure, ensure the thigh paddles are placed on top of the thigh, and the actuators are forward-facing.

Strap adjustments

There are several points of adjustment on the APEx. Starting from the front are the upper (A) and lower (D) front hip buckles and the left (B) and right (C) shoulder buckles. From the rear are the lower hip buckles (I-J), the left and right upper hip buckles (E-F), and the left (H) and right (G) vertical hip straps. The chart below indicates their positions and purposes.

There are two different types of strap adjustment mechanisms. The first is a standard slide buckle (used in A, B, C, D, E, G, H, & I) and can be tightened by pulling the strap. The second buckle, figure 2, is for fine adjustments (used at F & J). It can be adjusted by turning the handle to tighten the wiring. To release, press the red button. This second mechanism should only be used after the larger macro adjustments have been made.

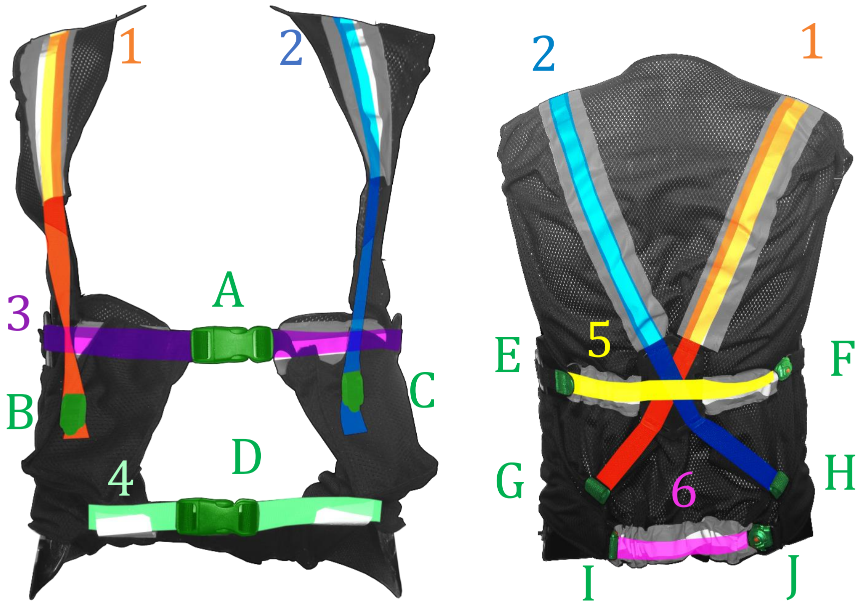


Figure 1: (Left) Front view of the APEx. (Right) Rear view of the APEx. Green labels A-J indicate adjustable points. Numbers 1-6 indicate straps.

	Medium		Large	
Strap	**Minimum**	**Maximum**	**Minimum**	**Maximum**
1			39”	58”
2			39”	58”
3			13”	44”
4			8”	48”
5			12”	33”
6			7”	33”
Waist (3 & 5)			24”	81”
Hips (4 & 6)			33"	99"

Table 1: Sizing range of the APEx color-coded to match Figure 1.

Figure 2: A micro-adjustment mechanism. This mechanism allows for 3" of adjustment.

Doffing

Storage

To properly store the APEx, first remove the battery from the vest. Then, place the device on a hangar and store it in a hanging position. Ensure the thigh paddles are hanging down and the elastic is not in an extended position. Finally, plug the battery into the charging deck.

Basic Operation

Pre-flight check

After donning the APEx, review the device has a proper fit.

1. Lift the left leg and ensure the pad doesn't slide along the leg but sits on the same spot throughout the motion
2. Verify that the pad is held against the leg while moving the leg
3. Verify the connections are tight and secure *at the pad/actuator attach point*
4. Check the cable connection on the back of the left actuator to ensure a tight and secure fit with the plugs
5. Check the pins connecting the actuator to the left hip stabilizer for a complete hinged connection
6. Check that the left hip stabilizer is vertical, running up the side of the wearer
7. Check the two buckles at the midsection for a tight fit
8. Move to check the shoulder straps, lower back, and mid-back
9. Check that the right hip stabilizer is vertical, running up the side of the wearer
10. Check the pins connecting the actuator to the right hip stabilizer for a complete hinged connection
11. Check the cable connection on the back of the right actuator to ensure a tight and secure fit with the plugs
12. Verify the connections are tight and secure *at the pad/actuator attach point*
13. Lift the right leg and ensure the pad doesn't slide along the leg but sits on the same spot throughout the motion

14. Verify that the pad is held against the leg while moving the leg

Turning on

To turn on the APEx, stand up straight and toggle the I/O switch on the top of the battery pack. Next, verify that power is being applied by checking for lights on the torque control box. Once the torque control box has a green and flashing yellow light, the wearer can move.

Torque control/codes

The torque control dial is capable of selecting between 2 different levels: Off and On. To activate torque assistance, rotate the knob fully clockwise. To remove the torque, rotate the knob fully anti-clockwise.

Use

The APEx makes use of an activity recognition algorithm and center of gravity model. If the body is in a position to activate (knees bent, body weight in front of the heels), it activates. If this is a first-time wear, practice different movements to get used to the device. **NOTE:** This device is only to be used for pushing and squat lifting activities. During other activities, the device should be powered off, adjusted to inactive mode (dial adjusted fully anti-clockwise), or removed.

