ARCTiC LawE: Armed Robotic Control for Training in Civilian Law Enforcement

by

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DEDICATION

This work is dedicated in part to my parents, my sister, my brother-in-law, and my nephew – the youngest addition to my ever-growing family – and to my cousins Kent and Rhonda. My parents for helping me develop my critical thinking skills, my sister and brother-in-law for their support, my nephew who I will, slowly but surely, turn to a STEM related field, and Kent and Rhonda who often babysat me and helped put me on the engineering track.

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ABSTRACT

Much of this thesis looked at performing a cogent literature review of exoskeletons to determine the state-of-the-art and to determine the remaining needs in exoskeletal design. The literature review of over 80 journals, allowed the researcher to determine the lack of research in upper body exoskeletons for training in civilian, military, and law enforcement personnel.

Thus the genesis of the **A**rmed **R**obotic **C**ontrol for **T**raining in **C**ivilian **Law E**nforcement, or ARCTiC LawE, an upper body exoskeleton designed to assist civilian, military, and law enforcement personnel in accurate, precise, and reliable handgun techniques. This exoskeleton training utilizes 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 project aims to train and test subjects with no handgun training/experience with the ARCTiC LawE, and without, and compare the results of accuracy, precision, and speed. 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 hand guns to reduce the cost of training time and munitions and will increase accuracy and precisions for typical law enforcement and military live fire drills. Additionally, this project increases the breadth of knowledge for exoskeletons as a tool for training.

CHAPTER I:

GENERAL INTRODUCTION

This paper begins by telling the reader that the following chapter is material written for a paper currently under review for publication – Thomas M. Schnieders and Richard T. Stone, “Current Work in the Human-Machine Interface for Ergonomic Intervention with Exoskeletons”, Journal of Human-Robot Interaction, under review. The paper may go through some changes in the review process that are not included in this thesis, so it may not be exactly the same paper.

Research Motivation

Research has shown that tremors in the arm have negative affect on aiming [43, 53, 81] however, accuracy when aiming and firing a handgun depends on three primary factors: (1), environmental, (2) hardware, and (3) human factors [6]. A lot of devices have been developed to mitigate environmental impact and hardware impact on accuracy, but few exist to assist in training or augmenting humans. The human factors that affect aim include (1) fatigue [23], (2) experience [26], (3) body sway [7], (4) heart rate [86] and (5) arm tremors [6].

There are many exoskeletons that focus on limiting motion or suppressing tremors. However, as of the writing of this thesis, there has only been one other publication that looks at applying exoskeletons specifically for handgun training – MAXFAS, a mobile arm exoskeleton for firearm aim stabilization [6] designed and

Figure 1: MAXFAS [6]

validated by Dan Baechle as a partial completion of his master's 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 essentially a series of cuffs, tension sensors, motors, and cables mounted to the exoskeleton and an aluminum frame above 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 experiments demonstrated that the MAXFAs, a cable-driven arm exoskeleton, is a viable method of improving piston 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 exoskeleton, and (7) evaluate the effect of learning later than 5 minutes after removing exoskeleton.

Thesis Organization

The second chapter of this thesis is a journal publication currently under review by *The Journal of Human-Robot Interaction*. It is essentially 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 III takes the results of the second chapter and uses it as the driving force for the **A**rmed **R**obotic **C**ontrol for **T**raining **i**n **C**ivilian **Law E**nforcement, or ARCTiC LawE for short. This chapter covers the design, development, and manufacturing processes for The ARCTiC LawE which segues into Chapter IV and Chapter V, which cover the methodology and results, respectively, for the first study. Chapter VI and Chapter VII cover the methodology and results, respectively, for the second study. The final chapter, Chapter VIII provides a conclusion, implications of the research, and potential for future research which will be continued in Doctoral research.

CHAPTER II:

CURRENT WORK IN THE HUMAN-MACHINE INTERFACE FOR ERGONOMIC INTERVENTION WITH EXOSKELETONS

A paper in review by *The Journal of Human-Robot Interaction*

Thomas M. Schnieders and Richard T. Stone

Abstract

This literature review of exoskeleton design provides a brief history of exoskeleton development, discusses current research of exoskeletons with respect to the innate human-machine interface, and the incorporation of exoskeletons for ergonomic intervention, and offers a review of needed future work. Development of assistive exoskeletons began in the 1960’s but older designs lacked design for human factors and ergonomics and had low power energy density and power to weight ratios. Advancements in technology have spurred a broad spectrum of research aimed at enhancing human performance and assisting in rehabilitation. The review underwent a holistic and extensive search of over 80 journals and provides a reflective snapshot of the state of the art in exoskeleton design as it pertains to the incorporation of exoskeletons for ergonomic intervention. The key technologies in the state of the art involve sensing the user’s intent and actuating the movement of limbs based on that intent. There are many exoskeleton designs that deal with utilizing exoskeletons as rehabilitative devices or for human augmentation. Some of the remaining challenges include improving the energy density of exoskeleton power supplies, improving the power to weight ratio of actuation devices, improving the mechanical human-machine interface, and dealing with variability between users.

Introduction

The field of exoskeleton design is broad and expansive. This paper serves as a literature review of exoskeleton design with respect to the human-machine interface. It provides an outline of a brief history, current research, the potential benefits of exoskeleton use, and finishes with a discussion of the possible future of exoskeletons.

It is imperative to begin this paper by clearly defining the difference between exoskeletons and orthotics. It is also important to note that these two terms often overlap in the media as well as in the scientific literature.

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 [62]

An orthotic, or orthosis (plural: orthoses) refers to a device that is externally applied to the body. It is different from a prosthetic where a device substitutes a missing body part. External devices such as dental braces, insoles, or a pair of glasses are examples of orthotic devices [77]. Active orthoses are limited by the daunting issue that the specific nature of disability varies from one person to another. This makes it difficult to create one generally applicable device. 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 [18].

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” [31].

Initial development of exoskeletons can be tracked 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 [39].

General Electric (GE) developed the first exoskeleton device, beginning in the 19060’s and continuing until 1971, called the Hardiman. 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 ideas was well received, but the Hardiman had practical difficulties due to its own weight of 1500 pounds. The walking speed of 2.5 ft. /sec limited its uses. Any attempted practical testing with the exoskeleton was impossible with a human inside due to the uncontrolled violent movements [2].

Figure 2: GE Hardiman [2]

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. 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 [55]. 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 [39].

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 my bipedal robots [97].

Overview of Exoskeletons

Uses and Market

Exoskeletons are used in two primary roles: rehabilitation and human performance augmentation. However, their use is quickly expanding into other fields such as sports, firefighting, and law enforcement. According to Rocon [72] and Harwin [30], 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. Applications include fatigue reduction and heavy lifting, with much 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 [11], or any application that requires heavy gear and heavy lifting in rough terrain impassable by vehicle.

This paper 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, as well as enhancement capabilities of a healthy human being.

Most lower body exoskeleton robots first started to assist soldiers in supporting equipment. Wearable lower suits can greatly reduce the oxygen consumption of soldiers; support energy for walking, running, and jumping; and help movement and operational capability of soldiers [100]. Therefore, the exoskeleton robot, also called a wearable robot, is a mechanical robot that humans can wear [18]. It is important to understand the biomechanics of humans in order to develop ergonomic designs of exoskeletons and active orthoses for the lower limbs [18].

BLEEX

The Berkeley Lower Extremity Exoskeleton, or BLEEX, is the first energetically autonomous robotic exoskeleton that was successfully demonstrated to provide an operator with the ability to carry significant loads with minimal effort over any type of terrain. BLEEX has four critical features: (1) a novel control scheme, (2) high-powered compact power supplies – hydraulic and electric actuations that have been designed to power BLEEX, (3) a special communication protocol and electronics, and (4) a design architecture that decreases complexity and power consumption [15, 103].

Figure 3: BLEEX [15]

The BLEEX enables its wearer to carry a heavy load. It was first presented from U.C. Berkeley's Human Engineering and Robotics Laboratory supported by the Defense Advance Research Project Agency (DARPA) [18]. The BLEEX seeks to supplement the intelligence and sensory systems of a human with the significant strength and endurance of a pair of wearable robotic legs that offers a payload capacity [15].

HAL-5

Figure 4: HAL-5 [29]

HAL-5, the fifth rendition of the Hybrid Assistive Limb (HAL), is a powered exoskeleton suit which now includes upper-body limbs, lighter and more compact power units, longer battery life, and a better body shape to fit humans more easily and ergonomically. This suit also includes two control systems – voluntary control and autonomous control [29]. HAL-5 is designed to not only help disabled patients in hospitals and the elderly, but also to support workers with demanding physical jobs, such as disaster rescue or construction [29].

XOS2

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 [66]. 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 [100].

Figure 6: XOS2 [66]

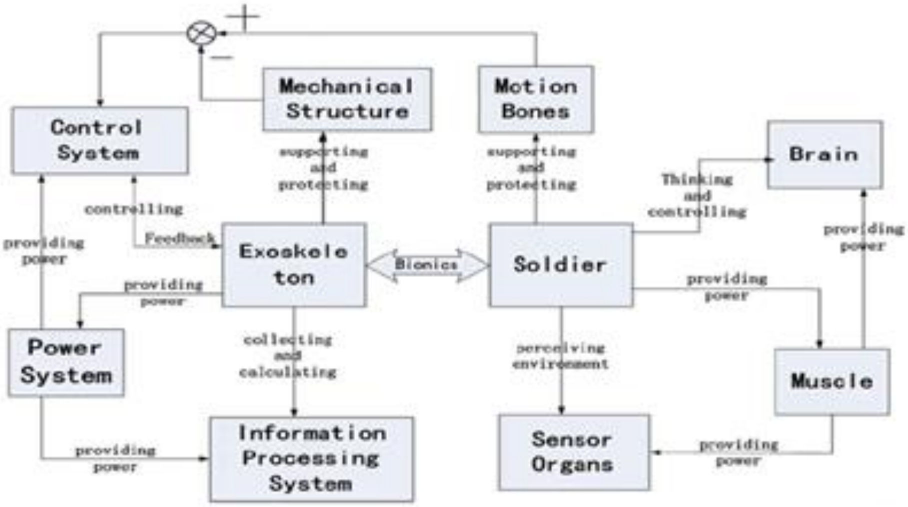


Figure 5: The Control principle of Exoskeleton [66]

Figure 5, above, shows the control system created by Jack Dobson, inventor of the XOS2. The control system was designed to “counteract the force on the sensors and take the force on the sensors to zero by opening the valves, so the soldier does not feel any force on his/her body" [82, 15]. The XOS2 is a whole-body exoskeleton, larger than a human's body, but does not entirely imitate the shape of humans [100]. The human body, using an XOS2, receives output from the exoskeleton's sensors to minimize the assistance a soldier wearing it can receive, with less effort required to carry heavier loads because the exoskeleton supports the load providing less stress on the human frame [100].

ReWalk

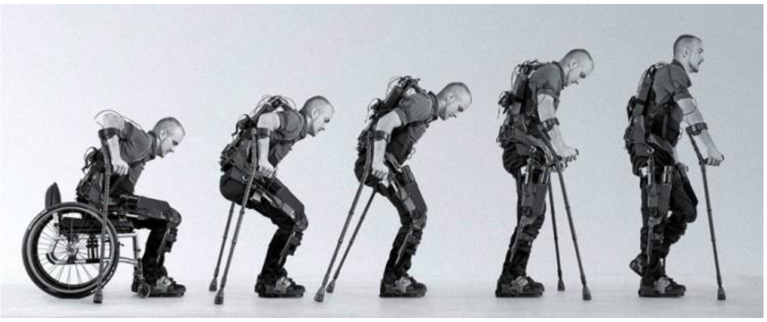


Figure 7: ReWalk [69]

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 [69]. 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.

Soft Exosuit

Developed by the Wyss Institute, the Soft Exosuit consists of a combination of sensors, such as a hyperelastic strain sensor and sensors around the wearer's hips, calves, and ankles secured by straps [86]. The soft flexible materials, composed of "soft, functional textiles woven into a piece of smart clothing"[86], not only interface with the wearer, but also provide a flexible structure so assistive torques can be applied to biological joints [86]. This soft exosuit has strong commercial potential for helping spinal-cord injury patients walk or helping soldiers carry heavy loads [86]. 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 [4]. 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 [4].

