

THE RELATIONSHIP BETWEEN PREFERENCE AND PERFORMANCE USING THREE
PASSIVE EXOSKELETONS DURING SIMULATED AIRCRAFT MANUFACTURING
TASKS

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The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Biomedical Engineering.

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ABSTRACT

Exoskeletons are a promising technology that could bridge the gap between unassisted human operations and conventional robots. Many studies on shoulder exoskeletons have shown great benefit in reducing strain and loads on tested muscles. The link between user preference and muscle activity reduction using exoskeletons has not been investigated. The objective of this study was to determine if user preference correlates to shoulder exoskeleton benefit. To fulfill this objective, 16 participants participated in performing 6 different simulated manufacturing aircraft tasks, using three different passive exoskeletons (Skelex, Paexo, and Evo) and No-Exoskeleton. Multiple analyses of variance (ANOVA) and multinomial logistics were run. Significant differences in muscle activity levels were found between the exoskeleton condition and the without exoskeleton condition. In every task, the use of an exoskeleton significantly reduced muscle activity. Overhead tasks, showed a greater reduction in the anterior deltoid muscle ranging from a minimum of 10% to a maximum of 17.5% when compared to tasks working at shoulder level the reduction ranged from a minimum of 5% to a maximum of 8%. Preference and performance did not correlate to the exoskeleton with the greatest muscle benefit. This may have been due to participants preferring an exoskeleton based on other factors such as comfort. Therefore, a user preference may not be an effective method in determining exoskeleton benefit.

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CHAPTER 1

INTRODUCTION

Exoskeletons have shown benefit as rehabilitation and disability devices. They have demonstrated promising results in accelerating the recovery process. Currently, they are heavily studied to be implemented in manufacturing sectors. The implantation of an exoskeletons could increase worker safety in performing their jobs. This paper will focus on the shoulder passive supporting exoskeleton for manufacturing use. This thesis is divided into two parts.

First, this paper provides the basic definition of an exoskeleton. After the definition, it outlines the literature review covering the very start of the exoskeleton as a conceptual idea to the level it is today. Then, there is a focus on how the current shoulder exoskeletons are studied. Lastly, the current gaps in the research are then discussed.

The second part outlines the experimental work carried out in the research study on how the exoskeletons affected the muscle activity, and how their preference was affected by the benefit. In particular, the study measured muscle activity using electromyography (EMG) from participants during their performance of six different overhead aircraft manufacturing simulated tasks, utilizing three different exoskeletons. The EMG was then processed, and multiple statistical analyses were run to determine which exoskeletons yielded significant reductions in muscle activity levels and which exoskeletons had a high probability of being selected for use.

CHAPTER 2 LITERATURE REVIEW

2.1 Exoskeleton Definition

An exoskeleton is a Greek term; ‘exo’ means the outer shield to support and ‘skeleton’ means the body part. Skeleton was introduced by English anatomist Sir Richard Owen, as a biological term. Crabs are the best example of animals that have an exoskeleton, their exoskeleton not only provides support but also as a surface for muscle connection and a waterproof wall [1].

For the purpose of this thesis, the exoskeleton mentioned is intended for human use. The exoskeleton can be defined as a wearable device that consists of a mechanical structural, sensor, and actuator. Exoskeletons are designed to match human anthropometric form, and it moves in parallel with the user [2]. According to the American Society for Testing and Materials (ATSM International), the word exoskeleton is defined as an external wearable structure that enhances the physical activity and/or aids the worker’s performance through mechanical interaction [3]. The purpose of designing exoskeletons is to replicate the kinematics and dynamics of the user’s musculoskeletal structure, thus, enhancing, extending, assisting, or complementing the user’s strength and capability [4].

The exoskeleton can be passive or active. A passive exoskeleton does not have any electrical power source but uses materials, springs, or dampers that have the ability to store energy from human movement and release it when needed [5]. An active exoskeleton can be powered through various types of actuators, such as electric, pneumatic, hydraulic, or a combination of these actuators [6]. Also, exoskeletons can be categorized depending on the body region in which they are used, such as upper extremity (i.e., upper limb), lower extremity, and full body.

Exoskeletons were initially developed for military purposes to enhance the physical strength of soldiers and endurance. However, the use was extended to medicine and industry. Respectively, exoskeletons have been used to help patients in rehabilitation, as they showed excellence in accelerating the recovery process. In industry, exoskeletons have been used to increase the workers' strength to lift heavy loads for a longer duration [7].

2.2 History

2.2.1 Early Years (1890-1997)

The origin of exoskeleton research work can be traced back to 1890 and Nicholas Yagn's conceptual model of robotic exoskeleton. Nicholas Yagn's work, which received a US Patent (US420179A), was a conceptual model consisting of two long bow/leaf-springs that operated in parallel to the user's legs to store and release energy to augment running [8]. Nicholas Yagn's conceptual model was passive, and it was conceived to help people in walking, running, and jumping [2]. Figure 1 shows the concept of Nicholas Yagn's exoskeleton. In a second concept design, also patented (US440684A) [9], the exoskeleton used compressed gas to store energy instead of the giant bow springs. Thus, Nicholas Yagn's exoskeletons designs are examples of a passive exoskeleton.

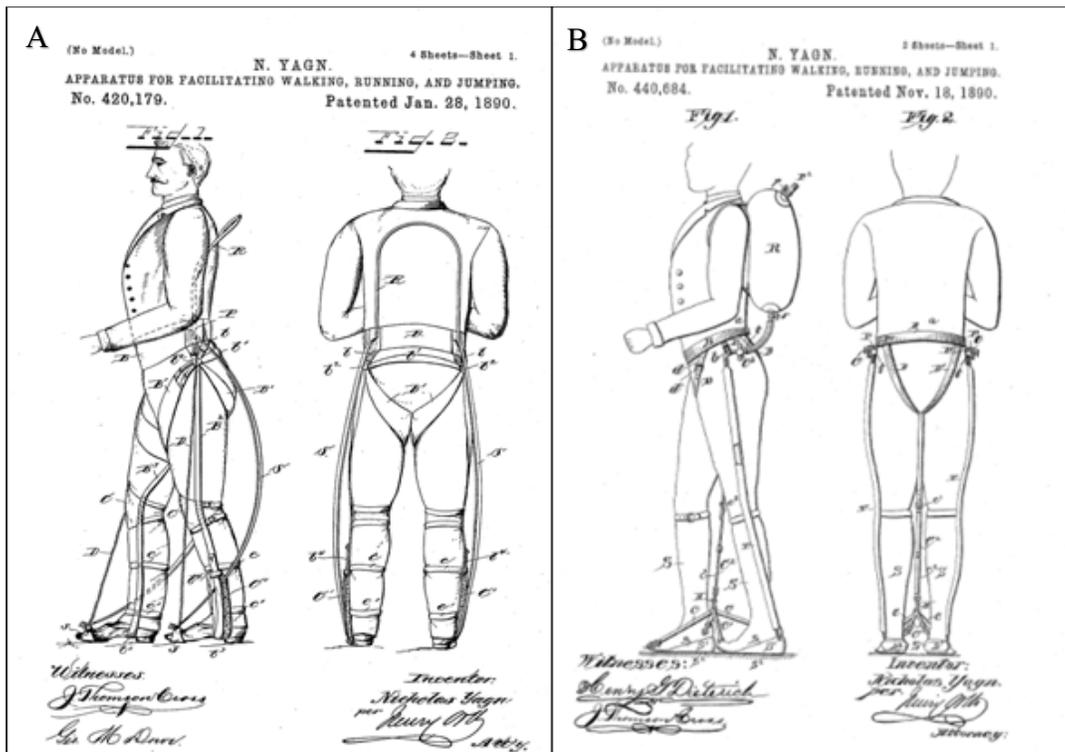


Figure 1: Nicholas Yagn’s first conceptual model of a lower extremity exoskeleton [8] (A), and the last version of Nicholas Yagn’s conceptual model [9] (B)

From 1960 to 1971, the development of the Hardiman Exoskeleton began as a cooperative Army-Navy effort by the General Electric Company. Hardiman stands for ‘Human Augmentation Research and Development Investigation Manipulator.’ The US Defense Department was interested in developing a man-amplifier, that is a “powered suit” that could improve a soldier’s lifting and carrying abilities [10]. Hardiman was a hydraulic powered exoskeleton. It had 30 degrees of freedom, weight of 680kg, and force ratio of 25:1, so the weight of 680kg would feel like 27kg to the user [2], [11].

The Hardiman was intended to be heavy and bulky for military use, Figure 2. It had a feedback feature that enabled the user to feel the forces. Moreover, it was a series of overlapping exoskeletons. The outer exoskeletons (the controlled) were followed by the motions of the inner

exoskeletons (the controller), which in turn followed the motion of the human user. The overall concept was well-received, but studies found that replicating all human motions and using a controller-controlled system was not feasible. Hardiman was never used in practice, any attempts with the user inside were impossible due to its uncontrolled violent movement [10], [12]. Further research focusing on one arm has been successful, and the arm was able to lift a load of 340 kg. However, since the arm structure weighed three-quarters of a ton, all components were impossible to work together so the final project was limited. Finally, Hardiman was kept as a prototype due to safety concerns, complexity, and technological limitations [13].



Figure 2: Hardiman I Prototype, Image credit: Museum of Innovation and Science Schenectady [14].

Around the same time, scientists at the Mihailo Pupin Institute developed the world's first active exoskeleton to help gait rehabilitation on patients with paraplegia. They built several designs

over the years (1960-1970), and Kinematic Walker was the first of the three designs. Each design was an improvement of the previous, however, their exoskeleton was limited to a predefined motion and had limited success. Similar to the Hardiman, it could not carry its own power source [10], [15]. Kinematic Walker was a lower limb exoskeleton that was kinematically coupled with a single hydraulic actuator for driving the hip and the knee [12]. In 1970, the “partial active exoskeleton” was developed. This device used pneumatic actuators with electronic programming to operate. Later, this design became a “complete exoskeleton” by extending the attachment at the torso, to provide greater trunk support. It had an overall weight of 12 kg, Figure 3. Hundreds of trials were performed to test the complete exoskeleton, and several patients with different degrees of paralysis were able to improve their walking with the support of crutches [12].

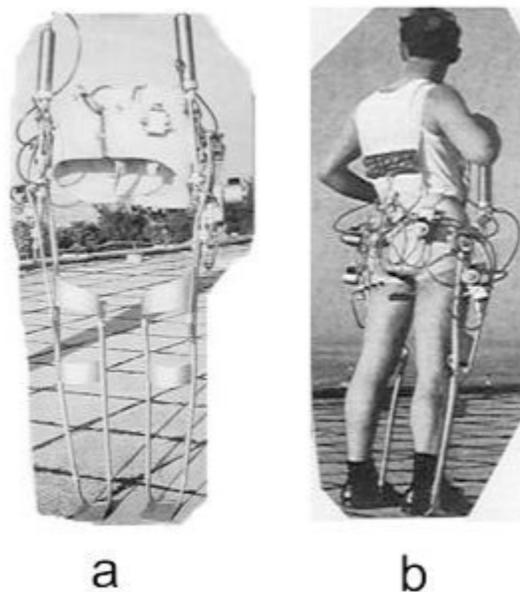


Figure 3: Kinematic Walker, the world's first walking active exoskeleton (a and b) [16].

During the development of active exoskeletons, gait balance arose as a problem. Zero-Moment Point (ZMP method) was introduced as a solution. In brief, the ZMB method is a point on the sole of the foot which has a resultant moment of all acting forces equal to zero. This solution

provided sufficient conditions for maintaining balance during gait. This concept is still used in today's humanoid robots [17].

2.2.2 21st Century Exoskeletons

2.2.2.1 Military Interest

The field of exoskeletons sparked a deep interest that led to extensive research. In 2000, the US Defense Advanced Research Projects Agency (DARPA) began a seven-year, \$75-million program entitled “Exoskeleton for Human Performance Augmentation”. Fourteen designs were submitted, and one design from Sarcos, now part of Raytheon, was selected. The first prototype “XOS” was a full body exoskeleton that used a hydraulic actuator, weighed 68 kg, and gave the user the ability to lift 91 kg. In 2010, “XOS2” was revealed. XOS2 used a high pressure hydraulic actuator, enabling the user to easily lift 91 kg hundreds of times without getting tired. Also, it was lighter, faster, can generate higher forces, and used 50% less power than the first prototype. However, this development is tethered to its power supply, and it is no longer funded by DAPRA [13].

