A top-down human-centered approach to exoskeleton design

by

Thomas M. Schnieders

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Major: Industrial Manufacturing Systems Engineering

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Program of Study Committee:

Richard T. Stone, Major Professor

Guiping Hu

Jason C. Gillette

Stephen B. Vardeman

David Sly

Iowa State University

Ames, Iowa

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Dedication

This work is dedicated in part to my parents, my sister, my brother-in-law, and my nephew for all their help in developing my critical thinking skills and helping me embrace my curiosity and creativity. This work is also dedicated to my wonderful wife Susan. Without her constant support and cheering me on, I know this work would not have been completed.

TABLE OF CONTENTS

List Of Figures

LIST OF TABLES

Acknowledgments

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Abstract

This dissertation begins, as all good research does, with a thorough review of the literature. The literature is broken into three primary sections covering the early 1960's when information on exoskeletons was first published up to 1970, then the formative years of 1970 to 2000 where much of the primary technology was developed, and finally 2000 to present where new advancements in battery density, computer processing, and materials leads to more robust and advanced exoskeleton designs. The literature review determines the areas where there is a dearth of research or places needing further examination and lays the groundwork for the development of a design methodology specifically for the design of exoskeletons.

This design methodology is built on the shoulders of prior work and utilizes the **A**rmed **R**obotic **C**ontrol for **T**raining in **C**ivilian **Law E**nforcement, or ARCTiC LawE, as one of multiple test beds for validation. This upper body exoskeleton was designed to assist civilian, military, and law enforcement personnel in the training of accurate, precise, and reliable handgun techniques utilizing a laser-based handgun with similar dimensions, trigger pull, and break action to a Glock ® 19 pistol, common to both public and private security sectors.

The work developed in this dissertation provides an initial methodology for exoskeleton development and provides a case study in the development of exoskeletons as a tool for training healthy individuals. The results of the final studies provided in this dissertation validate the methodology as a viable guide for the design and evaluation of exoskeletons.

Chapter I Introduction To The Dissertation

This dissertation is completed as a culmination of information. It continues work from my Master of Science in Human Computer Interaction and Industrial Manufacturing Systems Engineering program. Elements of my background in Mechanical Engineering and Bioengineering are also found throughout. Essentially, an abridgement of my engineering background at Iowa State University can be found throughout this tome.

The primary goal of this dissertation is to show that there is a need for an exoskeleton design and evaluation methodology and that this methodology can directly improve exoskeleton designs and evaluate the viability of multiple exoskeleton alternatives quantitatively and qualitatively.

Research Motivation

What will hopefully become clearer as this dissertation progresses is the need for a design methodology that pertains to exoskeletons. There are numerous design methodologies in most fields of engineering and these can broadly be applied to exoskeletons. However, none have been specifically designed around exoskeletons. What appears in the literature is a penchant to design around discipline-based metrics; these design considerations were rarely shared with the scientific community, if at all.

It became clear through the literature review and having worked hands on in designing and manufacturing numerous exoskeletons, that much of the guess work in designing exoskeletons can be mitigated, or eliminated entirely, by following a clear set of ground rules in the form of a design methodology. Hence, the genesis of a design methodology built around exoskeleton design – a **Qu**antitative **A**ssessment of **N**on-**T**ested **U**niversally **M**ade **Ex**oskeletons, or The QuANTUM Ex Method for short.

The hypotheses of this dissertation are as follows:

1) The QuANTUM Ex Method will produce theoretically superior exoskeleton designs via quantitative and qualitative metrics
2) When exoskeleton prototypes are based on the same information and under the same limiting factors, the QuANTUM Ex Method can accurately and reliably determine superior designs from multiple alternatives

Dissertation Organization

This dissertation will begin by familiarizing the reader with exoskeletons by presenting a literature review over four chapters that cover relevant exoskeletal work from its inception in the early 1960's to present day. It continues by broadly introducing and familiarizing the reader with traditional design assessment methods such as design for Six Sigma (DMADVR), human factors and ergonomics approaches to design, creativity approaches to design etc. In chapters five and six, this dissertation will detail the need for an assessment method. It will detail and demonstrate the QuANTUM Ex Method for design and evaluation of multiple prototypes.

The dissertation continues by discussing and detailing the methods, experimental design, and procedure used in the research studies. It presents the detailed results and analysis of the experiments of the exoskeletons used. The overall findings and implications of the results will be discussed in concluding chapters. The dissertation will conclude by leaving the reader with a functional understanding of theoretically superior exoskeleton design, as defined by the

QuANTUM Ex Method, and the implication for human performance enhancement and augmentation, and the sciences as a whole.

The following three chapters are modified and expanded on from a publication in *The International Journal of Robotics Applications and Technologies* titled “Current Work in the Human Machine Interface for Ergonomic Intervention with Exoskeletons” as well as a textbook chapter in *Novel Design and Applications of Robotics Technologies*, titled “Current Work in the Human-Machine Interface for Ergonomic Intervention with Exoskeletons.” The original paper provided the background, literature review, and the driving force for new research. The paper covers current work in the human-machine interface for ergonomic intervention with exoskeletons ranging in topics from current lower body exoskeletons, upper body exoskeletons, extremities (hands/ankles/feet), and full body exoskeletons. The paper concludes by covering the benefits of exoskeletons (rehabilitation, industrial application, and military application), determining what we don’t yet know about exoskeletons, what we can do to make exoskeletons better, and what issues are faced when designing exoskeletons (power density, degrees of freedom vs. complexity of model, mobility, variability, and safety).

Chapter II Introduction To Exoskeletons

The field of exoskeleton design is broad and expansive. The following three chapters serves as a cogent literature review of exoskeleton design with respect to the innate human-machine interface. It provides an outline of history and current research from the advent of exoskeletons in the early 1960's to present day advancements.

It is imperative to begin this paper by clearly defining the difference between exoskeletons, orthotics, and prosthetics. It is also important to note that these terms often overlap in the media as well as in the scientific literature. This is especially prevalent in the early years of exoskeleton design where the term exoskeleton more frequently referred to the traditional sense of the word – that is, a rigid external covering for some invertebrates like arthropods.

In early publications on exoskeletons, it was common for researchers to refer to exoskeletons with a descriptive adjective (i.e. powered exoskeleton, robotic exoskeleton, etc.). This helped mitigate confusion when referring to the new technology. In today's literature search, the term exoskeleton will more often than not yield the desired results.

A prosthetic is a device that substitutes a missing body part (Sansoni, Wodehouse, & Buis, 2014). An orthotic, or orthosis (plural: orthoses) refers to a device that is externally applied to the body. Unlike the prosthetic, an orthotic does not act to substitute a missing body part. External devices, in this case, refers to things like dental braces, insoles, or glasses (Sarakoglou, Tsagarakis, & Caldwell, 2004).

Active orthoses are limited by the daunting issue that the specific nature of disability often varies from one person to another. This makes it difficult to create one generally applicable device. As is the case with off the rack dress shirts compared to tailor made dress shirts. While they will both work, one may be ill fitting, too loose in some areas and too tight in others, while the other will match one's form. Ideally, a compact, energetically autonomous orthosis can provide the wearer assistance and therapy in everyday life. The issue of portability is one of the major factors that limits the application of active orthoses outside of clinical therapy (Dollar & Herr, 2008). In kind, exoskeletons suffer from similar inter- and intra-person difficulties in terms of fit and function, in fact, this is considered one of the most difficult challenges currently facing exoskeleton design. This topic will be further investigated in later chapters.

According to Pons, Rocon, and Morenso, an exoskeleton can be identified as an external mechanical structure whose joints match those of the human body. This mechanical structure shares physical contact with the operator and enables a direct transfer of mechanical power and information signals through either passive or active actuation (Pons, Rocon, & Moresno, 2007).

Hugh Herr defines exoskeletons and orthoses as follows: "The term 'exoskeleton' is used to describe a device that augments the performance of an able-bodied wearer, whereas the term 'orthosis' is typically used to describe a device that is used to assist a person with a limb pathology" (Herr, 2009).

The online dictionary site Dictionary.com defines the term exoskeleton as "an external covering or integument, especially when hard, as the shells of crustaceans" (Random House, Inc., 2017). We see multiple different definitions of the term across the years which will be discussed more later in this dissertation. The term itself needs to be updated.

Across the 50+ years of research into exoskeleton design, there have been numerous different names for the technology and multiple different definitions of the term 'exoskeleton'. Some of the most prevalent can be seen in the following list.

- Active orthoses
- Anthropomorphic exoskeleton
- Anthropomorphic robot
- Anthropomorphic systems
- Bilateral manipulators
- Biped locomotion machine/system
- Exoskeleton
- Exosuit
- Man amplifier
- Man-augmentation systems
- Master/slave control manipulator
- Master-slave robotic system
- Medical manipulator system
- Outer mechanical garment
- Powered suit of armor
- Powered rehabilitation suit
- Robotic exoskeleton
- Teleoperator system
- Wearable robotics

We define the term exoskeleton, in terms of this dissertation and hopefully more universally, as: an external mechanical structure that shares physical contact with the operator that allows a direct transfer of mechanical power and information through passive and/or active actuation that is designed to augment performance.

It can be seen through the literature that there is little in terms of a governing body on the development of exoskeletal devices, especially when it comes to what defines an exoskeleton and what measures need to be in place to guarantee user safety. Until recently, user safety has always been left to the competency of the engineering design team with little to no regulation. Research into possible negative outcomes of exoskeleton use provides a dearth of anything substantial. If there were any negative outcomes, it does not appear in the literature. In 2017 the American Section of the International Association for Testing Materials (ASTM) formed committee F48 on exoskeletons and exosuits, with subcommittees on design and manufacturing, human factors and ergonomics, task performance and environmental considerations, maintenance and disposal, security and information technology, executive, and terminology. As of the publication of this dissertation, no standards or specifications have been fully developed and approved by the committee.

Exoskeletons are used in two primary roles: rehabilitation and human performance augmentation. While their uses are quickly expanding into other fields such as sports, firefighting, and law enforcement, their primary function remains the same. According to Rocon (Rocon, et al., 2007) and Harwin (Harwin, Leiber, Austwick, & Dislis, 1998), rehabilitation robotics, and by extension rehabilitation exoskeletons, can be classified into three categories:

1. Posture support mechanisms
2. Rehabilitation mechanisms
3. Robots [and exoskeletons] to assist or replace body functions

The goal of human performance augmentation (HPA) is to enhance the capabilities of otherwise healthy people. It is the use of engineering to enhance or augment humans in tasks to perform better than before. HPA enhances capability while preserving safety and quality of life. Applications include fatigue reduction and heavy lifting, with much of the research focused on military uses, such as enhancing the ability to carry large loads onto the battlefield and increasing the endurance of the soldier. Other possible markets for HPA include emergency services such as fire and disaster response, and construction and material handling (Brown, Tsagarakis, & Caldwell, 2003), or any application that requires heavy gear and heavy lifting in rough terrain impassable by vehicle.

This dissertation divides exoskeletons into four broad categories of lower body, upper body, hands/feet, and full body exoskeletons.

Lower Body Exoskeletons

Lower body exoskeletons are mainly comprised of the hip joint, the knee joint, and the ankle joint. Among different challenges involved in developing an exoskeleton for the lower body are the interface between the human and the exoskeleton, portable energy sources, controls, and actuators. Lower body exoskeletons can be broadly divided into two types based on the application: rehabilitation and as enhancement capabilities of a healthy human being.

Most lower body exoskeletons were first developed to assist soldiers in supporting equipment. Wearable lower body exoskeletons can greatly reduce the oxygen consumption of soldiers; support energy for walking, running, and jumping; and help movement and operational capability of soldiers (Yuan, Wang, Ma, & Gong, 2014). It is important to understand the biomechanics of humans in order to develop ergonomic designs for exoskeletons for the lower limbs (Dollar & Herr, 2008).

Upper Body Exoskeletons

Development of upper body exoskeletons presents additional challenges beyond those of lower body devices. These challenges owe largely to the purpose of upper limbs versus lower limbs. Whereas the purpose of the lower limbs is largely to bear and transport the load of the upper body, “the main function of the arm is to position the hand for functional activities (Rocon, et al., 2007).” Furthermore, upper limb joint anatomy is complex. The shoulder, for example, is located by three bones (the clavicle, scapula, and humerus), and allows four articulations, resulting in a dynamic and irregular center of rotation (Gopura & Kiguchi, 2009) making efficient and ergonomic designs difficult, complex, and expensive to make.

Much of the research in upper body exoskeletons has been focused in the medical field, on exoskeletons that provide rehabilitative training, or on exoskeletons that provide assistance in the daily activities of living. However, upper body exoskeletons could also be applied to augment the performance of healthy individuals (Brown, Tsagarakis, & Caldwell, 2003) (Schnieders, Stone, Oviatt, & Danford-Klein, 2017), to provide a haptic interface in virtual reality simulations, or to act as a master device in teleoperation (Perry, Rosen, & Burns, 2007).

Extremities

For the purpose of this dissertation, we break down the extremities into two primary sections: the hands and the feet/ankles.

Hands

By necessity, hand exoskeletons include the wrists due to the complexity and degrees of freedom involved. Much of the literature for hand exoskeletons points towards their use in rehabilitation. However, there has also been work done looking at the use of hand exoskeletons as haptic interfaces for interaction with virtual environments and extravehicular activities in space. Extravehicular activity refers to work done outside of the vehicle.

Feet

Similar to hand exoskeletons, feet exoskeletons frequently include the ankles due to the complexity and degrees of freedom involved. Literature covering exoskeletons specifically for the feet is rather sparse. Much of the work couples the feet with the ankles and the rest of the lower body. Similar to upper body exoskeletons and hand exoskeletons, the anthropometry is extremely complex leading to difficult and expensive design solutions. The literature for this section of the body primarily focuses on plantarflexion in terms of balance and energy efficiency or directed towards gait assistance for the elderly or disabled.

Full Body

There are only a few full body exoskeletons in the published literature. This is due to the increasing complexity and cost of developing a full body articulating exoskeleton that can work in tandem with the human body in a safe manner. The upper body contains 52 muscle pairs, the lower body 62 pairs, the back has 112 pairs, the chest 52 pairs, the pelvic region 8 pairs, the neck 16 pairs, and the head 25 pairs. The muscular system has vast complexity and is capable of arbitrarily difficult skeletal activities (Vukobratovic, Ciric, & Hristic, 1972).

Full body exoskeletons typically have vast resources of hundreds of thousands to millions of dollars funded by government grants and military entities and have a team of researchers working on research and development. The area is a highly multi-disciplinary track with the need for active and passive actuation, complex programming, anthropometric and ergonomic designs, and optimization of material selection.

As can be seen in the following figure, interest and work in the field of exoskeletons has shown a dramatic increase especially in the last two decades. From 1962 (what is commonly seen as the advent of the first robotic exoskeleton) to present, there have been some 81,000 publications; roughly 75% of which has been done in the last 20 years.

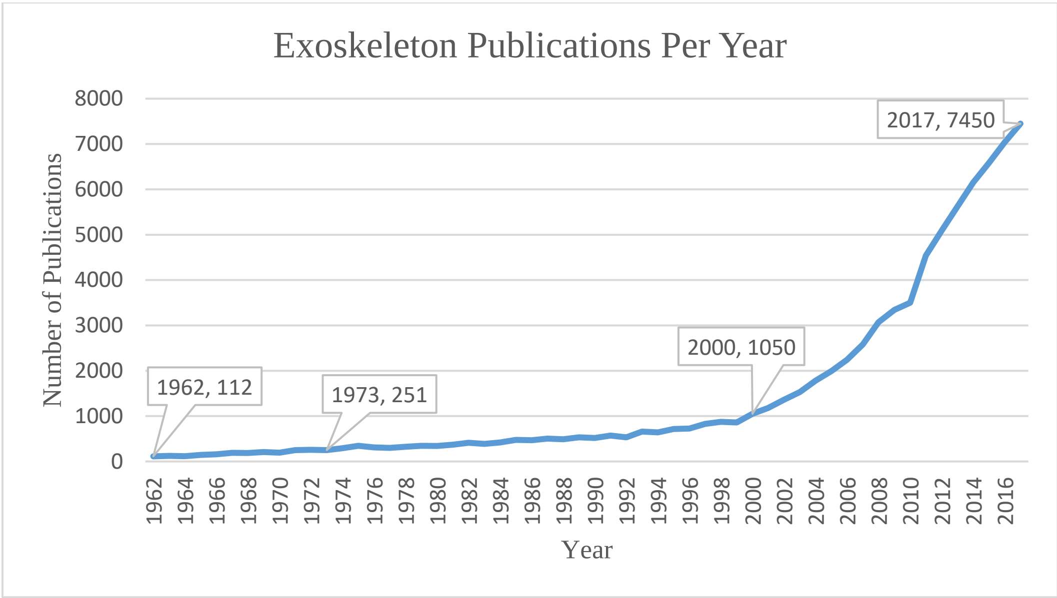

Figure 1: Exoskeleton Publications Per Year

Chapter III Exoskeleton Early Years (1960-1972)

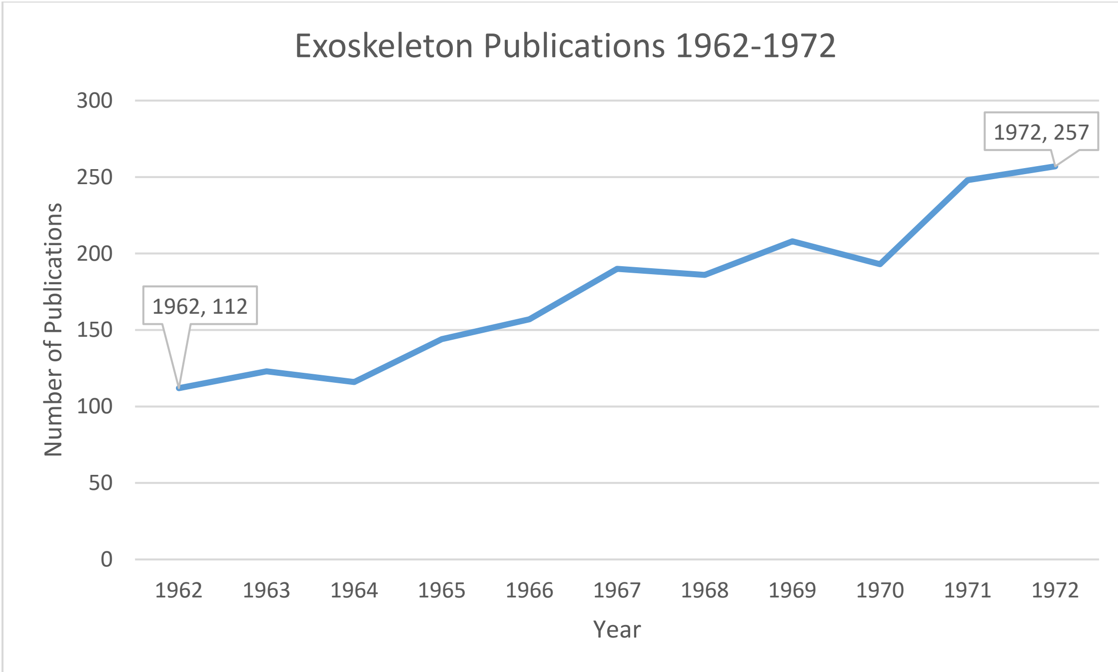

Figure 2: Exoskeleton Publications 1962-1972

Initial development of exoskeletons can be traced back to the early 1960's with the US Defense Department's interest in the development of a man-amplifier. A man-amplifier was a "powered suit of armor" which could augment a soldier's lifting and carrying capabilities (Kazerooni, Steger, & Huang, 2006).

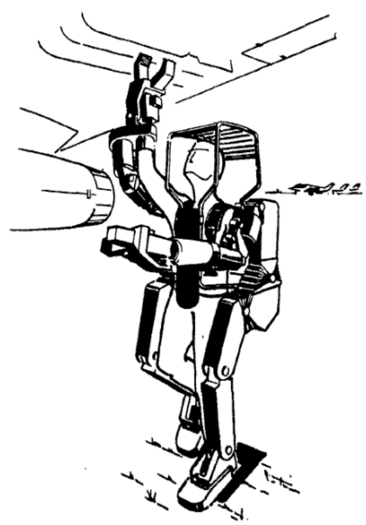

Figure 3: G.E. Hardiman (Fick & Makinson, 1971)

General Electric (GE) developed the first exoskeleton device, beginning in the 1960's and continuing until 1971, called the Hardiman (Mosher & Wendell, Force-Reflecting Electrohydraulic Servomanipulator, 1960). It was developed by Ralph Mosher, an engineer for GE. The suit made carrying 250 pounds seem like 10 pounds. It was a hydraulic and electrical body suit. The outer body suit followed the motions of the inner body suit in a master-slave system. It was determined to be too heavy and bulky for military use. The general idea was well received, but the Hardiman had practical difficulties due to its own weight of 1500 pounds and walking speed of 2.5ft/sec. Any attempted practical testing with the exoskeleton was impossible with a human inside due to the uncontrolled violent movements (Ali, 2014). The Hardiman incorporated force feedback to the operator while expanding from imitation of human manipulation to augmentation (Mosher, 1967).

In 1962, the US Air Force commissioned the study of a master-slave robotic system for use as a man-amplifier from the Cornell Aeronautical Laboratory (Clark, Deleys, & Matheis, 1962) (Mizen N. J., 1962) (Mizen N. J., 1963) (Mizen N. J., Design and Test of a Full-Scale, Wearable, Exoskeletal Structure, 1964). Through their study, the Cornell Aeronautical laboratory found that an exoskeleton, even one with fewer degrees of freedom (DoF) than the human body, could accomplish most desired tasks (Mizen N. J., 1965). However, the master-slave system that the man-amplifiers used were deemed impractical, had difficulty in human sensing, and were overly complex, making walking and other tasks difficult to complete (Kazerooni, Steger, & Huang, 2006) (Clark, Deleys, & Matheis, 1962).

Cornell Aeronautical Laboratory and General Electric weren’t the only groups producing master-slave systems. Case Institute of Technology extended traditional master-slave systems design concepts of bracing and brought them to exoskeletal designs with externally powered manipulation of the body. Their exoskeleton system was able to move patients’ paralyzed arms to perform desired manipulations (Reswick & Mergler, 1962) (Corell & Wijnschenk, 1964). In January of 1972, the National Aeronautics and Space Administration (NASA) performed comprehensive work on the viability of an exoskeleton for extravehicular activities (EVA). In particular, their work looked to the development of sizing and design of future manned spacecraft and stabilization systems as well as a derivation of a mathematical model of human body motion for analysis of "man-motion activities" (Conway, 1972).

Exoskeleton research and design continued. The University of Belgrade, located in Serbia, developed several designs throughout the 1960's and 1970's to aid paraplegics. These exoskeletons were limited to predefined motion with limited success. The balancing algorithms developed for these exoskeletons are still used in many bipedal robots (Vukobratovic, Ciric, & Hristic, 1972). Previous to Vukobratovic's active orthosis, many orthoses were passive in nature and designed to be controlled by the swinging leg (Belforte, Sorli, & Gastaldi, 1997). These passive orthoses like the A.F.O. (ankle-foot orthosis), K.A.F.O. (knee-ankle-foot-orthosis), and H.K.A.F.O. (hip-knee-ankle-foot-orthosis) acted as passive exoskeletons providing a support capacity from the foot up to the thigh (Figure 4: K.A.F.O. Orthosis).

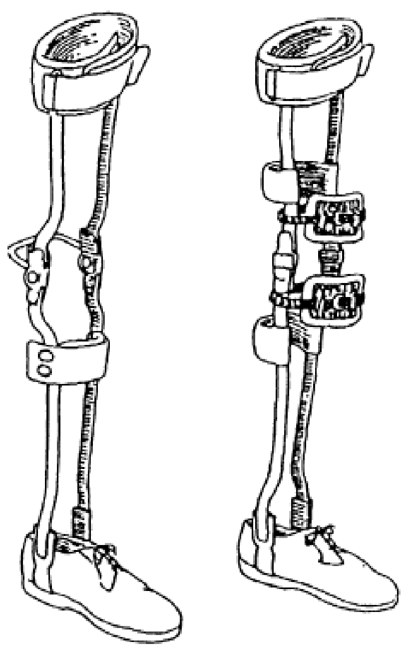

Figure 4: K.A.F.O. Orthosis
(Belforte, Sorli, & Gastaldi, 1997)

Chapter IV Exoskeleton Formative Years (1973-2000)

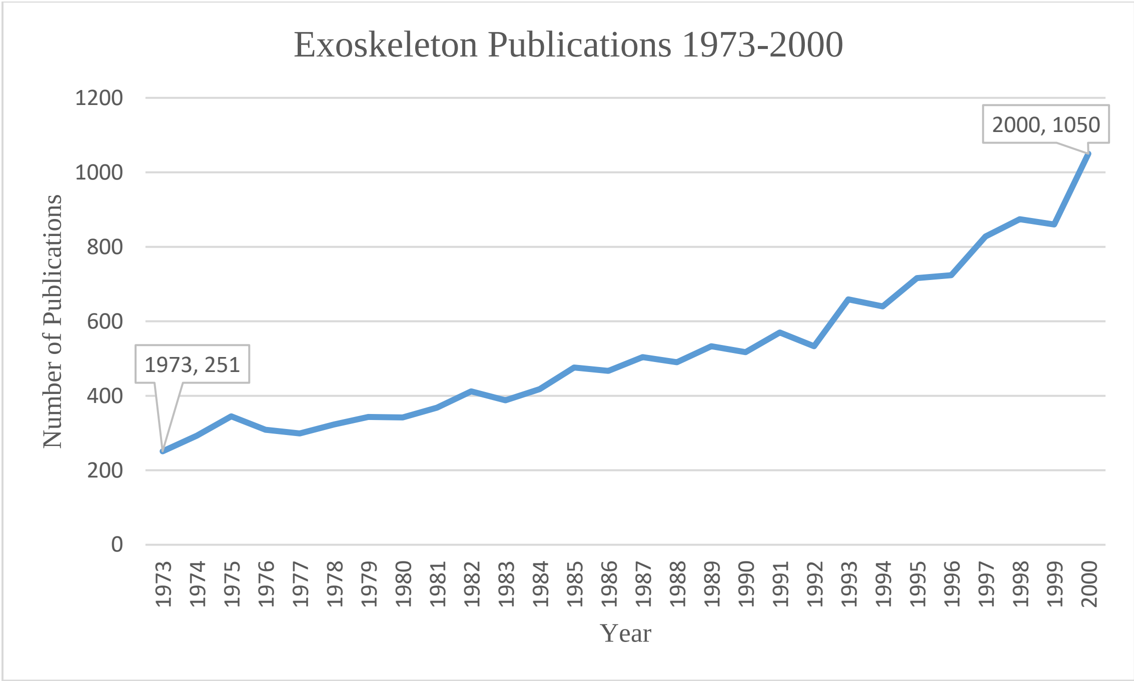

Figure 5: Exoskeleton Publications 1973-2000

During the years of 1973 to 2000, there was a large development of interest in the field of exoskeleton design. This was in no small part due to the previous work done by General Electric, NASA, and Cornell, among others. A lot of the technology and thought processes that we see in modern exoskeleton design really took root during this era and saw lots of research.

While modern robotic manipulators originated in the early 1950's, it is during the early 1970's where we see the first generation of viable industrial level robotic manipulators (Kelly & Huston, 1980). These robotic manipulators eventually began their use in exoskeletons as part of an active actuation mechanism. By 1979, the concept of using anthropomorphic designs with robotic manipulators in exoskeleton design had become well established (Corker, Lyman, & Sheredos, 1979) (Vertut, 1974).

One research focus is geared towards assisting astronauts in extravehicular activities or EVA. The current gloves used by NASA are less flexible than desired, requiring mechanical work to displace the glove and to hold the glove in any given position. This additional required work reduces EVA productivity and fatigues astronauts' hands. Work has been done to create a motorized hand exoskeleton with the ability to perform a power hand grasp and a precision finger grasp. The design consisted of a series of drivers, mechanical stops, sensor arrays, four bar linkages, DC motors, and cable driven cam systems. Human hands are particularly complex with over 25 degrees of freedom (Shields, Main, Peterson, & Strauss, 1997). The hand exoskeleton reduced the allotted degrees of freedom significantly, creating the system's primary shortcoming: the coupling of joints in the hand exoskeleton. The researchers found that if motion for one finger was attempted, the other fingers would also be forced to move, if only a little bit. Additionally, the sensor array would sometimes pick up hand motions that were not there, causing undesired exoskeleton motion.

A robotic apparatus called Skil Mate was introduced to revitalize almost all skilled workers on production sites by introducing cooperation between humans and machines. The aim of the project was to manufacture an exoskeletal structure to be worn by astronauts for EVA. It was designed to have no intelligence or memory, but to work synchronously with skilled workers. The exoskeletal structure covers the worker's arms, hands, fingers, body and legs (Umetani, Yamada, Morizono, Yoshida, & Aoki, 1999).

Chapter V Exoskeleton Current State (2001- PRESENT)

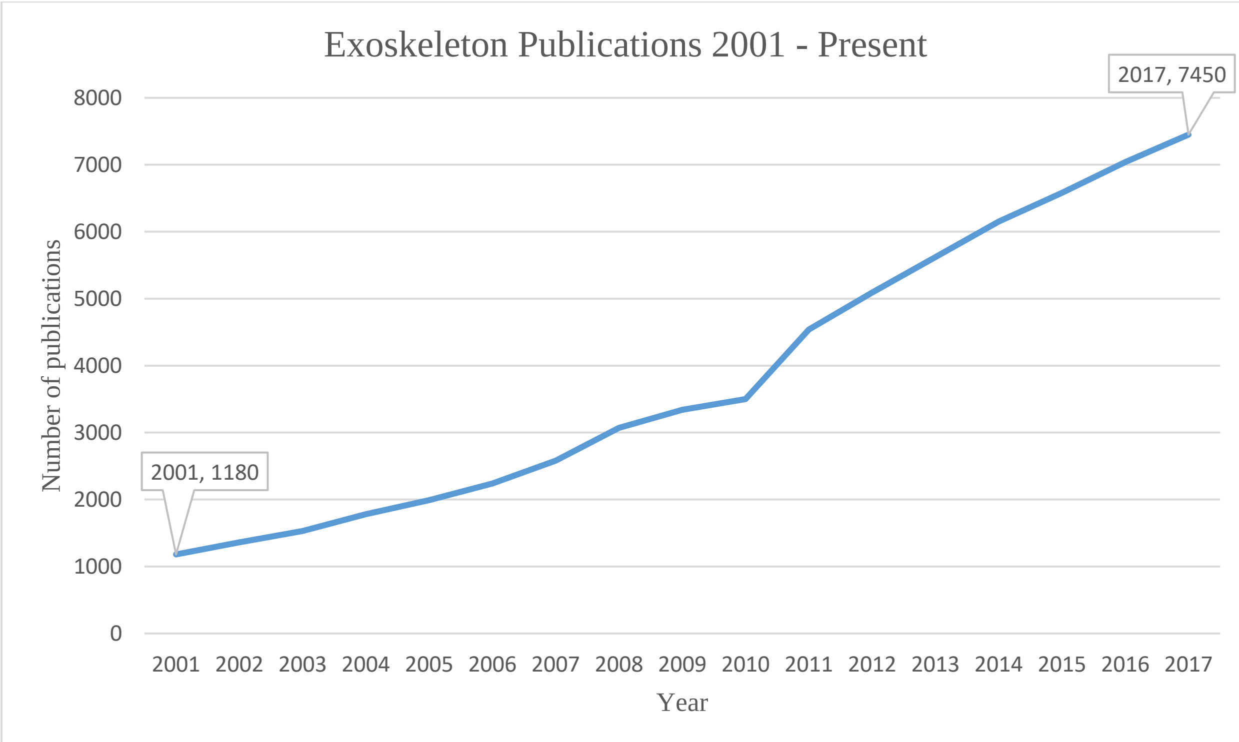

Figure 6: Exoskeleton Publications 2001 - Present

Lo et al. (2012) stated that exoskeleton training used in rehabilitation could potentially enable self-therapy activities without the involvement of therapists, which can reduce the rehabilitation cost. Exoskeleton training could be flexible – not limited to time and location, which can reduce schedule conflicts and provide a more frequent training. The cost associated with these problems can be reduced (Lo & Xie, 2012).

Rehabilitation improvement relies on intensity of training and patients' motivation. Recent studies on exoskeleton for rehabilitation indicate that the exoskeleton can provide trainings with different levels and more frequently compared to the traditional therapist training. Experimental results also show that exoskeleton assisted trainings are effective for activities of daily living, which could benefit stroke patients recover from neurological and orthopedic damages (Mihelj, Nef, & Riener, 2007). Games are integrated into some exoskeleton training activities. Training processes are designed as games in order to provide patients with entertaining experiences, which can improve their motivation of therapy (Lo & Xie, 2012) (Housman, Le, Rahman, Sanchez, & Reinkensmeyer, 2007).

Exoskeletons are used as human assistive devices in industrial environment by reducing the load on human body, which extend human capabilities. In virtual reality, the exoskeleton can be used as a haptic device to allow human users to interact with virtual objects by parameterizing proper force based on their characteristics. Additionally, the exoskeleton serves as a master device for manipulating control systems (Rosen, Perry, Manning, Burns, & Hannaford, 2005).

In order to enhance a soldier's capability and reduce soldier's workload, exoskeletons were developed to assist soldiers with better performance for heavy weapon carrying and firing (Winder & Esposito, 2008). Among the most critical challenge lies in the design of a controller to allow natural movement of a highly articulate prosthetic with minimal ethical and physical invasion. For the foreseeable future, the first step is to determine a mapping from EMG patterns to muscle forces; this should be a primary research focus over the next few years. This method will allow individual finger movements coordinated with the hand, wrist, and elbow, unlike anything current prosthetics can accomplish. This will significantly increase the quality of life for the wearer and the utility of any prosthetic. Furthermore, perceiving and exploiting the intricacies of low-level neural signals will open the door for deeper understanding of cortical control and other methods tapping into spinal or peripheral nerves, thus jumpstarting the field of neuroprosthetics (Dellon & Matsuoka, 2007).

Actuator and power supply technologies still have limitations: Current actuators are unable to provide both a high power-to-weight ratio and high bandwidth while modern power supplies have insufficient energy density (Lo & Xie, 2012). PMA has a high power-to-weight ratio but lack the bandwidth while motors have sufficient bandwidth but have a poor power-to-weight ratio (Lo & Xie, 2012).

Figure 7: HAL-5 (Lo & Xie, 2012)

Current mobile exoskeleton robots rely on a lower limb exoskeleton to carry the weight of the actuators and power supply. Although this has been shown to be a feasible approach with the recent success of the full body HAL-5 exoskeleton for assisting the elderly and physically weak, improvements on the weight and efficiency of the actuators and power supplies are needed to achieve better exoskeleton performance (Lo & Xie, 2012).

Another limitation is the singular configurations present in the exoskeletons 3 DOF shoulder complex which occurs when two rotary joints align with each other, resulting in the loss of 1 DOF. The current method used to address the problem merely shifts the configuration to an uncommon posture rather than eliminating the configuration from the upper limb workspace (Lo & Xie, 2012).

There is limited consideration of the interactions between the exoskeleton and the human user. The mechanical HRI location and interface area for optimal load transfer and comfort have not been considered in current exoskeletons (Lo & Xie, 2012).

The attachment locations of mechanical interfaces and EMG electrodes will inevitably vary each time the exoskeleton is worn. To enable better use of exoskeletons in practice, the device needs to be able to adapt to variations without long calibration downtimes.

Sarcos, an engineering and robotics firm, first developed the XOS2, a second-generation robotics suit, in 2006 after receiving a grant from DARPA. Sarcos was purchased by Raytheon in 2007. The wearable suit enables the user to enhance human strength, agility, support a soldier's capabilities for movement with power, and lift heavy objects (Raytheon XOS 2 Exoskeleton, Second-Generation Robotics Suit, United States of America, 2014). The XOS2 has the capability of weight loading on one foot by using powered limbs. Although dynamic functions of the suit have been developed, an energy problem with the suit has not yet been resolved. It is limited due to a low capacity battery (Yuan, Wang, Ma, & Gong, 2014).

Figure 8: XOS2 (Raytheon XOS 2 Exoskeleton, Second-Generation Robotics Suit, United States of America, 2014)

The ReWalk (Argo Medical Technologies Ltd.) is a wearable robotic exoskeleton which supports powered hip and knee motion to enable individuals with a spinal cord injury (SCI) to stand upright and walk (ReWalk Robotics Announces Reimbursement Coverage by

Figure 9: Rewalk (ReWalk Robotics Announces Reimbursement Coverage by Major German Insurance Company, 2014)

Major German Insurance Company, 2014). The system of ReWalk allows independent, controlled walking and standing while simulating the natural gait patterns of the legs. Although these devices have significant potential physiological benefits, they still have not attained proficiency to be a functional daily use device. Like many exoskeletons today, one of the major issues is the high-energy demands impedes the functional use of the commercially available ambulation devices for paraplegics.

Figure 10: Soft Exosuit (Asbeck, Dyer, Larusson, & Walsh, 2013)

Most exoskeletons currently produced are made of relatively heavy and bulky material. A newer research thrust is in the field of soft exoskeletons, such as the one developed by Harvard's Wyss Institute known as the Soft Exosuit (Asbeck, Dyer, Larusson, & Walsh, 2013). This exoskeleton consists of a combination of hyperelastic strain sensors and sensors located around the wearer's hips, calves, and ankles that are secured by traps. The soft flexible materials, composed of "soft, functional textiles woven into a piece of smart clothing" (Asbeck, Dyer, Larusson, & Walsh, 2013), not only interface with the wearer, but also provides a flexible structure so assistive torques can be applied to biological joints. This soft Exosuit has strong commercial potential for helping spinal-cord injury patients walk or helping soldiers carry heavy loads. The main benefit of the Soft Exosuit is its extremely light design due to the soft material. The wearer's bone structure must sustain all the compressive forces normally encountered by the body plus the forces generated by the body. Therefore, the Soft Exosuit, as a potential tool, can help physical workers with hard tasks and support gait, and also assist in rehabilitation and protection from injury, including spinal cord impairment from heavy physical activity.

This soft exoskeleton can be considered the first of its kind and introduces a new categorization of exoskeletons. Research in the technology progression of soft exoskeletons has begun a new advancement in technology. This concept is able to more readily make its way into more consumer markets when coupled with additive manufacturing technology. The ATHENA Lab, where the author and major professor are based out of, are also working on utilizing additive manufacturing on textiles as a potential manufacturing test bed for future soft-hard hybrid exoskeletons to be used in military, paramilitary, and rehabilitation tasks.

Focused on low impedance, the RoboKnee (a prototype exoskeleton), presents low impedance to the wearer and has a natural interface. To achieve transparency between human and machine, the exoskeleton must successfully perform the following functions:

- Determine the user's intent
- Apply forces when and where appropriate
- Present low impedance

User intent is determined through the knee joint angle and ground reaction forces (Pons, Rocon, & Moresno, 2007). The RoboKnee allows the wearer to climb stairs and perform deep knee bends while carrying a significant load in a backpack. The device provides most of the energy required to work against gravity while the user stays in control, deciding when and where to walk, as well as providing balance and control (Pratt, Krupp, & Morse, 2014).

Due to low energy density batteries, the RoboKnee does not yet achieve a long-life requirement. While it is very comfortable to use, the current implementation is somewhat difficult to don and doff. While the RoboKnee enhances strength and endurance, it was not designed for enhancing the user's speed and in fact, restricts the user from running (Pratt, Krupp, & Morse, 2014). Further recommendation from authors was to develop an exoskeleton that incorporate other joints than just the knee (Pratt, Krupp, & Morse, 2014).

The overall challenges of lower body exoskeleton robots are to (1) have lightweight action and efficient transmission; (2) maintain power, actuation, and other subsystems, (off the shelf components do not typically meet the low weight, high efficiency, and other criteria needed to accomplish their design objective); and (3) examine quantitative performance results for exoskeleton devices that reportedly improve human locomotion.

To achieve the above challenges, lower body exoskeleton robots should develop computing, sensing, and control without pervasive application. Therefore, matching the structure of the exoskeleton to the wearer is a fundamental factor. Four criteria must be considered and met, including the need for (1) alignment between joints of the robot and wearer; (2) segment running and/or jumping ability; (3) safety of the human operator; and (4) a naturally interfacing exoskeleton or active orthoses with the human body.

What Are The Issues Faced In Designing For Exoskeletons?

Current power supplies have insufficient energy density for truly mobile exoskeletons (Lo & Xie, 2012). Large, heavy power supplies limit portability and are one of the major factors limiting application of exoskeletons outside of clinical therapy (Lo & Xie, 2012) and other "grounded" applications. Some researchers have proposed interim solutions such as mounting upper body exoskeletons to powered wheelchairs (Kiguchi, Rahman, Sasaki, & Teramoto, 2008), but improvements on the weight and efficiency of power supplies are still needed to achieve better exoskeleton performance (Lo & Xie, 2012).

> "A mechanism that synthesizes a human-type motion will necessarily also be complex, particularly from the control standpoint. Therefore, researchers in this area have often tried to reduce the number of degrees of freedom to as great an extent as is practical (Shields, Main, Peterson, & Strauss, 1997)."

In designing a prototype hand exoskeleton (Shields, Main, Peterson, & Strauss, 1997), researchers reduced complexity by reducing DOF to one per finger but discovered problems with this approach. "The human hand has over 25 degrees of freedom, many of which are coupled by the ligamentous structure and location of tendon insertions. This coupling was clearly evident during exoskeleton tests (Shields, Main, Peterson, & Strauss, 1997)," in which undesired exoskeleton motion was observed. "One obvious solution to this problem is to add more degrees of freedom to the exoskeleton. This will unfortunately also result in added complexity, weight, and bulk, not to mention a more sophisticated controller (Shields, Main, Peterson, & Strauss, 1997)."

Figure 12: BLEEX (Zoss, Kazerooni, & Chu, 2006)

Researchers involved with the BLEEX lower body exoskeleton took a different approach to this tradeoff. “Each BLEEX leg has 7 DOF... but actuating all of them creates unnecessarily high- power consumption and control complexity. Instead, only joints that require substantial power should be actuated… [S]ince the primary goal of a lower-extremity exoskeleton is locomotion, the joint power requirements for the BLEEX were determined by analyzing the walking cycle…. (Zoss, Kazerooni, & Chu, 2006)” Additionally, the hip and other joints were simplified such that overall the BLEEX represents a “near anthropomorphic” design (Zoss & Kazerooni, Design of an Electrically Actuated Lower Extremity Exoskeleton, 2006). Many current upper body exoskeletons overcome weight or bulk issues by being mounted

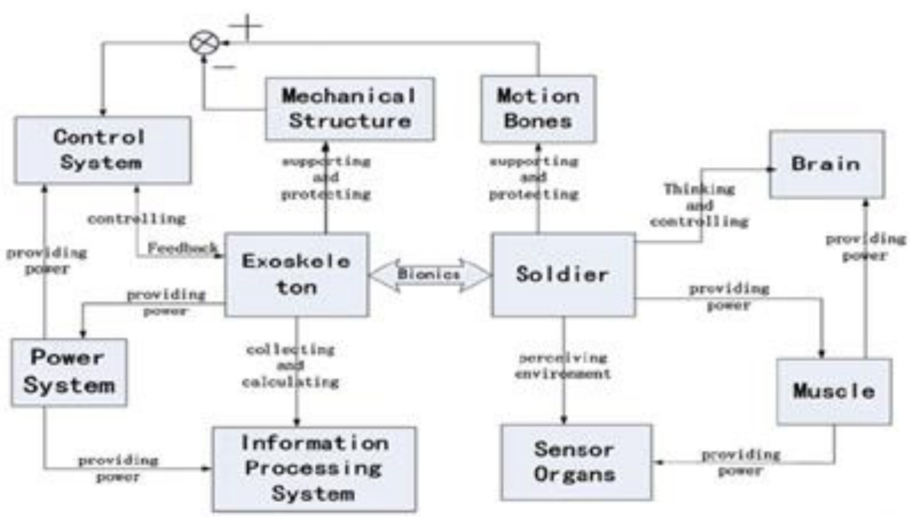

Figure 11: The control principle of exoskeletons (Yuan, Wang, Ma, & Gong, 2014)

to a wall or stand (i.e., "grounded"), or to a wheelchair (Lo & Xie, 2012). This is adequate for applications where a limited and defined workspace is involved, or where a patient requires a wheelchair. While lower body and full body exoskeletons bear their own weight, there are many applications for which a wearable, "ambulatory" orthotic or assistive device is all that is needed. Improvements in mass, power density, and actuation are necessary precursors to widespread use.

The aesthetic appeal of the exoskeleton will eventually have to be addressed, at least for some applications. For example, like many current exoskeletons, WOTAS was designed as a platform to explore a specific concept, and not as a final orthotic solution. While it successfully demonstrated the feasibility of mechanical tremor suppression, it was too bulky and heavy to be used day-to-day (Rocon, et al., 2007). "The main wish expressed by the potential users was the possibility of hiding the exoskeleton under clothing (Rocon, et al., 2007)."

Skin surface EMG signals are often used as a control input because they directly reflect the intentions of the user, but EMG-based control is difficult to realize due to several issues: obtaining the same EMG signals for the same motion is difficult even with the same person, the activity of antagonist muscles affects the joint torque, many muscles are involved in a single joint motion, one muscle is simultaneously involved in more than one motion, the role of each muscle for a certain motion varies in accordance with joint angles, the activity level of some muscles such as bi-articular muscles are affected by the motion of other joints (Kiguchi, Rahman, Sasaki, & Teramoto, 2008) and the EMG signals can vary due to muscle fatigue (Lalitharatne, Teramoto, Hayashi, Nanayakkara, & Kiguchi, 2013).

Additional uncertainty is related to the differences between humans and machines. "The exact locations of the human joint axes of rotation cannot be known on living subjects, due to coverage of the joints. Biological joints are not ideal "single DOF" joints, but have rather complex joint surface geometries, which cause shifting axes of rotation during motion. Additionally, fixation of a robotic device on a human limb is never rigid, such that slippage between the device and the limb will occur. This will lead to further misalignment between the mechanism and human joints (Schiele & van der Helm, Kinematic Design to Improve Ergonomics in Human Machine Interaction, 2006)," on the order of a few centimeters (Schiele & van der Helm, 2006). Such misalignment can lead to pressure sores on the skin, long-term joint damage, joint dislocation and cartilage damage, and stumbling (Schiele & van der Helm, 2006).

The activity level of each muscle and the way of using each muscle for a certain motion is different between persons (Kiguchi, Rahman, Sasaki, & Teramoto, 2008). Several solutions proposed to provide adaptive control between users: adjusting impedance (Kiguchi, Rahman, Sasaki, & Teramoto, 2008), myoprocessors with optimization ("gene" modelling) (Cavallaro, Rosen, Perry, & Burns, 2006), adaptive gain (Kang & Wang, 2013), and neuro fuzzy modifiers (Gopura, Kiguchi, & Li, 2009).

Safety is a paramount concern with robotic systems, especially for robots that must interact with humans. Unfortunately, "there is no industry-standard approach to designing these safety-critical robot systems. Numerous safety-critical software systems have been developed and deployed in other domains ranging from aircraft flight management systems to nuclear power plants (Roderick & Carignan, 2005)." Similar analytical methods, such as fault tree analysis, should be applied to the design of robotic exoskeletons. Some common concerns with these systems are moving the human outside their safe position range, moving the human at an excessive velocity, and applying excessive torque to the human or allowing the human to apply excessive torque against the robot.

It is especially important when designing and manufacturing an exoskeleton for those who are severely disabled. Many paralyzing pathologies can result in the person's inability to have feeling in the affected limbs making it very dangerous to fit any anthropomorphic device because the patient has no sensory feedback if they are inadvertently injured from the fitting process (Corker, Lyman, & Sheredos, 1979).

The system reaction to fault detection must also be carefully considered. For example, upon fault detection, the system could be commanded to either halt motion or power down the affected motors. Removing power has the undesirable effect of leaving the human to bear the weight of the device, which presents hazards of its own. This approach is only appropriate in response to more severe failures (Roderick & Carignan, 2005).

The safety requirements for mechanical design of the upper body exoskeleton include: "axes deviation of wrist flexion/extension axis and wrist radial/ulnar axis" should be satisfied; "ill effect caused by the movement of the center of rotation of shoulder joint due to upper-arm motions should be canceled out"; "the mechanical singularity should not be occurred within the workspace of the robot (Gopura & Kiguchi, 2009)."

The two main aspects that need more consideration are: (Schiele, Undesired Constraint Forces in Non-Ergonomic Wearable Exoskeletons, 2007) (1) implementation of the actuation and motor control and (2) intrinsic mechanical and kinematic design of their structure. In order to ensure human safety when using exoskeletons, mechanical constraints combined with software limitations are the most popular methods. CADEN-7 used mechanical constraints to prevent the excessive movement of body segments. CADEN-7 also used pulley in design to enable slip when limitation reached. Electrical system of CADEN-7 contained 3 shutoff switches to set electrical constraints. Gopura et al. also used mechanical stops and control limitations to ensure safety (Gopura, Kiguchi, & Li, 2009).

What Can We Do To Make Exoskeletons Better?

There are a few areas related to the mechanical design of exoskeletons that show promise and have largely been overlooked. An improved understanding of walking and other movement may shed light on more effective exoskeleton leg architectures (Dollar & Herr, 2008) Gait models based on actual machine elements that capture the major features of human locomotion may enhance the understanding of human leg morphology and control and lead to analogous improvements in the design of efficient, low-mass exoskeletons (Dollar & Herr, 2008).

Investigation of nonanthromorphic architectures may provide solutions to some of the problems associated with closely matching the structure of the exoskeleton to the wearer such as the need for close alignment between joints of the wearer and the exoskeleton (Dollar & Herr, 2008). More research is required on recreational exoskeletons that augment running or with jumping ability (Dollar & Herr, 2008).

Besides enabling technology and mechanical design there are a few issues related to the implementation of exoskeletons and active orthoses that needs further studying (Dollar & Herr, 2008). Designing an exoskeleton with good mechanical strength, less weight, sufficient grip force, low power consumption, computational capability compatible to control scheme, and high speed of operation in tandem is difficult and costly to do (Singh & Chatterji, 2012).

The design of structure is one area where an imaginative design may reduce lot of stress from weight constraint. The grip force and power consumption can be taken care by the proper choice of the actuators (Singh & Chatterji, 2012).

The ideal requirements are material for mechanical structure having mechanical strength, flexibility and weight like bone, the controller having computational capability, speed and adaptability like brain, actuator having high torque and flexibility like muscles, and the feedback elements having sensing capability like skin (Singh & Chatterji, 2012).

EMG has a definite potential to be used as control signal for multifunction prosthesis. There is need to draw correlation between the physiological, physical factors and the EMG signal (Song & Guo, 2011). Advanced algorithms need to be developed to extract useful neural information (Song & Guo, 2011). One of the innovative aspects is the combined use of electroencephalogram (EEG) and electromyography (EMG) to relay information for controlling the lower-limb exoskeleton (Singh & Chatterji, 2012).

Chapter VI The Call For A Design Methodology

The literature shows the inherent multidisciplinary requirements and different approaches that engineers use for designing and developing their exoskeletons. Naturally, every field has their own approach to design and there is no standardization for exoskeleton design across the disciplines. These various approaches lead to inconsistent design practices, inconsistent analyses, and inconsistent solutions. There are no published guidelines for designing and developing exoskeletons that not only works but is ultimately safe and useful for the user.

This multidisciplinary methodology approach aims to address the lack of consistency in the design process for exoskeletons in such a way to make the process applicable to a wide range of engineering applications.

This dissertation will look at designing upper body exoskeletons for the training of healthy law enforcement personnel as a case study of QuANTUM Ex. The QuANTUM Ex Method is a design methodology for exoskeletons that train healthy people. Ultimately, the goal is to provide a safe and reliable method for exoskeleton design.

It is important to note that this dissertation looks at laying the groundwork for exoskeleton design. It supplies the initial set of rules and methods for this design methodology. By necessity, as tools and techniques evolve, so will the QuANTUM Ex Method. Part of this evolution can be seen during the development stages of the QuANTUM Ex Method lifecycle found in the proceeding chapters. The methodology development chapters are being prepared for submission as a journal.

Chapter VII Methodology Development Stage 1.1 – Engineering Design Considerations

It is important to recognize that any model is a simplified description of a more complicated reality. Engineering design has become a technology intensive process (Siddall, 1990) with a multitude of rules, procedures, and information. So much so that a simple task of recalling relevant information during a design task becomes tedious and overwhelming. Smith and Reinertsen's efficiency reports show that tasks that involve information recall hinder streamlined operations slowing down product development and deployment (Smith & Reinertsen, 1991). This information is implemented in the QuANTUM Ex Method by supplying the engineering design team basic information that helps them complete each section of the associated workbook. This helps reduce the amount of cognitive loading of recalling from long term memory and even working memory by having basic information and concepts recalled for them. In the actual design process, the design team should review the workbook concepts and further research can be done to bridge any additional gaps.

As shown in the previous literature review, as well as what was found by Winter in his dissertation (Winter, 1998), the number of definitions and diversity of views of design are large and varied.

There have been numerous attempts to define the design process, but there is no single accepted definition (Fingers & Dixon, 1989). Many attempts have been made in an attempt to define the design process, however, there is no single accepted definition. A generic flow diagram of the design process was developed by Winter and can be seen recreated below (Winter, 1998):

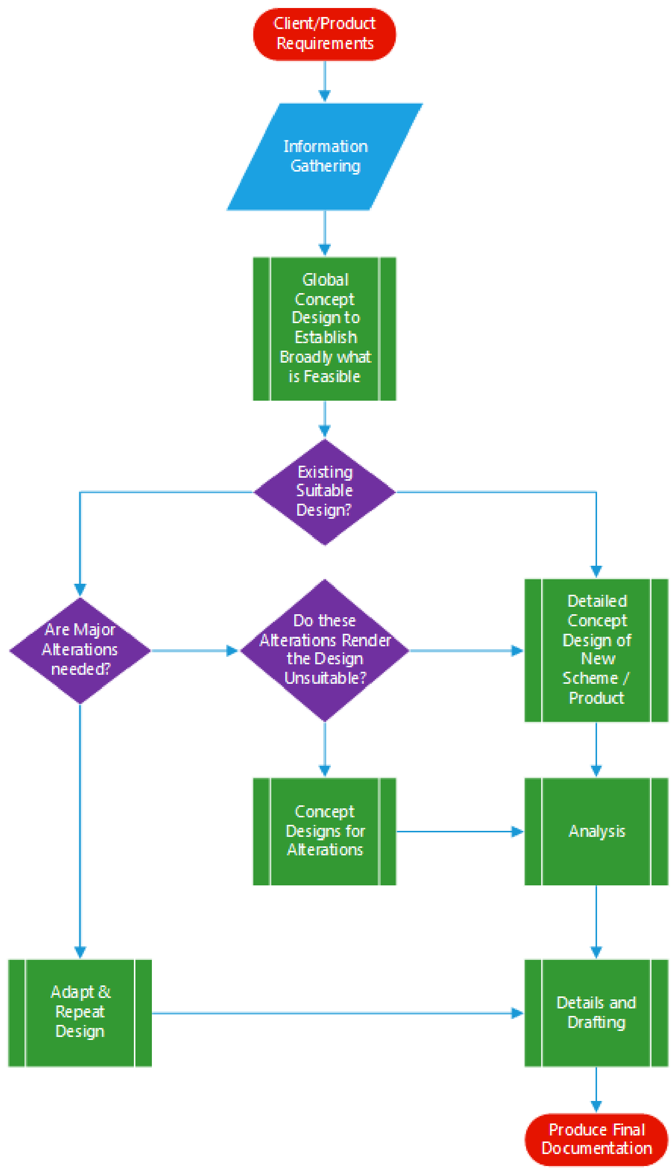

Figure 13: Flow diagram of the design process (adapted from (Winter, 1998))

A thorough review of the existing literature on what defines design yields numerous diverse views and definitions. A 1990 study asked the question of "What constitutes design?" (Talukdar, Rehy, & Elfes, 1990). The most common responses were:

- Satisfying constraints and meeting objectives
- Problem solving

- Decision making
- Reasoning under certainty
- Search
- planning

Classes of Design

Design tasks can be split into three generalized classes (Krishnamoorthy & Rajeev, 1996) as follows: Class 1: Major inventions or completely new products; Class 2: Designs which involve substantial innovation; and Class 3: Routine design which involves selecting among previous known alternatives. Krishnamoorthy and Rajeev go on to explain that simply reworking existing designs do not constitute design unless substantial alterations are made. The QuANTUM Ex Method is designed primarily for Class 1 designs to assist in developing new exoskeletons and exoskeleton design alternatives. Its robust design allows it to compare and evaluate these alternatives and therefore can also work with Class 2 and Class 3 designs.

Design Tasks

In all design tasks there are a core set of rules, laws, principles, and techniques that engineers use for problem solving. Engineers' ability to use their knowledge and the afore stated core principles to produce optimal designs in minimal time are defining characteristics of what is considered a good engineer. Their expertise is the result of experience and training, much of which has been taught to them during a four-year education and previous exposure to similar design problems. Problem modeling is inherent to the scientific method and is a central theme found in engineering (Burr & Cheathma, 1995).

Task Analysis Methods in Industry

Task analysis is one of the most basic tools used in ergonomics for investigating and designing tasks. According to Drury, it provides a formal comparison between task demands and the capability of the human. There are three types of tasks analyses: (1) sequential, (2) branching, and (3) process control (Drury, 1983):

(1) Sequential – A sequence of tasks follow a rigid pattern with a minimum number of alternatives (i.e. a detailed start-up sequence for any equipment).

(2) Branching – The sequence is determined by the outcome of particular ‘choice’ tasks within the operation (i.e. a trouble-shooting guide).

(3) Process control – The operator is in continuous control of multiple variables and has a flexible strategy for monitoring, sampling, and initiating control actions based on complex patterns of the controlled variables

The QuANTUM Ex Method has the design team complete multiple iterations of either sequential or branching task analyses (based on the appropriateness of the design). The initial task analysis is done early on in the design process to understand the task that is being completed. As more assumptions and constraints are uncovered during the design process, additional task analyses are completed – expanding or contracting as needed.

Professional design survey

The following chapter is a conference paper published in the proceedings of the *Human Factors and Ergonomics Society Annual Meeting*. It provides an initial framework and reasoning behind the weighting method developed for the QuANTUM Ex Method. This work is expanded on and redeveloped based on the results found in the next chapter.

Chapter VIII Ranking Importance Of Exoskeleton Design Aspects

A paper published in the proceedings of the *Human Factors and Ergonomics Society*

Thomas M. Schnieders and Richard T. Stone

Abstract

The objective of this research project was to determine what a conglomerate of professionals consider as the most important metrics to consider when designing an exoskeleton for training. Over 400 researchers, engineers, and scientists were polled in a ranked order survey covering more than 50 different aspects in engineering design. These aspects were identified from a cogent literature review for consideration. While there are a slew of papers covering the results of exoskeleton designs as posture support mechanisms, rehabilitation mechanisms, tools to assist or replace body functions, and human performance augmentation, few cover what aspects were considered in the engineering design phase.

INTRODUCTION

There is a wide variety of exoskeletons designs and published that are used in many applications such as posture support mechanisms, rehabilitation mechanisms, tools to assist or replace body functions (Rocon, et al., 2007), and human performance augmentation (Schnieders & Stone, Current Work in the Human-Machine Interface for Ergonomic Intervention with Exoskeletons, 2017).

However, few papers look at utilizing exoskeleton devices as a tool for training healthy humans. Some recent work has looked at how to train healthy police officers in handgun training (Schnieders, Stone, Oviatt, & Danford-Klein, ARCTiC LawE - An Upper Body Exoskeleton for

Firearm Training, 2017) and specifically the effect of locking out wrist flexion and extension (Schnieders, Stone, Danford-Klein, & Oviatt, 2017) and locking out radial and ulnar deviation (Schnieders, Stone, Oviatt, & Danford-Kelin, The Effect of Locking out Radial and Ulnar Deviation with an Upper Body Exoskeleton on Handgun Training, 2017).

The vast literature on exoskeletons from as early as 1962 to present has been void of any ranking or recommendations on what aspects of design should be prioritized when designing exoskeletons (Schnieders & Stone, Current Work in the Human-Machine Interface for Ergonomic Intervention with Exoskeletons, 2017). Over 40 different aspects in engineering design were identifed as potentially important aspects to consider and were comiled into a master list within a rank order survey. These aspects were identified from a cogent literature review (Schnieders & Stone, Current Work in the Human-Machine Interface for Ergonomic Intervention with Exoskeletons, 2017) for consideration.

It would make for poor engineering design practice to attempt to satisfice all 50+ different engineering design aspects into a single exoskeleton design. To alleviate this issue, a ranked order survey was conducted. It is important, however, that when conducting a survey across such a broad, multidisciplinary topic that one determines the order of importance and which metrics to be concerned about.

Prior to our analysis of the rank order, it is important to discuss how we classify an expert. It is known that an expert is often unaware of the range and scope of his knowledge (Cheyayeb, Conor, & Slater, 1985). Therefore, there is a need to recognize what constitutes an expert and determine who to recognize an expert. In their doctoral dissertation, S. J. Winter states that experts have many abilities, such as easily solving simple problems, asking appropriate questions, be able to explain why they asked those questions, easily talk to other experts in their field, and be able to transfer knowledge from one domain to another (Winter, 1998).

Materials and Methods

Ranked Order Survey

Professionals in engineering, human-computer interaction, and other related fields who hold a post-secondary degree were defined as subject matter experts and as qualified experts in their field.

These professionals were contacted via email to take part in a survey. After completing the informed consent, they were asked qualitative questions such as highest degree earned, the university they obtained that degree, their current institution, and to list three journal publications that they are an author for, if applicable.

They were then asked to perform a ranked order survey for designing an upper body exoskeleton for training with over 50 different metrics identified in a literature review. Some of the identified metrics included:

- Cost
- Manufacturability
- Weight
- Anthropometry
- Comfort

- Ease of use
- Degrees of freedom
- Social impact
- Biomechanics

The ranked order portion of the survey has participants order the 55-different metrics in the order of most important aspect to consider. They were told to assume that the ranked order will be considered when designing an upper body exoskeleton for training.

Categorization Task

Independently, a categorization task was conducted by 4 experts who either hold, or are pursuing, a doctoral degree. These experts have backgrounds in industrial engineering, human factors, ergonomics, mechanical engineering, manufacturing, and human-computer interaction. Following the categorization, a Fleiss' kappa analysis was conducted on the categorization to assess the reliability of agreement between the 4 experts.

Results

Ranked Order Survey

Over 400 participants were identified from a survey of the literature. Of those 400 surveyed, 40 participants from 35 different institutions, and 12 different countries responded.

The participants of the ranked order survey held 21 doctoral degrees, 11 master's degrees, and 8 baccalaureate degrees as their highest degree earned.