Figure 8: Soft Exosuit [86]

The RoboKnee

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 [62]. 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 [63].

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 [63]. Further recommendation from authors was to develop an exoskeleton that incorporate other joints than just the knee [63].

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.

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 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” [72]. Furthermore, upper limb joint anatomy is complex. The shoulder, for example, is located by three bones (the clavicle, scapula, and humerus), and allows for four articulations, resulting in a dynamic and irregular center of rotation [28] 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 assistance in the daily activities of living. However, upper body exoskeletons could also be applied to augment the performance of healthy individual [11], to provide a haptic interface in virtual reality simulations, or to act as a master device in teleoperation [58]. Some specific samples from the literature are described in the following sections.

Posture Support

An important function of upper body exoskeletons has been posture support. The SUEFUL-7 is a 7DoF upper-limb motion assist exoskeleton robot that is used to test electromyography (EMG) control methods using neuro-fuzzy modifiers in assisting the motions of the shoulder, elbow, forearm, and wrist of physically weak individuals. The use of the neuro-fuzzy modifiers allows impedance parameters to be adjusted in real time by considering the upper-limb posture and EMG activity levels [27].

The T-WREX or Therapy Wilmington Robotic Exoskeleton, is a 5DoF upper arm exoskeleton containing an orthosis, a grip sensor, and software that is used in the training of stroke patients. WREX, the original design, was developed to assist children in daily living activities who do not have enough strength in their arms. The T-WREX enables a wide reach of the arm across a workspace, hand grip pressure detection, and functional training movement simulation [71].

The Wearable Orthosis for Tremor Assessment and Suppression (WOTAS) provides a means of testing and validating control strategies for orthotic tremor suppression [75]. Unlike most exoskeletons that seek to enhance intended muscle movement, the purpose of WOTAS is to dampen unintended movement, and it is capable of operating in both active and passive damping modes. The control algorithm of WOTAS must distinguish between wanted and unwanted movement.

Rehabilitation

One of the most useful and most research functions of upper body exoskeletons has been rehabilitation of the body. The Cable-Actuated Dextrous Exoskeleton for Neurorehabilitation (CADEN-7) is an anthropometric 7DoF powered exoskeleton system with negligible backlash, backdriveable transmissions, low-inertia links, high stiffness transmissions, open mechanical human machine interfaces (mHMI's), and a range of motion (ROM) representing 88% of a human physiological ROM [59]. CADEN-7 was used in the development of myoprocessors for upper limbs based on the Hill phenomenological muscle model. Genetic algorithms were used to optimize the internal parameters of the myoprocessors using an experimental database that provided inputs to the model. Research results indicated high correlation between joint predictions of the model and the measured data, suggesting that the myoprocessor was sufficiently robust for further integration into exoskeleton control systems [59].

Most upper limb rehabilitation systems have been developed for unilateral training, but the upper limb exoskeleton rehabilitation device (ULERD) can be used for bilateral training. The ULERD has three active DoF and four passive DoF. The ULERD incorporates a commercial haptic device known as Phantom Premium, as well as an inertia sensor known as MTx, to detect input signals from one arm which is held stationary. The output movement is performed by a wearable exoskeleton on the right arm, and also shown graphically using an OpenGL animation [87].

Figure 9: ARMin II [54]

ARMin is used for rehabilitation purpose of the arm, which has 4DoF and 2 passive DoF enabling elbow flexion/extension and shoulder rotations. It was installed with multiple sensors for position, force, and torque, so that this robotic system can combine the cooperation and motivation of patients into therapy activities, and give support to the patients based on their needs. Special mechanical design can be seen in ARMin, which includes a customized module for upper arm rotation, enabling small friction during rotation and patient comfort while wearing the device rotation, enabling small friction during rotation and patient comfort while wearing the device [54]. ARMin II, which is a 7DoF robotic system for therapy purposes, was developed after the first version. ARMin II can adapt to different patients' sizes with adjustments of five parts and be optimized for combining user cooperation with control strategies. The ARMin II is under evaluation and testing for further improvements [53].

The Cable-driven Arm Exoskeleton (CAREX) is lighter weight compare to a traditional rigid exoskeleton. Cables are used to move human upper body segments, which are powered by motors and guided by cuffs. CAREX can provide push and pull with predefined force in required direction during rehabilitation trainings [52].

The Mirror Image Movement Enabler (MIME) robotic device is the result of development work that has been happening since 1998. Early research indicated that bilateral training was more effective than unilateral training when using similar movements. A robotic controller (PUMA 560) was used to manipulate the forces needed, which therapists use for normal therapy training. The movements assisted by robot can be classified as four different types: passive, active-assisted, active-constrained, and bilateral. During passive training, the robot moves the human arm to reach the target with a defined path without human effort. During active-assisted training, a human initiates the movement using force and collaborates with the robotic device to reach the target. During active-constrained training, desired movements are defined by the robot and the maximum effort of the operator needed to reach the target. During bilateral training, the target arm is assisted by the robot to do the same movement as the contralateral arm. In this study Fugl-Meyer and EMG data were collected and analyzed for rating the improvement of the participants and the muscle engagement during the training [51].

Significant research and development of exoskeleton use in medical and rehabilitation fields has been completed. ABLE was developed at CEA-LIST Interactive Robotics Unit, a French public research institute specializing in digital systems design. The first applications were used in a rehabilitation project. Further applications for industry and professional fields include intuitive telerobotics, haptic devices for Virtual Reality (VR), and sports training. ABLE used a circular guide for the shoulder joint, which solved the problem of singularity. ABLE used a screw cable system and could be integrated with the motor power transmission of another robotic without modification. ABLE with 4 axes benefited the rehabilitation project. The ABLE-7 axis model has a lighter weight and a 3-axis open forearm-wrist, which can be used for teleoperation and virtual reality [24].

Human Performance Augmentation

The Titan Arm is a lightweight upper body exoskeleton designed to closely mimic human range of motion and assist weakened individuals with regained mobility and independence. The Titan Arm provides 3DoF with non-localized actuation, and a ratchet based braking system that allows it to hold static loads without requiring force from the user [8]. The Titan Arm carries most of its weight in the back-plate and is capable of augmenting the user’s lifting strength by up to 40 lbs. In addition, the system is able to provide real-time joint tracking, which can be streamed to a computer for analysis.

Extremities

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

Extremities: Hands

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.

Rehabilitation

The Hand Exoskeleton Rehabilitation Robot, or HEXORR, is an exoskeleton whose robot joints are aligned with anatomical joints of the human hand and provides direct control of these hand joints. HEXORR uses a low-friction gear train and electric motors. This combination allows for both position and torque control, which is an advantage. Another advantage, which HEXORR provides, is psychologically accurate grasping patterns, which are controlled with just two actuators, compared to other complex designs that use eighteen actuators. All of these factors make HEXORR unique compared to other devices [79].

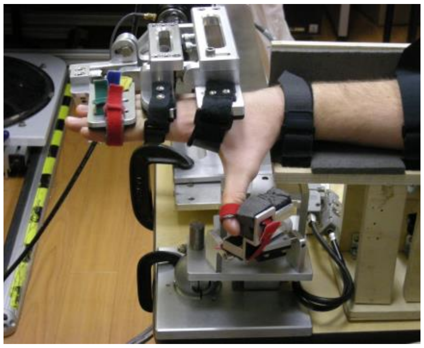


Figure 10: HEXORR [79]

The use of EMG signals to control exoskeletons is becoming more commonplace, especially in paraplegics and quadriplegics [5, 36, 40, 44]. There are over 12,000 new cases of spinal cord injury per year [22] and “nearly half of these cases result in a loss of sensation or motion to the arms and hands” [50]. The researchers at Carnegie Mellon University developed an effective EMG-based hand exoskeleton that enabled pinching movements in patients who lacked hand mobility. It uses a functional electrical stimulation system (a system that stimulates muscles that no longer receive signals from the central nervous system), and a low-profile lightweight exoskeleton that consists of “an aluminum anchoring plate mounted to the back of the hand and three aluminum bands, one for each of the finger bands [50],” in conjunction with steel cabling that runs along the front of each finger band, a pneumatic cylinder, and a mechanical linkage mechanism.

An exoskeleton designed for upper arm rehabilitation and hand grasp training called the IntelliArm is able to control the user’s shoulder, elbow, wrist, and finger with 8+2DoF. The IntelliArm builds on the research of the following: MIT MANUS, an upper body arm exoskeleton that assisted in arm reaching movements in post stroke rehabilitation [33, 43]; Reinkensmeyer et al.’s Arm Guide robot, another upper body arm exoskeleton that was used to treat and evaluate post stroke patients by guiding their arm along a linear guide [67]; and an industrial robot attached to a forearm splint called MIME, or a mirror image motion enabler, that assisted movement passively or actively [12]. The IntelliArm also built on the work of the ARMin, described in section 3.3 Upper Body. The designs of the other rehabilitation robots that the IntelliArm built upon did not consider patients’ hand posture. The researchers found that if they were to “ignore a proper control of the muscle tension of a subject’s hand, the robotic training may lower hand/finger flexibility and potentially cause an abnormal muscle tone [68].”

A tendon-driven exoskeleton that controls flexion of 2DoF per finger was designed for physical therapy at the University of Salford [77]. A hand exoskeleton for the rehabilitation of stroke patients is the Rutgers Master II, which actuates the user’s fingers via four pneumatic pistons located inside the palm [10].

Another hand exoskeleton designed for stroke patients is the Wrist/Finger Force Sensing module (WFFS), which is used during movements of the upper limb in chronic hemiparetic stroke patients. “The WFFS measures isometric flexion/extension forces generated by the wrist, fingers, and thumb during 3-D movements of the paretic upper limb [54].” Unlike other hand exoskeletons, the WFFS is able to generalize 3-D movements of the hand in conjunction with the rest of the limb. This hand exoskeleton acts as a lightweight, portable, and rigid forearm orthosis of the ACT3D robot, an arm coordination training device. This allows for measurements of wrist and finger forces during any tasks that the ACT3D normally performs.

EVA

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 [83]. 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. This project was implemented in August 1998. 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 [94].

VR/AR-Haptic


Figure 11: CyberGrasp [98]

Much of the early literature for hand exoskeletons is geared towards their use as haptic feedback for virtual reality and augmented reality environments. VRLogic's CyberGrasp is a commercially available haptic interface for the hand that delivers a force feedback system to the fingers and hand. It utilizes pull cables with brakes on their distant end to restrict movement [98]. A hand exoskeleton was developed at the Robotics Center-Ecole des Mines de Paris that is able to support bidirectional movement for two fingers. It is capable of four degrees of freedom for each finger, but can only control one at a time through the use of a pull cable [88]. Another hand exoskeleton developed for haptic feedback is the LRP Hand Master. It is capable of supporting 14 bidirectional and actuated degrees of freedom [92].

Extremities: Ankles/Feet

KAFO

The reason for building the Knee Ankle Foot Orthosis, or KAFO, was to extend the pneumatically powered ankle orthosis concept to the knee and test its performance on healthy walkers. The KAFO was built with a unilateral powered knee-ankle-foot-orthosis with antagonistic pairs of artificial pneumatic muscles at both the ankle (i.e., plantar flexor and dorsiflexor) and the knee (i.e., extensors and flexors) [78].

GAIT

GAIT is an exoskeleton conceived as a compensation and evaluation system of pathological gait for application in real conditions as a combined assistance and assessment method of the problems affecting mobility in individuals with neuromotor disorders. Interaction with the human neuromotor system to assist locomotion requires adequate design of the components, including both the biomechanical and functional aspects. Robotic exoskeletons conceived as an aid to mobility are designed to be used in numerous environments [61].

Full Body Exoskeletons

BLEEX

The Berkeley Lower Extremity Exoskeleton, mentioned in the Lower Body portion of this document, is just the beginning work for the University of California, Berkeley. The researchers also plan to develop an upper body exoskeleton. After they are certain that both are capable of functioning independently, they will attempt to integrate the two systems [38].