Another Military Exoskeleton is the Human Universal Load Carrier (HULC), which was developed by Berkeley Bionics, now known as Ekso Bionics. Compared to XOS, it is untethered, battery powered, and a lower body exoskeleton. HULC uses high pressure hydraulic actuators and weighs 24 kg without batteries. It allows the user to lift a load of 90 kg with minimum fatigue by having the loads transferred to the ground through the shoes of the exoskeleton. HULC is flexible enough for the user to squat and crawl, has a specific mission attachment that it can carry, and can sustain extreme environmental conditions [2], [13].

Berkeley Lower Extremity Exoskeleton (BLEEX) has been the outstanding exoskeleton of the DARPA program. BLEEX is an energetically autonomous lower-limb exoskeleton that augments human strength and endurance during locomotion. BLEEX has a walking speed of 0.9

m/s with the capacity to support loads up to 75 kg (exoskeleton weights +payload); walking speeds can reach 1.3m/s without a load. It contains a power unit and a backpack-like frame that can carry a variety of heavy loads [20].

BLEEX has a total of seven Degrees of Freedom (DOFs) on each leg, three at the hip, one at the knee, and three at the ankle, which are powered by a linear hydraulic actuator. BLEEX allows the user to comfortably squat, bend, twist, and walk on ascending and descending slopes as well as to step over and under obstructions while carrying a heavy load [10]. However, actuating all actuators leads to high power consumption and control complexity. As a result, only four actuators were actuated (flexion/extension at the ankle, knee, and hip and abduction/adduction at the hip) [15]. The joint power for BLEEX was determined by utilizing a clinical gait data analysis for walking. The data was used to ensure kinematic flexibility to allow natural dynamic movement. The hip and other joints were simplified so the overall BLEEX was almost anthropometric [10]. The control algorithm mirrors the user's voluntary and involuntary movement quickly, with minimal interaction between the user and the exoskeleton [10].

2.2.2.2 Exoskeletons for Rehabilitations

Rehabilitation is an important treatment to improve the recovery of patients who suffer from neurological disorders such as: stroke, spinal cord injuries (SCI), muscular dystrophy, or cerebral palsy. These disorders lead to muscular weakness, which is the main reason for the development of rehabilitation of exoskeletons [19]. To date, the major focus of the exoskeleton is on lower limb exoskeletons [20]. Some of the most significant work in the field and Food and Drug Administration (FDA) approved are: Hybrid Assistive Limb (HAL), Exoskeleton Lower Extremity Gait System (eLEGS), ReWalk, and Indego. Each one of these exoskeletons has a unique mechanism, but their overall goal is to enable the patient to walk, see Figure 4.

HAL was developed in Japan by Tsukuba University and Cyberdyne Systems Company. It is a wearable exoskeleton designed for different applications, including rehabilitation, rescue support, firefighters, and heavy labor support. Since launching the project in 1992, several versions of HAL have been released: full body, lower body, and a single-leg version [20]. Each version was an improvement in design, mobility, weight, and power. The single-leg version of HAL was developed to support patients with hemiplegia. The latest version of this device, HAL5, is a battery-powered full body exoskeleton targeting the needs of paraplegic patients. It is comprised of a controller, a main unit, and sensor shoes. It was the first to receive a global safety certification. The lower body of HAL weighs 15 kg and HAL5 weighs 23 kg, and can lift a load up to 70kg. HAL has two DOFs, one at the hip joint and one at the knee joint. They are actuated based on DC servo motors and harmonic drive gears, while the ankle is passively controlled [20]. HAL's control algorithm can be modified to be used on patients for gait assistance [2]. HAL provides interactive motion according to the user's voluntary motor drive. It can detect a bioelectrical signal that is generated when the user attempts to move or lift. When a user attempts to move, the brain sends electrical signals to the muscles, and weak traces of these signals are detected by a surface sensor attached to the skin through a process called surface electromyography (sEMG) [21]. sEMG is used to drive a robotic autonomous control system known as Cybernetic Voluntary Control. With disabled lower limb patients, Cybernetic Autonomous Control can be used for automatic motion support [22], [23]

eLEGS was developed by the University of California, Berkeley and Berkeley Bionics that originally developed BLEEX and HULC exoskeletons for military use. In October 2010, they released a rehabilitation version of the exoskeleton BLEEX named eLEEGS. eLEGS allows paraplegics and a person with lower extremity weakness to stand and walk with the aid of crutches

or a walker [24]. In 2011, eLEGS was renamed Ekso. Ekso weighs 20 kg, has a maximum speed of 3.2 km/hr, and a battery life of six hours [2], [12]. Ekso has three actuated DOFs on each leg, the hip and knee joints are actuated in the sagittal plane and the ankle joint is passive with freedom of movement in the sagittal plane only [24]. eLEGS adopted the use of a human-machine interface (HMI). The HMI is a method that involves a set of sensors attached to the exoskeleton and crutches to determine the patient's motion [24]. In 2012, eLEGS became the first exoskeleton to receive a 501(k) clearance from the U.S. Food and Drug Administration for rehabilitation use [20].

Ekso GT, “Exoskeleton lower extremity Gait System”, is the second generation of Ekso released. In 2016 it received FDA approval for patients with hemiplegia due to stroke, or SCI (level fourth thoracic vertebra (T4) to fifth lumbar vertebra L5), making it the only exoskeleton available for a wider range of patients. It is a wearable exoskeleton that has a total of 6 DOFs (3 per leg). The hip and knee joints are active, the ankle is passive and sprung [25]. It weighs 23 kg and has a walking speed of 2.3 km/hr. Ekso GT requires the user to use crutches, not only for additional support but also to control the exoskeleton [26]. For rehabilitation applications, the assistance provided to each leg can be modified from a smart software (Variable Assist Software) based on the individual need [26], [27]. Compared to traditional rehabilitation, clinical studies on Ekso GT verified that gait training using the exoskeleton improved the patient step pattern and allowed them to take longer steps faster [27].

The latest version of Ekso is EksoNR (NeuroRehabilitation), which was released in 2019. It is a lower body exoskeleton that weighs approximately 27 kg with batteries. It is designed so patients can bear their own weight. The biggest change from the Ekso GT was the added feature of a real-time feedback screen. With that feature, physical therapists can monitor their patient's progress instantly and customize it easily [28]. In 2020, EksoNR received FDA clearance for use

on patients with an acquired brain injury (ABI) [29]. To date, EksoNR is the exoskeleton that serves the widest range of patients.

ReWalk was developed by the scientist Amit Goffer and marketed by ReWalk Robotic, Massachusetts; originally known as (Argo Medical Technologies, Ltd.) [20]. Two versions of ReWalk are available, ReWalk-I (institutional), and ReWalk-P (personal) [30]. Both have the same design, a brace-like, lower limb battery-powered exoskeleton designed to help paraplegic patients with SCI walk independently. The difference between the two versions mainly depends on the use. It is for rehabilitation use if it is used on patients with SCI from level T4 to L6, and it is for personal use if it is for patients with SCI level T7 to L5 [27], [31]. In addition, ReWalk-I comes with a graphical user interface (GUI) for clinicians to use and adjust for different patients, while ReWalk-P is customized for one user need and does not come with a GUI [26]. ReWalk has 2 actuated DOFs on each leg, one at the hip, one at the knee, and has a passive spring joint at the ankle. It weighs 30 kg and has a walking speed of 2.3 km/hr [31]. The exoskeleton control system is based on the change of center of gravity of the patient [8]. It can execute a pre-programmed step when the trunk exceeds a predefined threshold angle [31]. A wireless remote controller that is worn on the wrist is used to switch between three active modes (sit, stand, and walk) [31]. Crutches are still in need to maintain patient stability. The backpack contains a rechargeable battery and a computerized system. From the software, the robot kinematic, joints ROM, and speed can be personalized. ReWalk requires a training program, prior to using the exoskeleton for physical therapy and patients.

Indego was developed at the University of Vanderbilt in the Center for Intelligent Mechatronics [20]. It is a powered lower-limb exoskeleton that weighs 13 kg and has a walking speed of 0.8 km/hr. It is designed to provide gait assistance to paraplegia patients [20]. It has

brushless DC motor actuators only at the hip and knee joints. Ankle and foot support are not provided with Indego, but a set of standard ankle-foot orthoses must be used instead [32]. The control system is based on the estimation of the location of the user center of pressure (CoP). When the user tilts their body forward/back, the CoP changes, which commands the controller to transition respectively [33]. This control system enables the user to be independent without the assistance of an external operator [33]. Similar to ReWalk, Indego can be customized to be used as a personal device and can be used in rehabilitation facilities. In 2016, Indego received FDA approval for the use on individuals with SCI at levels up to T7 for personal use and up to T4 for rehabilitation use [26]. Indego features vibratory feedback LED indicators and wireless software which provides control for gait parameters. An Indego application is required to allow the user to control operation and change settings [13].



Figure 4: From Left to right, HAL [18], EksoNR [23], ReWalk [25], and Indego [28] lower extremity exoskeletons.

2.2.2.3 Industrial Exoskeletons

The interest of using exoskeletons in industrial applications is rapidly increasing. The primary motivation is to prevent work-related musculoskeletal disorders (WMSDs) and the associated financial consequences [34]. The main contributors to WMSDs are lifting and handling heavy materials and supporting heavy tools (overexertion injuries). Such injuries accounted for approximately 23% of all-time workplace injuries and illnesses in 2018. The direct cost of injuries in the United States due to overexertion, lifting, pushing, pulling, holding, carrying, or throwing objects is \$13.30 billion or 23% of the overall workplace injuries direct cost based on 2018 data from Liberty Mutual, the U.S. Bureau of Labor Statistics and the National Academy of Social Insurance [35]. Full automation would possibly reduce or solve these problems, but that is not always possible. Some tasks involve small manufacturers where automation is not cost-effective, while others involve complex and varied moves that are beyond the capabilities of conventional robots [34]. Exoskeletons could bridge the gap between unassisted human operations and conventional robots [34]. The commercially available industrial exoskeletons can be categorized into: back assist, shoulder and arm assist, tool holding/support, and leg assist [5].

Described below are two out of many companies that have on the market available passive industrial exoskeletons. SuitX was selected because it is the only US Company that has multiple different parts of exoskeletons available on the market, and FORTIS is the only available tool holding US company exoskeleton. SuitX Company (SuitX, Emeryville, CA, USA) has three types of industrial exoskeletons: BackX, a passive upper-body exoskeleton for the back; LegX, a passive lower-body exoskeleton for the legs; and ShoulderX, a passive upper body exoskeleton for the arms. Each exoskeleton can be worn individually or in combination depending on the need. Figure 5 illustrates the three exoskeletons in use. The BackX weighs 3.2 kg and has two modes: Smart

Mode, which maximizes mobility while wearing the device, enabling the user to freely walk, climb up/down, and use a work vehicle all while providing protection when needed. The second mode is Instant Mode that provides back support during every posture. The LegX supports the user's knee by reducing the force of the quadricep muscles. LegX allows the user to squat repeatedly, or for long periods of time. The weight of LegX and forces generated are transferred to the ground directly. The ShoulderX weighs 3.17 kg and the support mechanism increases as the user lifts their arms and becomes near zero when the arms are lowered [36].

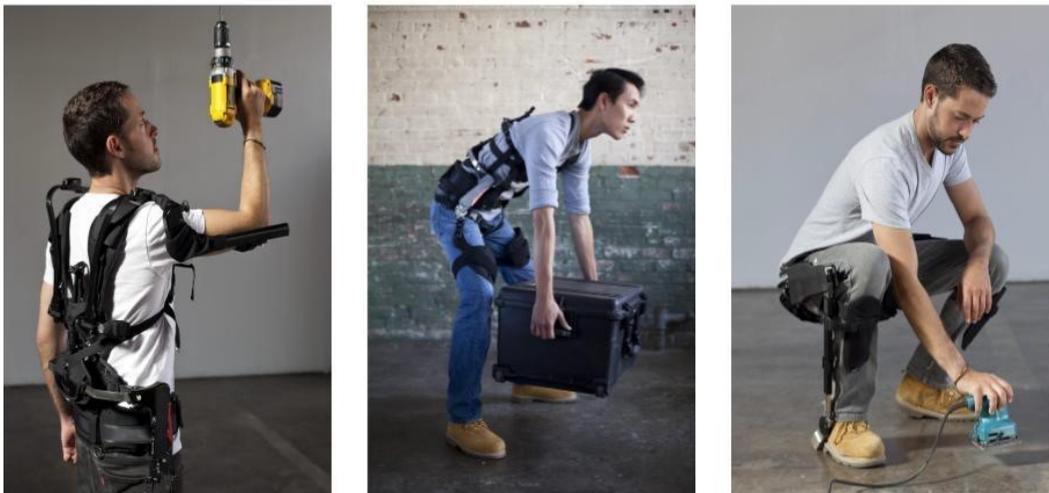


Figure 5: From left to right, SuitX ShoulderX, BackX, and LegX. image retrieved from SuitX [36].