Forty participants with 55 ranked metrics yields a 40x55 matrix of 2200 cells. A heat map was used to identify design metrics considered by the experts as the top 1/3, middle 1/3, and bottom 1/3 for importance (see Figure 14: Ranked Order Heat Map). Bright green on the heat map indicates highest importance at a rank of 1. Bright yellow on the heat map indicates exactly half and bright red on the heat map indicates lowest importance at a rank of 55. The heat map was designed to show a range of color between those three indicators to represent their degree of closeness to a particular cut-off rank.

Each design metric, after being placed into the heat map in Figure 1, was then assessed to determine a count of times the metric was placed in the top ¼, top ½, the bottom ½, and the bottom ¼.

In the top ½ were design metrics where more than half of the participants agreed that the metric was in the top 20 metrics to consider when designing an upper body exoskeleton for training. These metrics included: cost, manufacturability, weight, variability within persons, variability between persons, number of parts vs. ability to actuate, training motivation, how the exoskeleton attaches to the body, statics, dynamics, range of motion/flexibility, comfort, every day carry vs. tool for training, muscle memory and response, sensory motor learning, form factor, ease of manufacturing, anthropometry, battery density, use as protection, maximum push forces, formability to body, degrees of freedom, and ease of use.

In the top ¼ were design metrics where more than 75% of the participants agreed that the metric was in the top 10 metrics to consider when designing an upper body exoskeleton for training. These metrics included variability between persons, how the exoskeleton attaches to the body, range of motion/flexibility, and comfort.

The bottom ½ were design metrics where more than half of the participants agreed that the metric was in the bottom 20 metrics to consider when designing an upper body exoskeleton for training. These metrics included: environmental factors, perspiration mitigation, maximum pull forces, type of fuel (battery/gas/etc.), actual exertion, actual fatigue, perceived exertion, perceived fatigue, intuitive use (affordances), lifespan of exoskeleton (standard conditions), lifespan of exoskeleton (extreme conditions), temperature considerations, humidity considerations, iterative design, human factors/ergonomics considerations, potential stress/strain on joints/muscles, distribution of mass, center of mass, sound, repetition and fatigue, high speed motion, effect of unequal loading, psychophyiscs, abrasion of material on body, social impact, replaceable parts, material strength, material elasticity, biomechanics.

The bottom ¼ were design metrics where more than 75% of the participants agreed that the metric was in the bottom 10 metrics to consider when designing an upper body exoskeleton for training. These metrics included: center of mass, sound, high speed motion, effect of unequal loading, psychophysics, social impact, replaceable parts, material strength, and material elasticity.

Categorization Task

The 4 experts completed this task independently and determine the following categories: maintenance, manufacturing, functionality, material properties, power options, human factors, environment, biomechanics, form and fit considerations/limitations, design factors, build factors, financial factors, performance factors, and social factors.

These categories were combined into the following four categories: Human Factors, Design Factors, Financial Factors, and Performance Factors. This was done to combine similar subcategories and to produce more overarching meta-categories on an ordinal scale, making the inter-rater reliability analysis more appropriate for this ranked order analysis.

A Fleiss' kappa analysis was conducted on the categorization to assess the reliability of agreement between the fixed number of raters over the four categories. Fleiss' kappa is defined as

$$\kappa = \frac{\bar{P} - \bar{P}_e}{1 - \bar{P}_e}$$

Where $1 - \bar{P}_e$ is defined as the degree of agreement that is attainable above chance and $\bar{P} - \bar{P}_e$ is defined as the degree of agreement actually achieved above chance. The number of design metrics are indexed by $i = 1, \ldots, N$ where N represents the total number of metrics. The number of categories is indexed by $j = 1, \ldots, k$. The variable n_{ij} represents the number of raters who have assigned the i-th subjects to the j-th category. P_j represents the proportion of all assignments in the j-th category and is defined as

$$p_j = \frac{1}{Nn} \Sigma_{i=1}^{k} n_{ij}(n_{ij} - 1)$$

P_i represents the extent to which raters agree for the i-th subjects and is defined as

$$P_i = \frac{1}{n(n-1)} \Sigma_{j=1}^{k} n_{ij}\left(n_{ij} - 1\right)$$

Which can be expanded to

$$P_i = \frac{1}{n(n-1)} \left[\left(\Sigma_{j=1}^{k} n_{ij}^2\right) - (n)\right]$$

$\bar{P}$ represents the mean of P_i and is defined as

$$\bar{P} = \frac{1}{N} \Sigma_{i=1}^{N} P_i$$

$\overline{P_e}$ represents the mean of P_e and is defined as

$$\overline{P_e} = \Sigma_{j=1}^{k} P_j^2$$

Figure 14: Ranked Order Heat Map

Equations (2)-(6)(2)(2)(2)(2) are then plugged back into equation (1) to calculate Fleiss' kappa. A kappa value of 0.42 was calculated. The categorizations developed by the four experts can then be applied to the rank order analysis.

The categories are ranked from most important to consider to least important to consider as follows: Human factors, design factors, performance factors, financial factors, and social factors. This ranking was determined by the number of design metrics scoring in the top ½ from the rank order survey.

Discussion

Rank Order Survey

This rank order survey provides a basic, yet intuitive way to look at engineering design metrics when approaching upper body exoskeletons for training.

From this analysis, we see that the most important metrics (i.e. the metrics to consider first) are:

- Variability between persons
- How the exoskeleton attaches to the body
- Range of motion/flexibility
- Comfort

And the least important metrics (i.e. the metrics to consider later) are:

- Center of mass

- Sound
- High speed motion
- Effect of unequal loading
- Psychophysics
- Social impact
- Replaceable parts
- Material strength
- Material elasticity

However, a split into the most important and least important aspects, according to this rank order survey, is not enough. Looking at a higher level, we, by default, split the group into the top half and the bottom half. However, it is important to also look at the actual data. To see the entire picture. There were numerous metrics that had an almost even split (20±2) that ended in one half or the other. These metrics were environmental factors (18/22), perspiration mitigation (18/22), formability to the body (20/20), degrees of freedom (22/18), perceived fatigue (19/21), intuitive use (affordance) (19/21), and human factors / ergonomics considerations (19/21).

It is important to note that human factors and ergonomics considerations ranked in the lower half of the distribution. With some considerations such as biomechanical aspects ranking last. This is consistent with the current state of research, as most exoskeleton studies (and the associated designers of these devices) focus on the functional components rather than the impact or even need for the device itself.

This analysis was conducted to give designers and researchers a starting point as to which aspects to consider as most important. However, it should be noted that these results are not necessarily indicative of the only metrics to consider. Certainly, aspects that are categorized as less important may not be less important depending on the actual design and purpose of that exoskeleton. These are things that the research/design team should take into consideration first. Recall that, in an ideal scenario, all 55 metrics as well as others would be considered and that this ranked order is looking at where to begin with the design.

Categorization Task

Landis and Koch provide the table below to interpret kappa values (Landis & Koch, 1977).

Table 1: Fleiss' Kappa Interpretation (Landis & Koch, 1977)

κ	Interpretation
<0	Poor agreement
0.01 – 0.20	Slight agreement
0.21 -0.40	Fair agreement
0.41 – 0.60	Moderate agreement
0.61 – 0.80	Substantial agreement
0.81 – 1.00	Almost perfect agreement

With a calculated κ value of 0.42, the four experts are in moderate agreement with the categorization. However, the above table may not be the best interpretation and could be misleading (Gwet, 2014). This categorization task was appropriate to determine the overarching most important categories to consider followed by the most important sub-categories or design metrics to consider.

Conclusion and Future Work

A categorization task involving four experts with backgrounds in industrial engineering, human factors, ergonomics, manufacturing, mechanical engineering, and human-computer interaction and a rank order survey involving 40 participants from 35 different institutions, and 12 different countries were completed.

The results indicate the most important categories and design metrics to consider when designing upper body exoskeletons for training. Ideally, all of the 55 different design metrics should be considered, but this study proposes the most crucial to consider first or when time and/or resource demands constrains the design challenge.

Future work includes taking the ranked order information and applying it to an exoskeleton design methodology. The author of this work is currently developing the QuANTUM Ex Method. QuANTUM Ex is short for **Qu**antitative **A**ssessment for **N**on-**T**ested **U**niversally **M**ade **Ex**oskeletons and is being designed as a methodology for exoskeleton design. The ranked order survey data will be applied as part of a metric weighting system within the QuANTUM Ex Method.

In more general applications, this data can be used to determine which design aspects should be considered of highest importance when designing exoskeletons for training. Similar methods could be implemented to determine a ranked order for other types of exoskeletal applications.

To construct a similar heat map, a thorough literature review should be conducted pertaining to the exoskeletons' location on the body as well as the function. This will help identify the most important aspects of engineering design to consider when conducting analyses.

Chapter IX Re-Evaluation Of Exoskeleton Design Metrics

The following chapter is currently under review in *Human Factors*. After reviewing the results of the previous chapter, the authors believed further analysis could be completed. The paper presented in the previous chapter was an initial look at how a conglomerate of experts in design and exoskeletal research would rank 55 engineering design metrics.

As discussed, the mental demand of simultaneously assessing all 55 metrics simultaneously and placing those metrics in ordinal scale may have proved to be difficult. A categorization task was proposed but the research team believes this categorization should rely not only on how well each metric fits within a category, but it should also consider the inherent interdependencies found within the 55 metrics. The following chapter utilized the analytic network process to evaluate weighted ranking using interdependencies.

Chapter X A Comparison Of Analytic Network Process And Weighted Rank Order In The Exoskeleton Design Process

A paper submitted to Human Factors

Thomas M. Schnieders, Ahmad A. Mumani, and Richard T. Stone

Abstract

Objective

The objective was to compare a weighted rank order approach and an analytic network process (ANP) approach to ranking metrics in the exoskeleton design process.

Background

In nearly 60 years of research on exoskeleton design, manufacturing, testing, and application, few researchers study what goes into the process of designing these devices that augment human performance. How to best design an exoskeleton remains under-researched and ultimately unclear. ANP was used due to its ability to consider multi-levels of interaction and interdependencies between decision criteria while encapsulating the advantages of expert opinion.

Methods

A panel of experts categorized 55 engineering design metrics into five categories. Discussion sessions were conducted to identify the metrics' interdependencies yielding an unweighted, weighted, and limit priority super-matrix from the ANP model.

Results

The results of the ANP model provide an analysis of how interdependencies impact the importance of design metrics in exoskeleton design. This is compared to a 2018 study where a panel of 40 experts individually ranked the importance of engineering design metrics without considering interdependencies.

Conclusion

The interdependency-based approach to ranking metrics shifted the importance of many design metrics. The use of the analytic network process can provide a stronger, more holistic approach to the inherently multicriteria decision making involved in exoskeleton design.

Application

The results of this study are currently being used and evaluated in an exoskeleton design and evaluation methodology developed by the authors. The resulting effectiveness of these exoskeletons, alongside the exoskeleton design and evaluation methodology, will help inform the next generation of exoskeleton design.

Introduction & Background

Hugh Herr describes an exoskeleton as a device that “augments the performance of an able-bodied wearer” (Herr, 2009). More generally, we can define the term as an external mechanical structure that shares physical contact with the operator that allows a direct transfer of mechanical power and information through passive and/or active actuation that is designed to augment performance. Exoskeletons, historically, are used in two primary roles - rehabilitation and human performance augmentation. (Schnieders &

Stone, Current Work in the Human-Machine Interface for Ergonomic Intervention with Exoskeletons, 2017) also divides exoskeletons into four broad categories based on anatomical location - lower body, upper body, extremities, and full body exoskeletons.

Initial development of traditional exoskeletons can be traced back to the early 1960’s with General Electric’s Hardiman (Mosher & Wendell, Force-Reflecting Electrohydraulic Servomanipulator, 1960). Initial exoskeleton designs were deemed bulky, cumbersome, and, at the time, impractical for military operations (Ali, 2014) (Schnieders & Stone, A Current Review of Human Factors and Ergonomic Intervention with Exoskeletons, 2019). Cornell Aeronautical Laboratory (Clark, Deleys, & Matheis, 1962) (Mizen N. J., Investigation Leading to the Design, Fabrication, and Tests of a Full-Scale, Wearable Mockup of an Exoskeletal Structure, 1962) (Mizen N. J., Preliminary Design fo a Full-Scale, Wearable Exoskeletal Structure, 1963) (Mizen N. J., Design and Test of a Full-Scale, Wearable, Exoskeletal Structure, 1964), Case Institute of Technology (Reswick & Mergler, 1962) (Corell & Wijnschenk, 1964), the National Aeronautics and Space Administration's (Conway, 1972), and the University of Belgrade (Vukobratovic, Ciric, & Hristic, 1972) were the primary researchers in the field of exoskeletons until around 1973. From 1973 to 2000, the researchers in the area realized more work needed to be conducted in the development of technology (i.e. power density, motors, robotic manipulators, anthropometric considerations, etc.) before more work could be done on exoskeletons themselves. Much of the research in this time period looked at technology development as well as an explosion of interest in areas outside of military applications.

From 2000 to present, there has been a large growth in interest in exoskeletons. Outside of simple military operations and rehabilitation, exoskeletons are being used in industry applications, paramilitary applications, sports, firefighting, and law enforcement. The use of exoskeletons as a tool for training healthy adults and augmenting experiences is a new field that is quickly gaining interest. Recent work in the area includes utilizing exoskeletons as a means to train novices in proper handgun training techniques (Baechle, 2013) (Schnieders, Stone, Danford-Klein, & Oviatt, 2017) (Schnieders, Stone, Oviatt, & Danford-Kelin, The Effect of Locking out Radial and Ulnar Deviation with an Upper Body Exoskeleton on Handgun Training, 2017).

In nearly 60 years of research and well over 81,000 publications, little of the literature on exoskeleton design focus on how exoskeletons *should* be designed (Schnieders & Stone, Current Work in the Human-Machine Interface for Ergonomic Intervention with Exoskeletons, 2017) but rather focuses on “here is a problem area” and “here is the exoskeleton designed to solve that problem.” Much of the work revolves around the intervention that the exoskeleton provides and rarely focuses on the why an exoskeleton was used or how it was designed.

A 2018 study (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018) surveyed 40 participants from 35 institutions and 12 countries who held 21 doctoral degrees, 11 master’s degrees, and 8 baccalaureate degrees as their highest degree held. This survey looked at 55 engineering design metrics and created a heatmap rank order to determine the most important and least important metrics to consider when designing an exoskeleton. This rank order analysis was concluded with a categorization tasks and a Fleiss’ kappa analysis to assess the reliability of agreement between experts.

The results of that study indicate that the most important metrics to consider were (1) variability between persons, (2) how the exoskeleton attaches to the body, (3) range of motion/flexibility, and (4) comfort. The least important metrics to consider were (1) center of mass, (2) sound, (3) high speed motion, (4) effect of unequal loading, (5) psychophysics, (6) social impact, (7) replaceable parts, (8) material strength, and (9) material elasticity. It is very important to note, at this stage, that the experts were tasked to rank these metrics specifically when designing an upper body exoskeleton for firearm training, rather than exoskeleton design in general.

This initial look at the level of importance for different metrics to consider, while rudimentary, was an important first step in understanding exoskeleton design more holistically. One major drawback of having experts rank 55 separate engineering design metrics is the mental demand of simultaneously assessing all 55 metrics and creating a mental model of their relative importance. The authors of the 2018 study acknowledged this flaw and included the categorization task to create overarching meta-categories on an ordinal scale to group metrics and analyze their importance in that way. This categorization concluded with moderate agreement between 4 experts.

The simplified methodology performed in 2018 was sufficient to roughly determine the relative importance of the metrics, however, the authors believe that such simplification may mislead designers when considering critical factors in exoskeleton design. Accordingly, an alternative methodology should be considered that not only considers categorization of the 55 metrics, but also their interdependencies. A powerful tool, which has proven its ability to handle complex situations where many dependent and independent metrics are considered in evaluation, is called the analytic network process (ANP).

The ANP methodology proved its ability to deal with complex decision-making problems where heavy interdependencies exists among many decision criteria. (Al-Hawari, Mumani, & Momani, 2014) applied the ANP methodology to choose an efficient facility layout plan while considering many qualitative and quantitative decision criteria. This methodology has applications in multiple different fields. For instance, it was utilized to select an efficient facility layout where many interacting evaluation measures were considered (Al-Hawari, Mumani, & Momani, 2014). Additionally, an algorithm was proposed based on ANP to allow considerations of dependencies covering strategic factors in use in strength, weaknesses, and opportunities and threats analyses. (Gencer & Gürpinar, 2007) structured the strategic problem of supplier selection in the form of a network which is capable of handling interdependencies and feedbacks between evaluation metrics. (Cheng, Li, & Yu, 2005) applied the ANP methodology to the problem of site placement of a shopping center; the results were compared when no interdependencies were considered. In general, the inclusion of interdependencies among the decision criteria is recommended if there is a potential impact on the final decision. Recently, ANP has been applied in the petroleum industry; it helped select the best method to deal with polluted production sites (Okparanman, Ukpenevi, & Ayotamuno, 2018) also utilized ANP to determine the best choice of water treatment plants while considering interactions between important parameters.

Analytic Network Process (ANP)

Among the many available decision-making tools, the analytic network process is unique in terms of its ability to consider multi-levels of interactions and interdependencies between the decision criteria. The ANP methodology simply structures the decision-making problem as a network connecting interacting decision criteria. The decision criteria are first to be organized in clusters, in which each cluster contains a group of common decision criteria (Saaty, 2006).

After building clusters of decision criteria, the network structure is achieved through connections between them. These connections connect between nodes (decision criteria). A node influenced by another node is known as a parent node, while the affecting one is called a child node. To determine connections between decision criteria, each criterion is assumed to be a parent node which may potentially be affected by any other decision criteria, which act as potential children nodes (Saaty, 2006). The node that represents the origin of the path of influence is called a source node and the destination of this influence path is called a sink node. The direction of influence depends on the user of the network; some consider the base of an arrow as a sink and the node at the head as a source of influence, in other words, children nodes influence parent nodes (Saaty, 2006).

The main steps of the ANP methodology can be summarized as follows:

1. Define the problem. In our case, the aim is to determine the most important factor to consider when designing an exoskeleton for specific purposes.
2. The decision criteria or the evaluation metrics should then be identified. These metrics were selected to cover design, cost, manufacturing, and human factors metrics.

3. Building clusters containing evaluation metrics with synergic function or common goal. It is important here to make sure that the cluster itself has distinguishable names different from its elements.
4. Each element or decision criteria is then considered as a parent node while testing the potential of the rest of the decision criteria to influence that node. This will result in a network with parent nodes and their children nodes connected through influence arrows. Within this network, two types of dependencies may result: inner and outer dependencies. Inner dependency occurs when a node in a cluster affects another node within the same cluster, while outer dependency occurs in case of having a node affecting another node out of its cluster (Saaty, 2006).
5. For each parent node, the children nodes belonging to a particular cluster are pairwise compared with respect to their influence on the parent node in achieving an effective exoskeleton design, this pairwise comparison can be performed utilizing the same scale used in the analytic network process AHP (Buyukyazici & Sucu, 2003) (Saaty, 2006).
6. The resulting pairwise comparison can then be arranged in a matrix known as an unweighted supermatrix. In this matrix, each row represents the influence of children nodes on their parent node. (Saaty, 2006) (Saaty, Basic Theory of the Analytic Hierarchy Process: How to Make a Decision, 1999).
7. A cluster matrix which contains the influence priorities among the clusters is then required to be built. If a cluster has elements which are affected by

other elements contained in other clusters, this cluster is said to be influenced by those clusters. Such clusters are pairwise compared with respect to their ability to influence a cluster in achieving the main goal of designing an efficient exoskeleton.

8. Each block in the unweighted supermatrix is then weighted by multiplying the corresponding weights in the cluster matrix. For example, influence priorities of an element contained in Cluster A influenced by elements in Cluster B is multiplied by the influence priority of Cluster B on Cluster A.
9. The unweighted supermatrix then is raised to a power equivalent to the required level of influence. The unweighted supermatrix to the power of 1 catches the direct influence between the metrics, while the same matrix raised to the power 2 catches the second level of influence resulted from a child node affecting the parent node through an intermediate node, and so on. Generally, the more the power raised the more the level of influence that can be caught. The steady state priorities can then be achieved after raising the weighted supermatrix to a large power and this matrix has rows with similar priorities. It is essential to find the limit priorities because the network structure might contain cycles and cycling may continue indefinitely. Practically speaking, these steps ensures considering all orders and levels of interdependencies among the evaluation metrics, which support efficient decision making (Saaty, Decision-making with the AHP: Why is the principal eigenvector necessary, 2003) (Saaty, The Analytic Network Process, 2006) (Buyukyazici & Sucu, 2003).

Four experts in the field of human factors and ergonomics participated in subsequent sessions to perform the method of ANP. The metric considered in the previous study were arranged in clusters. These metrics were then screened one by one to determine the children nodes for each parent metric. The experts worked together and reached an agreement on network structure. The weights of influence were then directly assigned and converted to pairwise comparisons, then they were further validated by the experts. The assigned weights represent the weights that were agreed on by the experts. Super Decision software was used to obtain the limit priorities which will be discussed later.

In (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018), a categorization task of the exoskeleton design aspects was performed by 4 experts who either hold, or are pursuing, a doctoral degree with backgrounds in human factors, ergonomics, manufacturing, human-computer interaction, industrial engineering, and mechanical engineering. Following this categorization task, a Fleiss' kappa analysis was performed. This analysis assesses the reliability of agreement. Fleiss' kappa is calculated as the ratio of degree of agreement that is attainable above chance to the degree of agreement actually achieved above chance. Fleiss' kappa value ranges from <0 (poor agreement) to 1.00 (perfect agreement). With a kappa value of 0.42, (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018)were categorized as having moderate agreement. It is important to note, however, that the original interpretation of Fleiss' Kappa (Landis & Koch, 1977) is debated and is sometimes misleading (Gwet, 2014).

Results

An ANP model was built to determine the most critical factors when designing an exoskeleton. The model includes 55 metrics with their interactions and dependencies identified. Initially, Experts included in the study voluntarily participated in sessions where they sat together and discussed the included metrics and their categorizations. The panel of four experts performed a similar categorization task as in (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018). Five categories were presented as having a primary interaction on exoskeleton design: (1) Human Factors (from a usability standpoint), (2) Human Factors (from a human-exoskeleton interaction standpoint), (3) performance factors, (4) Financial Factors, and (5) Design Factors. Each metric was then considered for which of these five categories it belonged, and the experts voted on the categories. The metric was placed in the category with a majority vote. In the event of a tie, the metric was further discussed until a consensus was made. A sample of experts' inputs regarding the metrics and categorizations are shown in the table below:

Design Metrics	◆ Human Factors (Usability)	▲ Human Factors (HEI)	✦ Performance Factors	■ Financial Factors	⬟ Design Factors
Cost ■				100%	
Manufacturability ⬟				25%	75%
Weight ⬟		50%			50%
Active vs. passive exoskeleton ⬟		50%			50%
Variability within persons ◆	50%	25%			25%

Variability between persons ◆	50%	25%			25%
Number of parts vs. ability to actuate ⬟	25%				75%
Training motivation ◆	75%		25%		
How the exoskeleton attaches to the body ▲	25%	75%			
Statics ⬟		25%			75%
Dynamics ⬟		25%			75%
Range of motion / flexibility ✦		25%	75%		

Table 2: Sample Categorization Phase (not all metrics shown)

After that, several discussion sessions were conducted to identify the interdependencies among the metrics. These sessions resulted in connections between metrics and led to a network structure. Once the interdependencies were identified, the influences of each metric on other metrics across the network were directly weighted by the experts using a 1-9 Likert scale. The network structure of the model is shown in Figure 1. Unweighted, weighted, and limit priority super-matrices were then obtained from the ANP model as explained in the previous section.

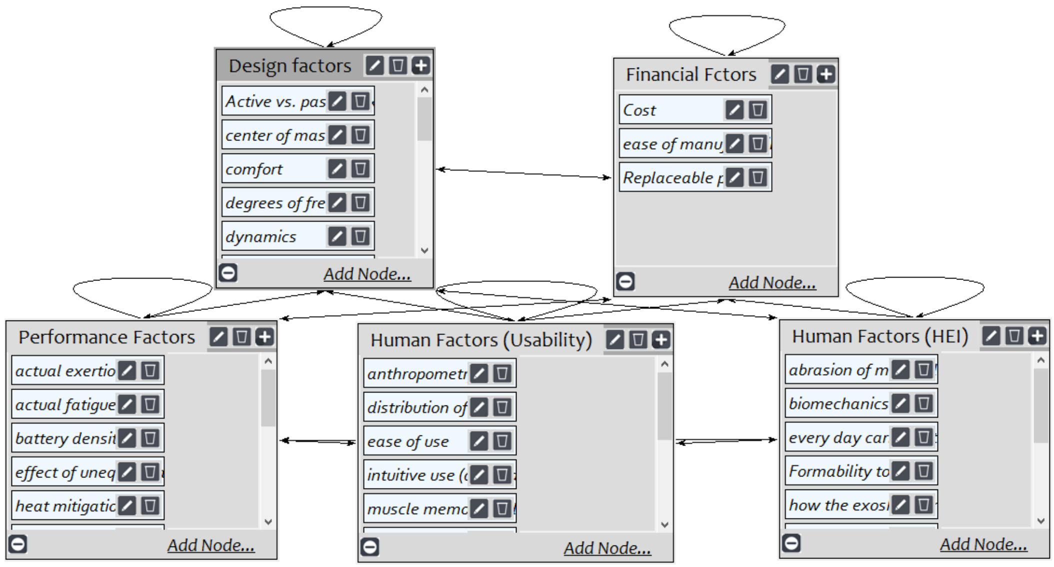

Figure 15: Network structure for the exoskeleton design problem (not all metrics are shown)

The main results of the model are the steady state priorities of the metrics listed in the limit supermatrix. These priorities were calculated after taking into account all interdependencies direct/indirect across the network and their relative weighted influences. Figure 2 shows the resulted limit priorities of the metrics considered in the model. Metrics with high priorities are considered to have more influence on the remaining metrics when designing an exoskeleton and thus are considered critical to exoskeleton design. Such metrics determine the performance of exoskeletons since changes on them will have considerable impacts on other metrics performance against an efficient exoskeleton design.

Table : Limit Priorities (Ordered by Rank)

Metric	**Limit Priority**	**Ranking**
Cost	0.074487	1
Ease of Manufacturing	0.066742	2
Range of Motion / Flexibility	0.041769	3
How the exoskeleton attaches to the body	0.034337	4
Anthropometry	0.032796	5
Replaceable parts	0.03216	6
Formability to the body	0.028646	7
High speed motion	0.027827	8

Variability between persons	0.026017	9
Comfort	0.02408	10
Repetition and fatigue	0.024012	11
Variability within persons	0.023475	12
Form factor	0.023154	13
Lifespan of exoskeleton (standard conditions)	0.021603	14
Weight	0.021277	15
Effect of unequal loading	0.020231	16
Biomechanics	0.019296	17
Battery density	0.018691	18
Distribution of mass	0.017708	19
Perspiration mitigation	0.017436	20
Number of parts vs. ability to actuate	0.017342	21
Active vs. passive exoskeleton	0.017141	22
Human factors / ergonomics considerations	0.017042	23
Degrees of freedom	0.016926	24
Environmental factors	0.016693	25
Heat mitigation	0.016269	26
Manufacturability	0.016149	27
Ease of use	0.015797	28
Actual fatigue	0.01561	29
Center of mass	0.015523	30
Actual exertion	0.015519	31
Lifespan of exoskeleton (extreme conditions)	0.014981	32
Temperature considerations	0.014661	33
Abrasion of material on body	0.014077	34
Dynamics	0.013699	35
Type of fuel (battery/gas/etc.)	0.01316	36
Statics	0.012728	37
Potential stress / strain on joints / muscles	0.012727	38
Humidity considerations	0.012662	39
Material elasticity	0.01185	40
Material strength	0.011847	41
Maximum pull forces	0.010361	42
Every day carry vs. tool for training	0.010238	43
Maximum push forces	0.009962	44
Use as protection	0.009713	45
Perceived fatigue	0.00759	46
Perceived exertion	0.007555	47
Psychophysics	0.006875	48
Muscle memory and response	0.006165	49
Sensory motor learning	0.005174	50
Social impact	0.005125	51
Sound	0.004587	52
Training motivation	0.003045	53

Iterative design	0.002909	54
Intuitive use (affordances)	0.002556	55

The results show that the most important metrics are identified to have the highest limit priorities among the metrics. These metrics include cost, ease of manufacturing, range of motion and flexibility, how the exoskeleton attaches to the body, variability between persons, variability within persons, high speed motion, form factor, comfort, weight, formability to body, and anthropometry. On the other hand, metrics with the lowest limit priorities are ranked to be the least important metrics to consider. Such metrics include Iterative design, psychophysics, intuitive use (affordances), muscle memory and response, perceived exertion, perceived fatigue, sensory motor learning, training motivation, social impact, and sound.

Generally speaking, directing design efforts toward the most important metrics ensures an efficient exoskeleton design with efficient resource allocation to satisfy these metrics. Once these metrics are satisfied and understood with their influences, a sustainable design is achievable. Such sustainability is rooted from the fact that the limit priorities represent the steady state priorities covering interdependencies at all possible levels.

Compared to the original paper by (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018), there are two metrics that both methods considered the most important, namely comfort and range of motion and flexibility. (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018) indicated that the top 1/4 were comprised of variability between persons, how the exoskeleton attaches to the body, range of motion and flexibility, and comfort. Their bottom 1/4 were comprised of center of mass, sound, high speed motion, effect of unequal loading, psychophysics, social impact, replaceable parts, material strength, and material elasticity.

Discussion

The ANP model offers a unique approach in identifying the key factors when designing an exoskeleton. Metrics were ranked by "Limit Priority," which details its significance when evaluating exoskeletons. The results between the ANP model and (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018) share a few similarities identifying the most and least significant metrics, and that is expected as both evaluation methods seek to identify which factors are most important in evaluating exoskeletons. However, as stated earlier, (Schnieders & Stone, Ranking Importance of Exoskeleton Design Aspects, 2018), identifies the most important and least important metrics for upper body exoskeletons for firearm training and not training in general. Additionally, the ANP model takes into account interdependencies. With that, the ANP is more holistic in including all types of exoskeleton designs. The most important metrics identified by the ANP model will aid in designing any type of exoskeleton device.

It is important to consider the interdependencies when evaluating exoskeletons and eliminate bias as (Lin, Chiu, & Tsai, 2008) explains that the ANP model eliminates "bias estimates from over simplification" (pg. 2162). This can further explain the difference in results from using the ANP model and the method described in Schnieders & Stone (2018). However, the model can ignore the "fuzziness of experts' judgments" on which metrics are important when designing exoskeletons (Lin, Chiu, & Tsai, 2008). (Saaty, The Analytic Network Process, 2006) detail how the results will be subjective "in this sense of using experts when needed." The authors also mention that ANP is needed to deal with cycling and feedback, something logic cannot deal with. Rather than normative and prescriptive, the ANP model is labeled as "descriptive in science," and this model considers the risks and hazards with each decision (Saaty, The Analytic Network Process, 2006). Therefore, when comparing this model to human understanding, the ANP model may incorporate facets such as interdependencies that may be missed through human understanding.

The ANP model, encapsulates the advantages of expert opinion with the ability to effectively handle the complexity of factorial interaction. The ANP model is the best current option to aid in the design of exoskeleton for human centered design.

Practical Applications

The results of this study are currently being used and evaluated as part of an exoskeleton design and evaluation methodology developed by the authors. The resulting effectiveness of these exoskeletons, alongside the exoskeleton design and evaluation methodology, will help inform the next generation of exoskeleton design. Placing proper emphasis on key engineering design metrics that are weighted higher and have stronger interdependencies, can drastically change not only the design process itself, but also the efficacy and effectiveness of the design. Many exoskeletons are limited by their scope, time, and budget. Focusing on the appropriate metrics can help alleviate the difficulties that are presented under these limitations.

Conclusion & Future Work

Technological advancement has led us to a period that advanced technologies such as exoskeletons a reality. But how to best design exoskeletons remains under researched and ultimately unclear. This work compared approaches to this problem and found that the ANP model demonstrates a capability that has the greatest capacity to impact the human centered design of exoskeletons. Like any model however it will require refinement and update exoskeleton evolve. To this end the work of expert analysis with consideration to both importance and interactions of design factors will be necessary to grow and refine the ANP model. The authors intend to both develop and test a series of exoskeletons using these methods in future work. The resulting effectiveness of these exoskeletons will inform the next generation the ANP model.

Key Points

- Research on how to design exoskeletons is limited.
- The analytic network process (ANP) is a robust multicriteria decision making tool that easily handles interdependencies between metrics.
- Use of the ANP provides a more holistic approach when considering a large number of engineering design metrics in the exoskeleton design process.
- The broader impact of the ANP approach compared to the weighted rank order approach leads to more effective design strategies.
- The proposed approach to using a large number of metrics in the exoskeleton design process is being analyzed with use cases.

Chapter XI Methodology Development Stage 1.2 – Human Factors Considerations

The advent of ergonomics as a field is traditionally traced back to World War II when technology and human sciences were systematically applied in a coordinated manner (Dul & Weerdmeester, 2008). The international ergonomics association provides a formal definition of ergonomics as follows:

> “Ergonomics (or human factors) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance” (International Ergonomics Association, 2018).

Some examples of what is considered core to the field of human factors include the study of designing equipment, devices, and processes that fit the human body and cognitive abilities, ethnographic analysis (where appropriate), iterative design, meta-analysis (time-permitting), task analyses, surveys, and questionnaires (Dul & Weerdmeester, 2008).

A primary focus in the field of human factors and ergonomics is the identification of occupational and non-occupational risk factors which can lead to musculoskeletal disorders (MSDs). The most important factor to consider is the balance between local soft tissue damage and fatigue and the individual’s ability to recover from that damage. Major workplace ergonomic risk factors include high task repetition, repetitive/sustained awkward postures, as well as forceful exertions.

High task repetition, when combined with the other two factors, can often contribute to the formation of MSDs. This high task repetition is often forced by hourly or daily production targets and other related work processes. A task falls under high repetition when cycle time is 30 seconds or less. Methods for decreasing high task repetition include engineering controls, work practice controls, job rotation, and counteractive stretch breaks.

Engineering controls can be used to eliminate excessive force and award postures and can be implemented by human factors engineers during the design of a tools and other products. Work practice controls are implemented by proper work technique training and by providing safe procedures and work environments. Having workers rotate between workstations and tasks can also help reduce fatigue that leads to MSDs. Appropriate counteractive stretch breaks allow for increased circulation in the affected regions. Repeated or sustained awkward postures overload the muscles and tendons around the effected joints. Without appropriate work design and adequate recovery time risk of MSDs are increased.

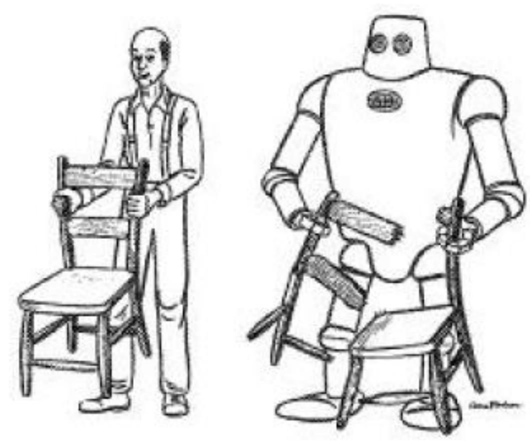

Figure 16: Lacking human sensing, robot shatters chair (Mosher, 1967)

Figure 17: Lacking human sensing, robot snaps door (Mosher, Handyman to Hardiman, 1967)

As early as 1967 human factors engineers considered psychophysics an appreciable area of importance in exoskeleton design. Humans are capable of intricate manipulation and control that is not easily transferred into exoskeletal design. Mosher (1967) provides multiple examples of potential issues with human sensing in robots and later exoskeletons in the design phase that lead to incorrect design. In his robot and chair example, he describes the human motor system feedback of knowing the amount of force used to pick up a chair (Figure 16: Lacking human sensing, robot shatters chair). Another of his examples discusses the difficulty for humans to draw perfect circles freehand, but utilizing devices like crank handles and doorknobs, we are able to do so.

The concept of anthropomorphic designs being utilized in exoskeletons is well established even in early manipulator style and master-slave systems (Johnsen & Corliss, 1967) (Johnsen E. G., 1971) (Croliss & Johnsen, 1968) (Vertut, 1974). This type of design benefits from having similar kinematics to human motion and results in better ease of use in master-slave control systems. Anthropomorphic designs fall into the operator's pre-existing mental model of how the body, and therefore the system, should work.

Both orthoses, prostheses, and exoskeletons are typically highly personalized by design or are adapted to the patient to account for different inter- and intra-person anthropomorphic measures and to adapt to existing pathologies (Belforte, Sorli, & Gastaldi, 1997) (Mizen N. J., 1964).

The following figure is adapted from (Fales, 2016) and provides a, overview of ergonomic analysis assessments/tools and their application areas.

Assessment / Tool	Repetition / Duration	Force: Gripping / Pinching	Force: Lift / Lower / Carry	Force: Push / Pull	Posture	Vibration	Contact Stress / Impact	Neck / Shoulder	Hand / Wrist / Arm	Back / Trunk / Hip	Leg / Knee / Ankle
Checklist Methods (Multiple hazards considered)											
MSD Hazard Risk Assessment Checklist	X	X	X	X	X	X	X	X	X	X	X
Washington Ergonomics Assessments	X	X	X		X	X	X	X	X	X	
Washington State Checklists (Caution / Hazard Zone)	X	X	X	X	X	X	X	X	X	X	X
Manual Material Handling (lifting, lowering, pushing, pulling, carrying)											
ACGIH: Lifting TLV	X		X	X				X		X	
NIOSH Lifting Equaiton	X		X	X				X		X	
Snook Tables	X		X	X				X		X	X
MAC (UK)	X		X	X				X		X	
Upper Limb											
ACGIH: HAL	X	X	X						X		
RULA	X			X				X	X	X	
Strain Index	X	X	X	X					X		
CTD Strain Index (CTD-RAM)	X	X	X					X	X		
LUBA				X				X	X	X	
OCRA	X	X	X	X	X	X	X	X	X		
Combined Methods (not checklist)											
QEC	X		X	X	X			X	X	X	X
REBA	X		X	X				X	X	X	X
ManTRA	X	X	X	X	X			X	X	X	X
OWAS	X	X	X	X				X		X	X

It is important to consider which analysis is the most appropriate when evaluating exoskeletons at work. Both REBA and RULA are used within the QuANTUM Ex Method due to their broad application areas, widespread use, ease of use, as well as for the application we are using as part of our ongoing case study. When the QuANTUM Ex Method is applied to other use cases, determining which ergonomic assessment/tool is most appropriate should be determined by the design team.

Chapter XII Methodology Development Stage 1.3 – Engineering Creativity Considerations

Lack of creativity in engineering is, and has been, a growing concern. As early as 1996, the Alliance of Artists Communities concluded that American creativity is at risk (Alliance of Artists Communities, 1996). This issue is not limited to the United States, nor is it limited to the arts. Employers in Australia stated that three-quarters of collegiate graduates had skill deficiencies in problem solving, independent and critical thinking, and creativity (Commonwealth of Australia, 1999). (Tilbury, Reid, & Podger, 2003) report that recent graduates in Australia lack creativity. (Cooper, Altman, & Garner, 2002) show that the UK education system discourages innovation. According to the (British General Medical Council, 1993), medical education focuses more on sheer memorization of information rather than critical thinking and the engendering of problem-solving skills.

In the United States, *Time Magazine* (White, 2013) and *Forbes* (Banerjee, 2014) show that recent graduates lack creativity and problem solving. The focus in engineering education seems to be memorizing information and equations for specific examples, with little emphasis put on actual creativity, critical thinking, or novel ideas.

> As engineers, we are supposed to be the innovators of the world, inspired by creativity and a passion for problem solving. However, many curricula drain students of excitement for challenges. Students are graduating unprepared. (Cropley, Creativity in engineeirng: Novle solutions to complex problems, 2015)

(Cropley, Promoting Creativity and Innovation in Engineering Education, 2015) explains that, "[c]reativity plays a central role in engineering problem solving." Traditional engineering education teaches students how to "solve well-defined, convergent, and analytical problems" (Cropley, Promoting Creativity and Innovation in Engineering Education, 2015) and does not develop the creativity, critical thinking, and abstract thinking that is required to develop effective and novel solutions.

(Zhong & Fan, 2016) explain that when technology, like 3D printers, become less expensive and more available at the consumer level, creativity can spread from large-scale corporations and governmental departments to the consumer. This movement, towards what is commonly referred to as a "Maker Space" (a space where people and communities who work in different areas come together), essentially creates a free economic system. This system allows for people to display their talents in order to "create wealth that would modernize the economy" (Zhong & Fan, 2016).

The association and function of common objects are often shown through the objects' names. For example, a paper clip is used to clip paper, a vegetable peeler is used to peel vegetables, and a 3D printer is used to print in three dimensions. This association is known as a functional fixedness (Cropley, Creativity in Engineering, 2015).

Creativity in problem solving is mostly predicted on (1) desire and fulfillment; (2) knowledge of objects and principles possessed or available (knowing how to obtain the needed knowledge and how to use it) that includes tacit knowledge gained in experiences, heuristics, and instinct ("gut" feeling); (3) openness (i.e. a willingness to accept criticisms and ideas from others); and (4) knowledge of process, especially design and problem solving processes (Santamarina & Salvendy, 1991) (Eder, 1994) (Klukken, Parsons, & Columbus, 1997).

Knowledge of objects and principles possessed for available (2) and knowledge of process, especially design and problem-solving processes (4) can be gained through formal learning settings and other experiences. Traditional idea generation methods such as brainstorming rely heavily on (2). Accordingly, these methods fall short when used as the main vehicle for creativity. Traditional approaches to creativity, which advocate using brainstorming, (Shah, Vargas-Hernandez, Summers, & Kulkarni, 2001), (Michalko, 1991), etc., call upon designers to look inward for inspiration, and then communicate their ideas to others to create a synergetic and shared experience. Using such methods, the problem solver may be confined to solutions/ideas or functions of objects that have become familiar through their formal education. For example, fixed function-object associations can be useful for engineers in routine solutions where standardization speeds up the design and manufacturing process. However, this only works for relatively trivial, non-unique problems where creative solutions are not needed. Many engineering institutions train their students to think in this manner, that is, how to develop a solution for common problems the student will have seen in lecture. The issue arises when novel solutions are needed. Creativity in engineering comes from "…a foundation of knowledge and requires effort. To be a creative engineer, you first need to be a capable, *technical* engineer" (Cropley, Creativity in Engineering, 2015).

(Kremer, McKenna, Plumb, Ro, & Yin, 2011) demonstrated quantitatively that engineering programs with an emphasis on creativity and innovation can be significantly correlated to problem solving skills. Their findings were supported with qualitative evidence as well.

When designing a product for human factors, it is critical to understand and choose how a design is going to affect the way people work. The goal is to achieve your goal while being held to a number of constraints. Often, when designing you must consider the tradeoffs between your goals and constraints such as materials, standards, costs, and regulations.

The theory of inventive problem solving, or TRIZ (Russian: теория решения изобретательских задач, literally "Theory of the resolution of invention-related tasks"), was developed by Soviet inventor and science fiction author Genrich Altshuller and colleagues beginning in 1946. Systematic creativity methods such as TRIZ guide the concept generation process using solution patterns derived from problems similar to the one at hand. It has generalizable patterns in the nature of inventive solutions and distinguishes characteristics of problems. The three primary findings form TRIZ are (1) problems and solutions are repeated across industries and sciences, (2) patterns of technical evolution are also repeated across industries and sciences, and (3) innovations used scientific efforts outside the field in which they were developed.

TRIZ is proven as an effective method for teaching creativity and innovation when used in an engineering education program. (Ogot & Kremer, 2006) conducted a study in a first-year engineering design course. The results indicated that students who were taught creativity with TRIZ were able to produce "…substantially more feasible design concepts for an industry-sponsored design problem…" compared to the control group who utilized more traditional brainstorming techniques.

on creativity measurements can be found in a monograph titled, “Assessing Creativity: A Guide for Educators,” published by The National Research Center on the Gifted and Talented (Treffinger, Young, Selby, & Shepardson, 2002). As per suggestions from this source, we assess the creative potential of students using a subscale of Torrance Test of Creative Thinking (TTCT). Specifically, the Unusual Uses Task will be used. This TTCT activity is a widely used measure on divergent thinking ability (Cramond, Matthews-Morgan, Bandalos, & Zuo, 2005). This test asks participants to generate as many unusual uses as they can for a tin can (or a cardboard box) in a ten-minute period (Torrance, 1992). At the end, originality, flexibility, and fluency are calculated based on the responses.

- **Originality** evaluates participants’ answers against a list of common responses to the same problem. Creativity is often understood to provide answers that are outside common societal experience.
- **Flexibility** measures the ability to develop a wide range of differing answers. Creativity is expected to encourage answers that will go beyond slight differences and produce responses that are quite distinct from those previously developed.
- **Fluency** is the ability to develop a large number of relevant responses to a given stimulus (how many different ideas can a participant develop to address the question at hand?).

Chapter XIII QuANTUM Ex Method Vrs. 1

The entire assessment method is comprised of two main parts: assessment of the lower body and assessment of the upper body. The assessment method can be used separately or as a whole and will be known as the QuANTUM Ex Method. The lower body assessment will be known as QuANTUM RECALL. The upper body assessment will be known as QuANTUM HAUL.

Exoskeletons and Affordances

The term 'affordance' was introduced in 1966 by the psychologist James J. Gibson (Gibson, The Senses Considered as Perceptual Systems, 1966). What is widely considered his best definition of the word was introduced later in 1979 as:

> The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment. (Gibson, The Ecological Approach to Visual Perception , 1979)

Even with a clearer definition provided in 1979, the term 'affordance' is still hard to express and thus, harder to evaluate (Mumani & Stone). Hsiao, Hsu, and Lee (2012) gathered typical affordances properties based on their definitions in the literature. They used these to evaluate a products' usability (Hsiao, Hsu, & Lee, 2012). Similarly, this can be applied when approaching exoskeleton design methods, as will be shown later in this dissertation. Similar approaches have been applied to help designers improve product usability (Galvao & Sato, 2005) (Chen, Lee, & Kion, 2009) (Maier & Fadel, 2009).

These methods, while viable, are complex, technically intensive, and are designed to deal with complex products (Mumani & Stone). Modification of their initial designs must be made to be more widely applicable to exoskeleton design.

Exoskeletons and Usability

Evaluating usability is a multi-dimensional problem with conflicting objects that need to be achieved for optimal success. Such an approach, by its nature, is complicated to design and complicated to implement. Multi-criteria Decision Making (MCDM) methods are designed specifically to systematically handle such complexities associated with such decisions (Asghar, 2009). These MCDM methods excel when multiple feasible alternatives exist, but only one is optimal based on the decision criteria.

Universal design principles

The equation that is suggested is a conglomeration of a number of different parts. As such, each part of the equation is justified in an a priori manner with as much reference to previous studies and literature as possible. In some cases, there is little to no research completed to fully justify each component and, therefore, parts of the equation are justified through a logical thought experiment. This allows room for future iterations on the equation as more parts are able to be more empirically justified.

The following case study is used as a demonstration on the iterative nature of creative design and what ultimately lead to developing an exoskeleton design method. The following two chapters are publications on the ARCTiC LawE and shows the progression from its first iteration that looks at a physical lockout of radial and ulnar deviation and the second iteration that looks at a physical lockout of wrist flexion and extension for training in handgun shooting. It is important to expand on the background and research motivation for the development of ARCTiC LawE.

Research has shown that tremors in the arm have a negative effect on aiming (Lakie, 2009) (Pellegrini & Schena, 2005) (Tang, Zhang, Huang, Young, & Hwang, 2006) however, accuracy when aiming and firing a handgun depends on three primary factors: (1) environment, (2) hardware, and (3) human factors (Baechle, 2013). A lot of devices have been developed to mitigate environmental impact and hardware impact on accuracy, but few exists to assist in training or augmenting humans. The human factors that affect aim include (1) fatigue (Fröberg, Karlsson, Levi, & Lidber, 1975), (2) experience (Goonetilleke, Hoffmann, & Lau, 2009), (3) body (Ball, Best, & Wrigley, 2003), (4) heart rate (Tharion, Santee, & Wallace, 1992), and (5) arm tremors (Baechle, 2013).

Figure 18: MAXFAS (Baechle, 2013)

There are many exoskeletons that focus on limiting motion or suppressing tremors, however, only two exoskeletons look at applying exoskeletons for handgun training – the mobile arm exoskeleton for firearm stabilization, or MAXFAS, and the ARCTiC LawE. The MAXFAS was designed and validated by Dan Baechle in 2013 as a partial completion of his Master of Science Research at the University of Delaware. Much of Baechle's research focused on manufacturing the exoskeleton out of carbon fiber and developing an algorithm that allowed for intended motion while suppressing natural tremors. The MAXFAS is essential a series of cuffs, tension sensors, motors, and cables mounted to the exoskeleton and an aluminum frame that rests above and behind the user. The MAXFAS utilized an airsoft pistol that uses a CO_2 cartridge to replicate recoil and had its 20 participants aim not with the gun's iron sights but rather with an attached red laser. The end results of Baechle's experiment demonstrated that the MAXFAS, a cable-drive arm exoskeleton, is a viable method of improving pistol shooting performance. Baechle lists possible limitations and future work as follows: (1) control mode limited with outdated motors, (2) tremor canceling algorithm should be tested on human subjects with new motors, (3) redesign of cuffs to reduce risk of pinching on participants' skin, (3) cabling should be routed through tubing, (4) increase participant pool with trained soldiers using a real pistol and aiming with the iron sights, (5) larger control group, (6) longer periods of shooting while wearing the exoskeleton, and (7) evaluate the effect of learning later than 5 minutes after removing exoskeleton.

Chapter XIV ARCTiC LawE Vrs. 1 Case Study

The Effect Of Locking Out Radial And Ulnar Deviation With An Upper Body Exoskeleton On Handgun Training

A paper accepted by the *Human Factors and Ergonomics Society*

Thomas M. Schnieders, Richard T. Stone, Tyler Oviatt, and Erik Danford-Klein

Abstract

This paper presents the first version of the ARCTiC LawE, short for the Armed Robotic Control for Training in Civilian Law Enforcement. The ARCTiC LawE is an upper body exoskeleton designed to assist in training civilians, military, and law enforcement personnel. The first iteration of this exoskeleton tests the effect of locking out radial and ulnar deviation for handgun training. The project trained and tested subjects with little to no handgun training/experience utilizing the ARCTiC LawE. An analysis of accuracy and precision was conducted with 24 participants. The experimental group scored statistically significantly higher than the control group at 21 feet and at 45 feet. Most police altercations with handguns occur at 10 feet or less. The results imply the ARCTiC LawE version one has enough statistical support for a second iteration to address some of the quantitative and qualitative results.

Introduction

Recent research shows that tremors in the arm have a negative effect on training (Lakie, 2009) (Mihelj, Nef, & Riener, 2007) (Schiele, 2007) Accuracy when aiming and firing a handgun depends on three primary factors: (1) environmental, (2) hardware, and (3) human factors (Baechle, 2013). A lot of devices have been developed to mitigate the impact that environmental and hardware factors have on accuracy, while few devices exist to assist in training or augmenting humans. The human factors that affect aim include (1) fatigue (Fröberg, Karlsson, Levi, & Lidber, 1975), (2) experience (Goonetilleke, Hoffmann, & Lau, 2009), (3) body sway (Ball, Best, & Wrigley, 2003), (4) heart rate (Tharion, Santee, & Wallace, 1992), and (5) arm tremors (Baechle, 2013).

One exoskeleton designed for handgun training is the MAXFAS, developed by Dan Baechle. The mobile arm exoskeleton designed for firearm aim stabilization, or MAXFAS is an exoskeleton that utilizes an algorithm to mitigate natural arm tremors while allowing intended motion. This exoskeleton is comprised of a series of cuffs, motors, tension sensors, and cables that connect the MAXFAS to a large aluminum frame that sits behind and above the shooter. The handgun used for training their 20 participants was an airsoft pistol. The pistol used a CO2 cartridge to replicate recoil and had a red laser pointer for aiming (Mihelj, Nef, & Riener, 2007). Ultimately, Baechle's research demonstrated that an exoskeleton is a viable method of improving pistol-shooting performance but requires a redesign to reduce potential risk to participants, using a different handgun replacement (or an actual handgun), longer training period, and evaluation of the effect of learning later than 5 minutes after removing the exoskeleton (Baechle, 2013).

The ARCTiC LawE, short for **A**rmed **R**obotic **C**ontrol for **T**raining **i**n **C**ivilian **Law E**nforcement provides a more mobile training method compared to the MAXFAS. This paper covers the design and evaluation of that upper body exoskeleton designed to assist civilian, military, and law enforcement personnel in accurate, precise, and reliable handgun techniques. This paper looks specifically at how locking out radial and ulnar deviation in the wrist with an upper body exoskeleton has an impact on handgun training. The training includes the use of the ARCTiC LawE and a laser-based handgun with similar dimensions, trigger pull, and break action to a Glock ® 19 pistol, common to both public and private security sectors as their firearm of choice. The laser-based handgun ensures the safety of the participants and provides a method to alleviate any impact on bullet trajectories (as in traditional handguns) due to humidity and/or temperature.

Figure 19: (Top) Glock 19® (GLOCK Pistols for Law Enforcement, 2016) (Bottom) LaserLyte® (LaserLyte, 2016)

Exoskeleton Design

When firing handguns, participants were instructed to squeeze the trigger with the center of the tip of the index finger (distal phalanx). If participants squeezed the trigger with the outer tip of their index finger, their shots erred to the left; if participants squeezed the trigger with the inner portion of the index finger, their shots erred to the right. To help


Figure 20: Neoprene Finger

guide participants in using the correct portion of their finger, a neoprene glove, which also acts as padding between the user and the exoskeleton, had a portion of its index finger removed (Figure 20: Neoprene Finger). This allowed the participants to not only more easily feel the trigger, but also served as a reminder as to which portion of the finger to squeeze with. There was also error caused by breaking the wrist up or down, pushing, heeling, thumbing, etc. when handling the handgun which caused the shots to fire up, down, left, right, and diagonally from the center of the target. Much of this result related to: anticipating the recoil of the gun, pulling the trigger rather than squeezing it, or how the user is holding the grip of the gun.

The cut-out portion of the neoprene glove served to mitigate the effects of too little trigger finger and too much trigger finger, which resulted in hitting the target to the left and right of center, respectively. The stainless plate steel helped mitigate the breaking wrist up and down which resulted in hitting the target above and below center. To mitigate the tightening of the fingers or tightening of grip while pulling the triggers, hook-and-loop fasteners were added to the pinky, ring, and middle fingers horizontal bars. Two bars of hook-and-loop fasteners were sewn onto the proximal phalanges location of the neoprene gloves while one bar of hook-and-loop fastener was sewn onto the intermediate phalanges location of the neoprene glove.

Figure 21: ARCTiC LawE Vrs. 1

The ARCTiC LawE can be seen in Figure 21: ARCTiC LawE Vrs. 1, above. It shows the neoprene glove mated to the metal exoskeleton as well as the hook-and-loop fasteners. The exoskeleton uses nylon webbing that can easily be swapped out to accommodate multiple sizes. The webbing was connected with bolts, washers, and nuts to help facilitate swapping of the webbing. The finger coupling of the exoskeleton also acted as a guide for the participants. They were instructed to keep the hook-and-loop fastener on the neoprene glove mated with the exoskeleton helping mitigate over squeezing. The overlapping plates allowed for some actuation in the flexion/extension of the wrist. This allows participants to easily draw and holster the LaserLyte ® training handgun during the experiment.

The overlapping plates also prevented radial and ulnar deviation. The stiffness of the metal would require strong loading be placed on the joints of the overlapping plates. Abduction of the wrist (moving the wrist towards the “thumb side”) is the result of activating the flexor carpi radialis and the extensor carpi radialis longus in radial deviation. Similarly, adduction of the wrist (moving the wrist towards the “pinkie side”) is the result of activating the flexor carpi ulnaris and the flexor carpi ulnaris in ulnar deviation. Locking out radial and ulnar deviation with The ARCTiC LawE helps keep the handgun in line with the rest of the forearm and mitigates inaccuracy from breaking the wrist up, breaking the wrist down, pushing forward, or dropping the head of the handgun.

Materials and Methods

Participants were required to fill out a pre-study survey and sign an informed consent document. The pre-study survey asked participants their experience with guns, their experience with handguns, and questions regarding experience with video games and first person shooters. Participants were comprised of civilians above the age of 18 who could legally give consent and could physically operate a handgun. Ideal participants had normal to corrected vision (contact lenses and glasses are okay except for bi-focals, tri-focals, layered lenses, or regression lenses), and little to no experience using handguns.

Participants were randomly put into a control group or an experimental group. Training for both groups involved teaching participants' proper use and handgun safety. While the study utilized a laser gun instead of live ammunition, participants were instructed to treat the laser gun as if it were a live gun using live ammunition. Examples of the use and handgun safety training included always pointing the gun towards the ground until ready to fire, participants may not fire the laser gun unless anyone with them (i.e. the PIs) are behind them, etc. Twenty participants originally signed up to participate in the study. However, from the data collected in the pre-study survey, four participants, all pre-allocated to the experimental group, self-identified as having moderate to advanced handgun experience. These four participants were removed from the study.

Participants were started at either 21 feet or 45 feet from the LaserLyte Score Tyme Board and then moved to the next distance to counteract the effect of learning on the results of the participants' scores. Participants were required to fire 25 shots at each distance for a total of 50 shots. The total score after the 25th shot was tallied and the target was reset. The testing was repeated for the remaining firing distance. Each distance had a potential for 250 points as a high score if each of the 25 shots hit the 10-point bull's-eye. The outermost ring of the target was worth four points and each ring increased value by one.

After completing the testing, participants filled out a post-study survey, which asked qualitative, self-identified metrics of perceived accuracy, perceived precision, etc.

Results

The participants were normally distributed. The statistical significance threshold was set at 0.05 with practical significance set at 0.1. On average, the experimental group scored 52.6 points higher than the control at a 21-foot distance and 27.2 points higher than the control at a 45-foot distance (Figure 22: Average Score).

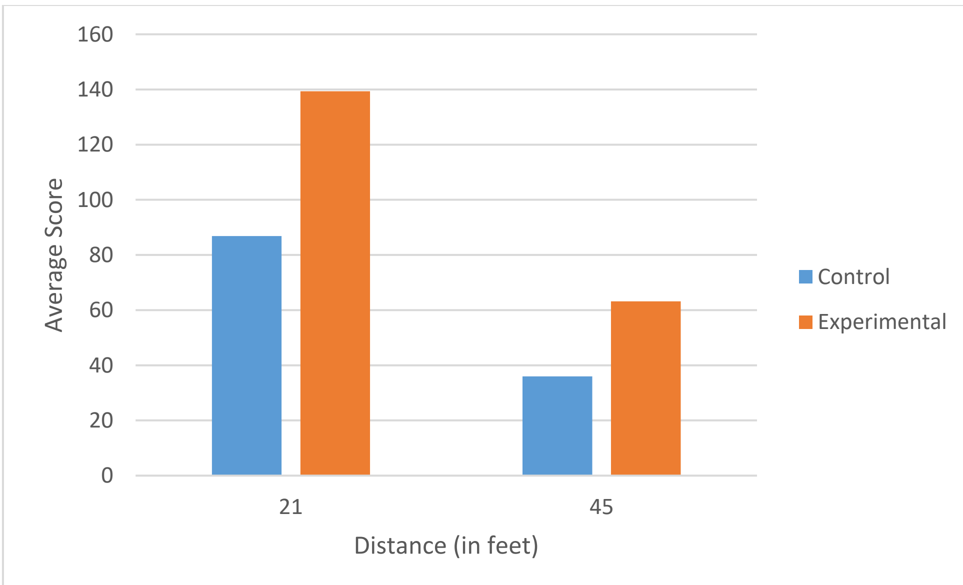

Figure 22: Average Score

Among the participants in the experiment (N=24), there was a statistically significant difference between the two groups at 21 feet, control (M = 86.84, SD = 47.01) and experimental (M = 139.4, SD = 38.29), t(24) = 0.003, p = 0.007. There was a statistically significant difference between the groups at 45 feet, control (M = 36.00, SD = 22.83) and experimental (M = 63.18, SD = 41.59), t(24) = 0.01, p = 0.05.

In the post study survey, participants were asked about the effectiveness of the training they underwent (Figure 23: Perceived Effectiveness of Training), their precision (Figure 25: Average Perceived Precision), their accuracy (Figure 24: Average Perceived

Accuracy), their stability (Figure 27: Average Perceived Stability), and how effective they thought the training would be over the course of three months.

On average, participants in the experimental group rated their perceived effectiveness of the training 1.81 points (or ~18%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 6.92, SD = 2.36) and experimental (M = 8.73, SD = 1.01), $t(24) = 0.01$, $p = 0.03$.

Figure 23: Perceived Effectiveness of Training

On average, participants in the experimental group rated their perceived precision 2.14 points (or ~21%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 3.77, SD = 1.54) and experimental (M = 5.91, SD = 1.81), $t(24) = 0.003$, $p < 0.01$.

On average, the experimental group rated their perceived accuracy 1.71 (or ~17%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 4.38, SD = 2.10) and experimental (M = 6.09, SD = 1.64), $t(24) = 0.02$, $p = 0.04$.