Ekso

Ekso by Ekso Bionics is a primarily lower body exoskeleton for individuals with any amount of lower extremity weakness or limb pathology related to standing and/or walking. The exoskeleton uses battery powered motors to drive the legs when the exoskeleton's sensors pick up intended movement. The exoskeleton is capable of providing natural gait and assists in gait training for patients who suffer from complete paralysis and who have minimal forearm strength [20]. The Ekso exoskeleton is considered a Class I medical device in the United States, a Class I medical device in Australia, and a Class IIa medical device in the European Union [20].

HULC

Lockheed Martin's Human Universal Load Carrier (HULC) is a hydraulic-powered, titanium, anthropomorphic exoskeleton designed for military use. It is capable of carrying up to 200lbs, march at 3 mph, sprint at 10 mph, can travel 20 km on level terrain at 4 km per hour, and can be set to a long-range mode for extended 72 hour missions [32]. The HULC weighs in at 53 lbs., is powered by lithium polymer batteries, and is capable of integrating with armor, heating and cooling systems, additional sensors, and other custom attachments.

TALOS

The U.S. Government has officially sanctioned a full body exosuit for military use. The Tactical Assault Light Operator Suit, or TALOS, is the planned future of warfare. The US Army requested white papers from academia, industry, public labs, and any interested individuals on how to design and build TALOS. Not much has been released on this in-development suit; however, there has been speculation that TALOS will feature an already designed exoskeleton at its core [95]. The most likely candidates at this time are Lockheed Martin’s HULC and Raytheon’s XOS 2.

TALOS, when fully completed, will be bulletproof, weaponized, able to monitor vitals, give its wearer superhuman strength and perception, have layers of smart materials and sensors, and use wide-area networking and on-board computers to provide more substantial situational awareness [3]. The U.S. Army Research, Development and Engineering Command, known as RDECOM will be involved in every aspect of TALOS development.

The Benefits of Exoskeletons

Personal Cost

Lo and Xie (2012) stated that exoskeleton training using in rehabilitation could potentially enable self-therapy activities without involvement of a therapist, which could reduce rehabilitation cost. Exoskeleton training could be flexible, not limited to time and location, which could reduce scheduling conflicts and provide for more frequent training. The cost associated with these problems could be reduced [49].

Rehabilitation

Rehabilitation improvement relies on intensity of training and patients’ motivation. Recent studies on exoskeleton for rehabilitation indicate that an exoskeleton can provide training at different levels and more frequently compared to traditional therapist training. Experimental results also indicate that exoskeleton assisted training is effective for daily living activities, which could benefit stroke patients recovering from neurological and orthopedic damages [53]. Games are integrated into some exoskeleton training activities. Training processes are designed as games in order to provide patients with an entertaining experience, which can increase their motivation to complete therapy [35, 49].

Industrial Application

An exoskeleton can be used as a human assistive device in industrial environments by reducing the load on the human body, which would 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 the virtual objects' characteristics. Additionally, exoskeletons have served as master devices for manipulating control systems [74].

Military Application

To enhance a soldier's capability and reduce their workload, exoskeletons were developed to assist soldiers with increased carrying and firing ability for heavy weapons [99]. There is plenty of room for research in military application.

What Don't We Know About Exoskeletons?

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 create a mapping from EMG patterns to muscle forces; this should be a primary research focus over the next three to four years.

This method of control 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, as well as 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 [17].

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 [49]. PMA has a high power-to-weight ratio but lacks bandwidth, while motors have sufficient bandwidth but have a poor power-to-weight ratio [49].

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 [49].

Another limitation is the singular configuration present in exoskeletons with a 3DoF shoulder complex, which occurs when two rotary joints align with each other, resulting in the loss of 1DoF. 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 [49].

There is limited consideration of the interactions between the exoskeleton and the human user. No major study has made any attempt to assess exoskeletons specific to human labor. Beyond work related to rehabilitation exoskeleton research does not effectively consider biomechanical or degenerative aspects of exoskeleton design on the human. The mechanical HRI location and interface area for optimal load transfer and comfort have not been considered in current exoskeletons [49].

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.

What Can We Do to Make Exoskeletons Better?

There are at least two 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 lead to more effective exoskeleton leg architectures [18]. 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 [18].

Investigation of non-anthropomorphic architectures may provide solutions to some of the problems associated with closely matching the structure of an exoskeleton to the wearer, such as the need for close alignment between joints of the wearer and the exoskeleton [18]. More research is required on recreational exoskeletons that augment running and/or jumping ability [18].

Besides enabling technology and mechanical design, there are at least three issues related to the implementation of exoskeletons and active orthoses that needs further studying [18]. An exoskeleton with good mechanical strength, less weight, sufficient grip force, low power consumption, a computational capability compatible to control scheme, and high speed of operation [85] would be an ideal design.

The design of structure is one area where an imaginative design may reduce a lot of stress from weight constraint. The grip force and power consumption can be addressed by the proper choice of actuators [85]. The ideal requirements include the material for the mechanical structure having mechanical strength, flexibility, and weight like bone; the controller having computational capability, speed, and adaptability like a brain; the actuator having high torque and flexibility like muscles; and the feedback elements having sensing capability like skin [85].

EMG is a relatively new technology. It has definite potential to be used as a control signal for multifunction prostheses. Correlation must be drawn between physiological factors, physical factors, and EMG signals [85]. Advanced algorithms need to be developed to extract useful neural information [85]. One of the innovative aspects is the combined use of electroencephalogram (EEG) and EMG to relay information for controlling the lower-limb exoskeleton [85].

What are the Issues Faced in Designing for Exoskeletons?

Power Supply (Power Density)

Current power supplies have insufficient energy density for truly mobile exoskeletons [49]. Large, heavy power supplies limit portability and are one of the major factors limiting the application of exoskeletons outside of clinical therapy [49] and other "grounded" (mounted to a wall or stand) applications. Some researchers have proposed interim solutions such as mounting upper body exoskeletons to powered wheelchairs [42], but improvements on the weight and efficiency of power supplies are still needed to achieve better exoskeleton performance [49].

Degrees of Freedom vs. Complexity of Model

"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 [83]."

In designing a prototype hand exoskeleton [83], 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 [83]," 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 [83].”

Researchers involved with the BLEEX lower body exoskeleton took a different approach to this tradeoff. “Each BLEEX leg has 7DoF..., 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…[103]” Additionally, the hip and other joints were simplified such that overall the BLEEX represents a “near anthropomorphic” design [102].

Mobility/Wearability

Many existing upper body exoskeletons overcome weight or bulk issues by being mounted to a wall or stand, or to a wheelchair [49]. 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.

Aesthetics (in Some Applications)

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 [72]. "The main wish expressed by the potential users was the possibility of hiding the exoskeleton under clothing [72]."

Variability/Uncertainty within the Same Person

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, and additionally, 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 [42], and EMG signals can vary due to muscle fatigue [47].

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 [78]," on the order of a few centimeters. Such misalignment can lead to pressure sores on the skin, long-term joint damage, joint dislocation and cartilage damage, and stumbling [82].

Variability between Persons

The activity level of each muscle and the way of using each muscle for a certain motion is different between persons [42]. Several solutions have been proposed to provide adaptive control between users: adjusting impedance [41], myoprocessors with optimization ("gene" modelling) [14], adaptive gain [37], and neuro fuzzy modifiers (single) [28].

Safety

Safety is of 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 [73]." 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 of 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.

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 to 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 [73].

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”; and “mechanical singularity should not occur within the workspace of the robot [28].”

The two main aspects that need full consideration are [81] implementation of the actuation and motor control, and intrinsic mechanical and kinematic design of their structure. To ensure human safety when using an exoskeleton, a mechanical constraint combined with software limitations is the most popular method. CADEN-7 uses mechanical constraints to prevent excessive movement of body segments. CADEN-7 also uses a pulley in the design to enable slip when limitations are reached. The electrical system of CADEN-7 contains three shutoff switches to set electrical constraints. Gupta et al. also used mechanical stops and control limitations to ensure safety [28].

CHAPTER III:

INTRODUCING ARCTIC LAWE

This chapter focuses on the ARCTiC LawE, the practical component of the thesis whose genesis lies in the lack of exoskeletons for physical training of handguns and serves as a demonstration of proficiency in designing and manufacturing a working prototype that is validated through experimentation.

Introduction

This thesis looks at expanding specifically the field of training with the use of an upper body exoskeleton. The following chapters proposes a design and evaluation of an upper body exoskeleton for firearm training to assist civilian, military, and law enforcement in accurate, precise, and reliable handgun techniques. The **A**rmed **R**obotic **C**ontrol for **T**raining **i**n **C**ivilian **Law** **E**nforcement, or ARCTiC LawE, for short, aims to train and test subjects with no handgun training/experience with the ARCTiC LawE, and without, and compare the results of accuracy, precision, and speed.

Figure 12: (Top) Glock 19® [25] (Bottom) LaserLyte® [48]

This upper body exoskeleton training utilizes 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 its firearm [25]. The laser based handgun is used to ensure the safety of the participants as well as to alleviate any impact on bullet trajectories (as in traditional handguns) due to humidity and/or wet bulb temperature.

Exoskeleton Design and Manufacturing

Modeling the Human Arm

As might be assumed, it was imperative to begin the design of the exoskeleton by first looking at the anthropometry of the human figure. Measurements for forearm length and breadth, the angle between the back of the hand and forearm, hand length (carpal to metacarpal bones), and hand breadth (across metacarpal bones) were taken from 8 participants (4 male, 4 female). In addition, first to second knuckle length (proximal phalanges), second to third knuckle length (medial phalanges), and third knuckle to tip length (distal phalanges) measurements were recorded for each finger.

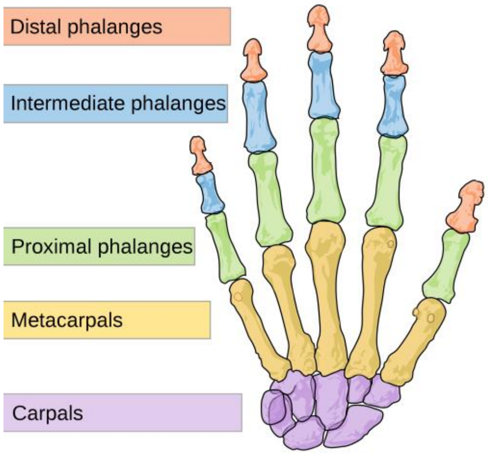


Figure 13: Bones of the Hand [9]

These measurements were divided into two groups: group 1, ‘small’ hand/forearm sizes with handbreadth 6.9”-8.6”, and group 2, ‘large’ hand/forearm sizes with handbreadth 8.9”-10.4”. The anthropometric data can be seen in its entirety in Appendix A at the end of this document. These two groups formed the basis for the two sizes of exoskeleton gauntlets – medium and large. These participants were not used for physical testing of The ARCTiC LawE and served merely as a sampling of anthropometric sizes.

Manufacturing the Exoskeleton

By looking at traditional medieval gauntlets and patterns, new templates, which took into consideration the anthropometry data, were created on paper. The patterns were transferred from standard A4 printer paper to card stock and then cut out. The card stock templates were roughly folded along critical fold lines to match the principle investigator (PI). A second set was created to match the anthropometry of the second group.