Lockheed Martin (Lockheed Martin, Bethesda, MD, USA) developed a passive tool handling exoskeleton called FORTIS. FORTIS was designed to support tools weighing up to 16 kg by attaching a third arm to the hips, (Figure 6). It transfers the load of the heavy tool through the exoskeleton to the ground in a standing or kneeling position. According to the FORTIS product card, the FORTIS exoskeleton reduces the muscle's fatigue and increases work rate by 2 to 27 times [37].



Figure 6 : FORTIS exoskeleton standing Image retrieved from Lockheed Martin [37].

2.3 Exoskeleton Standard

Safe adoption of new emerging technology is aided by international consensus standards. In the fall of 2017, ASTM International formed the Exoskeleton and Exosuits Standard Committee, now known as F48, to assess active, passive, and quasi-active/passive exoskeletons. Additionally, subcommittees were established to develop and maintain international standards that include standard safety, quality, and efficiency. Each subcommittee seeks to develop standards for the application of exoskeletons in industrial, medical, military, and consumer applications [3]. As of fall 2021, there are active standards under some of the subcommittees, (Table 1).

Table1. ASTM Subcommittees and Their Active Standards [3]

Subcommittee	Active Standard and Their Title
F48.01 Design and Manufacturing	<ul style="list-style-type: none"> • F3358-20 Standard Practice for Labeling and Information for Exoskeletons
F48.02 Human Factors and Ergonomics	<ul style="list-style-type: none"> • F3444/F3444M-20 Standard Practice for Training Exoskeleton Users • F3474-20 Standard Practice for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics • F3518-21 Standard Guide for Quantitative Measures for Establishing Exoskeleton Functional Ergonomic Parameters and Test Metrics • F3519-21 Standard Guide for Establishing a Reporting Structure for Exoskeleton Analysis • F3527-21 Standard Guide for Assessing Risks Related to Implementation of Exoskeletons in Task-Specific Environments
F48.03 Task Performance and Environmental Considerations	<ul style="list-style-type: none"> • F3427-20 Standard Practice for Documenting Environmental Conditions for Utilization with Exoskeleton Test Methods • F3443-20 Standard Practice for Load Handling When Using an Exoskeleton • F3517-21 Standard Practice for Movement Tests When Using an Exoskeleton
F48.04 Maintenance and Disposal	<ul style="list-style-type: none"> • F3392-20 Standard Practice for Exoskeleton Wearing, Care, and Maintenance Instructions
F48.05 Security and Information Technology	<p>There is one proposed standard, but it is not yet active</p> <ul style="list-style-type: none"> • WK76659 Effective Cybersecurity Management for Exoskeletons
F48.91 Terminology	<ul style="list-style-type: none"> • F3323-20 Standard Terminology for Exoskeletons and Exosuits

2.4 Current Research

The Occupational Ergonomics and Biomechanics Laboratory from Virginia Tech has researched exoskeletons with a focus on occupational applications. In one study, they compared three different designs of passive exoskeletons in terms of physical demands and quality in a simulated overhead drilling task while investigating the effect of tool mass (2 kg and 5 kg) [38]. The physical demands consisted of maximum acceptable frequency (MAF), rating of perceived discomfort (RPD), and muscular loading. Additionally, the quality was a measure of the task performance, which was quantified based on the total number of errors. Their research included one of each of the following: an upper-body exoskeleton (SHL), a mechanical arm attached to exoskeletons (ARM), and a full-body exoskeleton (FULL). The independent variables were the exoskeletons and tool mass, and the dependent variable was the physical demands as determined subjectively by MAF and RPD and objectively by EMG signals normalized to the respective muscle's maximum voluntary contraction. The results indicated that MAF significantly differed between the exoskeleton conditions for female participants only. Specifically, the FULL condition resulted in significantly lower MAF than all other conditions while the ARM condition resulted in higher MAF (though not significant). The lighter tool led to an increase in the number of errors among males, and females made more errors using the heavier tool. Furthermore, the heavier tool led to significantly higher peak loading among the female participants. Overall, the FULL/ARM exoskeletons resulted in the lowest/highest MAF, respectively, for females. The SHL reduced the shoulder peak loading, but it did not impact quality or MAF. All three exoskeleton designs reported lower levels of upper-arm RPDs compared to the without the exoskeleton condition. For males, the lower back RPDs was significantly reduced in the SHL condition compared to the without the exoskeleton condition. Heavier tool mass significantly increased the RPDs at the

hand/wrist (24%), upper arm (15%), shoulder (13%), thigh (15%), and lower leg/foot (14%). All three designs demonstrated various increases and/or decreased depending on the gender and tool mass. No particular type of exoskeleton was found to be more beneficial than the other [38].

In another similar study, Virginia Tech researchers compared the same three exoskeleton designs under three levels of task precision requirements [39]. The three levels of precision requirements consisted of six identical sets of three holes. Each set represented one level of a different hole's diameter (angular tolerance): Low ($\pm 5^\circ$), Middle ($\pm 3.5^\circ$), and High ($\pm 2^\circ$) respectively. Two independent variables were examined: exoskeletons and precision requirements, while physical demand was the dependent variable. They found the effects of precision requirements were quite consistent across all three of the exoskeleton designs. Regardless of the exoskeleton worn, higher precision requirements increased the physical demands and increased the number of errors by ~70% in the Low level and 500% in the Middle and High levels. FULL and ARM exoskeletons increased loads on the low back and decreased the task performance. The SHL exoskeleton led to more error at the highest level of precision, but also reduced the muscle overall activation and perceived demands at the upper body [39].

The most recent published work from the Virginia Tech researchers with Engineering and Ergonomic Specialists at Ford Motor Company investigated the long-term usability of an arm exoskeleton, factors contributing to user acceptance, and whether exoskeleton use influences the number of medical visits at six different automotive facilities [40]. The independent variable was the arm exoskeleton, and the dependent variable was the answer to six questions that were taken after each milestone: baseline (before using the exoskeleton), and after 1, 6, 12, and 18 months (i.e., M1, M6, M12, and M18). The questions were related to usability and had a scale of 0-10,

with 0 = ‘no discomfort’ and 10 = ‘most discomfort’. The questions included: overall fit and comfort, thermal comfort, perceived balance, perceived range of motion, overall perceived job safety, and perceived job performance. Additionally, participants were asked to provide open-ended feedback to all the questions except regarding thermal comfort, and were asked to respond to three open-ended questions. Then, at M12 and M18 they were asked to share their overall feelings about the exoskeleton and to indicate their intention to use it in the future. The results of the usability questionnaire were statistically consistent over time and across facilities. On average, participants expressed overall fit and discomfort as a minor concern, thermal discomfort as a moderate-to-high concern, balance as a minimal concern, ROM as a minor concern, perceived safety as equivalent/slightly better, and perceived job performance as slightly better. Moreover, 64.1% of the participants liked the arm support from the exoskeleton and the associated reduction in shoulder strain. Perceived job performance (i.e., whether the exoskeleton positively/negatively affected the performance) was the only statistically significant predictor of the intention of using the exoskeleton; there was a 179% increase in exoskeleton use for a positive effect in the perceived job performance. In M12 and M18, 61.5% of the participants reported their intention-to-use the exoskeleton. Medical visits appeared to be affected significantly by age. From the regression analysis, a one-unit increase in age decreased the probability of a medical visit by 5%, and when the exoskeleton was used, the medical visits decreased by 52% [40]. In a companion study, Virginia Tech researchers examined the long-term effects of the exoskeleton on physical demands at nine automotive manufacturing facilities. The occupational repetitive action (OCRA) method was utilized. Two OCRA score factors (posture factor based on the percentage of time exposed and force factor) were obtained from several cycles of recorded videos of the participants. The summation of the two scores produced a single physical demand score. The results indicated no

significant difference between the group that utilized the exoskeleton and the control group (i.e., No-Exoskeleton). However, in some facilities, MSD scores for neck and shoulder decreased over time. Wrist MSD score in some facilities remained the same for the group using the exoskeleton, while for those in the control group the score increased over time. Low back and upper arm MSD scores were close between the two groups. In brief, the effect of the exoskeleton on reducing physical demand is task-specific [41].

Currently, Virginia Tech researchers are conducting joint research with the University of California, Berkeley on evaluating trunk and arm support exoskeletons for construction. The aim of the study is to quantify the benefits and risks of exoskeleton use, understand the adoption of exoskeletons, and possibly prevent unexpected effects [42].

The University of California Human Engineering and Robotic Lab has done some research related to shoulder exoskeletons. In one study, they evaluated a shoulder exoskeleton design on static and dynamic overhead tasks [43]. The static task consisted of tracing a series of lines and the dynamic task consisted of inserting and removing a series of screws. In both types of tasks, participants used a lightweight drill and a heavyweight drill (0.45 kg and 2.25 kg). The support of the arm exoskeleton was investigated at four settings (no support, low, medium, and high). The independent variables were the exoskeleton, support setting (No 0, low 8.5, medium 13.0, and high 20.0 Nm peak torque), and tool weight levels. While the dependent variable was the muscles electrical activity. The results showed a significant reduction of electrical muscle activity in the anterior deltoid and trapezius when using the exoskeleton under all support levels and tool weights'. For the light tool, the average reduction in activation for the anterior deltoid was 32% at low support, 54% at medium support, and 80% at high support when compared to without the exoskeleton. For the heavy tool, it was reduced by 24%, 43%, and 64%, respectively. On the other

hand, trapezius muscle activity was reduced most at the high support settings by 46% for the light tool and 42% for the heavy tool. Medium and low support settings reduced the activation by 39% and 23% for the light tool and 27% and 18% for the heavy tool [43].

In another similar study, University of California researchers evaluated the physical demand and the subjective feedback [44]. The difference between the two studies is that they modified the torque level to (No 0 Nm, low 5 Nm, medium 10 Nm, and high 15 Nm peak torque). The results showed the largest significant reduction on the anterior deltoid (18% MVC) and trapezius (10%) when increasing the peak torque compared to the unassisted condition. Specifically, median muscle activities were significantly affected by the use of exoskeleton by up to 81%. Participants preferred the exoskeletons the most at the medium level (10 Nm peak torque) of assistance regardless of the task type and tool weight [44]. When comparing the reduction of anterior deltoid and trapezius, the results are consistent with the previous study [39]. In this study, the reduction of anterior deltoid found here exceeds those found by the Virginia Tech group. This could be due to the task characteristics, anthropometry, or torque settings [44].

Another group, from Iowa State University, has also researched shoulder exoskeletons. In one study, they assessed exoskeleton use during on-site job tasks [45]. They hypothesized the EMG amplitudes and fatigue risk values for the anterior deltoid would be significantly reduced when utilizing the exoskeleton. Additionally, they wanted to determine if EMG amplitudes and fatigue risk values would increase from the beginning to the end of a work shift. The independent variable was the arm support exoskeleton, and the dependent variable was the muscle activity. To determine fatigue risk, the percent maximum voluntary contraction (%MVC) EMG values were compared to threshold limit values. At a repeated job cycle, utilizing the exoskeleton significantly reduced the EMG amplitude and fatigue risk for the anterior deltoid. Over the duration of the shift,

utilizing the exoskeleton did not significantly reduce the anterior deltoid EMG amplitude or the fatigue risk. Overall, comparing both results from with the exoskeleton and without the exoskeleton, the EMG amplitude and fatigue risk level were reduced for the muscle, but the reduction was not statistically significant [45].

2.5 Research Gaps

To date, exoskeleton research has focused the evaluation on physiological measures, such as physical exertion and fatigue. Some studies focused on usability measures such as quality and perceived discomfort. However, there is a gap in the knowledge of how user preference is associated with exoskeleton muscle activity reduction.

2.5.1 Objective

Muscle benefit should be paired with user preference to assess the viability of exoskeletons for work tasks. With a large number of exoskeleton options, it would be beneficial to know if a relationship exists between user selection of an exoskeleton and the exoskeleton that best reduces their muscle activity. Therefore, the objective of this study was to investigate the relationship between the preferred exoskeleton and muscle activity reduction during six different simulated aircraft manufacturing tasks. Fulfillment of this goal was pursued by satisfying the following

1. Determine if there is a significant difference between the %MVC muscle activity reductions when using three different exoskeletons while performing the simulated manufacturing aircraft tasks.
2. Identify the probability of selecting a specific exoskeleton with respect to user preference and %MVC muscle activity reduction.
3. Assess the correlation between exoskeleton selection preference and %MVC muscle activity reduction.