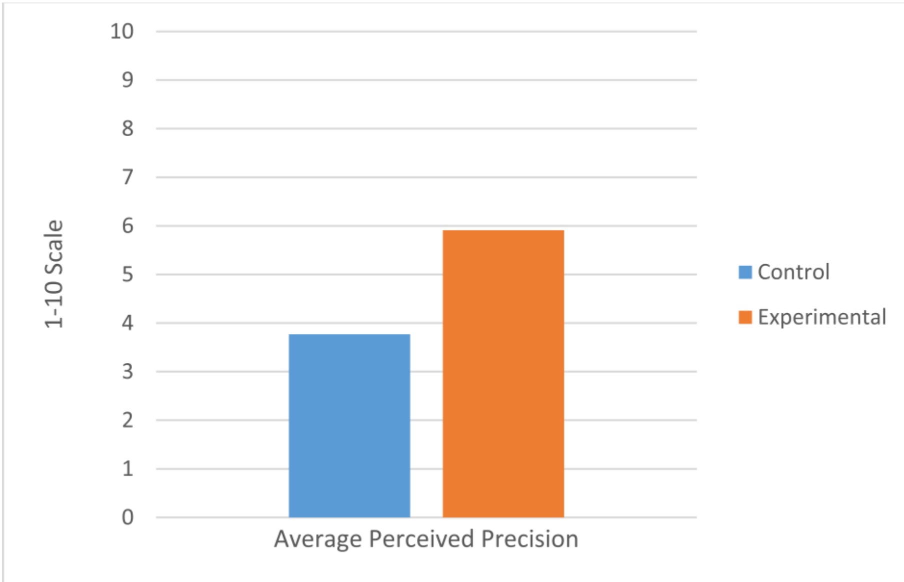

Figure 25: Average Perceived Precision

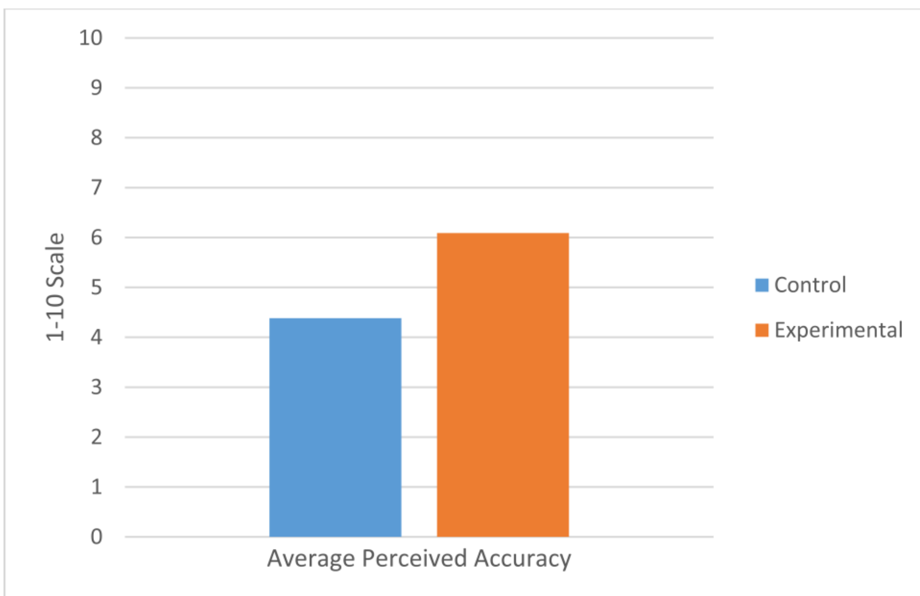

Figure 24: Average Perceived Accuracy

On average, the experimental group rated their perceived stability 2.36 (or ~24%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 5, SD = 1.96) and experimental (M = 7.36, SD = 1.75), $t(24) = 0.002$, $p < 0.01$.

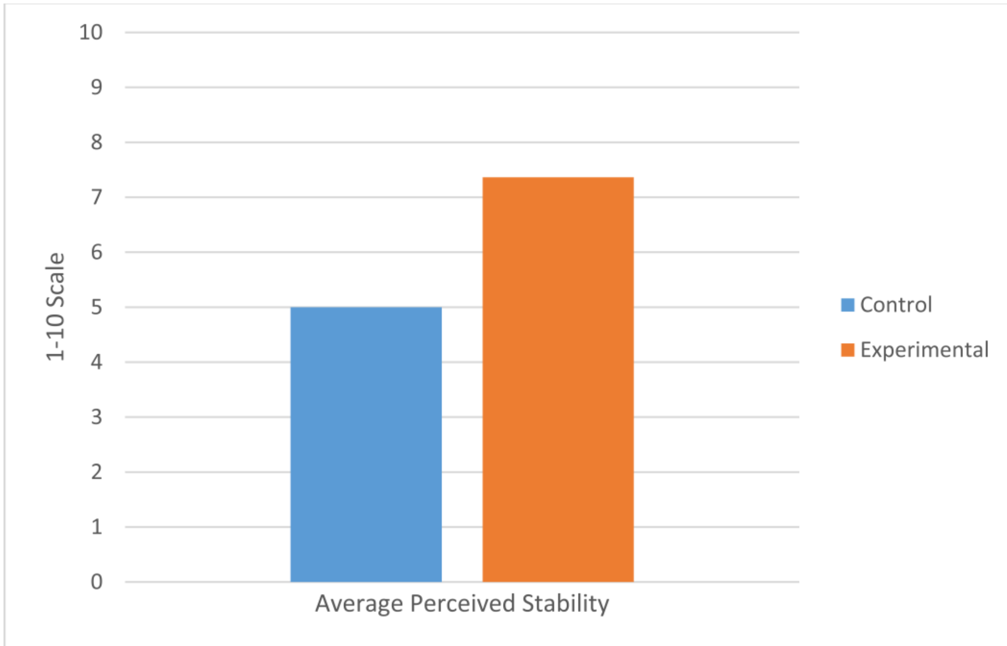

Figure 27: Average Perceived Stability

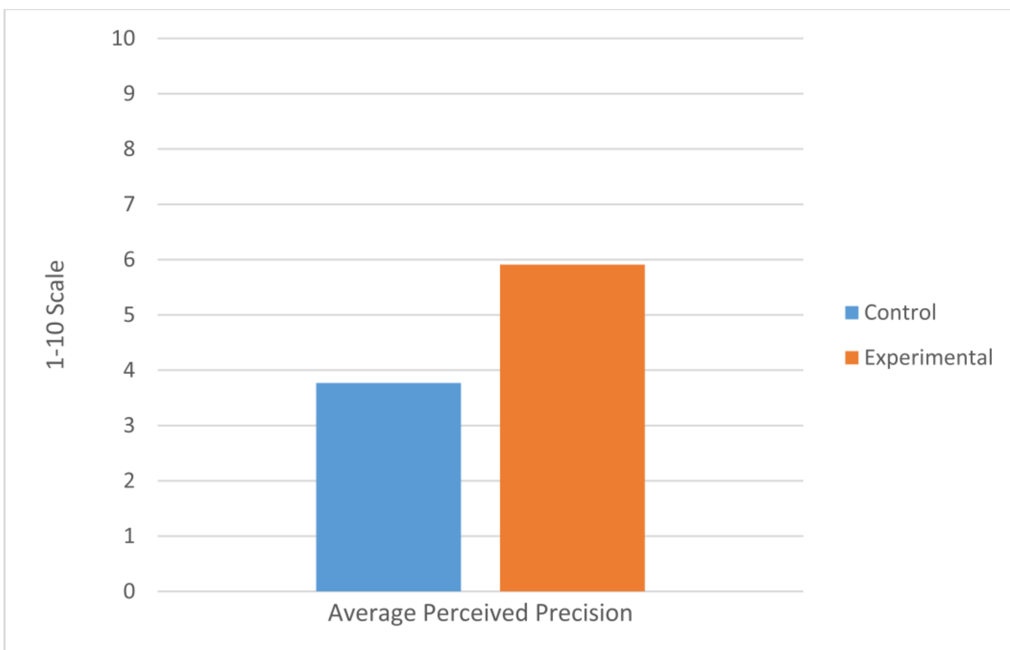

Figure 26: Average Perceived Precision

On average, the experimental group rated the perceived effectiveness over 3 months 1.28 points (or ~13%) higher than the control group. It is important to note that this measure was taken in the post-study survey immediately following the study and not after 3 months of training (Figure 8). There was not statistically significant difference between the two groups, control (M = 7.54, SD = 1.90) and experimental (M = 8.82, SD = 1.33), $t(24) = 0.03$, $p = 0.07$.

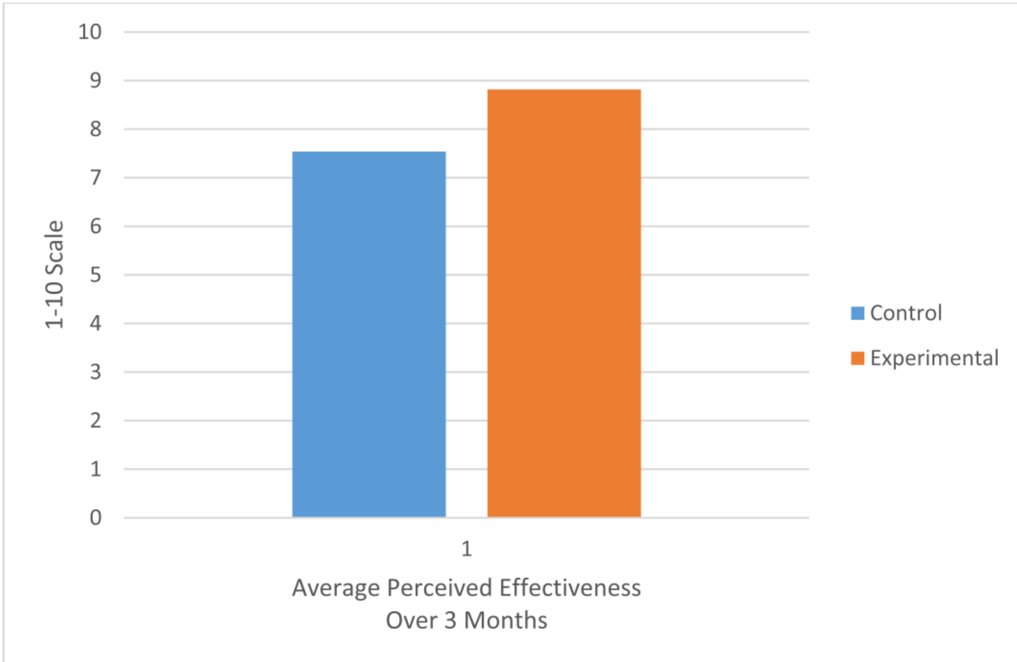

Figure 28: Average Perceived Effectiveness Over 3 Months

Discussion

The evidence was enough to warrant a second iteration of the ARCTiC LawE. This second iteration can address some of the qualitative and quantitative results. In particular, the study showed fatigue from the participants attempting to 'rapid fire.' The participants were attempting to draw the LaserLyte, quickly, fire the LaserLyte, holster the LaserLyte, and repeat.

The results showed a tendency for participants to miss the target entirely, typically to the left or right of the target. If participants were hitting the target in the outermost ring, they would have a minimum score of 100. This means that the exoskeleton needs to address wrist flexion and extension. Occasionally, participants would miss above or below the target, but this typically occurred within the first 10-15 shots when participants with no handgun experience learned how to aim with the handgun. Future work would look at the transfer of training effectiveness as well as locking out wrist flexion and extension. A larger sample size would also be beneficial.

Conclusion

The ARCTiC LawE trained and tested 24 participants (13 control, 11 experimental) on how to use a handgun. This upper body exoskeleton designed to assist civilian, military, and law enforcement personnel tested the effect of locking radial and ulnar deviation for handgun training. The results for average score at 21 feet and 45 feet, perceived effectiveness, perceived precision, perceived accuracy, and perceived stability were all statistically significant. The quantitative and qualitative metrics indicate locking out radial and ulnar deviation with an upper body exoskeleton has a positive impact on handgun training.

Chapter XV ARCTiC LawE Vrs. 2 Case Study

The Effect Of Locking Out Wrist Flexion And Extension With An Upper Body Exoskeleton On Handgun Training

A paper accepted by the *Human Factors and Ergonomics Society*

Thomas M. Schnieders, Richard T. Stone, Tyler Oviatt, and Erik Danford-Klein

Abstract

The second version of The Armed Robotic Control for Training in Civilian Law Enforcement, or ARCTiC LawE is presented in this paper. The ARCTiC LawE is an upper body exoskeleton designed to assist in training civilians, military, and law enforcement personnel. This second iteration tests the effect of locking out wrist flexion and extension for handgun training in addition to locking out the radial and ulnar deviation from the first version of The ARCTiC LawE. The experimental group scored significantly higher than the control group at 21 feet and 45 feet over a two-week period. The training occurred in week one and testing occurred in week two. This study lays the groundwork for continued research on transfer of training effectiveness with the ARCTiC LawE.

Introduction

Past research has shown that tremors in the arm have a negative effect on aiming (Ball, Best, & Wrigley, 2003) (Mihelj, Nef, & Riener, 2007). Accuracy when aiming and firing a handgun depends on three primary factors: (1) environmental, (2) hardware, and (3) human factors (Ball, Best, & Wrigley, 2003). Many exoskeletons have been developed to reduce the environmental and hardware impact on accuracy, while few devices exist to assist in training or augmenting humans. The human factors impacts are (1) fatigue (Fröberg, Karlsson, Levi, & Lidber, 1975), (2) experience (Goonetilleke, Hoffmann, & Lau, 2009), (3) body sway (Ball, Best, & Wrigley, 2003), (4) heart rate (Tharion, Santee, & Wallace, 1992), and (5) arm tremors (Baechle, 2013).

Two exoskeletons designed for handgun training are the MAXFAS (a mobile exoskeleton designed for firearm aim stabilization [1]) and the first iteration of ARCTiC LawE (**A**rmed **R**obotic **C**ontrol for **T**raining **i**n **C**ivilian **Law E**nforcement).

The first iteration of The ARCTiC LawE (consisted of a neoprene glove, a plate steel gauntlet like exoskeleton, and a laser-based handgun. This, more mobile, upper body exoskeleton was designed to assist civilian, military, and law enforcement personnel in accurate, precise, and reliable handgun techniques. Training included use of The ARCTiC LawE and the laser-based handgun that had similar dimensions, trigger pull, and break action to a Glock ® 19 pistol. The Glock ® 19 pistol is a handgun common to both public and private security sectors. The laser-based handgun was chosen to ensure the safety of the participants and to alleviate the impact of bullet trajectory (as in traditional guns) due to humidity, and/or temperature. The first iteration of the ARCTiC LawE focused on locking out radial and ulnar deviation of the wrist and resulted in statistically significant participant scores.

The focus of this paper is the second iteration of the ARCTiC LawE (Figure 1), which focused on locking out wrist flexion and extension. In addition, the research lays the groundwork for transfer of training effectiveness with a two-week long study.

Exoskeleton Design

A pull type linear solenoid with a set wrist extension of 25 degrees between the forearm and the back of the hand was used to address deflection to the left and right of the center of the target. The extension angle was determined based on measurements of eight volunteers holding a handgun.

Figure 29: ARCTiC LawE Vrs. 2
(Top) Top down view - unactuated
(Middle) Side view - actuated
(Bottom) Top down view - actuated)

As in the first iteration of the ARCTiC LawE, radial and ulnar deviation was locked out using overlapping metal plates. Wrist extension (movement where the back of the hand moves towards the forearm) is the result of activating the extensor digitorum. Similarly, wrist flexion (movement where the "palm" of your hand moves towards the forearm) is the result of activating the flexor carpi radialis, flexor carpi ulnaris, and palmaris longus.

Locking out the wrist flexion and extension with the ARCTiC LawE helps keep the handgun in line with the rest of the forearm and mitigates inaccuracy from: tightening fingers, jerking or slapping triggers, tightening grip while pulling trigger, thumbing through too much trigger finger, using too little trigger finger, and pushing and heeling from recoil anticipation.

In addition to testing wrist flexion and extension, this paper lays the groundwork for looking at the effect of transfer of training with the ARCTiC LawE. To do so, the participants in this study were required to participate in the study on two separate days with one-week in-between studies. Safety is always a primary concern when working with exoskeletons and humans. The ARCTiC LawE used the padding of the neoprene glove to provide a barrier between the plate steel (which has been filed down and deburred) and the user. The electrical components (solenoids, wiring, and battery pack) were a possible point of safety concern. However, this was addressed with proper care 44towards soldering the components and by using heat shrink wrap over any connection points ensuring safety to the participants. This study looks at utilizing the second version of the ARCTiC LawE and tests participants in week two after having been trained in week one.

Materials and Methods

Participant Selection

The 19 participants were randomly assigned to either the control group or the experimental group. The experimental group had ten participants and the control group had nine participants.

Participants were comprised of civilians above the age of 18 who could legally give consent and could physically operate a handgun. Ideal participants had normal to corrected vision (contact lenses and glasses were okay except for bi-focals, tri-focals, layered lenses, or regression lenses), and had little to no experience using handguns.

Before Beginning the Experiment

Participants were required to fill out a pre-study survey and sign an informed consent document. The pre-study survey asked participants their experience with guns and their experience with handguns. Training for both groups involved teaching participants proper handgun usage and safety. While the study utilized a laser handgun instead of live ammunition, participants were instructed to treat the laser handgun as if it were a live gun using live ammunition.

Study Day One

Participants in the experimental group were trained how to fire a handgun while using the exoskeleton while participants in the control group were trained without the exoskeleton. Participants were started at either 21 feet or 45 feet from the score board and then moved to the next distance to counteract the effect of learning on the results of the participants' scores. Participants were required to fire 25 shots at each distance for a total of 50 shots. The total score after the 25th shot was recorded, and the target was reset. The testing was repeated for the remaining firing distance. Each distance had a potential for 250 points as a high score if each of the 25 shots hit the 10-point bullseye. Participants in the experimental group fired their handgun wearing the ARCTiC LawE, while the participants in the control group fired their handgun wearing no exoskeleton. After completing the testing, participants filled out a post-study survey, which asked qualitative, self-identified metrics of perceived accuracy, perceived precision, etc.

Study Day Two

The second portion of the study took place one week after the original training. Participants were not retrained but were asked to fire at the two distances (starting at a different distance than their first study). This time, both the control and the experimental group were tested without the exoskeleton and were asked to fill out the same post study survey.

Results

Week One

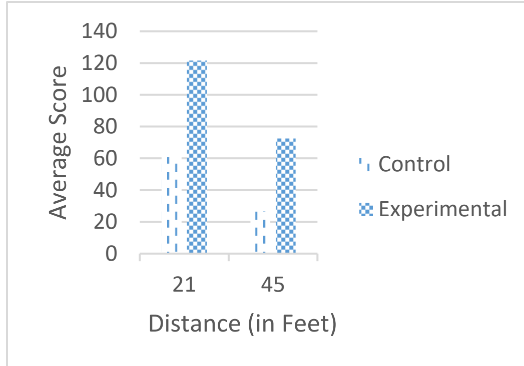

Figure 30: Average Score Week 1

The participants were normally distributed. On average, the experimental group scored 60.82 points higher than the control group at a 21-foot distance and 48.95 points higher than the control group at a 45-foot distance.

Among the participants in the experiment (N = 19), there was a statistically significant difference between the two groups at 21 feet, control (M = 60.78, SD = 39.42) and experimental (M = 121.60, SD = 56.24), t(18) = 0.007, p = 0.015. There was a statistically significant difference between the groups at 45 feet, control (M = 26.56, SD = 11.49) and experimental (M = 72.50, SD = 49.50), t(18) = 0.009, p = 0.015. In the post study survey, participants were asked about the effectiveness of the training they underwent, their precision, their accuracy, and their stability.

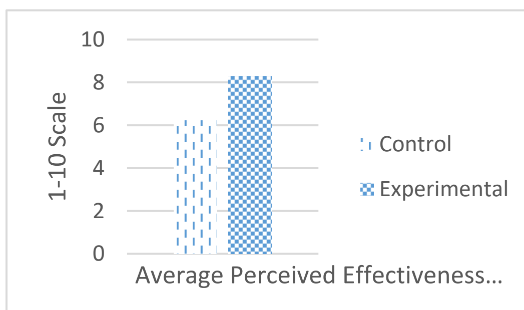

Figure 31: Average Perceived Effectiveness Week 1

On average, participants in the experimental group rated their perceived effectiveness of the training 2.08 points (or ~21%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 6.22, SD = 0.97) and experimental (M = 8.30, SD = 1.16), t(18) = 0.0003, p< 0.01.

On average, participants in the experimental group rated their perceived precision 2.81 points (or ~28%) higher than the control group. There was a statistically significant difference between the control (M = 2.89, SD = 1.54) and experimental (M = 5.70, SD = 2.67), t(18) = 0.006, p = 0.013.

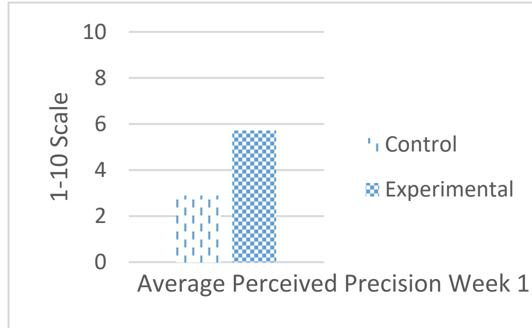

Figure 32: Average Perceived Precision Week 1

On average, the experimental group rated their perceived accuracy 4.09 points (or ~41%) higher than the control group. There was a statistically significant difference between the control (M = 2.11, SD = 1.45) and experimental (M = 6.20, SD = 3.19), t(18) = 0.001, p = 0.003.

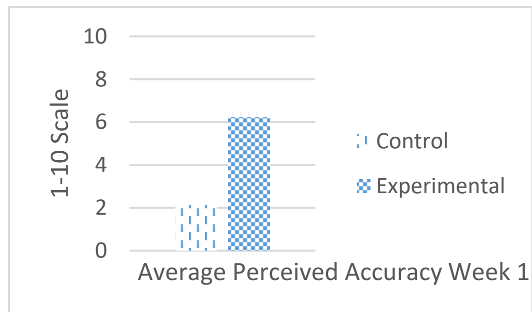

Figure 33: Average Perceived Accuracy Week 1

On average, participants in the experimental group rated their perceived stability 2.65 points (or ~27%) higher than the control group. There was a statistically significant difference between the control (M = 4.56, SD = 1.81) and the experimental (M = 7.20, SD = 2.30), t(18) = 0.006, p = 0.013.

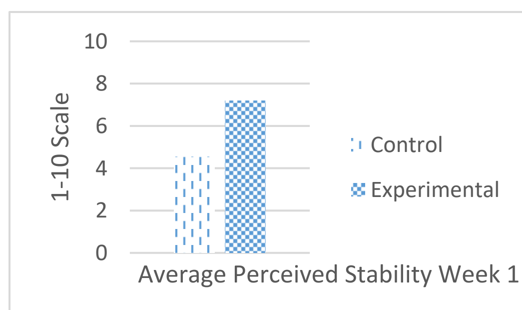

Figure 34: Average Perceived Stability Week 1

Week Two

Again, the participants were normally distributed. On average, the experimental group scored 77.07 points higher than the control group at 21 feet and 22.98 points higher than the control group at 45 feet. Among the participants in the experiment (N=19), there was a statistically significant difference between the two groups at 21 feet, control (M = 69.33, SD = 39.26) and experimental (M = 146.4, SD = 42.43), t(18) = 0.0004, p < 0.01. There was a statistically significant difference between the groups at 45 feet, control (M = 47.78, SD = 22.93) and experimental (M = 70.70, SD = 28.27), t(18) = 0.03, p = 0.07.

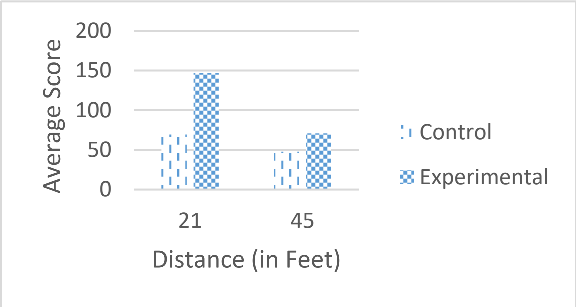

Figure 35: Average Score Week 2

In the post study survey, participants were asked about their perception of the effectiveness of the training they underwent, their perceived precision, their perceived accuracy, and their perceived stability.

On average, participants in the experimental group rated their perceived effectiveness of the training 1.58 points (or ~16%) higher than the control group. There was a statistically significant difference between the control (M = 6.22, SD = 1.09) and the experimental groups (M = 7.8, SD = 1.69), t(18) = 0.013, p = 0.03.

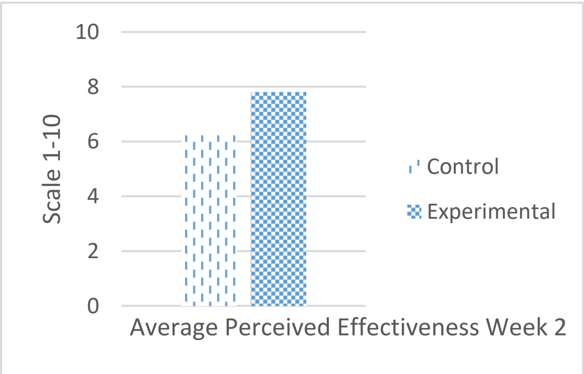

Figure 36: Average Perceived Effectiveness Week 2

On average, the experimental group rated their perceived precision 1.95 points (or ~20%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 4.56, SD = 1.88) and experimental (M = 6.50, SD = 2.17), $t(18) = 0.026$, $p = 0 .05$.

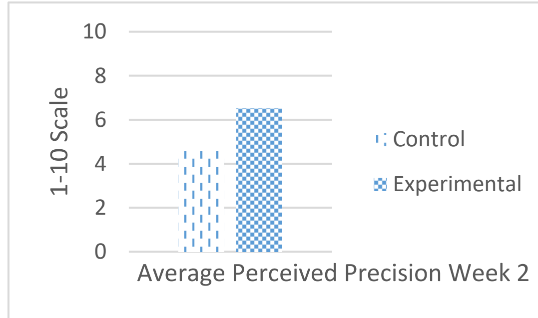

Figure 37: Average Perceived Precision Week 2

On average, the experimental group rated their perceived accuracy 2.00 points (Or ~20%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 4.56, SD = 1.88) and experimental (M = 6.50, SD = 2.07), $t(18) = 0.023$, $p = 0.05$.

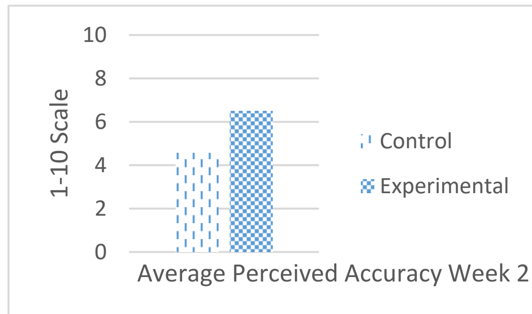

Figure 38: Average Perceived Accuracy Week 2

On average, the experimental group rated their perceived stability 2.03 points (or ~20%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 4.78, SD = 1.48) and experimental (M = 6.8, SD = 2.25), $t(18) = 0.017$, $p = 0.036$.

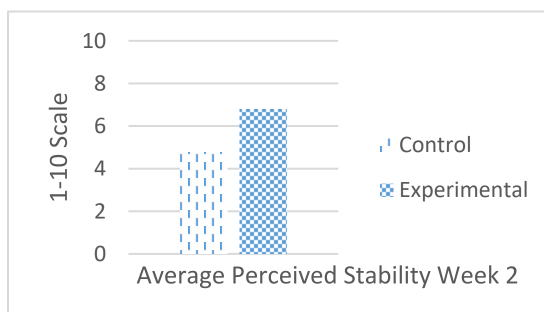

Figure 39: Average Perceived Stability Week 2

Discussion

Transfer of Training

It is at this stage where the basis of transfer of training can be analyzed. The performance limiting factor is the retrieval from one's long term memory. There are two types of knowledge that correspond to learning and training: (1) procedural and (2) declarative. The critical processes involved in cognitive learning are attention, rehearsal in working memory, retrieval from long-term memory, and metacognitive monitoring. Instructional technology directs cognitive learning processes.

Because many metrics involved in the analysis of The ARCTiC LawE involved qualitative metrics, the average score will be analyzed for transfer of training. The experimental group consistently outperformed the control group with The ARCTiC LawE during training and without The ARCTiC LawE one week after training. The potential exists for a transfer of training aspect. Future work could look at this aspect more in depth by including time to handgun certification for police officers trained with The ARCTiC LawE compared to time to handgun certification for police officers trained without an exoskeleton.

The Transfer of Training Paradigm has a training effectiveness ratio (TER) which is used to determine the transfer result of two or more groups – a control group using traditional technology and the experimental group using new technology. There are two possible transfer results: (1) negative transfer, where the experimental groups' performance is inferior to that of the control group and (2) positive transfer, where the experimental groups perform as well or better than the control group. For positive transfer to occur, not only should the experimental group perform as well or better than the control group, but the training should also be completed in a shorter time.

The amount of time taken for the training was not recorded for the study. However, it was noted that no appreciable difference existed in regard to training time between the control group and the experimental group. Additional future work would include determining the appropriate score for a qualified police officer and comparing the traditional training with the LaserLyte to the training with The ARCTiC LawE. This could then be used to compare the TER with a traditional handgun over a full training period.

Some potential future work includes changing what material the exoskeleton is made of. A change from the 14-gauge stainless plate steel to fiberglass or carbon fiber would reduce the weight while maintaining the rigidity and structural integrity of the exoskeleton. This would also allow for parts that could quickly and cheaply be replaced or swapped out for smaller or larger parts, or swapped out for specialized equipment.

The following extrapolation is made from the assumption that other environmental aspects like sound are not major factors. A document released by the U.S. Department of Homeland Security covers the ammunition usage and purchase history for fiscal years 2010-2012 and is summarized in the table below.

Table 3: US DHS Ammunition Usage and Spending FY 2010-2012 (Long, Accessed 31 March 2016)

FY 2010	148,314,825 bullets
FY 2011	108,664,054 bullets
FY 2012	103,178,200 bullets

Buying .40 S&W 180 grain full metal jacket rounds in bulk (cheaper than buying fewer rounds) costs $120 for 500 rounds [13] or about $0.24 each. Based on the information above, it can be expected that for the 2016 fiscal year, the Department of Homeland Security will have spent ~$6.4M just on the bullets for training. From discussions with a reserve deputy in Story County Iowa, as well as other police officers during the PI's initial training with handguns, it was found that there is a decrease in purchasing of ammunition and an increase in the cost per bullet each year, for various reasons. Even with the decreasing supply and increasing costs, servicemen and servicewomen cannot afford to not be at an appropriate level of training and the LaserLyte and The ARCTiC LawE can be a viable supplement for traditional training.

Even a small decrease in cost of ammunition, which can be experimentally determined with the comparison of The ARCTiC LawE training to live fire training can result in a large amount of savings. This would greatly reconcile any initial investment cost. This does not include any money saved on training personnel.

It is typical for police officer training to spend 40-hour weeks on firearms training, requiring approximately 1000 rounds of .40 caliber rounds per week. Forty hours is a minimum amount of training required to carry a handgun in the United States.

Based on results of transfer of training with virtual reality and welding (Byrd, Stone, & Anderson, 2015), and based on discussion with the local Sheriff's department, a reduction in number of bullets needed to train police officers of 50% could be considered a conservative amount. While real world application and virtual application is not a direct comparison, it has been proven to provide a positive transfer of training and is something that could be done in the future.

Conclusion

Ultimately, the exoskeleton greatly impacts sensory motor learning and the biomechanical implications are confirmed via both performance and physiological measurements. The researchers believe The ARCTiC LawE to be a viable substitute for training with live fire handguns to reduce the cost of training time and munitions and will increase accuracy and precision for typical law enforcement and military live fire drills. This project increases the breadth of knowledge for exoskeletons as a tool for training. This upper body exoskeleton designed to assist civilian, military, and law enforcement personnel tested the effect of locking out wrist flexion and extension for handgun training. The results for average score at 21 feet, average score at 45 feet, perceived effectiveness, perceived precision, perceived accuracy, and perceived stability were all statistically significant. The quantitative and qualitative metrics indicate locking out wrist flexion and extension with an upper body exoskeleton has a positive impact on handgun training. Initial analysis of transfer of training effectiveness indicates The ARCTiC LawE exoskeleton could be an effective tool for handgun training that could decrease cost of training time and cost of ammunition.

Chapter XVI The Quantum Ex Method

The QuANTUM Ex Method itself draws on many aspects of existing engineering design methodologies. These aspects are used based on their applicability to exoskeleton design and evaluation. There are two primary methodologies that QuANTUM Ex utilizes, namely TRIZ and design for manufacturing. TRIZ and design for manufacturing are highlighted for the magnitude of importance for coming up with innovative solutions in design as well as forcing engineering design teams to consider what not only works but is also feasible. The two aspects balance one another. A flowchart of the basic design process for The QuANTUM Ex Method can be seen in the figure on the next page. Due to the magnitude of scale of the flowchart, more detailed breakdowns of the flowchart can be seen in the appendices at the end of this document.

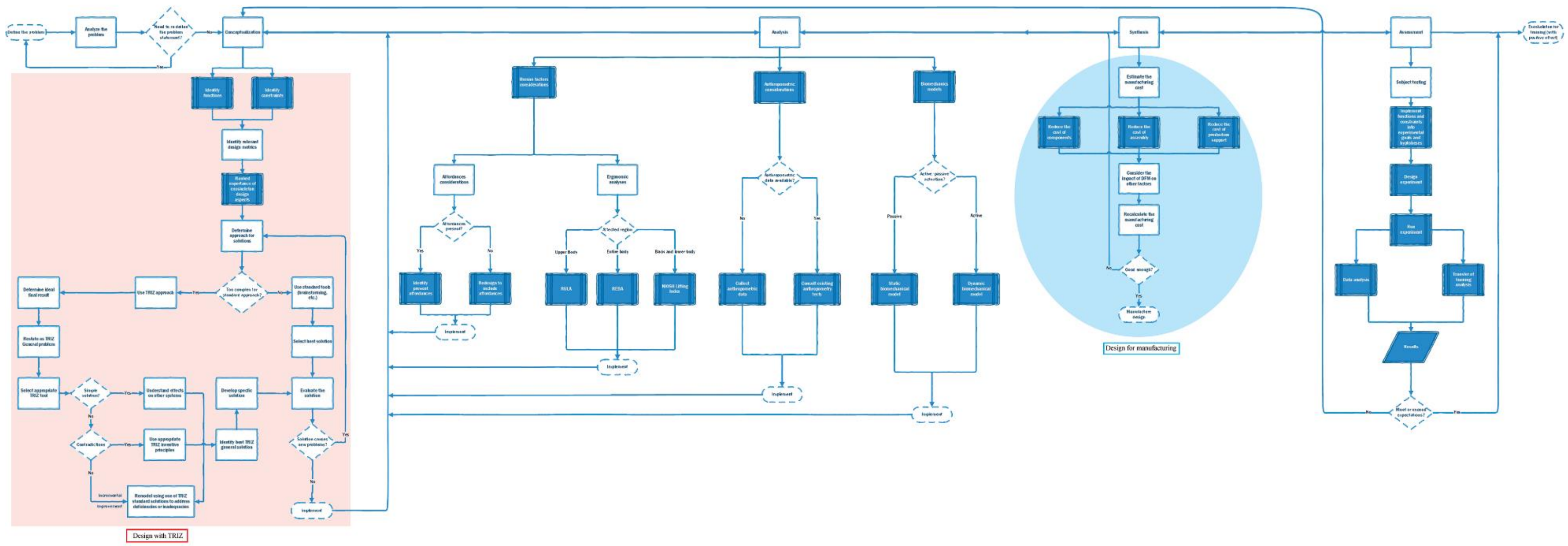

Figure 40: The QuANTUM Ex Method Flowchart

Chapter XVII QuANTUM Ex Method Vrs. 1 Experimental Set Up

The validation of this methodology was broken into two primary stages. In the first stage, validation of an exoskeleton assessment method, participants were tasked with designing an upper body exoskeleton for handgun training. In the second stage, aspects of affordances in exoskeleton design, participants were asked to validate and evaluate the exoskeletons designed and manufactured in the previous stage.

Participant Selection

Students were invited to participate in the studies for 5% extra credit in the class. Students were only allowed to participate in Stage 1 or in Stage 2 but not in both. Participants emailed the PI asking to participate in one of the experiments for extra credit. The PI compiled this list and randomly assigned participants to the different experiments.

Chapter XVIII QuANTUM Ex Method Vrs. 1 – Validation Of An Exoskeleton Method

The purpose of this study was to validate the QuANTUM Ex Method by having participants' design an upper body exoskeleton for handgun training. Participants were informed that the term 'exoskeleton' for the purposes of the study is used to describe any device that augments (changes or improves) the performance of an able-bodied wearer.

Before beginning the study, participants completed an informed consent document (Appendix C: Validation of an Exoskeleton Assessment method informed consent). After reading and signing the form, participants completed a pre-study survey, a self-efficacy survey, and an unusual uses form. Participants were then allotted a maximum of four hours to design an exoskeleton. Following their design period, the participants completed a post-study survey.

Demographic Information

A total of 16 participants took part in this study; eight in the control group and eight in the experimental group. Participants were from a graduate level human factors course and received 5% extra credit for participating in the study. Interested participants were randomly placed in either the control or experimental group. The control group was comprised of six males and two females with a mean age of 24.6 years (SD = 3.5 years). The experimental group was also comprised of 6 males and 2 females with a mean of 23.1 years (SD = 3.0 years). A two-tailed, two-sample unequal variance t-test was conducted yielding $t(14) = 0.92036$, $p = 0.3733$; therefore, the age of the two groups was not statistically different.

Each group was comprised of four participants pursuing a Bachelor of Science degree, three participants pursuing a Master of Science degree, and one participant pursuing a Doctor of Philosophy degree. There was not a significant difference in the participant's internship experience for the control (M = 4.375 months, SD = 5.0 months) and the experimental (M = 4.25 months, SD = 5.25 months) conditions; t(14) = 0.04867, p = 0.9619. From the results of participants' age, sex, degree pursued, and length of internship, it can be concluded that the two groups were not significantly different from each other in terms of background. The following section evaluates if the participant groups were significantly different from each other in their understanding of certain topics.

Self-Efficacy

Participants completed a self-efficacy survey. The purpose of the self-efficacy survey was to analyze if participants had a similar level of understanding. In this survey, they answered nine questions that asked their self-efficacy in certain important metrics related to engineering design. Each question had a scale from 0% to 100% where 0% indicates they do not have any understanding of a topic and 100% indicates they are fully knowledgeable in a topic. This scale was divided into increments of 10% and participants placed an 'x' on the line that best represented their self-efficacy.

The first statement was "I come up with creative designs". There was not a statistically significant difference between the control (M = 62.50, SD = 17.50) and the experimental (M = 63.75, SD = 26.69) conditions; t(14) = 0.11, p = 0.91.

The second statement was "I am comfortable using TRIZ". There was not a statistically significant difference between the control (M = 28.75, SD = 29.97) and the experimental (M = 13.75, SD = 31.59) conditions; t(14) = 0.97, p = 0.35.

The third statement was “I am comfortable designing for manufacturing”. There was not a statistically significant difference between the control ($M = 60.00$, $SD = 28.80$) and the experimental ($M = 48.75$, $SD = 34.80$) conditions; $t(14) = 0.70$, $p = 0.49$.

The fourth statement was “I am comfortable designing a functional prototype”. There was not a statistically significant difference between the control ($M = 62.50$, $SD = 18.30$) and the experimental ($M = 53.75$, $SD = 34.20$) conditions; $t(14) = 0.64$, $p = 0.54$.

The fifth statement was “I am comfortable using 3D modeling software”. There was not a statistically significant difference between the control ($M = 55.0$, $SD = 35.10$) and experimental ($M = 63.75$, $SD = 35.80$) conditions; $t(14) = 0.49$, $p = 0.63$.

The sixth statement was “I am comfortable with product analysis”. There was not a statistically significant difference between the control ($M = 52.50$, $SD = 22.52$) and the experimental ($M = 61.25$, $SD = 34.82$) conditions; $t(14) = 0.60$, $p = 0.56$.

The seventh statement was “I am comfortable with ergonomic testing”. There was not a statistically significant difference between the control ($M = 48.75$, $SD = 28.50$) and experimental ($M = 47.50$,$SD = 44.00$) conditions; $t(14) = 0.07$, $p = 0.95$.

The eight statement was “I am comfortable with concepts of human-centered design approaches”. There was not a statistically significant difference between the control ($M = 45.00$, $SD = 25.60$) and the experimental ($M = 60.00$ $SD = 34.60$) conditions; $t(14) = 0.98$, $p = 0.34$.

The final statement was “I am comfortable with the concept of affordances”. There was not a statistically significant difference between the control ($M = 50.00$, $SD = 29.76$) and the experimental ($M = 46.25$, $SD = 30.38$) conditions; $t(14) = 0.25$, $p = 0.81$.

With no statistically significant difference between the control and experimental groups in any of the nine categories, it can be concluded that the participants' held a similar level of understanding of engineering design.

Unusual Uses

Torrance's unusual uses test is one method to evaluated individual's ability to think creatively. It has been shown to be a reliable indicator of creative potential (Runco & Acar, 2012). The test is also recommended as a standard test of creativity for physical objects rather than language based (Dippo, 2013). It requires subjects to come up with creative uses for common objects. In this study, participants were told to come up with as many creative uses for cardboard boxes as they could. This was done in a 10 minute time span. Each item a participant lists is categorized and ranked for originality by the test administrator after the test. The unusual uses test grades on four metrics.

The first metric is fluency. This is the number of solutions a participant comes up with. An analysis of participants' fluency in creative thinking was conducted. There was not a statistically significant difference between the control ($M = 25.38$, $SD = 7.50$) and the experimental ($M = 22.5$, $SD = 9.23$) conditions; $t(14) = 0.68$, $p = 0.51$.

The second metric is flexibility. This is the number of unique categories a participant's set of solutions falls in. An analysis of participants' flexibility in creative thinking was conducted. There was not a statistically significant difference between the control ($M = 11.00$, $SD = 5.42$) and the experimental ($M = 11.50$, $SD = 3.07$) conditions; $t(14) = 0.23$, $p = 0.82$.

The third metric is originality. This is the sum of original solutions a participant comes up with. An analysis of participants' originality in creative thinking was conducted. There was not a statistically significant difference between the control ($M = 3.38$, $SD = 3.42$) and the experimental ($M = 5.63$, $SD = 4.53$) conditions; $t(14) = 1.12$, $p = 0.28$.

The final metric is simply the sum of the previous three. An analysis of the sum of participants' fluency, flexibility, and originality in creative thinking was conducted. There was not a statistically significant difference between the control ($M = 41.00$, $SD = 13.16$) and the experimental ($M = 39.63$, $SD = 13.37$) conditions; $t(14) = 0.21$, $p = 0.84$.

With no statistically significant difference between the control and experimental groups in any of the four categories, it can be concluded that the participants' held a similar level of divergent thinking and creativity in terms of physical objects.

Results

Time for Completion

The time it took for each participant to complete their exoskeleton design was recorded. There was a statistically significant difference between the control ($M = 103.50$ min, $SD = 41.57$ min) and the experimental ($M = 211.88$ min, $SD = 101.56$ min) conditions; $t(14) = 2.79$, $p = 0.0203$. The experimental group took significantly longer than the control group to complete their design.

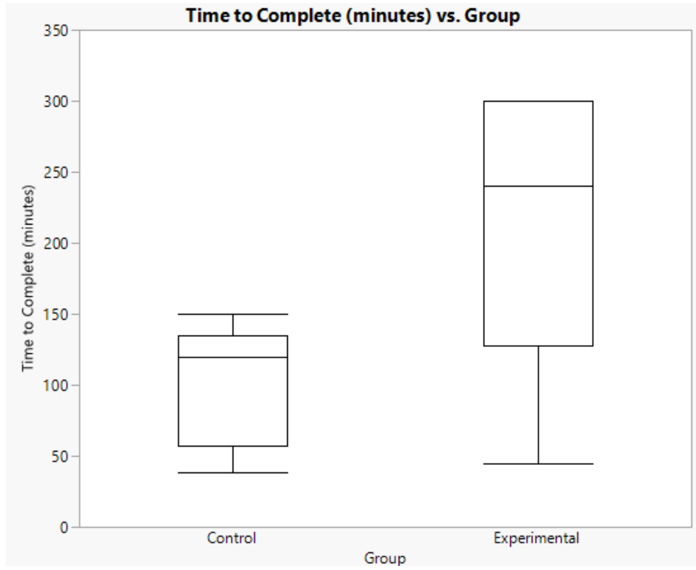

Figure 41: Time (minutes) Taken to Complete Exoskeleton Design

As part of the post-study questionnaire, all but one participant in the experimental group indicated that there was enough time to complete their design. The control group was asked if they followed any particular design methodology during the experiment. Of the eight participants in the control group, only two participants indicated they followed a specific methodology (design for fabrication and design for six sigma). The rest said they did not follow any methodology in particular but just tried to apply things they have learned throughout their educational and professional career. The experimental group rated their perception of difficulty using the methodology and associated workbook. They rated them as moderately easy to use (M = 3.06/10, SD = 2.24).

An analysis of important aspects of exoskeleton design was conducted from the 16 participants. It was assessed if participants in both the control and experimental group implemented each of the following aspects:

- Functions
- Constraints

- Task analysis
- Design metrics
- Who is the product for
- Why do they want the product
- What should the product be able to do
- Engineering parameters
- Inventive principles
- Affordances
- Ergonomic analysis
- Static analysis
- Dynamic analysis
- Synthesis
- Experimental design
- Transfer of training

A student's t-test was performed for each metric listed above. The metrics functions ($p = 0.277$), constraints ($p = 0.500$), dynamics analysis ($p = 0.167$), and synthesis ($p = 0.309$) were not statistically different. The metrics task analysis ($p = 3.124e\text{-}06$), design metrics ($p = 0.020$), who is the product for ($p = 0.002$), why do they want the product ($p = 0.0002$), what should the product be able to do ($p = 0.002$), engineering parameters ($p = 3.124e\text{-}06$), inventive principles ($p = 3.124e\text{-}06$), affordances ($p = 0.024$), ergonomic analysis ($p = 0.0004$), static analysis ($p = 3.124e\text{-}06$), experimental design ($p = 0.002$), and transfer of training ($p = 0.020$) were statistically significant.

While there is no guarantee that the control group did not consider similar aspects during their design phase, there was no indication in the participants' written notes (all of which were turned in after the experiment). All participants were instructed to write down all considerations they made during their design phase.

This analysis indicates that the experimental group considered many more aspects that have been shown as important during the exoskeleton design phase. With statistical significance in numerous areas, this analysis shows the impact on thought The QuANTUM Ex Method had on the design phase.

Manufacturing

After analyzing the results of the design phase of this research project, there were 16 designs, eight from the control group and eight from the experimental group. Experts were given the 16 designs in two piles without knowing which pile was the control group or which was the experimental group. They were told to choose their top two choices from both piles. These experts analyzed the exoskeleton designs independent from one another and consistently chose the same four exoskeletons. The design drawings are replicated below.

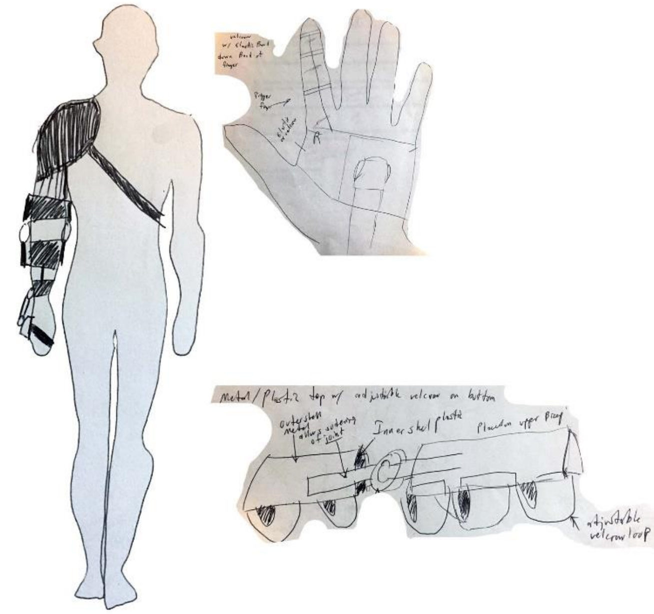

Figure 42: Exoskeleton A Drawings (Control)

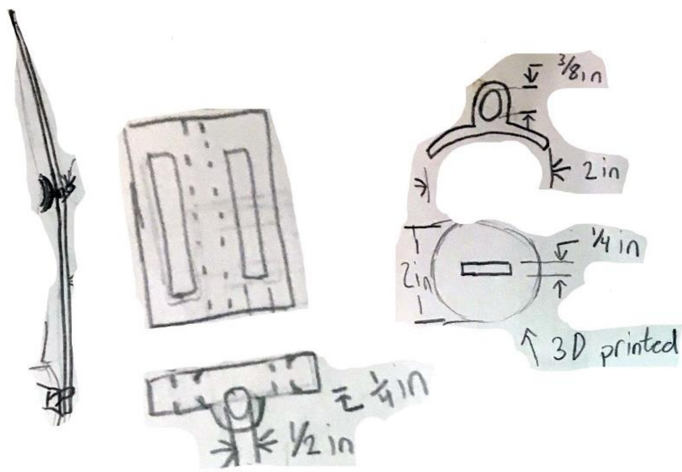

Figure 43: Exoskeleton B Drawings (Experimental)

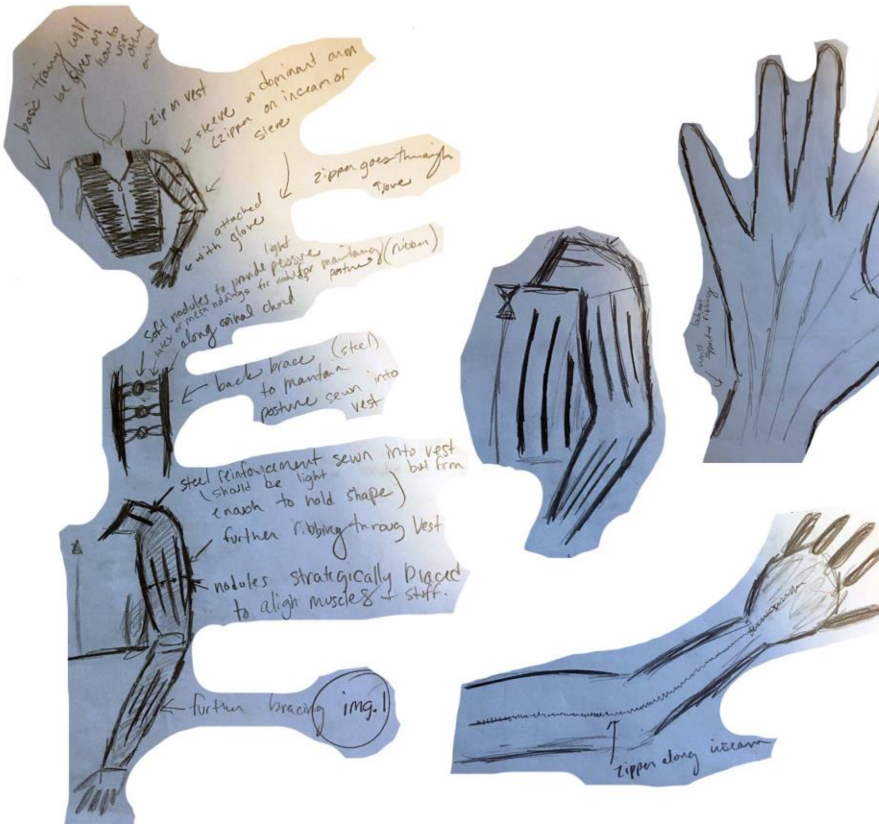

Figure 44: Exoskeleton C Drawings (Control)

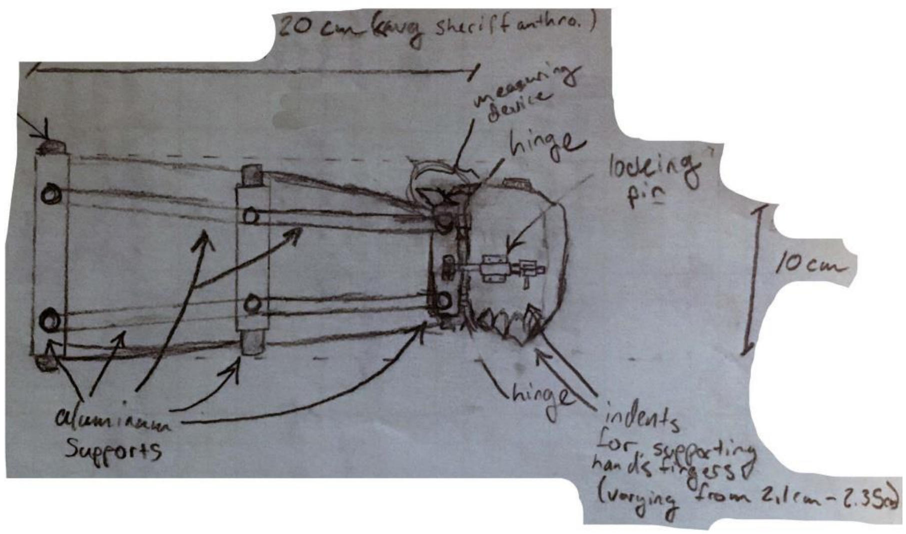

Figure 45: Exoskeleton D Drawings (Experimental)

The exoskeletons will now be designated a letter. Exoskeletons A and C are from the control group and Exoskeletons B and D are from the experimental group. The four exoskeletons now entered the synthesis and fabrication phase of the QuANTUM Ex Method. Some components of the exoskeletons were machined by a senior machinist. The rest of the fabrication and assembly of the exoskeletons was handled by a small team. This team was led by a single qualified engineer who directed the manufacturing process and controlled manufacturing quality. The final produced exoskeletons are shown in the following figures.

Figure 46: Exoskeleton A Prototype (Control Group)

Figure 47: Exoskeleton B Prototype (Experimental)

Figure 48: Exoskeleton C Prototype (Control)

Figure 49: Exoskeleton D Prototype (Experimental)

Chapter XIX QuANTUM Ex Method Vrs. 1 – Aspects Of Affordances In Exoskeleton Design

The purpose of this study was to analyze and evaluate the four exoskeletons that were manufactured as a result of the previous study. The study was designed to implement the results of rank order interdependencies with the evaluation aspect of The QuANTUM Ex Method by determining quantitatively and qualitatively which exoskeleton is considered the best design for the task. This study was comprised of two phases. Phase I had participants analyze each exoskeleton without using it. They determined which engineering design metrics they could see in the design and determine the level of importance they thought the designer gave each metric.

The second phase occurred after the participant was trained in handgun use and fired a LaserLyte with the exoskeleton on until they felt comfortable. In this phase, they determined which engineering design metrics they could see working in the design and determine the level of importance they thought the designer gave each metric. This analysis determined the affordances for each exoskeleton before and after use.

Participants completed an informed consent document, were trained on gun safety and how to fire a handgun, analyzed each exoskeleton (in a random order), donned the exoskeleton, fired a LaserLyte with the exoskeleton on, doffed the exoskeleton, analyzed each exoskeleton again, and then completed a post-study questionnaire.

Demographics

There were 26 participants who were part of the study. The participants were comprised of 19 males and seven females with a mean age of 24.19 years (SD = 5.12 years). There was not a statistically significant difference between the male (M = 23.74

years, SD = 3.93 years) and female (M = 25.43 years, SD = 7.79 years) participants; t(24) = 0.55, p = 0.60. The participants had a mean height of 69.73 inches (SD = 4.34 inches). There was not a statistically significant difference between the male (M = 70.79 inches, SD = 3.92 inches) and female (M = 66.86 inches, SD = 4.38 inches) participants; t(24) = 2.09, p = 0.06.

The participants had a mean 1.92 internships (SD = 1.20) with a mean internship/co-op length of 8.20 months (SD = 6.25). There was a statistically significant difference between the male (M = 9.16 months, SD = 6.60 months) and female (M = 4.43 months, SD = 4.16 months); t(24) = 2.17, p = 0.04.

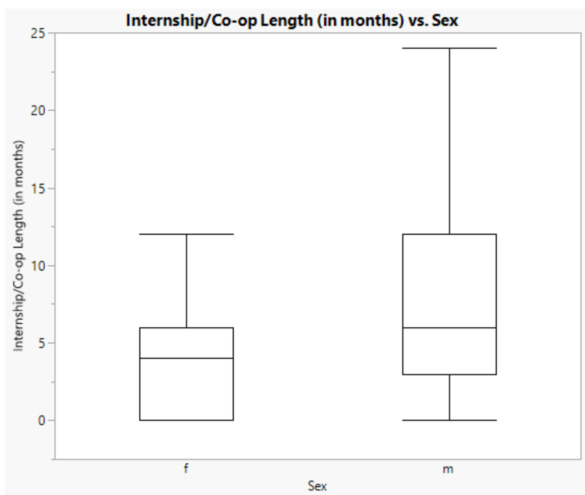

Figure 50: Boxplot of Internship/Co-op Length (in months)

While there was a statistically significant difference in internship/co-op length, this metric is not a critical factor in the study.

Weapon Experience

As part of their pre-study survey, participants reported their experience with guns and hand guns from 1 being absolutely no experience and 10 being military experience. This metric was used as an indicator of participants’ knowledge and potential ability to see application of the exoskeletons. Participants reported their experience with guns in general with an average of 3.54/10 (SD = 2.58).

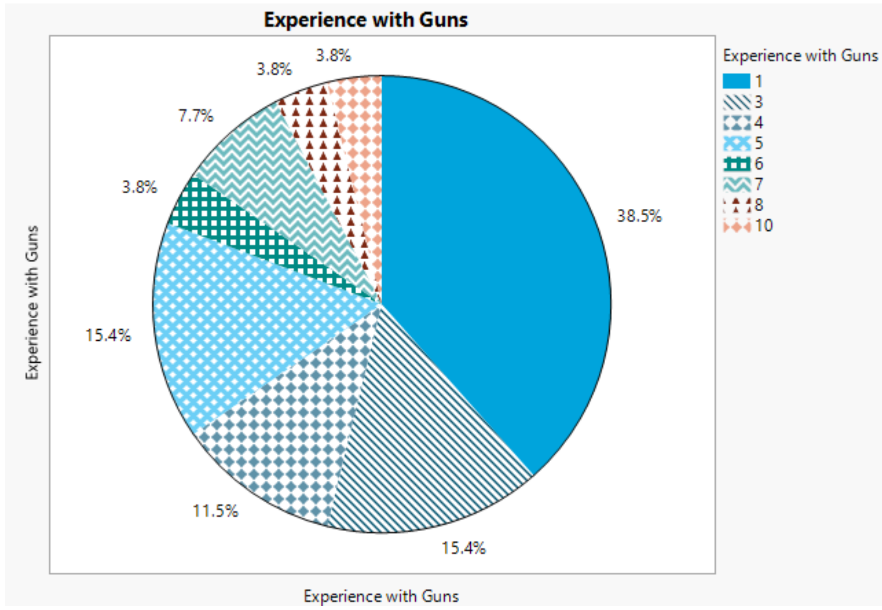

Figure 51: Pie Chart of Participants' Experience with Guns

Participants reported their experience with handguns with an average of 3.08/10 (SD = 2.37).

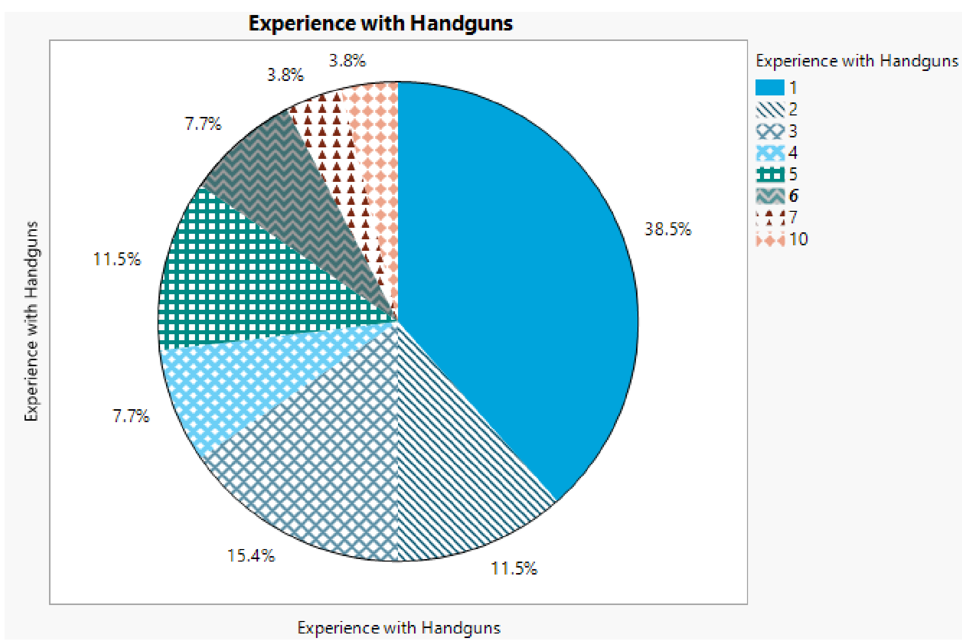

Figure 52: Pie Chart of Participants' Experience with Handguns

Self-Efficacy

As with the previous study, the purpose of the self-efficacy survey was to analyze if participants had a similar level of understanding. In this survey, they answered nine questions that asked their self-efficacy in certain important metrics related to engineering design. Each question had a scale from 0% to 100% where 0% indicates they do not have any understanding of a topic and 100% indicates they are fully knowledgeable in a topic. This scale was divided into increments of 10% and participants placed an ‘x’ on the line that best represented their self-efficacy.

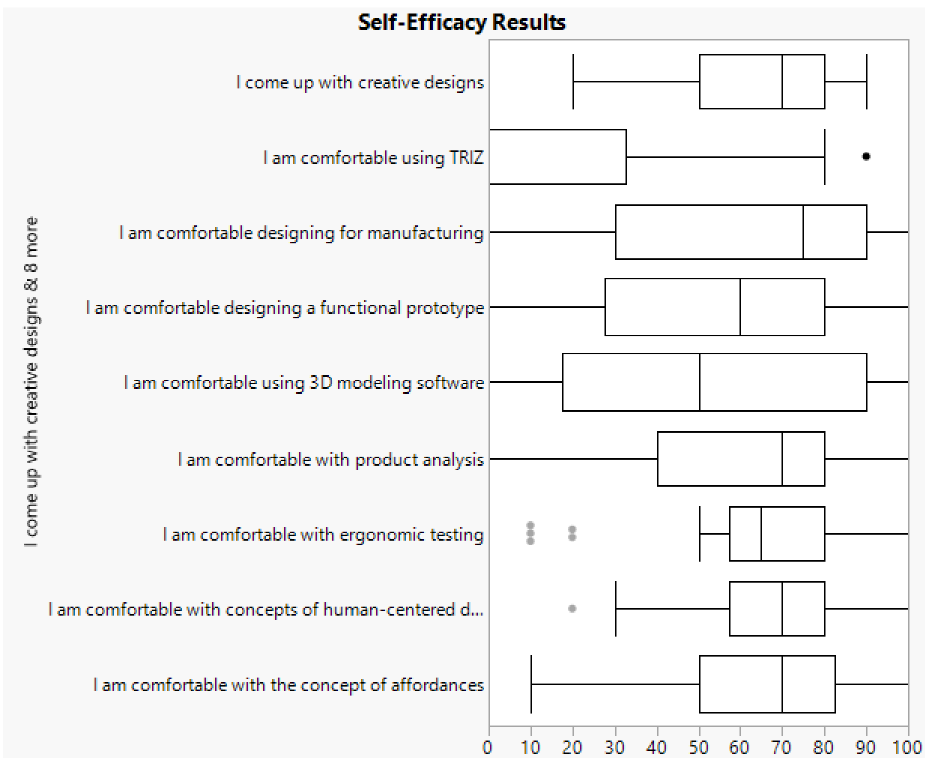

Figure 53: Self-Efficacy Results

Evaluation

Each participant was presented with one of the four exoskeletons in a random order. Exoskeletons were always presented in alternating fashion (i.e. if the participant was first presented with an exoskeleton designed by the control group, they would then be presented an exoskeleton designed by the experimental group, followed by control, and finally experimental. After each exoskeleton was presented, participants would complete the initial analysis phase where they answered two affordances related questions, identified which engineering design metrics were important to them, followed by ranking their chosen metrics. Finally, the participants answered four additional affordances related questions as part of the after use phase. Participants completed these four phases for each exoskeleton before completing a post-study survey.