Battery Care and Replacement

Custom Batteries

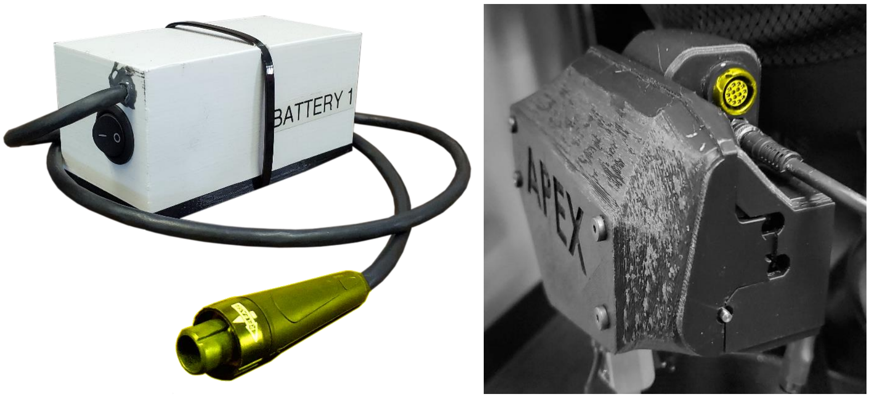
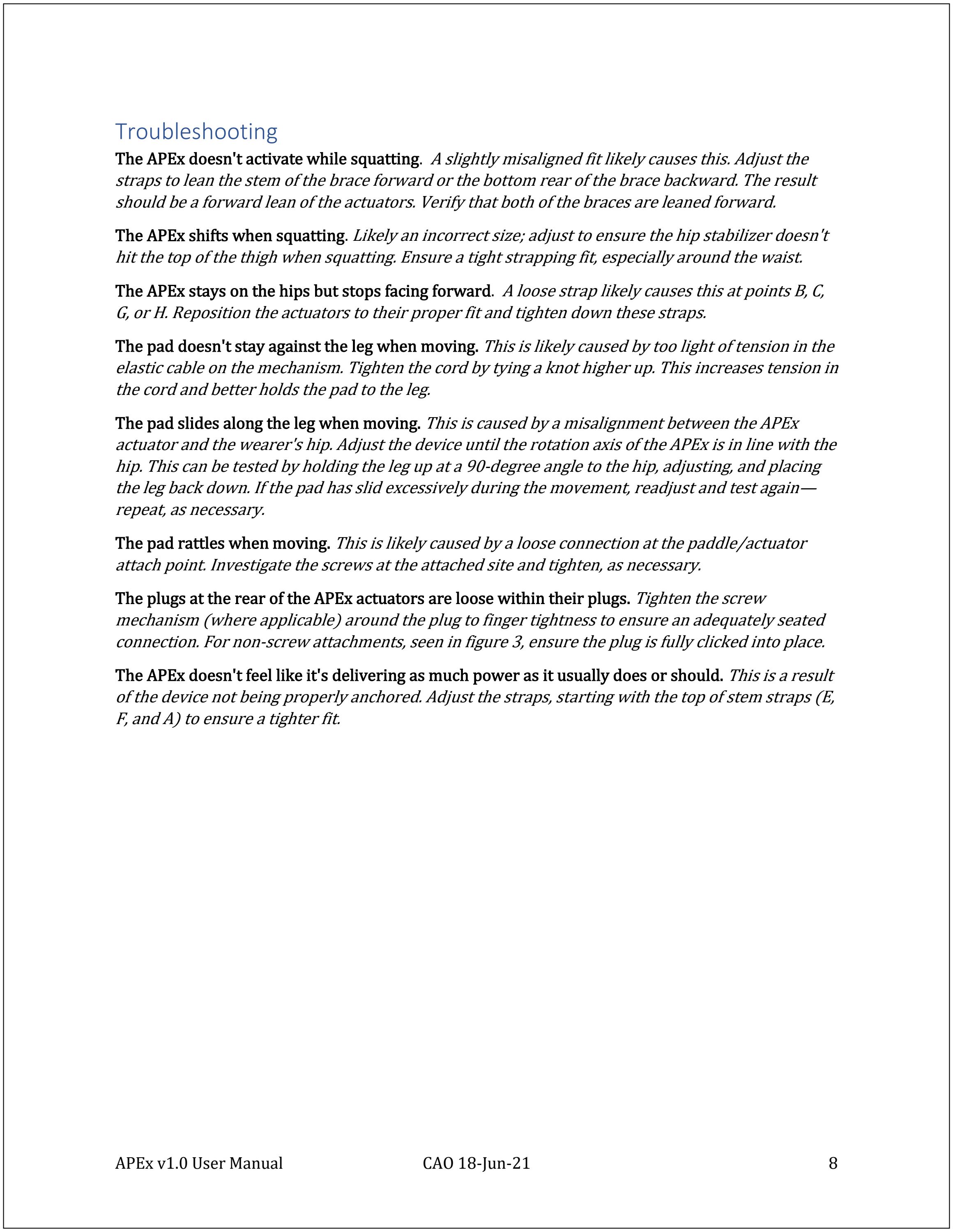


Figure 3: (Left) Battery solution for APEx V1 with power plug highlighted in yellow. (Right) Actuation mechanism with power port highlighted in yellow.

The batteries included with the APEx are custom built for the device. To charge the batteries, turn the battery pack off and remove it from the APEx vest by disconnecting the plug from the actuation mechanism. Pull the component free. Plug the included charger into the battery pack. The light in the charging cable turns green when the pack is fully charged. **NOTE:** Do not attempt to deconstruct the battery pack for individual cell replacement. Doing so can result in irreversible damage.



Troubleshooting

The APEx doesn't activate while squatting. *A slightly misaligned fit likely causes this. Adjust the straps to lean the stem of the brace forward or the bottom rear of the brace backward. The result should be a forward lean of the actuators. Verify that both of the braces are leaned forward.*

The APEx shifts when squatting. *Likely an incorrect size; adjust to ensure the hip stabilizer doesn't hit the top of the thigh when squatting. Ensure a tight strapping fit, especially around the waist.*

The APEx stays on the hips but stops facing forward. *A loose strap likely causes this at points B, C, G, or H. Reposition the actuators to their proper fit and tighten down these straps.*

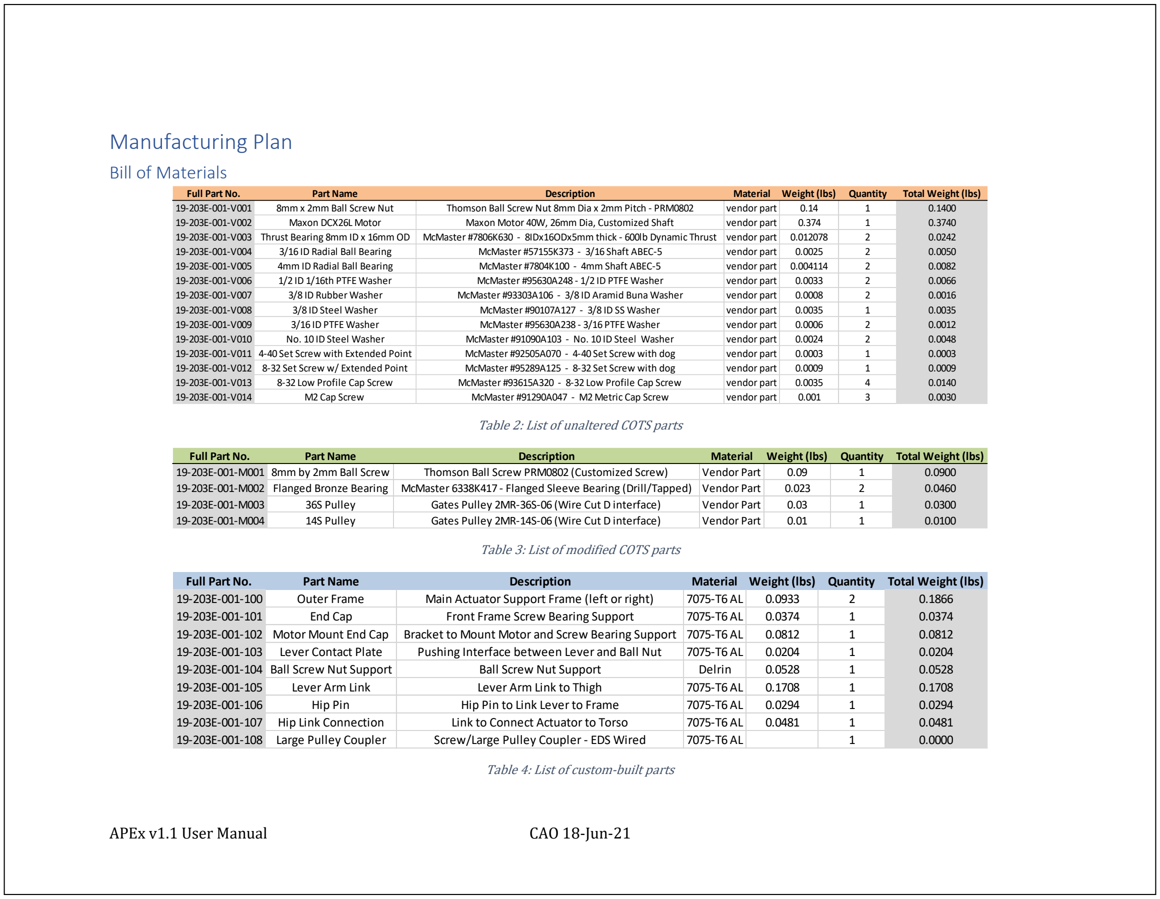
The pad doesn't stay against the leg when moving. *This is likely caused by too light of tension in the elastic cable on the mechanism. Tighten the cord by tying a knot higher up. This increases tension in the cord and better holds the pad to the leg.*