CHAPTER 3

METHODOLOGY

3.1 Participant and Ethical Approval

A total of 16 participants (8 male, 8 female) with aircraft manufacturing experience were recruited from a local aircraft manufacturing company to participate in this study. They had a mean age of 45.6 ± 10.9 years, height of 172.1 ± 10.5 cm, and mass of 87.2 ± 22.7 kg. Prior to participation, participants were informed of the experiment and signed a consent to participate in the study. Wichita State University's Institutional Review Board for Human Subjects Research approved the experiment (IRB Study #4898). Participants then answered an injury screening form to qualify for the study. If participants had knee, back, shoulder, or elbow surgery or had a significant injury within the prior six months, they were excluded from participating in the study.

3.2 Tasks Description

Participants performed six different simulated aircraft manufacturing tasks under four different conditions (i.e., without an exoskeleton and utilizing each of three different passive shoulder exoskeletons). The condition without the exoskeleton, hence forth referred to as "No-Exoskeleton", was the first tested for each subject, and it served as the baseline for the comparison of the three exoskeletons. The specific exoskeletons utilized were Evo (EV) (Ekso Bionics, Richmond, CA, USA), Skelex 360 XFR (SK) (Skelex, Rotterdam, Netherlands), and Paexo (OB) (OttoBock, Duderstadt, Germany), (Figure 7). Prior to performing the simulated tasks, each exoskeleton was adjusted to fit the participant as instructed by the exoskeleton manufacturer guidelines. The force resistance setting of each exoskeleton was adjusted to the minimum torque setting required to hold each subject's arm abducted at 90° with the elbow flexed at 90° . The maximum torque assistance angle for Skelex and Paexo was set to occur when the shoulder flexion

angle was $\geq 90^\circ$. The Evo assistance angle was set to occur at $\geq 115^\circ$, the closest of the discrete angle settings for the EVO. These settings were consistent across all participants.



Figure 7: Images of the three passive shoulder exoskeletons used in the study: A) the Ekso Bionics Evo [46], B) the Skelex Skelex 360 XFR [47], and C) the Ottobock Paexo [48].

The six different tasks consisted of four sealing tasks utilizing a 15 cm slender metal fairing tool (sealing tool) weighing less than 0.024 kg, and two riveting tasks utilizing a squeeze riveting tool (weigh = 2.7 kg, model = 60AH30HD, Atlantic Air Tool Company, Inc.), (Figure 8). The tasks were performed on a mock-up fuselage section comprised of four horizontal stringers equally separated by 24 cm in two vertically aligned braces separated by 94 cm, (Figure 9). The simulated fuselage section was constructed for use in the study and designed to be representative of an aircraft. In each of the horizontal stringers, there was a total of two sets of rivets, one set on each side (left and right). Each set included 8 rivets, spaced equally by 2.5 cm, and the distance between each set was 8 cm. The motion for all six tasks was horizontal; the participants performed the simulated sealing and squeezing actions going in both the left to right and right to left directions along designated stringers. Each combination of left to right and right to left motions along a single stringer comprised a trial.

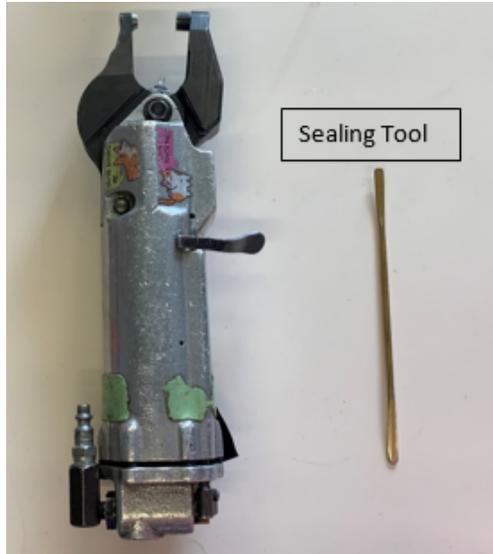


Figure 8: The riveting squeeze tool (left) and sealing fairing tool (right) used during the simulated air manufacturing riveting squeeze and sealing tasks.



Figure 9: Anterior view of the mock-up fuselage used in the study. The horizontal stringers were numbered in order 1 to 4 with stringer 1 at the top. Labeled in the figure are stringers 1 and 3 and the left and right braces.

Task 1 consisted of horizontal overhead sealing on stringer 1 (i.e., the top stringer) in the standing position. The mock-up fuselage height was adjusted for each participant so that the midpoint of stringer 1 was 25.4 cm above the top of the participant's acromion process while standing. After adjusting the height, the participant sealed the bottom (lower) side of stringer 1 starting from the left brace (i.e., the left side of the mock-up fuselage) moving right in a horizontal motion to the midpoint of the stringer (i.e., the midpoint of the mock-up fuselage), (Figure 10a), this motion comprised one trial. A second trial on the same stringer was in the opposite direction, starting from the right brace and moving left to the midpoint of the stringer. Both trials were repeated in order, resulting in a total of four trials for Task 1.

Task 2 consisted of horizontal shoulder height sealing on stringer 3 in the standing position. The mock-up fuselage height was adjusted for each participant so that the midpoint of stringer 2 was 7.6 cm above the top of the participant's acromion process while standing. After adjusting the height, the participant sealed the top (upper) side of stringer 3 starting from the left brace moving right in a horizontal motion to the midpoint of the stringer, (Figure 10b). This motion comprised one trial. A second trial on the same stringer was in the opposite direction, starting from the right brace and moving left to the midpoint of the stringer. Both trials were repeated in order, resulting in a total of four trials for Task 2.

Task 3 consisted of horizontal overhead sealing on stringer 1 in the seated position utilizing an Eidos stool (model 106-BC, Eidos Corporation Montréal, Quebec, Canada) with knees bent at 90 degrees. The mock-up fuselage height was adjusted for each participant so that the midpoint of stringer 1 was 45 cm above the top of the participant's acromion process while sitting. After adjusting the height, the participant sealed the bottom side of stringer 1 starting from the left brace moving right in a horizontal motion to the midpoint of the stringer, (Figure 10c). This motion

comprised one trial. A second trial on the same stringer was in the opposite direction, starting from the right brace and moving left to the midpoint of the stringer. Both trials were repeated in order, resulting in a total of four trials for Task 3.

Task 4 consisted of horizontal shoulder height sealing on stringer 4 in the sitting position utilizing an Eidos stool with knees bent at 90 degrees. The mock-up fuselage height was adjusted for each participant so that the midpoint of stringer 3 was 6 cm below the eye height of the participant while seated. After adjusting the height, the participant sealed the top side of stringer 4 starting from the left brace moving right in a horizontal motion to the midpoint of the stringer, (Figure 10d). This motion comprised one trial. A second trial on the same stringer was in the opposite direction, starting from the right brace and moving left to the midpoint of the stringer. Both trials were repeated in order, resulting in a total of four trials for Task 4.

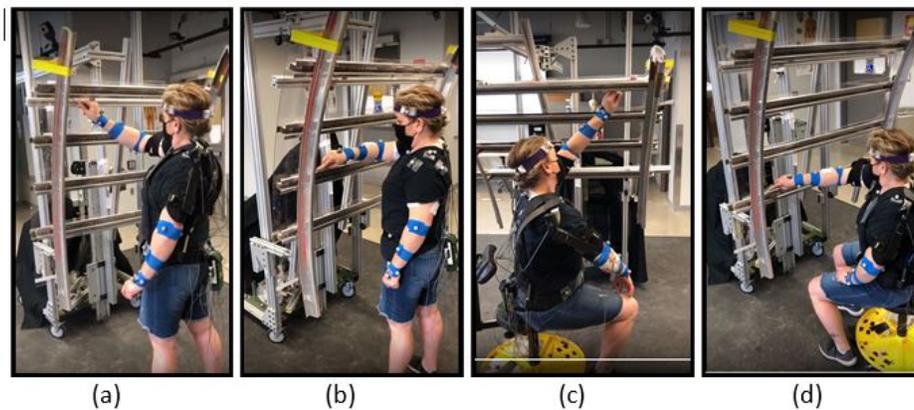


Figure 10: Illustration of the three sealing tasks: (a) Task 1- overhead standing, (b) Task 2- shoulder height standing, (c) Task 3 – overhead sitting, and (d) Task 4 - shoulder height sitting.

Task 5 consisted of horizontal overhead and shoulder height squeeze riveting in a standing position. The mock-up fuselage height was adjusted for each participant so that the midpoint of stringer 1 was 50.8 cm above the top of the participant’s acromion process while standing. After

adjusting the height, the participant started riveting the two groups of four rivets on the left side of stringer 1 starting from the left and moving right in a horizontal motion to the midpoint of the stringer, (Figure 11a). This motion comprised one trial. A second trial on the same stringer was in the opposite direction, riveting another two groups of four rivets starting from the right and moving left to the midpoint of the stringer. Both trials were repeated in order, resulting in a total of four trials for Task 5. The same process was performed on stringer 3 for Task 6, (Figure 11b).

After completing each task and condition, participants took rest breaks lasting at least 2 minutes. Participants could extend a rest break as needed.

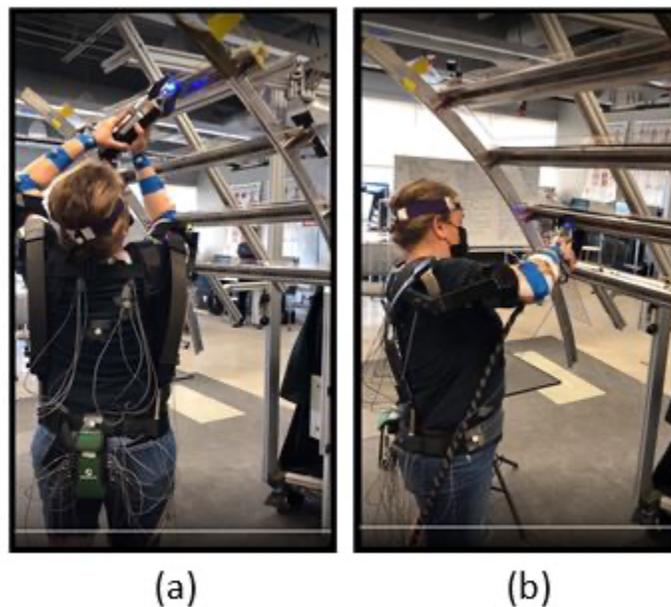


Figure 11: Illustration of squeeze riveting tasks (a) Task 5 – overhead riveting and (b) Task 6 – shoulder height riveting.

The riveting squeezing tasks required the participants to raise the squeeze tool to a specific height and hold it for 1.5 seconds on each rivet. A custom-made switch generated an electrical signal when the rivet squeeze tool trigger was activated – as would be done to squeeze a rivet. An unpressurized air hose was connected to the squeeze tool to a swivel fitting on the squeeze tool to

better replicate manufacturing conditions. The trigger signal was recorded along with surface EMG data, described below.

Subjective feedback was obtained at two different times. First, at the end of each exoskeleton condition, they were asked to rate the comfortable fit of the exoskeleton with a range of 1 as “very uncomfortable” to 5 as “very comfortable”. Second, after they finished all three exoskeletons' conditions and 6 tasks, they were asked to rank their preferred exoskeleton for use during sealing and squeezing, on a scale of 1 as “most preferred” and 3 as “least preferred”.

3.3 Electromyography

Muscle activity from surface EMG was sampled at 1200 Hz using a Noraxon TeleMyo G2 2400R telemetry EMG system (Noraxon USA, Inc., Scottsdale, AZ) and recorded through Cortex Motion Analysis Software (Version 8.0, Motion Analysis Corporation, Santa Rosa, CA, USA). Noraxon bipolar Ag/AgCl electrodes (Noraxon U.S.A Inc., Scottsdale, AZ, USA) with a 2 cm inter-electrode distance were placed over the bilateral anterior deltoid, medial deltoid, and trapezius muscles. These specific muscles were chosen because of their contributions to performing overhead tasks and their potential to be influenced by upper extremity passive exoskeletons [39], [49], [50]. The placement of the EMG electrodes over the muscles was based on Zipp’s EMG placement recommendation [51]. A soft measuring tape was used to identify the EMG electrode location. Prior to placing the EMG electrodes, the area was first gently abraded and cleaned by electrode skin prep pads. Following the preparation, self-adhesive Ag/AgCl snap electrodes were attached to the pairs of the EMG electrodes.