Figure 14: ARCTiC LawE vrs. 0.1

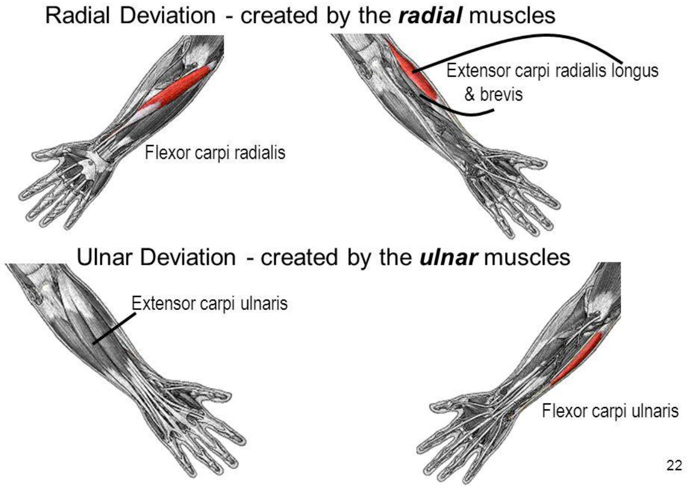
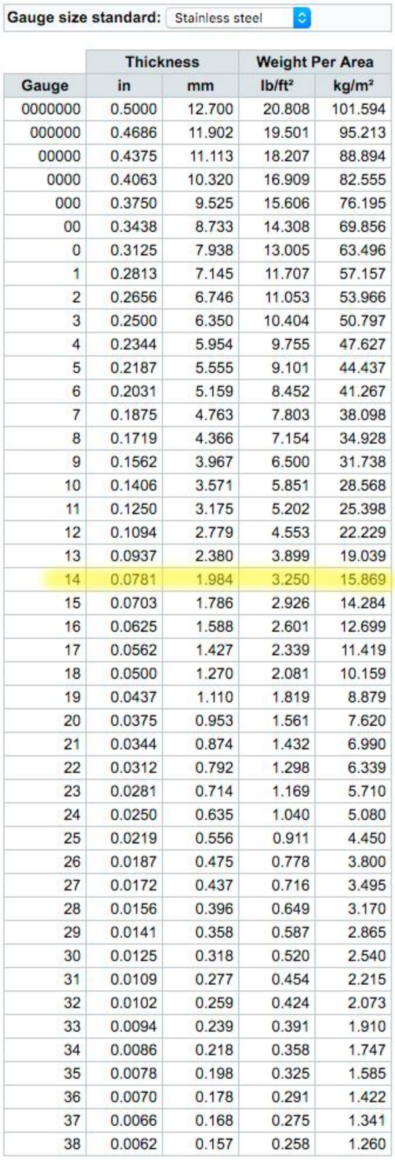


Figure 15: Radial and Ulnar Deviation [65]

Placeholder rivet holes were cut out at approximate joint locations, keeping in mind the change of material from the much more flexible and forgiving card stock to stainless plate steel. Using a permanent marker, the cardstock template was traced onto 0.475 mm, 26 gauge, stainless plate steel. This stainless plate steel was relatively thin and was used as a rapid prototype for

Figure 16: Two sizes of Exoskeleton

personal testing and verification of the template design. The sheet metal was cut and formed by hand. The initial design was verified with this thin sheet metal, however, with personal testing, it was found that the exoskeleton needed a better method for stopping radial and ulnar deviation, essentially locking out movement of the hand in the 'Y' direction. The thin sheet metal was relatively easy to bend by radial and ulnar deviation of the user.



Gauge size standard: Stainless steel

	Thickness		Weight Per Area	
Gauge	in	mm	lb/ft²	kg/m²
0000000	0.5000	12.700	20.808	101.594
000000	0.4686	11.902	19.501	95.213
00000	0.4375	11.113	18.207	88.894
0000	0.4063	10.320	16.909	82.555
000	0.3750	9.525	15.606	76.195
00	0.3438	8.733	14.308	69.856
0	0.3125	7.938	13.005	63.496
1	0.2813	7.145	11.707	57.157
2	0.2656	6.746	11.053	53.966
3	0.2500	6.350	10.404	50.797
4	0.2344	5.954	9.755	47.627
5	0.2187	5.555	9.101	44.437
6	0.2031	5.159	8.452	41.267
7	0.1875	4.763	7.803	38.098
8	0.1719	4.366	7.154	34.928
9	0.1562	3.967	6.500	31.738
10	0.1406	3.571	5.851	28.568
11	0.1250	3.175	5.202	25.398
12	0.1094	2.779	4.553	22.229
13	0.0937	2.380	3.899	19.039
14	0.0781	1.984	3.250	15.869
15	0.0703	1.786	2.926	14.284
16	0.0625	1.588	2.601	12.699
17	0.0562	1.427	2.339	11.419
18	0.0500	1.270	2.081	10.159
19	0.0437	1.110	1.819	8.879
20	0.0375	0.953	1.561	7.620
21	0.0344	0.874	1.432	6.990
22	0.0312	0.792	1.298	6.339
23	0.0281	0.714	1.169	5.710
24	0.0250	0.635	1.040	5.080
25	0.0219	0.556	0.911	4.450
26	0.0187	0.475	0.778	3.800
27	0.0172	0.437	0.716	3.495
28	0.0156	0.396	0.649	3.170
29	0.0141	0.358	0.587	2.865
30	0.0125	0.318	0.520	2.540
31	0.0109	0.277	0.454	2.215
32	0.0102	0.259	0.424	2.073
33	0.0094	0.239	0.391	1.910
34	0.0086	0.218	0.358	1.747
35	0.0078	0.198	0.325	1.585
36	0.0070	0.178	0.291	1.422
37	0.0066	0.168	0.275	1.341
38	0.0062	0.157	0.258	1.260

Figure 17: Stainless Steel Sizes [80]

The original cardstock template was transferred onto 1.984mm, 14 gauge, stainless plate steel and machined out. After retrieving the machined parts, they were filed and deburred to ensure smooth edges. The parts were hand forged utilizing a series of blacksmith cold-forging techniques (i.e. dishing, die forming, raising, etc.) with multiple hammers and anvil-shaped-objects.

Based on the anthropometric chart (Appendix A), the individual metal parts were hammered into shape, first by dishing the underside using a ball peen hammer to create a proper semi-conical shape (narrower towards the wrist). Each part was roughly hammered to size with more detailed and precise work following to ensure each part fit as needed. The smooth edges that would function as overlapping plates were slightly bent a few degrees with a small hammer to ensure ease of sliding. As this thesis's primary concern is with the results of the exoskeleton itself, more detailed research on cold forging is left to the interested reading.

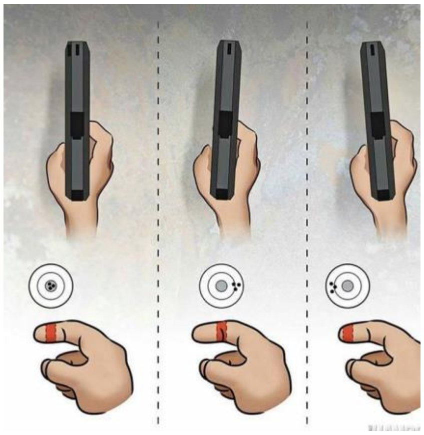
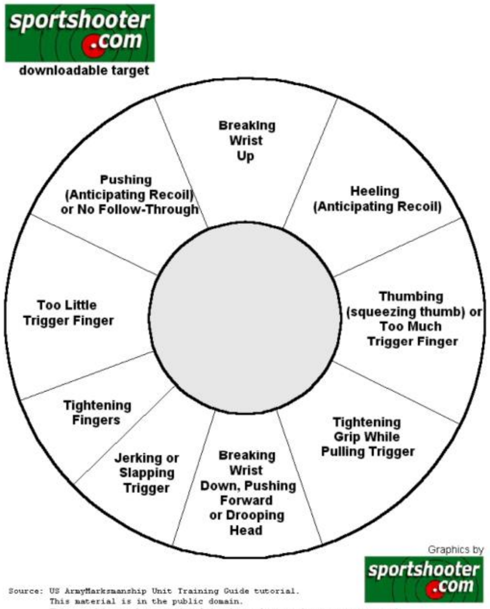


Figure 18: Finger Placement [64]

How it Works

For handguns, participants will want to squeeze the trigger with the center of the tip of the index finger (distal phalanx). If participants squeeze the trigger with the outer tip, their shots will err to the left; if participants squeeze the trigger with the inner portion, their shots will err to the right as in Figure 18. To help guide participants in using the correct portion of their index finger, a neoprene glove, which also acts as padding between the user and the exoskeleton, had a portion of its index finger removed (Figure 19). This allows the participant to not only more easily feel the trigger, but also serves as a reminder as to which portion of the finger to squeeze with. As shown in Figure 20, there is also error caused by breaking the wrist up or down, pushing, heeling, thumbing, etc. Much of this has to do with anticipating the recoil of the gun,

Figure 19: Neoprene Finger Cutout



Source: US ArmyMarksmanship Unit Training Guide tutorial.
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Figure 20: Target Error Causes [90]

pulling the trigger rather than squeezing it, or has to do how the user is holding the grip of the gun. The cut out portion of the neoprene glove serves to mitigate the effects of too little trigger finger and too much trigger finger which results in hitting the target to the left and right of center, respectively. The thicker, stiffer stainless steel helps mitigate the breaking wrist up and down which results in hitting the target above and below center. To mitigate the tightening of the fingers or tightening of grip while pulling the triggers, Velcro was added to the pinky, ring, and middle finger in horizontal bars. Two bars of Velcro® were sewn onto the proximal phalanges location of the neoprene glove while one bar of Velcro® was sewn onto the intermediate phalanges location of the neoprene glove (Figure 21). The two bars and one bar were used to help explain to the participant when matching up with the corresponding Velcro® strips glued on to the exoskeleton finger coupling.

Figure 21: Back of Neoprene Glove

Figure 22: ARCTiC LawE vrs. 1

The first version of the ARCTiC LawE can be seen in Figure 22, above. It shows the neoprene glove mated to the metal exoskeleton with the Velcro®. The exoskeleton uses webbing that can easily be swapped out to accommodate multiple sizes. The webbing was held on with bolts, washers, and nuts to help facilitate swapping of the webbing. The finger coupling piece of the exoskeleton also acts as a guide for the participants. They were instructed to keep the Velcro® on the neoprene glove mated with the exoskeleton helping mitigate over squeezing. The overlapping plates allows 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.

CHAPTER IV:

METHODOLOGY OF STUDY ONE

Participant Selection

Students were invited participate in the study for up to 5% extra credit in the class. Participants emailed the PI asking to participate in one of the experiments for extra credit. The PI compiled the list and randomly assigned participants to his numerous experiments. Ten of the PI’s students were selected to participate in the ARCTiC LawE study; an additional ten students were asked to participate in the study and were gathered by word of mouth. The twenty participants were split between the control group and the experimental group based on when they signed up for the experiment, alternating between control and experimental.

Participants were comprised of civilians above the age of 18 who could legally give consent and can 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 had little to no experience using handguns.

Before Beginning the Experiment

Driver’s licenses were checked to confirm that participants were over the age of 18 and asked if they can legally give consent and if they can physically operate a handgun. Next, participants were asked to read and then sign the non-disclosure agreement (Appendix C) as well as the consent form (Appendix D). Participants were then asked to fill out the pre-study survey (Appendix B).

From the data collected in the pre-study survey, we identified that four participants, all pre-allocated to the experimental group, self-identified as having moderate to significant handgun experience. These four participants were removed from the study.

After Signing

Participants were outfitted with standard issue police gear: inner duty belt, level III body armor, and a level III protection outer duty belt. The equipment weighed approximately 30lbs. and was worn to simulate traditional police training. The duty belt and body armor were adjusted to fit snugly on the participant. Participants were also required to wear eye protection. If in the experimental group, the participants were outfitted with the exoskeleton.

Determining Eye Dominance

Participants were tasked with determining eye dominance. The first method for determining eye dominance was for the PI to select a distant object in the lab and have the participant point at the object with their dominant eye. Then the participant was asked to close one eye. The participant was then asked to open that eye and close the other. Typically, the object the participant was looking at would seem to 'jump' due to eye dominance [84]. If the first method did not result in a conclusive result, a second method was employed where

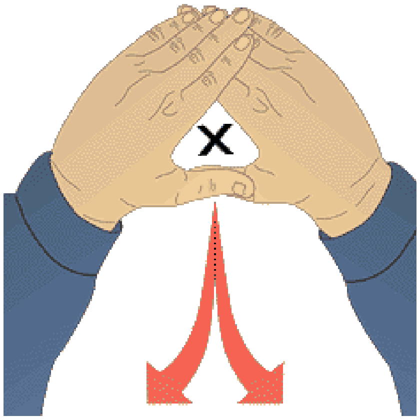

Figure 23: Eye Dominance Test [84]

participants would focus on a distant object, hold their arms straight out at eye level with their fingers up, palms out, and hand overlapping. Participants would leave a small gap between hands in the shape of a diamond or triangle. They would then bring their hands slowly back towards their face while maintaining focus on the distant object. Their hands would end up covering one eye or the other. The eye that could still see the object is the participant's dominant eye.