The pad slides along the leg when moving. *This is caused by a misalignment between the APEx actuator and the wearer's hip. Adjust the device until the rotation axis of the APEx is in line with the hip. This can be tested by holding the leg up at a 90-degree angle to the hip, adjusting, and placing the leg back down. If the pad has slid excessively during the movement, readjust and test again—repeat, as necessary.*

The pad rattles when moving. *This is likely caused by a loose connection at the paddle/actuator attach point. Investigate the screws at the attached site and tighten, as necessary.*

The plugs at the rear of the APEx actuators are loose within their plugs. *Tighten the screw mechanism (where applicable) around the plug to finger tightness to ensure an adequately seated connection. For non-screw attachments, seen in figure 3, ensure the plug is fully clicked into place.*

The APEx doesn't feel like it's delivering as much power as it usually does or should. *This is a result of the device not being properly anchored. Adjust the straps, starting with the top of stem straps (E, F, and A) to ensure a tighter fit.*



Manufacturing Plan

Bill of Materials

Full Part No.	Part Name	Description	Material	Weight (lbs)	Quantity	Total Weight (lbs)
19-203E-001-V001	8mm x 2mm Ball Screw Nut	Thomson Ball Screw Nut 8mm Dia x 2mm Pitch - PRM0802	vendor part	0.14	1	0.1400
19-203E-001-V002	Maxon DCX26L Motor	Maxon Motor 40W, 26mm Dia, Customized Shaft	vendor part	0.374	1	0.3740
19-203E-001-V003	Thrust Bearing 8mm ID x 16mm OD	McMaster #7806K630 - 8IDx16ODx5mm thick - 600lb Dynamic Thrust	vendor part	0.012078	2	0.0242
19-203E-001-V004	3/16 ID Radial Ball Bearing	McMaster #57155K373 - 3/16 Shaft ABEC-5	vendor part	0.0025	2	0.0050
19-203E-001-V005	4mm ID Radial Ball Bearing	McMaster #7804K100 - 4mm Shaft ABEC-5	vendor part	0.004114	2	0.0082
19-203E-001-V006	1/2 ID 1/16th PTFE Washer	McMaster #95630A248 - 1/2 ID PTFE Washer	vendor part	0.0033	2	0.0066
19-203E-001-V007	3/8 ID Rubber Washer	McMaster #93303A106 - 3/8 ID Aramid Buna Washer	vendor part	0.0008	2	0.0016
19-203E-001-V008	3/8 ID Steel Washer	McMaster #90107A127 - 3/8 ID SS Washer	vendor part	0.0035	1	0.0035
19-203E-001-V009	3/16 ID PTFE Washer	McMaster #95630A238 - 3/16 PTFE Washer	vendor part	0.0006	2	0.0012
19-203E-001-V010	No. 10 ID Steel Washer	McMaster #91090A103 - No. 10 ID Steel Washer	vendor part	0.0024	2	0.0048
19-203E-001-V011	4-40 Set Screw with Extended Point	McMaster #92505A070 - 4-40 Set Screw with dog	vendor part	0.0003	1	0.0003
19-203E-001-V012	8-32 Set Screw w/ Extended Point	McMaster #95289A125 - 8-32 Set Screw with dog	vendor part	0.0009	1	0.0009
19-203E-001-V013	8-32 Low Profile Cap Screw	McMaster #93615A320 - 8-32 Low Profile Cap Screw	vendor part	0.0035	4	0.0140
19-203E-001-V014	M2 Cap Screw	McMaster #91290A047 - M2 Metric Cap Screw	vendor part	0.001	3	0.0030

Table 2: List of unaltered COTS parts

Full Part No.	Part Name	Description	Material	Weight (lbs)	Quantity	Total Weight (lbs)
19-203E-001-M001	8mm by 2mm Ball Screw	Thomson Ball Screw PRM0802 (Customized Screw)	Vendor Part	0.09	1	0.0900
19-203E-001-M002	Flanged Bronze Bearing	McMaster 6338K417 - Flanged Sleeve Bearing (Drill/Tapped)	Vendor Part	0.023	2	0.0460
19-203E-001-M003	36S Pulley	Gates Pulley 2MR-36S-06 (Wire Cut D interface)	Vendor Part	0.03	1	0.0300
19-203E-001-M004	14S Pulley	Gates Pulley 2MR-14S-06 (Wire Cut D interface)	Vendor Part	0.01	1	0.0100

Table 3: List of modified COTS parts

Full Part No.	Part Name	Description	Material	Weight (lbs)	Quantity	Total Weight (lbs)
19-203E-001-100	Outer Frame	Main Actuator Support Frame (left or right)	7075-T6 AL	0.0933	2	0.1866
19-203E-001-101	End Cap	Front Frame Screw Bearing Support	7075-T6 AL	0.0374	1	0.0374
19-203E-001-102	Motor Mount End Cap	Bracket to Mount Motor and Screw Bearing Support	7075-T6 AL	0.0812	1	0.0812
19-203E-001-103	Lever Contact Plate	Pushing Interface between Lever and Ball Nut	7075-T6 AL	0.0204	1	0.0204
19-203E-001-104	Ball Screw Nut Support	Ball Screw Nut Support	Delrin	0.0528	1	0.0528
19-203E-001-105	Lever Arm Link	Lever Arm Link to Thigh	7075-T6 AL	0.1708	1	0.1708
19-203E-001-106	Hip Pin	Hip Pin to Link Lever to Frame	7075-T6 AL	0.0294	1	0.0294
19-203E-001-107	Hip Link Connection	Link to Connect Actuator to Torso	7075-T6 AL	0.0481	1	0.0481
19-203E-001-108	Large Pulley Coupler	Screw/Large Pulley Coupler - EDS Wired	7075-T6 AL		1	0.0000