The raw EMG data for MVC’s and all tasks were hardware filtered using a 1st order high pass filter (10 Hz, $\pm 10\%$ cutoff) and 8th order Butterworth/Bessels low pass anti-alias filter (500 Hz, $\pm 2\%$ cutoff). The EMG signals were then digitally post-processed in MATLAB software (The

Mathworks, Natick, MA, USA) using custom code. Then the EMG data were demeaned (i.e., subtracting the mean EMG signal from the overall signal), rectified, and filtered using a recursive (i.e., zero phase shift) digital 4th order Butterworth filter with a 3 Hz cut-off frequency.

EMG maximum voluntary contractions (MVC) were collected before any simulated manufacturing tasks were performed. They were collected while participants performed specific isolated MVC muscle exertions. The EMG MVC signal was processed in MATLAB as described above. The maximum measured signal for each muscle was used to normalize the simulated manufacturing's tasks EMG data. The percent maximum voluntary contraction (%MVC) was calculated by subtracting the normalized MVC EMG when using an exoskeleton from the corresponding No-Exoskeleton value and multiplying it by 100.

3.4 Data Processing

Outliers were identified and removed using the interquartile range method. For each sealing task and exoskeleton condition, the processed and normalized EMG data for each trial and muscle were averaged for both repetitions going in the same direction (left/right to midpoint). Then, the averaged pairs of trials were averaged. For each squeeze riveting task and exoskeleton condition, the average value of the processed and normalized EMG data for each muscle and each of the eight 1.5 sec simulated riveting actions, i.e., tool trigger activation, were averaged. The averaged values from each of the four trials within the task were averaged. The averaged data for each task (six), exoskeleton (four), and muscle (six) were then analyzed using statistics software.

Subjective feedback responses for exoskeleton ranking preference, and comfortable fit were all averaged, and the mean output was presented in the results.

3.5 Statistical Analysis

To address objective 1, separate one-way repeated measure analysis of variance (ANOVA) analyses were completed for each muscle using SPSS software (Version 27, IBM SPSS Statistics, IL,USA). In each case, the dependent variable was the % MVC reduction for each muscle and task. The exoskeleton condition was the independent variable. A one-way repeated measure ANOVA was run for the 6 muscles (for sealing tasks: the hand holding the tool was identified as “active” and the resting side as “passive”; for riveting squeezing tasks: it was the left side or right side), and 6 tasks for a total of $(6*6) = 36$ one-way ANOVAs. With each ANOVA, descriptive statistics were output from SPSS. The significant difference was determined at $\alpha = 0.05/n$, with $n = 3$ for number of exoskeletons, for the Bonferroni correction to reduce the risk of a type I error. Furthermore, significant muscles were followed by *post hoc* pairwise comparison for each condition and task to determine which exoskeleton use was significantly different from the remaining two exoskeletons. Only the muscle that was significantly different from the remaining exoskeletons was included in the results.

To address objective 2, statistical analyses were conducted using RStudio (version 4.1.2 statistical software (RStudio, Inc., Boston, MA). The statistical significance was determined at $\alpha = 0.10$. A previous study used α of 0.10 when using the multinomial logistic regression [40]. The first step was determining which muscle of each condition would best represent the muscles in predicting the preferred exoskeleton. The muscle was selected based on the lowest residual deviance from a multinomial logistic regression analysis performed using the *multinom* function from the *nnet* package [52]. The lower the deviance the better the model is able to predict the response variables [53]. After selecting the representative muscle, the nested model for each exoskeleton condition was built by adding one of the remaining five muscles one at a time and

running the likelihood ratio test to check the yielded p-value. If the p-value did not exceed 0.10 a third muscle was added and so on, but if the p-value exceeded the 0.10 then nothing more was added. After building the nested model for each exoskeleton condition (EV, OB, and SK), the linear components of the coefficients were calculated by taking the mean of the %MVC muscle activity reduction and multiplying it by the coefficients from the remaining two exoskeletons (e.g., EV nested model used OB and SK model coefficients), see equation 1. The coefficients describe the relationship between the %MVC muscle activity difference from the No-Exoskeleton condition and the preference for a particular exoskeleton, and how a change in the %MVC muscle activity difference from the No-Exoskeleton condition will change the probability of preferring an exoskeleton [54]. Then a probability plot for each muscle selection was computed, see equation 2, (see Appendix A for full details of the code). For some models, one muscle represented the relationship between %MVC muscle activity difference from the No-Exoskeleton condition and the probabilities of selecting a particular exoskeleton, for others there were more than one muscle.

An example of the computed probability plot can be seen in (Figure 12). To interpret the probability plot, first, the x-axis represents the %MVC from the No-Exoskeleton condition where negative values indicate a decrease in the %MVC muscle activity difference when using the exoskeleton compared to the No-Exoskeleton condition (i.e., subtract No-Exoskeleton %MVC values from a specific exoskeleton %MVC values; a negative difference indicates muscle activity reduction by the exoskeleton). The y-axis represents the probability of selecting a particular exoskeleton, (Figure 12).

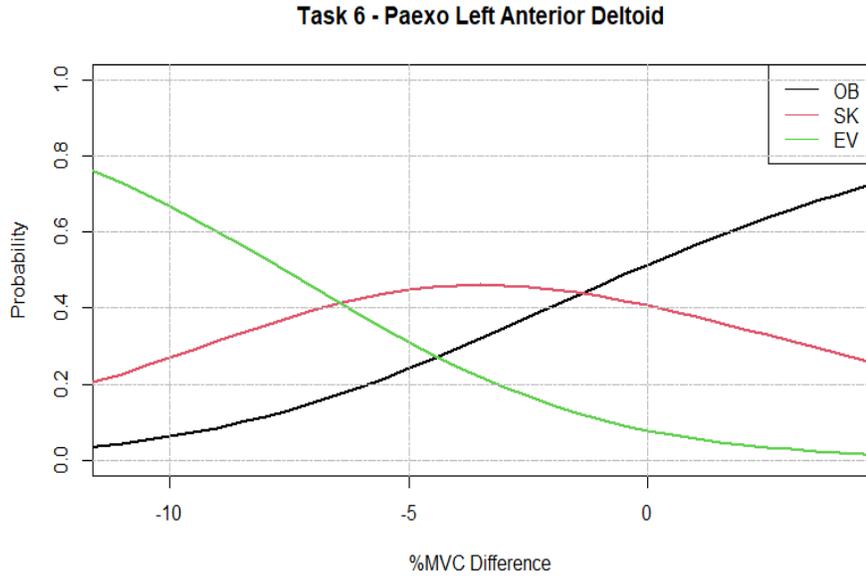


Figure 12: An example of the computed probability of selection plot for the left anterior deltoid during task 6. Color curves for the exoskeletons are: Paexo (OB) in black, Skelex (SK) in red, and Evo (EV) in green. From 5 to 0 %MVC Difference (x-axis), OB has a probability of 0.45 and then it decreases to a probability of 0.40, SK has a probability of 0.41 and then it increases to 0.42, and EV has a probability of 0.02 and then it increases to 0.12. Then from 0 to -5, OB has a probability of 0.40 and it decreases to 0.30, SK has a probability of 0.42 and then it decreases to 0.40, and EV has a probability of 0.12 and then increases to 0.38. Further interpretation will focus only on the 95% confidence interval of the %MVC Difference calculated with the separate one-way repeated measure ANOVA analyses.

$$\begin{aligned} \eta_{1i} &= \beta_{01} + \beta_{11}X_{1i} + \dots + \beta_{p1}X_{pi} \\ \eta_{2i} &= \beta_{02} + \beta_{12}X_{1i} + \dots + \beta_{p1}X_{pi} \end{aligned} \quad \text{Equation (1)}$$

$$\begin{aligned} P(Y = EV) &= \frac{1}{1 + \exp(\eta_{OB}) + \exp(\eta_{SK})} \\ P(Y = OB) &= \frac{\exp(\eta_{OB})}{1 + \exp(\eta_{OB}) + \exp(\eta_{SK})} \\ P(Y = SK) &= \frac{\exp(\eta_{SK})}{1 + \exp(\eta_{OB}) + \exp(\eta_{SK})} \end{aligned} \quad \text{Equation (2)}$$

Equation (1) is for creating the linear components. Where β is the regression coefficients; (OB and SK model coefficients) and X are the independent variables (the %MVC muscle activity reduction for a muscle). Each regression coefficient indicates the predicted change in Y (the preferred exoskeleton) for every single step increase in the independent variables, holding constant

the other independent variables in the model. Holding all other independent variables constant means that the regression coefficient is the relationship between η and specific independent variable [55]. Then computed the probability curves for each independent variable as in equation (2).

CHAPTER 4

RESULTS

The following sections cover the three objectives, subjective feedback, muscle utilization, and the participants' probability of selecting a particular exoskeleton. The results are presented in order below.

4.1 Subjective Feedback

The mean rating indicates that Skelex was the most comfortable exoskeleton with a mean rating of 3.80, followed by Paexo at 3.28, and then Evo at 2.81, see (Figure 13).

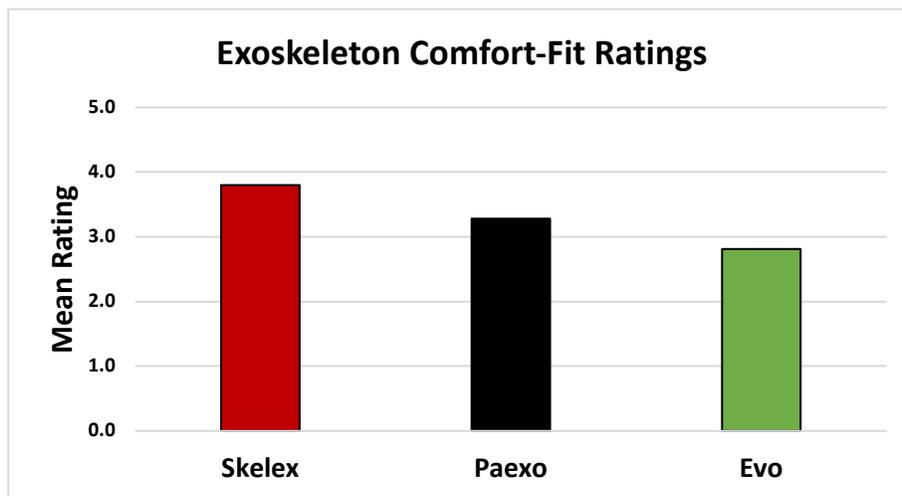


Figure 13: Mean rating of exoskeleton comfortable fit (1 as very uncomfortable to 5 as very comfortable).

At the end of the study, participants were asked to rank in order their preferred exoskeletons for sealing and squeezing riveting tasks, with 1 being the most preferred exoskeleton and 3 being the least preferred exoskeleton. For the sealing tasks, 9 participants selected the Skelex as their top preference followed by 4 participants selected the Evo as their top preference, and lastly 3 participants selected the Skelex as their top preference (Figure 14). For the riveting squeezing tasks, 6 participants selected the Skelex as their top preference followed by 5 participants selected

the Evo as their top preference, and lastly 5 participants selected the Skelex as their top preference (Figure 15).