Gun Safety and Training

Figure 24: Proper hand placement (Top) Left View (Bottom) Right View

Training for both groups involved teaching participants proper handgun safety and use. 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 hand gun safety and use 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. Participants were taught how to hold the LaserLyte handgun, how to draw the LaserLyte from the holster, and how to properly aim the LaserLyte.

Testing

Figure 25: LaserLyte Score Tyme Board [48]

Participants were started at a random distance (21 feet and 45 feet) and then moved to the next distance to counteract the effect of learning on the results of the participants' scores. Participants were instructed that they must holster the LaserLyte in between each shot and may only fire after being told to do so. 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 two firing distances. Each distance had a potential for 250 points as a high score if each of the 25 shots hit the 10 point bullseye. The outermost ring of the LaserLyte Score Tyme board was worth four points. Each ring increase value by one (Figure 25: LaserLyte Score Tyme Board [48]). The LaserLyte and its stand had the following properties:

Table 1: LaserLyte Score Tyme Board Dimensions

Ring Diameter	7 inches
Distance from bottom of target to bottom of ring	5.2 inches
Distance from top of ring to top of target	0.75 inches
Distances from sides of ring to sides of target	0.75 inches
Distance from floor to bottom of target	36.5 inches

Post-Study

After completing the testing phase, participants were asked to fill out the post-study survey (Appendix E). Body armor, duty belts, the LaserLyte, and the safety goggles were returned to the PI.

CHAPTER V:

RESULTS OF STUDY ONE

The participants are normally distributed. On average, the experimental group scored 64.9 points higher than the control at a 21-foot distance, and 24.13 points higher than the control at a 45-foot distance.

Among the participants in the experiment (N = 16), there was a statistically significant difference between the two groups at 21 feet, control (M = 91.6, SD = 49.84) and experimental (M = 156.5, SD = 23.83), t(15) = 0.0018, p = 0.01. There was no statistically significant difference between the groups at 45 feet, control (M = 37.2, SD = 24.81) and experimental (M = 61.33, SD = 35.81), t(15) = 0.09, p = 0.13).

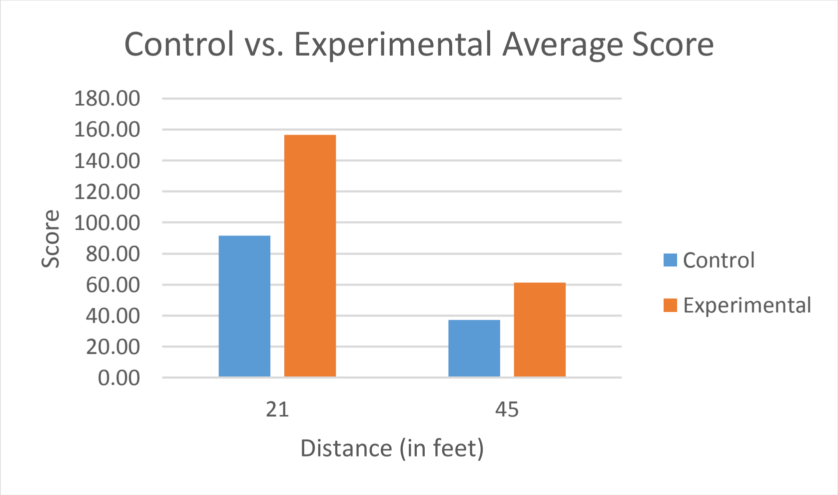

Figure 26: Average Score - Study One

In the post study survey, participants were asked about the effectiveness of the training they underwent (Figure 27), their precision (Figure 28), their accuracy (Figure

29), their stability (Figure 30), and how effective they think the training would be over the course of three months (Figure 31).

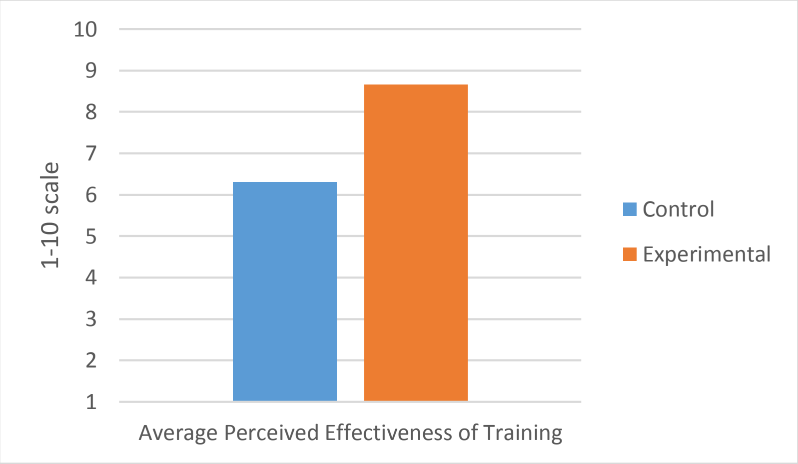

Figure 27: Perceived Effectiveness of Training - Study One

On average, participants in the experimental group rated their perceived effectiveness of the training 2.37 points (or ~24%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 7.19, SD = 2.3) and experimental (M = 8.67, SD = 0.82), t(15) = 0.006, p = 0.03.

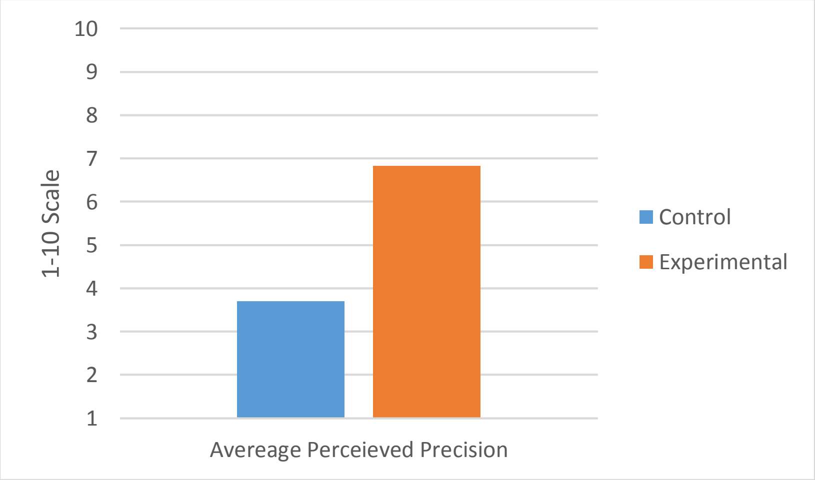

Figure 28: Perceived Precision - Study One

On average, participants in the experimental group rated their perceived precision 3.13 points (or ~31%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 3.7, SD = 1.25) and experimental (M = 6.83, SD = 1.17), t(15) = 0.00017, p < 0.01.

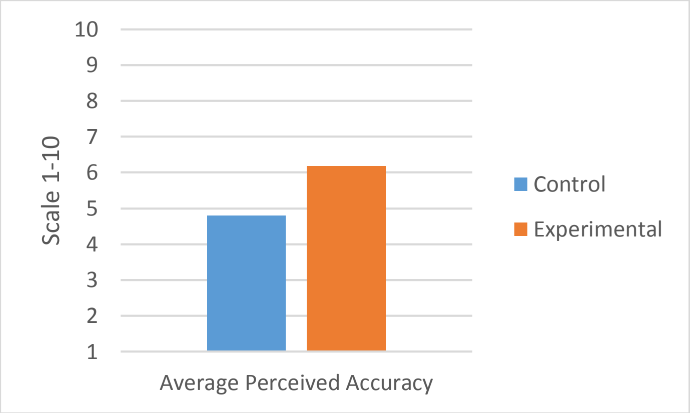

Figure 29: Perceived Accuracy - Study One

On average, the experimental group rated their perceived accuracy 1.37 points (or ~14%) higher than the control group. There was no statistically significant difference between the two groups, control (M = 4.8, SD = 1.87) and experimental (M = 6.17, SD = 1.60), t(15) = 0.07, p = 0.16.

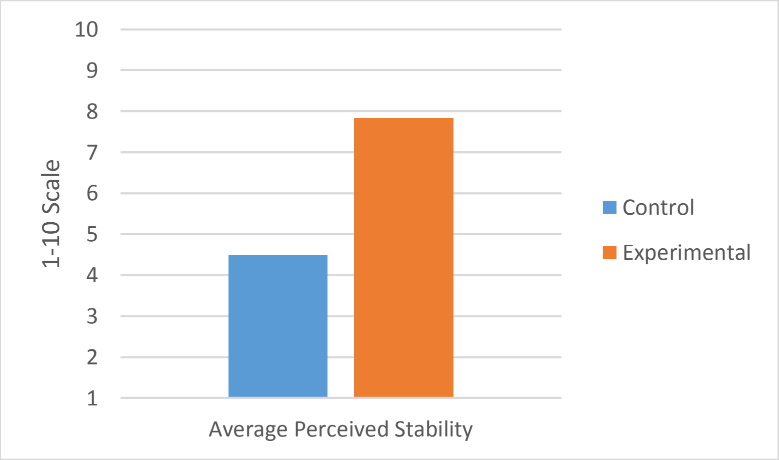

Figure 30: Perceived Stability - Study One

On average, the experimental group rated their perceived stability 3.33 points (or ~33.3%) higher than the control group. There was a statistically significant difference between the two groups, control (M = 4.5, SD = 1.65) and experimental (M = 7.83, SD = 1.17), t(15) = 0.00019, p < 0.01.

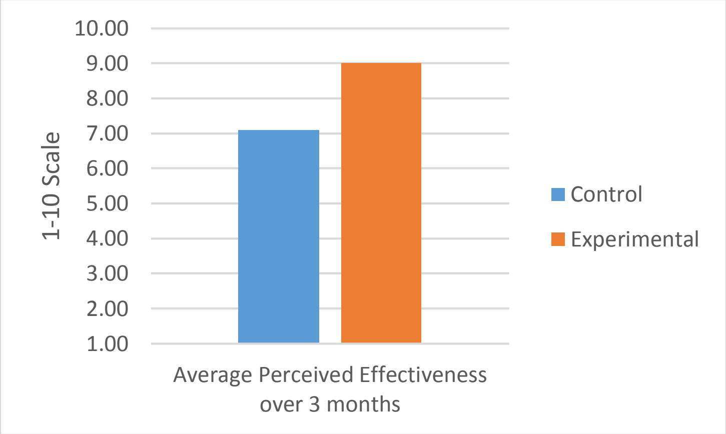

Figure 31: Perceived Effectiveness over 3 Months – Study One

On average, the experimental group rate their perceived effectiveness of the training over a course of 3 months 1.9 points or (~19%) higher than the control group. It is important to note that this measure was taken in the post-study survey following the study. There was a statistically significant difference between the two groups, control (M = 7.1, SD = 1.91) and experimental (M = 9, SD = 1.26), t(15) = 0.16, p = 0.049.

In terms of results of the first study, there is enough statistical support for a second iteration which can address some of the qualitative results as well as the quantitative results. In particular, the study showed fatigue from the participants attempting to 'rapid fire.' That is, the participants were attempting to draw the LasyerLyte, quickly fire the LaserLyte, holster the LaserLyte, and repeat.

The results also 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 tells us 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 better learned how to aim with the handgun.

ARCTiC LawE vrs. 2

To address potential deflection to the left and right of the center of the target, caused by the extension and flexion of the wrist, a pull type linear solenoid was used. The linear solenoid was attached to the gauntlet portion of the exoskeleton with a two part epoxy. The solenoid was connected via a set screw and spring to the knuckle plate portion of the exoskeleton. The solenoid was turned on manually and powered by six AA batteries.