Initial Analysis - Affordances

During the initial analysis phase, participants analyzed and rated each exoskeleton. The first question they rated the exoskeletons for were their ability to handle the exoskeleton properly without reading instructions. There was a statistically significant difference between the four exoskeletons as determined by one-way ANOVA ($F(3,100) = 12.86$, $p < 0.0001$).

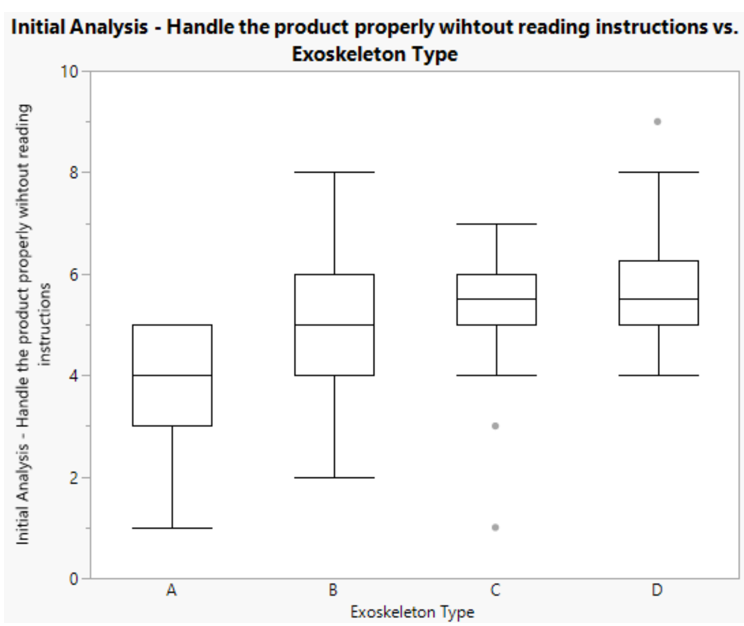

Figure 54: Initial Analysis - Handle Exoskeleton Properly Without Reading Instructions (Exoskeleton A vs. Exoskeleton B vs. Exoskeleton C vs. Exoskeleton D)

This metric was also compared by blocking the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). There was a statistically significant difference between the two groups as determined by a one-way ANOVA ($F(1, 102) = 14.57$, $p = 0.0002$).

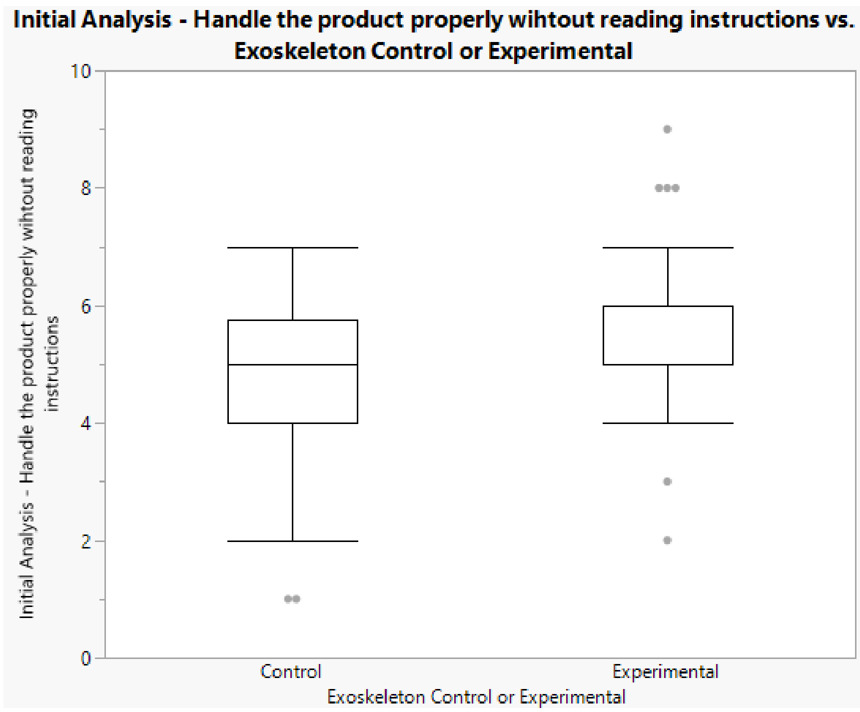

Figure 55: Initial Analysis - Handle Exoskeleton Properly Without Reading Instructions (Control Group vs. Experimental Group)

The second question they rated was their ability to understand how to use the exoskeleton properly without instructions. There was a statistically significant difference between the four exoskeletons as determined by a one-way ANOVA ($F(3, 100) = 8.00$, $p < 0.0001$).

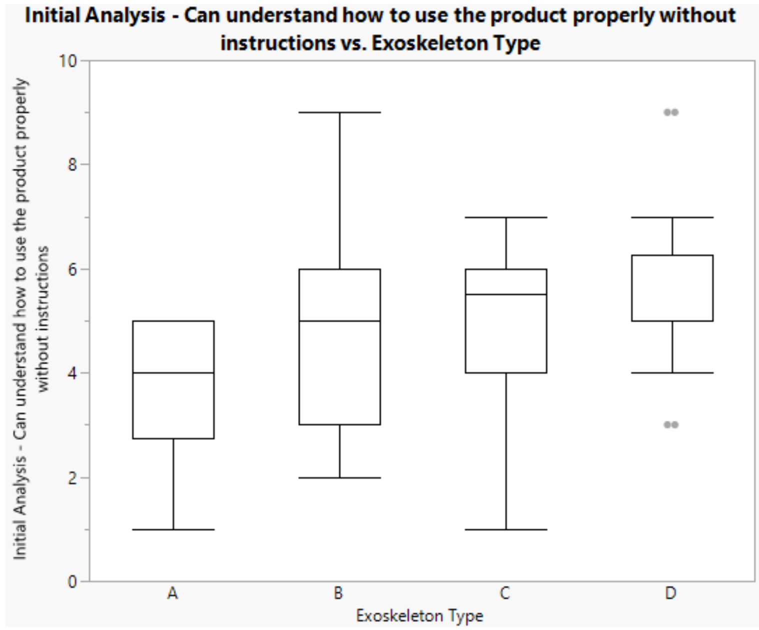

Figure 56: Initial Analysis - Can Understand How to Use the Exoskeleton Properly without Instructions (Exoskeleton A vs. Exoskeleton B vs. Exoskeleton C vs. Exoskeleton D)

This metric was also compared by blocking the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). There was a statistically significant difference between the two groups as determined by a one-way ANOVA ($F(1, 102) = 6.72$, $p = 0.01$).

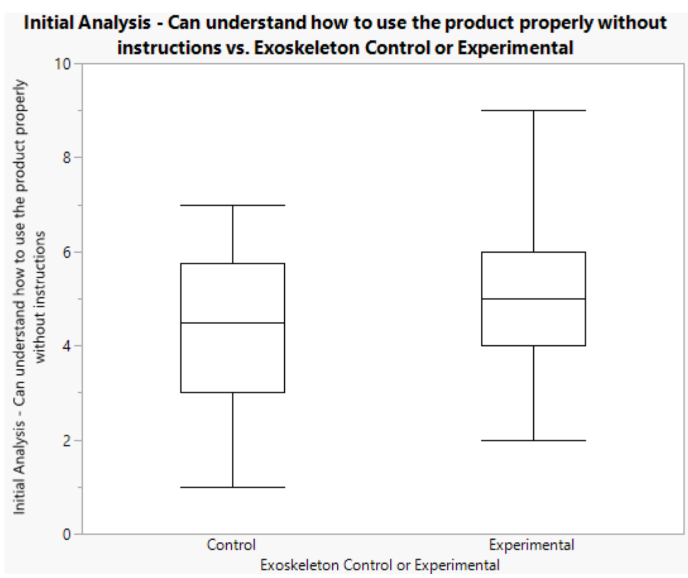

Figure 57: Initial Analysis - Can Understand How to Use the Exoskeleton Properly Without Instructions (Control Group vs. Experimental Group)

Exoskeleton Design Metrics Initial Analysis

Previous work introduced a multi-criteria decision making model to evaluate packaging affordances (Mumani, User-Packaging Interaction (UPI): A Comprehensive research platform and techniques for improvement, evaluation, and design, 2018). It utilized requirements found through the literature to serve as evaluation criteria in terms of innate affordances properties. Products were evaluated for their affordances properties using the simple additive weighting (SAW) method with swing weighting to asses their relative importance. This provided an overall affordance level for each package. The current exoskeleton study will utilize a similar approach to evaluate the exoskeletons' relative affordances.

SAW is comprised of four primary steps (Adriyendi, 2015) (Goodridge, 2016):

(1) Evaluation criteria

(2) Relative importance of evaluation criteria

(3) Feasible alternatives

(4) Rating of alternatives against evaluation criteria

Affordance properties represent the evaluation criteria for each feasible alternative l_i, where $i = 1, \dots, n$. In this case, the feasible alternatives are the four exoskeletons that were designed and manufactured. The evaluation criteria are weighted utilizing the swing weighting method, thus representing their relative importance with respect to each affordance A_j, where $j = 1, \dots, S$. An affordance property related to an affordance property A_j is represented by p_{jm}, where $m = 1, \dots M$. There are steps used in this MCDM evaluation approach.

Step 1

The evaluation criteria related to affordance A_j is represented by the vector *P*:

$$P = \left[p_{j1}, p_{j2}, p_{j3}, \dots p_{jM}\right]^T \tag{1}$$

where p_{jm} is an evaluation criterion related to affordance A_j.

The relative importance of the evaluation criteria is represented by the vector *W*:

$$W = \left[w_{j1}, w_{j2}, w_{j3}, \dots, w_{jM}\right]^T \tag{2}$$

where W_{jm} is the relative importance of evaluation criteria p_{jm} with respect to affordance property A_j.

Step 2

Next the feasible alternatives are identified and evaluated against the respective evaluation criteria. These alternatives are normalized to obtain a dimensionless value:

$$N_{ijm} = \frac{X_{ijm}}{MAX(X_{ijm})} \forall i, \text{ for all beneficial criteria} \tag{3}$$

$$N_{ijm} = \frac{MIN(X_{ijm})}{X_{ijm}} \ \forall i, \text{ for all non-beneficial criteria} \tag{4}$$

where N_{ijm} is the normalized rate of alternative l_i with respect to p_{jm}; X_{ijm} is the rate of the alternative l_i with respect to p_{jm}.

Step 3

An alternative's score is then calculated with respect to each affordance:

$$V_{ij} = \Sigma_{m=1}^{M} w_{jm} N_{ijm}, \forall i, j \tag{5}$$

where V_{ij} is the alternative l_i score with respect to affordance A_j; w_{jm} represents the relative importance of property p_{jm} with respect to affordance A_j; and N_{ijm} is the normalized rate of alternative l_i against property p_{jm} of affordance A_j.

Step 4

The overall affordance score is then calculated for each alternative as follows:

$$V_i = \sum_{j=1}^{s} w_j V_{ij}, \ \forall i \qquad (6)$$

where V_i is the overall affordance score of alternative l_i; and w_j is the relative importance of affordances A_j with respect to the overall affordance level.

Step 5

Finally, the best alternative associated with the highest overall affordance level can be calculated as follows:

$$V_{BEST} = Max_{i=1}^{n} V_i \qquad (7)$$

This exoskeleton study will focus on two affordance properties defined in the table below.

Table 4: Affordance Properties and Descriptions

Affordance property	Description
Without thought	Has the property where the user does not need to learn and/or memorize instructions to interact with the exoskeleton
Intuitiveness	The exoskeleton can be used without instructions

Evaluation criteria are then weighted using the swing method to gain a normalized relative importance. This is done by normalizing the assigned scores by the participants by their total scores.

$$w_{jm} = \frac{z_{jm}}{\Sigma_{m=1}^{M} z_{jm}} \forall j \qquad (8)$$

where w_{jm} is the relative importance of evaluation criteria p_{jm} with respect to affordance A_j such that $\Sigma_{m=1}^{M} w_{jm} = 1$ and $0 \leq w_{jm} \leq 1 \; \forall \; j$; Z_{jm} is the corresponding swing score; and M is the number of the evaluation criteria related to affordance A_j.

The weights of importance are calculated as follows:

$$w_j = \frac{Z_j}{\Sigma_{j=1}^{S} Z_j} \quad (9)$$

where w_j is the relative importance of affordances A_j such that $\Sigma_{j=1}^{S} w_j = 1$ and $0 \leq w_j \leq 1 \; \forall \; j$; Z_j is the corresponding swing score; and S is the number of affordances considered in the evaluation.

Exoskeleton A

Value Properties

Analysis of the value properties of Exoskeleton A can now begin. In this section, it is important to see if each of the 55 engineering design metrics was marked as important at least once. By inspecting the value properties from the study, it is confirmed that for exoskeleton A, each metric was marked as important to consider at least once.

It is now important to see if each design metric for exoskeleton A maintained its relative property value after being used as compared to prior to use. That is, for each of the 55 engineering design metrics, did the participants continue to mark each metric as important. This is done by subtracting the sum of the number of times the metric was marked important before use from the sum of the number of times the metric was marked important after use. This results in the table of relative change below:

Table 5: Exoskeleton A Value Properties Relative Change

	Cost	Manufacturability	Weight	Active vs. passive	Variability within persons	Variability between persons	number of parts vs. ability	training motivation	how the exoskeleton	statics	dynamics	range of motion / flexibility	comfort	every day carry vs. tool for	muscle memory and	sensory motor learning	Form factor	anthropometry	battery density	environmental factors	use as protection	heat mitigation	perspiration mitigation	maximum push forces	maximum pull forces	formatibilty to body
Sum Before	10	12	16	4	8	12	5	5	24	3	4	17	22	8	4	1	4	4	1	2	7	8	5	4	4	14
Sum After	10	9	15	1	6	12	6	5	21	3	4	17	23	5	1	1	5	7	1	2	6	3	2	2	2	11
Relative Change	0	-3	-1	-3	-2	0	1	0	-3	0	0	0	1	-3	-3	0	1	3	0	0	-1	-5	-3	-2	-2	-3

	type of fuel	degrees of freedom	actual exertion	actual fatigue	perceived exertion	perceived fatigue	ease of use	intuitive use (affordances)	lifespan of exoskeleton	lifespan of exoskeleton	temperature considerations	humidity considerations	iterative design	human factors /ergonomics	potential stress / strain on	distribution of mass	center of mass	sound	repetition and fatigue	high speed motion	effect of unequal loading	psychophyiscs	abrasion of material on	social impact	repalceable parts	material strength	material elasticity	biomechanics
Sum Before	3	13	6	6	4	7	21	9	10	7	10	5	5	9	10	7	3	3	8	7	2	1	13	1	10	11	4	4
Sum After	1	11	6	6	2	3	13	6	8	6	5	3	4	8	8	3	2	2	3	6	2	2	9	1	5	8	4	2
Relative Change	-2	-2	0	0	-2	-4	-8	-3	-2	-1	-5	-2	-1	-1	-2	-4	-1	-1	-5	-1	0	1	-4	0	-5	-3	0	-2

An idealized hypothetical exoskeleton designed with affordances in mind, should yield a net change of 0. That is, the sum of the number of times the metric is marked important by participants before use is the same as the sum of the number of times the metric was marked important after use. We can later compare the sum of the relative change in metrics for all exoskeletons. In reality, most exoskeletons will not yield a net change of 0.

In this case, exoskeleton A yields a summed relative change of -88. This implies that the majority of metrics deemed important for exoskeleton A were not present when the participants actually used the exoskeletons. This led to a lost value property.

Property Ranking

Now the simple additive weighting method with swing weighting can be applied by looking at each design metric's relative weight. First, the initial ranking completed by the participants in this study is analyzed, which can be seen in Table 6.

Table 6: Exoskeleton A - Initial Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	18	0	0	0	0	0	0	5	1	0	0	1	11	0	16	0	0	0	0	1	0	0	0	3	13	3
Manufacturability	15	0	0	7	0	0	9	7	2	0	0	4	4	0	0	0	24	3	0	6	0	0	1	0	3	0
Weight	7	0	0	0	5	4	8	6	3	0	0	0	5	6	15	0	14	0	0	7	3	3	0	0	4	2
Active vs. passive exoskeleton	0	0	0	0	6	0	7	0	0	0	0	2	0	0	0	0	0	0	0	8	0	0	0	0	24	0
Variability within persons	0	0	0	0	7	3	0	0	0	0	0	0	3	0	10	0	20	0	7	4	0	0	0	0	0	5
Variability between persons	17	0	0	0	8	4	0	0	16	0	0	0	2	0	9	7	21	0	6	5	4	0	0	0	25	0
Number of parts vs. ability to actuate	0	0	2	0	0	3	0	0	0	0	0	0	25	0	0	0	0	0	0	35	0	0	0	0	11	0
Training motivation	0	0	0	0	0	0	0	0	15	0	0	15	0	0	0	0	0	0	0	34	0	0	9	0	30	0
How the exoskeleton attaches to the body	1	0	4	5	23	1	6	13	14	3	1	0	24	5	3	4	22	1	5	33	6	4	8	1	33	6
Statics	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	35	0
Dynamics	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	5	0	0	0	31	0	0	0	0	36	0
Range of motion / flexibility	9	5	3	2	1	4	2	11	32	0	0	0	21	3	7	6	2	0	0	54	5	0	0	0	7	0
Comfot	0	4	1	1	14	2	3	0	4	0	3	3	12	4	1	3	1	2	3	3	1	1	2	2	18	0
Every day carry vs. tool for training	0	0	0	0	13	0	0	0	13	0	0	14	0	0	8	8	23	0	0	53	0	0	0	0	38	0
Muscle memory and response	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	15	0	0	51	0	0	0	0	32	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0	0	0	0	0
Form factor	0	0	0	0	24	0	0	0	0	4	0	0	0	0	0	0	0	0	0	49	0	0	0	0	0	0
Anthropometry	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	50	0	0	0	0	26	1
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	48	0	0	0	0	0	0
Use as protection	0	0	0	0	21	0	0	2	0	0	0	5	0	0	13	0	0	0	0	29	8	0	0	0	23	0
Heat mitigation	0	0	0	0	0	0	0	0	17	1	0	13	0	0	0	0	16	4	0	3	0	0	7	0	22	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	17	0	0	55	0	0	0	0	21	0
Maximum push forces	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	9	0	0	0	25	0	0	0	0	5	0
Maximum pull forces	0	0	0	0	18	0	0	0	0	0	0	0	0	0	0	10	0	0	0	26	0	0	0	0	6	0
Formability to the body	3	1	5	4	3	0	0	0	18	0	2	6	0	0	2	0	18	0	8	27	7	0	6	0	0	0
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	20	0
Degrees of freedom	6	0	0	5	2	4	1	1	9	0	9	16	0	0	0	1	0	0	1	40	0	0	5	5	0	0
Actual exertion	5	0	0	0	0	0	0	0	28	0	0	0	10	0	0	0	3	0	0	39	0	0	0	0	0	0
Actual fatigue	0	0	0	8	0	0	10	0	30	0	0	0	8	0	0	0	4	0	0	36	9	0	0	0	0	0
Perceived exertion	0	0	0	0	9	0	0	0	29	0	7	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0
Perceived fatigue	0	0	0	9	4	0	0	0	31	0	8	0	9	0	0	0	0	0	0	38	0	0	0	0	0	0
Ease of use	14	2	6	0	10	2	0	8	10	0	4	7	1	2	4	2	12	0	9	9	2	2	4	0	12	0
Intuitive use (affordances)	0	0	0	0	11	0	5	0	11	0	5	8	13	1	0	20	13	0	0	41	10	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	13	0	0	0	0	0	0	9	12	0	11	9	19	0	0	22	25	0	0	10	0	0	0	0	2	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	10	22	0	0	0	20	0	0	21	26	0	0	11	0	0	0	0	1	0
Temperature considerations	0	0	0	0	15	5	0	12	23	5	12	0	0	0	0	0	10	0	0	42	0	0	0	0	27	0
Humidity considerations	0	0	0	0	16	0	0	0	21	0	0	0	0	0	0	0	11	0	0	43	0	0	0	0	28	0
Iterative design	0	0	0	0	0	0	0	0	20	0	0	0	22	0	0	0	0	0	0	13	0	0	0	0	0	0
Human factors / ergonomics considerations	0	0	7	0	0	0	0	0	19	0	0	10	7	0	14	19	9	0	0	12	0	0	0	4	31	0
Potential stress / strain on the joints / muscles	2	0	8	0	0	0	0	0	0	0	0	11	14	0	0	18	5	0	0	14	11	0	0	0	34	0
Distribution of mass	0	0	0	0	25	0	0	0	0	0	0	0	15	0	0	3	0	0	0	16	0	0	3	0	16	0
Center of mass	0	0	0	0	26	0	0	0	0	0	0	0	0	0	0	15	0	0	0	17	0	0	0	0	17	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	18	0	0	0	0	15	0
Repetition and fatigue	0	0	0	0	17	0	0	0	24	0	0	0	16	0	11	17	6	0	0	19	12	0	0	0	19	0
High speed motion	0	0	0	0	0	0	0	0	25	0	0	0	0	0	5	0	27	0	0	23	13	0	0	0	14	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	24	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	46	0	0	0	0	0	0
Abrasion of material on body	4	3	9	0	0	5	0	0	8	0	6	0	0	0	6	0	28	0	2	45	0	0	0	0	29	4
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	44	0	0	0	0	0	0
Replaceable parts	12	0	0	0	22	0	0	0	7	0	0	12	17	0	0	0	7	0	0	20	14	0	0	0	10	0
Material strength	11	0	0	0	20	0	0	3	5	6	10	0	23	0	12	0	8	0	0	21	0	0	0	0	8	0
Material elasticity	10	0	0	0	0	0	0	0	6	0	0	0	0	0	0	11	0	0	0	22	0	0	0	0	9	0
Biomechanics	0	0	0	0	0	0	0	0	26	0	0	0	0	0	0	0	19	0	0	2	0	0	0	0	0	0

These property ranks should now be normalized by relative importance for each participant. This is done by summing across each row for each participant. This yields a value that represents each participants' maximum rank value. Next, for each participant, each metric’s initial ranking is divided by the respective participants’ maximum rank value. This yields Table 7.

Normalized property ranks can now be summed by relative maximum rank value by combining each participants’ metrics’ score. This value is then normalized again by the number of participants. This yields a table that represents the overall relative importance for each of the ranked properties normalized by both the relative maximum value property as well as the number of participants as shown in Table 8.

Table 7: Exoskeleton A - Initial Properties Rank Normalized by Relative Maximum Rank Value

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0.116	0.000	0.000	0.000	0.000	0.000	0.000	0.055	0.002	0.000	0.000	0.007	0.037	0.000	0.118	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.200	0.018	0.143
Manufacturability	0.097	0.000	0.000	0.159	0.000	0.000	0.164	0.077	0.004	0.000	0.000	0.029	0.013	0.000	0.000	0.000	0.059	0.300	0.000	0.004	0.000	0.000	0.022	0.000	0.004	0.000
Weight	0.045	0.000	0.000	0.000	0.014	0.108	0.145	0.066	0.006	0.000	0.000	0.000	0.017	0.286	0.110	0.000	0.034	0.000	0.000	0.005	0.029	0.300	0.000	0.000	0.006	0.095
Active vs. passive exoskeleton	0.000	0.000	0.000	0.000	0.017	0.000	0.127	0.000	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.034	0.000
Variability within persons	0.000	0.000	0.000	0.000	0.020	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.000	0.074	0.000	0.049	0.000	0.137	0.003	0.000	0.000	0.000	0.000	0.000	0.238
Variability between persons	0.110	0.000	0.000	0.000	0.023	0.108	0.000	0.000	0.030	0.000	0.000	0.000	0.007	0.000	0.066	0.027	0.052	0.000	0.118	0.003	0.038	0.000	0.000	0.000	0.036	0.000
Number of parts vs. ability to actuate	0.000	0.000	0.044	0.000	0.000	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.083	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.000	0.000	0.000	0.000	0.016	0.000
Training motivation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.028	0.000	0.000	0.110	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.000	0.000	0.200	0.000	0.043	0.000
How the exoskeleton attaches to the body	0.006	0.000	0.089	0.114	0.066	0.027	0.109	0.143	0.027	0.143	0.013	0.000	0.080	0.238	0.022	0.016	0.054	0.100	0.098	0.022	0.057	0.400	0.178	0.067	0.047	0.286
Statics	0.052	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.021	0.000	0.000	0.000	0.000	0.050	0.000
Dynamics	0.000	0.000	0.000	0.000	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020	0.000	0.000	0.000	0.021	0.000	0.000	0.000	0.000	0.051	0.000
Range of motion / flexibility	0.058	0.333	0.067	0.045	0.003	0.108	0.036	0.121	0.061	0.000	0.000	0.000	0.070	0.143	0.051	0.023	0.005	0.000	0.000	0.036	0.048	0.000	0.000	0.000	0.010	0.000
Comfot	0.000	0.267	0.022	0.023	0.040	0.054	0.055	0.000	0.008	0.000	0.038	0.022	0.040	0.190	0.007	0.012	0.002	0.200	0.059	0.002	0.010	0.100	0.044	0.133	0.026	0.000
Every day carry vs. tool for training	0.000	0.000	0.000	0.000	0.037	0.000	0.000	0.000	0.025	0.000	0.000	0.103	0.000	0.000	0.059	0.031	0.057	0.000	0.000	0.035	0.000	0.000	0.000	0.000	0.054	0.000
Muscle memory and response	0.000	0.000	0.000	0.000	0.000	0.000	0.073	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.000	0.034	0.000	0.000	0.000	0.000	0.045	0.000
Sensory motor learning	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.035	0.000	0.000	0.000	0.000	0.000	0.000
Form factor	0.000	0.000	0.000	0.000	0.068	0.000	0.000	0.000	0.000	0.190	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.000	0.000	0.000	0.000	0.000	0.000
Anthropometry	0.000	0.000	0.000	0.068	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.196	0.033	0.000	0.000	0.000	0.000	0.037	0.048
Battery density	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.000	0.000	0.000	0.000	0.000	0.000
Environmental factors	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.044	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000	0.000	0.000
Use as protection	0.000	0.000	0.000	0.000	0.060	0.000	0.000	0.022	0.000	0.000	0.000	0.037	0.000	0.000	0.096	0.000	0.000	0.000	0.000	0.019	0.076	0.000	0.000	0.000	0.033	0.000
Heat mitigation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.048	0.000	0.096	0.000	0.000	0.000	0.000	0.039	0.400	0.000	0.002	0.000	0.000	0.156	0.000	0.031	0.000
Perspiration mitigation	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.095	0.000	0.000	0.000	0.000	0.000	0.000	0.042	0.000	0.000	0.037	0.000	0.000	0.000	0.000	0.030	0.000
Maximum push forces	0.000	0.000	0.000	0.000	0.054	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.035	0.000	0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.007	0.000
Maximum pull forces	0.000	0.000	0.000	0.000	0.051	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.039	0.000	0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.009	0.000
Formability to the body	0.019	0.067	0.111	0.091	0.009	0.000	0.000	0.000	0.034	0.000	0.026	0.044	0.000	0.000	0.015	0.000	0.044	0.000	0.157	0.018	0.067	0.000	0.133	0.000	0.000	0.000
Type of fule (battery/gas/etc.)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.051	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.000	0.000	0.000	0.000	0.028	0.000
Degrees of freedom	0.039	0.000	0.000	0.114	0.006	0.108	0.018	0.011	0.017	0.000	0.115	0.118	0.000	0.000	0.000	0.004	0.000	0.000	0.020	0.027	0.000	0.000	0.111	0.333	0.000	0.000
Actual exertion	0.032	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.053	0.000	0.000	0.000	0.033	0.000	0.000	0.000	0.007	0.000	0.000	0.026	0.000	0.000	0.000	0.000	0.000	0.000
Actual fatigue	0.000	0.000	0.000	0.182	0.000	0.000	0.182	0.000	0.057	0.000	0.000	0.000	0.027	0.000	0.000	0.000	0.010	0.000	0.000	0.024	0.086	0.000	0.000	0.000	0.000	0.000
Perceived exertion	0.000	0.000	0.000	0.000	0.026	0.000	0.000	0.000	0.055	0.000	0.090	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.000	0.000
Perceived fatigue	0.000	0.000	0.000	0.205	0.011	0.000	0.000	0.000	0.059	0.000	0.103	0.000	0.030	0.000	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.000	0.000	0.000	0.000
Ease of use	0.090	0.133	0.133	0.000	0.028	0.054	0.000	0.088	0.019	0.000	0.051	0.051	0.003	0.095	0.029	0.008	0.030	0.000	0.176	0.006	0.019	0.200	0.089	0.000	0.017	0.000
Intuitive use (affordances)	0.000	0.000	0.000	0.000	0.031	0.000	0.091	0.000	0.021	0.000	0.064	0.059	0.043	0.048	0.000	0.078	0.032	0.000	0.000	0.027	0.095	0.000	0.000	0.000	0.000	0.000
Lifespan of exoskeleton (standard conditions)	0.084	0.000	0.000	0.000	0.000	0.000	0.000	0.099	0.023	0.000	0.141	0.066	0.063	0.000	0.000	0.086	0.062	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.003	0.000
Lifespan of exoskeleton (extreme conditions)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.110	0.042	0.000	0.000	0.000	0.066	0.000	0.000	0.082	0.064	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.001	0.000
Temperature considerations	0.000	0.000	0.000	0.000	0.043	0.135	0.000	0.132	0.044	0.238	0.154	0.000	0.000	0.000	0.000	0.000	0.025	0.000	0.000	0.028	0.000	0.000	0.000	0.000	0.038	0.000
Humidity considerations	0.000	0.000	0.000	0.000	0.046	0.000	0.000	0.000	0.040	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.027	0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.040	0.000
Iterative design	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.038	0.000	0.000	0.000	0.073	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.000	0.000
Human factors / ergonomics considerations	0.000	0.000	0.156	0.000	0.000	0.000	0.000	0.000	0.036	0.000	0.000	0.074	0.023	0.000	0.103	0.074	0.022	0.000	0.000	0.008	0.000	0.000	0.000	0.267	0.044	0.000
Potential stress / strain on the joints / muscles	0.013	0.000	0.178	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.081	0.047	0.000	0.000	0.070	0.012	0.000	0.000	0.009	0.105	0.000	0.000	0.000	0.048	0.000
Distribution of mass	0.000	0.000	0.000	0.000	0.071	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.050	0.000	0.000	0.012	0.000	0.000	0.000	0.011	0.000	0.000	0.067	0.000	0.023	0.000
Center of mass	0.000	0.000	0.000	0.000	0.074	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.059	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.024	0.000
Sound	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.063	0.000	0.000	0.000	0.012	0.000	0.000	0.000	0.000	0.021	0.000
Repetition and fatigue	0.000	0.000	0.000	0.000	0.048	0.000	0.000	0.000	0.045	0.000	0.000	0.000	0.053	0.000	0.081	0.066	0.015	0.000	0.000	0.013	0.114	0.000	0.000	0.000	0.027	0.000
High speed motion	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047	0.000	0.000	0.000	0.000	0.000	0.037	0.000	0.067	0.000	0.000	0.015	0.124	0.000	0.000	0.000	0.020	0.000
Effect of unequal loading	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.055	0.000	0.000	0.000	0.016	0.000	0.000	0.000	0.000	0.000	0.000
Psychophysics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.051	0.000	0.000	0.000	0.031	0.000	0.000	0.000	0.000	0.000	0.000
Abrasion of material on body	0.026	0.200	0.200	0.000	0.000	0.135	0.000	0.000	0.015	0.000	0.077	0.000	0.000	0.000	0.044	0.000	0.069	0.000	0.039	0.030	0.000	0.000	0.000	0.000	0.041	0.190
Social impact	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047	0.000	0.000	0.000	0.029	0.000	0.000	0.000	0.000	0.000	0.000
Replaceable parts	0.077	0.000	0.000	0.000	0.063	0.000	0.000	0.000	0.013	0.000	0.000	0.088	0.056	0.000	0.000	0.000	0.017	0.000	0.000	0.013	0.133	0.000	0.000	0.000	0.014	0.000
Material strength	0.071	0.000	0.000	0.000	0.057	0.000	0.000	0.033	0.009	0.286	0.128	0.000	0.076	0.000	0.088	0.000	0.020	0.000	0.000	0.014	0.000	0.000	0.000	0.000	0.011	0.000
Material elasticity	0.065	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.000	0.013	0.000
Biomechanics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.047	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000

Table 8: Exoskeleton A - Initial Properties Rank Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	0.69650349	0.026788596
Manufacturability	0.93251545	0.035865979
Weight	1.26585154	0.048686598
Active vs. passive exoskeleton	0.19850399	0.007634769
Variability within persons	0.61180174	0.023530836
Variability between persons	0.6173609	0.02374465
Number of parts vs. ability to actuate	0.24757149	0.00952198
Training motivation	0.40401377	0.015538991
How the exoskeleton attaches to the body	2.39961747	0.092292979
Statics	0.12269063	0.00471887
Dynamics	0.12554991	0.004828843
Range of motion / flexibility	1.21839407	0.04686131
Comfot	1.35377184	0.052068148
Every day carry vs. tool for training	0.40068098	0.015410807
Muscle memory and response	0.18917302	0.007275886
Sensory motor learning	0.03471295	0.001335113
Form factor	0.29156254	0.011213944
Anthropometry	0.38218895	0.014699575
Battery density	0.03137517	0.001206737
Environmental factors	0.07599877	0.00292303
Use as protection	0.3423801	0.013168465
Heat mitigation	0.80362135	0.030908513
Perspiration mitigation	0.20365518	0.007832892
Maximum push forces	0.1130785	0.004349173
Maximum pull forces	0.11622375	0.004470144
Formability to the body	0.83436593	0.032090997
Type of fule (battery/gas/etc.)	0.09823704	0.003778348
Degrees of freedom	1.04006092	0.040002343
Actual exertion	0.15193483	0.005843647
Actual fatigue	0.56663116	0.021793506
Perceived exertion	0.19500846	0.007500325
Perceived fatigue	0.43248518	0.016634045
Ease of use	1.32193928	0.050843819
Intuitive use (affordances)	0.58956859	0.022675715
Lifespan of exoskeleton (standard conditions)	0.63285471	0.024340566
Lifespan of exoskeleton (extreme conditions)	0.3728362	0.014339854
Temperature considerations	0.83626051	0.032163866
Humidity considerations	0.18092804	0.006958771
Iterative design	0.11964673	0.004601797
Human factors / ergonomics considerations	0.80636448	0.031014019
Potential stress / strain on the joints / muscles	0.56310591	0.02165792
Distribution of mass	0.23285256	0.008955868
Center of mass	0.16816402	0.006467847
Sound	0.09582284	0.003685494
Repetition and fatigue	0.4630686	0.017810331
High speed motion	0.30966535	0.011910206
Effect of unequal loading	0.07070886	0.002719572
Psychophysics	0.08148886	0.003134187
Abrasion of material on body	1.06702446	0.041039402
Social impact	0.0762475	0.002932596
Replaceable parts	0.47619909	0.018315349
Material strength	0.79403796	0.030539921
Material elasticity	0.14631885	0.005627648
Biomechanics	0.09737557	0.003745214

For this study, it is important to also analyze the after properties rank values. In this case, these are the ranks assigned after the participants have actually put on the exoskeleton and had the chance to practice drawing and shooting a LaserLyte. The approach used to analyze the initial value properties is now conducted on the after use value properties. The results of this analysis can be seen in Table 9, Table 10, and Table 11.

Table 9: Exoskeleton A - After Use Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	0	0	0	0	0	7	1	14	8	1	16	0	0	0	0	0	0	1	0	4	0	0	4	9
Manufacturability	0	0	0	0	0	0	0	9	10	16	0	16	5	0	0	0	0	4	0	3	0	0	8	0	1	0
Weight	9	0	0	0	5	0	5	8	4	15	0	2	20	0	0	4	10	0	0	4	5	3	0	0	9	3
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0
Variability within persons	0	0	0	0	0	3	0	0	0	0	0	0	2	0	14	0	8	0	0	25	0	0	0	0	0	0
Variability between persons	0	11	0	5	0	4	2	0	18	1	0	0	3	0	12	6	7	3	0	24	0	0	0	1	0	0
Number of parts vs. ability to actuate	8	0	0	0	0	2	0	0	0	2	0	13	21	0	0	0	0	0	0	23	0	0	0	0	0	0
Training motivation	7	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	22	0	0	0	0	0	0
How the exoskeleton attaches to the body	4	10	1	0	2	1	8	6	0	17	7	15	8	4	5	5	6	5	0	21	4	2	7	0	0	5
Statics	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	55	0	0	0	0	0	0
Dynamics	6	8	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	20	0	0	0	0	0	0
Range of motion / flexibility	0	7	2	2	1	4	0	5	0	3	3	0	15	0	3	8	5	0	0	19	0	1	6	2	2	0
Comfot	5	6	3	1	4	1	0	2	2	4	1	3	6	1	2	1	4	2	0	18	0	5	1	4	10	2
Every day carry vs. tool for training	0	5	0	0	0	0	0	0	6	0	0	0	0	0	13	9	0	0	0	26	0	0	0	0	0	0
Muscle memory and response	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	54	0	0	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	0	0	0	0	0	0
Form factor	0	0	0	0	3	0	0	0	5	0	4	0	0	0	0	0	11	0	0	37	0	0	0	0	0	0
Anthropometry	0	0	0	8	0	0	9	0	0	18	0	0	4	0	0	0	0	0	0	27	0	0	5	0	0	1
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0
Use as protection	0	4	0	0	0	0	0	0	0	0	0	11	0	0	15	0	0	0	0	30	6	6	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	31	0	0	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	15	12	0	12	0	0	0	0	0	0	0	36	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	32	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	33	0	0	0	0	0	0
Formability to the body	0	0	0	9	0	2	10	11	8	0	2	0	0	0	1	0	12	0	0	34	0	0	0	0	0	0
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	0	0	0	0	0	0
Degrees of freedom	1	0	0	0	0	0	0	1	10	5	0	0	0	0	0	2	0	1	0	42	1	0	0	3	8	0
Actual exertion	2	0	0	0	0	0	6	0	0	0	0	0	10	0	17	0	3	0	0	41	0	0	0	0	0	0
Actual fatigue	0	0	0	6	0	0	7	0	0	6	0	0	11	0	0	0	1	0	0	40	0	0	0	0	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	0	38	0	0	0	0	0	0
Perceived fatigue	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	39	0	0	4	0	0	0
Ease of use	3	0	4	0	0	3	0	4	9	0	6	4	1	3	6	3	0	0	0	6	0	0	3	0	0	0
Intuitive use (affordances)	0	3	0	0	0	0	0	0	0	0	5	5	7	2	0	0	0	0	0	7	0	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0	0	0	0	0	0	1	0	16	7	0	6	17	0	0	19	0	0	0	8	0	0	0	0	6	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0	17	8	0	0	18	0	0	20	0	0	0	9	0	0	0	0	5	0
Temperature considerations	0	0	0	0	0	0	0	3	0	10	0	0	0	0	18	0	0	0	0	43	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	1	44	0	0	0	0	0	0
Iterative design	0	0	0	0	0	0	0	0	0	0	0	7	19	0	0	0	0	0	2	45	0	0	2	0	0	0
Human factors / ergonomics considerations	0	0	0	3	0	0	0	0	0	0	9	8	9	0	7	17	2	0	0	10	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	0	0	0	7	0	2	0	0	7	9	0	9	0	0	8	18	0	0	0	46	0	0	0	0	0	0
Distribution of mass	0	0	0	0	0	0	0	0	0	0	0	10	14	0	0	14	0	0	0	13	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	12	0	0	0	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	47	0	0	0	0	0	0
Repetition and fatigue	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	0	0	0	0	0	0
High speed motion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	12	0	0	0	49	2	0	0	0	3	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	50	0	0	0	0	7	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	0	0	0	0	0	0
Abrasion of material on body	0	0	5	0	0	1	0	0	3	0	0	0	0	0	4	11	9	0	0	17	3	0	0	0	0	6
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0	0	0	0	0
Replaceable parts	0	0	0	10	0	0	0	0	12	0	0	0	22	0	0	0	0	0	0	14	0	0	0	0	0	0
Material strength	0	0	0	0	0	0	4	12	13	0	0	0	23	0	11	21	0	0	0	19	0	0	0	0	0	0
Material elasticity	10	0	0	0	0	0	0	0	11	0	0	0	0	0	10	0	0	0	0	16	0	0	0	0	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	2	0	0	0	0	0	0

Table 10: Exoskeleton A - After Use Properties Normalized by Relative Maximum Rank Value

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	0	0	0	0	0	0.0897	0.006	0.0819	0.1778	0.0074	0.058	0	0	0	0	0	0	0.0007	0	0.1905	0	0	0.0727	0.3462
Manufacturability	0	0	0	0	0	0	0	0.1154	0.0599	0.0936	0	0.1176	0.0181	0	0	0	0	0.2667	0	0.002	0	0	0.2222	0	0.0182	0
Weight	0.1636	0	0	0	0.3333	0	0.0909	0.1026	0.024	0.0877	0	0.0147	0.0725	0	0	0.0158	0.1282	0	0	0.0026	0.2381	0.1429	0	0	0.1636	0.1154
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0033	0	0	0	0	0	0
Variability within persons	0	0	0	0	0	0.1304	0	0	0	0	0	0	0.0072	0	0.0819	0	0.1026	0	0	0.0163	0	0	0	0	0	0
Variability between persons	0	0.193	0	0.0909	0	0.1739	0.0364	0	0.1078	0.0058	0	0	0.0109	0	0.0702	0.0237	0.0897	0.2	0	0.0156	0	0	0	0.1	0	0
Number of parts vs. ability to actuate	0.1455	0	0	0	0	0.087	0	0	0	0.0117	0	0.0956	0.0761	0	0	0	0	0	0	0.015	0	0	0	0	0	0
Training motivation	0.1273	0	0	0	0	0	0	0	0	0	0	0.1029	0	0	0	0	0	0	0	0.0143	0	0	0	0	0	0
How the exoskeleton attaches to the body	0.0727	0.1754	0.0667	0	0.1333	0.0435	0.1455	0.0769	0	0.0994	0.1556	0.1103	0.029	0.4	0.0292	0.0198	0.0769	0.3333	0	0.0137	0.1905	0.0952	0.1944	0	0	0.1923
Statics	0	0.0175	0	0	0	0	0.0545	0	0	0	0	0	0	0	0	0	0	0	0	0.0358	0	0	0	0	0	0
Dynamics	0.1091	0.1404	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0277	0	0	0	0.013	0	0	0	0	0	0
Range of motion / flexibility	0	0.1228	0.1333	0.0364	0.0667	0.1739	0	0.0641	0	0.0175	0.0667	0	0.0543	0	0.0175	0.0316	0.0641	0	0	0.0124	0	0.0476	0.1667	0.2	0.0364	0
Comfot	0.0909	0.1053	0.2	0.0182	0.2667	0.0435	0	0.0256	0.012	0.0234	0.0222	0.0221	0.0217	0.1	0.0117	0.004	0.0513	0.1333	0	0.0117	0	0.2381	0.0278	0.4	0.1818	0.0769
Every day carry vs. tool for training	0	0.0877	0	0	0	0	0	0	0.0359	0	0	0	0	0	0.076	0.0356	0	0	0	0.0169	0	0	0	0	0	0
Muscle memory and response	0	0.0351	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0351	0	0	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0345	0	0	0	0	0	0
Form factor	0	0	0	0	0.2	0	0	0	0.0299	0	0.0889	0	0	0	0	0	0.141	0	0	0.0241	0	0	0	0	0	0
Anthropometry	0	0	0	0.1455	0	0	0.1636	0	0	0.1053	0	0	0.0145	0	0	0	0	0	0	0.0176	0	0	0.1389	0	0	0.0385
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0182	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0.1282	0	0	0	0	0	0	0	0	0	0	0	0.0189	0	0	0	0	0	0
Use as protection	0	0.0702	0	0	0	0	0	0	0	0	0	0.0809	0	0	0.0877	0	0	0	0	0.0195	0.2857	0.2857	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0.0643	0	0	0	0	0	0	0	0	0	0.0202	0	0	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0.0898	0.0702	0	0.0882	0	0	0	0	0	0	0	0.0234	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0395	0	0	0	0.0208	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.087	0	0	0	0.0215	0	0	0	0	0	0
Formability to the body	0	0	0	0.1636	0	0.087	0.1818	0.141	0.0479	0	0.0444	0	0	0	0.0058	0	0.1538	0	0	0.0221	0	0	0	0	0	0
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0254	0	0	0	0	0	0
Degrees of freedom	0.0182	0	0	0	0	0	0	0.0128	0.0599	0.0292	0	0	0	0	0	0.0079	0	0.0667	0	0.0273	0.0476	0	0	0.3	0.1455	0
Actual exertion	0.0364	0	0	0	0	0	0.1091	0	0	0	0	0	0.0362	0	0.0994	0	0.0385	0	0	0.0267	0	0	0	0	0	0
Actual fatigue	0	0	0	0.1091	0	0	0.1273	0	0	0.0351	0	0	0.0399	0	0	0	0.0128	0	0	0.026	0	0	0	0	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0936	0	0	0	0	0.0247	0	0	0	0	0	0
Perceived fatigue	0	0	0	0	0	0	0	0	0	0	0	0	0.0435	0	0	0	0	0	0	0.0254	0	0	0.1111	0	0	0
Ease of use	0.0545	0	0.2667	0	0	0.1304	0	0.0513	0.0539	0	0.1333	0.0294	0.0036	0.3	0.0351	0.0119	0	0	0	0.0039	0	0	0.0833	0	0	0
Intuitive use (affordances)	0	0.0526	0	0	0	0	0	0	0	0	0.1111	0.0368	0.0254	0.2	0	0	0	0	0	0.0046	0	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0	0	0	0	0	0	0.0182	0	0.0958	0.0409	0	0.0441	0.0616	0	0	0.0751	0	0	0	0.0052	0	0	0	0	0.1091	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0	0.1018	0.0468	0	0	0.0652	0	0	0.0791	0	0	0	0.0059	0	0	0	0	0.0909	0
Temperature considerations	0	0	0	0	0	0	0	0.0385	0	0.0585	0	0	0	0	0.1053	0	0	0	0	0.028	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0.076	0	0	0	0	0	0	0	0	0.3333	0.0286	0	0	0	0	0	0
Iterative design	0	0	0	0	0	0	0	0	0	0	0	0.0515	0.0688	0	0	0	0	0	0.6667	0.0293	0	0	0.0556	0	0	0
Human factors / ergonomics considerations	0	0	0	0.0545	0	0	0	0	0	0	0.2	0.0588	0.0326	0	0.0409	0.0672	0.0256	0	0	0.0065	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	0	0	0	0.1273	0	0.087	0	0	0.0419	0.0526	0	0.0662	0	0	0.0468	0.0711	0	0	0	0.0299	0	0	0	0	0	0
Distribution of mass	0	0	0	0	0	0	0	0	0	0	0	0.0735	0.0507	0	0	0.0553	0	0	0	0.0085	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0593	0	0	0	0.0078	0	0	0	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0632	0	0	0	0.0306	0	0	0	0	0	0
Repetition and fatigue	0	0	0	0.0727	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0312	0	0	0	0	0	0
High speed motion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0526	0.0474	0	0	0	0.0319	0.0952	0	0	0	0.0545	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0514	0	0	0	0.0325	0	0	0	0	0.1273	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0332	0	0	0	0	0	0
Abrasion of material on body	0	0	0.3333	0	0	0.0435	0	0	0.018	0	0	0	0	0	0.0234	0.0435	0.1154	0	0	0.0111	0.1429	0	0	0	0	0.2308
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0338	0	0	0	0	0	0
Replaceable parts	0	0	0	0.1818	0	0	0	0	0.0719	0	0	0	0.0797	0	0	0	0	0	0	0.0091	0	0	0	0	0	0
Material strength	0	0	0	0	0	0	0.0727	0.1538	0.0778	0	0	0	0.0833	0	0.0643	0.083	0	0	0	0.0124	0	0	0	0	0	0
Material elasticity	0.1818	0	0	0	0	0	0	0	0.0659	0	0	0	0	0	0.0585	0	0	0	0	0.0104	0	0	0	0	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	0.0471	0	0	0	0	0	0	0.0013	0	0	0	0	0	0

Table 11: Exoskeleton A - After Use Properties Rank Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	1.03071262	0.039642793
Manufacturability	0.913617669	0.035139141
Weight	1.695875172	0.065225968
Active vs. passive exoskeleton	0.00325309	0.000125119
Variability within persons	0.338382059	0.013014695
Variability between persons	1.117919454	0.042996902
Number of parts vs. ability to actuate	0.430746381	0.016567169
Training motivation	0.244527502	0.009404904
How the exoskeleton attaches to the body	2.653660562	0.102063868
Statics	0.107873309	0.004148973
Dynamics	0.290122132	0.011158544
Range of motion / flexibility	1.312022685	0.050462411
Comfot	2.088117318	0.080312205
Every day carry vs. tool for training	0.252160027	0.009698463
Muscle memory and response	0.070221096	0.002700811
Sensory motor learning	0.034482759	0.00132626
Form factor	0.483927519	0.018612597
Anthropometry	0.623763936	0.023990921
Battery density	0.018217306	0.000700666
Environmental factors	0.147073053	0.005656656
Use as protection	0.829724204	0.031912469
Heat mitigation	0.084496646	0.003249871
Perspiration mitigation	0.271653343	0.010448206
Maximum push forces	0.06034547	0.00232098
Maximum pull forces	0.108426919	0.004170266
Formability to the body	0.847600466	0.032600018
Type of fule (battery/gas/etc.)	0.025374105	0.000975927
Degrees of freedom	0.715093694	0.027503604
Actual exertion	0.346238514	0.013316866
Actual fatigue	0.350151664	0.013467372
Perceived exertion	0.118290739	0.004549644
Perceived fatigue	0.179963477	0.006921672
Ease of use	1.157371926	0.044514305
Intuitive use (affordances)	0.430424041	0.016554771
Lifespan of exoskeleton (standard conditions)	0.450032392	0.017308938
Lifespan of exoskeleton (extreme conditions)	0.389613461	0.014985133
Temperature considerations	0.230180806	0.008853108
Humidity considerations	0.437983921	0.016845535
Iterative design	0.871811204	0.0335312
Human factors / ergonomics considerations	0.486254235	0.018702086
Potential stress / strain on the joints / muscles	0.522811769	0.020108145
Distribution of mass	0.188048053	0.007232617
Center of mass	0.067095955	0.002580614
Sound	0.093820157	0.003608468
Repetition and fatigue	0.103956941	0.003998344
High speed motion	0.281726245	0.010835625
Effect of unequal loading	0.211187031	0.008122578
Psychophysics	0.033181522	0.001276212
Abrasion of material on body	0.961717236	0.036989124
Social impact	0.033832141	0.001301236
Replaceable parts	0.342493267	0.013172818
Material strength	0.547444253	0.021055548
Material elasticity	0.316575867	0.012175995
Biomechanics	0.048402685	0.001861642

Each metric's normalized relative value can now be easily compared to other exoskeleton alternatives.

Table 12: Exoskeleton A - Properties Rank Relative Change

	Normalized by Participant		
Design Metrics	Before	After	Relative Change
Cost	0.026788596	0.039642793	0.012854197
Manufacturability	0.035865979	0.035139141	-0.000726838
Weight	0.048686598	0.065225968	0.016539371
Active vs. passive exoskeleton	0.007634769	0.000125119	-0.00750965
Variability within persons	0.023530836	0.013014695	-0.010516142
Variability between persons	0.02374465	0.042996902	0.019252252
Number of parts vs. ability to actuate	0.00952198	0.016567169	0.007045188
Training motivation	0.015538991	0.009404904	-0.006134087
How the exoskeleton attaches to the body	0.092292979	0.102063868	0.009770888
Statics	0.00471887	0.004148973	-0.000569897
Dynamics	0.004828843	0.011158544	0.006329701
Range of motion / flexibility	0.04686131	0.050462411	0.003601101
Comfot	0.052068148	0.080312205	0.028244057
Every day carry vs. tool for training	0.015410807	0.009698463	-0.005712344
Muscle memory and response	0.007275886	0.002700811	-0.004575074
Sensory motor learning	0.001335113	0.00132626	-8.85354E-06
Form factor	0.011213944	0.018612597	0.007398653
Anthropometry	0.014699575	0.023990921	0.009291346
Battery density	0.001206737	0.000700666	-0.000506072
Environmental factors	0.00292303	0.005656656	0.002733626
Use as protection	0.013168465	0.031912469	0.018744004
Heat mitigation	0.030908513	0.003249871	-0.027658642
Perspiration mitigation	0.007832892	0.010448206	0.002615314
Maximum push forces	0.004349173	0.00232098	-0.002028193
Maximum pull forces	0.004470144	0.004170266	-0.000299878
Formability to the body	0.032090997	0.032600018	0.000509021
Type of fule (battery/gas/etc.)	0.003778348	0.000975927	-0.002802421
Degrees of freedom	0.040002343	0.027503604	-0.012498739
Actual exertion	0.005843647	0.013316866	0.007473218
Actual fatigue	0.021793506	0.013467372	-0.008326135
Perceived exertion	0.007500325	0.004549644	-0.002950681
Perceived fatigue	0.016634045	0.006921672	-0.009712373
Ease of use	0.050843819	0.044514305	-0.006329514
Intuitive use (affordances)	0.022675715	0.016554771	-0.006120944
Lifespan of exoskeleton (standard conditions)	0.024340566	0.017308938	-0.007031627
Lifespan of exoskeleton (extreme conditions)	0.014339854	0.014985133	0.000645279
Temperature considerations	0.032163866	0.008853108	-0.023310758
Humidity considerations	0.006958771	0.016845535	0.009886765
Iterative design	0.004601797	0.0335312	0.028929403
Human factors / ergonomics considerations	0.031014019	0.018702086	-0.012311933
Potential stress / strain on the joints / muscles	0.02165792	0.020108145	-0.001549775
Distribution of mass	0.008955868	0.007232617	-0.00172325
Center of mass	0.006467847	0.002580614	-0.003887233
Sound	0.003685494	0.003608468	-7.70263E-05
Repetition and fatigue	0.017810331	0.003998344	-0.013811987
High speed motion	0.011910206	0.010835625	-0.001074581
Effect of unequal loading	0.002719572	0.008122578	0.005403007
Psychophysics	0.003134187	0.001276212	-0.001857975
Abrasion of material on body	0.041039402	0.036989124	-0.004050278
Social impact	0.002932596	0.001301236	-0.00163136
Replaceable parts	0.018315349	0.013172818	-0.005142531
Material strength	0.030539921	0.021055548	-0.009484373
Material elasticity	0.005627648	0.012175995	0.006548347
Biomechanics	0.003745214	0.001861642	-0.001883572

The initial and after use property value analysis is now conducted for Exoskeleton B, Exoskeleton C, and Exoskeleton D.

Exoskeleton B

Table 13: Exoskeleton B - Value Properties Relative Change

	Cost	Manufacturability	Weight	Active vs. passive	Variability within persons	Variability between persons	number of parts vs. ability	training motivation	how the exoskeleton	statics	dynamics	range of motion / flexibility	comfort	every day carry vs. tool for	muscle memory and	sensory motor learning	Form factor	anthropometry	battery density	environmental factors	use as protection	heat mitigation	perspiration mitigation	maximum push forces	maximum pull forces	formatibilty to body	type of fuel	degrees of freedom
Su	12	12	19	1	10	13	3	5	18	3	5	20	22	9	2	2	5	7	1	2	4	1	1	3	7	6	1	16
Su	8	8	19	2	6	10	5	5	16	2	3	15	19	5	2	1	4	5	1	1	2	1	2	1	2	10	1	13
Re	-4	-4	0	1	-4	-3	2	0	-2	-1	-2	-5	-3	-4	0	-1	-1	-2	0	-1	-2	0	1	-2	-5	4	0	-3

	actual exertion	actual fatigue	perceived exertion	perceived fatigue	ease of use	intuitive use (affordances)	lifespan of exoskeleton	lifespan of exoskeleton	temperature considerations	humidity considerations	iterative design	human factors /ergonomics	potential stress / strain on	distribution of mass	center of mass	sound	repetition and fatigue	high speed motion	effect of unequal loading	psychophyiscs	abrasion of material on	social impact	repalceable parts	material strength	material elasticity	biomechanics
Su	7	11	5	7	17	11	12	8	2	2	5	11	12	6	6	3	8	7	2	2	7	2	10	11	7	3
Su	4	5	2	4	21	8	8	7	1	1	2	8	5	6	3	2	6	5	3	1	10	1	5	3	2	4
Re	-3	-6	-3	-3	4	-3	-4	-1	-1	-1	-3	-3	-7	0	-3	-1	-2	-2	1	-1	3	-1	-5	-8	-5	1

Exoskeleton B yields a summed relative change of -98.