Table 4: List of custom-built parts

APEx v1.1 User Manual CAO 18-Jun-21

Design of the Actuator

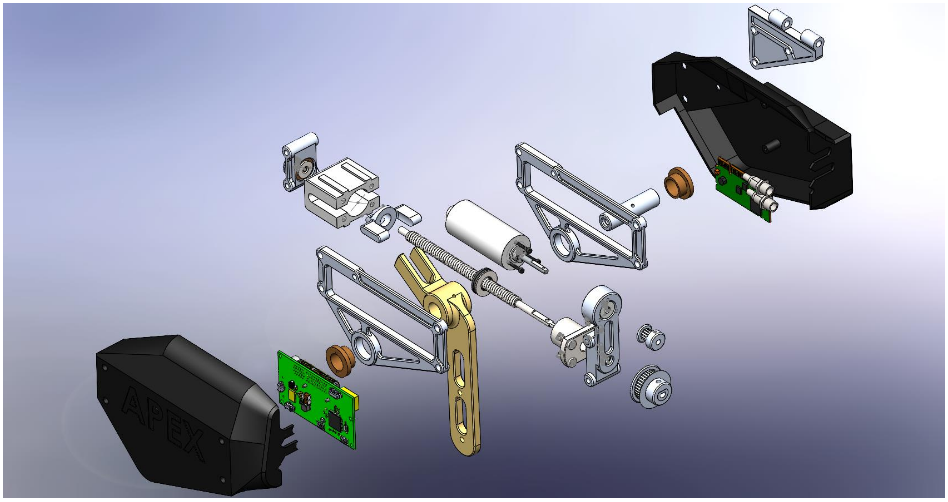
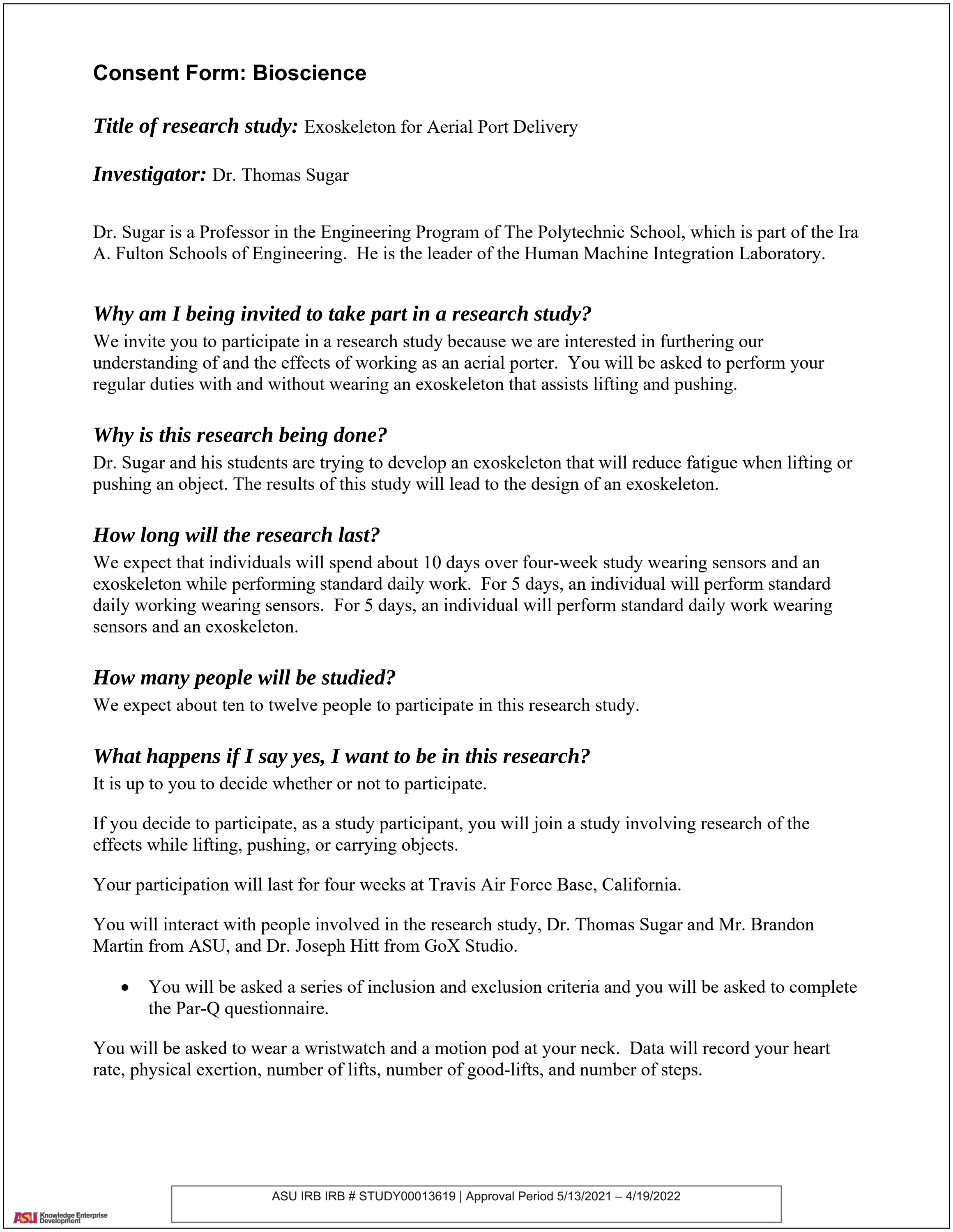


Figure 4: An exploded view of the APEx actuator.

APPENDIX D

APEX IRB DOCUMENTATION

D.1 Approved Consent Form



Consent Form: Bioscience

Title of research study: Exoskeleton for Aerial Port Delivery

Investigator: Dr. Thomas Sugar

Dr. Sugar is a Professor in the Engineering Program of The Polytechnic School, which is part of the Ira A. Fulton Schools of Engineering. He is the leader of the Human Machine Integration Laboratory.

Why am I being invited to take part in a research study?

We invite you to participate in a research study because we are interested in furthering our understanding of and the effects of working as an aerial porter. You will be asked to perform your regular duties with and without wearing an exoskeleton that assists lifting and pushing.

Why is this research being done?

Dr. Sugar and his students are trying to develop an exoskeleton that will reduce fatigue when lifting or pushing an object. The results of this study will lead to the design of an exoskeleton.

How long will the research last?

We expect that individuals will spend about 10 days over four-week study wearing sensors and an exoskeleton while performing standard daily work. For 5 days, an individual will perform standard daily working wearing sensors. For 5 days, an individual will perform standard daily work wearing sensors and an exoskeleton.

How many people will be studied?

We expect about ten to twelve people to participate in this research study.

What happens if I say yes, I want to be in this research?

It is up to you to decide whether or not to participate.

If you decide to participate, as a study participant, you will join a study involving research of the effects while lifting, pushing, or carrying objects.

Your participation will last for four weeks at Travis Air Force Base, California.

You will interact with people involved in the research study, Dr. Thomas Sugar and Mr. Brandon Martin from ASU, and Dr. Joseph Hitt from GoX Studio.

- You will be asked a series of inclusion and exclusion criteria and you will be asked to complete the Par-Q questionnaire.

You will be asked to wear a wristwatch and a motion pod at your neck. Data will record your heart rate, physical exertion, number of lifts, number of good-lifts, and number of steps.