Moving out of study one requires testing of training affect. To do so, the participants in study two were required to participate in the study on two separate days with approximately one week in between studies.

Again, safety is always a primary concern when working with exoskeletons and humans. We use the padding of the neoprene glove again to provide a barrier between the metal (which has been filed down and deburred) and the user. The electrical components (solenoid, wiring, and battery pack) are a possible point of safety concern. However, this is addressed with proper care towards soldering the components and by using heat shrink wrap over any connection point ensuring safety to the participants.

CHAPTER VI:

METHODOLOGY OF STUDY TWO

The second study looks at repeating study one but utilizing the second version of ARCTiC LawE and includes a second week where participants are tested after having only been trained in week one.

Participant Selection

Similar to Study One, students in one of the PI's courses were invited to participate in the study for up to 5% extra credit in the class. Participants emailed the PI asking to participate in one of their experiments for extra credit, were compiled into a list, and randomly assigned to experiments. Nineteen students were selected to participate in the second ARCTiC LawE study. The Nineteen 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 can 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 had little to no experience using handguns. Again, there were participants who, after filling out the pre-study survey (Appendix B), self-identified as having moderate to significant handgun experience. These four participants were removed from the study. An additional two participants were removed for not responding to the scheduling poll, leaving a total of only thirteen participants.

Two more participants were removed from the data set due to environmental factors during the testing that negatively impacted their scores. Both of these participants showed clear visible stress during the incidences. Thus leaving only eleven participants for the second study. The experimental group had six participants and the control group had five participants.

Before Beginning the Experiment

The rest of the methodology for study two, day one is the same as study one with the following exceptions: (1) participants were not required to draw the LaserLyte handgun from the holster in study two, (2) study two, week one used the second version of the ARCTiC LawE, Figure 32.

Figure 32: ARCTiC LawE vrs. 2
(Top) Top down view - unactuated
(Middle) Side view - actuated
(Bottom) Top down view - actuated

Second Study Day Two

The second portion of the study took place approximately 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 groups were tested without the exoskeleton and were asked to fill out the same post study survey (Appendix E).

CHAPTER VII:

RESULTS OF STUDY TWO

Week One

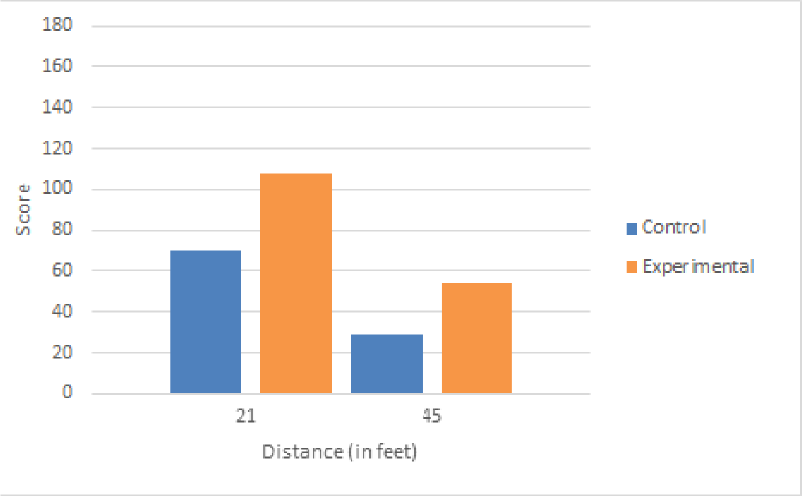

Figure 33: Average Score - Study Two Week One

On average, at a distance of 21 feet, the experimental group scored 37.1 points higher than the control group. There was not a statistically significant difference between the groups at 21 feet, control (M = 70.4, SD = 52.35) and experimental (M = 107.5, SD = 65.99), t(10) = 0.16, p = 0.34. At a distance of 45 feet, the experimental group scored an average of 25.06 points higher than the control group. There was not a statistically significant difference between the two groups at 45 feet, control (M = 28.6, SD = 12.36) and experimental (M = 53.67, SD = 51.11), t(10) = 0.15, p = 0.32.

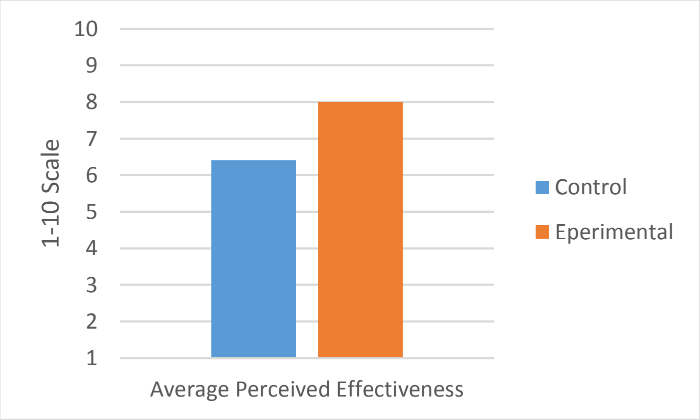

Figure 34: Average Perceived Effectiveness - Study Two Week One

The experimental group, on average, rated the effectiveness of the training with the exoskeleton 1.6 points (~16%) higher than the control group's training without the exoskeleton. There was a statistically significant difference between the groups, control (M = 6.4, SD = 1.14) and experimental (M = 8, SD = 1.1), t(10) = 0.022, p = 0.04.

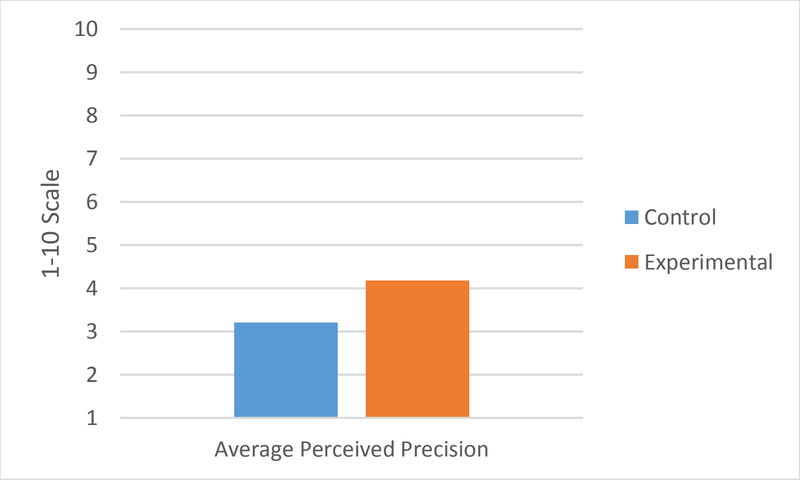

Figure 35: Average Perceived Precision - Study Two Week One

The experimental group, on average rated their perceived precision 0.97 points (~9.7%) higher than the control group. There was no statistically significant difference between the groups, control (M = 3.2, SD = 1.79) and experimental (M = 4.17, SD = 2.32), t(10) = 0.228, p = 0.47.

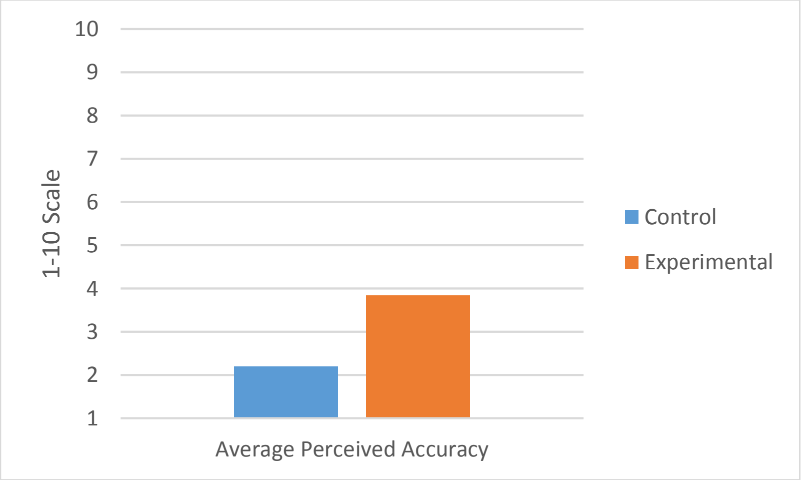

Figure 36: Average Perceived Accuracy - Study Two Week One

The experimental group rated their perceived accuracy 1.63 points (~16.3%) higher than the control group. This result was no statistically significant difference between the groups, control (M = 2.2, SD = 1.64) and experimental (M = 3.83, SD = 1.94), t(10) = 0.083, p = 0.17.

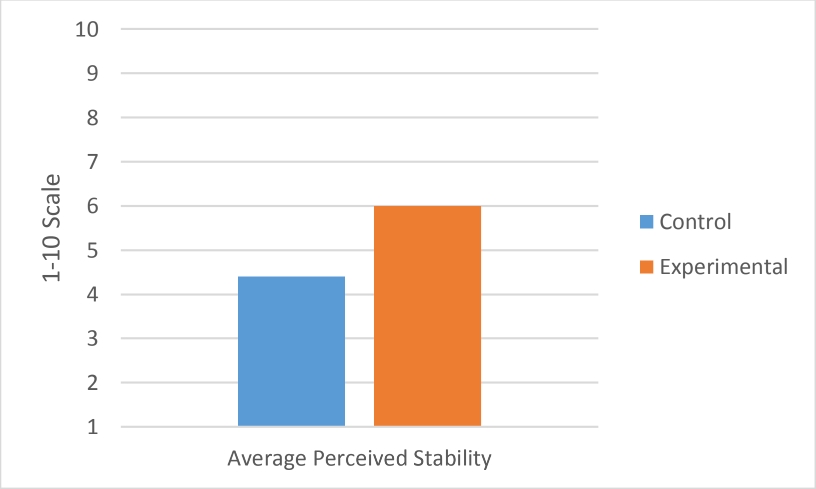

Figure 37: Average Perceived Stability - Study Two Week One

The experimental group rated their perceived stability with the exoskeleton 1.6 points (~16%) higher than the control group. There was no statistically significant difference between the groups, control (M = 4.4, SD = 1.82) and experimental (M = 6, SD = 1.67), t(10) = 0.084, p value = 0.16.

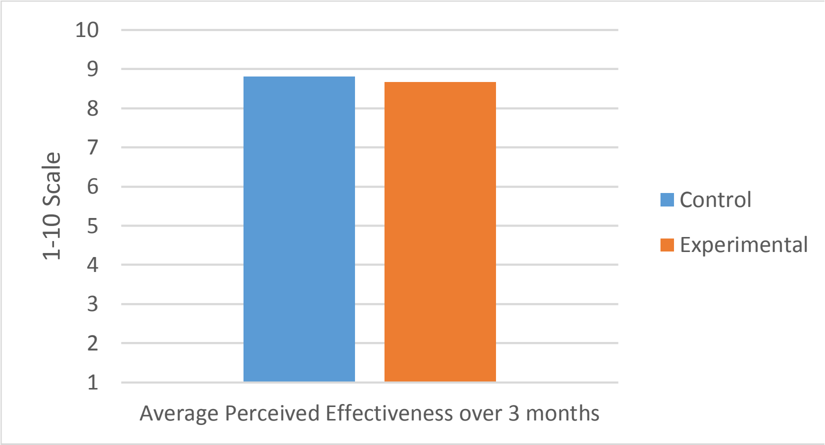

Figure 38: Average Perceived Effectiveness over 3 months - Study Two Week One

The experimental group perceived the effectiveness of the exoskeleton training over a period of three months 0.123 points (~1.2%) lower than the control group. There was no statistically significant difference between the groups, control (M = 8.8, SD = 1.79) and experimental (M = 8.67, SD = 1.21), t(10) = 0.445, p = 0.89.