Table 14: Exoskeleton B - Initial Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	16	0	0	0	0	2	6	0	1	0	0	1	24	0	14	0	0	0	1	1	0	2	0	4	9	0
Manufacturability	15	0	0	0	0	3	7	3	13	8	0	6	11	0	0	0	0	0	2	5	0	0	1	0	1	0
Weight	14	2	0	3	0	1	0	0	2	1	1	2	15	5	1	1	0	2	0	4	3	1	2	0	10	1
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0
Variability within persons	0	4	0	0	7	0	5	0	0	4	0	0	3	0	0	0	9	0	0	25	0	41	0	0	0	9
Variability between persons	8	3	0	0	0	2	4	0	0	3	0	0	4	0	6	9	10	0	0	24	2	42	0	0	0	10
Number of parts vs. ability to actuate	0	0	0	0	6	0	0	0	0	0	0	0	25	0	0	0	0	0	0	49	0	40	0	0	0	0
Training motivation	13	5	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	52	0	39	0	0	0	0
How the exoskeleton attaches to the body	5	6	1	0	2	3	0	7	9	0	0	0	6	3	7	5	11	6	0	48	4	38	12	0	0	5
Statics	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	51	0	35	0	0	0	0
Dynamics	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	50	0	36	0	0	3	0
Range of motion / flexibility	6	17	2	2	1	1	0	1	6	5	10	0	16	6	5	6	12	0	0	47	0	37	11	1	2	0
Comfot	7	18	3	1	0	1	0	0	3	6	3	3	2	2	2	4	1	1	3	9	1	6	4	5	4	0
Every day carry vs. tool for training	0	20	0	0	0	0	0	0	12	18	0	9	0	0	10	8	0	0	0	45	0	0	0	0	0	11
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	0	32	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	0	33	0	0	0	0
Form factor	0	0	0	0	0	0	0	0	11	0	11	0	0	0	0	0	0	0	0	42	0	34	10	0	0	0
Anthropometry	0	1	0	0	0	0	9	0	0	17	0	0	10	0	0	0	0	0	0	17	0	31	0	0	0	4
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	11	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	19	13	10	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	30	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	41	0	29	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	21	0	9	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	22	0	8	0	0	0	0
Formability to the body	0	21	4	5	0	2	0	0	5	0	12	0	0	0	13	0	13	0	0	23	12	0	9	0	0	0
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
Degrees of freedom	1	0	0	6	0	4	0	2	8	2	0	11	17	0	0	2	0	3	5	26	5	0	8	2	6	0
Actual exertion	3	8	0	0	0	0	0	0	0	9	6	0	13	0	0	0	4	0	0	27	0	0	0	0	0	0
Actual fatigue	4	9	0	0	0	2	0	0	0	11	7	0	0	4	9	0	5	0	0	28	6	3	0	3	0	0
Perceived exertion	0	10	0	0	0	0	0	0	0	10	4	0	12	0	0	0	0	0	0	29	0	0	0	0	0	2
Perceived fatigue	0	11	0	0	0	0	0	0	0	12	5	0	14	0	8	0	0	4	0	30	0	4	0	0	0	0
Ease of use	2	12	0	0	3	1	0	0	7	0	8	12	1	1	3	3	2	5	0	32	7	5	7	0	0	0
Intuitive use (affordances)	0	13	5	0	0	2	0	0	0	13	9	0	5	0	0	19	3	0	0	31	8	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	12	25	0	0	0	4	2	4	14	14	0	13	18	0	0	21	0	0	0	33	0	12	0	0	0	6
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	3	5	15	0	0	14	19	0	0	20	0	0	0	34	0	13	0	0	0	7
Temperature considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	0	14	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36	0	0	0	0	0	0
Iterative design	0	0	0	0	0	2	0	0	0	0	0	0	20	0	0	0	0	0	0	8	0	0	6	0	0	0
Human factors / ergonomics considerations	0	14	6	4	4	1	0	0	0	0	0	4	9	0	12	17	0	0	0	7	0	15	0	0	0	8
Potential stress / strain on the joints / muscles	0	15	7	0	0	1	0	0	10	7	0	5	8	0	11	18	6	0	0	37	9	0	0	0	0	0
Distribution of mass	0	16	0	0	0	0	0	0	0	0	2	0	21	0	4	4	0	0	6	10	0	25	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	13	15	0	0	0	14	0	0	0	11	0	26	3	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	12	0	27	0	0	0	0
Repetition and fatigue	0	7	0	0	0	0	10	0	0	0	0	0	0	0	0	16	7	0	0	13	10	16	0	0	0	3
High speed motion	0	0	0	0	0	3	0	0	0	15	0	0	0	0	0	0	0	0	0	17	11	22	0	0	5	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	16	0	23	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	53	0	24	0	0	0	0
Abrasion of material on body	0	0	0	0	0	0	0	0	4	0	14	0	0	0	15	0	8	0	0	54	0	17	5	0	0	0
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38	0	28	0	0	0	0
Replaceable parts	9	22	0	0	5	5	8	0	16	0	0	7	22	0	0	0	0	0	0	39	14	20	0	0	0	0
Material strength	10	23	0	0	0	3	0	6	0	16	0	0	23	0	0	0	0	0	7	14	0	19	0	0	7	0
Material elasticity	11	24	0	0	0	4	0	0	0	0	0	0	0	0	0	12	0	0	0	15	0	21	0	0	8	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	2	0	7	0	0	0	0

Table 15: Exoskeleton B - Initial Properties Normalized by Relative Maximum Rank Value

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0.1176	0	0	0	0	0.0426	0.1091	0	0.0074	0	0	0.0083	0.0738	0	0.1167	0	0	0	0.0417	0.0007	0	0.0023	0	0.2667	0.1636	0
Manufacturability	0.1103	0	0	0	0	0.0638	0.1273	0.1071	0.0956	0.0468	0	0.05	0.0338	0	0	0	0	0	0.0833	0.0034	0	0	0.0128	0	0.0182	0
Weight	0.1029	0.0062	0	0.1429	0	0.0213	0	0	0.0147	0.0058	0.0095	0.0167	0.0462	0.2381	0.0083	0.0043	0	0.0952	0	0.0027	0.0286	0.0011	0.0256	0	0.1818	0.0152
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0041	0	0	0	0	0	0
Variability within persons	0	0.0123	0	0	0.25	0	0.0909	0	0	0.0234	0	0	0.0092	0	0	0	0.0989	0	0	0.0172	0	0.0463	0	0	0	0.1364
Variability between persons	0.0588	0.0092	0	0	0	0.0426	0.0727	0	0	0.0175	0	0	0.0123	0	0.05	0.0383	0.1099	0	0	0.0165	0.019	0.0475	0	0	0	0.1515
Number of parts vs. ability to actuate	0	0	0	0	0.2143	0	0	0	0	0	0	0	0.0769	0	0	0	0	0	0	0.0337	0	0.0452	0	0	0	0
Training motivation	0.0956	0.0154	0	0	0	0	0	0	0	0	0	0.0833	0	0	0	0	0	0	0	0.0357	0	0.0441	0	0	0	0
How the exoskeleton attaches to the body	0.0368	0.0185	0.0357	0	0.0714	0.0638	0	0.25	0.0662	0	0	0	0.0185	0.1429	0.0583	0.0213	0.1209	0.2857	0	0.033	0.0381	0.0429	0.1538	0	0	0.0758
Statics	0	0	0	0	0	0	0.0182	0	0	0	0	0	0	0	0	0	0	0	0	0.035	0	0.0395	0	0	0	0
Dynamics	0	0.0585	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0298	0	0	0	0.0343	0	0.0407	0	0	0.0545	0
Range of motion / flexibility	0.0441	0.0523	0.0714	0.0952	0.0357	0.0213	0	0.0357	0.0441	0.0292	0.0952	0	0.0492	0.2857	0.0417	0.0255	0.1319	0	0	0.0323	0	0.0418	0.141	0.0667	0.0364	0
Comfot	0.0515	0.0554	0.1071	0.0476	0	0.0213	0	0	0.0221	0.0351	0.0286	0.025	0.0062	0.0952	0.0167	0.017	0.011	0.0476	0.125	0.0062	0.0095	0.0068	0.0513	0.3333	0.0727	0
Every day carry vs. tool for training	0	0.0615	0	0	0	0	0	0	0.0882	0.1053	0	0.075	0	0	0.0833	0.034	0	0	0	0.0309	0	0	0	0	0	0.1667
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0295	0	0.0362	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0302	0	0.0373	0	0	0	0
Form factor	0	0	0	0	0	0	0	0	0.0809	0	0.1048	0	0	0	0	0	0	0	0	0.0288	0	0.0384	0.1282	0	0	0
Anthropometry	0	0.0031	0	0	0	0	0.1636	0	0	0.0994	0	0	0.0308	0	0	0	0	0	0	0.0117	0	0.035	0	0	0	0.0606
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0124	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0137	0	0.0124	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0	0	0	0	0.0667	0	0	0	0	0	0	0	0.013	0.1238	0.0113	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0275	0	0.0339	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0282	0	0.0328	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0426	0	0	0	0.0144	0	0.0102	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0468	0	0	0	0.0151	0	0.009	0	0	0	0
Formability to the body	0	0.0646	0.1429	0.2381	0	0.0426	0	0	0.0368	0	0.1143	0	0	0	0.1083	0	0.1429	0	0	0.0158	0.1143	0	0.1154	0	0	0
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0021	0	0	0	0	0	0
Degrees of freedom	0.0074	0	0	0.2857	0	0.0851	0	0.0714	0.0588	0.0117	0	0.0917	0.0523	0	0	0.0085	0	0.1429	0.2083	0.0179	0.0476	0	0.1026	0.1333	0.1091	0
Actual exertion	0.0221	0.0246	0	0	0	0	0	0	0	0.0526	0.0571	0	0.04	0	0	0	0.044	0	0	0.0185	0	0	0	0	0	0
Actual fatigue	0.0294	0.0277	0	0	0	0.0426	0	0	0	0.0643	0.0667	0	0	0.1905	0.075	0	0.0549	0	0	0.0192	0.0571	0.0034	0	0.2	0	0
Perceived exertion	0	0.0308	0	0	0	0	0	0	0	0.0585	0.0381	0	0.0369	0	0	0	0	0	0	0.0199	0	0	0	0	0	0.0303
Perceived fatigue	0	0.0338	0	0	0	0	0	0	0	0.0702	0.0476	0	0.0431	0	0.0667	0	0	0.1905	0	0.0206	0	0.0045	0	0	0	0
Ease of use	0.0147	0.0369	0	0	0.1071	0.0213	0	0	0.0515	0	0.0762	0.1	0.0031	0.0476	0.025	0.0128	0.022	0.2381	0	0.022	0.0667	0.0056	0.0897	0	0	0
Intuitive use (affordances)	0	0.04	0.1786	0	0	0.0426	0	0	0	0.076	0.0857	0	0.0154	0	0	0.0809	0.033	0	0	0.0213	0.0762	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0.0882	0.0769	0	0	0	0.0851	0.0364	0.1429	0.1029	0.0819	0	0.1083	0.0554	0	0	0.0894	0	0	0	0.0227	0	0.0136	0	0	0	0.0909
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0.0545	0.1786	0.1103	0	0	0.1167	0.0585	0	0	0.0851	0	0	0	0.0234	0	0.0147	0	0	0	0.1061
Temperature considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.024	0	0.0158	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0247	0	0	0	0	0	0
Iterative design	0	0	0	0	0	0.0426	0	0	0	0	0	0	0.0615	0	0	0	0	0	0	0.0055	0	0	0.0769	0	0	0
Human factors / ergonomics considerations	0	0.0431	0.2143	0.1905	0.1429	0.0213	0	0	0	0	0	0.0333	0.0277	0	0.1	0.0723	0	0	0	0.0048	0	0.0169	0	0	0	0.1212
Potential stress / strain on the joints / muscles	0	0.0462	0.25	0	0	0.0213	0	0	0.0735	0.0409	0	0.0417	0.0246	0	0.0917	0.0766	0.0659	0	0	0.0254	0.0857	0	0	0	0	0
Distribution of mass	0	0.0492	0	0	0	0	0	0	0	0	0.019	0	0.0646	0	0.0333	0.017	0	0	0.25	0.0069	0	0.0282	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	0.1238	0.125	0	0	0	0.0596	0	0	0	0.0076	0	0.0294	0.0385	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0638	0	0	0	0.0082	0	0.0305	0	0	0	0
Repetition and fatigue	0	0.0215	0	0	0	0	0.1818	0	0	0	0	0	0	0	0	0.0681	0.0769	0	0	0.0089	0.0952	0.0181	0	0	0	0.0455
High speed motion	0	0	0	0	0	0.0638	0	0	0	0.0877	0	0	0	0	0	0	0	0	0	0.0117	0.1048	0.0249	0	0	0.0909	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0553	0	0	0	0.011	0	0.026	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0364	0	0.0271	0	0	0	0
Abrasion of material on body	0	0	0	0	0	0	0	0	0.0294	0	0.1333	0	0	0	0.125	0	0.0879	0	0	0.0371	0	0.0192	0.0641	0	0	0
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0261	0	0.0316	0	0	0	0
Replaceable parts	0.0662	0.0677	0	0	0.1786	0.1064	0.1455	0	0.1176	0	0	0.0583	0.0677	0	0	0	0	0	0	0.0268	0.1333	0.0226	0	0	0	0
Material strength	0.0735	0.0708	0	0	0	0.0638	0	0.2143	0	0.0936	0	0	0.0708	0	0	0	0	0	0.2917	0.0096	0	0.0215	0	0	0.1273	0
Material elasticity	0.0809	0.0738	0	0	0	0.0851	0	0	0	0	0	0	0	0	0	0.0511	0	0	0	0.0103	0	0.0237	0	0	0.1455	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	0.0215	0	0	0	0	0	0	0.0014	0	0.0079	0	0	0	0

Table 16: Exoskeleton B - Initial Properties Rank Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	0.95040665	0.036554102
Manufacturability	0.75252723	0.028943355
Weight	0.96710825	0.037196471
Active vs. passive exoskeleton	0.00412088	0.000158495
Variability within persons	0.68460211	0.026330851
Variability between persons	0.64587821	0.02484147
Number of parts vs. ability to actuate	0.37006038	0.014233091
Training motivation	0.27408827	0.010541856
How the exoskeleton attaches to the body	1.53350123	0.058980817
Statics	0.09275731	0.003567589
Dynamics	0.21781285	0.008377417
Range of motion / flexibility	1.37654852	0.052944174
Comfot	1.19212707	0.045851041
Every day carry vs. tool for training	0.64498606	0.024807156
Muscle memory and response	0.06569116	0.002526583
Sensory motor learning	0.06750792	0.002596458
Form factor	0.38111362	0.014658216
Anthropometry	0.40420786	0.015546456
Battery density	0.01236264	0.000475486
Environmental factors	0.02616564	0.001006371
Use as protection	0.21482508	0.008262503
Heat mitigation	0.06137083	0.002360417
Perspiration mitigation	0.0609277	0.002343373
Maximum push forces	0.06714576	0.002582529
Maximum pull forces	0.07095795	0.002729152
Formability to the body	1.13582889	0.043685726
Type of fule (battery/gas/etc.)	0.00206044	7.92477E-05
Degrees of freedom	1.43426163	0.055163909
Actual exertion	0.25894864	0.009959563
Actual fatigue	0.83083612	0.031955235
Perceived exertion	0.21448769	0.008249527
Perceived fatigue	0.47698459	0.018345561
Ease of use	0.94028266	0.036164718
Intuitive use (affordances)	0.64954669	0.024982565
Lifespan of exoskeleton (standard conditions)	0.99451095	0.038250421
Lifespan of exoskeleton (extreme conditions)	0.74774711	0.028759504
Temperature considerations	0.03985767	0.001532987
Humidity considerations	0.02472527	0.000950972
Iterative design	0.18650924	0.007173432
Human factors / ergonomics considerations	0.9883076	0.038011831
Potential stress / strain on the joints / muscles	0.84350043	0.032442324
Distribution of mass	0.4683651	0.018014042
Center of mass	0.38377901	0.014760731
Sound	0.10258002	0.003945385
Repetition and fatigue	0.51606513	0.019848659
High speed motion	0.38375466	0.014759795
Effect of unequal loading	0.09229686	0.003549879
Psychophysics	0.06351974	0.002443067
Abrasion of material on body	0.4960567	0.019079104
Social impact	0.05773732	0.002220666
Replaceable parts	0.99066835	0.038102629
Material strength	1.03677433	0.039875936
Material elasticity	0.47038428	0.018091703
Biomechanics	0.03082169	0.00118545

Table 17: Exoskeleton B - After Use Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	0	0	0	0	4	0	0	0	0	2	20	0	14	3	0	0	0	1	0	2	0	0	5	0
Manufacturability	10	0	0	0	0	0	5	9	0	0	0	3	9	0	0	0	0	0	0	5	0	0	5	0	4	0
Weight	9	1	0	7	6	0	0	0	9	0	8	1	17	4	1	1	6	4	1	6	0	1	6	0	6	1
Active vs. passive exoskeleton	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	31	0	0	0	0	0	0
Variability within persons	8	0	0	0	0	3	0	0	0	0	0	0	10	0	0	0	4	0	8	29	0	0	0	0	0	0
Variability between persons	7	0	0	0	0	4	7	0	0	0	0	0	11	0	15	9	5	5	7	30	0	0	0	0	0	0
Number of parts vs. ability to actuate	6	0	0	0	5	0	8	0	0	0	0	0	0	0	0	0	0	0	0	54	0	0	7	0	0	0
Training motivation	5	5	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	28	0	4	0	0	0	0
How the exoskeleton attaches to the body	1	0	1	0	2	2	0	8	0	0	7	0	4	0	3	6	3	6	2	27	1	3	8	0	0	0
Statics	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	26	0	0	0	0	0	0
Dynamics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	25	0	0	0	0	1	0
Range of motion / flexibility	4	0	0	2	1	0	0	1	10	5	2	0	18	0	8	7	11	0	0	55	0	0	9	2	3	0
Comfot	0	3	6	1	0	1	0	0	1	6	3	11	2	2	4	4	2	1	0	3	0	5	7	4	2	0
Every day carry vs. tool for training	0	0	0	0	0	0	0	0	12	0	0	0	0	0	9	5	0	0	0	32	0	0	0	0	0	9
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0	0	1	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34	0	0	0	0	0	0
Form factor	0	0	0	0	0	0	0	0	2	0	4	0	0	0	0	0	0	0	0	35	0	0	2	0	0	0
Anthropometry	0	2	0	0	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	36	0	0	0	0	0	8
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	38	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	39	3	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	3
Formability to the body	0	11	3	3	0	0	0	0	3	2	1	0	0	0	6	0	10	0	0	53	0	0	0	0	0	2
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0
Degrees of freedom	2	0	0	0	0	5	0	2	8	0	5	7	19	0	0	2	0	3	0	15	0	6	0	3	8	0
Actual exertion	0	7	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	14	0	0	0	0	0	0
Actual fatigue	0	6	0	0	0	0	0	0	0	0	0	0	12	0	0	0	7	0	0	13	0	0	0	0	0	7
Perceived exertion	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0
Perceived fatigue	0	9	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	12	0	0	0	0	0	6
Ease of use	3	10	2	5	4	2	0	7	7	4	0	8	1	3	2	19	1	2	0	7	0	8	4	0	7	0
Intuitive use (affordances)	0	0	0	0	0	0	0	0	6	0	0	9	5	1	0	20	0	0	0	10	2	0	0	0	0	10
Lifespan of exoskeleton (standard conditions)	0	0	0	0	0	0	2	0	0	0	0	10	15	0	0	21	0	0	3	8	0	0	0	0	0	11
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	3	3	0	0	0	0	16	0	0	22	0	0	4	9	0	0	0	0	0	12
Temperature considerations	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	41	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42	0	0	0	0	0	0
Iterative design	0	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	43	0	0	0	0	0	0
Human factors / ergonomics considerations	0	0	4	4	2	0	0	0	0	3	0	5	6	0	10	17	0	0	0	51	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	0	0	5	0	0	0	0	0	0	7	0	0	7	0	0	18	0	0	0	50	0	0	0	0	0	0
Distribution of mass	0	0	0	0	0	0	0	0	5	0	6	0	22	0	0	10	0	0	0	49	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	11	0	0	0	16	0	0	3	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	52	0	0	0	0	0	0
Repetition and fatigue	0	0	0	6	0	0	0	0	11	0	0	0	0	0	0	13	8	0	0	17	0	0	0	0	0	5
High speed motion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	15	0	0	0	44	0	0	0	0	9	4
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	16	0	0	0	47	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	0	0	0	0	0	0
Abrasion of material on body	0	4	0	0	0	0	0	0	4	0	0	6	0	0	12	0	9	0	5	45	0	0	0	0	10	13
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46	0	0	0	0	0	0
Replaceable parts	11	0	0	0	0	0	9	6	13	0	0	12	23	0	0	0	0	0	0	18	0	0	0	0	0	0
Material strength	0	0	0	0	0	0	10	5	0	0	0	0	24	0	0	0	0	0	0	19	0	0	0	0	0	0
Material elasticity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	20	0	0	0	0	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	8	0	7	0	0	0	6	2	0	0	0	0	0	0

Table 18: Exoskeleton B - After Use Properties Normalized by Relative Maximum Rank Value

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	0	0	0	0	0.0727	0	0	0	0	0.0256	0.0667	0	0.1167	0.0119	0	0	0	0.0007	0	0.069	0	0	0.0909	0
Manufacturability	0.1515	0	0	0	0	0	0.0909	0.2	0	0	0	0.0385	0.03	0	0	0	0	0	0	0.0033	0	0	0.098	0	0.0727	0
Weight	0.1364	0.0152	0	0.25	0.3	0	0	0	0.0989	0	0.2222	0.0128	0.0567	0.4	0.0083	0.004	0.0909	0.1905	0.0278	0.0039	0	0.0345	0.1176	0	0.1091	0.011
Active vs. passive exoskeleton	0	0	0	0	0	0	0.1091	0	0	0	0	0	0	0	0	0	0	0	0	0.0202	0	0	0	0	0	0
Variability within persons	0.1212	0	0	0	0	0.1765	0	0	0	0	0	0	0.0333	0	0	0	0.0606	0	0.2222	0.0189	0	0	0	0	0	0
Variability between persons	0.1061	0	0	0	0	0.2353	0.1273	0	0	0	0	0	0.0367	0	0.125	0.0356	0.0758	0.2381	0.1944	0.0195	0	0	0	0	0	0
Number of parts vs. ability to actuate	0.0909	0	0	0	0.25	0	0.1455	0	0	0	0	0	0	0	0	0	0	0	0	0.0352	0	0	0.1373	0	0	0
Training motivation	0.0758	0.0758	0	0	0	0	0	0	0	0	0	0.0513	0	0	0	0	0	0	0	0.0182	0	0.1379	0	0	0	0
How the exoskeleton attaches to the body	0.0152	0	0.0476	0	0.1	0.1176	0	0.1778	0	0	0.1944	0	0.0133	0	0.025	0.0237	0.0455	0.2857	0.0556	0.0176	0.1667	0.1034	0.1569	0	0	0
Statics	0	0	0	0	0	0	0.0182	0	0	0	0	0	0	0	0	0	0	0	0	0.0169	0	0	0	0	0	0
Dynamics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0316	0	0	0	0.0163	0	0	0	0	0.0182	0
Range of motion / flexibility	0.0606	0	0	0.0714	0.05	0	0	0.0222	0.1099	0.1786	0.0556	0	0.06	0	0.0667	0.0277	0.1667	0	0	0.0358	0	0	0.1765	0.2	0.0545	0
Comfot	0	0.0455	0.2857	0.0357	0	0.0588	0	0	0.011	0.2143	0.0833	0.141	0.0067	0.2	0.0333	0.0158	0.0303	0.0476	0	0.002	0	0.1724	0.1373	0.4	0.0364	0
Every day carry vs. tool for training	0	0	0	0	0	0	0	0	0.1319	0	0	0	0	0	0.075	0.0198	0	0	0	0.0208	0	0	0	0	0	0.0989
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0215	0	0	0	0.1	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0221	0	0	0	0	0	0
Form factor	0	0	0	0	0	0	0	0	0.022	0	0.1111	0	0	0	0	0	0	0	0	0.0228	0	0	0.0392	0	0	0
Anthropometry	0	0.0303	0	0	0	0	0	0	0	0.0357	0	0	0.01	0	0	0	0	0	0	0.0234	0	0	0	0	0	0.0879
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0241	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0247	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0156	0	0	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.015	0	0	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0254	0.5	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0143	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0137	0	0	0	0	0	0.033
Formability to the body	0	0.1667	0.1429	0.1071	0	0	0	0	0.033	0.0714	0.0278	0	0	0	0.05	0	0.1515	0	0	0.0345	0	0	0	0	0	0.022
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.026	0	0	0	0	0	0
Degrees of freedom	0.0303	0	0	0	0	0.2941	0	0.0444	0.0879	0	0.1389	0.0897	0.0633	0	0	0.0079	0	0.1429	0	0.0098	0	0.2069	0	0.3	0.1455	0
Actual exertion	0	0.1061	0	0	0	0	0	0	0	0	0	0	0.0467	0	0	0	0	0	0	0.0091	0	0	0	0	0	0
Actual fatigue	0	0.0909	0	0	0	0	0	0	0	0	0	0	0.04	0	0	0	0.1061	0	0	0.0085	0	0	0	0	0	0.0769
Perceived exertion	0	0.1212	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0072	0	0	0	0	0	0
Perceived fatigue	0	0.1364	0	0	0	0	0	0	0	0	0	0	0.0433	0	0	0	0	0	0	0.0078	0	0	0	0	0	0.0659
Ease of use	0.0455	0.1515	0.0952	0.1786	0.2	0.1176	0	0.1556	0.0769	0.1429	0	0.1026	0.0033	0.3	0.0167	0.0751	0.0152	0.0952	0	0.0046	0	0.2759	0.0784	0	0.1273	0
Intuitive use (affordances)	0	0	0	0	0	0	0	0	0.0659	0	0	0.1154	0.0167	0.1	0	0.0791	0	0	0	0.0065	0.3333	0	0	0	0	0.1099
Lifespan of exoskeleton (standard conditions)	0	0	0	0	0	0	0.0364	0	0	0	0	0.1282	0.05	0	0	0.083	0	0	0.0833	0.0052	0	0	0	0	0	0.1209
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0.0545	0.0667	0	0	0	0	0.0533	0	0	0.087	0	0	0.1111	0.0059	0	0	0	0	0	0.1319
Temperature considerations	0	0	0	0	0	0	0	0.0889	0	0	0	0	0	0	0	0	0	0	0	0.0267	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0273	0	0	0	0	0	0
Iterative design	0	0	0	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0.028	0	0	0	0	0	0
Human factors / ergonomics considerations	0	0	0.1905	0.1429	0.1	0	0	0	0	0.1071	0	0.0641	0.02	0	0.0833	0.0672	0	0	0	0.0332	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	0	0	0.2381	0	0	0	0	0	0	0.25	0	0	0.0233	0	0	0.0711	0	0	0	0.0326	0	0	0	0	0	0
Distribution of mass	0	0	0	0	0	0	0	0	0.0549	0	0.1667	0	0.0733	0	0	0.0395	0	0	0	0.0319	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0417	0.0435	0	0	0	0.0104	0	0	0.0588	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0474	0	0	0	0.0339	0	0	0	0	0	0
Repetition and fatigue	0	0	0	0.2143	0	0	0	0	0.1209	0	0	0	0	0	0	0.0514	0.1212	0	0	0.0111	0	0	0	0	0	0.0549
High speed motion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0917	0.0593	0	0	0	0.0286	0	0	0	0	0.1636	0.044
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1083	0.0632	0	0	0	0.0306	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0313	0	0	0	0	0	0
Abrasion of material on body	0	0.0606	0	0	0	0	0	0	0.044	0	0	0.0769	0	0	0.1	0	0.1364	0	0.1389	0.0293	0	0	0	0	0.1818	0.1429
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0299	0	0	0	0	0	0
Replaceable parts	0.1667	0	0	0	0	0	0.1636	0.1333	0.1429	0	0	0.1538	0.0767	0	0	0	0	0	0	0.0117	0	0	0	0	0	0
Material strength	0	0	0	0	0	0	0.1818	0.1111	0	0	0	0	0.08	0	0	0	0	0	0	0.0124	0	0	0	0	0	0
Material elasticity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0553	0	0	0	0.013	0	0	0	0	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	0.0267	0	0.0583	0	0	0	0.1667	0.0013	0	0	0	0	0	0

Table 19: Exoskeleton B - After Use Properties Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	0.45408499	0.017464807
Manufacturability	0.68490748	0.026342595
Weight	2.0896906	0.080372715
Active vs. passive exoskeleton	0.1292732	0.004972046
Variability within persons	0.63272453	0.024335559
Variability between persons	1.19369575	0.045911375
Number of parts vs. ability to actuate	0.65877479	0.025337492
Training motivation	0.3589574	0.013806054
How the exoskeleton attaches to the body	1.54596879	0.059460338
Statics	0.0351089	0.001350342
Dynamics	0.06607841	0.002541477
Range of motion / flexibility	1.3360986	0.051388408
Comfot	1.95705816	0.075271468
Every day carry vs. tool for training	0.34636541	0.013321747
Muscle memory and response	0.12148438	0.004672476
Sensory motor learning	0.02213542	0.000851362
Form factor	0.19509128	0.007503511
Anthropometry	0.1873669	0.007206419
Battery density	0.02408854	0.000926482
Environmental factors	0.02473958	0.000951522
Use as protection	0.015625	0.000600962
Heat mitigation	0.01497396	0.000575921
Perspiration mitigation	0.52539063	0.020207332
Maximum push forces	0.01432292	0.000550881
Maximum pull forces	0.04663891	0.001793804
Formability to the body	0.80683843	0.031032247
Type of fule (battery/gas/etc.)	0.02604167	0.001001603
Degrees of freedom	1.56162203	0.060062386
Actual exertion	0.16184186	0.006224687
Actual fatigue	0.32235632	0.01239832
Perceived exertion	0.12837358	0.004937445
Perceived fatigue	0.25344354	0.009747828
Ease of use	2.25793804	0.086843771
Intuitive use (affordances)	0.82677059	0.031798869
Lifespan of exoskeleton (standard conditions)	0.5069935	0.01949975
Lifespan of exoskeleton (extreme conditions)	0.51034059	0.019628484
Temperature considerations	0.1155816	0.004445446
Humidity considerations	0.02734375	0.001051683
Iterative design	0.09799479	0.00376903
Human factors / ergonomics considerations	0.80830889	0.031088803
Potential stress / strain on the joints / muscles	0.6151269	0.023658727
Distribution of mass	0.36637179	0.014091223
Center of mass	0.15438512	0.005937889
Sound	0.081285	0.003126346
Repetition and fatigue	0.57377312	0.022068197
High speed motion	0.38719345	0.014892056
Effect of unequal loading	0.2021734	0.0077759
Psychophysics	0.03125	0.001201923
Abrasion of material on body	0.91070991	0.035027304
Social impact	0.02994792	0.001151843
Replaceable parts	0.84872508	0.032643272
Material strength	0.38529908	0.014819196
Material elasticity	0.0683568	0.002629108
Biomechanics	0.25296875	0.009729567

Table 20: Exoskeleton B - Properties Rank Relative Change

	Normalized by Participant		
Design Metrics	Before	After	Relative Change
Cost	0.036554102	0.017464807	-0.019089295
Manufacturability	0.028943355	0.026342595	-0.00260076
Weight	0.037196471	0.080372715	0.043176244
Active vs. passive exoskeleton	0.000158495	0.004972046	0.004813551
Variability within persons	0.026330851	0.024335559	-0.001995292
Variability between persons	0.02484147	0.045911375	0.021069905
Number of parts vs. ability to actuate	0.014233091	0.025337492	0.0111044
Training motivation	0.010541856	0.013806054	0.003264198
How the exoskeleton attaches to the body	0.058980817	0.059460338	0.000479522
Statics	0.003567589	0.001350342	-0.002217247
Dynamics	0.008377417	0.002541477	-0.00583594
Range of motion / flexibility	0.052944174	0.051388408	-0.001555766
Comfot	0.045851041	0.075271468	0.029420427
Every day carry vs. tool for training	0.024807156	0.013321747	-0.01148541
Muscle memory and response	0.002526583	0.004672476	0.002145893
Sensory motor learning	0.002596458	0.000851362	-0.001745096
Form factor	0.014658216	0.007503511	-0.007154705
Anthropometry	0.015546456	0.007206419	-0.008340037
Battery density	0.000475486	0.000926482	0.000450996
Environmental factors	0.001006371	0.000951522	-5.48484E-05
Use as protection	0.008262503	0.000600962	-0.007661541
Heat mitigation	0.002360417	0.000575921	-0.001784495
Perspiration mitigation	0.002343373	0.020207332	0.017863959
Maximum push forces	0.002582529	0.000550881	-0.002031648
Maximum pull forces	0.002729152	0.001793804	-0.000935348
Formability to the body	0.043685726	0.031032247	-0.012653479
Type of fule (battery/gas/etc.)	7.92477E-05	0.001001603	0.000922355
Degrees of freedom	0.055163909	0.060062386	0.004898477
Actual exertion	0.009959563	0.006224687	-0.003734876
Actual fatigue	0.031955235	0.01239832	-0.019556915
Perceived exertion	0.008249527	0.004937445	-0.003312081
Perceived fatigue	0.018345561	0.009747828	-0.008597733
Ease of use	0.036164718	0.086843771	0.050679053
Intuitive use (affordances)	0.024982565	0.031798869	0.006816304
Lifespan of exoskeleton (standard conditions)	0.038250421	0.01949975	-0.018750671
Lifespan of exoskeleton (extreme conditions)	0.028759504	0.019628484	-0.00913102
Temperature considerations	0.001532987	0.004445446	0.002912459
Humidity considerations	0.000950972	0.001051683	0.000100711
Iterative design	0.007173432	0.00376903	-0.003404402
Human factors / ergonomics considerations	0.038011831	0.031088803	-0.006923027
Potential stress / strain on the joints / muscles	0.032442324	0.023658727	-0.008783597
Distribution of mass	0.018014042	0.014091223	-0.00392282
Center of mass	0.014760731	0.005937889	-0.008822842
Sound	0.003945385	0.003126346	-0.000819039
Repetition and fatigue	0.019848659	0.022068197	0.002219538
High speed motion	0.014759795	0.014892056	0.000132261
Effect of unequal loading	0.003549879	0.0077759	0.004226021
Psychophysics	0.002443067	0.001201923	-0.001241144
Abrasion of material on body	0.019079104	0.035027304	0.0159482
Social impact	0.002220666	0.001151843	-0.001068823
Replaceable parts	0.038102629	0.032643272	-0.005459357
Material strength	0.039875936	0.014819196	-0.02505674
Material elasticity	0.018091703	0.002629108	-0.015462595
Biomechanics	0.00118545	0.009729567	0.008544118

Exoskeleton C

Table 21: Exoskeleton C - Value Properties Relative Change

	Cost	Manufacturability	Weight	Active vs. passive	Variability within persons	Variability between persons	number of parts vs. ability	training motivation	how the exoskeleton	statics	dynamics	range of motion / flexibility	comfort	every day carry vs. tool for	muscle memory and	sensory motor learning	Form factor	anthropometry
Su	14	11	18	2	8	13	1	4	15	1	3	18	20	9	3	2	2	8
Su	9	9	16	1	6	13	2	2	12	0	4	16	20	7	1	0	6	3
Re	-5	-2	-2	-1	-2	0	1	-2	-3	-1	1	-2	0	-2	-2	-2	4	-5

	battery density	environmental factors	use as protection	heat mitigation	perspiration mitigation	maximum push forces	maximum pull forces	formatibilty to body	type of fuel	degrees of freedom	actual exertion	actual fatigue	perceived exertion	perceived fatigue	ease of use	intuitive use (affordances)	lifespan of exoskeleton	lifespan of exoskeleton
Su	2	3	7	9	6	2	2	11	1	12	5	9	5	7	18	12	8	5
Su	0	1	2	7	6	2	2	8	1	8	4	8	2	2	15	11	8	4
Re	-2	-2	-5	-2	0	0	0	-3	0	-4	-1	-1	-3	-5	-3	-1	0	-1

	temperature considerations	humidity considerations	iterative design	human factors /ergonomics	potential stress / strain on	distribution of mass	center of mass	sound	repetition and fatigue	high speed motion	effect of unequal loading	psychophyiscs	abrasion of material on	social impact	repalceable parts	material strength	material elasticity	biomechanics
Su	7	3	4	10	7	4	5	3	6	10	3	1	10	1	9	11	10	5
Su	5	0	2	9	7	4	2	2	6	6	0	0	10	0	6	9	10	2
Re	-2	-3	-2	-1	0	0	-3	-1	0	-4	-3	-1	0	-1	-3	-2	0	-3

Exoskeleton C yields a summed relative change of -87.

Table 22: Exoskeleton C - Initial Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	5	8	0	0	0	0	7	0	15	1	22	0	3	3	0	0	0	1	0	2	7	3	5	1
Manufacturability	0	0	6	9	1	0	0	0	8	0	16	14	11	0	0	5	0	0	1	3	0	0	0	0	4	0
Weight	12	0	7	10	0	2	2	6	0	7	10	15	15	5	4	4	9	0	13	4	8	3	2	0	6	0
Active vs. passive exoskeleton	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0	
Variability within persons	5	0	20	0	0	3	0	0	0	0	0	0	4	0	18	0	7	0	11	20	0	0	0	0	0	0
Variability between persons	6	0	21	0	2	0	0	0	0	1	0	0	5	0	13	23	8	2	12	18	2	0	6	0	0	0
Number of parts vs. ability to actuate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0
Training motivation	3	1	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0
How the exoskeleton attaches to the body	4	0	24	0	4	0	9	1	0	0	17	2	10	0	5	1	0	0	10	30	0	1	8	0	0	0
Statics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0
Dynamics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	5	0	0	0	0	3	0
Range of motion / flexibility	1	0	23	2	7	0	6	3	4	0	6	11	16	4	7	7	11	0	23	19	0	0	3	0	1	0
Comfot	2	3	1	1	0	1	7	14	1	0	7	12	2	3	1	8	1	4	0	14	1	4	0	0	2	0
Every day carry vs. tool for training	0	0	25	0	0	0	0	12	9	0	0	13	0	0	6	11	0	0	6	16	0	0	0	0	0	0
Muscle memory and response	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	13	0	0	0
Sensory motor learning	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0
Form factor	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	48	0	0	0	0	0	0
Anthropometry	0	0	0	5	0	0	0	0	0	2	18	0	3	0	19	0	0	0	2	47	0	0	0	0	0	2
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	49	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	46	0	0	5	0	0	0
Use as protection	0	0	9	0	0	0	0	15	0	0	0	9	0	0	0	0	0	0	8	54	0	5	4	0	0	0
Heat mitigation	0	6	10	0	0	0	0	0	0	0	19	10	0	0	21	0	2	1	19	53	0	0	0	0	0	0
Perspiration mitigation	0	0	11	0	0	0	0	10	0	3	0	0	0	0	20	0	3	0	0	55	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	50	0	0	0	0	0	0
Maximum pull forces	0	0	0	0		0	0	0	0	0	0	0	0	0	0	10	0	0	0	49	0	0	0	0	0	0
Formability to the body	0	2	2	3	6	0	0	5	3	0	0	0	0	0	22	0	15	0	0	51	3	0	0	0	0	7
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0	0	0	0	0
Degrees of freedom	7	0	0	0	0	5	1	4	2	0	0	3	17	0	0	2	0	0	14	7	4	0	0	0	8	0
Actual exertion	8	0	13	0	0	0	0	0	0	0	1	0	14	0	0	0	0	0	0	8	0	0	0	0	0	0
Actual fatigue	9	0	15	0	0	0	0	0	0	0	2	0	0	0	10	0	4	0	0	9	5	6	12	0	0	0
Perceived exertion	0	0	14	0	0	0	3	0	0	0	3	0	12	0	0	0	0	0	0	31	0	0	0	0	0	0
Perceived fatigue	0	0	16	0	0	0	4	0	0	0	4	0	13	0	9	0	0	0	0	32	0	0	0	0	0	0
Ease of use	10	5	17	0	0	4	5	8	6	6	12	0	1	2	2	19	6	0	15	33	6	7	1	0	7	0
Intuitive use (affordances)	0	4	18	0	5	0	0	9	0	0	11	6	6	1	0	20	0	0	0	34	7	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0	0	19	11	0	0	0	0	0	0	13	4	19	0	14	21	0	0	0	35	0	0	0	0	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0	0	0	0	5	20	0	23	22	0	0	0	36	0	0	0	0	0	0
Temperature considerations	0	0	28	0	0	6	0	0	0	4	0	0	0	0	0	0	5	3	16	37	0	0	0	1	0	0
Humidity considerations	0	0	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34	0	0	0	2	0	0
Iterative design	0	0	30	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	10	0	0	0	0	0	0
Human factors / ergonomics considerations	0	0	31	4	3	0	0	13	0	0	8	0	7	0	8	24	0	0	0	11	0	0	10	0	0	0
Potential stress / strain on the joints / muscles	0	0	32	0	0	0	0	0	0	0	14	0	9	0	15	25	14	0	0	12	0	0	0	0	0	4
Distribution of mass	0	0	33	0	0	0	0	0	0	0	7	0	0	0	0	12	0	0	17	26	0	0	0	0	0	0
Center of mass	0	0	34	0	0	0	0	0	0	0	0	0	18	0	0	13	0	0	18	25	0	0	0	0	0	0
Sound	0	0	35	0	0	0	0	0	0	0	0	0	0	0	0	14	0	0	0	24	0	0	0	0	0	0
Repetition and fatigue	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0	15	10	0	9	28	0	0	0	0	0	0
High speed motion	0	0	37	0	0	0	0	11	0	5	0	0	0	0	0	16	0	0	20	40	9	0	0	0	9	5
Effect of unequal loading	0	0	38	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	5	44	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	43	0	0	0	0	0	0
Abrasion of material on body	0	0	12	0	0	6	10	0	5	0	0	7	0	0	11	0	0	0	22	41	0	0	0	0	10	6
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42	0	0	0		0	0
Replaceable parts	0	0	8	12	0	0	0	0	0	0	0	8	23	0	24	0	0	0	21	23	0		0	0	0	8
Material strength	0	0	3	7	0	0	0	0	0	0	0	0	24	0	16	0	13	0	0	22	0	8	9	4	0	0
Material elasticity	11	0	4	6	0	7	0	2	0	0	0	0	0	0	17	18	12	0	4	21	0	0	0	0	0	3
Biomechanics	0	0	0	0	0	0	0	0	0	0	9	0	8	0	12	0	0	0	0	2	0	0	0	0	0	0

Table 23: Exoskeleton C - Initial Properties Normalized by Relative Maximum Rank Value

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	0.0067	0.1026	0	0	0	0	0.1556	0	0.0781	0.0083	0.0733	0	0.01	0.0092	0	0	0	0.0007	0	0.0556	0.0875	0.3	0.0909	0.0278
Manufacturability	0	0	0.0081	0.1154	0.0357	0	0	0	0.1778	0	0.0833	0.1167	0.0367	0	0	0.0154	0	0	0.0036	0.002	0	0	0	0	0.0727	0
Weight	0.1538	0	0.0094	0.1282	0	0.0588	0.0364	0.05	0	0.25	0.0521	0.125	0.05	0.3333	0.0133	0.0123	0.075	0	0.0471	0.0026	0.1778	0.0833	0.025	0	0.1091	0
Active vs. passive exoskeleton	0	0	0	0	0	0	0.1455	0	0	0	0	0	0	0	0	0	0	0	0	0.0125	0	0	0	0	0	0
Variability within persons	0.0641	0	0.027	0	0	0.0882	0	0	0	0	0	0	0.0133	0	0.06	0	0.0583	0	0.0399	0.0132	0	0	0	0	0	0
Variability between persons	0.0769	0	0.0283	0	0.0714	0	0	0	0	0.0357	0	0	0.0167	0	0.0433	0.0708	0.0667	0.2	0.0435	0.0118	0.0444	0	0.075	0	0	0
Number of parts vs. ability to actuate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0112	0	0	0	0	0	0
Training motivation	0.0385	0.0476	0.0297	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0191	0	0	0	0	0	0
How the exoskeleton attaches to the body	0.0513	0	0.0324	0	0.1429	0	0.1636	0.0083	0	0	0.0885	0.0167	0.0333	0	0.0167	0.0031	0	0	0.0362	0.0197	0	0.0278	0.1	0	0	0
Statics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0039	0	0	0	0	0	0
Dynamics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0185	0	0	0	0.0033	0	0	0	0	0.0545	0
Range of motion / flexibility	0.0128	0	0.031	0.0256	0.25	0	0.1091	0.025	0.0889	0	0.0313	0.0917	0.0533	0.2667	0.0233	0.0215	0.0917	0	0.0833	0.0125	0	0	0.0375	0	0.0182	0
Comfot	0.0256	0.1429	0.0013	0.0128	0	0.0294	0.1273	0.1167	0.0222	0	0.0365	0.1	0.0067	0.2	0.0033	0.0246	0.0083	0.4	0	0.0092	0.0222	0.1111	0	0	0.0364	0
Every day carry vs. tool for training	0	0	0.0337	0	0	0	0	0.1	0.2	0	0	0.1083	0	0	0.02	0.0338	0	0	0.0217	0.0105	0	0	0	0	0	0
Muscle memory and response	0	0	0.0351	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0184	0	0	0.1625	0	0	0
Sensory motor learning	0	0	0.0364	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0178	0	0	0	0	0	0
Form factor	0	0	0	0	0	0	0	0.0583	0	0	0	0	0	0	0	0	0	0	0	0.0316	0	0	0	0	0	0
Anthropometry	0	0	0	0.0641	0	0	0	0	0	0.0714	0.0938	0	0.01	0	0.0633	0	0	0	0.0072	0.0309	0	0	0	0	0	0.0556
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0109	0.0322	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0254	0.0303	0	0	0.0625	0	0	0
Use as protection	0	0	0.0121	0	0	0	0	0.125	0	0	0	0.075	0	0	0	0	0	0	0.029	0.0355	0	0.1389	0.05	0	0	0
Heat mitigation	0	0.2857	0.0135	0	0	0	0	0	0	0	0.099	0.0833	0	0	0.07	0	0.0167	0.1	0.0688	0.0349	0	0	0	0	0	0
Perspiration mitigation	0	0	0.0148	0	0	0	0	0.0833	0	0.1071	0	0	0	0	0.0667	0	0.025	0	0	0.0362	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0277	0	0	0	0.0329	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0308	0	0	0	0.0322	0	0	0	0	0	0
Formability to the body	0	0.0952	0.0027	0.0385	0.2143	0	0	0.0417	0.0667	0	0	0	0	0	0.0733	0	0.125	0	0	0.0336	0.0667	0	0	0	0	0.1944
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0342	0	0	0	0	0	0
Degrees of freedom	0.0897	0	0	0	0	0.1471	0.0182	0.0333	0.0444	0	0	0.025	0.0567	0	0	0.0062	0	0	0.0507	0.0046	0.0889	0	0	0	0.1455	0
Actual exertion	0.1026	0	0.0175	0	0	0	0	0	0	0	0.0052	0	0.0467	0	0	0	0	0	0	0.0053	0	0	0	0	0	0
Actual fatigue	0.1154	0	0.0202	0	0	0	0	0	0	0	0.0104	0	0	0	0.0333	0	0.0333	0	0	0.0059	0.1111	0.1667	0.15	0	0	0
Perceived exertion	0	0	0.0189	0	0	0	0.0545	0	0	0	0.0156	0	0.04	0	0	0	0	0	0	0.0204	0	0	0	0	0	0
Perceived fatigue	0	0	0.0216	0	0	0	0.0727	0	0	0	0.0208	0	0.0433	0	0.03	0	0	0	0	0.0211	0	0	0	0	0	0
Ease of use	0.1282	0.2381	0.0229	0	0	0.1176	0.0909	0.0667	0.1333	0.2143	0.0625	0	0.0033	0.1333	0.0067	0.0585	0.05	0	0.0543	0.0217	0.1333	0.1944	0.0125	0	0.1273	0
Intuitive use (affordances)	0	0.1905	0.0243	0	0.1786	0	0	0.075	0	0	0.0573	0.05	0.02	0.0667	0	0.0615	0	0	0	0.0224	0.1556	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0	0	0.0256	0.141	0	0	0	0	0	0	0.0677	0.0333	0.0633	0	0.0467	0.0646	0	0	0	0.023	0	0	0	0	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0	0	0	0	0.0417	0.0667	0	0.0767	0.0677	0	0	0	0.0237	0	0	0	0	0	0
Temperature considerations	0	0	0.0378	0	0	0.1765	0	0	0	0.1429	0	0	0	0	0	0	0.0417	0.3	0.058	0.0243	0	0	0	0.1	0	0
Humidity considerations	0	0	0.0391	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0224	0	0	0	0.2	0	0
Iterative design	0	0	0.0405	0	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0.0066	0	0	0	0	0	0
Human factors / ergonomics considerations	0	0	0.0418	0.0513	0.1071	0	0	0.1083	0	0	0.0417	0	0.0233	0	0.0267	0.0738	0	0	0	0.0072	0	0	0.125	0	0	0
Potential stress / strain on the joints / muscles	0	0	0.0432	0	0	0	0	0	0	0	0.0729	0	0.03	0	0.05	0.0769	0.1167	0	0	0.0079	0	0	0	0	0	0.1111
Distribution of mass	0	0	0.0445	0	0	0	0	0	0	0	0.0365	0	0	0	0	0.0369	0	0	0.0616	0.0171	0	0	0	0	0	0
Center of mass	0	0	0.0459	0	0	0	0	0	0	0	0	0	0.06	0	0	0.04	0	0	0.0652	0.0164	0	0	0	0	0	0
Sound	0	0	0.0472	0	0	0	0	0	0	0	0	0	0	0	0	0.0431	0	0	0	0.0158	0	0	0	0	0	0
Repetition and fatigue	0	0	0.0486	0	0	0	0	0	0	0	0	0	0	0	0	0.0462	0.0833	0	0.0326	0.0184	0	0	0	0	0	0
High speed motion	0	0	0.0499	0	0	0	0	0.0917	0	0.1786	0	0	0	0	0	0.0492	0	0	0.0725	0.0263	0.2	0	0	0	0.1636	0.1389
Effect of unequal loading	0	0	0.0513	0	0	0	0	0	0	0	0	0	0	0	0	0.0523	0	0	0.0181	0.0289	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0283	0	0	0	0	0	0
Abrasion of material on body	0	0	0.0162	0	0	0.1765	0.1818	0	0.1111	0	0	0.0583	0	0	0.0367	0	0	0	0.0797	0.027	0	0	0	0	0.1818	0.1667
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0276	0	0	0	0	0	0
Replaceable parts	0	0	0.0108	0.1538	0	0	0	0	0	0	0	0.0667	0.0767	0	0.08	0	0	0	0.0761	0.0151	0	0	0	0	0	0.2222
Material strength	0	0	0.004	0.0897	0	0	0	0	0	0	0	0	0.08	0	0.0533	0	0.1083	0	0	0.0145	0	0.2222	0.1125	0.4	0	0
Material elasticity	0.141	0	0.0054	0.0769	0	0.2059	0	0.0167	0	0	0	0	0	0	0.0567	0.0554	0.1	0	0.0145	0.0138	0	0	0	0	0	0.0833
Biomechanics	0	0	0	0	0	0	0	0	0	0	0.0469	0	0.0267	0	0.04	0	0	0	0	0.0013	0	0	0	0	0	0

Table 24: Exoskeleton C - Initial Properties Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	1.00629005	0.038703464
Manufacturability	0.66734927	0.02566728
Weight	1.79267788	0.068949149
Active vs. passive exoskeleton	0.15795455	0.006075175
Variability within persons	0.36400805	0.014000309
Variability between persons	0.78460672	0.030177182
Number of parts vs. ability to actuate	0.01118421	0.000430162
Training motivation	0.13484914	0.005186505
How the exoskeleton attaches to the body	0.74052932	0.028481897
Statics	0.00394737	0.000151822
Dynamics	0.07629647	0.002934479
Range of motion / flexibility	1.27345075	0.048978875
Comfot	1.43655614	0.055252159
Every day carry vs. tool for training	0.52818313	0.020314736
Muscle memory and response	0.21600877	0.00830803
Sensory motor learning	0.0542004	0.002084631
Form factor	0.08991228	0.003458165
Anthropometry	0.39633745	0.015243748
Battery density	0.04310641	0.001657939
Environmental factors	0.11812548	0.004543288
Use as protection	0.46554646	0.017905633
Heat mitigation	0.7718769	0.029687573
Perspiration mitigation	0.33317187	0.012814303
Maximum push forces	0.06058704	0.002330271
Maximum pull forces	0.06300607	0.00242331
Formability to the body	0.95201481	0.036615954
Type of fule (battery/gas/etc.)	0.03421053	0.001315789
Degrees of freedom	0.71025586	0.027317533
Actual exertion	0.17724612	0.006817158
Actual fatigue	0.64640969	0.024861911
Perceived exertion	0.14945858	0.005748407
Perceived fatigue	0.20953901	0.008059193
Ease of use	1.86998793	0.071922613
Intuitive use (affordances)	0.90175989	0.034683073
Lifespan of exoskeleton (standard conditions)	0.46535003	0.017898078
Lifespan of exoskeleton (extreme conditions)	0.27637652	0.010629866
Temperature considerations	0.88109429	0.033888242
Humidity considerations	0.26150472	0.010057874
Iterative design	0.11706478	0.004502491
Human factors / ergonomics considerations	0.60634326	0.023320895
Potential stress / strain on the joints / muscles	0.50869714	0.019565275
Distribution of mass	0.19661529	0.007562127
Center of mass	0.2275487	0.008751873
Sound	0.10609987	0.004080764
Repetition and fatigue	0.22909992	0.008811536
High speed motion	0.9707062	0.037334854
Effect of unequal loading	0.15065305	0.005794348
Psychophysics	0.02828947	0.001088057
Abrasion of material on body	1.03576289	0.039837034
Social impact	0.02763158	0.001062753
Replaceable parts	0.70141647	0.026977556
Material strength	1.08465475	0.04171749
Material elasticity	0.76958901	0.029599577
Biomechanics	0.11485746	0.004417594

Table 25: Exoskeleton C - After Use Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	11	0	0	0	0	0	8	0	0	1	20	0	11	3	0	0	0	1	0	0	0	4	9	0
Manufacturability	0	0	12	7	1	0	0	0	9	0	0	5	11	0	0	2	0	0	0	4	0	0	0	0	8	0
Weight	9	0	13	0	0	9	4	0	0	7	8	14	16	5	8	4	12	0	0	3	0	5	3	0	7	0
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0
Variability within persons	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0	13	0	1	14	0	0	0	1	0	0
Variability between persons	11	0	0	0	9	1	0	0	0	1	0	0	2	3	2	5	14	4	5	12	2	0	0	0	0	0
Number of parts vs. ability to actuate	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0
Training motivation	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0	0
How the exoskeleton attaches to the body	1	0	14	0	8	3	6	4	0	0	0	3	5	0	0	6	0	0	2	10	1	0	4	0	0	0
Statics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dynamics	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	9	0	0	0	0	4	0
Range of motion / flexibility	4	0	15	2	6	4	2	3	2	3	8	13	9	0	7	7	0	0	0	33	0	0	6	0	5	0
Comfot	3	2	1	1	7	2	3	8	1	0	0	4	8	4	1	8	1	1	4	0	0	1	5	0	1	0
Every day carry vs. tool for training	0	4	0	0	0	0	7	9	12	0	0	12	0	0	0	10	0	0	0	8	0	0	0	0	0	0
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	15	0	0	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Form factor	0	0	0	0	0	0	0	7	5	0	0	0	0	0	0	0	3	0	0	0	3	0	7	0	0	0
Anthropometry	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	16	0	0	0	0	0	1
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0	0	0	0	2	0	0	4	0	0	0	0	0	0	0	0	0	0	0
Heat mitigation	0	0	0	0	2	0	0	0	0	0	0	15	0	0	13	0	7	2	0	0	0	0	8	2	0	0
Perspiration mitigation	0	0	0	0	3	0	0	10	0	6	0	0	0	0	14	0	8	0	0	34	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	19	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	18	0	0	0	0	0	0
Formability to the body	0	5	6	11	0	0	0	1	4	0	11	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0
Degrees of freedom	0	0	0	0	0	0	1	5	3	0	0	11	10	0	0	1	0	3	0	0	0	0	0	0	3	0
Actual exertion	5	0	0	0	0	0	0	0	0	0	3	0	15	0	0	0	4	0	0	0	0	0	0	0	0	0
Actual fatigue	6	0	0	0	0	0	0	0	0	0	4	16	13	0	0	0	5	0	0	31	4	3	0	0	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0
Perceived fatigue	0	0	0	0	0	0	0	0	0	0	2	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0
Ease of use	7	0	8	0	0	6	0	0	7	0	6	6	0	2	0	20	10	0	0	29	6	2	2	0	6	0
Intuitive use (affordances)	0	0	9	5	0	0	5	6	10	0	5	0	4	1	0	21	11	0	7	28	5	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0	0	10	4	0	0	0	0	0	0	0	7	17	0	9	22	0	0	0	0	0	0	0	3	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0	0	0	0	0	18	0	12	23	0	0	0	27	0	0	0	0	0	0
Temperature considerations	0	0	0	0	4	7	0	0	0	4	0	0	0	0	0	0	9	0	0	26	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Iterative design	0	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0	8	6	0	0	0	0	0	0
Human factors / ergonomics considerations	0	0	0	3	5	0	0	11	0	0	10	8	6	0	10	18	0	0	0	5	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	8	0	0	0	0	0	0	0	0	0	0	9	7	0	6	19	0	0	0	7	0	0	0	0	0	0
Distribution of mass	0	0	7	0	0	0	0	0	6	0	0	0	0	0	0	15	0	0	0	0	0	0	1	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	16	0	0	0	36	0	0	0	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	37	0	0	0	0	0	0
Repetition and fatigue	0	0	0	6	0	0	0	0	0	0	9	10	0	0	0	14	6	0	0	23	0	0	0	0	0	0
High speed motion	0	0	3	0	0	0	0	12	0	0	0	0	0	0	0	13	0	0	0	0	7	0	0	0	10	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	0	0	0	0	0	0
Abrasion of material on body	0	0	2	0	0	8	8	0	0	0	0	0	0	0	5	0	0	0	3	0	8	4	0	0	2	3
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0
Replaceable parts	0	0	0	10	0	0	0	0	11	0	0	0	21	0	0	0	0	0	0	24	0	0	0	0	0	4
Material strength	0	0	4	8	0	0	0	0	0	0	0	0	22	0	15	24	15	0	0	21	0	0	0	0	0	0
Material elasticity	10	1	5	9	0	5	0	2	0	5	0	0	0	0	16	0	16	0	0	20	0	0	0	0	0	5
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	2	0	0	0	0	0	0

Table 26: Exoskeleton C - After Use Properties Normalized by Relative Maximum Rank Value

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	0.0917	0	0	0	0	0	0.1026	0	0	0.0074	0.0791	0	0.0809	0.01	0	0	0	0.0014	0	0	0	0.4	0.1636	0
Manufacturability	0	0	0.1	0.1061	0.0222	0	0	0	0.1154	0	0	0.0368	0.0435	0	0	0.0067	0	0	0	0.0057	0	0	0	0	0.1455	0
Weight	0.1364	0	0.1083	0	0	0.2	0.1111	0	0	0.25	0.1194	0.1029	0.0632	0.3333	0.0588	0.0133	0.0882	0	0	0.0043	0	0.3333	0.0833	0	0.1273	0
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0185	0	0	0	0	0	0
Variability within persons	0	0	0	0	0	0	0	0	0	0	0	0	0.004	0	0.0221	0	0.0956	0	0.0278	0.0199	0	0	0	0.1	0	0
Variability between persons	0.1667	0	0	0	0.2	0.0222	0	0	0	0.0357	0	0	0.0079	0.2	0.0147	0.0167	0.1029	0.4	0.1389	0.0171	0.0556	0	0	0	0	0
Number of parts vs. ability to actuate	0	0	0	0	0	0	0	0	0	0.0714	0	0	0	0	0	0	0	0	0	0.0156	0	0	0	0	0	0
Training motivation	0.0303	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0455	0	0	0	0	0	0
How the exoskeleton attaches to the body	0.0152	0	0.1167	0	0.1778	0.0667	0.1667	0.0513	0	0	0	0.0221	0.0198	0	0	0.02	0	0	0.0556	0.0142	0.0278	0	0.1111	0	0	0
Statics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dynamics	0	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03	0	0	0	0.0128	0	0	0	0	0.0727	0
Range of motion / flexibility	0.0606	0	0.125	0.0303	0.1333	0.0889	0.0556	0.0385	0.0256	0.1071	0.1194	0.0956	0.0356	0	0.0515	0.0233	0	0	0	0.0469	0	0	0.1667	0	0.0909	0
Comfot	0.0455	0.1333	0.0083	0.0152	0.1556	0.0444	0.0833	0.1026	0.0128	0	0	0.0294	0.0316	0.2667	0.0074	0.0267	0.0074	0.1	0.1111	0	0	0.0667	0.1389	0	0.0182	0
Every day carry vs. tool for training	0	0.2667	0	0	0	0	0.1944	0.1154	0.1538	0	0	0.0882	0	0	0	0.0333	0	0	0	0.0114	0	0	0	0	0	0
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1667	0.0213	0	0	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Form factor	0	0	0	0	0	0	0	0.0897	0.0641	0	0	0	0	0	0	0	0.0221	0	0	0	0.0833	0	0.1944	0	0	0
Anthropometry	0	0	0	0	0	0	0	0	0	0	0	0	0.0119	0	0	0	0	0	0	0.0228	0	0	0	0	0	0.0667
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0313	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0	0	0	0	0.0147	0	0	0.0294	0	0	0	0	0	0	0	0	0	0	0
Heat mitigation	0	0	0	0	0.0444	0	0	0	0	0	0	0.1103	0	0	0.0956	0	0.0515	0.2	0	0	0	0	0.2222	0.2	0	0
Perspiration mitigation	0	0	0	0	0.0667	0	0	0.1282	0	0.2143	0	0	0	0	0.1029	0	0.0588	0	0	0.0484	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0367	0	0	0	0.027	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0	0	0	0.0256	0	0	0	0	0	0
Formability to the body	0	0.3333	0.05	0.1667	0	0	0	0.0128	0.0513	0	0.1642	0	0	0	0	0	0.0147	0	0	0	0	0	0	0	0	0.1333
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0242	0	0	0	0	0	0
Degrees of freedom	0	0	0	0	0	0	0.0278	0.0641	0.0385	0	0	0.0809	0.0395	0	0	0.0033	0	0.3	0	0	0	0	0	0	0.0545	0
Actual exertion	0.0758	0	0	0	0	0	0	0	0	0	0.0448	0	0.0593	0	0	0	0.0294	0	0	0	0	0	0	0	0	0
Actual fatigue	0.0909	0	0	0	0	0	0	0	0	0	0.0597	0.1176	0.0514	0	0	0	0.0368	0	0	0.0441	0.1111	0.2	0	0	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	0.0149	0	0	0	0	0	0	0	0	0.0427	0	0	0	0	0	0
Perceived fatigue	0	0	0	0	0	0	0	0	0	0	0.0299	0	0.0553	0	0	0	0	0	0	0	0	0	0	0	0	0
Ease of use	0.1061	0	0.0667	0	0	0.1333	0	0	0.0897	0	0.0896	0.0441	0	0.1333	0	0.0667	0.0735	0	0	0.0413	0.1667	0.1333	0.0556	0	0.1091	0
Intuitive use (affordances)	0	0	0.075	0.0758	0	0	0.1389	0.0769	0.1282	0	0.0746	0	0.0158	0.0667	0	0.07	0.0809	0	0.1944	0.0398	0.1389	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0	0	0.0833	0.0606	0	0	0	0	0	0	0	0.0515	0.0672	0	0.0662	0.0733	0	0	0	0	0	0	0	0.3	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0	0	0	0	0	0.0711	0	0.0882	0.0767	0	0	0	0.0384	0	0	0	0	0	0
Temperature considerations	0	0	0	0	0.0889	0.1556	0	0	0	0.1429	0	0	0	0	0	0	0.0662	0	0	0.037	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Iterative design	0	0	0	0	0	0	0	0	0	0	0	0	0.0751	0	0	0	0	0	0.2222	0.0085	0	0	0	0	0	0
Human factors / ergonomics considerations	0	0	0	0.0455	0.1111	0	0	0.141	0	0	0.1493	0.0588	0.0237	0	0.0735	0.06	0	0	0	0.0071	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	0.1212	0	0	0	0	0	0	0	0	0	0	0.0662	0.0277	0	0.0441	0.0633	0	0	0	0.01	0	0	0	0	0	0
Distribution of mass	0	0	0.0583	0	0	0	0	0	0.0769	0	0	0	0	0	0	0.05	0	0	0	0	0	0	0.0278	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0533	0	0	0	0.0512	0	0	0	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0567	0	0	0	0.0526	0	0	0	0	0	0
Repetition and fatigue	0	0	0	0.0909	0	0	0	0	0	0	0.1343	0.0735	0	0	0	0.0467	0.0441	0	0	0.0327	0	0	0	0	0	0
High speed motion	0	0	0.025	0	0	0	0	0.1538	0	0	0	0	0	0	0	0.0433	0	0	0	0	0.1944	0	0	0	0.1818	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0498	0	0	0	0	0	0
Abrasion of material on body	0	0	0.0167	0	0	0.1778	0.2222	0	0	0	0	0	0	0	0.0368	0	0	0	0.0833	0	0.2222	0.2667	0	0	0.0364	0.2
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0356	0	0	0	0	0	0
Replaceable parts	0	0	0	0.1515	0	0	0	0	0.141	0	0	0	0.083	0	0	0	0	0	0	0.0341	0	0	0	0	0	0.2667
Material strength	0	0	0.0333	0.1212	0	0	0	0	0	0	0	0	0.087	0	0.1103	0.08	0.1103	0	0	0.0299	0	0	0	0	0	0
Material elasticity	0.1515	0.0667	0.0417	0.1364	0	0.1111	0	0.0256	0	0.1786	0	0	0	0	0.1176	0	0.1176	0	0	0.0284	0	0	0	0	0	0.3333
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	0.0474	0	0	0	0	0	0	0.0028	0	0	0	0	0	0

Table 27: Exoskeleton C - After Use Properties Rank Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	0.93657629	0.036022165
Manufacturability	0.58172152	0.022373905
Weight	2.13332566	0.082050987
Active vs. passive exoskeleton	0.01849218	0.000711238
Variability within persons	0.26929206	0.010357387
Variability between persons	1.37833618	0.05301293
Number of parts vs. ability to actuate	0.0870758	0.003349069
Training motivation	0.07582223	0.00291624
How the exoskeleton attaches to the body	0.86470221	0.033257777
Statics	0	0
Dynamics	0.31552955	0.012135752
Range of motion / flexibility	1.29481799	0.049800692
Comfot	1.40491069	0.054035027
Every day carry vs. tool for training	0.86329031	0.033203473
Muscle memory and response	0.18800379	0.007230915
Sensory motor learning	0	0
Form factor	0.45368276	0.017449337
Anthropometry	0.10128398	0.003895538
Battery density	0	0
Environmental factors	0.03129445	0.001203633
Use as protection	0.04411765	0.001696833
Heat mitigation	0.92401961	0.035539216
Perspiration mitigation	0.61928637	0.023818706
Maximum push forces	0.06369369	0.002449757
Maximum pull forces	0.06560455	0.002523252
Formability to the body	0.92632088	0.035627726
Type of fule (battery/gas/etc.)	0.02418208	0.00093008
Degrees of freedom	0.60862871	0.023408797
Actual exertion	0.209234	0.008047461
Actual fatigue	0.71161359	0.027369753
Perceived exertion	0.05759963	0.00221537
Perceived fatigue	0.08518671	0.003276412
Ease of use	1.30890174	0.050342374
Intuitive use (affordances)	1.17592347	0.045227826
Lifespan of exoskeleton (standard conditions)	0.70211346	0.027004364
Lifespan of exoskeleton (extreme conditions)	0.27445503	0.010555963
Temperature considerations	0.49046241	0.018863939
Humidity considerations	0	0
Iterative design	0.30585589	0.011763688
Human factors / ergonomics considerations	0.67002576	0.025770222
Potential stress / strain on the joints / muscles	0.33246488	0.012787111
Distribution of mass	0.21303419	0.008193623
Center of mass	0.10454244	0.004020863
Sound	0.10929825	0.004203779
Repetition and fatigue	0.4222681	0.016241081
High speed motion	0.59844211	0.023017004
Effect of unequal loading	0	0
Psychophysics	0.04978663	0.00191487
Abrasion of material on body	1.26201723	0.048539124
Social impact	0.03556188	0.001367765
Replaceable parts	0.67635081	0.026013493
Material strength	0.57196219	0.021998546
Material elasticity	1.30861264	0.050331255
Biomechanics	0.05027578	0.001933684

Table 28: Exoskeleton C - Properties Rank Relative Change

	Normalized by Participant		
Design Metrics	Before	After	Relative Change
Cost	0.038703464	0.036022165	-0.002681299
Manufacturability	0.02566728	0.022373905	-0.003293375
Weight	0.068949149	0.082050987	0.013101838
Active vs. passive exoskeleton	0.006075175	0.000711238	-0.005363937
Variability within persons	0.014000309	0.010357387	-0.003642923
Variability between persons	0.030177182	0.05301293	0.022835749
Number of parts vs. ability to actuate	0.000430162	0.003349069	0.002918907
Training motivation	0.005186505	0.00291624	-0.002270266
How the exoskeleton attaches to the body	0.028481897	0.033257777	0.004775881
Statics	0.000151822	0	-0.000151822
Dynamics	0.002934479	0.012135752	0.009201272
Range of motion / flexibility	0.048978875	0.049800692	0.000821817
Comfot	0.055252159	0.054035027	-0.001217132
Every day carry vs. tool for training	0.020314736	0.033203473	0.012888738
Muscle memory and response	0.00830803	0.007230915	-0.001077115
Sensory motor learning	0.002084631	0	-0.002084631
Form factor	0.003458165	0.017449337	0.013991172
Anthropometry	0.015243748	0.003895538	-0.011348211
Battery density	0.001657939	0	-0.001657939
Environmental factors	0.004543288	0.001203633	-0.003339655
Use as protection	0.017905633	0.001696833	-0.016208801
Heat mitigation	0.029687573	0.035539216	0.005851643
Perspiration mitigation	0.012814303	0.023818706	0.011004404
Maximum push forces	0.002330271	0.002449757	0.000119487
Maximum pull forces	0.00242331	0.002523252	9.99415E-05
Formability to the body	0.036615954	0.035627726	-0.000988228
Type of fule (battery/gas/etc.)	0.001315789	0.00093008	-0.00038571
Degrees of freedom	0.027317533	0.023408797	-0.003908736
Actual exertion	0.006817158	0.008047461	0.001230303
Actual fatigue	0.024861911	0.027369753	0.002507842
Perceived exertion	0.005748407	0.00221537	-0.003533037
Perceived fatigue	0.008059193	0.003276412	-0.004782781
Ease of use	0.071922613	0.050342374	-0.021580238
Intuitive use (affordances)	0.034683073	0.045227826	0.010544753
Lifespan of exoskeleton (standard conditions)	0.017898078	0.027004364	0.009106286
Lifespan of exoskeleton (extreme conditions)	0.010629866	0.010555963	-7.39032E-05
Temperature considerations	0.033888242	0.018863939	-0.015024303
Humidity considerations	0.010057874	0	-0.010057874
Iterative design	0.004502491	0.011763688	0.007261197
Human factors / ergonomics considerations	0.023320895	0.025770222	0.002449327
Potential stress / strain on the joints / muscles	0.019565275	0.012787111	-0.006778164
Distribution of mass	0.007562127	0.008193623	0.000631496
Center of mass	0.008751873	0.004020863	-0.00473101
Sound	0.004080764	0.004203779	0.000123015
Repetition and fatigue	0.008811536	0.016241081	0.007429545
High speed motion	0.037334854	0.023017004	-0.014317849
Effect of unequal loading	0.005794348	0	-0.005794348
Psychophysics	0.001088057	0.00191487	0.000826814
Abrasion of material on body	0.039837034	0.048539124	0.00870209
Social impact	0.001062753	0.001367765	0.000305011
Replaceable parts	0.026977556	0.026013493	-0.000964064
Material strength	0.04171749	0.021998546	-0.019718945
Material elasticity	0.029599577	0.050331255	0.020731678
Biomechanics	0.004417594	0.001933684	-0.002483911

Exoskeleton D

Table 29: Exo D - Value Properties Relative Change

	Cost	Manufacturability	Weight	Active vs. passive	Variability within persons	Variability between persons	number of parts vs. ability	training motivation	how the exoskeleton	statics	dynamics	range of motion / flexibility	comfort	every day carry vs. tool for	muscle memory and	sensory motor learning	Form factor	anthropometry
Sum Before	12	9	17	3	7	9	4	4	16	3	5	17	20	4	2	3	3	4
Sum After	9	9	16	1	7	13	4	5	16	2	4	14	20	4	2	1	4	4
Relative Change	-3	0	-1	-2	0	4	0	1	0	-1	-1	-3	0	0	0	-2	1	0

	battery density	environmental factors	use as protection	heat mitigation	perspiration mitigation	maximum push forces	maximum pull forces	formatibilty to body	type of fuel	degrees of freedom	actual exertion	actual fatigue	perceived exertion	perceived fatigue	ease of use	intuitive use (affordances)	lifespan of exoskeleton	lifespan of exoskeleton
Sum Before	2	2	5	4	11	2	2	13	4	15	4	11	2	6	17	11	8	8
Sum After	1	1	3	1	1	2	2	7	1	12	5	4	2	2	14	11	8	6
Relative Change	-1	-1	-2	-3	##	0	0	-6	-3	-3	1	-7	0	-4	-3	0	0	-2

	temperature considerations	humidity considerations	iterative design	human factors /ergonomics	potential stress / strain on	distribution of mass	center of mass	sound	repetition and fatigue	high speed motion	effect of unequal loading	psychophyiscs	abrasion of material on	social impact	repalceable parts	material strength	material elasticity	biomechanics
Sum Before	5	2	5	9	10	7	3	4	4	5	1	2	8	2	10	10	4	4
Sum After	1	1	4	11	6	5	3	2	3	5	2	1	12	1	5	6	2	2
Relative Change	-4	-1	-1	2	-4	-2	0	-2	-1	0	1	-1	4	-1	-5	-4	-2	-2

Exoskeleton D yields a summed relative change of -74.