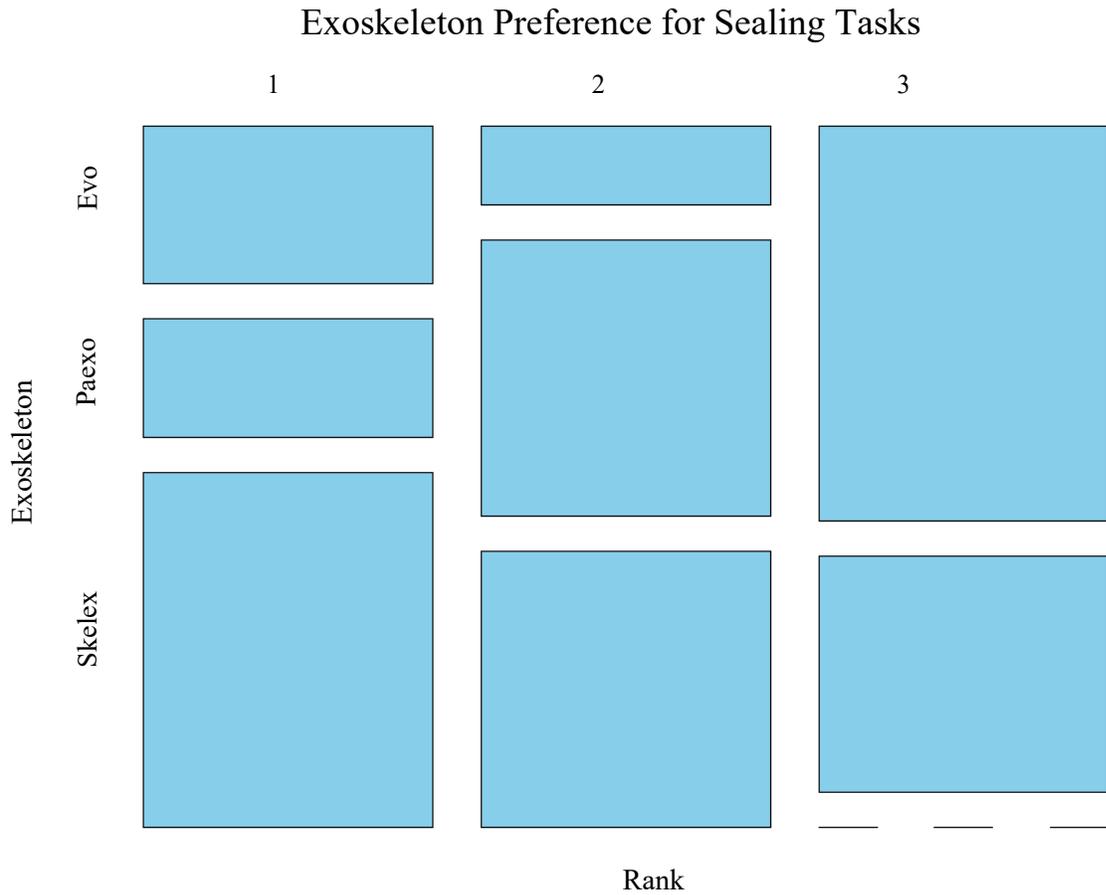


Figure 14: Mosaic plot illustrating the distribution of exoskeleton preference ranking for sealing tasks. The rankings are represented by column (1 as most preferred and 3 as least preferred) and the exoskeleton preference is presented by row. The figure above illustrates that 9 participants selected Skelex as their top preference, 7 participants selected Skelex as their second preferred exoskeleton, and none of the participants selected Skelex as their third preferred exoskeleton.

Exoskeleton Preference for Squeezing Tasks

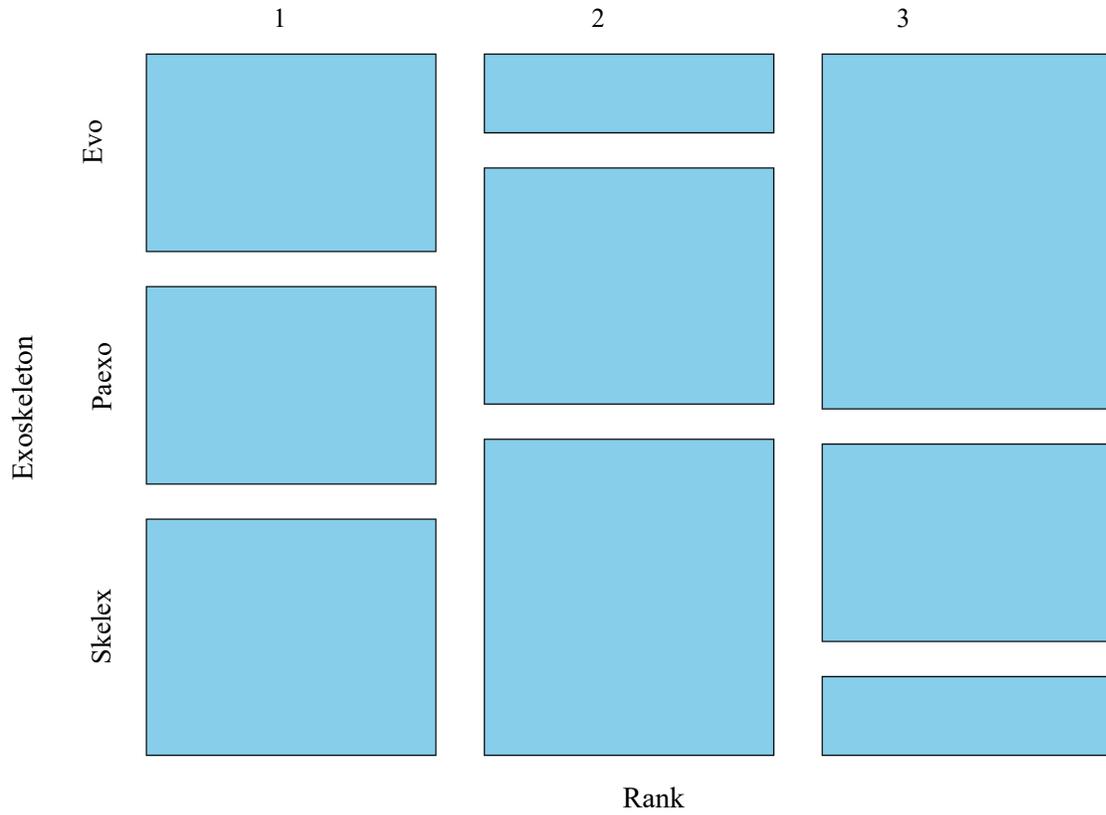


Figure 15: Mosaic plot illustrating the distribution of exoskeleton preference ranking for squeezing tasks. The rankings are represented by column (1 as most preferred and 3 as least preferred) and the exoskeleton preference is presented by row. The figure above illustrates that 6 participants selected Skelex as their top preference, 8 participants selected Skelex as their second preferred exoskeleton, and 2 of the participants selected Skelex as their third preferred exoskeleton.

4.2 Exoskeleton Effect on Muscle Activity

To fulfill Objective 1, one-way ANOVAs were completed for each task, condition, and muscle studied. The reduction in %MVC for the six bilateral muscles (anterior deltoid, medial deltoid, and trapezius) for all exoskeleton ranged from 0.01% to 17.5%.

The active anterior deltoid for sealing tasks had %MVC reduction ranging from 6.5% to 15.7%. The passive anterior deltoid for sealing tasks had %MVC reduction ranging from 0.01% to 0.80%. The active trapezius for sealing tasks has %MVC reduction ranging from 0.44% to 10.81%, and the passive trapezius % MVC reduction ranged from 0.10% to 1.81%.

For riveting squeezing tasks, the left anterior deltoid %MVC reduction ranged from 3.3% to 17.5% and the right anterior deltoid %MVC reduction ranged from 2.3% to 10.68%. The left medial deltoid %MVC reduction ranged from 1.79% to 10.72%, and the right medial deltoid %MVC reduction ranged from 1.20% to 9.14%. The left trapezius %MVC reduction ranged from 2.6% to 8.82%, and the right trapezius %MVC reduction ranged from 0.15% to 7.58%.

4.3 Probabilities

The multinomial logistic regression analyses yielded a total of 53 probability plots. Of the 53 total plots, 31 are associated with ANOVA analysis results that indicate a significant reduction in %MVC muscle activity for the muscle-task combinations represented in the probability plots. These 31 probability plots are presented below. The remaining 22 probability plots were for muscle-task combinations that did not indicate a significant reduction in %MVC muscle activity for the muscle of interest and are presented in Appendix B. Across the 31 probability plots, the Skelex had the highest probability of being selected in 14 of the 31 probability plots, followed by the Evo, which had the highest probability of being selected in 9 of the probability plots, and then

Paexo, which had the highest probability of being selected in 8 of the plots. The Evo shared a high probability of being selected in two plots, one with the Paexo and one with the Skelex.

The following sub-sections will cover each task’s %MVC reduction and the associated probabilities of selecting the exoskeletons in detail.

Task 1: Standing Sealing on Stringer 1

The %MVC muscle activity in the active anterior deltoid was significantly reduced by 12.86% from the No-Exoskeleton condition during the utilization of the Evo exoskeleton, 10.96% during the utilization of the Paexo exoskeleton, and 10.95% during the utilization of the Skelex exoskeleton. The active medial anterior deltoid was significantly reduced by 7.18%, 6.02%, and 5.88% during the utilization of the Evo, Paexo, and Skelex, respectively.

None of the %MVC muscle activity levels recorded from the passive side muscles were significantly different from the corresponding values in the No-Exoskeleton condition, (see Table 2).

Table 2. Task 1 - Absolute %MVC Difference from No-Exoskeleton on both the active and passive sides of the body for the three exoskeletons tested.

Active Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-12.86*	-7.18*	-3.83
Paexo	-10.96*	-6.02*	-0.45
Skelex	-10.95*	-5.88*	-3.15
Passive Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-0.39	-0.49	-0.14
Paexo	0.05	-0.50	1.63
Skelex	-0.53	-0.48	-0.43

The * indicates a significant reduction compared to the No-Exoskeleton condition

Based on the nested model, the active anterior deltoid muscle is representative of all the muscles examined (active and passive anterior deltoid, passive and active medial deltoid, and passive and active trapezius) when utilizing the Paexo and Skelex exoskeletons in Task 1, summary of the probabilities in (Table 3).

Based on the %MVC muscle activity difference contained within a 95% confidence interval (8%-14%, vertical bars; (Figure 16)), during the utilization of the Paexo exoskeleton, Figure 16, the probability ranges associated with selecting a particular exoskeleton are:

- Evo 20% - 25%
- Paexo 0%
- Skelex 75% - 80%

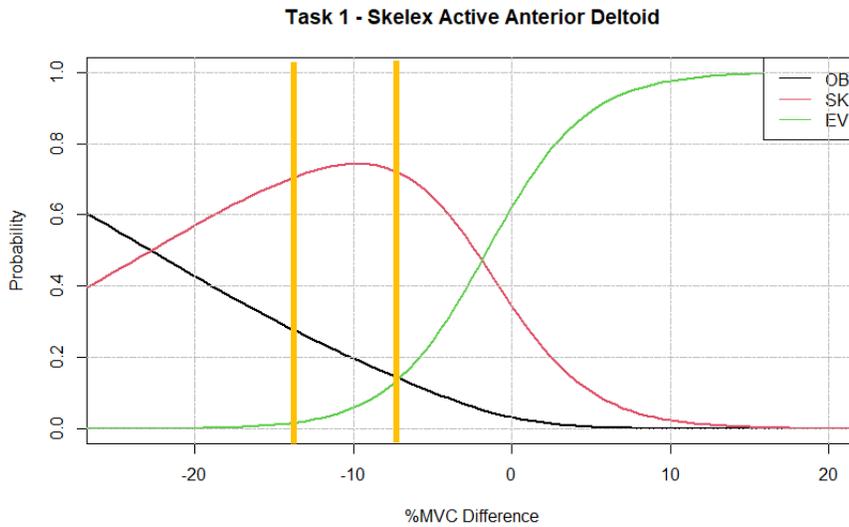


Figure 16: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Paexo active anterior deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (7%-14%, vertical bars; (Figure 17)), during the utilization of the Skelex exoskeleton,

Figure 17, the probability ranges associated with selecting a particular exoskeleton are:

- Evo 1% - 18%
- Paexo 18% - 35%
- Skelex 64%

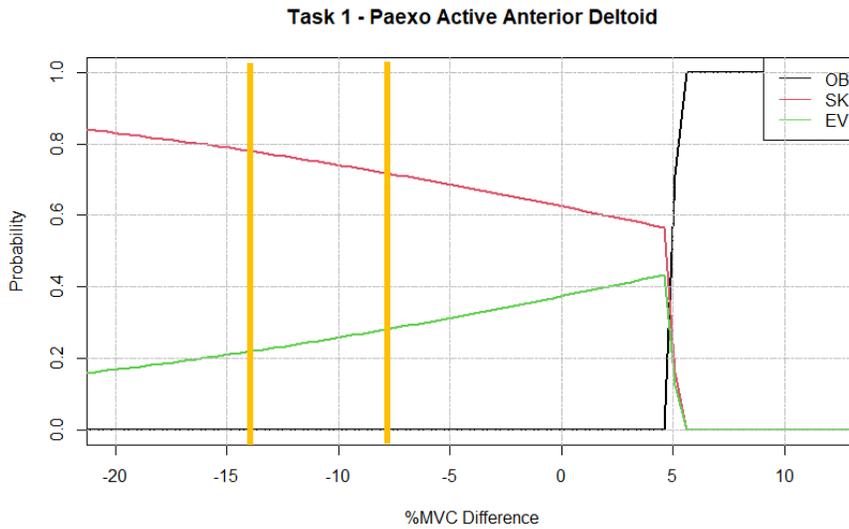


Figure 17: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex active anterior deltoid muscle.

Table 3. Task 1 - Summary of the exoskeletons probabilities.