Week Two

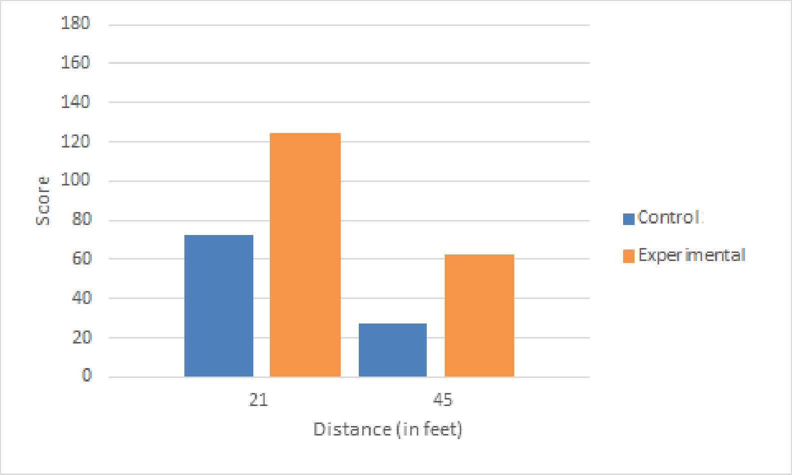

Figure 39: Average Score - Study Two Week Two

On average, at a distance of 21 feet, the experimental group scored 72 points higher than the control and at a distance of 45 feet, the experimental group scored 14.7 points higher than the control group. There was no statistically significant difference between the groups at 21 feet, control (M = 72.2, SD = 52.31) and experimental (M =

124.17, SD = 43.03), t(10) = 0.057, p = 0.10). There was no statistically significant difference between the groups at 45 feet, control (M = 47.8, SD = 27.14) and experimental (M = 62.5, SD = 34.39), t(10) 0.224, p = 0.46.

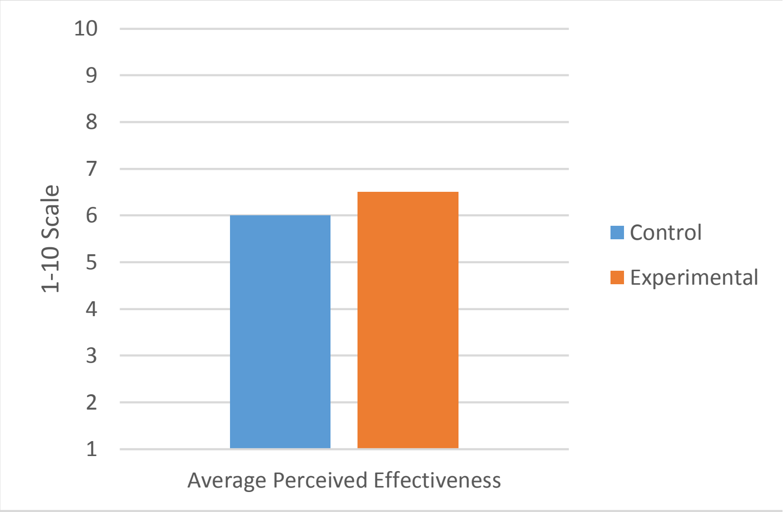

Figure 40: Average Perceived Effectiveness - Study Two Week Two

The experimental group perceived the effectiveness of the training only 0.5 points (or 5%) higher than the control group. There was no statistically significant difference between the groups, control (M = 6, SD = 1) and experimental (M = 6.5, SD = 1.76), t(10) = 0.29, p = 0.59.

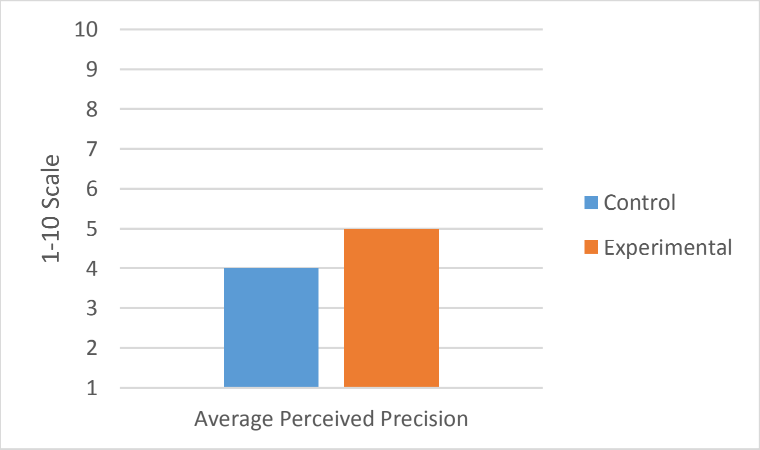

Figure 41: Average Perceived Precision - Study Two Week Two

The experimental group rated their perceived precision 1 point higher (~10%) higher than the control group. There was no statistically significant difference between the groups, control (M = 4, SD = 2) and experimental (M = 5, SD = 2.19), t(10) = 0.22, p = 0.45.

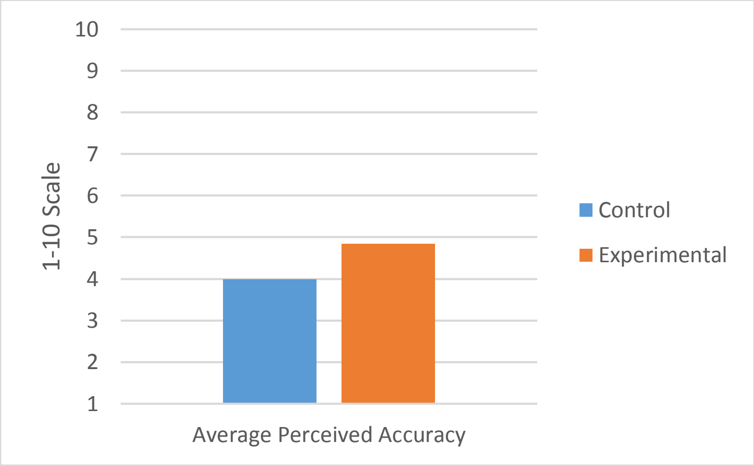

Figure 42: Average Perceived Accuracy - Study Two Week Two

The experimental group rated their perceived accuracy 0.83 points higher (~8.3%) higher than the control group. There was no statistically significant difference between the groups, control (M = 4, SD = 1.41) and experimental (M = 4.83, SD = 1.72), t(10) = 0.20, p = 0.41.

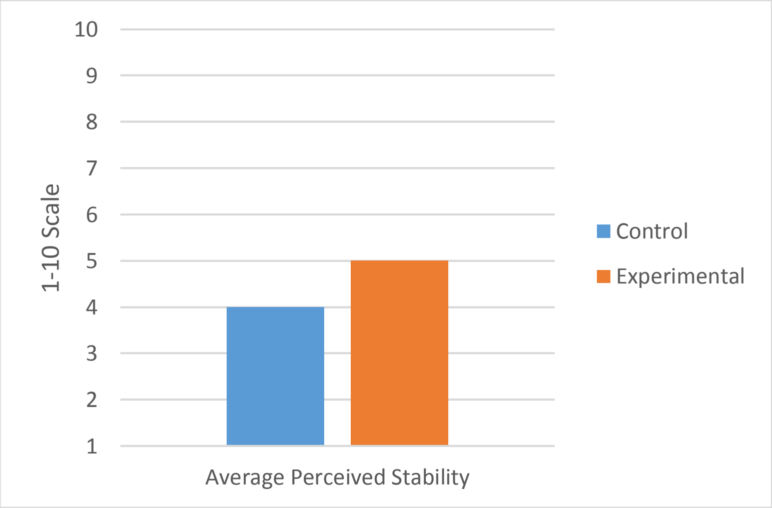

Figure 43: Average Perceived Stability - Study Two Week Two

The experimental group rated their perceived stability 1 point higher (~10%) higher than the control group. There was no statistically significant difference between the groups, control (M = 4, SD = 1.22) and experimental (M = 5, SD = 2), t(10) = 0.17, p = 0.36.

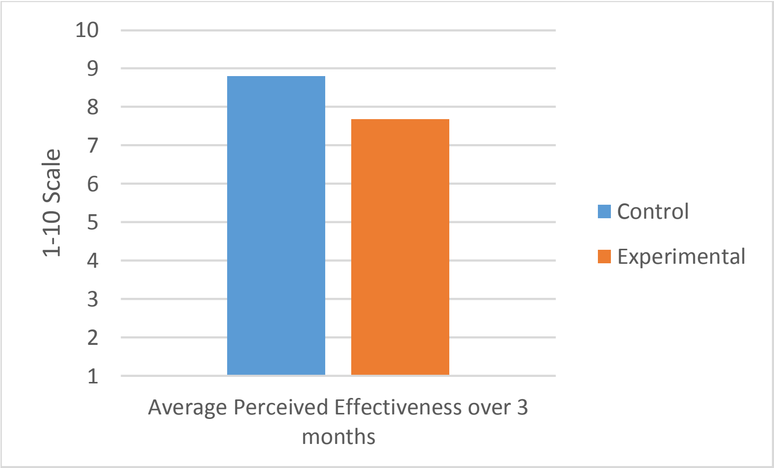

Figure 44: Average Perceived Effectiveness over 3 months - Study Two Week Two

The experimental group rated their perceived the effectiveness of the training over the course of three months to be 1.13 points (~11.3%) lower than the control group. There was no statistically significant difference between the groups, control (M = 8.8, SD = 1.79) and experimental (M = 7.67, SD = 1.75), t(10) = 0.16, p = 0.32.

Transfer of training

It is at this stage where transfer of training can be looked at. 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. Augmented reality and virtual reality have been proven to be effective instructional technologies and able to display a transfer of training demonstrated in previous work with their use of virtual reality integrated weld training [70, 71].

Transfer of Training is “training is designed to direct the cognitive processes of learning and to minimize disruptions from unwanted external information.” Holton (1996) transfer of training framework (Figure 45) has three critical factors: (1) motivation to transfer, (2) transfer climate, and (3) transfer design.

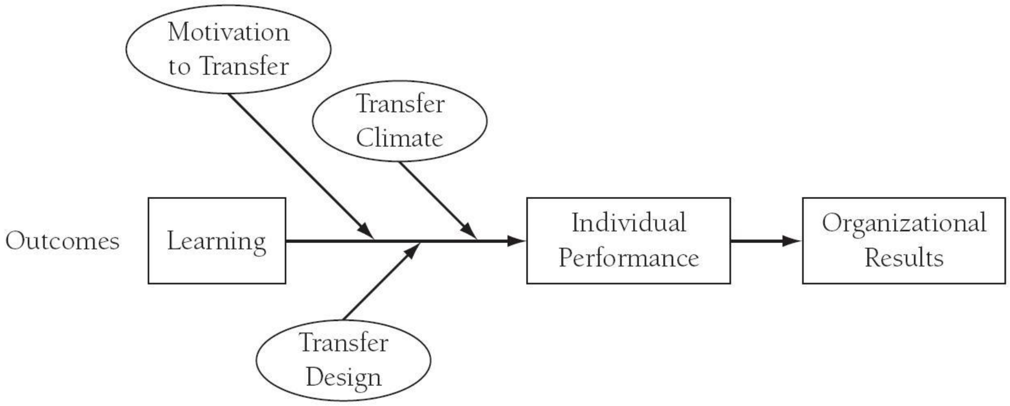

Figure 45: Transfer of Training Framework [34]

It can be stated that with respect to average score, the experimental group outperformed the control group with and without the ARCTiC LawE exoskeleton and that there is potential for a transfer of learning aspect. Future work would look at this aspect more in depth.

CHAPTER VIII:

CONCLUSION, IMPLICATIONS, AND FUTURE RESEARCH

This thesis set out to determine the state-of-the-art in exoskeletons, determine what has been done, what hasn't been done, and what challenges remain as well as to design, develop, manufacture, test, and validate an exoskeleton.

Some future work includes replacing the manual activation of the solenoid with a gyroscope that would automatically activate when the shooter's arm is in a firing position.

The Transfer of Training Paradigm has a training effective 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.

The training effectiveness ratio is as follows:

$$\frac{Y_c - Y_x}{Y_c}$$

Where Y_c is the time, trials, or errors required by a control group to reach a performance criterion and Y_x is the corresponding value for an experimental, or transfer, group having received prior practice on another task.

For future studies, the group trained with the LaserLyte handgun would be the control group and the group trained with the ARCTiC LawE and the LaserLyte handgun would be the experimental group. Time was not recorded for study one or study two.