ASU Knowledge Enterprise Development

ASU IRB IRB # STUDY00013619 | Approval Period 5/13/2021 – 4/19/2022

- You will be asked to sit down and put on the sensors
- You will go through a 10-minute training demonstration of how the wristwatch device works and how to use it
- You will go through a 20-minute training demonstration of how the APEx works and how to use it
- You will be asked to perform your regular work activities. You will wear the motion pod and wristwatch for a shift typically lasting 5 hours. You will wear the APEx in training for one week, and measured work for one week. The total testing procedure will last four weeks.
- You are welcome to describe any problems to the research staff.
- You can opt-out of the experiment at any time if the procedure feels uncomfortable.

What happens if I say yes, but I change my mind later?

You can leave the research at any time.

If you decide to leave the research, there will be no adverse consequences, and no one will try to convince you otherwise or change your mind. If you choose to leave the study, contact the investigator.

Is there any way being in this study could be bad for me?

Some certain risks and discomforts may be associated with this research. They include but are not limited to:

1. The risks associated with lifting and moving objects
2. Fatigue associated with lifting and moving objects.

The participant will be asked to wear a heart rate monitor. If their heart rate goes above the maximum level, the heart rate monitor will beep, and you will be asked to stop.

From CDC, "This maximum rate is based on the person's age. An estimate of a person's maximum age-related heart rate can be obtained by subtracting the person's age from 220. For example, for a 50-year-old person, the estimated maximum age-related heart rate would be calculated as 220 - 50 years = 170 beats per minute (bpm)."

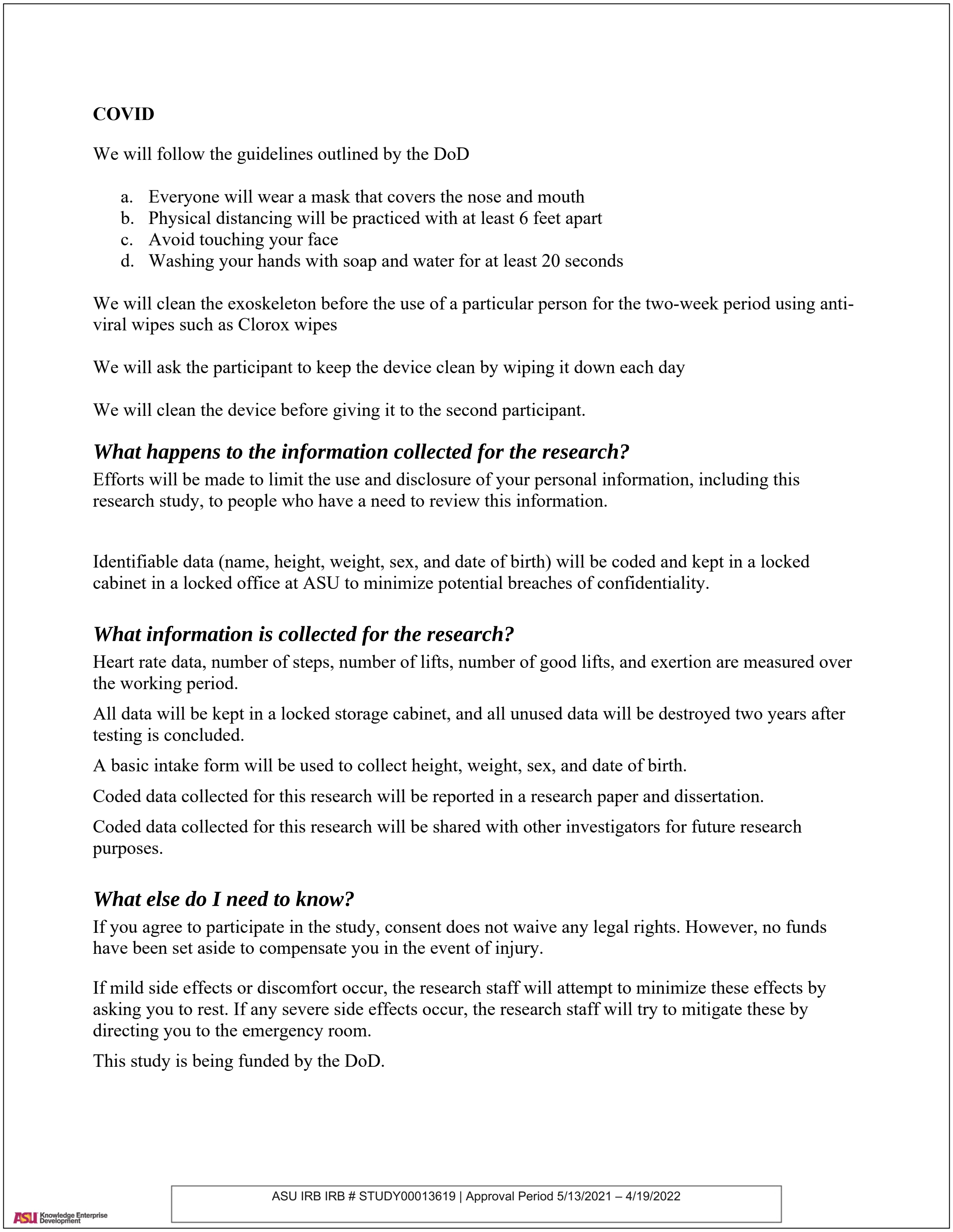
Participation in this study may cause all or some of the side effects listed above. There is, in addition, always the risk of developing previously unknown side effects.

If mild side effects or discomfort occur, the research staff will attempt to minimize these effects by asking you to rest. If any severe side effects occur, the research staff will try to reduce these by directing you to the emergency room.

If there are any significant side effects, the research staff will call 911 immediately.

The investigator is willing to discuss any questions you might have about these risks and discomforts.

The participant must wear closed-toe shoes, not sandals.



COVID

We will follow the guidelines outlined by the DoD

a. Everyone will wear a mask that covers the nose and mouth
b. Physical distancing will be practiced with at least 6 feet apart
c. Avoid touching your face
d. Washing your hands with soap and water for at least 20 seconds

We will clean the exoskeleton before the use of a particular person for the two-week period using anti-viral wipes such as Clorox wipes

We will ask the participant to keep the device clean by wiping it down each day

We will clean the device before giving it to the second participant.

What happens to the information collected for the research?

Efforts will be made to limit the use and disclosure of your personal information, including this research study, to people who have a need to review this information.

Identifiable data (name, height, weight, sex, and date of birth) will be coded and kept in a locked cabinet in a locked office at ASU to minimize potential breaches of confidentiality.

What information is collected for the research?

Heart rate data, number of steps, number of lifts, number of good lifts, and exertion are measured over the working period.

All data will be kept in a locked storage cabinet, and all unused data will be destroyed two years after testing is concluded.

A basic intake form will be used to collect height, weight, sex, and date of birth.

Coded data collected for this research will be reported in a research paper and dissertation.

Coded data collected for this research will be shared with other investigators for future research purposes.

What else do I need to know?

If you agree to participate in the study, consent does not waive any legal rights. However, no funds have been set aside to compensate you in the event of injury.

If mild side effects or discomfort occur, the research staff will attempt to minimize these effects by asking you to rest. If any severe side effects occur, the research staff will try to mitigate these by directing you to the emergency room.

This study is being funded by the DoD.

Who can I talk to?

If you have questions, concerns, or complaints or think the research has hurt you, talk to the research team: Dr. Thomas Sugar at 480-727-1127.