Table 30: Exoskeleton D - Initial Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	4	12	0	7	0	0	7	0	0	1	22	0	16	0	0	2	2	11	0	0	0	1	0	2
Manufacturability	0	0	5	0	0	0	10	2	8	0	0	0	10	0	0	0	0	1	15	6	0	0	0	0	9	0
Weight	11	3	6	0	0	6	0	0	6	0	1	2	15	5	5	0	4	0	14	7	0	2	2	0	0	3
Active vs. passive exoskeleton	0	0	0	0	0	0	8	0	0	0	0	18	0	0	0	0	0	0	0	9	0	0	0	22	0	0
Variability within persons	0	0	0	3	0	0	0	11	0	0	0	0	8	0	13	9	0	0	3	24	0	0	0	15	0	0
Variability between persons	0	0	0	0	6	4	0	12	0	0	0	0	9	0	12	10	0	0	4	23	3	0	0	0	0	0
Number of parts vs. ability to actuate	10	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0
Training motivation	4	1	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	51	0	0	0	13	0	0
How the exoskeleton attaches to the body	1	0	0	0	0	3	9	13	5	0	0	5	3	4	6	16	0	3	0	3	4	0	5	21	0	0
Statics	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	19	0	0	0	0	10	0
Dynamics	0	0	0	0	0	0	4	0	0	0	0	20	0	0	0	0	0	0	0	2	0	0	0	11	1	0
Range of motion / flexibility	2	0	3	2	1	5	3	0	4	2	0	21	12	6	4	0	1	0	0	21	2	0	0	5	3	0
Comfot	2	0	2	1	4	1	2	0	1	0	6	22	4	1	3	2	3	0	7	8	1	1	6	3	2	0
Every day carry vs. tool for training	0	2	0	0	0	0	0	0	11	0	0	0	0	0	0	14	10	0	0	50	0	0	1	0	0	0
Muscle memory and response	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0
Sensory motor learning	0	0	0	9	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	26	0	0	0	0	0	0
Form factor	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	15	0	0	0	28	0	0	0	0	0	0
Anthropometry	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	9	25	0	0	0	0	0	1
Battery density	0	0	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	30	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	29	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	1	0	0	0	6	0	0	0	0	0	0	0	52	0	0	7	2	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	13	0	0	0	36	0	0	0	20	0	6
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	35	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	34	0	0	0	0	0	0
Formability to the body	0	0	1	5	3	1	6	0	2	0	3	26	0	0	2	0	0	0	5	33	5	0	0	9	0	0
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	27	0	0	0	17	0	0	0	32	0	0	0	25	0	0
Degrees of freedom	0	0	0	6	0	0	1	0	30	4	9	14	13	0	0	1	5	0	6	38	6	0	3	8	7	0
Actual exertion	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	6	0	0	39	0	0	0	19	0	0
Actual fatigue	0	0	0	7	0	0	0	0	0	0	0	15	0	0	0	18	7	0	12	40	7	3	0	18	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	8	0	16	0	0	0	0	0	0	41	0	0	0	16	0	0
Perceived fatigue	0	0	0	8	0	0	0	0	0	0	10	0	17	0	0	0	0	0	13	42	0	0	0	17	0	0
Ease of use	5	4	7	0	0	0	0	0	0	0	7	3	1	3	1	3	8	0	0	5	0	4	4	10	8	0
Intuitive use (affordances)	0	5	0	0	0	0	0	4	9	0	6	0	2	2	0	20	9	0	16	12	0	0	0	12	0	0
Lifespan of exoskeleton (standard conditions)	0	0	0	0	0	0	7	3	10	0	0	13	19	0	14	21	0	0	10	10	0	0	0	14	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	5	0	0	0	12	20	0	15	19	0	0	11	11	0	0	0	0	0	4
Temperature considerations	0	0	0	0	0	0	0	7	0	5	0	11	0	0	0	0	0	0	0	43	0	0	0	4	0	0
Humidity considerations	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	44	0	0	0	0	0	0
Iterative design	8	0	0	0	0	2	0	6	0	0	0	0	21	0	0	0	0	0	0	13	0	0	0	0	0	0
Human factors / ergonomics considerations	6	0	8	0	0	0	5	10	0	0	0	10	11	0	8	24	0	0	0	4	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	7	0	9	0	0		0	14	0	0	0	0	5	0	7	23	0	0	0	46	0	0	0	24	6	0
Distribution of mass	0	0	0	0	0	0	0	0	12	0	4	29	14	0	9	5	0	0	0	14	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	6	0	16	0	0	0	6	0	0	0	47	0	0	0	0	0	0
Sound	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	7	0	0	0	53	0	0	0	0	0	0
Repetition and fatigue	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	8	2	0	0	15	0	0	0	0	0	0
High speed motion	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	4	0	0	0	54	8	0	0	0	5	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0
Psychophysics	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	0	0	0	0	0	0
Abrasion of material on body	9	0	0	0	0	6	0	0	0	0	2	0	0	0	11	0	0	0	1	49	0	5	0	0	4	0
Social impact	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	31	0	0	0	0	0	0
Replaceable parts	0	0	0	0	0	9	0	15	13	7	0	9	23	0	0	0	0	0	12	18	0	0	0	7	0	5
Material strength	0	0	10	0	0	0	0	9	14	0	0	7	24	0	10	22	0	0	13	16	0	0	0	6	0	0
Material elasticity	0	0	11	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0	0	17	0	0	0	23	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	11	28	6	0	0	0	0	0	0	2	0	0	0	0	0	0

Table 31: Exoskeleton D - Initial Properties Normalized by Relative Maximum Rank Value

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0	0	0.0606	0.1538	0	0.1346	0	0	0.053	0	0	0.0022	0.0733	0	0.1176	0	0	0.3333	0.0131	0.0076	0	0	0	0.0031	0	0.0952
Manufacturability	0	0	0.0758	0	0	0	0.1818	0.0167	0.0606	0	0	0	0.0333	0	0	0	0	0.1667	0.098	0.0042	0	0	0	0	0.1636	0
Weight	0.1692	0.2	0.0909	0	0	0.1154	0	0	0.0455	0	0.0149	0.0043	0.05	0.2381	0.0368	0	0.0727	0	0.0915	0.0048	0	0.1333	0.0714	0	0	0.1429
Active vs. passive exoskeleton	0	0	0	0	0	0	0.1455	0	0	0	0	0.0387	0	0	0	0	0	0	0	0.0062	0	0	0	0.0677	0	0
Variability within persons	0	0	0	0.0385	0	0	0	0.0917	0	0	0	0	0.0267	0	0.0956	0.03	0	0	0.0196	0.0166	0	0	0	0.0462	0	0
Variability between persons	0	0	0	0	0.2857	0.0769	0	0.1	0	0	0	0	0.03	0	0.0882	0.0333	0	0	0.0261	0.0159	0.0833	0	0	0	0	0
Number of parts vs. ability to actuate	0.1538	0	0	0	0.0952	0	0	0	0	0.0357	0	0	0	0	0	0	0	0	0	0.0152	0	0	0	0	0	0
Training motivation	0.0615	0.0667	0	0	0	0	0	0	0	0	0	0.0086	0	0	0	0	0	0	0	0.0353	0	0	0	0.04	0	0
How the exoskeleton attaches to the body	0.0154	0	0	0	0	0.0577	0.1636	0.1083	0.0379	0	0	0.0108	0.01	0.1905	0.0441	0.0533	0	0.5	0	0.0021	0.1111	0	0.1786	0.0646	0	0
Statics	0	0	0	0	0	0	0	0	0	0	0	0.0409	0	0	0	0	0	0	0	0.0132	0	0	0	0	0.1818	0
Dynamics	0	0	0	0	0	0	0.0727	0	0	0	0	0.043	0	0	0	0	0	0	0	0.0014	0	0	0	0.0338	0.0182	0
Range of motion / flexibility	0.0308	0	0.0455	0.0256	0.0476	0.0962	0.0545	0	0.0303	0.0714	0	0.0452	0.04	0.2857	0.0294	0	0.0182	0	0	0.0145	0.0556	0	0	0.0154	0.0545	0
Comfot	0.0308	0	0.0303	0.0128	0.1905	0.0192	0.0364	0	0.0076	0	0.0896	0.0473	0.0133	0.0476	0.0221	0.0067	0.0545	0	0.0458	0.0055	0.0278	0.0667	0.2143	0.0092	0.0364	0
Every day carry vs. tool for training	0	0.1333	0	0	0	0	0	0	0.0833	0	0	0	0	0	0	0.0467	0.1818	0	0	0.0346	0	0	0.0357	0	0	0
Muscle memory and response	0	0	0	0.1282	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0187	0	0	0	0	0	0
Sensory motor learning	0	0	0	0.1154	0	0	0	0	0	0	0	0.0495	0	0	0	0	0	0	0	0.018	0	0	0	0	0	0
Form factor	0	0	0	0	0.2381	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0	0.0194	0	0	0	0	0	0
Anthropometry	0	0	0	0	0	0	0	0	0	0	0	0	0.0233	0	0	0	0	0	0.0588	0.0173	0	0	0	0	0	0.0476
Battery density	0	0	0	0	0	0	0	0	0	0	0	0.0516	0	0	0	0	0	0	0	0.0208	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0.0538	0	0	0	0	0	0	0	0.0201	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0.0083	0	0	0	0.0129	0	0	0	0	0	0	0	0.036	0	0	0.25	0.0062	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0.1071	0	0	0	0	0	0.0433	0	0	0	0.0249	0	0	0	0.0615	0	0.2857
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0256	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0367	0	0	0	0.0242	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0	0	0	0.0235	0	0	0	0	0	0
Formability to the body	0	0	0.0152	0.0641	0.1429	0.0192	0.1091	0	0.0152	0	0.0448	0.0559	0	0	0.0147	0	0	0	0.0327	0.0229	0.1389	0	0	0.0277	0	0
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0.0581	0	0	0	0.0567	0	0	0	0.0222	0	0	0	0.0769	0	0
Degrees of freedom	0	0	0	0.0769	0	0	0.0182	0	0.2273	0.1429	0.1343	0.0301	0.0433	0	0	0.0033	0.0909	0	0.0392	0.0263	0.1667	0	0.1071	0.0246	0.1273	0
Actual exertion	0	0	0	0	0	0	0	0	0	0	0	0	0.06	0	0	0	0.1091	0	0	0.027	0	0	0	0.0585	0	0
Actual fatigue	0	0	0	0.0897	0	0	0	0	0	0	0	0.0323	0	0	0	0.06	0.1273	0	0.0784	0.0277	0.1944	0.2	0	0.0554	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	0.1194	0	0.0533	0	0	0	0	0	0	0.0284	0	0	0	0.0492	0	0
Perceived fatigue	0	0	0	0.1026	0	0	0	0	0	0	0.1493	0	0.0567	0	0	0	0	0	0.085	0.0291	0	0	0	0.0523	0	0
Ease of use	0.0769	0.2667	0.1061	0	0	0	0	0	0	0	0.1045	0.0065	0.0033	0.1429	0.0074	0.01	0.1455	0	0	0.0035	0	0.2667	0.1429	0.0308	0.1455	0
Intuitive use (affordances)	0	0.3333	0	0	0	0	0	0.0333	0.0682	0	0.0896	0	0.0067	0.0952	0	0.0667	0.1636	0	0.1046	0.0083	0	0	0	0.0369	0	0
Lifespan of exoskeleton (standard conditions)	0	0	0	0	0	0	0.1273	0.025	0.0758	0	0	0.028	0.0633	0	0.1029	0.07	0	0	0.0654	0.0069	0	0	0	0.0431	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0.0417	0	0	0	0.0258	0.0667	0	0.1103	0.0633	0	0	0.0719	0.0076	0	0	0	0	0	0.1905
Temperature considerations	0	0	0	0	0	0	0	0.0583	0	0.1786	0	0.0237	0	0	0	0	0	0	0	0.0298	0	0	0	0.0123	0	0
Humidity considerations	0	0	0	0	0	0	0	0.0667	0	0	0	0	0	0	0	0	0	0	0	0.0305	0	0	0	0	0	0
Iterative design	0.1231	0	0	0	0	0.0385	0	0.05	0	0	0	0	0.07	0	0	0	0	0	0	0.009	0	0	0	0	0	0
Human factors / ergonomics considerations	0.0923	0	0.1212	0	0	0	0.0909	0.0833	0	0	0	0.0215	0.0367	0	0.0588	0.08	0	0	0	0.0028	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	0.1077	0	0.1364	0	0	0	0	0.1167	0	0	0	0	0.0167	0	0.0515	0.0767	0	0	0	0.0319	0	0	0	0.0738	0.1091	0
Distribution of mass	0	0	0	0	0	0	0	0	0.0909	0	0.0597	0.0624	0.0467	0	0.0662	0.0167	0	0	0	0.0097	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0	0.2143	0	0.0344	0	0	0	0.02	0	0	0	0.0325	0	0	0	0	0	0
Sound	0	0	0	0	0	0.1538	0	0	0	0	0	0	0	0	0	0.0233	0	0	0	0.0367	0	0	0	0	0	0
Repetition and fatigue	0	0	0	0.0513	0	0	0	0	0	0	0	0	0	0	0	0.0267	0.0364	0	0	0.0104	0	0	0	0	0	0
High speed motion	0	0	0	0	0	0	0	0	0	0	0	0.0366	0	0	0	0.0133	0	0	0	0.0374	0.2222	0	0	0	0.0909	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0104	0	0	0	0	0	0
Psychophysics	0	0	0	0.141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0312	0	0	0	0	0	0
Abrasion of material on body	0.1385	0	0	0	0	0.1154	0	0	0	0	0.0299	0	0	0	0.0809	0	0	0	0.0065	0.0339	0	0.3333	0	0	0.0727	0
Social impact	0	0	0	0	0	0	0	0	0	0	0	0.0172	0	0	0	0	0	0	0	0.0215	0	0	0	0	0	0
Replaceable parts	0	0	0	0	0	0.1731	0	0.125	0.0985	0.25	0	0.0194	0.0767	0	0	0	0	0	0.0784	0.0125	0	0	0	0.0215	0	0.2381
Material strength	0	0	0.1515	0	0	0	0	0.075	0.1061	0	0	0.0151	0.08	0	0.0735	0.0733	0	0	0.085	0.0111	0	0	0	0.0185	0	0
Material elasticity	0	0	0.1667	0	0	0	0	0	0	0	0	0.0645	0	0	0	0	0	0	0	0.0118	0	0	0	0.0708	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0.1642	0.0602	0.02	0	0	0	0	0	0	0.0014	0	0	0	0	0	0

Table 32: Exoskeleton D - Initial Properties Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	1.04756681	0.040291031
Manufacturability	0.80067919	0.030795353
Weight	1.48176265	0.056990871
Active vs. passive exoskeleton	0.25808922	0.009926508
Variability within persons	0.36476529	0.014029434
Variability between persons	0.73961109	0.02844658
Number of parts vs. ability to actuate	0.30003399	0.011539769
Training motivation	0.21212584	0.008158686
How the exoskeleton attaches to the body	1.54798075	0.059537721
Statics	0.23583629	0.009070627
Dynamics	0.16915104	0.006505809
Range of motion / flexibility	0.96041247	0.036938941
Comfot	1.01424288	0.039009342
Every day carry vs. tool for training	0.51549184	0.019826609
Muscle memory and response	0.14690319	0.005650123
Sensory motor learning	0.18285252	0.007032789
Form factor	0.30748582	0.011826378
Anthropometry	0.14708893	0.005657267
Battery density	0.07238853	0.002784174
Environmental factors	0.07384654	0.002840252
Use as protection	0.31340149	0.012053903
Heat mitigation	0.52265969	0.020102296
Perspiration mitigation	0.02562327	0.00098551
Maximum push forces	0.06090489	0.002342496
Maximum pull forces	0.06354571	0.002444066
Formability to the body	0.70309452	0.027042097
Type of fule (battery/gas/etc.)	0.21381492	0.008223651
Degrees of freedom	1.25847552	0.048402905
Actual exertion	0.25456076	0.009790798
Actual fatigue	0.86523564	0.033278294
Perceived exertion	0.25036044	0.009629248
Perceived fatigue	0.47484539	0.018263284
Ease of use	1.45878773	0.05610722
Intuitive use (affordances)	1.00641701	0.038708346
Lifespan of exoskeleton (standard conditions)	0.60762341	0.023370131
Lifespan of exoskeleton (extreme conditions)	0.57775658	0.022221407
Temperature considerations	0.30264676	0.01164026
Humidity considerations	0.09713758	0.003736061
Iterative design	0.29054123	0.011174663
Human factors / ergonomics considerations	0.58752789	0.022597227
Potential stress / strain on the joints / muscles	0.72031955	0.027704598
Distribution of mass	0.35218127	0.013545433
Center of mass	0.30124279	0.011586261
Sound	0.21388309	0.008226273
Repetition and fatigue	0.12470017	0.00479616
High speed motion	0.40041991	0.015400766
Effect of unequal loading	0.01038781	0.000399531
Psychophysics	0.17218908	0.006622657
Abrasion of material on body	0.81110932	0.031196512
Social impact	0.03867245	0.001487402
Replaceable parts	1.09311372	0.042042836
Material strength	0.68900146	0.026500056
Material elasticity	0.31372488	0.012066342
Biomechanics	0.2457792	0.009453046

Table 33: Exoskeleton D - After Use Properties Ranking

	Participants																									
Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	18	0	0	0	0	0	0	0	7	0	0	1	0	0	12	0	0	1	0	1	0	0	0	4	3	0
Manufacturability	17	0	0	0	0	0	7	6	8	0	0	0	9	0	0	0	0	2	0	3	0	0	7	0	4	0
Weight	16	4	0	8	0	5	6	0	15	5	8	2	20	0	13	0	7	0	0	9	1	1	0	0	5	0
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0
Variability within persons	12	0	0	4	0	3	0	12	0	0	0	0	3	0	0	0	0	0	1	12	0	0	0	0	0	0
Variability between persons	13	0	0	0	4	1	0	13	0	3	0	0	4	0	5	4	0	3	2	11	2	0	0	0	0	0
Number of parts vs. ability to actuate	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	6	0	0	0
Training motivation	2	1	0	0	5	0	0	0	0	0	0	4	8	0	0	0	0	0	0	21	0	0	0	0	0	0
How the exoskeleton attaches to the body	1	5	0	0	0	2	8	11	5	0	2	3	0	0	11	0	0	0	4	20	0	1	5	0	1	7
Statics	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0
Dynamics	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	5	0	0	0	17	0	0	0	0	7	0
Range of motion / flexibility	0	3	1	2	0	2	0	0	4	0	0	0	14	4	2	6	5	0	0	19	3	0	0	1	6	0
Comfot	5	0	2	1	3	4	4	0	3	0	3	10	2	1	3	3	6	4	0	6	0	0	1	3	2	2
Every day carry vs. tool for training	0	2	0	0	0	0	0	0	9	0	0	0	0	0	4	0	0	0	0	16	0	0	0	0	0	0
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	46	0	0	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0
Form factor	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	47	4	0	0	0	0	0
Anthropometry	0	0	0	0	0	0	0	0	0	4	0	0	5	0	0	0	0	0	0	14	0	0	0	0	0	1
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	1	0	0	0	5	0	0	0	0	0	0	0	48	0	0	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	31	0	0	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	33	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	34	0	0	0	0	0	0
Formability to the body	0	0	0	3	0	2	0	0	2	0	9	0	0	0	7	0	0	0	0	35	0	0	0	0	0	4
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	36	0	0	0	0	0	0
Degrees of freedom	3	0	0	5	0	0	1	0	6	1	0	0	15	0	0	1	3	0	0	55	0	0	2	2	10	0
Actual exertion	7	0	0	0	0	0	0	0	0	0	0	0	19	0	0	0	4	0	0	23	0	0	0	0	0	3
Actual fatigue	8	0	0	6	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	24	0	4	0	0	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0
Perceived fatigue	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0	0	0	0	26	0	0	0	0	0	0
Ease of use	6	0	3	0	0	2	0	0	11	0	6	6	1	3	0	2	1	0	5	4	0	3	3	0	0	0
Intuitive use (affordances)	0	0	0	0	0	1	0	5	12	0	5	7	6	2	6	17	2	0	0	28	0	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	9	0	0	0	0	0	0	2	13	0	0	8	21	0	0	19	0	0	6	27	0	0	0	0	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	3	14	0	0	0	22	0	0	18	0	0	7	29	0	0	0	0	0	0
Temperature considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	44	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	0	0	0	0	0	0
Iterative design	4	0	0	0	0	0	0	10	0	0	0	0	23	0	0	0	0	0	0	43	0	0	0	0	0	0
Human factors / ergonomics considerations	10	0	4	7	0	0	3	9	0	2	0	9	13	0	10	11	0	0	0	7	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	11	0	5	0	0	0	0	8	0	0	0	0	11	0	0	12	0	0	0	8	0	0	0	0	0	0
Distribution of mass	0	0	0	0	0	0	0	0	0	0	4	0	16	0	0	13	0	0	0	42	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	10	0	7	0	0	0	0	14	0	0	0	41	0	0	0	0	0	
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	54	0	0	0	0	0	0
Repetition and fatigue	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	8	0	0	53	0	0	0	0	0	0
High speed motion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	9	0	0	0	49	5	0	0	0	8	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	0	0	0	40	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	0	0	0	0	0	0
Abrasion of material on body	0	0	0	0	1	4	5	0	1	0	1	0	0	0	14	16	0	0	3	50	0	0	4	0	9	5
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	51	0	0	0	0	0	0
Replaceable parts	15	0	0	0	0	0	0	7	0	0	0	0	24		0	0	0	0	0	39	0	0	0	0	0	6
Material strength	0	0	0	0	0	0	0	4	0	0	0	0	25	0	8	10	0	0	0	37	0	0	0	0	0	0
Material elasticity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	38	0	0	0	0	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	2	0	0	0	0	0	0

Table 34: Exoskeleton D - After Use Properties Normalized by Relative Maximum Rank Value

Design Metrics	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Cost	0.1053	0	0	0	0	0	0	0	0.0583	0	0	0.0182	0	0	0.1143	0	0	0.1	0	0.0007	0	0	0	0.4	0.0545	0
Manufacturability	0.0994	0	0	0	0	0	0.1273	0.0659	0.0667	0	0	0	0.0286	0	0	0	0	0.2	0	0.002	0	0	0.25	0	0.0727	0
Weight	0.0936	0.2667	0	0.2222	0	0.1923	0.1091	0	0.125	0.3333	0.1778	0.0364	0.0635	0	0.1238	0	0.1944	0	0	0.0059	0.0667	0.1111	0	0	0.0909	0
Active vs. passive exoskeleton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0065	0	0	0	0	0	0
Variability within persons	0.0702	0	0	0.1111	0	0.1154	0	0.1319	0	0	0	0	0.0095	0	0	0	0	0	0.0357	0.0078	0	0	0	0	0	0
Variability between persons	0.076	0	0	0	0.1905	0.0385	0	0.1429	0	0.2	0	0	0.0127	0	0.0476	0.02	0	0.3	0.0714	0.0072	0.1333	0	0	0	0	0
Number of parts vs. ability to actuate	0.0819	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0143	0	0	0.2143	0	0	0
Training motivation	0.0117	0.0667	0	0	0.2381	0	0	0	0	0	0	0.0727	0.0254	0	0	0	0	0	0	0.0137	0	0	0	0	0	0
How the exoskeleton attaches to the body	0.0058	0.3333	0	0	0	0.0769	0.1455	0.1209	0.0417	0	0.0444	0.0545	0	0	0.1048	0	0	0	0.1429	0.013	0	0.1111	0.1786	0	0.0182	0.25
Statics	0	0	0	0	0	0	0.1636	0	0	0	0	0	0	0	0	0	0	0	0	0.0117	0	0	0	0	0	0
Dynamics	0	0	0	0	0	0	0.1818	0	0	0	0	0	0	0	0	0.025	0	0	0	0.0111	0	0	0	0	0.1273	0
Range of motion / flexibility	0	0.2	0.0667	0.0556	0	0.0769	0	0	0.0333	0	0	0	0.0444	0.4	0.019	0.03	0.1389	0	0	0.0124	0.2	0	0	0.1	0.1091	0
Comfot	0.0292	0	0.1333	0.0278	0.1429	0.1538	0.0727	0	0.025	0	0.0667	0.1818	0.0063	0.1	0.0286	0.015	0.1667	0.4	0	0.0039	0	0	0.0357	0.3	0.0364	0.0714
Every day carry vs. tool for training	0	0.1333	0	0	0	0	0	0	0.075	0	0	0	0	0	0.0381	0	0	0	0	0.0104	0	0	0	0	0	0
Muscle memory and response	0	0	0	0	0	0	0	0	0	0	0	0	0.0222	0	0	0	0	0	0	0.03	0	0	0	0	0	0
Sensory motor learning	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0085	0	0	0	0	0	0
Form factor	0	0	0	0	0.0952	0	0.0364	0	0	0	0	0	0	0	0	0	0	0	0	0.0306	0.2667	0	0	0	0	0
Anthropometry	0	0	0	0	0	0	0	0	0	0.2667	0	0	0.0159	0	0	0	0	0	0	0.0091	0	0	0	0	0	0.0357
Battery density	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0098	0	0	0	0	0	0
Environmental factors	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0195	0	0	0	0	0	0
Use as protection	0	0	0	0	0	0	0	0.011	0	0	0	0.0909	0	0	0	0	0	0	0	0.0313	0	0	0	0	0	0
Heat mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0202	0	0	0	0	0	0
Perspiration mitigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0208	0	0	0	0	0	0
Maximum push forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.035	0	0	0	0.0215	0	0	0	0	0	0
Maximum pull forces	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.04	0	0	0	0.0221	0	0	0	0	0	0
Formability to the body	0	0	0	0.0833	0	0.0769	0	0	0.0167	0	0.2	0	0	0	0.0667	0	0	0	0	0.0228	0	0	0	0	0	0.1429
Type of fule (battery/gas/etc.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0235	0	0	0	0	0	0
Degrees of freedom	0.0175	0	0	0.1389	0	0	0.0182	0	0.05	0.0667	0	0	0.0476	0	0	0.005	0.0833	0	0	0.0358	0	0	0.0714	0.2	0.1818	0
Actual exertion	0.0409	0	0	0	0	0	0	0	0	0	0	0	0.0603	0	0	0	0.1111	0	0	0.015	0	0	0	0	0	0.1071
Actual fatigue	0.0468	0	0	0.1667	0	0	0	0	0	0	0	0	0.054	0	0	0	0	0	0	0.0156	0	0.4444	0	0	0	0
Perceived exertion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0163	0	0	0	0	0	0
Perceived fatigue	0	0	0	0	0	0	0	0	0	0	0	0	0.0571	0	0	0	0	0	0	0.0169	0	0	0	0	0	0
Ease of use	0.0351	0	0.2	0	0	0.0769	0	0	0.0917	0	0.1333	0.1091	0.0032	0.3	0	0.01	0.0278	0	0.1786	0.0026	0	0.3333	0.1071	0	0	0
Intuitive use (affordances)	0	0	0	0	0	0.0385	0	0.0549	0.1	0	0.1111	0.1273	0.019	0.2	0.0571	0.085	0.0556	0	0	0.0182	0	0	0	0	0	0
Lifespan of exoskeleton (standard conditions)	0.0526	0	0	0	0	0	0	0.022	0.1083	0	0	0.1455	0.0667	0	0	0.095	0	0	0.2143	0.0176	0	0	0	0	0	0
Lifespan of exoskeleton (extreme conditions)	0	0	0	0	0	0	0	0.033	0.1167	0	0	0	0.0698	0	0	0.09	0	0	0.25	0.0189	0	0	0	0	0	0
Temperature considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0287	0	0	0	0	0	0
Humidity considerations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0293	0	0	0	0	0	0
Iterative design	0.0234	0	0	0	0	0	0	0.1099	0	0	0	0	0.073	0	0	0	0	0	0	0.028	0	0	0	0	0	0
Human factors / ergonomics considerations	0.0585	0	0.2667	0.1944	0	0	0.0545	0.0989	0	0.1333	0	0.1636	0.0413	0	0.0952	0.055	0	0	0	0.0046	0	0	0	0	0	0
Potential stress / strain on the joints / muscles	0.0643	0	0.3333	0	0	0	0	0.0879	0	0	0	0	0.0349	0	0	0.06	0	0	0	0.0052	0	0	0	0	0	0
Distribution of mass	0	0	0	0	0	0	0	0	0	0	0.0889	0	0.0508	0	0	0.065	0	0	0	0.0274	0	0	0	0	0	0
Center of mass	0	0	0	0	0	0	0	0	0.0833	0	0.1556	0	0	0	0	0.07	0	0	0	0.0267	0	0	0	0	0	0
Sound	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.075	0	0	0	0.0352	0	0	0	0	0	0
Repetition and fatigue	0	0	0	0	0.2857	0	0	0	0	0	0	0	0	0	0	0	0.2222	0	0	0.0345	0	0	0	0	0	0
High speed motion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0095	0.045	0	0	0	0.0319	0.3333	0	0	0	0.1455	0
Effect of unequal loading	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05	0	0	0	0.0261	0	0	0	0	0	0
Psychophysics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0339	0	0	0	0	0	0
Abrasion of material on body	0	0	0	0	0.0476	0.1538	0.0909	0	0.0083	0	0.0222	0	0	0	0.1333	0.08	0	0	0.1071	0.0326	0	0	0.1429	0	0.1636	0.1786
Social impact	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0332	0	0	0	0	0	0
Replaceable parts	0.0877	0	0	0	0	0	0	0.0769	0	0	0	0	0.0762	0	0	0	0	0	0	0.0254	0	0	0	0	0	0.2143
Material strength	0	0	0	0	0	0	0	0.044	0	0	0	0	0.0794	0	0.0762	0.05	0	0	0	0.0241	0	0	0	0	0	0
Material elasticity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0857	0	0	0	0	0.0248	0	0	0	0	0	0
Biomechanics	0	0	0	0	0	0	0	0	0	0	0	0	0.0381	0	0	0	0	0	0	0.0013	0	0	0	0	0	0

Table 35: Exoskeleton D - After Use Properties Rank Normalized by Relative Maximum Rank Value and Number of Participants

Design Metrics	Sum Rank	Normalized by Participant
Cost	0.851260944	0.032740806
Manufacturability	0.912541763	0.03509776
Weight	2.212625582	0.085100984
Active vs. passive exoskeleton	0.006514658	0.000250564
Variability within persons	0.481594982	0.018522884
Variability between persons	1.240063752	0.04769476
Number of parts vs. ability to actuate	0.310489307	0.011941896
Training motivation	0.428262691	0.016471642
How the exoskeleton attaches to the body	1.641607317	0.063138743
Statics	0.175362748	0.006744721
Dynamics	0.345165828	0.013275609
Range of motion / flexibility	1.486328344	0.057166475
Comfot	1.997268885	0.076818034
Every day carry vs. tool for training	0.256852024	0.009878924
Muscle memory and response	0.052189649	0.002007294
Sensory motor learning	0.008469055	0.000325733
Form factor	0.428887291	0.016495665
Anthropometry	0.327374489	0.012591327
Battery density	0.009771987	0.000375846
Environmental factors	0.019543974	0.000751691
Use as protection	0.13316846	0.005121864
Heat mitigation	0.02019544	0.000776748
Perspiration mitigation	0.020846906	0.000801804
Maximum push forces	0.056498371	0.002173014
Maximum pull forces	0.062149837	0.002390378
Formability to the body	0.609248189	0.023432623
Type of fule (battery/gas/etc.)	0.023452769	0.00090203
Degrees of freedom	0.916310986	0.03524273
Actual exertion	0.334490814	0.012865031
Actual fatigue	0.72749817	0.027980699
Perceived exertion	0.016286645	0.000626409
Perceived fatigue	0.074080968	0.002849268
Ease of use	1.608707569	0.061873368
Intuitive use (affordances)	0.866777506	0.033337596
Lifespan of exoskeleton (standard conditions)	0.721939437	0.027766901
Lifespan of exoskeleton (extreme conditions)	0.578367478	0.022244903
Temperature considerations	0.028664495	0.001102481
Humidity considerations	0.029315961	0.001127537
Iterative design	0.234310825	0.009011955
Human factors / ergonomics considerations	1.166075091	0.044849042
Potential stress / strain on the joints / muscles	0.585705268	0.022527126
Distribution of mass	0.232044103	0.008924773
Center of mass	0.335598987	0.012907653
Sound	0.110179153	0.00423766
Repetition and fatigue	0.542464195	0.020864008
High speed motion	0.565233512	0.02173975
Effect of unequal loading	0.076058632	0.002925332
Psychophysics	0.033876221	0.001302932
Abrasion of material on body	1.161044263	0.044655549
Social impact	0.033224756	0.001277875
Replaceable parts	0.480525732	0.018481759
Material strength	0.273615834	0.010523686
Material elasticity	0.110469986	0.004248846
Biomechanics	0.03939817	0.001515314

Table 36: Exoskeleton D - Properties Rank Relative Change

	Normalized by Participant		
Design Metrics	Before	After	Relative Change
Cost	0.040291031	0.032740806	-0.007550226
Manufacturability	0.030795353	0.03509776	0.004302407
Weight	0.056990871	0.085100984	0.028110113
Active vs. passive exoskeleton	0.009926508	0.000250564	-0.009675945
Variability within persons	0.014029434	0.018522884	0.004493449
Variability between persons	0.02844658	0.04769476	0.019248179
Number of parts vs. ability to actuate	0.011539769	0.011941896	0.000402128
Training motivation	0.008158686	0.016471642	0.008312956
How the exoskeleton attaches to the body	0.059537721	0.063138743	0.003601022
Statics	0.009070627	0.006744721	-0.002325906
Dynamics	0.006505809	0.013275609	0.0067698
Range of motion / flexibility	0.036938941	0.057166475	0.020227534
Comfot	0.039009342	0.076818034	0.037808692
Every day carry vs. tool for training	0.019826609	0.009878924	-0.009947685
Muscle memory and response	0.005650123	0.002007294	-0.003642828
Sensory motor learning	0.007032789	0.000325733	-0.006707056
Form factor	0.011826378	0.016495665	0.004669287
Anthropometry	0.005657267	0.012591327	0.00693406
Battery density	0.002784174	0.000375846	-0.002408328
Environmental factors	0.002840252	0.000751691	-0.00208856
Use as protection	0.012053903	0.005121864	-0.006932039
Heat mitigation	0.020102296	0.000776748	-0.019325548
Perspiration mitigation	0.00098551	0.000801804	-0.000183706
Maximum push forces	0.002342496	0.002173014	-0.000169482
Maximum pull forces	0.002444066	0.002390378	-5.36873E-05
Formability to the body	0.027042097	0.023432623	-0.003609474
Type of fule (battery/gas/etc.)	0.008223651	0.00090203	-0.007321621
Degrees of freedom	0.048402905	0.03524273	-0.013160174
Actual exertion	0.009790798	0.012865031	0.003074233
Actual fatigue	0.033278294	0.027980699	-0.005297595
Perceived exertion	0.009629248	0.000626409	-0.009002838
Perceived fatigue	0.018263284	0.002849268	-0.015414016
Ease of use	0.05610722	0.061873368	0.005766148
Intuitive use (affordances)	0.038708346	0.033337596	-0.00537075
Lifespan of exoskeleton (standard conditions)	0.023370131	0.027766901	0.00439677
Lifespan of exoskeleton (extreme conditions)	0.022221407	0.022244903	2.34961E-05
Temperature considerations	0.01164026	0.001102481	-0.010537779
Humidity considerations	0.003736061	0.001127537	-0.002608524
Iterative design	0.011174663	0.009011955	-0.002162708
Human factors / ergonomics considerations	0.022597227	0.044849042	0.022251815
Potential stress / strain on the joints / muscles	0.027704598	0.022527126	-0.005177472
Distribution of mass	0.013545433	0.008924773	-0.00462066
Center of mass	0.011586261	0.012907653	0.001321392
Sound	0.008226273	0.00423766	-0.003988613
Repetition and fatigue	0.00479616	0.020864008	0.016067847
High speed motion	0.015400766	0.02173975	0.006338985
Effect of unequal loading	0.000399531	0.002925332	0.002525801
Psychophysics	0.006622657	0.001302932	-0.005319725
Abrasion of material on body	0.031196512	0.044655549	0.013459036
Social impact	0.001487402	0.001277875	-0.000209527
Replaceable parts	0.042042836	0.018481759	-0.023561077
Material strength	0.026500056	0.010523686	-0.01597637
Material elasticity	0.012066342	0.004248846	-0.007817496
Biomechanics	0.009453046	0.001515314	-0.007937732

Comparing Property Ranks for All Exoskeletons

It is now important to look at how the four exoskeletons compare to one another both before and after use. This analysis will help us understand which exoskeleton can quantitatively be considered the best.

Table 37: All Exoskeletons - Initial Property Rank Coded by Best Value

Design Metrics	Exoskeleton A	Exoskeleton B	Exoskeleton C	Exoskeleton D
Cost	0.026788596	0.036554102	0.038703464	0.040291031
Manufacturability	0.035865979	0.028943355	0.02566728	0.030795353
Weight	0.048686598	0.037196471	0.068949149	0.056990871
Active vs. passive exoskeleton	0.007634769	0.000158495	0.006075175	0.009926508
Variability within persons	0.023530836	0.026330851	0.014000309	0.014029434
Variability between persons	0.02374465	0.02484147	0.030177182	0.02844658
number of parts vs. ability to actuate	0.00952198	0.014233091	0.000430162	0.011539769
training motivation	0.015538991	0.010541856	0.005186505	0.008158686
how the exoskeleton attaches to the body	0.092292979	0.058980817	0.028481897	0.059537721
statics	0.00471887	0.003567589	0.000151822	0.009070627
dynamics	0.004828843	0.008377417	0.002934479	0.006505809
range of motion / flexibility	0.04686131	0.052944174	0.048978875	0.036938941
comfort	0.052068148	0.045851041	0.055252159	0.039009342
every day carry vs. tool for training	0.015410807	0.024807156	0.020314736	0.019826609
muscle memory and response	0.007275886	0.002526583	0.00830803	0.005650123
sensory motor learning	0.001335113	0.002596458	0.002084631	0.007032789
Form factor	0.011213944	0.014658216	0.003458165	0.011826378
anthropometry	0.014699575	0.015546456	0.015243748	0.005657267
battery density	0.001206737	0.000475486	0.001657939	0.002784174
environmental factors	0.00292303	0.001006371	0.004543288	0.002840252
use as protection	0.013168465	0.008262503	0.017905633	0.012053903
heat mitigation	0.030908513	0.002360417	0.029687573	0.020102296
perspiration mitigation	0.007832892	0.002343373	0.012814303	0.00098551
maximum push forces	0.004349173	0.002582529	0.002330271	0.002342496
maximum pull forces	0.004470144	0.002729152	0.00242331	0.002444066
formatibilty to body	0.032090997	0.043685726	0.036615954	0.027042097
type of fuel (battery/gas/etc.)	0.003778348	7.92477E-05	0.001315789	0.008223651
degrees of freedom	0.040002343	0.055163909	0.027317533	0.048402905
actual exertion	0.005843647	0.009959563	0.006817158	0.009790798
actual fatigue	0.021793506	0.031955235	0.024861911	0.033278294
perceived exertion	0.007500325	0.008249527	0.005748407	0.009629248
perceived fatigue	0.016634045	0.018345561	0.008059193	0.018263284
ease of use	0.050843819	0.036164718	0.071922613	0.05610722
intuitive use (affordances)	0.022675715	0.024982565	0.034683073	0.038708346
lifespan of exoskeleton (standard conditions)	0.024340566	0.038250421	0.017898078	0.023370131
lifespan of exoskeleton (extreme conditions)	0.014339854	0.028759504	0.010629866	0.022221407
temperature considerations	0.032163866	0.001532987	0.033888242	0.01164026
humidity considerations	0.006958771	0.000950972	0.010057874	0.003736061
iterative design	0.004601797	0.007173432	0.004502491	0.011174663
human factors /ergonomics consideerations	0.031014019	0.038011831	0.023320895	0.022597227
potential stress / strain on joints / muscles	0.02165792	0.032442324	0.019565275	0.027704598
distribution of mass	0.008955868	0.018014042	0.007562127	0.013545433
center of mass	0.006467847	0.014760731	0.008751873	0.011586261
sound	0.003685494	0.003945385	0.004080764	0.008226273
repetition and fatigue	0.017810331	0.019848659	0.008811536	0.00479616
high speed motion	0.011910206	0.014759795	0.037334854	0.015400766
effect of unequal loading	0.002719572	0.003549879	0.005794348	0.000399531
psychophyiscs	0.003134187	0.002443067	0.001088057	0.006622657
abrasion of material on body	0.041039402	0.019079104	0.039837034	0.031196512
social impact	0.002932596	0.002220666	0.001062753	0.001487402
repalceable parts	0.018315349	0.038102629	0.026977556	0.042042836
material strength	0.030539921	0.039875936	0.04171749	0.026500056
material elasticity	0.005627648	0.018091703	0.029599577	0.012066342
biomechanics	0.003745214	0.00118545	0.004417594	0.009453046

The number of categories each exoskeleton is ranked best in can now be determined. The sum of best ranked categories can be seen in the following table.

Table 38 Sum of Initial Properties Best Value

Exoskeleton	Sum of Metrics Highest Ranked
A (Control)	9
B (Experimental)	18
C (Control)	14
D (Experimental)	16

It can be seen that both of the experimental scored higher than their control counterparts individually as well as in a group. While this information is useful, it is also important to consider the 55 metrics interdependency ranks. The metrics are now broken into five categories and color coded to match their category of importance.

Table 39: All Exoskeletons - Initial Property Rank Coded by Best Value and Compared to Interdependencies

Design Metrics	Interdpendency Rank	Exoskeleton A	Exoskeleton B	Exoskeleton C	Exoskeleton D
Cost	1	4	3	2	1
Manufacturability	26	1	3	4	2
Weight	14	3	4	2	1
Active vs. passive exoskeleton	19	2	4	3	1
Variability within persons	13	2	1	4	3
Variability between persons	9	4	3	1	2
number of parts vs. ability to actuate	20	3	1	4	2
training motivation	43	1	2	4	3
how the exoskeleton attaches to the body	4	1	3	4	2
statics	37	2	3	4	1
dynamics	35	3	1	4	2
range of motion / flexibility	3	3	1	2	4
comfort	10	2	3	1	4
every day carry vs. tool for training	42	4	1	2	3
muscle memory and response	48	2	4	1	3
sensory motor learning	49	4	2	3	1
Form factor	11	3	1	4	2
anthropometry	5	3	1	2	4
battery density	17	3	4	2	1
environmental factors	21	2	4	1	3
use as protection	43	2	4	1	3
heat mitigation	27	1	4	2	3
perspiration mitigation	23	2	3	1	4
maximum push forces	44	1	2	4	3
maximum pull forces	41	1	2	3	4
formatibilty to body	7	3	1	2	4
type of fuel (battery/gas/etc.)	34	2	4	3	1
degrees of freedom	22	3	1	4	2
actual exertion	31	4	1	3	2
actual fatigue	30	4	2	3	1
perceived exertion	45	3	2	4	1
perceived fatigue	46	3	1	4	2
ease of use	29	3	4	1	2
intuitive use (affordances)	54	4	3	2	1
lifespan of exoskeleton (standard conditions)	15	2	1	4	3
lifespan of exoskeleton (extreme conditions)	33	3	1	4	2
temperature considerations	32	2	4	1	3
humidity considerations	38	2	4	1	3
iterative design	52	4	2	3	1
human factors /ergonomics consideerations	25	2	1	3	4
potential stress / strain on joints / muscles	39	3	1	4	2
distribution of mass	20	3	1	4	2
center of mass	28	4	1	3	2
sound	51	4	3	2	1
repetition and fatigue	12	2	1	3	4
high speed motion	8	4	3	1	2
effect of unequal loading	16	3	2	1	4
psychophyiscs	47	2	3	4	1
abrasion of material on body	36	1	4	2	3
social impact	50	1	2	4	3
repalceable parts	6	4	2	3	1
material strength		3	2	1	4
material elasticity	40	4	2	1	3
biomechanics	18	3	4	2	1

The sum of quintile best category for each exoskeleton can be seen in Table 40.

Table 40: Count of Initial Properties Quartile Best

	Q1 Best	Q2 Best	Q3 Best	Q4 Best	Q5 Best	Sum
Exoskeleton A	1	0	2	4	1	8
Exoskeleton B	4	5	5	3	1	18
Exoskeleton C	3	2	3	3	1	12
Exoskeleton D	2	4	1	2	6	15

The analysis is continued for after use properties.

Table 41: All Exoskeletons - After Use Property Rank Coded by Best Value

Design Metrics	Exoskeleton A	Exoskeleton B	Exoskeleton C	Exoskeleton D
Cost	0.039642793	0.017464807	0.036022165	0.032740806
Manufacturability	0.035139141	0.026342595	0.022373905	0.03509776
Weight	0.065225968	0.080372715	0.082050987	0.085100984
Active vs. passive exoskeleton	0.000125119	0.004972046	0.000711238	0.000250564
Variability within persons	0.013014695	0.024335559	0.010357387	0.018522884
Variability between persons	0.042996902	0.045911375	0.05301293	0.04769476
number of parts vs. ability to actuate	0.016567169	0.025337492	0.003349069	0.011941896
training motivation	0.009404904	0.013806054	0.00291624	0.016471642
how the exoskeleton attaches to the body	0.102063868	0.059460338	0.033257777	0.063138743
statics	0.004148973	0.001350342	0	0.006744721
dynamics	0.011158544	0.002541477	0.012135752	0.013275609
range of motion / flexibility	0.050462411	0.051388408	0.049800692	0.057166475
comfort	0.080312205	0.075271468	0.054035027	0.076818034
every day carry vs. tool for training	0.009698463	0.013321747	0.033203473	0.009878924
muscle memory and response	0.002700811	0.004672476	0.007230915	0.002007294
sensory motor learning	0.00132626	0.000851362	0	0.000325733
Form factor	0.018612597	0.007503511	0.017449337	0.016495665
anthropometry	0.023990921	0.007206419	0.003895538	0.012591327
battery density	0.000700666	0.000926482	0	0.000375846
environmental factors	0.005656656	0.000951522	0.001203633	0.000751691
use as protection	0.031912469	0.000600962	0.001696833	0.005121864
heat mitigation	0.003249871	0.000575921	0.035539216	0.000776748
perspiration mitigation	0.010448206	0.020207332	0.023818706	0.000801804
maximum push forces	0.00232098	0.000550881	0.002449757	0.002173014
maximum pull forces	0.004170266	0.001793804	0.002523252	0.002390378
formatibilty to body	0.032600018	0.031032247	0.035627726	0.023432623
type of fuel (battery/gas/etc.)	0.000975927	0.001001603	0.00093008	0.00090203
degrees of freedom	0.027503604	0.060062386	0.023408797	0.03524273
actual exertion	0.013316866	0.006224687	0.008047461	0.012865031
actual fatigue	0.013467372	0.01239832	0.027369753	0.027980699
perceived exertion	0.004549644	0.004937445	0.00221537	0.000626409
perceived fatigue	0.006921672	0.009747828	0.003276412	0.002849268
ease of use	0.044514305	0.086843771	0.050342374	0.061873368
intuitive use (affordances)	0.016554771	0.031798869	0.045227826	0.033337596
lifespan of exoskeleton (standard conditions)	0.017308938	0.01949975	0.027004364	0.027766901
lifespan of exoskeleton (extreme conditions)	0.014985133	0.019628484	0.010555963	0.022244903
temperature considerations	0.008853108	0.004445446	0.018863939	0.001102481
humidity considerations	0.016845535	0.001051683	0	0.001127537
iterative design	0.0335312	0.00376903	0.011763688	0.009011955
human factors /ergonomics consideerations	0.018702086	0.031088803	0.025770222	0.044849042
potential stress / strain on joints / muscles	0.020108145	0.023658727	0.012787111	0.022527126
distribution of mass	0.007232617	0.014091223	0.008193623	0.008924773
center of mass	0.002580614	0.005937889	0.004020863	0.012907653
sound	0.003608468	0.003126346	0.004203779	0.00423766
repetition and fatigue	0.003998344	0.022068197	0.016241081	0.020864008
high speed motion	0.010835625	0.014892056	0.023017004	0.02173975
effect of unequal loading	0.008122578	0.0077759	0	0.002925332
psychophyiscs	0.001276212	0.001201923	0.00191487	0.001302932
abrasion of material on body	0.036989124	0.035027304	0.048539124	0.044655549
social impact	0.001301236	0.001151843	0.001367765	0.001277875
repalceable parts	0.013172818	0.032643272	0.026013493	0.018481759
material strength	0.021055548	0.014819196	0.021998546	0.010523686
material elasticity	0.012175995	0.002629108	0.050331255	0.004248846
biomechanics	0.001861642	0.009729567	0.001933684	0.001515314

The number of categories each exoskeleton is ranked best in can now be determined. The sum of best ranked categories can be seen in the following table.

Table 42: Sum of After Use Properties Best Value

Exoskeleton	Sum of Metrics Highest Ranked
A (Control)	15
B (Experimental)	12
C (Control)	18
D (Experimental)	11

In this case, it can be seen that the control group outranked the experimental group. The analysis is continued by looking at the quintile split for the metric interdependency rank.

Table 43: All Exoskeletons - After Use Property Rank Coded by Best Value and Compared to Interdependencies

Design Metrics	Interdpendency Rank	Exoskeleton A	Exoskeleton B	Exoskeleton C	Exoskeleton D
Cost	1	1	4	3	2
Manufacturability	26	1	3	4	1
Weight	14	4	3	2	1
Active vs. passive exoskeleton	19	4	1	2	3
Variability within persons	13	3	1	4	2
Variability between persons	9	4	3	1	2
number of parts vs. ability to actuate	20	2	1	4	3
training motivation	43	3	2	4	1
how the exoskeleton attaches to the body	4	1	3	4	2
statics	37	2	3	4	1
dynamics	35	3	4	2	1
range of motion / flexibility	3	3	3	4	1
comfort	10	1	3	4	2
every day carry vs. tool for training	42	4	3	1	4
muscle memory and response	48	3	2	1	4
sensory motor learning	49	1	2	4	3
Form factor	11	1	4	2	2
anthropometry	5	1	3	4	3
battery density	17	2	1	4	4
environmental factors	21	1	3	2	2
use as protection	43	1	4	3	4
heat mitigation	27	3	4	1	4
perspiration mitigation	23	3	2	1	4
maximum push forces	44	2	4	1	2
maximum pull forces	41	1	4	2	2
formatibilty to body	7	2	2	1	4
type of fuel (battery/gas/etc.)	34	2	1	3	4
degrees of freedom	22	3	1	4	2
actual exertion	31	1	4	3	1
actual fatigue	30	4	4	1	1
perceived exertion	45	2	1	3	4
perceived fatigue	46	2	1	3	4
ease of use	29	4	1	3	2
intuitive use (affordances)	54	4	3	1	2
lifespan of exoskeleton (standard conditions)	15	4	3	1	1
lifespan of exoskeleton (extreme conditions)	33	3	2	4	1
temperature considerations	32	2	3	1	4
humidity considerations	38	1	3	4	2
iterative design	52	1	4	2	3
human factors /ergonomics consideerations	25	4	2	3	1
potential stress / strain on joints / muscles	39	3	1	4	2
distribution of mass	20	4	1	3	2
center of mass	28	4	2	3	1
sound	51	3	4	1	2
repetition and fatigue	12	4	1	3	2
high speed motion	8	4	3	1	2
effect of unequal loading	16	1	2	4	3
psychophyiscs	47	3	4	1	2
abrasion of material on body	36	3	4	1	2
social impact	50	2	4	1	3
repalceable parts	6	4	1	2	3
material strength		2	3	1	4
material elasticity	40	2	4	1	3
biomechanics	18	2	1	3	4

Table 44: Count of After Use Quartile Best

	Q1 Best	Q2 Best	Q3 Best	Q4 Best	Q5 Best	Sum
Exoskeleton A	5	2	2	3	2	14
Exoskeleton B	1	7	2	2	2	14
Exoskeleton C	3	1	4	4	5	17
Exoskeleton D	1	1	3	3	0	8

By taking each metric's relative value (fully normalized) and compare them based on the weighted importance of the metrics as well as the weighted interdependency importance, the design team can quantitatively compare alternatives based on the metrics they have deemed most important for their specialized task. The continuation of this analysis would have the design team choose which of the 55 metrics apply for their task. For example, many lower cost exoskeletons are passive in nature and do not require a fuel source. Therefore, the design team would exclude metrics such as "active vs. passive exoskeleton", "battery density", "type of fuel", etc. This allows the QuANTUM Ex Method to be more robust.

After Use - Affordances

For the first question, participants rated each exoskeleton's ability to help them pay attention during the training task. There was a statistically significant difference between the four groups as determined by one-way ANOVA ($F(3, 100) = 13.39$, $p < 0.0001$).

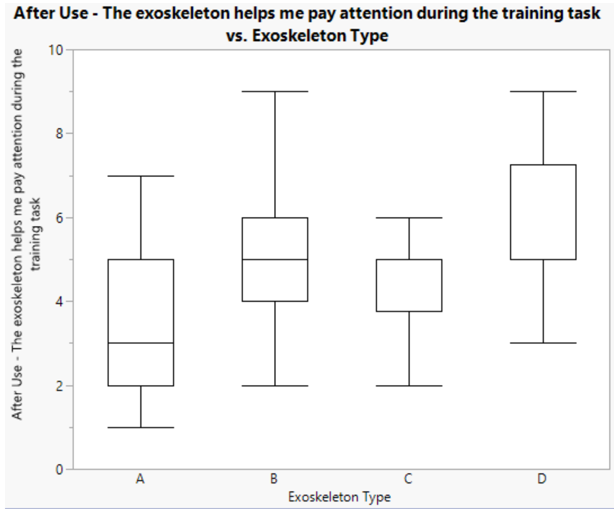

Figure 58: After Use - The Exoskeleton Helps Me Pay Attention During the Training Task (Exoskeleton A vs. Exoskeleton B vs. Exoskeleton C vs. Exoskeleton D)

This metric was also compared by blocking the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). There was a statistically significant difference between the two groups as determined by a one-way ANOVA ($F(1, 102) = 26.65$, $p = <0.0001$).

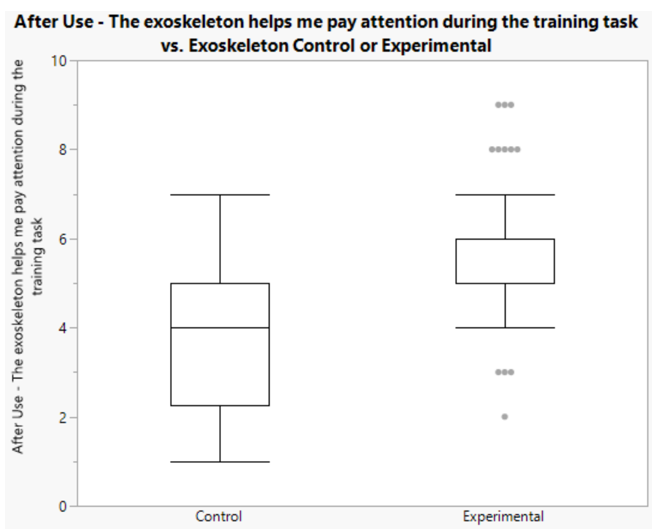

Figure 59: After Use - The Exoskeleton Helps Me Pay Attention During the Training Task (Control group vs. Experimental group)

For the second question, participants rated their ability to understand how to use the exoskeleton without reading handling instructions. There was a statistically significant difference between the four groups as determined by one-way ANOVA (F(3, 100) = 13.00, p < 0.0001).

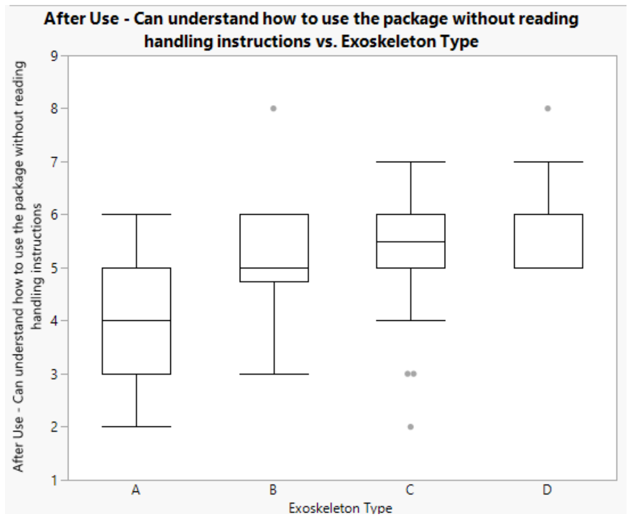

Figure 60: After Use - Can understand how to use the exoskeleton without reading handling instructions (Exoskeleton A vs. Exoskeleton B vs. Exoskeleton C vs. Exoskeleton D)

This metric was also compared by blocking the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). There was a statistically significant difference between the two groups as determined by a one-way ANOVA (F(1, 102) = 14.52, p = 0.0002).