Representative Muscle - Exoskeleton	Active Anterior Deltoid - Skelex	Active Anterior Deltoid - Paexo
Evo	20% - 25%	1% - 18%
Paexo	0%	18% - 35%
Skelex	75% - 80%	64%

Task 2: Standing Sealing on Stringer 3

The muscle activity in the active anterior deltoid was significantly reduced by 6.59% during the utilization of the Evo exoskeleton, 7.35% during the utilization of Paexo exoskeleton, and 6.82% during the utilization of the Skelex. The active medial anterior deltoid was significantly reduced by 4.72%, 5.10%, and 4.61% during the utilization of the Evo, Paexo, and Skelex, respectively. The trapezius was significantly reduced by 3.75%, 3.67% during the utilization of the Evo and the Skelex.

None of the %MVC muscle activity levels recorded from the passive side muscles were significantly different from the corresponding values in the No-Exoskeleton condition, (Table 3).

Table 4. Task 2 - Absolute %MVC Difference from No-Exoskeleton on both the active and passive sides of the body for the three exoskeletons tested.

Active Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-6.59*	-4.72*	-3.75*
Paexo	-7.35*	-5.1*	0.72
Skelex	-6.82*	-4.61*	-3.67*
Passive Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-0.02	-0.42	-0.09
Paexo	-0.01	-0.48	-0.37
Skelex	-0.04	-0.38	-1.89

The * indicates a significant reduction compared to the No-Exoskeleton condition

For Task 2, the active anterior deltoid and active medial deltoid are the representatives of the full model. Summary of the probabilities in (Table 5). Based on the %MVC muscle activity difference contained within a 95% confidence interval (5%-9%, vertical bars; (Figure 18)) of the

active anterior deltoid, during the utilization of the Paexo exoskeleton, (Figure 18), the probability ranges associated with a subject selecting a particular exoskeleton are:

- Evo 0%
- Paexo 0%
- Skelex 100%

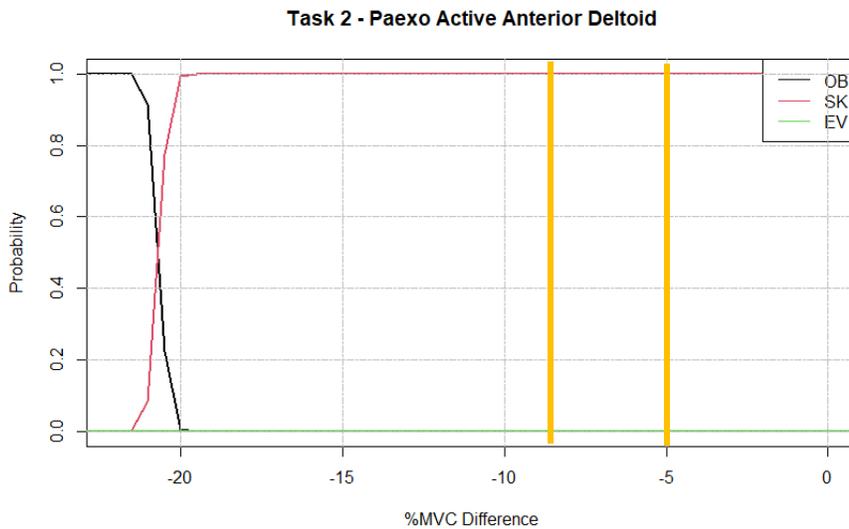


Figure 18: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Paexo active anterior deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (5%-8%, vertical bars; (Figure 19)), of the active anterior deltoid, during the utilization of the Skelex exoskeleton, (Figure 19), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 90% - 100%
- Paexo 0% - 10%
- Skelex 0%

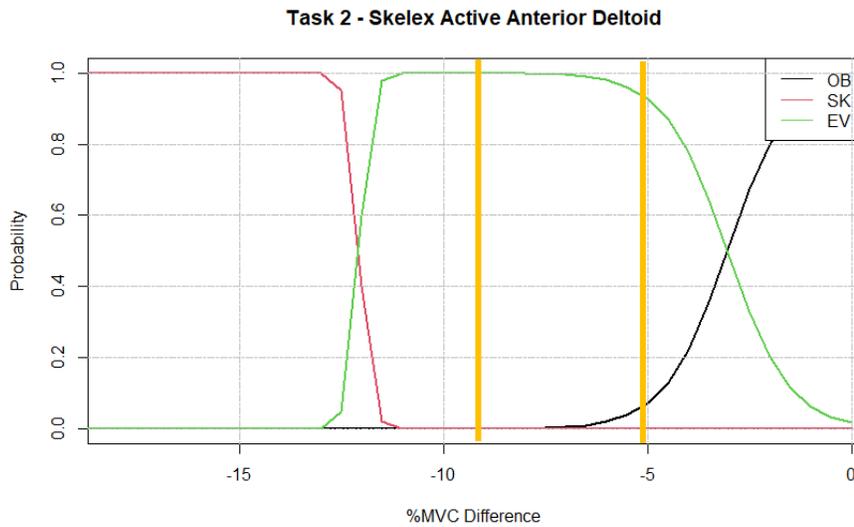


Figure 19: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex active anterior deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (3%-6%, vertical bars; (Figure 20)) of the active medial deltoid, during the utilization of the Skelex exoskeleton, (Figure 20), the probability ranges associated with a subject selecting a particular exoskeleton are:

- Evo 0%
- Paexo 100%
- Skelex 0%

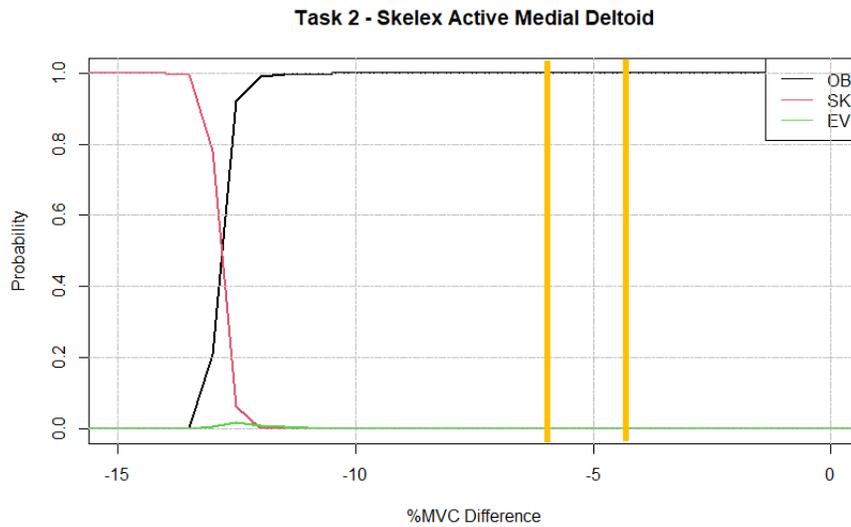


Figure 20: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex active medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (3%-6%, vertical bars; (Figure 21)) of the active medial deltoid, during the utilization of the Evo exoskeleton, (Figure 21), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 0% - 5%
- Skelex 95% - 100%

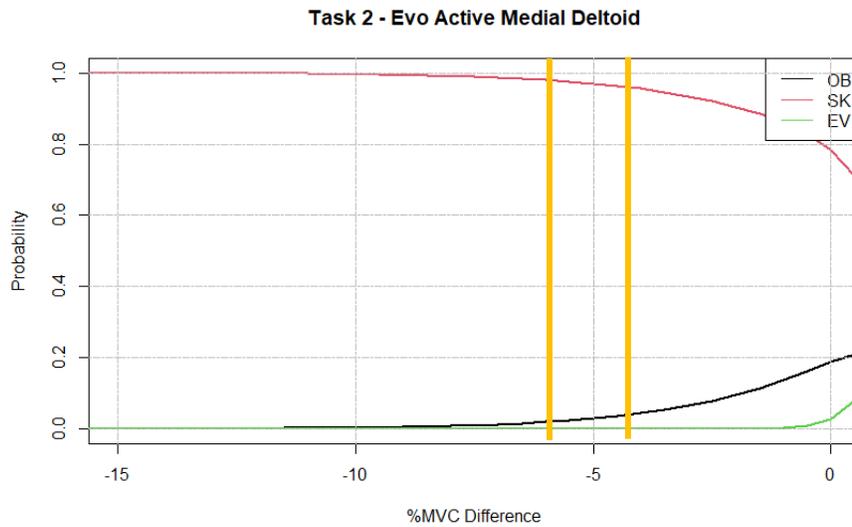


Figure 21: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo active medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (3%-7%, vertical bars; (Figure 22)) of the active medial deltoid, during the utilization of the Paexo exoskeleton, (Figure 22), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 100%
- Skelex 0%

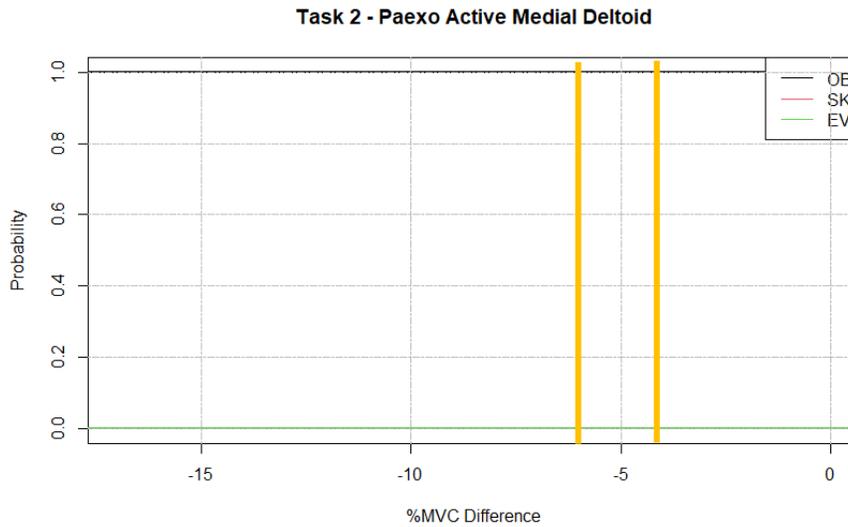


Figure 22: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Paexo active medial deltoid muscle.

Table 5. Task 2 - Summary of the exoskeletons probabilities.

Representative Muscle - Exoskeleton	Active Anterior Deltoid - Paexo	Active Anterior Deltoid - Skelex	Active Medial Deltoid - Skelex	Active Medial Deltoid - Evo	Active Medial Deltoid – Paexo
Evo	0%	90% - 100%	0%	0%	0%
Paexo	0%	0% - 10%	100%	0%	100%
Skelex	100%	0%	0%	95% - 100%	0%

Task 3: Seated Sealing on Stringer 1

The muscle activity in the active anterior deltoid was significantly reduced by 15.73% during the utilization of the Evo exoskeleton, 12.78% during the utilization of the Paexo exoskeleton, and 11.12% during the utilization of the Skelex. The active medial anterior deltoid was significantly reduced by 11.30%, 7.81%, and 7.96% during the utilization of the Evo, Paexo, and Skelex exoskeletons, respectively. The active trapezius was significantly reduced by 10.81% during the utilization of the Evo exoskeleton.

None of the %MVC muscle activity levels recorded from the passive side muscles were significantly different from the corresponding values in the No-Exoskeleton condition, (see Table 4). From the pairwise comparison there was a significant difference between the Evo exoskeleton when compared to Paexo and Skelex, (see Table 5 and 6).

Table 6. Task 3 - Absolute %MVC Difference from No-Exoskeleton on both the active and passive sides of the body for the three exoskeletons tested.

Active Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-15.73*	-11.30*	-10.81*
Paexo	-12.78*	-7.81*	-5.34
Skelex	-11.12*	-7.96*	-6.44
Passive Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-0.01	-0.15	-1.60
Paexo	0.097	-0.10	0.79
Skelex	0.80	0.02	1.38

The * indicates a significant reduction compared to the No-Exoskeleton condition

Table 7. Task 3 - Pairwise Comparison for the active anterior deltoid computed from SPSS for the three exoskeletons conditions.

Condition (I)	Condition (J)	Mean Difference (I-J)	Significant
Evo	Paexo	-0.030*	0.000
	Skelex	-0.046*	0.000
Paexo	Evo	0.030*	0.000
	Skelex	-0.017	0.552
Skelex	Evo	0.046*	0.000
	Paexo	0.017	0.522

The * indicates a significant difference at the 0.016 level.

Table 8. Task 3 - Pairwise Comparison for the active medial deltoid computed from SPSS for the three exoskeletons conditions.