This research has been reviewed and approved by the Bioscience IRB ("IRB"). You may talk to them at 480-965-6788 or research.integrity@asu.edu if:

- The research team is not answering your questions, concerns, or complaints
- You cannot reach the research team
- You want to talk to someone besides the research team
- You have questions about your rights as a research participant
- You want to get information or provide input about this research

Screening Process:

You will be asked a series of questions to determine if you meet the inclusion criteria.

You will also be asked questions to determine if you can participate in this study based on the exclusion criteria.

Inclusion Criteria:

1. Between the ages of 18-65
2. Full range of limbs including arms, knees, legs, and hips
3. Ability to wear test equipment and heart rate monitors
4. Ability to follow simple instructions
5. Must have proof of medical insurance
6. Must answer no to all the questions in the Par-Q questionnaire

Exclusion Criteria:

1. They have a history of back or knee issues
2. They are unable to lift 45 lbs
3. They are unable to walk 5 minutes at 3mph
4. Unable to wear the exoskeleton because it does not fit
5. They are unable to jog for 1 minute at 5 mph
6. They are not between 5’ – 6’5”
7. The individual has pain when bending over or moving legs
8. The individual has pain when moving arms or moving arms above their head
9. Restricted joint movement in the arms and legs
10. Inability to meet inclusion criteria
11. Any past medical problems of heart disease

Covid Restrictions:

1. They have recently tested positive for COVID-19 or have COVID-19-related symptoms.

Signature Block for Capable Adult

Your signature documents your permission to take part in this research.

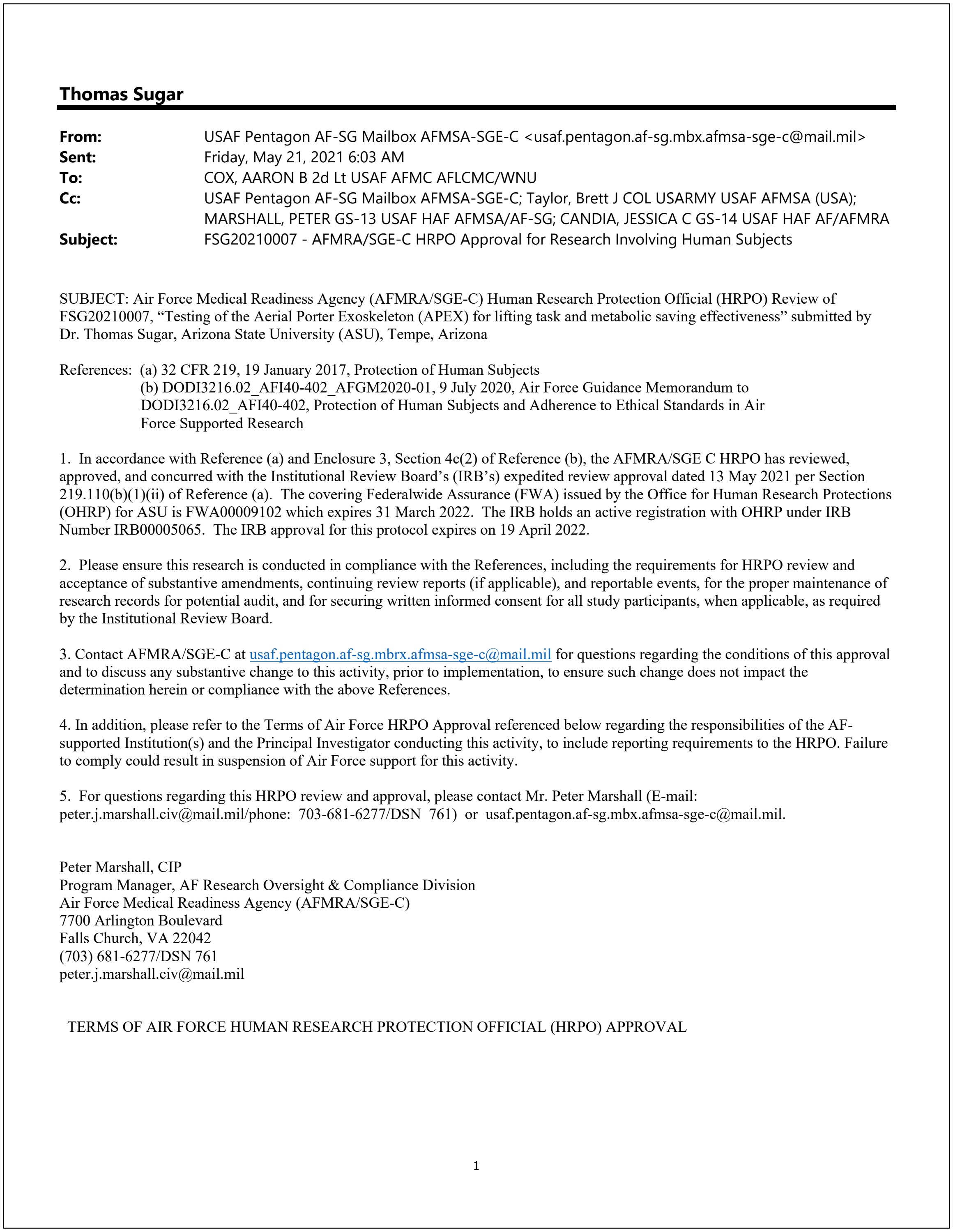
Signature of participant ____________ Date ____________

Printed name of the participant ____________

Signature of the person obtaining consent ____________ Date ____________

Printed name of person obtaining consent ____________

D.2 HRPO Approval



Thomas Sugar

From: USAF Pentagon AF-SG Mailbox AFMSA-SGE-C <usaf.pentagon.af-sg.mbx.afmsa-sge-c@mail.mil>
Sent: Friday, May 21, 2021 6:03 AM
To: COX, AARON B 2d Lt USAF AFMC AFLCMC/WNU
Cc: USAF Pentagon AF-SG Mailbox AFMSA-SGE-C; Taylor, Brett J COL USARMY USAF AFMSA (USA); MARSHALL, PETER GS-13 USAF HAF AFMSA/AF-SG; CANDIA, JESSICA C GS-14 USAF HAF AF/AFMRA
Subject: FSG20210007 - AFMRA/SGE-C HRPO Approval for Research Involving Human Subjects

SUBJECT: Air Force Medical Readiness Agency (AFMRA/SGE-C) Human Research Protection Official (HRPO) Review of FSG20210007, "Testing of the Aerial Porter Exoskeleton (APEX) for lifting task and metabolic saving effectiveness" submitted by Dr. Thomas Sugar, Arizona State University (ASU), Tempe, Arizona

References: (a) 32 CFR 219, 19 January 2017, Protection of Human Subjects
(b) DODI3216.02_AFI40-402_AFGM2020-01, 9 July 2020, Air Force Guidance Memorandum to DODI3216.02_AFI40-402, Protection of Human Subjects and Adherence to Ethical Standards in Air Force Supported Research

1. In accordance with Reference (a) and Enclosure 3, Section 4c(2) of Reference (b), the AFMRA/SGE C HRPO has reviewed, approved, and concurred with the Institutional Review Board's (IRB's) expedited review approval dated 13 May 2021 per Section 219.110(b)(1)(ii) of Reference (a). The covering Federalwide Assurance (FWA) issued by the Office for Human Research Protections (OHRP) for ASU is FWA00009102 which expires 31 March 2022. The IRB holds an active registration with OHRP under IRB Number IRB00005065. The IRB approval for this protocol expires on 19 April 2022.