However, it was noted that there was no appreciable difference in training time between the control group and the experimental group.

While future studies that look more in-depth at the TER may be required, it is important to note that the studies involved with the ARCTiC LawE gave much more time between training and re-testing than the MAXFAS exoskeleton. Participants in the second ARCTiC LawE study had a week long gap between training and testing, whereas the MAXFAS exoskeleton study (involving five control participants and fifteen experimental participants) gave only a five minute gap. The future work here would include determining the appropriate score for a qualified police officer and comparing the LaserLyte training to the training with the ARCTiC LawE. An additional task would be 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 from. A change from the 14 gauge stainless steel to fiberglass will reduce the weight while maintaining the rigidity and structural integrity of the exoskeleton. Another possible replacement material would be 3D printed ABS plastic. This material would also reduce the weight without compromising the structural integrity of the exoskeleton. This would also allow for parts that could be quickly and cheaply replaced or swapped out for smaller or larger parts, or swapped out for specialized equipment.

Another point of potential future work, based on advice from military personnel, would be to include different training routines that involve testing a Weaver stance where the nondominant foot is in the forward position instead of the dominant foot; including walking drills (forward and/or sideways) to test the effectiveness of mobile training and rapid response time; including moving targets; and to look at integrating the exoskeleton not only for handguns but also as a tool for rifle training.

Multiple military personnel whose data was excluded from the study really liked the idea of the exoskeleton and originally thought it was designed as an everyday carry piece of equipment. One stated that they would be willing to purchase the exoskeleton for everyday carry. They initially thought it was a little cumbersome and heavy, but after running through the study, stated that they barely felt it on their arm and helped them stabilize their shooting arm. They stated that they had to worry less about stabilizing their arm and could focus more on aiming at their target. When the military personnel were informed that it was not originally designed as an everyday carry but rather as a training tool for novice shooters they were even more ecstatic and enthusiastic about the project.

The following extrapolation is made from the assumption that other environmental aspects like sound are not major factors.

$$Y(x^*) = \frac{y_{k-1} + (x^* - x_{k-1})}{x_{k-x} * y_{k-y_{k-1}}}$$

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 2: US DHS Ammunition Usage and Spending FY 2010-2012 [91]

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 when buying fewer rounds) costs $120 for 500 rounds [1] or about $0.24 each. Based on the information above, it can be expected that tor the 2016 fiscal year, the Department of Homeland Security will have spent ~$6.4M just on the bullets for training. From discussions with Dr. Richard T. Stone, a reserve deputy in Story County, 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 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.

Based on discussions with Dr. Stone, 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 [70, 71], and based on Dr. Stone's insights, 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.

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APPENDIX A

ANTHROPOMETRIC DATA

Participant	Gender	Height	Weight	Forearm length	Forearm Breadth	Hand length	Hand breadth
1	Female	72"	210	10.4"	11.6"	3.9"	8.6"
2	Male	66"	188	9.5"	11.5"	3.5"	8.9"
3	Male	68"	200	9.75"	11"	4.25"	9.25"
4	Female	64"	111	9.7"	9.5"	3.7"	6.9"
5	Female	67.5"	142	10.6"	10.5"	4"	8.9"
6	Female	67"	122	9.2"	8.2"	3.6"	7"
7	Male	76"	258	12"	12.2"	3.1"	10"
8	Male	73"	225	11.1"	11.9"	3.2"	10.4"

Participant	First to second knuckle (Index)	Second to third knuckle (index)	Third to tip (index)	First to second knuckle (middle)	Second to third knuckle (middle)	Third to tip (middle)
1	1.7"	1.2"	0.9"	2.2"	1.6"	1.1"
2	1.9"	1.1"	1"	2.1"	1.5"	0.9"
3	1.75"	1.25"	1"	2.25"	1.3"	.9"
4	1.5"	.9"	0.9"	1.7"	1.1"	.9"
5	1.5"	1"	0.9"	1.7"	1.2"	1"
6	1.5"	1"	0.8"	1.9"	1.2"	0.7"
7	1.5"	1.2"	0.9"	2.1"	1.3"	1"
8	1.6"	1"	0.7"	2.1"	1.4"	1"

Participant	First to second knuckle (ring)	Second to third knuckle (ring)	Third to tip (ring)	First to second knuckle (pinky)	Second to third knuckle (pinky)	Third to tip (pinky)
1	2.2"	1.6"	1"	1.8"	1.2"	0.9"
2	2"	1.3"	0.9"	1.3"	0.9"	0.8"
3	2.1"	1.5"	1"	1.75"	1"	0.75"
4	1.2"	1.1"	.9"	1.5"	1.0"	.75"
5	1.5"	1"	1"	1.5"	0.8"	0.9"
6	1.7"	1.1"	0.8"	1.4"	0.9"	0.6"
7	2.1"	1.5"	1.1"	1.8"	0.8"	0.7"
8	1.5"	1.2"	1"	1.6"	1"	0.7"

Participant	Angle from forearm to hand
1	10
2	25
3	20
4	18
5	17
6	10
7	25
8	20

APPENDIX B

PRE-STUDY SURVEY

Participant # ______________

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 hand guns?

   1 2 3 4 5 6 7 8 9 10

   None at all Some Military training

3. How many hours do you play video games?

4. How many hours do you play first person shooters?

5. On a scale from 1-10, how good are you at first person shooters?

   1 2 3 4 5 6 7 8 9 10

   Terrible Somewhat Leaderboard ranked

APPENDIX C

NON-DISCLOSURE AGREEMENT

This non-disclosure agreement (the “Agreement”) is entered into by and between Thomas M. Schnieders, (“Disclosing Party”) and _______________________, (“Receiving Party”) for the purpose of preventing the unauthorized disclosure of Confidential Information as defined below. The parties agree to enter into a confidential relationship with respect to the disclosure of certain proprietary and confidential information (“Confidential Information”).

1. Definition of Confidential Information. For purposes of thie Agreement, “Confidential Information” shall include all information or material that has or could have commerical value or other utility in the business in which the Disclosing Party is engaged. If Confidential Information is in written form, the Disclosing Party shall label or stamp the materials with the word “Confidential” or some similar warning. If Cofnidential Information is transmitted orally, the Disclosing Party shall promptly provide a writing indiciating that such oral communication constituted Confidential Information.

Confidentiality extends to all social networks, where the Receiving Party is disallowed from disclosing any existence of a relationship with the Disclosing Party. This extends to social networks, including but not limited to LinkedIn, Facebook, and Twitter.

2. Exclusions from Confidential Information. The Receiving Party’s obligations under this Agreement do not extend to information that is: (a) publicly known at the time of disclosure or subsequently becomes publicly known through no fault of the Receiving Party; (b) discovered or created by the Receiving Party before disclosure by the Disclosing Party; (c) learned by the Receiving Party through legitimate means other than from the Disclosing Party or the Disclosing Party’s representatives; or (d) is disclosed by the Receiving Party with the Disclosing Party’s prior written approval.

3. Obligations of the Receiving Party. The Receiving Party shall hold and maintain the Confidential Information in strictest confidence for the sole and exclusive benefit of the Disclosing Party. The Receiving Party shall carefully restrict access to Confidential Information to employees, contractors, and third parties as is reasonably require and shall require those persons to sign nondisclosure restrictions at least as protective as those in this Agreement. The Receiving Party shall not, without prior written approval of the Disclosing Party, use for the Receiving Party’s own benefit, publish, copy, or otherwise disclose to others, or permit the use by others for their benefit or to the detriment of the Disclosing Party, any Confidential Information. The Receiving Party shall return to the Disclosing Party any and all records, notes, and other written, printed, or tangible materials in its possession pertaining to Confidential Information immediately if the Disclosing Party requests it in writing.

4. Time Periods. The non-disclosure provisions of this Agreement shall survive the termination of this Agreement and the Receiving Party's duty to hold Confidential Information in confidence shall remain in effect until the Confidential Information no longer qualifies as a trade secret or until the Disclosing Party sends Receiving Party written notice releasing the Receiving Party from this Agreement, whichever occurs first.
5. Relationships. Nothing contained in this Agreement shall be deemed to constitute either party a partner, joint venture, or employee of the other party for any purpose.

6. Severability. If a court finds any provision of this Agreement invalid or unenforceable, the remainder of this Agreement shall be interpreted so as best to effect the intent of the parties.

7. Integration. This Agreement expresses the complete understanding of the parties with respect to the subject matter and supersedes all prior proposals, agreements, representations, and understandings. This Agreement may not be amended except in a writing signed by both parties.

8.Waiver. The failure to exercise any right provided in this Agreement shall not be a waiver of prior or subsequent rights.

____ (Signature)
____ (Name)
Date: __________________
____ (Signature)
____ (Name)
Date: __________________

APPENDIX D

INFORMED CONSENT DOCUMENT

Title of Study: Upper Limb Exoskeleton for Fire Arm Training

Investigators: Thomas M. Schnieders and Richard T. Stone

This form describes a research project. It has information to help you decide whether or not you wish to participate. Research studies include only people who choose to take part—your participation is completely voluntary. Please discuss any questions you have about the study or about this form with the project staff before deciding to participate.

Introduction

The purpose of this study is to test the effectiveness of an upper arm exoskeleton in training police officers, military personnel, and civilians in the proper use of small firearms (i.e. handguns). This research will advance the knowledge in upper body exoskeletons as well as assist in training in small firearms. The term ‘exoskeleton’ is used to describe a device that augments the performance of an able-bodied wearer.

Civilians above the age of 18 who can legally give consent and are able to physical operate a handgun are asked to participate in the study. 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 pre-study survey, fire a LaserLyte electronic laser handgun that is similar in size and weight to a Glock 19, and fill out a post-study survey. The pre- and post-study surveys will ask qualitative questions such as, “Did you find the teaching method effective?” You will participate in two sessions, each approximately 90 minutes in length.

If you are placed in the experimental group, you will be outfitted with an upper limb exoskeleton. This exoskeleton is comprised of sheet metal and is designed to fit over the participants’ right arm with a layer of padding between the participant and metal. The exoskeleton and LaserLyte will be similar to that in the image below:

Before being allowed to fire the LaserLyte electronic laser handgun, you will be instructed on safety and proper use of handguns. As a participant, you will be asked to stand and fire approximately 50 shots at a laser sensitive target with short 1-2 minute breaks in between shots.

You will be asked to return in approximately one week to fire the LaserLyte electronic laser handgun a second time.

Risks or Discomforts

It is possible that the straps attaching the exoskeleton to the participant's arm may cause some discomfort. If the participant feels any discomfort please notify the investigator as soon as possible to have the straps 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 knowledge in upper body exoskeletons. In addition, the exoskeleton may be used to train civilians, law enforcement, or military personnel in the future.

For students in I E 577, or I E 271, up to 5% extra credit will be offered. Half credit (2.5%) will be given for completion of the first session and half credit (2.5%) will be given after the second session. 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 name will be associated with a code and key. Participant information will not be stored with the key and the key will be destroyed after the second session. Only the two principal investigators 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 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 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 E

POST-STUDY SURVEY

Participant # ____________

Post-Study Survey

1. On a scale of 1-10, where 1 is not at all effective and 10 is extremely effective, how effective was the training method?

   1 2 3 4 5 6 7 8 9 10

   Not at all Somewhat Extremely

2. On a scale of 1-10, where 1 is didn't hit the target and 10 is always hit a bull's-eye, how precise do you think you fired?

   1 2 3 4 5 6 7 8 9 10

   Didn't hit Sometimes Always

3. On a scale of 1-10, where 1 is shot everywhere and 10 is always hit the same spot, how accurate do you think you fired?

   1 2 3 4 5 6 7 8 9 10

   Everywhere Sometimes Same spot

4. On a scale of 1-10, where 1 is completely unstable and 10 is perfectly stable, how stable do you think your firing arm was?

   1 2 3 4 5 6 7 8 9 10

   Completely unstable Somewhat Perfectly stable

5. On a scale of 1-10, how effective do you think the training would be over a period of 3 months?

   1 2 3 4 5 6 7 8 9 10

   Not at all Somewhat Extremely