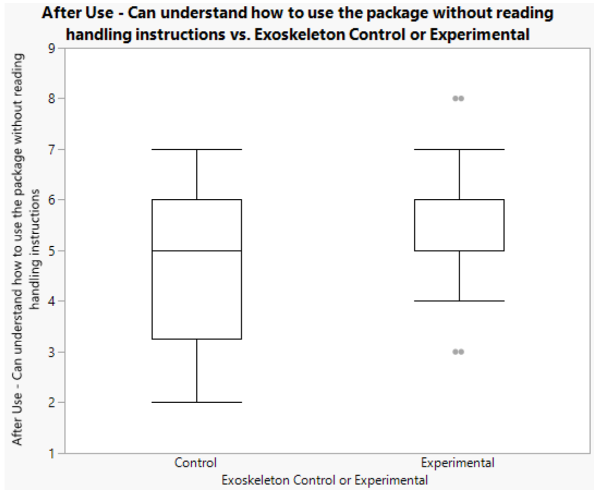

Figure 61: After Use - Can understand how to use the exoskeleton without reading handling instructions (Control group vs. Experimental group)

For the third question, participants rated their ability to find the handling features of the exoskeletons immediately. There was a statistically significant difference between the four groups as determined by one-way ANOVA ($F(3, 100) = 9.77$, $p < 0.0001$).

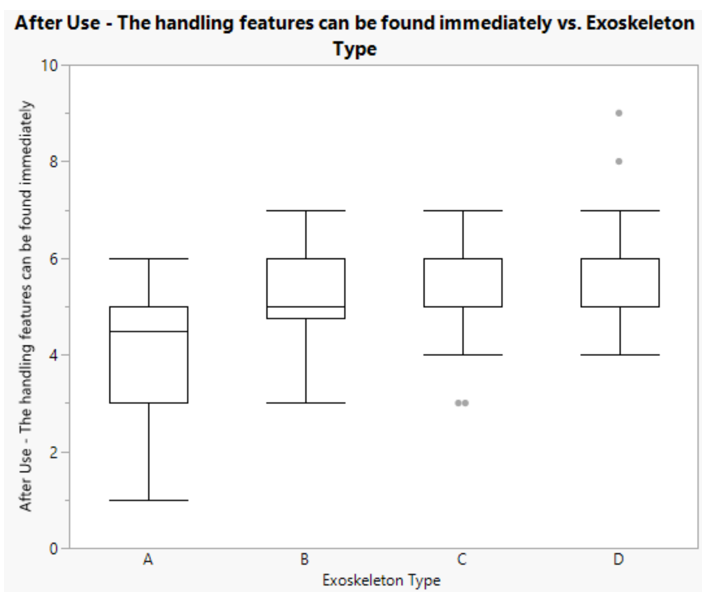

Figure 62: After Use - The handling features of the exoskeleton can be found immediately (Exoskeleton A vs. Exoskeleton B vs. Exoskeleton C vs. Exoskeleton D)

This metric was also compared by blocking the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). There was a statistically significant difference between the two groups as determined by one-way ANOVA ($F(1, 102) = 9.34$, $p = 0.0029$).

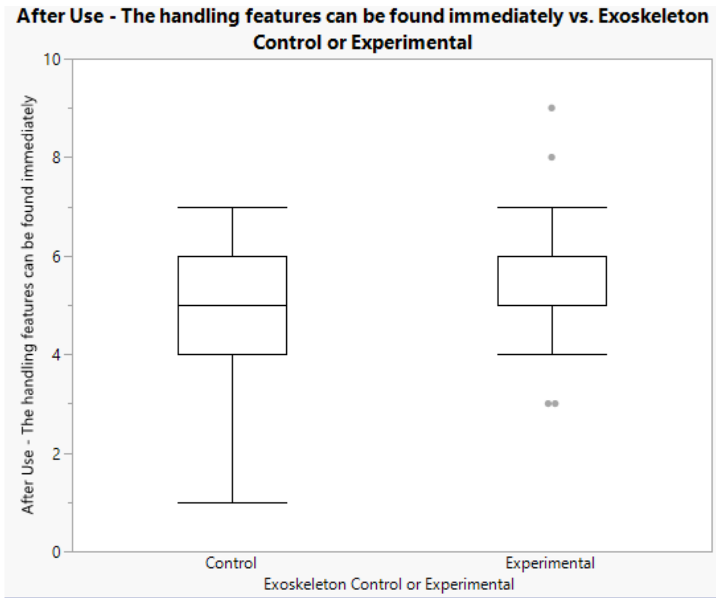

Figure 63: After Use - The handling features of the exoskeleton can be found immediately (Control group vs. Experimental group)

The final question asked participants to rate the handling instructions of each exoskeleton. There was a statistically significant difference between the four groups as determined by one-way ANOVA ($F(3, 100) = 8.49$, $p < 0.0001$).

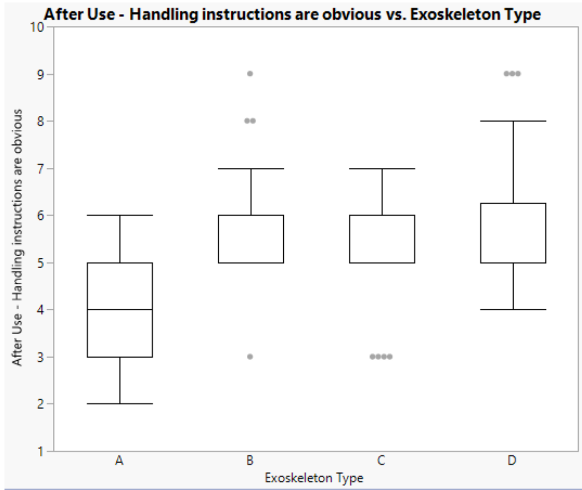

Figure 64: After Use - Handling instructions of exoskeleton are obvious (Exoskeleton A vs. Exoskeleton B vs. Exoskeleton C vs. Exoskeleton D)

This metric was also compared by blocking the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). There was a statistically significant difference between the two groups as determined by one-way ANOVA ($F(1, 102) = 16.15$, $p = 0.0001$).

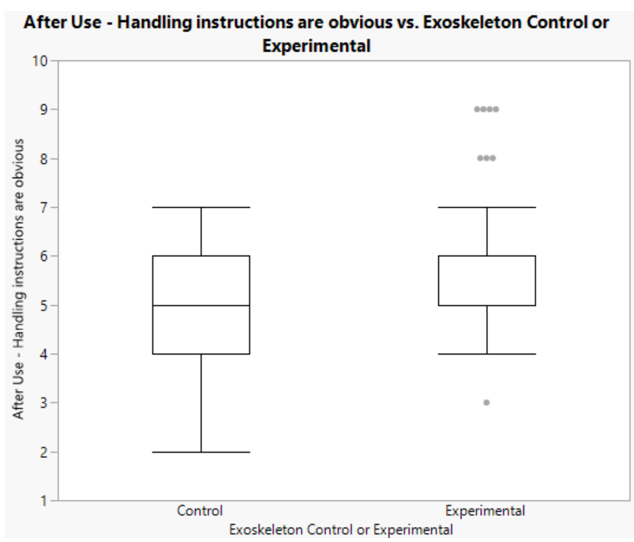

Figure 65: After Use - Handling instructions of exoskeleton are obvious (Control group vs. Experimental group)

Post-Study Questionnaire

After completing their analysis of the four exoskeletons, the participants were asked a series of questions during a post-study questionnaire. Participants were asked “In general, which exoskeleton seemed the most useful for handgun training?”. Of the 26 participants, 69% indicated exoskeleton D was the most useful exoskeleton for handgun training.

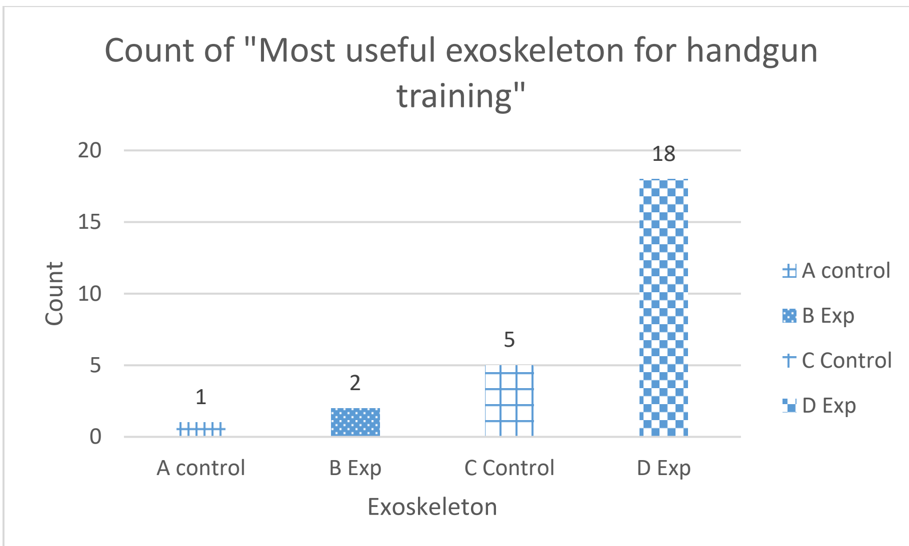

Figure 66: Count of "Most useful exoskeleton for handgun training" by Exoskeleton

This metric was also analyzed by placing the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). Grouping by category yields 76.9% indicating an experimentally designed exoskeleton would be the most useful for handgun training.

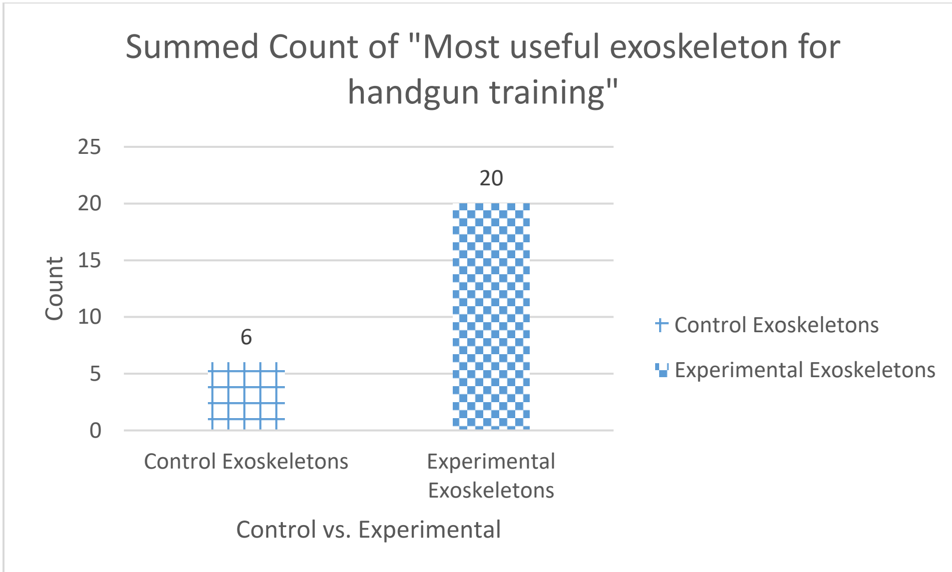

Figure 67: Count of "Most useful exoskeleton for handgun training" by Group

The next question in the post-study survey participants were asked was "In general, which exoskeleton seemed the least useful for handgun training". Of the 26 participants, 57.7% indicated exoskeleton A would be the least useful for handgun training.

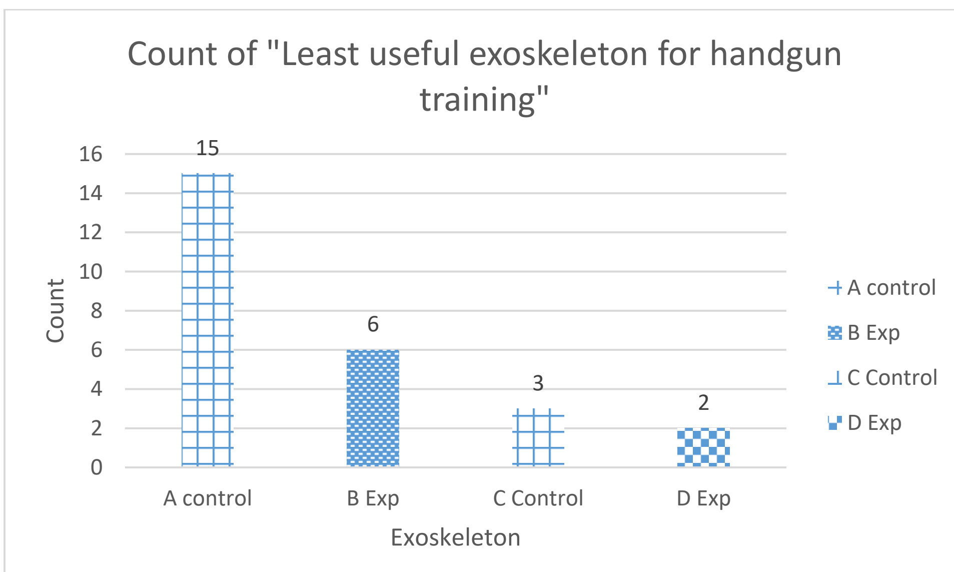

Figure 68: Count of "Least useful exoskeleton for handgun training" by Exoskeleton

This metric was also analyzed by placing the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method). Grouping by category indicates that 69.2% of participants thought the control group designed exoskeletons would be the least useful for handgun training.

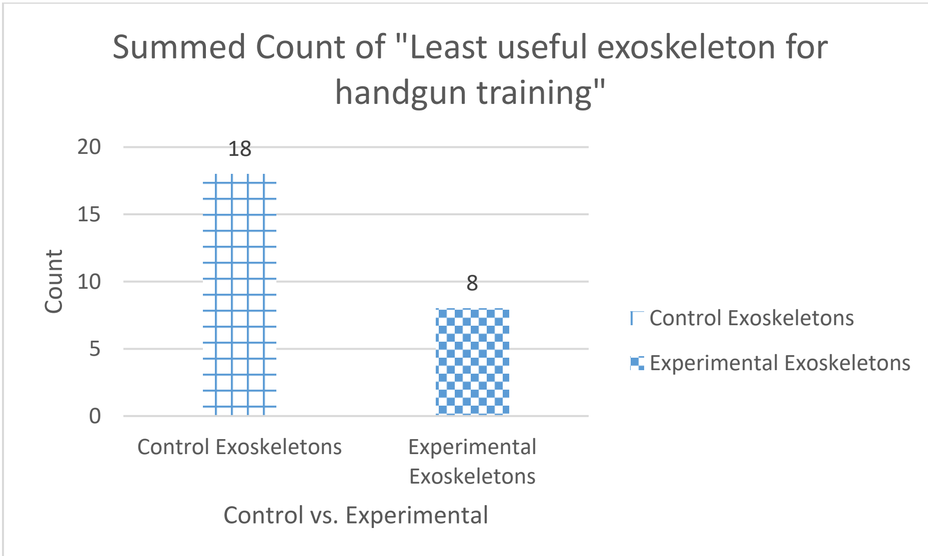

Figure 69: Count of "Least useful exoskeleton for handgun training" by Group

The third question in the post-study survey was “In general, which exoskeleton seemed the most comfortable”. Of the 26 participants, 65.4% indicated exoskeleton C was the most comfortable. This was most likely due to the affordance provided by the shirt like design, compared to the other exoskeletons which were more rigid in nature.

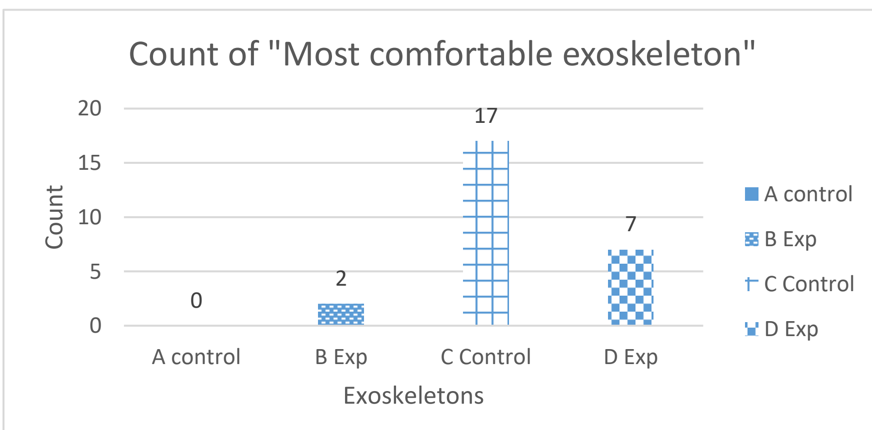

Figure 70: Count of "Most comfortable exoskeleton" by Exoskeleton

This metric was also analyzed by placing the four exoskeletons into either the control (exoskeleton designed without using the QuANTUM Ex Method) and the experimental (exoskeleton designed using the QuANTUM Ex Method).

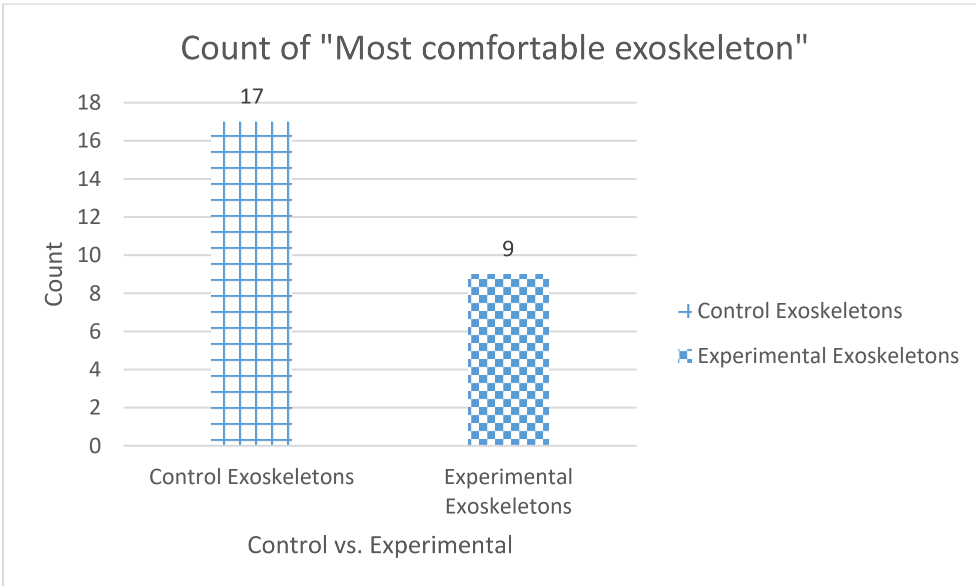

Figure 71: Count of "Most comfortable exoskeleton" by Group

Chapter XX Conclusion

The results of this study indicate that it is possible to apply the QuANTUM Ex method with relatively novice users to great success. Evaluation of the exoskeletons by the expert panel were also consistent and lead to the same four exoskeletons chosen to be evaluated. Evaluation completed by participants were as expected. Participants initial perceived affordances were significantly higher in the experimental group than the control group. However, this did not remain consistent after participants tried on the exoskeletons and used them. This could imply that the less complex designs created by the control group did not initially demonstrate all of the potential functionality of the exoskeletons, or it could simply demonstrate that simpler designs don’t provide as many initial affordances that aren’t there and therefore, they have fewer affordances to be lost after use.

The results of the validation portion of the exoskeleton showed quantitatively and qualitatively that the QuANTUM Ex Method could not only assist in developing a better exoskeleton, it can also evaluate which exoskeleton is better than alternatives.

Chapter XXI Limitations

One limitation to this study was the constrained budget for prototyping the exoskeleton designs. The designs themselves were not limited in scope but were limited to a manufacturing budget of $100. This was done primarily to illicit creativity in design. A course developed by the PI and supervising major professor for the National Science Foundation has found that limiting the budget for design forces designers to think more creatively while still meeting customer requirements. A secondary reason for the limited budget was the amount the PI could reasonably afford per design.

Another limiting factor was the amount of time allowed to design each exoskeleton. While the majority of the participants expressed that enough time was given, in real world application settings, exoskeletons are designed over the course of months instead of five hours. In the course developed under the National Science Foundation grant, the trend from design projects have shown that restricted time forces design teams to come up with less creative solutions that typically follow designs that already exist. This was a necessary limitation done to balance creativity and practicality. The results of this were clear from the submitted designs. Many of the designs used similar patterns to achieve the same end goal.

Chapter XXII Recommended Modifications

The modifications recommended to improve this methodology include implementation with an engineering design team in industry. This would allow for a larger budget, more advanced manufacturing capability, longer design time, as well as a full engineering design team who could also further validation by testing in real world application areas.

An additional modification involves revisions to the QuANTUM Ex Method itself. Recommend modifications include more explicit instructions for each section involved in the method as well as making it clearer when the design team should be making sketches of ideas or testing prototypes. This was not included in the methodological study due to the time and budget constraints.

More work could be done to incorporate more information on creativity-based designs, affordances-based designs, and how the engineering teams' designs can be improved on. More information could be provided in terms of anthropometry considerations and analysis of designs at each step.

Additional improvement could be made to make the methodology more domain independent. This could lead to more wide-spread adoption and make it easier for multi-disciplinary design teams. The current form of The QuANTUM Ex Method was designed incorporating backgrounds in mechanical engineering, industrial engineering, statistics, biomedical engineering, and human-computer interaction.

The final recommended improvement would be an overarching equation that provides a number from each section of the methodology. The overarching equation could provide a summed value that could more thoroughly compare exoskeletons. This would also provide a way for the design team to see which areas their design is weak. An ideal methodology would provide recommended changes based on the number for each section within the methodology.

Additional future work involves a research-based case study. The research team is currently working on applying the QuANTUM Ex Method in a longer design timeline and evaluating how well the exoskeleton works. The results of the case study are being prepared for publication in a journal. The case study, when published, will highlight how the QuANTUM Ex Method works when time constraints are greatly relaxed, and budget constraints are marginally relaxed. It shows how the QuANTUM Ex Method is applied in practical settings when the design team chooses to use a selection of the 55 engineering design constraints instead of considering all of them. It introduced the concept of “functional importance of metrics” and “non-functional importance of metrics” to apply the interdependency-based limit priority weighting in the design process.

The functional importance of metrics is essentially the sum of the interdependency-based limit priority weighting for metrics the design team deemed relevant to their chosen task. When considering only a select group of metrics, the weighting of non-chosen or non-functional importance of metrics cannot be ignored or distributed to the chosen metrics.

Chapter XXIII Overall Conclusions

This dissertation presented a brief history on exoskeletons and exoskeleton design through multiple published papers. The dissertation provided the logic, reasoning, and the need for an exoskeleton design methodology through additional published papers. Published case studies on exoskeleton design and validation by the PI were also provided.

It provided basic introduction to multiple topics and concepts that lead to the design of The QuANTUM Ex Method and presented the use of the method in the design phase as well as in the assessment phase.

This dissertation had two primary goals: the design and evaluation of the first methodology for exoskeleton design. The success of the QuANTUM Ex Method relies on two hypotheses restated from the first chapter:

1) The QuANTUM Ex Method will produce theoretically superior exoskeleton designs via quantitative and qualitative metrics
2) When exoskeleton prototypes are based on the same information and under the same limiting factors, the QuANTUM Ex Method can accurately and reliably determine superior designs from multiple alternatives.

Based on the results of the studies throughout this dissertation, both of these hypotheses were proven true. The QuANTUM Ex Method was able successful in assisting novice users in designing theoretically superior exoskeletons utilizing both quantitative and qualitative metrics where both the control and experimental group had the same information and the same limiting factors. These exoskeletons were then validated by a relatively large participant pool. In almost every category the experimental group outperformed the control group.

This dissertation provides the first exoskeleton design and evaluation methodology, contributing to the 50+ years of research in the area. It advances the science of what already exists in a thorough, quantitative and qualitative way. This research is backed by numerous publications demonstrating the potential for a large impact in not only industrial engineering, but the field of exoskeleton research as a whole. In terms of the field of exoskeleton research, this QuANTUM Ex Method presented in this dissertation has the potential to revolutionize the approach to designing as well as evaluating exoskeletons.

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APPENDIX A: RANKED ORDER IRB APPROVAL

IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 12/21/2017

To: Thomas Michael Schnieders
3004 Black Engr

CC: Dr. Richard T Stone
3004 Black Engineering

From: Office for Responsible Research

Title: Ranking Importance of Exoskeleton Design Features by Online Professionals

IRB ID: 17-548

Study Review Date: 12/21/2017

The project referenced above has been declared exempt from the requirements of the human subject protections regulations as described in 45 CFR 46.101(b) because it meets the following federal requirements for exemption:

- (2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey or interview procedures with adults or observation of public behavior where
    - Information obtained is recorded in such a manner that human subjects cannot be identified directly or through identifiers linked to the subjects; or
    - Any disclosure of the human subjects' responses outside the research could not reasonably place the subject at risk of criminal or civil liability or be damaging to their financial standing, employability, or reputation.

The determination of exemption means that:

- **You do not need to submit an application for annual continuing review.**

- **You must carry out the research as described in the IRB application.** Review by IRB staff is required prior to implementing modifications that may change the exempt status of the research. In general, review is required for any modifications to the research procedures (e.g., method of data collection, nature or scope of information to be collected, changes in confidentiality measures, etc.), modifications that result in the inclusion of participants from vulnerable populations, and/or any change that may increase the risk or discomfort to participants. Changes to key personnel must also be approved. The purpose of review is to determine if the project still meets the federal criteria for exemption.

  Non-exempt research is subject to many regulatory requirements that must be addressed prior to implementation of the study. Conducting non-exempt research without IRB review and approval may constitute non-compliance with federal regulations and/or academic misconduct according to ISU policy.

  Detailed information about requirements for submission of modifications can be found on the Exempt Study Modification Form. A Personnel Change Form may be submitted when the only modification involves changes in study staff. If it is determined that exemption is no longer warranted, then an Application for Approval of Research Involving Humans Form will need to be submitted and approved before proceeding with data collection.

Please note that you must submit all research involving human participants for review. **Only the IRB or designees may make the determination of exemption**, even if you conduct a study in the future that is exactly like this study.

Please be aware that **approval from other entities may also be needed.** For example, access to data from private records (e.g. student, medical, or employment records, etc.) that are protected by FERPA, HIPAA, or other confidentiality policies requires permission from the holders of those records. Similarly, for research conducted in institutions other than ISU (e.g., schools, other colleges or universities, medical facilities, companies, etc.), investigators must obtain permission from the institution(s) as required by their policies. **An IRB determination of exemption in no way implies or guarantees that permission from these other entities will be granted.**

APPENDIX B: RANKED ORDER EMAIL

Participants are Needed for Brief Survey on Engineering Design

Hello,

You are invited to participate in a study to determine the ranked importance of exoskeleton design features by professionals in the field of engineering and related disciplines. The study contains some qualitative questions about your background and publications and a ranked order survey. The background questions will be used only to verify that you qualify as a professional for the purposes of this study and will not be publicized. The survey is expected to take 10-15 minutes.

Your participation is voluntary and you may choose to stop the study at any time. All data will be kept confidential. Participants' names will be associated with a code and key. Results of this research will be made available upon your request.

If you are interested in participating and/or would like more information, please contact me via email at tms@iastate.edu.

Sincerely,

Tom Schnieders

APPENDIX C: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD INFORMED CONSENT

Introduction

The purpose of this study is to validate a theoretical model proposed to evaluate the design of an upper body exoskeleton. For this study, the term ‘exoskeleton’ is used to describe a device that augments the performance of an able-bodied wearer.

Inclusion Criteria

Students who are above the age of 18 may participate in the study.

Description of Procedures

If you agree to participate, you will be asked to fill out a demographic survey followed by a pre-study survey. You will then be randomly placed in either the control group or the experimental group.

You will be presented with a design problem that will task you with designing a theoretical solution that can be manufactured and implemented to solve the given design problem. You will have up to 240 minutes to complete this design challenge. After completing the challenge, you will be asked a series of questions in a debriefing. This anonymized debriefing will ask questions based on your final design and will cover questions similar to “walk me through your design methodology”, “describe the engineering design aspects you considered”, etc. There will also be a creativity measurement assessment based on Torrance’s Test of Creativity which will ask you to come up with multiple ways to use a common object. All design drawings and justification for designs will be collected along with demographic information (name, age, major, industrial experience, etc.) for the research project. All data will be anonymized.

Participation in the study is expected to last for approximately 260 – 300 minutes in total for both the design challenge and interview.

Control Group

If you are in the control group, you will follow any design methods taught to you in your previous educational and industrial experiences to design an upper body exoskeleton for firearm training.

Experimental Group

If you are in the experimental group, you will follow a pre-designated design method known as The QuANTUM Ex Method alongside your previous educational and industrial experiences to design an upper body exoskeleton for firearm training. The QuANTUM Ex Assessment Method is a theoretical design method used to help find the optimal design solution. QuANTUM Ex is an acronym and stands for the Quantitative Assessment of Non-Tested Universally Made Exoskeletons.

Risks or Discomforts

There is no expected risks or discomfort greater than what engineering students would undergo in a normal engineering lab. Being a research participant doesn’t increase any risk.

Benefits

If you decide to participate in this study, there may be no direct benefit to you. It is hoped that the information gained in this study will benefit society by advancing the field of exoskeleton design for training.

For students in I E 577, I E 578, I E 271, or HCI 587, up to 5% extra credit will be offered. If you choose to not participate in this study, an alternative lab or project will be offered also offering up to 5% extra credit.

The creator of the best exoskeleton design will win a tablet device.

Costs and Compensation

You will not have any costs from participating in this study. You will not be compensated for participating in this study.

Participant Rights

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. You can skip any questions in the pre- and post-survey that you do not wish to answer.

If you have any questions *about the rights of research subjects or research-related injury*, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

Research Injury

Emergency treatment of any injuries that may occur as a direct result of participation in this research is available at the Iowa State University Thomas B. Thielen Student Health Center and/or referred to Mary Greeley Medical Center or another physician or medical facility at the location of the research activity. Compensation for any injuries will be paid if it is determined under the Iowa Tort Claims Act, Chapter 669 Iowa Code. Claims for compensation should be submitted on approved forms to the State Appeals Board and are available from the Iowa State University Office of Risk Management and Insurance.

Confidentiality

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy study records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: participants' names will be replaced with their participant number and names will not be collected other than for informed consent reasons. Participant names will be associated with a code and key. Participant information will not be stored with the key and the key will be destroyed after data analysis has been completed. Only the research team will have access to the data and study records. Physical copies of the informed consent forms will be kept with one of the principal investigators and stored in a locked filing cabinet. The room of the principal investigator will be locked when the principal investigator is not in the room. The electronic data will be stored on a password protected external hard drive.

Audio recordings of the debriefing will be stored on CyBox in a password protected folder. Only the research team will have access to the folder. The audio recordings will not be disseminated.

Questions

You are encouraged to ask questions at any time during this study. For further information ***about the study***, contact the principal investigator: Thomas M. Schnieders (tms@iastate.edu) or the supervising faculty: Dr. Richard T. Stone (rstone@iastate.edu).

Consent and Authorization Provisions

Your signature indicates that you voluntarily agree to participate in this study, that the study has been thoroughly explained to you, that you have been given the time to read the document, and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant's Name (printed) ____

______________________________________ ______________________

Participant's Signature Date

APPENDIX D: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD

PRE-STUDY SURVEY

Participant #: _______________

Demographic Survey

Age: _____ Sex: ______

Height: ____ Feet ____ Inch

Hand dominance: ____________

Eye dominance: ______________

**If unknown, please speak to research team.

Research Team Use

- ☐ Self-identified
- ☐ Jump Test
- ☐ Triangle Test

Pre-Study Survey

Graduate Major: Degree Pursued:

Previous degrees (if applicable):

Institution degree(s) earned (if applicable):

Number of publications if applicable (list them below):

Number of internships:

Length of internships:

Responsibilities during internships:

Industrial sector:

Main technical principles observed:

Experience in applied settings:

Length of industrial experience (full time):

Responsibilities during industrial experience (full time):

Industrial sector during industrial experience (full time):

Main technical principles observed during industrial experience (full time):

APPENDIX E: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD – UNUSUAL USES (CARDBOARD BOXES)

Participant #:

Most people throw their empty cardboard boxes away, but they have thousands of interesting and usual uses. In the spaces below and on the next page, list as many of these interesting and usual uses as you can think of. Do not limit yourself to any one size of box. You may use as many boxes as you like. Do not limit yourself to the uses you have seen or heard about; think about as many possible new uses as you can.

1. ______________________________
2. ______________________________
3. ______________________________
4. ______________________________
5. ______________________________
6. ______________________________
7. ______________________________
8. ______________________________
9. ______________________________
10. ______________________________
11. ______________________________
12. ______________________________
13. ______________________________
14. ______________________________
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16. ______________________________

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22. ______________________________

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25. ______________________________

26. ______________________________

27. ______________________________

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33. ______________________________

34. ______________________________

35. ______________________________

36. ______________________________

37. ______________________________

38. ______________________________

APPENDIX F: VALIDAITON OF AN EXOSKELETON ASSESSMENT METHOD –

SELF-EFFICACY SURVEY

Participant #: _____________

Please rate how certain you are that you can accomplish what is being asked at each of the levels described below.

Rate your degree of confidence by recording a number from 0 to 100 using the scale given below

0	10	20	30	40	50	60	70	80	90	100
Cannot do at all					Moderately can do					Highly certain can do

Place an 'x' on the line that best describes your confidence level.

	Confidence (0-100)
I come up with creative designs 0% of the time	_________
" " " " " " " " 10% " " " " " " " "	_________
" " " " " " " " 20% " " " " " " " "	_________
" " " " " " " " 30% " " " " " " " "	_________
" " " " " " " " 40% " " " " " " " "	_________
" " " " " " " " 50% " " " " " " " "	_________
" " " " " " " " 60% " " " " " " " "	_________
" " " " " " " " 70% " " " " " " " "	_________
" " " " " " " " 80% " " " " " " " "	_________
" " " " " " " " 90% " " " " " " " "	_________
" " " " " " " 100% " " " " " " " "	_________

	Confidence (0-100)
I am comfortable using TRIZ 0% of the time	_________
" " " " " " " " 10% " " " " " " " "	_________
" " " " " " " " 20% " " " " " " " "	_________
" " " " " " " " 30% " " " " " " " "	_________
" " " " " " " " 40% " " " " " " " "	_________
" " " " " " " " 50% " " " " " " " "	_________
" " " " " " " " 60% " " " " " " " "	_________
" " " " " " " " 70% " " " " " " " "	_________
" " " " " " " " 80% " " " " " " " "	_________
" " " " " " " " 90% " " " " " " " "	_________
" " " " " " " 100% " " " " " " " "	_________

Confidence
(0-100)

I am comfortable designing for manufacturing 0% of the time	__________
“ “ “ “ “ “ “ “ 10% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 20% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 30% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 40% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 50% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 60% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 70% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 80% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 90% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ 100% “ “ “ “ “ “ “ “	__________
	Confidence (0-100)
I am comfortable designing a functional prototype 0% of the time	__________
“ “ “ “ “ “ “ “ 10% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 20% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 30% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 40% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 50% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 60% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 70% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 80% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 90% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ 100% “ “ “ “ “ “ “ “	__________
	Confidence (0-100)
I am comfortable using 3D modeling software 0% of the time	__________
“ “ “ “ “ “ “ “ 10% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 20% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 30% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 40% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 50% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 60% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 70% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 80% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 90% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ 100% “ “ “ “ “ “ “ “	__________
	Confidence (0-100)

I am 0% comfortable with product analysis	__________
“ “ “ “ “ “ “ “ 10% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 20% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 30% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 40% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 50% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 60% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 70% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 80% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 90% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ 100% “ “ “ “ “ “ “ “	__________
	Confidence (0-100)

I am 0% comfortable with the Ergonomic Testing	__________
“ “ “ “ “ “ “ “ 10% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 20% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 30% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 40% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 50% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 60% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 70% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 80% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 90% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ 100% “ “ “ “ “ “ “ “	__________
	Confidence (0-100)

I am 0% comfortable with concepts of human-centered design approaches	__________
“ “ “ “ “ “ “ “ 10% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 20% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 30% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 40% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 50% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 60% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 70% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 80% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ “ 90% “ “ “ “ “ “ “ “	__________
“ “ “ “ “ “ “ 100% “ “ “ “ “ “ “ “	__________
	Confidence (0-100)

I am 0% comfortable with the concept of affordances	__________
" " " " " " " " 10% " " " " " " " "	__________
" " " " " " " " 20% " " " " " " " "	__________
" " " " " " " " 30% " " " " " " " "	__________
" " " " " " " " 40% " " " " " " " "	__________
" " " " " " " " 50% " " " " " " " "	__________
" " " " " " " " 60% " " " " " " " "	__________
" " " " " " " " 70% " " " " " " " "	__________
" " " " " " " " 80% " " " " " " " "	__________
" " " " " " " " 90% " " " " " " " "	__________
" " " " " " " 100% " " " " " " " "	__________

APPENDIX G: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD – EXOSKELETON DESIGN CHALLENGE (CONTROL)

Problem Statement (Control Group)

This multidisciplinary design challenge enables students to expand their knowledge, test and showcase new skills and inspire innovation. This individual design challenge will span a four-hour block of time and will challenge your imagination and technical design skills. You will be given a number of design requirements, functions, and constraints and be asked to submit a design and justification for why your solution works. Any and all work done towards the generation of your solution should be submitted for consideration.

Your final design will be judged not only on the design working, but also the feasibility of producing the design, the work gone into developing your design, as well as your justification.

You are tasked to design an upper body exoskeleton to be used for handgun training.

You may use any design methods and processes you have learned in your education or through work experiences to develop the exoskeleton.

Functions

- Ability to train law enforcement agents in proper handgun use
- Ability to train law enforcement agents faster than traditional methods

- Ability to increase precision compared to traditional methods
- Ability to increase accuracy compared to traditional methods
- Ability to be used with multiple types of handguns
- Ability to be worn on the body

Constraints

- The use of the internet or your cellular device is prohibited for the duration of this design challenge
- The exoskeleton device should cost less than $100 to the consumer
- The exoskeleton device must be able to be manufactured in large-scale production
- The exoskeleton device should weigh less than 25 lbs.
- The exoskeleton device should be able to safely be used to train law enforcement agents

Deliverables

All designs should be hand drawn on provided paper with detailed explanations of why design choices were made.

APPENDIX H: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD – EXOSKELETON DESIGN CHALLENGE (EXPERIMENTAL)

Problem Statement (Experimental Group)

This multidisciplinary design challenge enables students to expand their knowledge, test and showcase new skills and inspire innovation. This individual design challenge will span a four-hour block of time and will challenge your imagination and technical design skills. You will be given a number of design requirements, functions, and constraints and be asked to submit a design and justification for why your solution works. Any and all work done towards the generation of your solution should be submitted for consideration.

Your final design will be judged not only on the design working, but also the feasibility of producing the design, the work gone into developing your design, as well as your justification.

You are tasked to design an upper body exoskeleton to be used for handgun training.

You will be following the QuANTUM Ex Assessment method which is outlined in the attached document.

Functions

- Ability to train law enforcement agents in proper handgun use
- Ability to train law enforcement agents faster than traditional methods

- Ability to increase precision compared to traditional methods
- Ability to increase accuracy compared to traditional methods
- Ability to be used with multiple types of handguns
- Ability to be worn on the body

Constraints

- The use of the internet or your cellular device is prohibited for the duration of this design challenge
- The exoskeleton device should cost less than $100 to the consumer
- The exoskeleton device must be able to be manufactured in large-scale production
- The exoskeleton device should weigh less than 25 lbs.
- The exoskeleton device should be able to safely be used to train law enforcement agents

Deliverables

All designs should be hand drawn on provided paper with detailed explanations of why design choices were made.

APPENDIX I: EXOSKELETON DESIGN CHALLENGE – EXPERIMENTAL GROUP METHODOLOGY

PROBLEM STATEMENT (EXPERIMENTAL GROUP)

This multidisciplinary design challenge enables students to expand their knowledge, test and showcase new skills, and inspire innovation. This individual design challenge will span a four-hour block of time and will challenge your imagination and technical design skills. You will be given a number of design requirements, functions, and constraints and be asked to submit a design and justification for why your solution works. Any and all work done towards the generation of your solution should be submitted for consideration.

Your final design will be judged not only on the design working, but also the feasibility of producing the design, the work gone into developing your design, as well as your justification. **You are tasked to design an upper body exoskeleton to be used for handgun training.** You will be following the QuANTUM Ex Assessment method which is outlined in the attached document.

DESIGN APPROACH

For this study, you are asked to follow the following multi-criteria hybrid-design method. To begin, read the method on the following pages. Then, familiarize yourself with the workbook at the end of this document. Finally, begin designing your exoskeleton for handgun training.

This exoskeleton design method follows a hybrid approach to design where the overview of the system is understood and conceptualized first. Then, each first-level subsystem is identified and defined, followed by the refinement of each subsequent subsystem. This method has four primary stages: conceptualization, analysis, synthesis, and assessment. However, unlike many other design methods, these stages are fluidic and iterative in nature.

Conceptualization may be completed throughout the analysis, synthesis and/or assessment stages; analysis may be completed throughout the conceptualization, synthesis, and/or assessment stages; synthesis may be completed throughout the conceptualization, analysis, and/or assessment stages; and assessment may be completed throughout the conceptualization, analysis, and/or synthesis stages.

CONCEPTUALIZATION

Engineering Design Considerations

The first step in this methodology is identifying the functions and constraints that are at play. You should consider what your exoskeleton should be able to accomplish and what constrains your device from working. An initial set of functions and constraints can be seen below. This is by no means an exhaustive list but should be the bare minimum considered when designing your exoskeleton. Fill out the "**Functions"** and "**Constraints**" section of the workbook at the end of this document.

Functions

- Ability to train law enforcement agents in proper handgun use
- Ability to train law enforcement agents faster than traditional methods

- Ability to increase precision compared to traditional methods
- Ability to increase accuracy compared to traditional methods
- Ability to be used with multiple types of handguns
- Ability to be worn on the body

Constraints

- The use of the internet or your cellular device is prohibited for the duration of this design challenge
- The exoskeleton device should cost less than $100 to the consumer
- The exoskeleton device must be able to be manufactured in large-scale production
- The exoskeleton device should weigh no more than 25 lbs.
- The exoskeleton device should be able to safely be used to train law enforcement agents
- Materials used for your design are limited to common 3D printing plastics (ABS, PLA, Nylon) and common inexpensive stock metals (aluminum, steel, etc.)

Task Analysis

Task analysis is one of the most basic tools used in ergonomics for investigating and designing tasks. Task analysis provides a formal comparison between task demands and the capability of the human. There are three types of tasks analyses: (1) sequential, (2) branching, and (3) process control.

(1) Sequential – A sequence of tasks follow a rigid pattern with a minimum number of alternatives (i.e. a detailed start-up sequence for any equipment).

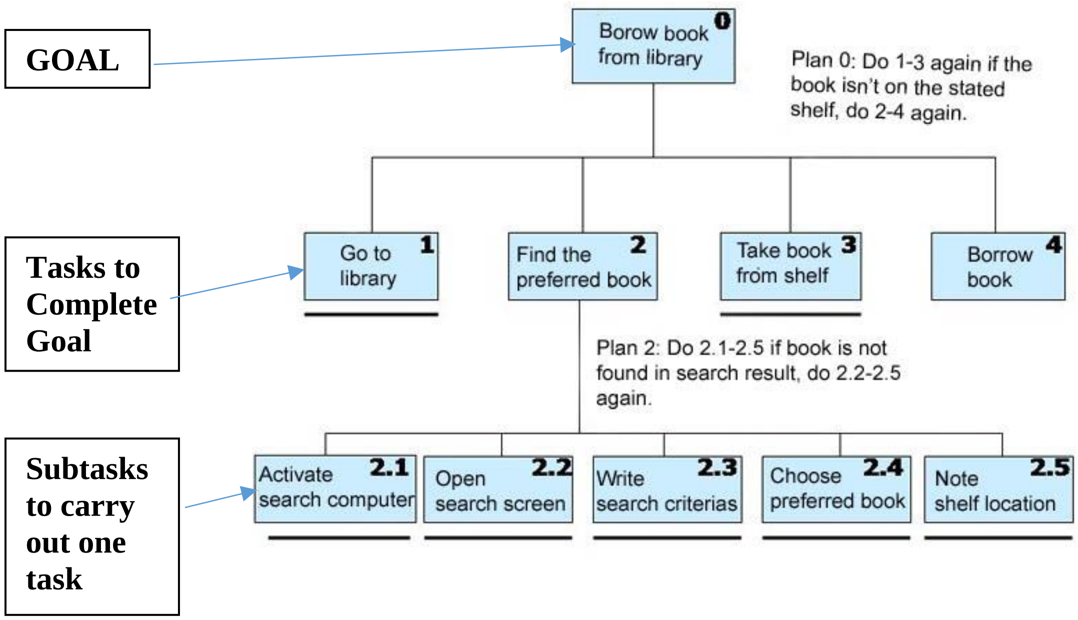
(2) Branching – The sequence is determined by the outcome of particular ‘choice’ tasks within the operation (i.e. a trouble-shooting guide).

(3) Process control – The operator is in continuous control of multiple variables and has a flexible strategy for monitoring, sampling, and initiating control actions based on complex patterns of the controlled variables

Choose to follow a sequential or branching task analysis and complete the **"Preliminary Sequential Task Analysis"** or the **"Preliminary Branching Task Analysis"** section of the workbook at the end of this document. For this methodology, you will perform this preliminary task analysis early and continue to refine them until they more definitively provide a procedural description of your exoskeleton. The workbook at the end of this document provides room for preliminary task analysis as well as two additional refinements. You may need to conduct refinements more than twice in your design.

A task analysis will focus on observable behaviors (i.e. what are the practices, methods, steps, objects, etc., used?). You would think about what users need to do or accomplish and define design decisions to accomplish those goals. Think about information about the typified user, a description of environment (i.e. where the tasks will be performed), major goals of the job (what is considered a success and what is considered a failure), user preferences and needs.

A rudimentary example of a branching task analysis may be similar to below:



From *Interaction Design*, Preece Rogers and Sharp

Figure 72: Example of a Branching Task Analysis

Ranked Importance of Exoskeleton Design Aspects

A thorough search of the literature yields 55 different design metrics that should be considered when designing an exoskeleton for training. These 55 metrics are listed below ranked highest to lowest by a panel of 40 experts. All 55 metrics should ideally be considered when designing your exoskeleton with more time devoted to higher ranked design metrics.

The ranked order analysis provides a basic, yet intuitive way to look at engineering design metrics when approaching upper body exoskeletons for training.

All 55 of these metrics should be considered to some degree in your design. The amount of time and effort put into the analysis of each metric should follow the ranked order analysis. The metrics are listed below in order of most important to least important.

For this experiment, back of the envelope math should be conducted during the design phase. Complete the "**Design Metrics**" section of the workbook.

Table 45: 55 Engineering Design Metrics

1. Range of motion / flexibility	2. Variability between persons
3. How the exoskeleton attaches to the body	4. Comfort
5. Variability within persons	6. Active vs. passive exoskeleton
7. Cost	8. Weight
9. Training motivation	10. Number of parts vs. ability to actuate
11. Manufacturability	12. Dynamics
13. Muscle memory and response	14. Statics
15. Everyday carry vs. tool for training	16. Ease of manufacturing
17. Sensory motor learning	18. Form factor
19. Anthropometry	20. Heat mitigation
21. Ease of use	22. Battery density
23. Use as protection	24. Maximum push forces
25. Degrees of freedom	26. Formability to body
27. Human factors and ergonomics	28. Intuitive use (affordances)
29. Environmental factors	30. Perspiration mitigation
31. Perceived fatigue	32. Actual fatigue
33. Biomechanics	34. Maximum pull forces
35. Type of fuel (battery/gas/etc.)	36. Repetition and fatigue
37. Abrasion of material on the body	38. Perceived exertion
39. Potential stress/strain on joints/muscles	40. Actual exertion
41. Sound	42. Iterative design
43. Distribution of mass	44. Material strength
45. Temperature considerations	46. Lifespan of exoskeleton (standard conditions)
47. Center of mass	48. Psychophysics
49. Replaceable parts	50. High speed motion
51. Humidity considerations	52. Social impact
53. Material elasticity	54. Lifespan of exoskeleton (extreme conditions)
55. Effect of unequal loading	

Creativity Considerations

There are many different techniques for eliciting creativity. Three techniques will be used within this method: (1) brainstorming, (2) devil's advocate, and (3) TRIZ. Brainstorming and devil's advocate are primarily group creativity exercises. As such, an iterative design approach to TRIZ will be the focus for this experiment.

In this section of the methodology, it is important to return to your functions and constraints section of your workbook. When looking at your functions, also consider their goals or purpose. Ask yourself questions such as who is the product for, why do they want the product?

Answer these questions in the **"Creativity Considerations"** section of the workbook. Now return to your constraints and consider them in tandem with your functions and goals. Think of each goal, function, and constraint as a series of see-saws. As you put more time/effort/money etc. into fulfilling one goal, how does it affect a different goal/function/constraint? Ideally, all goals/functions/constraints should be in a perfect balanced state of equilibrium.

Traditionally, to balance these tradeoffs, one must choose which goals or constraints can be relaxed so that others can be met. However, in TRIZ (the Russian theory of inventive problem solving), one should embrace constraints. Rather than comprising, do both.

There are 39 engineering parameters and 40 inventive principles. The 39 engineering parameters are the contradictions that are in need of balancing and the 40 inventive principles are the creative solutions used to balance your contradictions. The workbook includes what is known as the contradiction matrix.

Table 46: TRIZ Engineering Parameters

1. Weight of moving object	2. Weight of nonmoving object	3. Length of moving object
4. Length of nonmoving object	5. Area of moving object	6. Area of nonmoving object
7. Volume of moving object	8. Volume of nonmoving object	9. Speed
10. Force	11. Tension, pressure	12. Shape
13. Stability of object	14. Strength	15. Durability of moving object
16. Durability of nonmoving object	17. Temperature	18. Brightness
19. Energy spent by moving object	20. Energy spent by nonmoving object	21. Power
22. Waste of energy	23. Waste of substance	24. Loss of information
25. Waste of time	26. Amount of substance	27. Reliability
28. Accuracy of measurement	29. Accuracy of manufacturing	30. Harmful factors acting on object
31. Harmful side effects	32. Manufacturability	33. Convenience of use
34. Repairability	35. Adaptability	36. Complexity of device
37. Complexity of control	38. Level of automation	39. Productivity

Table 47: TRIZ Inventive Principles

1. Segmentation	2. Extraction, Separation, Removal, Segregation	3. Local Quality	4. Asymmetry
5. Combining, Integration, Merging	6. Universality, Multi-functionality	7. Nesting	8. Counterweight, Levitation
9. Preliminary anti-action, Prior counteraction	10. Prior action	11. Cushion in advance, compensate before	12. Equipotentiality, remove stress
13. Inversion, The other way around	14. Spheroidality, Curvilinearity	15. Dynamicity, Optimization	16. Partial or excessive action
17. Moving to a new dimension	18. Mechanical vibration/oscillation	19. Periodic action	20. Continuity of a useful action

21. Rushing through	22. Convert harm into benefit, "Blessing in disguise"	23. Feedback	24. Mediator, intermediary
25. Self-service, self-organization	26. Copying	27. Cheap, disposable objects	28. Replacement of a mechanical system with 'fields'
29. Pneumatics or hydraulics:	30. Flexible membranes or thin film	31. Use of porous materials	32. Changing color or optical properties
33. Homogeneity	34. Rejection and regeneration, Discarding and recovering	35. Transformation of the physical and chemical states of an object, parameter change, changing properties	36. Phase transformation
37. Thermal expansion	38. Use strong oxidizers, enriched atmospheres, accelerated oxidation	39. Inert environment or atmosphere	40. Composite materials

The contradiction matrix is a grid of 39x39 engineering parameters with cells comprised of the inventive principles that can be used to balance the engineering parameter tradeoffs. At this stage, identify the engineering parameters in your design that need to be balanced and determine the inventive principles that correspond to your tradeoffs in the **"Creativity Considerations"** section of the workbook.

ANALYSIS

Human Factors Considerations

Human factors is the study, analysis, and design of human-technology systems to ensure safe, efficient, effective, and error free system performance.

Affordances are perceived properties that may or may not exist. They give suggestions or clues about how to use these properties. This is a key concept to consider in human factors related to design. List the affordances built into your design in the **"Affordances"** section of the workbook.

There are many different types of quick ergonomic analyses that can and should be performed as part of your human factors considerations. Some of the most common ones are REBA (rapid entire body assessment), RULA (rapid upper limb assessment), OWAS (ovako working posture analysis system), and Washington Ergonomics Assessments to name a few.

Some things to consider when performing a human factors analysis include: high task repetition, high force loads, repetitive/sustained awkward postures, repeated impact, moderate to high hand/arm vibration, overstretching of the muscles, twist of the back, awkward reach, and awkward rotations.

Determine which ergonomic assessment is most appropriate for your exoskeleton design and conduct a full ergonomic analysis in the **"Ergonomic Analysis"** section of the workbook.

Anthropometric Considerations

Whenever designing a device that will be following the form of the human body, especially if the device is powered, a designer must consider anthropometry. That is, the measurements and proportions of the human body. This consideration is very important to consider making sure the device made is not only functional but is also safe for its user.

There are numerous anthropometric guidelines to consider for designing. A non-exhaustive list includes:

- Guidelines for using anthropometric data in product design – HFES 300 committee
- MIL-STD-1472D
- ANSI/HFES-100 VDT
- ANSI/HFES-200
- ISO 9355-3
- ISO 2006-E

It is important to consider these standards when looking at the 55-design metrics as well as the engineering parameters found in the previous sections.

For the purposes of this study, a table of anthropometry is provided. This data is collected from Story County Sheriffs' officers. Incorporating this information into your design is crucial for success especially when considering the two core tenants of human factors.

Biomechanical Models

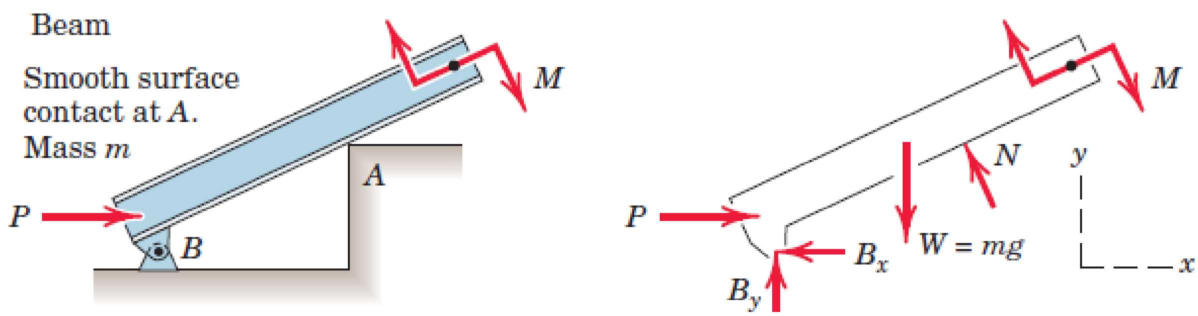
The human biomechanical system is very complex and internal forces can rarely be measured directly. The initial practitioner should begin with elementary, static models of the isolated body segments and expand them into three-dimensional, whole-body models. This can further be expanded into dynamic models of the sagittal planes. Due to the complexity of the region and the popularity of the research, there are many special models that look specifically at the lower back, shoulder, hand, and wrist.

Some important assumptions that can drastically decrease the difficulty of the biomechanical model include assuming rigid links instead of complex anatomy of segments and using the idea of a single equivalent muscle instead of the more complicated reality of multiple muscles and tendons. These assumptions are good enough to get a rough approximation of what is happening to the body. If the error in the model is too large, improvements to the model parameters can be made by increasing the complexity of the model.

Modeling allows us to estimate the forces acting on different components of the body and these forces are related to stress, and therefore injury.

Statics

Before we continue to biomechanical models and the statics approach to human factors, it is important to review the concept of free body diagrams. There are four primary rules for developing a static free body diagram: (1) Determine the system to isolate, (2) isolate system and draw the diagram representing the complete external boundary, (3) identify the forces acting on the chosen isolated system, and (4) determining your coordinate axes. A sample free body diagram can be seen below.



In a statics analysis of rigid bodies, the system must be in equilibrium, that is, the sum of all forces should be equal to zero (i.e. $\Sigma F_X = 0, \Sigma F_y = 0, \Sigma F_z = 0, \Sigma M_x = 0, \Sigma M_y = 0, \Sigma M_z = 0$)

See the **appendix** for examples of static occupational biomechanical models (single body segment static models, two-body segment static models, and joint reaction forces).

Create a free body diagram using your exoskeleton and the corresponding regions of the body in the **"Static Free Body Diagram"** section of the workbook.

If appropriate in to your design, conduct a dynamic analysis in the **"Dynamic Analysis"** section of the workbook.

SYNTHESIS

Your exoskeleton design should be fully developed. You will know need to consider what type of material your final product will be made out of. Aspects of weight, rigidity, structural strength, cost, and ease of manufacturing should all be considered.

Discuss your material choices and the reasoning behind your choices in the **"Synthesis"** section of the workbook. Remember, that as part of your constraints, you are limited to common 3D printing plastics (ABS, PLA, Nylon) and common inexpensive stock metals (aluminum, steel, etc.).

ASSESSMENT

At this stage, you should devise an experimental design to test your exoskeleton design. Remember, that the study should be able to prove not only does your device work, but that it is also safe to the user, feasible to manufacture, and will have a positive transfer effect.

Write up your experimental design in the **"Experimental Design"** section of the workbook.

Transfer of Training

There are three critical factors that affect transfer of training: (1) motivation to transfer, (2) the transfer climate, and (3) the transfer design.

Motivation to transfer can be described as a trainee's desire to use the knowledge and the skills mastered in training to perform a task. Transfer climate, also known as the transfer conditions, refers to a sense of imperative that is generated from a subject's perception of the work environment. Transfer design is concerned with the impact of the actual training methods and the tools involved. Transfer of training success is dictated by the degree of correspondence among the training setting stimuli, responses and conditions, and those related factors that are operative in the performance setting.

There are three possible outcomes to consider. A negative transfer is when training results in deskilling. A neutral transfer is when the intervention had no statistically significant, or practically significant, impact on the skill. A positive transfer is when the intervention yields a positive change in skill level.

Discuss which type of transfer of training you expect in the **"Transfer of Training"** section of the workbook. What variables will you measure to determine your outcomes of the transfer of training?

APPENDIX J: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD – WORKSHEET

***Note: For the purposes of this dissertation and to save paper, sections of the workbook that are primarily blank space have been combined into headings onto a single page. During the study, these pages are intentionally left blank to allow participants to fill out the workbook.*

ADDITIONAL FUNCTIONS

- Ability to train law enforcement agents in proper handgun use
- Ability to train law enforcement agents faster than traditional methods
- Ability to increase precision compared to traditional methods
- Ability to increase accuracy compared to traditional methods
- Ability to be used with multiple types of handguns
- Ability to be worn on the body
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ADDITIONAL CONSTRAINTS

- The use of the internet or your cellular device is prohibited for the duration of this design challenge
- The exoskeleton device should cost less than $100 to the consumer
- The exoskeleton device must be able to be manufactured in large-scale production
- The exoskeleton device should weigh less than 25 lbs.
- The exoskeleton device should be able to safely be used to train law enforcement agents
- Materials used for your design are limited to common 3D printing plastics (ABS, PLA, Nylon) and common inexpensive stock metals (aluminum, steel, etc.)

PRELIMINARY SEQUENTIAL TASK ANALYSIS

SECONDARY SEQUENTIAL TASK ANALYSIS

TERTIARY SEQUENTIAL TASK ANALYSIS

PRELIMINARY BRANCHING TASK ANALYSIS

SECONDARY BRANCHING TASK ANALYSIS

TERTIARY BRANCHING TASK ANALYSIS

DESIGN METRICS

Consider each of the 55 metrics below. For each metric, how strongly does it impact your design (not at all, small impact, moderate impact, large impact)?
How well does your exoskeleton address each metric (0 = does not apply, 1 =strongly addresses, 2 = moderately addresses, 3 = somewhat addresses, 4 = does not address).

1. Range of motion / flexibility
2. Variability between persons
3. How the exoskeleton attaches to the body
4. Comfort
5. Variability within persons
6. Active vs. passive exoskeleton
7. Cost
8. Weight
9. Training motivation
10. Number of parts vs. ability to actuate
11. Manufacturability
12. Dynamics
13. Muscle memory and response
14. Statics
15. Everyday carry vs. tool for training
16. Ease of manufacturing
17. Sensory motor learning
18. Form factor
19. Anthropometry
20. Heat mitigation
21. Ease of use
22. Battery density
23. Use as protection
24. Maximum push forces
25. Degrees of freedom
26. Formability to body
27. Human factors and ergonomics
28. Intuitive use (affordances)
29. Environmental factors
30. Perspiration mitigation
31. Perceived fatigue
32. Actual fatigue
33. Biomechanics
34. Maximum pull forces
35. Type of fuel (battery/gas/etc.)
36. Repetition and fatigue
37. Abrasion of material on the body
38. Perceived exertion
39. Potential stress/strain on joints/muscles
40. Actual exertion

41. Sound
42. Iterative design
43. Distribution of mass
44. Material strength
45. Temperature considerations
46. Lifespan of exoskeleton (standard conditions)
47. Center of mass
48. Psychophysics
49. Replaceable parts
50. High speed motion
51. Humidity considerations
52. Social impact
53. Material elasticity
54. Lifespan of exoskeleton (extreme conditions)
55. Effect of unequal loading

After scoring each of the 55 metrics, look at anything marked with a 3 or a 4. These should be revised, if applicable, by making changes to your design. It may be beneficial to continue through this workbook and come back to this section before addressing the synthesis stage.

Sum up your score for the 55 metrics. A score of 220 would be deemed a not acceptable design. A score of 110 would fall into the acceptable design but could be improved upon. A score close to 55 falls into an ideal exoskeleton design.

CREATIVITY CONSIDERATIONS

Who is the product for?

Why do they want the product?

What should the product be able to do?