2. Please ensure this research is conducted in compliance with the References, including the requirements for HRPO review and acceptance of substantive amendments, continuing review reports (if applicable), and reportable events, for the proper maintenance of research records for potential audit, and for securing written informed consent for all study participants, when applicable, as required by the Institutional Review Board.

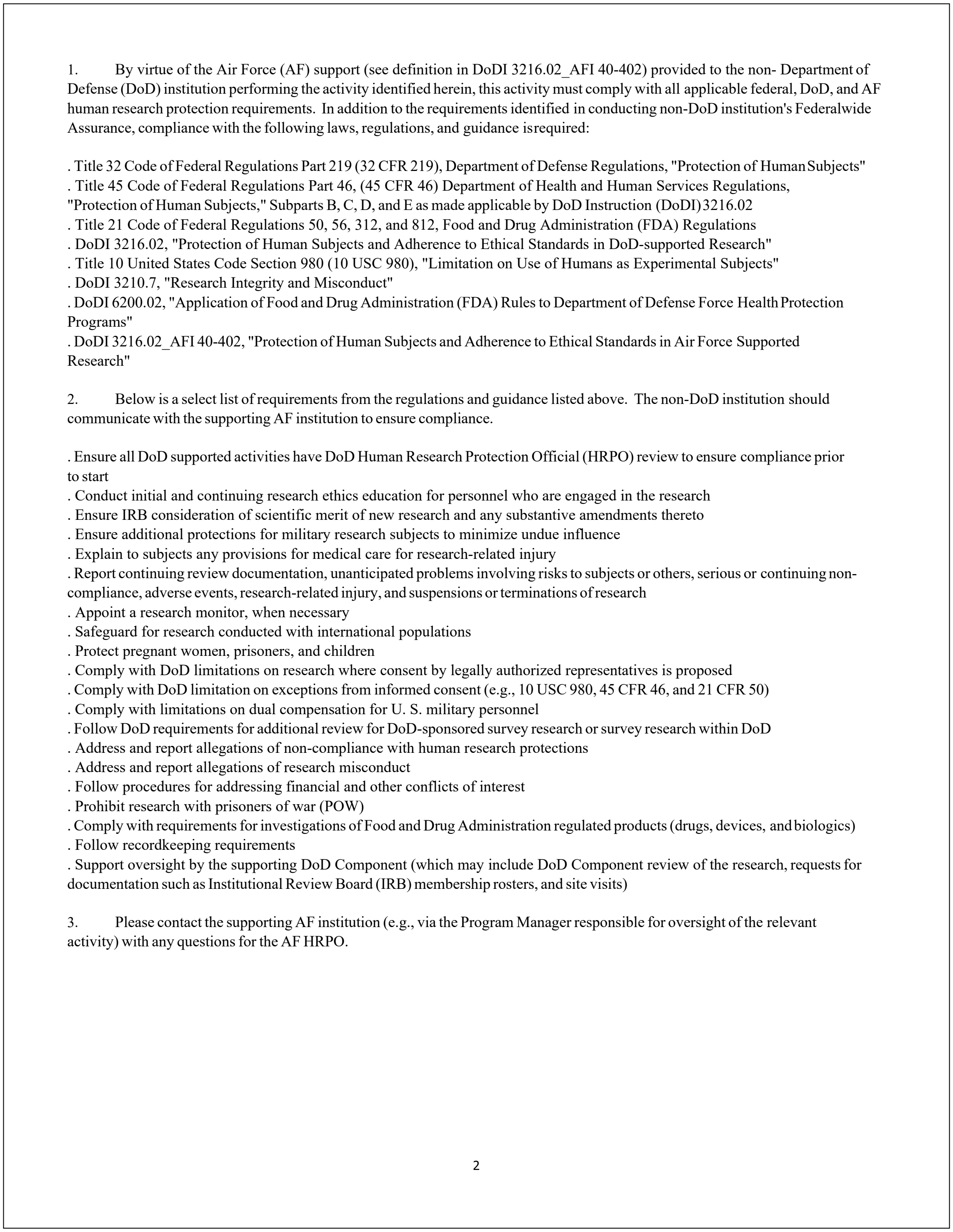
3. Contact AFMRA/SGE-C at usaf.pentagon.af-sg.mbrx.afmsa-sge-c@mail.mil for questions regarding the conditions of this approval and to discuss any substantive change to this activity, prior to implementation, to ensure such change does not impact the determination herein or compliance with the above References.

4. In addition, please refer to the Terms of Air Force HRPO Approval referenced below regarding the responsibilities of the AF-supported Institution(s) and the Principal Investigator conducting this activity, to include reporting requirements to the HRPO. Failure to comply could result in suspension of Air Force support for this activity.

5. For questions regarding this HRPO review and approval, please contact Mr. Peter Marshall (E-mail: peter.j.marshall.civ@mail.mil/phone: 703-681-6277/DSN 761) or usaf.pentagon.af-sg.mbx.afmsa-sge-c@mail.mil.

Peter Marshall, CIP
Program Manager, AF Research Oversight & Compliance Division
Air Force Medical Readiness Agency (AFMRA/SGE-C)
7700 Arlington Boulevard
Falls Church, VA 22042
(703) 681-6277/DSN 761
peter.j.marshall.civ@mail.mil

TERMS OF AIR FORCE HUMAN RESEARCH PROTECTION OFFICIAL (HRPO) APPROVAL



1. By virtue of the Air Force (AF) support (see definition in DoDI 3216.02_AFI 40-402) provided to the non- Department of Defense (DoD) institution performing the activity identified herein, this activity must comply with all applicable federal, DoD, and AF human research protection requirements. In addition to the requirements identified in conducting non-DoD institution's Federalwide Assurance, compliance with the following laws, regulations, and guidance is required:

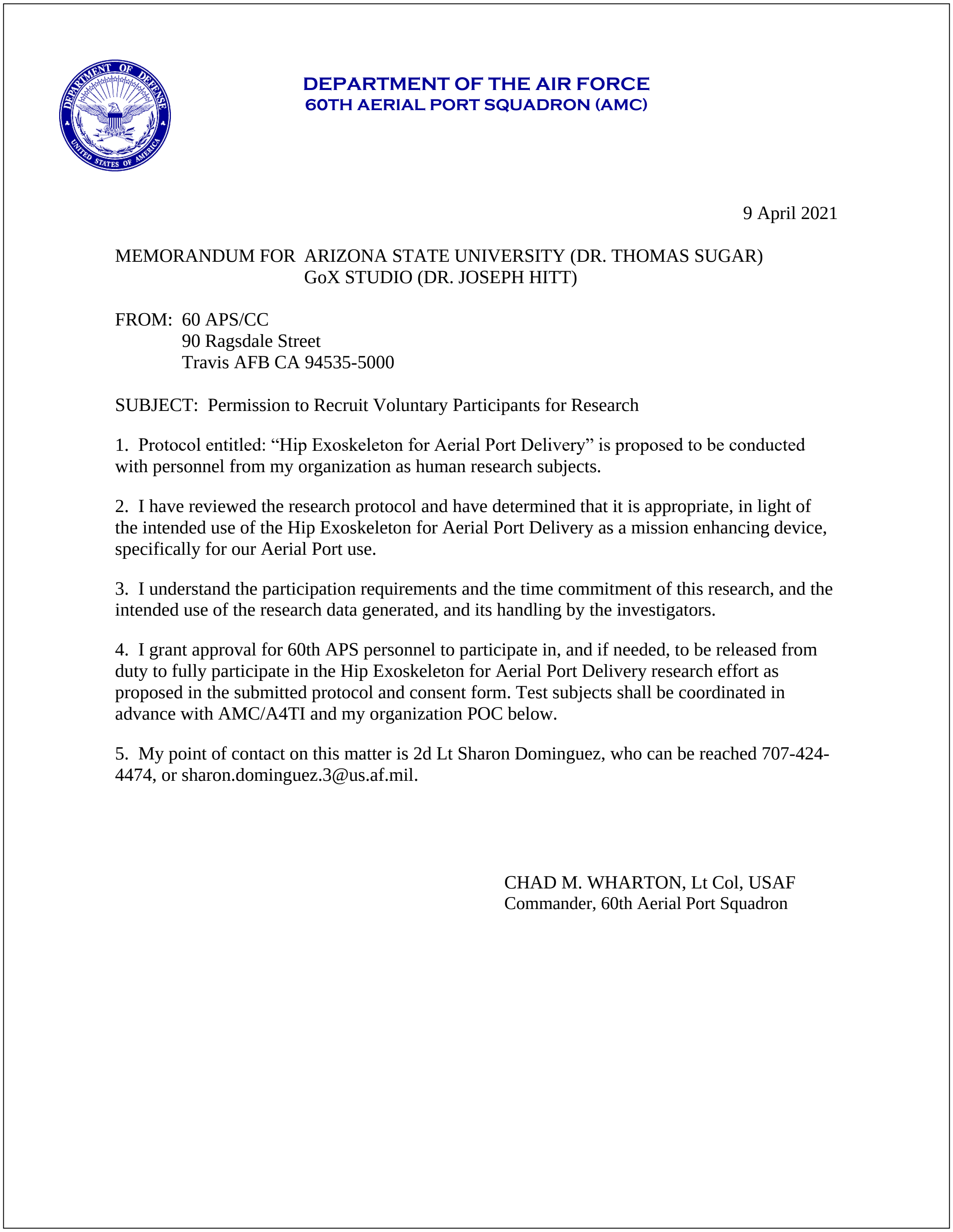
- Title 32 Code of Federal Regulations Part 219 (32 CFR 219), Department of Defense Regulations, "Protection of Human Subjects"
- Title 45 Code of Federal Regulations Part 46, (45 CFR 46) Department of Health and Human Services Regulations, "Protection of Human Subjects," Subparts B, C, D, and E as made applicable by DoD Instruction (DoDI) 3216.02
- Title 21 Code of Federal Regulations 50, 56, 312, and 812, Food and Drug Administration (FDA) Regulations
- DoDI 3216.02, "Protection of Human Subjects and Adherence to Ethical Standards in DoD-supported Research"
- Title 10 United States Code Section 980 (10 USC 980), "Limitation on Use of Humans as Experimental Subjects"
- DoDI 3210.7, "Research Integrity and Misconduct"
- DoDI 6200.02, "Application of Food and Drug Administration (FDA) Rules to Department of Defense Force Health Protection Programs"
- DoDI 3216.02_AFI 40-402, "Protection of Human Subjects and Adherence to Ethical Standards in Air Force Supported Research"

2. Below is a select list of requirements from the regulations and guidance listed above. The non-DoD institution should communicate with the supporting AF institution to ensure compliance.

- Ensure all DoD supported activities have DoD Human Research Protection Official (HRPO) review to ensure compliance prior to start
- Conduct initial and continuing research ethics education for personnel who are engaged in the research
- Ensure IRB consideration of scientific merit of new research and any substantive amendments thereto
- Ensure additional protections for military research subjects to minimize undue influence
- Explain to subjects any provisions for medical care for research-related injury
- Report continuing review documentation, unanticipated problems involving risks to subjects or others, serious or continuing non-compliance, adverse events, research-related injury, and suspensions or terminations of research
- Appoint a research monitor, when necessary
- Safeguard for research conducted with international populations
- Protect pregnant women, prisoners, and children
- Comply with DoD limitations on research where consent by legally authorized representatives is proposed
- Comply with DoD limitation on exceptions from informed consent (e.g., 10 USC 980, 45 CFR 46, and 21 CFR 50)
- Comply with limitations on dual compensation for U. S. military personnel
- Follow DoD requirements for additional review for DoD-sponsored survey research or survey research within DoD
- Address and report allegations of non-compliance with human research protections
- Address and report allegations of research misconduct
- Follow procedures for addressing financial and other conflicts of interest
- Prohibit research with prisoners of war (POW)
- Comply with requirements for investigations of Food and Drug Administration regulated products (drugs, devices, and biologics)
- Follow recordkeeping requirements
- Support oversight by the supporting DoD Component (which may include DoD Component review of the research, requests for documentation such as Institutional Review Board (IRB) membership rosters, and site visits)

3. Please contact the supporting AF institution (e.g., via the Program Manager responsible for oversight of the relevant activity) with any questions for the AF HRPO.

D.3 Permission to Recruit Voluntary Participants for Research



DEPARTMENT OF THE AIR FORCE
60TH AERIAL PORT SQUADRON (AMC)

9 April 2021

MEMORANDUM FOR ARIZONA STATE UNIVERSITY (DR. THOMAS SUGAR)
GoX STUDIO (DR. JOSEPH HITT)

FROM: 60 APS/CC
90 Ragsdale Street
Travis AFB CA 94535-5000

SUBJECT: Permission to Recruit Voluntary Participants for Research

1. Protocol entitled: “Hip Exoskeleton for Aerial Port Delivery” is proposed to be conducted with personnel from my organization as human research subjects.

2. I have reviewed the research protocol and have determined that it is appropriate, in light of the intended use of the Hip Exoskeleton for Aerial Port Delivery as a mission enhancing device, specifically for our Aerial Port use.

3. I understand the participation requirements and the time commitment of this research, and the intended use of the research data generated, and its handling by the investigators.

4. I grant approval for 60th APS personnel to participate in, and if needed, to be released from duty to fully participate in the Hip Exoskeleton for Aerial Port Delivery research effort as proposed in the submitted protocol and consent form. Test subjects shall be coordinated in advance with AMC/A4TI and my organization POC below.

5. My point of contact on this matter is 2d Lt Sharon Dominguez, who can be reached 707-424-4474, or sharon.dominguez.3@us.af.mil.

CHAD M. WHARTON, Lt Col, USAF
Commander, 60th Aerial Port Squadron