Engineering parameters that correspond to your design:

▪
▪
▪
▪
▪
▪

Inventive principles that correspond to your tradeoffs:

▪
▪
▪
▪
▪
▪

AFFORDANCES

ERGONOMIC ANALYSIS

STATIC FREE BODY DIAGRAM

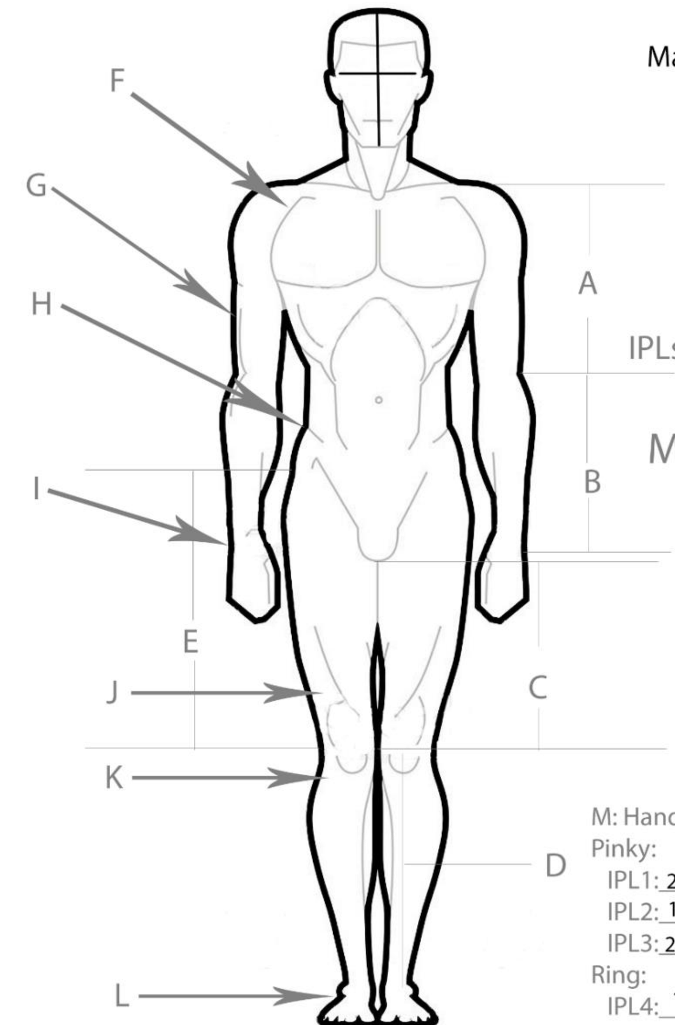
DYNAMIC ANALYSIS

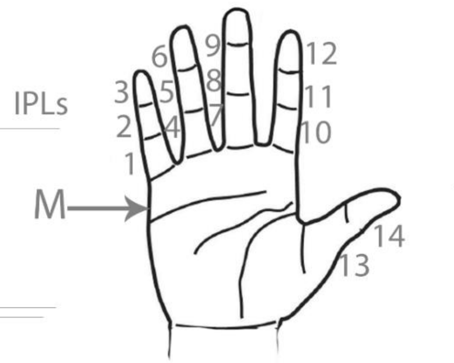
SYNTHESIS

EXPERIMENTAL DESIGN

TRANSFER OF TRAINING

Male Sheriff Average Anthropometry





Height: 181cm
Weight: 176.5lb
Sex: M
Eye Dominance: L / R 71.4% R
Hand Dominance: L / R 92.9% R

A: Shoulder to elbow length: 34.1 cm
B: Elbow to wrist length: 30 cm
C: Hip to knee inseam: 52 cm
D: Knee to top of ankle midline: 42 cm
E: Hip to knee outer measure: 48.2 cm

F: Chest circumference: 124 cm
G: Upper arm circumference: 42 cm
H: Waist Circumference: 95 cm
I: Wrist Circumference: 21 cm
J: Circumference above knee: 55 cm
K: Circumference below knee: 46 cm
L: Circumference of ankle: 28 cm

M: Hand breadth (minus thumb): 9.5 cm

Pinky:
IPL1: 2.3 cm
IPL2: 1.9 cm
IPL3: 2.4 cm

Ring:
IPL4: 1.9 cm
IPL5: 2.1 cm
IPL6: 2.1 cm

Middle:
IPL7: 2.8 cm
IPL8: 2.6 cm
IPL9: 2.6 cm

Index:
IPL10: 2.3 cm
IPL11: 2.2 cm
IPL12: 2.5 cm

Thumb:
IPL13: 3.3 cm
IPL14: 3.5 cm

Notes:

APPENDIX K: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD – DEBRIEFING (CONTROL GROUP)

Participant #: _______________

1) Did you have enough time to complete your design?

2) Walk me through your design and how it works.

3) What type of design methodology did you follow?

4) Did you learn this in your major or through industrial experience?

5) Walk me through your design methodology from beginning to end.

6) Describe what engineering design aspects you considered when designing (i.e. fit, form, function, battery density, heat mitigation, aesthetics, etc.)

7) Was your design centered on design for manufacturing or design for RP? Why that design focus?

8) How quickly do you think it will take to train police officers to be proficient with handguns with your design? Why do you think this is?

Additional comments and notes:

APPENDIX L: VALIDATION OF AN EXOSKELETON ASSESSMENT METHOD – DEBRIEFING (EXPERIMENTAL GROUP)

Participant #: ___________________

1) What were your thoughts on the design method?

2) Did you find the method easy to use?

3) What would you change about the method?

4) Did the method make you consider design aspects you might not have without the method? If so, were these helpful things to consider?

5) Walk me through your design and how it works.

6) Walk me through the method you just followed from beginning to end.

APPENDIX M: ASPECTS OF AFFORDANCES IN EXOSKELETON DESIGN – INFORMED CONSENT

Introduction

The purpose of this study is to validate a theoretical model proposed to evaluate the design of an upper body exoskeleton. Specifically, this study looks at the aspect of affordance. The term ‘exoskeleton’ is used to describe a device that augments the performance of an able-bodied wearer. This study is comprised of two phases. Phase I is designed to determine the most important factors to consider when designing an upper body exoskeleton for firearm training. Phase II is designed to evaluate exoskeleton designs based on the factors determined in Phase I. You may only participate in either Phase I or Phase II but not both.

Inclusion Criteria

Civilians above the age of 18 who can legally give consent and can physically operate a handgun will be included in the study. Ideal participants have normal to corrected vision (contact lenses and glasses are okay except for bi-focals, tri-focals, layered lenses, or regression lenses); and have little to no experience using handguns. These limitations in the inclusion criteria are included for the safety of the participants as well as the investigators.

Description of Procedures

If you agree to participate, you will be asked to fill out a demographic survey followed by a pre-study survey. You will then be randomly placed in either the Phase I group or the Phase II group.

Phase I Group

Phase I is designed around determining and validating a ranked order for design criteria to be considered when designing an upper body exoskeleton for firearm training. Numerous upper body exoskeletons will be presented to you in series. The order of presentation will be randomized. For each of these exoskeletons, you will be asked to examine and try out each of these exoskeletons.

You will be trained how to fire an electronic laser handgun (LaserLyte) that is similar in size and weight to a Glock 19. Training will cover safety as well as proper use of handguns. As a participant, you will be asked to stand and fire approximately 50 shots (five shots at 21 feet and five shots at 45 feet for five different exoskeleton) at a laser sensitive target with short breaks in between testing periods.

After each short testing period, you will be provided with an evaluation survey to assess your experiences during this interaction. At the end of this experiment, a short informal interview will be conducted. The entire study is expected to last 80-120 minutes.

Phase II Group

Phase II is designed around the evaluation of exoskeleton designs with respect to numerous design criteria. A number of upper body exoskeletons will be presented to you in series. The order of presentation will be randomized. For each of these exoskeletons, you will be asked to examine and try out each of these exoskeletons.

You will be trained how to fire an electronic laser handgun (LaserLyte) that is similar in size and weight to a Glock 19. Training will cover safety as well as proper use of handguns. As a participant, you will be asked to stand and fire approximately 50 shots (five shots at 21 feet and five shots at 45 feet for five different exoskeleton) at a laser sensitive target with short breaks in between testing periods.

After each short testing period, you will be provided with an evaluation survey to assess your experiences during this interaction. At the end of this experiment, a short informal interview will be conducted. The entire study is expected to last 80-120 minutes.

Risks or Discomforts

There is no expected risks or discomfort greater than what engineering students would undergo in a normal engineering lab. Being a research participant doesn't increase any risk. It is possible that the mechanism for attaching the exoskeleton to the participant's arm may cause some minor discomfort. If the participant feels any discomfort, please notify a research team member as soon as possible to have the exoskeleton adjusted. You will be asked to wear laser glasses, which confer protection from lasers, in the very unlikely event the laser is misfired.

Benefits

If you decide to participate in this study, there may be no direct benefit to you. It is hoped that the information gained in this study will benefit society by advancing the field of exoskeleton design for training.

For students in I E 577, I E 578, or I E 271, up to 5% extra credit will be offered. If you choose to not participate in this study, an alternative lab or project will be offered also offering up to 5% extra credit.

Costs and Compensation

You will not have any costs from participating in this study. You will not be compensated for participating in this study.

Participant Rights

Participating in this study is completely voluntary. You may choose not to take part in the study or to stop participating at any time, for any reason, without penalty or negative consequences. You can skip any questions in the pre- and post-survey that you do not wish to answer.

If you have any questions *about the rights of research subjects or research-related injury*, please contact the IRB Administrator, (515) 294-4566, IRB@iastate.edu, or Director, (515) 294-3115, Office for Responsible Research, Iowa State University, Ames, Iowa 50011.

Research Injury

Emergency treatment of any injuries that may occur as a direct result of participation in this research is available at the Iowa State University Thomas B. Thielen Student Health Center and/or referred to Mary Greeley Medical Center or another physician or medical facility at the location of the research activity. Compensation for any injuries will be paid if it is determined under the Iowa Tort Claims Act, Chapter 669 Iowa Code. Claims for compensation should be submitted on approved forms to the State Appeals Board and are available from the Iowa State University Office of Risk Management and Insurance.

Confidentiality

Records identifying participants will be kept confidential to the extent permitted by applicable laws and regulations and will not be made publicly available. However, federal government regulatory agencies, auditing departments of Iowa State University, and the Institutional Review Board (a committee that reviews and approves human subject research studies) may inspect and/or copy study records for quality assurance and data analysis. These records may contain private information.

To ensure confidentiality to the extent permitted by law, the following measures will be taken: participants' names will be replaced with their participant number and names will not be collected other than for informed consent reasons. Participant names will be associated with a code and key. Participant information will not be stored with the key and the key will be destroyed after data analysis has been completed. Only the research team will have access to the data and study records. Physical copies of the informed consent forms will be kept with one of the principal investigators and stored in a locked filing cabinet. The room of the principal investigator will be locked when the principal investigator is not in the room. The electronic data will be stored on a password protected external hard drive.

Questions

You are encouraged to ask questions at any time during this study. For further information ***about the study***, contact the principal investigator: Thomas M. Schnieders (tms@iastate.edu) or the supervising faculty: Dr. Richard T. Stone (rstone@iastate.edu).

Consent and Authorization Provisions

Your signature indicates that you voluntarily agree to participate in this study, that the study has been thoroughly explained to you, that you have been given the time to read the document, and that your questions have been satisfactorily answered. You will receive a copy of the written informed consent prior to your participation in the study.

Participant's Name (printed) ____

____ ___________________________

Participant's Signature Date

APPENDIX N: ASPECTS OF AFFORDANCES IN EXOSKELETON DESIGN – PRE-STUDY SURVEY

Demographics

Age: _____ Sex: ______

Height: ____ Feet ____ Inch

Hand dominance: ___________

Eye dominance: _____________
**If unknown, please speak to research team.

Graduate Major: Degree Pursued:

Previous degrees (if applicable):
Number of internships:
Length of internships:
Responsibilities during internships:

Industrial sector:
Main technical principles observed:

Experience in applied settings:

Length of industrial experience (full time):

Responsibilities during industrial experience (full time):

Industrial sector during industrial experience (full time):

Main technical principles observed during industrial experience (full time):

Pre-Study Survey

1. On a scale from 1-10, how much experience do you have with guns?

1	2	3	4	5	6	7	8	9	10
None at all				Some					Military training

2. On a scale from 1-10, how much experience do you have with handguns?

1	2	3	4	5	6	7	8	9	10
None at all				Some					Military training

3. If you were

APPENDIX O: ASPECTS OF AFFORDANCES IN EXOSKELETON DESIGN – TASK DESCRIPTION (PHASE I)

Initial Analysis **Exoskeleton 1 ( )**

For this exoskeleton, please do the following:

1. Handle the product properly without reading instructions.

Strongly Disagree (1) — Disagree (2) — Somewhat disagree (3) — Neither agree or disagree (4) — Somewhat agree (5) — Agree (6) — Strongly agree (7)

2. Can understand how to use the product properly without instructions.

Strongly Disagree (1) — Disagree (2) — Somewhat disagree (3) — Neither agree or disagree (4) — Somewhat agree (5) — Agree (6) — Strongly agree (7)

When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	√	**Aspects**	√
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	

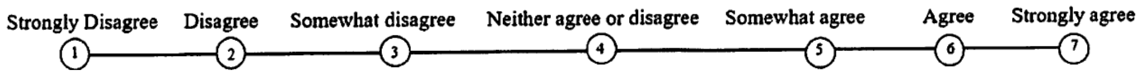
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

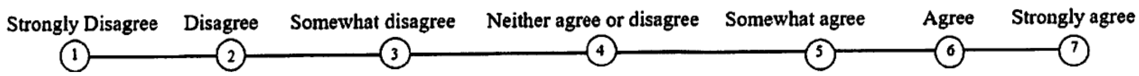
Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

After use **Exoskeleton 1 ( )**

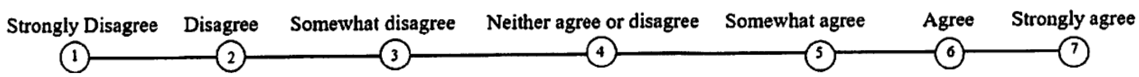
1. The exoskeleton helps me pay attention during the training tasks



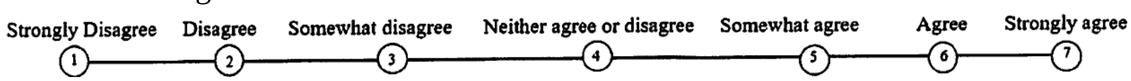
2. Can understand how to use the package without reading handling instructions



3. The handling features can be found immediately



4. Handling instructions are obvious



When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	√	**Aspects**	√
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	

Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

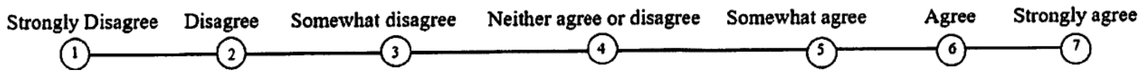
Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

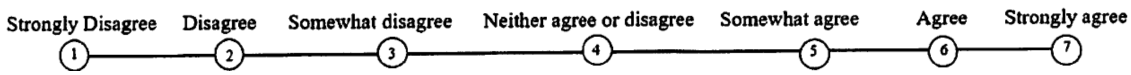
Initial Analysis **Exoskeleton 2 ( )**

For this exoskeleton, please do the following:

3. Handle the product properly without reading instructions.



4. Can understand how to use the product properly without instructions.



When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	**√**	**Aspects**	**√**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	

Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

After use **Exoskeleton 2 ( )**

5. The exoskeleton helps me pay attention during the training tasks

Strongly Disagree (1) — Disagree (2) — Somewhat disagree (3) — Neither agree or disagree (4) — Somewhat agree (5) — Agree (6) — Strongly agree (7)

6. Can understand how to use the package without reading handling instructions

Strongly Disagree (1) — Disagree (2) — Somewhat disagree (3) — Neither agree or disagree (4) — Somewhat agree (5) — Agree (6) — Strongly agree (7)

7. The handling features can be found immediately

Strongly Disagree (1) — Disagree (2) — Somewhat disagree (3) — Neither agree or disagree (4) — Somewhat agree (5) — Agree (6) — Strongly agree (7)

8. Handling instructions are obvious

Strongly Disagree (1) — Disagree (2) — Somewhat disagree (3) — Neither agree or disagree (4) — Somewhat agree (5) — Agree (6) — Strongly agree (7)

When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	√	**Aspects**	√
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	

Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Initial Analysis **Exoskeleton 3 ( )**

For this exoskeleton, please do the following:

5. Handle the product properly without reading instructions.

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

6. Can understand how to use the product properly without instructions.

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	√	**Aspects**	√
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	

Biomechanics			

Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

After use **Exoskeleton 3 ( )**

9. The exoskeleton helps me pay attention during the training tasks

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

10. Can understand how to use the package without reading handling instructions

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

11. The handling features can be found immediately

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

12. Handling instructions are obvious

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	√	Aspects	√
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	

Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Initial Analysis **Exoskeleton 4 ( )**

For this exoskeleton, please do the following:

7. Handle the product properly without reading instructions.

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

8. Can understand how to use the product properly without instructions.

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	√	**Aspects**	√
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

After use **Exoskeleton 4 ( )**

13. The exoskeleton helps me pay attention during the training tasks

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

14. Can understand how to use the package without reading handling instructions

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

15. The handling features can be found immediately

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

16. Handling instructions are obvious

Strongly Disagree	Disagree	Somewhat disagree	Neither agree or disagree	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

When using this product, please select the aspects/properties of this exoskeleton that are of value to you. Use the table below and use (√) to select from the list.

Aspects	**√**	**Aspects**	**√**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	

Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

Please rank the aspects/properties that you chose in the section above in order of highest importance to you.

Aspects	**Rank**	**Aspects**	**Rank**
Cost		Degrees of freedom	
Manufacturability		Actual exertion	
Weight		Perceived exertion	
Active vs passive exoskeleton		Actual fatigue	
Variability within persons		Perceived fatigue	
Variability between persons		Ease of use	
Number of parts vs. ability to actuate		Intuitive use (affordances)	
Training motivation		Lifespan of exoskeleton (standard conditions)	
How the exoskeleton attaches to the body		Lifespan of exoskeleton (extreme conditions)	
Statics		Temperature considerations	
Dynamics		Humidity considerations	
Range of motion/flexibility		Iterative design	
Comfort		Human factors / ergonomic considerations	
Every day carry vs. tool for training		Potential stress/strain on joints/muscles	
Muscle memory and response		Comfort	
Sensory motor learning		Distribution of mass	
Form factor		Center of mass	
Anthropometry		Sound	
Battery density		Repetition and fatigue	
Environmental factors		High speed motion	
Use as protection		Effect of unequal loading	
Heat mitigation		Psychophysics	
Perspiration mitigation		Abrasion of material on body	
Maximum push forces		Social impact	
Maximum pull forces		Replaceable parts	
Formability to the body		Material strength	
Type of fuel (battery/gas/etc.)		Material elasticity	
Biomechanics			

APPENDIX P: ASPECTS OF AFFORDANCES IN EXOSKELETON DESIGN – DEBRIEFING (PHASE I)

1. Do you prefer to read an instructions manual instead of relying on your experience when dealing with new products and why?

2. Can you usually comprehend, interpret, and understand the way you should use the exoskeletons in this study without relying on written information?

3. In general, which exoskeleton seemed the most useful for handgun training and why?

4. In general, which exoskeleton seemed the least useful for handgun training and why?

5. In general, which exoskeleton seemed the most comfortable and why?

6. What are your suggestions to improve the most useful exoskeleton?

7. What are your suggestions to improve the least useful exoskeleton?

APPENDIX Q: RULA EMPLOYEE ASSESSMENT WORKSHEET

ERGONOMICS PLUS

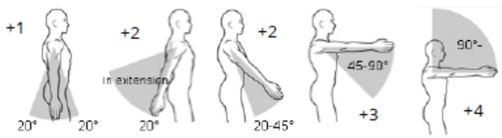
RULA Employee Assessment Worksheet

Task Name:

Date:

A. Arm and Wrist Analysis

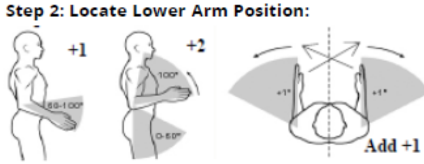
Step 1: Locate Upper Arm Position:



Step 1a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

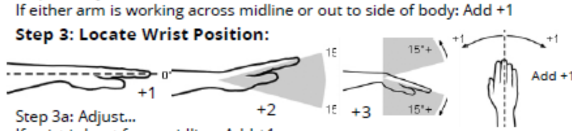
Step 2: Locate Lower Arm Position:



Lower Arm Score

Step 2a: Adjust...
If either arm is working across midline or out to side of body: Add +1

Step 3: Locate Wrist Position:



Step 3a: Adjust...
If wrist is bent from midline: Add +1

Step 4: Wrist Twist:
If wrist is twisted in mid-range: +1
If wrist is at or near end of range: +2

Wrist Twist Score

Wrist Score

Step 5: Look-up Posture Score in Table A:
Using values from steps 1-4 above, locate score in Table A

Posture Score A

+

Step 6: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score

+

Step 7: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

Force / Load Score

=

Step 8: Find Row in Table C
Add values from steps 5-7 to obtain
Wrist and Arm Score. Find row in **Table C.**

Wrist & Arm Score

Scores

Table A		Wrist Score 1		Wrist Score 2		Wrist Score 3		Wrist Score 4	
Upper Arm	Lower Arm	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2	Wrist Twist 1	Wrist Twist 2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

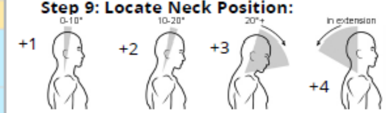
Table C	Neck, Trunk, Leg Score 1	2	3	4	5	6	7+
Wrist / Arm Score 1	1	2	3	3	4	5	5
2	2	2	3	4	4	5	5
3	3	3	3	4	4	5	6
4	3	3	3	4	5	6	6
5	4	4	4	5	6	7	7
6	4	4	5	6	6	7	7
7	5	5	6	6	7	7	7
8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 = acceptable posture
3-4 = further investigation, change may be needed
5-6 = further investigation, change soon
7 = investigate and implement change

RULA Score

B. Neck, Trunk and Leg Analysis

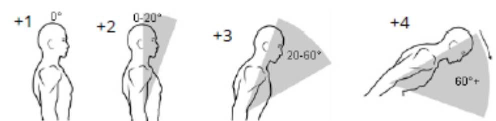
Step 9: Locate Neck Position:



Neck Score

Step 9a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 10: Locate Trunk Position:



Step 10a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score

Step 11: Legs:
If legs and feet are supported: +1
If not: +2

Leg Score

Neck Posture Score	Table B: Trunk Posture Score 1		2		3		4		5		6	
	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2	Legs 1	Legs 2
1	1	3	2	3	3	4	5	5	6	6	7	7
2	2	3	2	3	4	5	5	5	6	7	7	7
3	3	3	3	4	4	5	5	6	6	7	7	7
4	5	5	5	6	6	7	7	7	7	7	8	8
5	7	7	7	7	7	8	8	8	8	8	8	8
6	8	8	8	8	8	8	8	9	9	9	9	9

Step 12: Look-up Posture Score in Table B:
Using values from steps 9-11 above,
locate score in Table B

Posture B Score

+

Step 13: Add Muscle Use Score
If posture mainly static (i.e. held>10 minutes),
Or if action repeated occurs 4X per minute: +1

Muscle Use Score

+

Step 14: Add Force/Load Score
If load < .4.4 lbs. (intermittent): +0
If load 4.4 to 22 lbs. (intermittent): +1
If load 4.4 to 22 lbs. (static or repeated): +2
If more than 22 lbs. or repeated or shocks: +3

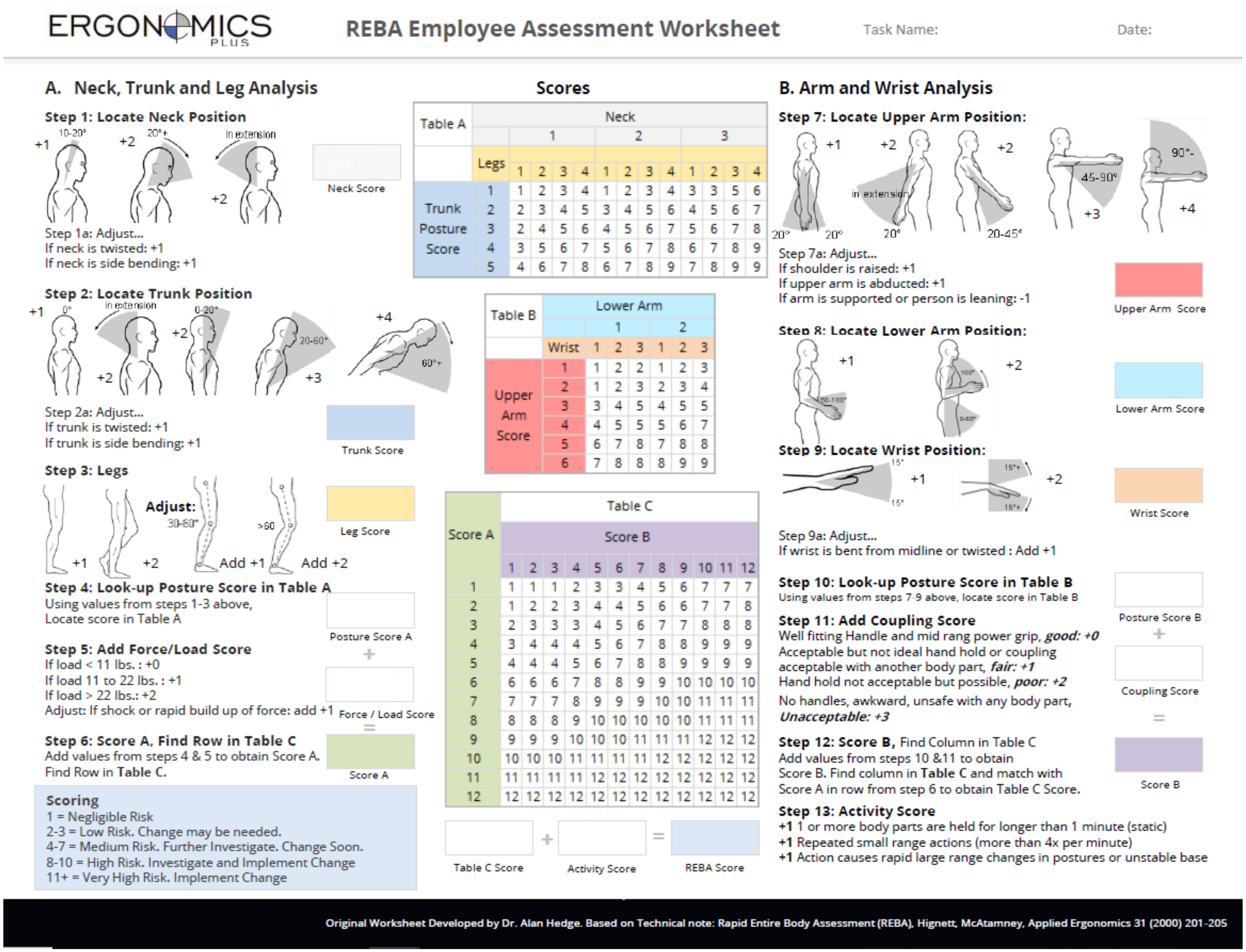
Force / Load Score

=

Step 15: Find Column in Table C
Add values from steps 12-14 to obtain
Neck, Trunk and Leg Score. Find Column in **Table C.**

Neck, Trunk, Leg Score

APPENDIX R: REBA EMPLOYEE ASSESSMENT WORKSHEET



ERGONOMICS PLUS

REBA Employee Assessment Worksheet

Task Name: Date:

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 10-20° +2 20°+ in extension +2

Neck Score

Step 1a: Adjust...
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 0° in extension +2 0-20° +2 20-60° +3 +4 60°+

Trunk Score

Step 2a: Adjust...
If trunk is twisted: +1
If trunk is side bending: +1

Step 3: Legs

+1 +2 **Adjust:** 30-60° Add +1 >60 Add +2

Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A

+

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score

=

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C.**

Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A		Neck 1				Neck 2				Neck 3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

Table B		Lower Arm 1			Lower Arm 2		
	Wrist	1	2	3	1	2	3
Upper Arm Score	1	1	2	2	1	2	3
	2	1	2	3	2	3	4
	3	3	4	5	4	5	5
	4	4	5	5	5	6	7
	5	6	7	8	7	8	8
	6	7	8	8	8	9	9

Table C	Score B											
Score A	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score + Activity Score = REBA Score

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 20° 20° +2 in extension 20° +2 20-45° +3 45-90° +4 90°+

Step 7a: Adjust...
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 8: Locate Lower Arm Position:

+1 +2

Lower Arm Score

Step 9: Locate Wrist Position:

15° +1 15° 15°+ +2 15°+

Wrist Score

Step 9a: Adjust...
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B

+

Step 11: Add Coupling Score
Well fitting Handle and mid rang power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score

=

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Original Worksheet Developed by Dr. Alan Hedge. Based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205

APPENDX S: TRIZ CONTRADICTION MATRIX

Improve this one ↓ without making this one worse →

39 Technical Parameters — Contradiction Matrix for Solving Technical Contradictions

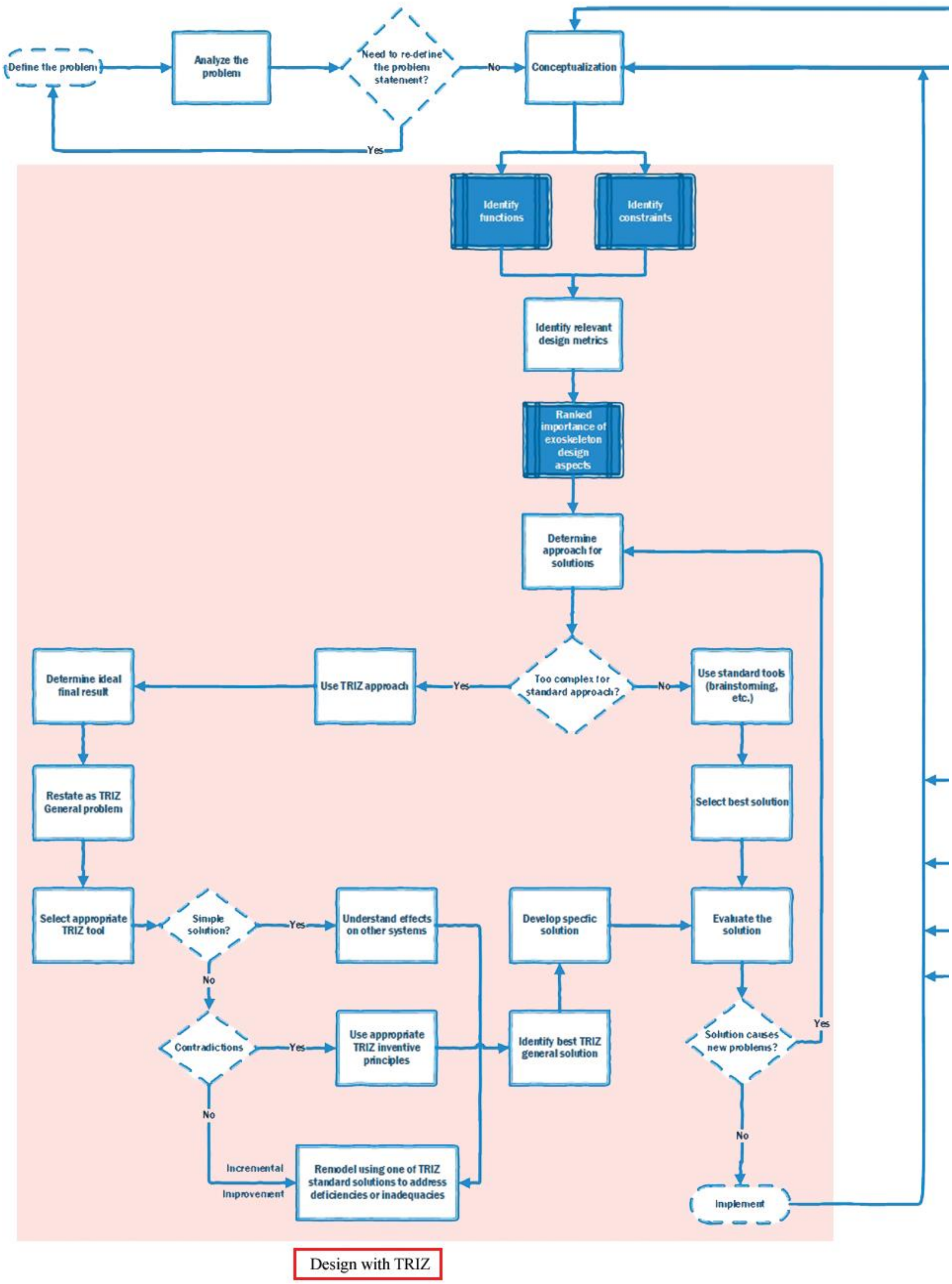
Improving \ Worsening	1 Weight of moving object	2 Weight of Stationary Object	3 Length of moving object	4 Length of Stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force (intensity)	11 Stress or pressure	12 Shape	13 Stability of the object's composition	14 Strength	15 Duration of action of a moving object	16 Duration of action of a stationary object	17 Temperature	18 Illumination Intensity	19 Use of energy by a moving object	20 Use of energy by a stationary object	21 Power	22 Loss of energy	23 Loss of substance	24 Loss of information	25 Loss of time	26 Quantity of substance	27 Reliability	28 Measurement accuracy	29 Manufacturing precision	30 Object-affected harmful factors	31 Object-generated harmful factors	32 Ease of manufacture	33 Convenience of Use	34 Ease of repair	35 Adaptability or versatility	36 Device complexity	37 Difficulty of detecting and measuring	38 Extent of automation	39 Productivity
1 Weight of moving object		-	15 8 29 34	-	29 17 38 34	-	29 2 40 28	-	2 8 15 38	8 10 18 37	10 36 37 40	10 14 35 40	1 35 19 39	28 27 18 40	5 34 31 35	-	6 29 4 38	19 1 32	35 12 34 31	-	12 36 18 31	6 2 34 19	5 35 3 31	10 24 35	10 35 20 28	3 26 18 31	3 11 1 27	28 27 35 26	28 35 26 18	22 21 18 27	22 35 31 39	27 28 1 36	35 3 2 24	2 27 28 11	29 5 15 8	26 30 36 34	28 29 26 32	26 35 18 19	35 3 24 37
2 Weight of stationary object	-		-	10 1 29 35	-	35 30 13 2	-	5 35 14 2	-	8 10 19 35	13 29 10 18	13 10 29 14	26 39 1 40	28 2 10 27	-	2 27 19 6	28 19 32 22	19 32 35	-	18 19 28 1	15 19 18	18 19 28 15	5 8 13 30	10 15 35	10 20 35 26	19 6 18 26	10 28 8 3	18 26 28	10 1 35 27	2 19 22 37	35 22 1 39	28 1 9	6 13 1 32	2 27 28 11	19 15 29	1 10 26 39	25 28 17 15	2 26 35	1 28 15 35
3 Length of moving object	8 15 29 34	-		-	15 17 4	-	7 17 4 35	-	13 4 8	17 10 4	1 8 35	1 8 10 29	1 8 15 34	8 35 29 34	19	-	10 15 19	32	8 35 24	-	1 35	7 2 35 39	4 29 23 10	1 24	15 2 29	29 35	10 14 29 40	28 32 4	10 28 29 37	1 15 17 24	17 15	1 29 17	15 29 35 4	1 28 10	14 15 1 16	1 19 26 24	35 1 26 24	17 24 26 16	14 4 28 29
4 Length of stationary object		35 28 40 29	-		-	17 7 10 40	-	35 8 2 14	-	28 10	1 14 35	13 14 15 7	39 37 35	15 14 28 26	-	1 40 35	3 35 39 18	3 25	-		12 8	6 28	10 28 24 35	24 26	30 29 14		15 29 28	32 28 3	2 32 10	1 18		15 17 27	2 25	3	1 35	1 26	26		30 14 7 26
5 Area of moving object	2 17 29 4	-	14 15 18 4	-		-	7 14 17 4		29 30 4 34	19 30 35 2	10 15 36 28	5 34 29 4	11 2 13 39	3 15 40 14	6 3	-	2 15 16	15 32 19 13	19 32	-	19 10 32 18	15 17 30 26	10 35 2 39	30 26	26 4	29 30 6 13	29 9	26 28 32 3	2 32	22 33 28 1	17 2 18 39	13 1 26 24	15 17 13 16	15 13 10 1	15 30	14 1 13	2 36 26 18	14 30 28 23	10 26 34 2
6 Area of stationary object	-	30 2 14 18	-	26 7 9 39	-		-		-	1 18 35 36	10 15 36 37		2 38	40	-	2 10 19 30	35 39 38		-		17 32	17 7 30	10 14 18 39	30 16	10 35 4 18	2 18 40 4	32 35 40 4	26 28 32 3	2 29 18 36	27 2 39 35	22 1 40	40 16	16 4	16	15 16	1 18 36	2 35 30 18	23	10 15 17 7
7 Volume of moving object	2 26 29 40	-	1 7 4 35	-	1 7 4 17	-		-	29 4 38 34	15 35 36 37	6 35 36 37	1 15 29 4	28 10 1 39	9 14 15 7	6 35 4	-	34 39 10 18	2 13 10	35	-	35 6 13 18	7 15 13 16	36 39 34 10	2 22	2 6 34 10	29 30 7	14 1 40 11	26 28	25 28 2 16	22 21 27 35	17 2 40 1	29 1 40	15 13 30 12	10	15 29	26 1	29 26 4	35 34 16 24	10 6 2 34
8 Volume of stationary object	-	35 10 19 14	19 14	35 8 2 14	-		-		-	2 18 37	24 35	7 2 35	34 28 35 40	9 14 17 15	-	35 34 38	35 6 4		-		30 6		10 39 35 34		35 16 32 18	35 3	2 35 16		35 10 25	34 39 19 27	30 18 35 4	35		1		1 31	2 17 26		35 37 10 2
9 Speed	8 28 13 38	-	13 14 8	-	29 30 34	-	7 29 34	-		13 28 15 19	6 18 38 40	35 15 18 34	28 33 1 18	8 3 26 14	3 19 35 5	-	28 30 36 2	10 13 19	8 15 35 38	-	19 35 38 2	14 20 19 35	10 13 28 38	13 26		10 19 29 38	11 35 27 28	28 32 1 24	10 28 32 25	1 28 35 23	2 24 35 21	35 13 8 1	32 28 13 12	34 2 28 27	15 10 26	10 28 4 34	3 34 27 16	10 18	
10 Force (Intensity)	8 1 37 18	18 13 1 28	17 19 9 36	28 10	19 10 15	1 18 36 37	15 9 12 37	2 36 18 37	13 28 15 12		18 21 11	10 35 40 34	35 10 21	35 10 14 27	19 2		35 10 21	-	19 17 10	1 16 36 37	19 35 18 37	14 15	8 35 40 5		10 37 36	14 29 18 36	3 35 13 21	35 10 23 24	28 29 37 36	1 35 40 18	13 3 36 24	15 37 18 1	1 28 3 25	15 1 11	15 17 18 20	26 35 10 18	36 37 10 19	2 35	3 28 35 37
11 Stress or pressure	10 36 37 40	13 29 10 18	35 10 36	35 1 14 16	10 15 36 28	10 15 36 37	6 35 10	35 24	6 35 36	36 35 21		35 4 15 10	35 33 2 40	9 18 3 40	19 3 27		35 39 19 2		14 24 10 37		10 35 14	2 36 25	10 36 3 37		37 36 4	10 14 36	10 13 19 35	6 28 25	3 35	22 2 37	2 33 27 18	1 35 16	11	2	35	19 1 35	2 36 37	35 24	10 14 35 37
12 Shape	8 10 29 40	15 10 26 3	29 34 5 4	13 14 10 7	5 34 4 10		14 4 15 22	7 2 35	35 15 34 18	35 10 37 40	34 15 10 14		33 1 18 4	30 14 10 40	14 26 9 25		22 14 19 32	13 15 32	2 6 34 14		4 6 2	14	35 29 3 5		14 10 34 17	36 22	10 40 16	28 32 1	32 30 40	22 1 2 35	35 1	17 32 1 28	32 15 26	2 13 1	1 15 29	16 29 1 28	15 13 39	15 1 32	17 26 34 10
13 Stability of the object's composition	21 35 2 39	26 39 1 40	13 15 1 28	37	2 11 13	39	28 10 19 39	34 28 35 40	33 15 28 18	10 35 21 16	2 35 40	22 1 18 4		17 9 15	13 27 10 35	39 3 35 23	35 1 32	32 3 27 15	13 19	27 4 29 18	32 35 27 31	14 2 39 6	2 14 30 40		35 27	15 32 35		13	18	35 24 30 18	35 40 27 39	35 19	32 35 30	2 35 10 16	35 30 34 2	2 35 22 26	35 22 39 23	18 35	23 35 40 3
14 Strength	1 8 40 15	40 26 27 1	1 15 8 35	15 14 28 26	3 34 40 29	9 40 28	10 15 14 7	9 14 17 15	8 13 26 14	10 18 3 14	10 3 18 40	10 30 35 40	13 17 35		27 3 26		30 10 40	35 19	19 35 10	35	10 26 35 28	35	35 28 31 40		29 3 28 10	29 10 27	11 3	3 27 16	3 27	18 35 37 1	15 35 22 2	11 3 10 32	32 40 28 2	27 11 3	15 3 32	2 13 28	27 3 15 40	15	29 35 10 14
15 Duration of action by moving object	19 5 34 31	-	2 19 9	-	3 17 19	-	10 2 19 30	-	3 35 5	19 2 16	19 3 27	14 26 28 25	13 3 35	27 3 10		-	19 35 39	2 19 4 35	28 6 35 18	-	19 10 35 38		28 27 3 18	10	20 10 28 18	3 35 10 40	11 2 13	3	3 27 16 40	22 15 33 28	21 39 16 22	27 1 4	12 27	29 10 27	1 35 13	10 4 28 15	19 29 39 35	6 10	35 17 14 19
16 Duration of action by Stationary object	-	6 27 19 16	-	1 40 35	-		-	35 34 38	-				39 35 3 23		-		19 18 36 40		-		16		27 16 18 38	10	28 20 10 16	3 35 31	34 27 6 40	10 26 24		17 1 40 33	22	35 10	1	1	2		25 34 6 35	1	20 10 16 38
17 Temperature	36 22 6 38	22 35 32	15 19 9	15 19 9	3 35 39 18	35 38	34 39 40 18	35 6 4	2 28 36 30	35 10 3 21	35 39 19 2	14 22 19 32	1 35 32	10 30 22 40	19 13 39	19 18 36 40		32 30 21 16	19 15 3 17		2 14 17 25	21 17 35 38	21 36 39 31		35 28 21 18	3 17 30 39	19 35 3 10	32 19 24	24	22 33 35 2	22 35 2 24	26 27	26 27	4 10 16	2 18 27	2 17 16	3 27 35 31	26 2 19 16	15 28 35
18 Illumination Intensity	19 1 32	2 35 32	19 32 16		19 32 26		2 13 10		13 19 10	26 19 6		32 30	32 3 27	35 19	2 19 6		32 35 19		32 1 19	32 35 1 15	32	13 16 1 6	13 1	1 6	19 1 26 17	1 19		11 15 32	3 32	15 19	35 19 32 39	19 35 28 26	28 26 19	15 17 13 16	15 1 19	6 32 13	32 15	2 26 10	2 25 16
19 Use of energy by moving object	12 18 28 31	-	12 28	-	15 19 25	-	35 13 18	-	8 15 35	16 26 21 2	23 14 25	12 2 29	19 13 17 24	5 19 9 35	28 35 6 18	-	19 24 3 14	2 15 19		-	6 19 37 18	12 22 15 24	35 24 18 5		35 38 19 18	34 23 16 18	19 21 11 27	3 1 32		1 35 6 27	2 35 6	28 26 30	19 35	1 15 17 28	15 17 13 16	2 29 27 28	35 38	32 2	12 28 35
20 Use of energy by stationary object	-	19 9 6 27								36 37			27 4 29 18	35				19 2 35 32	-				28 27 18 31			3 35 31	10 36 23			10 2 22 37	19 22 18	1 4					19 35 16 25		16
21 Power	8 36 38 31	19 26 17 27	1 10 35 37		19 38	17 32 13 38	35 6 38	30 6 25	15 35 2	26 2 36 35	22 10 35	29 14 2 40	35 32 15 31	26 10 28	19 35 10 38	16	2 14 17 25	16 6 19	16 6 19 37			10 35 38	28 27 18 38	10 19	35 20 10 6	4 34 19	19 24 26 31	32 15 2	32 2	19 22 31 2	18 2 35	26 10 34	26 35 10	35 2 10 34	19 17 34	20 19 30 34	19 35 16	28 2 17	28 35 34
22 Loss of energy	15 6 19 28	19 6 18 9	7 2 6 13	6 38 7	15 26 17 30	17 7 30 18	7 18 23	7	16 35 38	36 38			14 2 39 6	26			19 38 7	1 13 32 15			3 38		35 27 2 37	19 10	10 18 32 7	7 18 25	11 10 35	32		21 22 35 2	21 35 2 22		35 32 1	2 19		7 23	35 3 15 23	2	28 10 29 35
23 Loss of Substance	35 6 23 40	35 6 22 32	14 29 10 39	10 28 24	35 2 10 31	10 18 39 31	1 29 30 36	3 39 18 31	10 13 28 38	14 15 18 40	3 36 37 10	29 35 3 5	2 14 30 40	35 28 31 40	28 27 3 18	27 16 18 38	21 36 39 31	1 6 13	35 18 24 5	28 27 12 31	28 27 18 38	35 27 2 31			15 18 35 10	6 3 10 24	10 29 39 35	16 34 31 28	35 10 24 31	33 22 30 40	10 1 34 29	15 34 33	32 28 2 24	2 35 34 27	15 10 2	35 10 28 24	35 18 10 13	35 10 18	28 35 10 23
24 Loss of Information	10 24 35	10 35 5	1 26	26	30 26	30 16		2 22	26 32						10	10		19			10 19	19 10			24 26 28 32	24 28 35	10 28 23			22 10 1	10 21 22	32	27 22				35 33	35	13 23 15
25 Loss of Time	10 20 37 35	10 20 26 5	15 2 29	30 24 14 5	26 4 5 16	10 35 17 4	2 5 34 10	35 16 32 18		10 37 36 5	37 36 4	4 10 34 17	35 3 22 5	29 3 28 18	20 10 28 18	28 20 10 16	35 29 21 18	1 19 26 17	35 38 19 18	1	35 20 10 6	10 5 18 32	35 18 10 39	24 26 28 32		35 38 18 16	10 30 4	24 34 28 32	24 26 28 18	35 18 34	35 22 18 39	35 28 34 4	4 28 10 34	32 1 10	35 28	6 29	18 28 32 10	24 28 35 30	
26 Quantity of Substance	35 6 18 31	27 26 18 35	29 35 14 18		15 14 29	2 18 40 4	15 20 29		35 29 34 28	35 14 3	10 36 14 3	35 14	15 2 17 40	14 35 34 10	3 35 10 40	3 35 31	3 17 39		34 29 16 18	3 35 31	35	7 18 25	6 3 10 24	24 28 35	35 38 18 16		18 3 28 40	3 2 28	33 30	35 33 29 31	3 35 40 39	29 1 35 27	35 29 25 10	2 32 10 25	15 3 29	3 13 27 10	3 27 29 18	8 35	13 29 3 27
27 Reliability	3 8 10 40	3 10 8 28	15 9 14 4	15 29 28 11	17 10 14 16	32 35 40 4	3 10 14 24	2 35 24	21 35 11 28	8 28 10 3	10 24 35 19	35 1 16 11		11 28	2 35 3 25	34 27 6 40	3 35 10	11 32 13	21 11 27 19	36 23	21 11 26 31	10 11 35	10 35 29 39	10 28	10 30 4	21 28 40 3		32 3 11 23	11 32 1	27 35 2 40	35 2 40 26		27 17 40	1 11	13 35 8 24	13 35 1	27 40 28	11 13 27	1 35 29 38
28 Measurement Accuracy	32 35 26 28	28 35 25 26	28 26 5 16	32 28 3 16	26 28 32 3	26 28 32 3	32 13 6		28 13 32 24	32 2	6 28 32	6 28 32	32 35 13	28 6 32	28 6 32	10 26 24	6 19 28 24	6 1 32	3 6 32		3 6 32	26 32 27	10 16 31 28		24 34 28 32	2 6 32	5 11 1 23			28 24 22 26	3 33 39 10	6 35 25 18	1 13 17 34	1 32 13 11	13 35 2	27 35 10 34	26 24 32 28	28 2 10 34	10 34 28 32
29 Manufacturing Precision	28 32 13 18	28 35 27 9	10 28 29 37	2 32 10	28 33 29 32	2 29 18 36	32 23 2	25 10 35	10 28 32	28 19 34 36	3 35	32 30 40	30 18	3 27	3 27 40		19 26	3 32	32 2		32 2	13 32 2	35 31 10 24		32 26 28 18	32 30	11 32 1			26 28 10 36	4 17 34 26		1 32 35 23	25 10		26 2 18		26 28 18 23	10 18 32 39
30 Object affected harmful factors	22 21 27 39	2 22 13 24	17 1 39 4	1 18	22 1 33 28	27 2 39 35	22 23 37 35	34 39 19 27	21 22 35 28	13 35 39 18	22 2 37	22 1 3 35	35 24 30 18	18 35 37 1	22 15 33 28	17 1 40 33	22 33 35 2	1 19 32 13	1 24 6 27	10 2 22 37	19 22 31 2	21 22 35 2	33 22 19 40	22 10 2	35 18 34	35 33 29 31	27 24 2 40	28 33 23 26	26 28 10 18			24 35 2	2 25 28 39	35 10 2	35 11 22 31	22 19 29 40	22 19 29 40	33 3 34	22 35 13 24
31 Object generated harmful factors	19 22 15 39	35 22 1 39	17 15 16 22		17 2 18 39	22 1 40	17 2 40	30 18 35 4	35 28 3 23	35 28 1 40	2 33 27 18	35 1	35 40 27 39	15 35 22 2	15 22 33 31	21 39 16 22	22 35 2 24	19 24 39 32	2 35 6	19 18 22	2 35 18	21 35 2 22	10 1 34	10 21 29	1 22	3 24 39 1	24 2 40 39	3 33 26	4 17 34 26							19 1 31	2 21 27 1	2	22 35 18 39
32 Ease of manufacture	28 29 15 16	1 27 36 13	1 29 13 17	15 17 27	13 1 26 12	16 40	13 29 1 40	35	35 13 8 1	35 12	35 19 1 37	1 28 13 27	1 13 11	13 10 32	27 1 4	35 16	27 26 18	28 24 27 1	28 26 27 1	1 4	27 1 12 24	19 35	15 34 33	32 24 18 16	35 28 34 4	35 23 1 24		1 35 12 18		24 2			2 5 13 16	35 1 11 9	2 13 15	27 26 1	6 28 11 1	8 28 1	35 10 28 1
33 Convenience of Use	25 2 13 15	6 13 1 25	1 17 13 12		1 17 13 16	18 16 15 39	1 16 35 15	4 18 39 31	18 13 34	28 13 35	2 32 12	15 34 29 28	32 35 30	32 40 3 28	29 3 8 25	1 16 25	26 27 13	13 17 1 24	1 13 24		35 34 2 10	2 19 13	28 32 2 24	4 10 27 22	4 28 10 34	12 35	17 27 8 40	25 13 2 34	1 32 35 23	2 25 28 39		2 5 12		12 26 1 32	15 34 1 16	32 26 12 17		1 34 12 3	15 1 28
34 Ease of repair	2 27 35 11	2 27 35 11	1 28 10 25	3 18 31	15 13 32	16 25	25 2 35 11	1	34 9	1 11 10	13	1 13 2 4	2 35	11 1 2 9	11 29 28 27	1	4 10	15 1 13	15 1 28 16		15 10 32 2	15 1 32 19	2 35 34 27		32 1 10 25	2 28 10 25	11 10 1 16	10 2 13	25 10	35 10 2 16		1 35 11 10	1 12 26 15		7 1 4 16	35 1 13 11		34 35 7 13	1 32 10
35 Adaptability or versatility	1 6 15 8	19 15 29 16	35 1 29 2	1 35 16	35 30 29 7	15 16	15 35 29		35 10 14	15 17 20	35 16	15 37 1 8	35 30 14	35 3 32 6	13 1 35	2 16	27 2 3 35	6 22 26 1	19 35 29 13		19 1 29	18 15 1	15 10 2 13		35 28	3 35 15	35 13 8 24	35 5 1 10		35 11 32 31		1 13 31	15 34 1 16	1 16 7 4		15 29 37 28	1	27 34 35	35 28 6 37
36 Device complexity	26 30 34 36	2 26 35 39	1 19 26 24	26	14 1 13 16	6 36	34 26 6	1 16	34 10 28	26 16	19 1 35	29 13 28 15	2 22 17 19	2 13 28	10 4 28 15		2 17 13	24 17 13	27 2 29 28		20 19 30 34	10 35 13 2	35 10 28 29		6 29	13 3 27 10	13 35 1	2 26 10 34	26 24 32	22 19 29 40	19 1	27 26 1 13	27 9 26 24	1 13	29 15 28 37		15 10 37 28	15 1 24	12 17 28
37 Difficulty of detecting and measuring	27 26 28 13	6 13 28 1	16 17 26 24	26	2 13 18 17	2 39 30 16	29 1 4 16	2 18 26 31	3 4 16 35	36 28 40 19	35 36 37 32	27 13 1 39	11 22 39 30	27 3 15 28	19 29 39 25	25 34 6 35	3 27 35 16	2 24 26	35 38	19 35 16	19 1 16 10	35 3 15 19	1 18 10 24	35 33 27 22	18 28 32 9	3 27 29 18	27 40 28 8	26 24 32 28		22 19 29 28	2 21	5 28 11 29	2 5	12 26	1 15	15 10 37 28		34 21	35 18
38 Extent of automation	28 26 18 35	28 26 35 10	14 13 17 28	23	17 14 13		35 13 16		28 10	2 35	13 35	15 32 1 13	18 1	25 13	6 9		26 2 19	8 32 19	2 32 13		28 2 27	23 28	35 10 18 5	35 33	24 28 35 30	35 13	11 27 32	28 26 10 34	28 26 18 23	2 33	2	1 26 13	1 12 34 3	1 35 13	27 4 1 35	15 24 10	34 27 25		5 12 35 26
39 Productivity	35 26 24 37	28 27 15 3	18 4 28 38	30 7 14 26	10 26 34 31	10 35 17 7	2 6 34 10	35 37 10 2		28 15 10 36	10 37 14	14 10 34 40	35 3 22 39	29 28 10 18	35 10 2 18	20 10 16 38	35 21 28 10	26 17 19 1	35 10 38 19	1	35 20 10	28 10 29 35	28 10 35 23	13 15 23		35 38	1 35 10 38	1 10 34 28	18 10 32 1	22 35 13 24	35 22 18 39	35 28 2 24	1 28 7 19	1 32 10 25	1 35 28 37	12 17 28 24	35 18 27 2	5 12 35 26	

OXFORD CREATIVITY

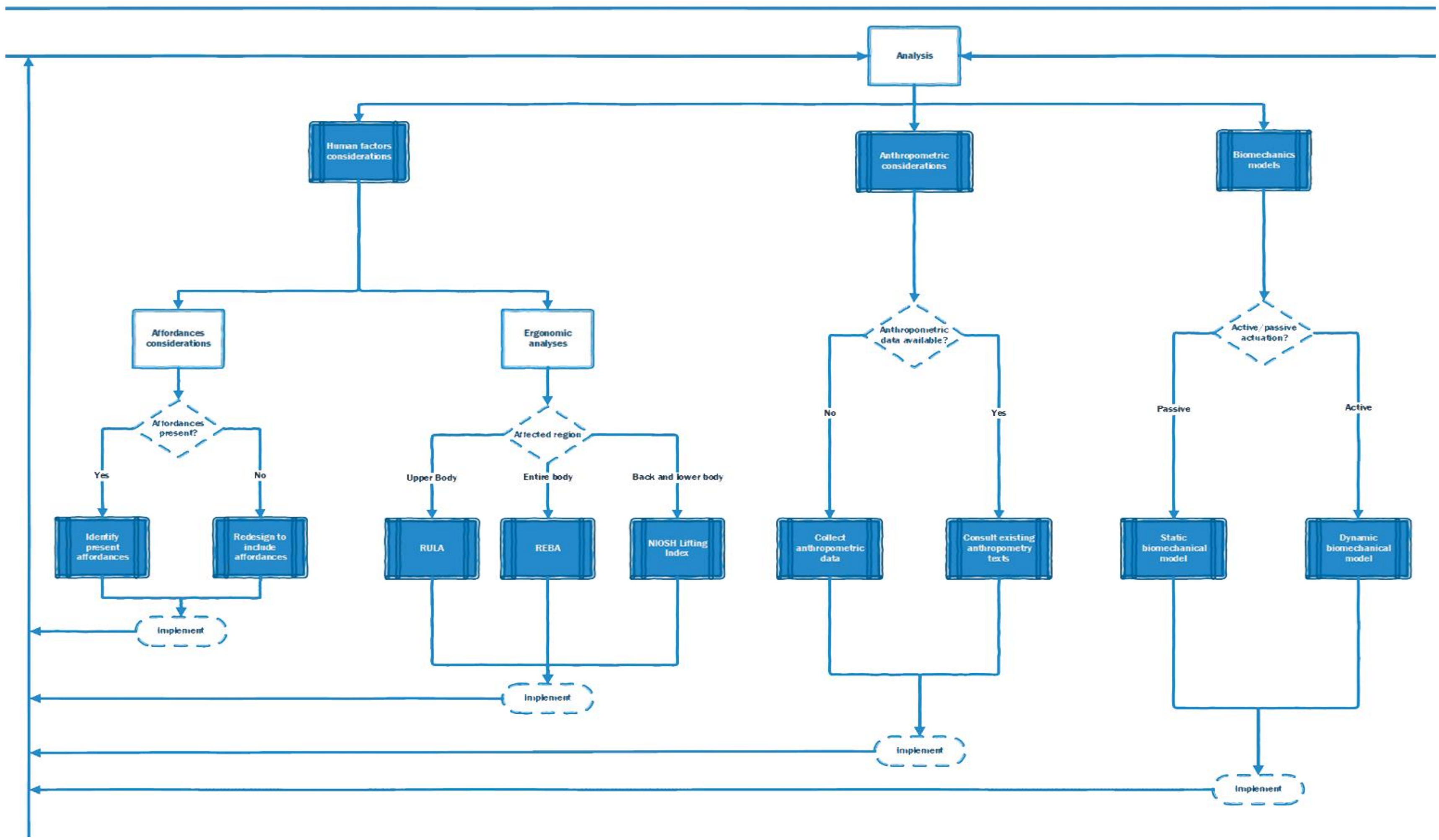
40 Inventive Principles — Separation Principles for Solving Physical Contradictions

No.	Inventive Principle	Space	Time	Condition	Scale
1	Segmentation	✓	✓		✓
2	Taking Out	✓			
3	Local Quality	✓			✓
4	Asymmetry	✓			
5	Merging				✓
6	Universality				✓
7	Nested Doll	✓	✓		
8	Anti-Weight				✓
9	Prior Counteraction		✓		
10	Prior Action		✓		
11	Cushion In Advance		✓		
12	Equipotentiality				✓
13	The Other Way Round	✓			✓
14	Spheroidality - Curvature	✓			
15	Dynamics		✓		
16	Partial or Excessive Action		✓		
17	Another Dimension	✓			
18	Mechanical Vibration		✓		
19	Periodic Action		✓		
20	Continuity of Useful Action		✓		
21	Rushing Through		✓		
22	Blessing in Disguise				✓
23	Feedback				✓
24	Intermediary	✓	✓		
25	Self-Service				✓
26	Copying	✓	✓		
27	Cheap Short-Living Objects		✓		✓
28	Replace Mechanical System			C	
29	Pneumatics and Hydraulics		✓	C	
30	Flexible Membranes / Thin Films	✓			
31	Porous Materials			C	
32	Colour Change			C	
33	Homogeneity				✓
34	Discarding and Recovering		✓		
35	Parameter Change			C	
36	Phase Transition			C	
37	Thermal Expansion		✓		
38	Accelerate Oxidation			C	
39	Inert Environment			C	
40	Composite Materials	✓			✓

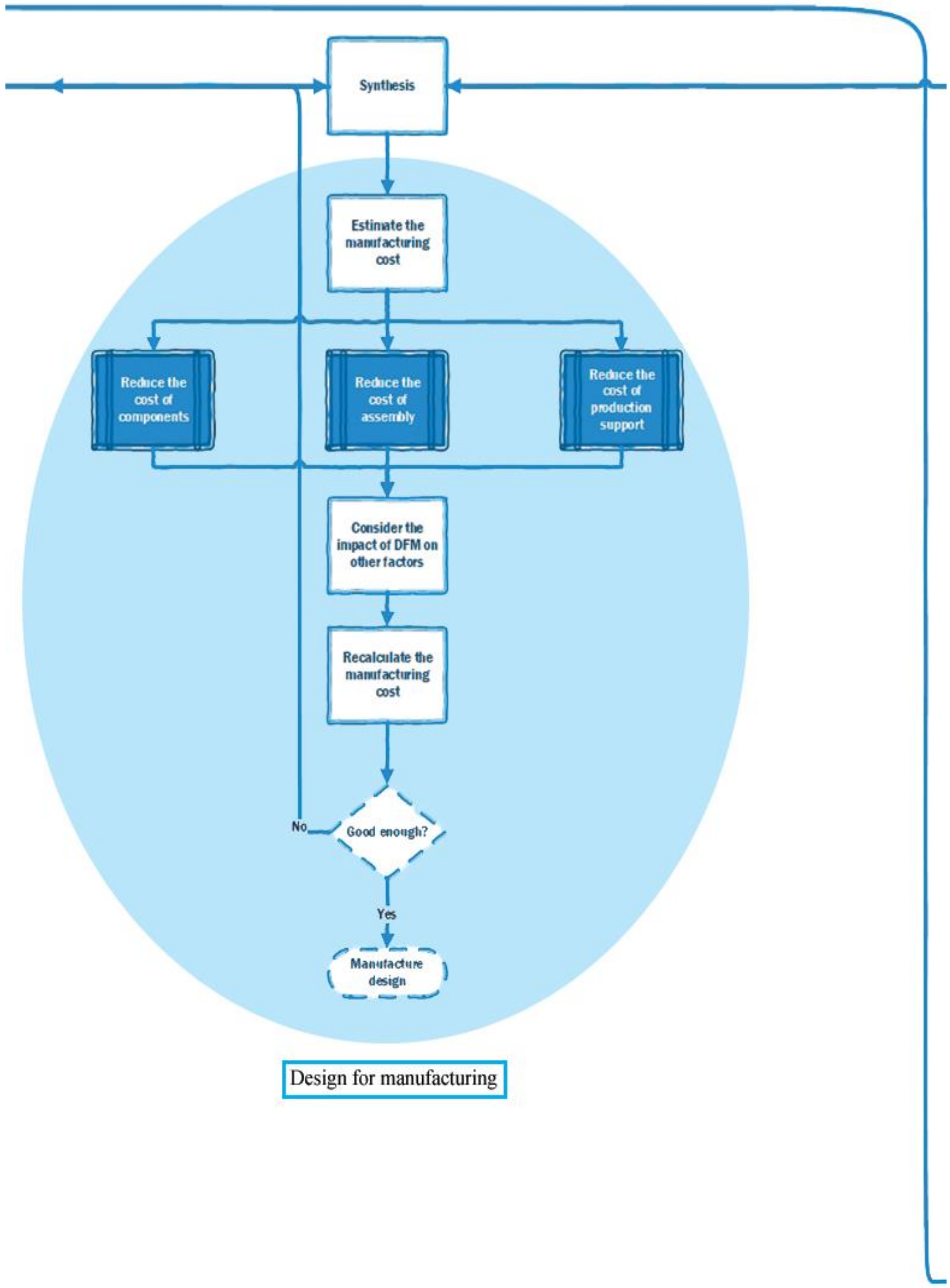
APPENDIX T: QUANTUM EX FLOWCHART 1 OF 4



APPENDIX U: QUANTUM EX FLOWCHART 2 OF 4



APPENDIX V: QUANTUM EX FLOWCHART 3 OF 4



APPENDIX W: QUANTUM EX METHOD 4 OF 4