Condition (i)	Condition (j)	Mean Difference (i-j)	Significant
Evo	Paexo	-0.035*	0.001
	Skelex	-0.033*	0.000
Paexo	Evo	0.035	0.001
	Skelex	0.002	1.000
Skelex	Evo	0.033*	0.000
	Paexo	-0.002	1.000

The * indicates a significant difference at the 0.016 level.

For Task 3, the active anterior deltoid and active trapezius are the representatives of the full model. Summary of the probabilities in (Table 9). Based on the %MVC muscle activity difference contained within a 95% confidence interval (6%-15%, vertical bars; (Figure 23)) of the active trapezius, during the utilization of the Evo exoskeleton, (Figure 23), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0% - 100%
- Paexo 0% - 100%
- Skelex 0%

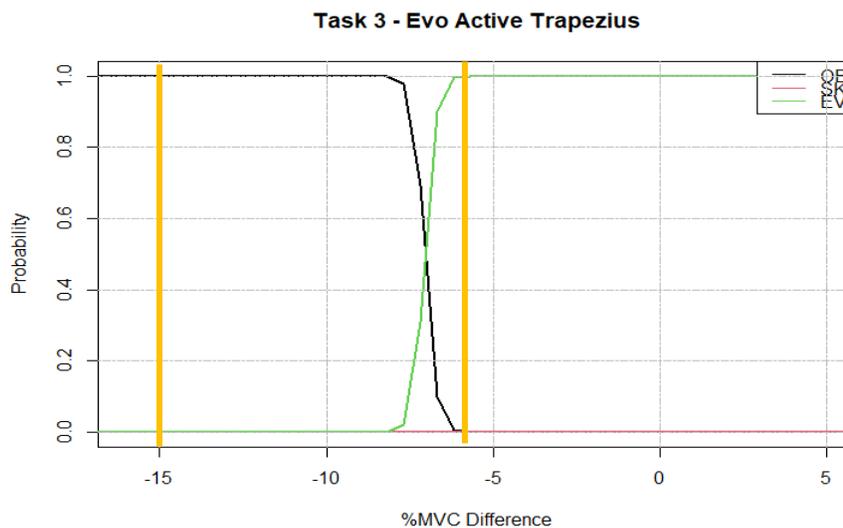


Figure 23: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo active trapezius muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (5%-17%, vertical bars; (Figure 24)) of the active anterior deltoid, during the utilization of the Skelex exoskeleton, (Figure 24), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 42% - 90%
- Paexo 0%
- Skelex 10% - 58%

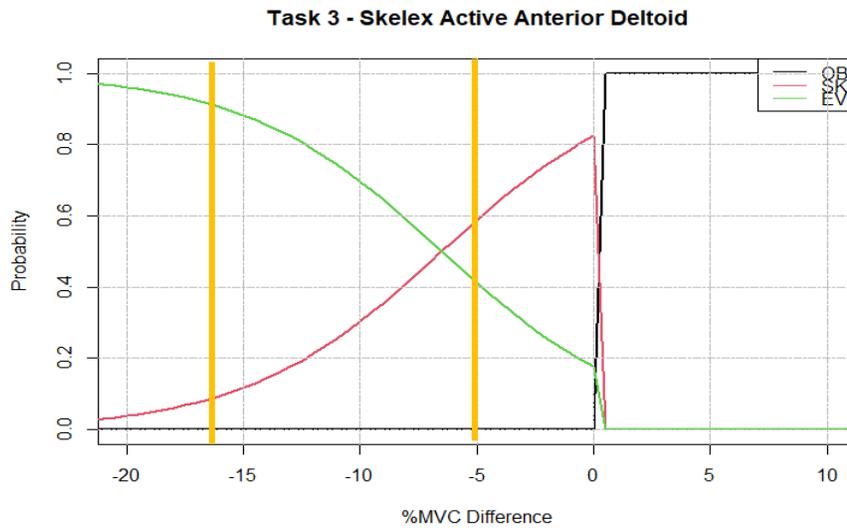


Figure 24: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex active anterior deltoid muscle.

Table 9. Task 3 - Summary of the exoskeletons probabilities

Representative Muscle - Exoskeleton	Active Trapezius - Evo	Active Anterior Deltoid - Skelex
Evo	0% - 100%	42% - 90%
Paexo	0% - 100%	0%
Skelex	0%	10% - 58%

Task 4: Seated Sealing on Stringer 4

The muscle activity in the active anterior deltoid was significantly reduced by 8.23% during the utilization of the Evo exoskeleton, 7.79% during the utilization of the Paexo exoskeleton, and 7.07% during the utilization of the Skelex exoskeleton. The active medial anterior deltoid was significantly reduced by 5.62%, 5.82%, and 5.60% during the utilization of the Evo, Paexo, and Skelex, respectively. The trapezius was significantly reduced by 4.85% and 4.19% during the utilization of Evo and Skelex.

In the passive side the muscle activity in the medial deltoid was significantly increased by 0.23%, 0.27% during the utilization of the Evo and Skelex exoskeleton, (Table 7).

Table 10. Task 4 - Absolute %MVC Difference from No-Exoskeleton on both the active and passive sides of the body for the three exoskeletons tested.

Active Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-8.23*	-5.62*	-4.85*
Paexo	-7.79*	-5.82*	-2.13
Skelex	-7.07*	-5.60*	-4.19*
Passive Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-0.02	0.23*	-1.59
Paexo	0.05	0.02	-1.14
Skelex	-0.07	0.27*	-1.70

The * indicates a significant reduction compared to the No-Exoskeleton condition

For Task 4, the active anterior deltoid, and active and passive medial deltoid are representative of the full model. Summary of the probabilities in (Table 11). Based on the %MVC muscle activity difference contained within a 95% confidence interval (5%-10%, vertical bars;

(Figure 25)) of the active medial deltoid, during the utilization of the Skelex exoskeleton, (Figure 25), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 90% - 100%
- Paexo 0%
- Skelex 0% - 10%

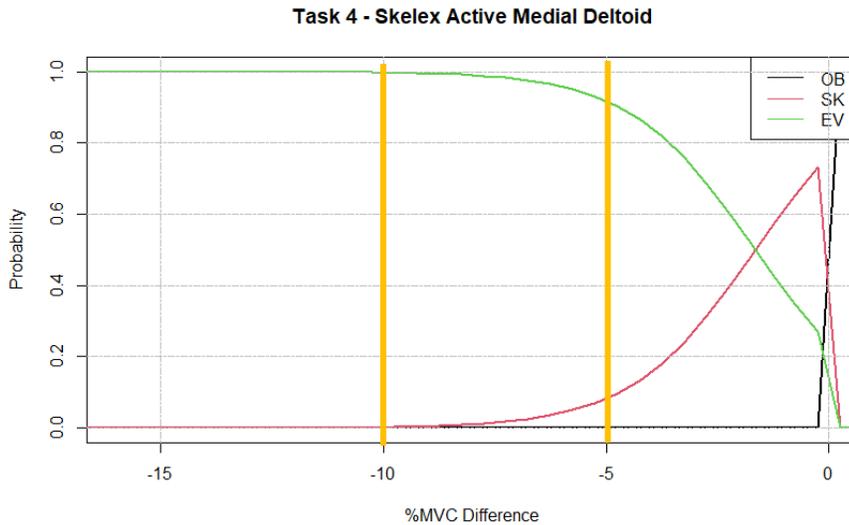


Figure 25: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex active medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (4%-8%, vertical bars; (Figure 26)) of the active medial deltoid, during the utilization of the Evo exoskeleton, (Figure 26), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 20% - 40%
- Paexo 0%
- Skelex 60% - 80%

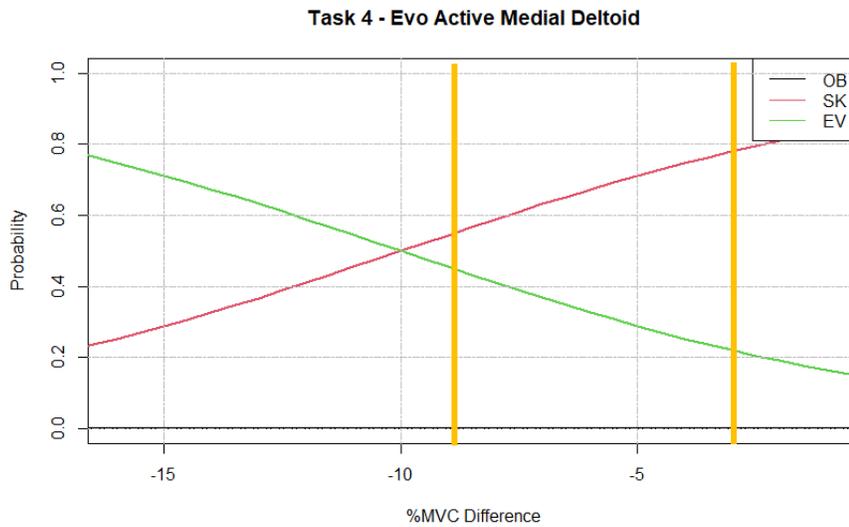


Figure 26: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo active medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (4%-8%, vertical bars; Figure 27)) of the active medial deltoid, during the utilization of the Paexo exoskeleton, (Figure 27), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 100%
- Skelex 0%

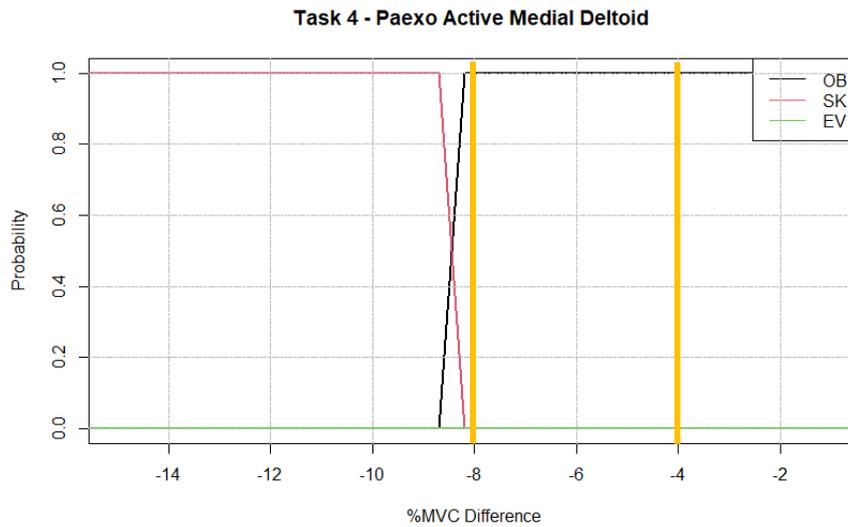


Figure 27: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Paexo active medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (3%-8%, vertical bars; (Figure 28)) of the active anterior deltoid, during the utilization of the Skelex exoskeleton, (Figure 28), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 65% - 100%
- Paexo 0%
- Skelex 0% - 35%

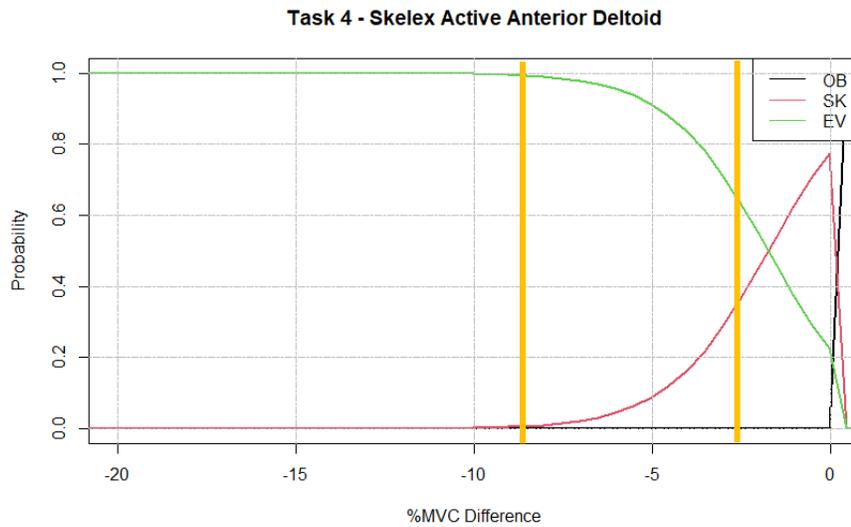


Figure 28: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex active anterior deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (0.1%-0.5%, vertical bars; (Figure 29)) of the passive medial deltoid, during the utilization of the Evo exoskeleton, (Figure 29), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 0%
- Skelex 100%

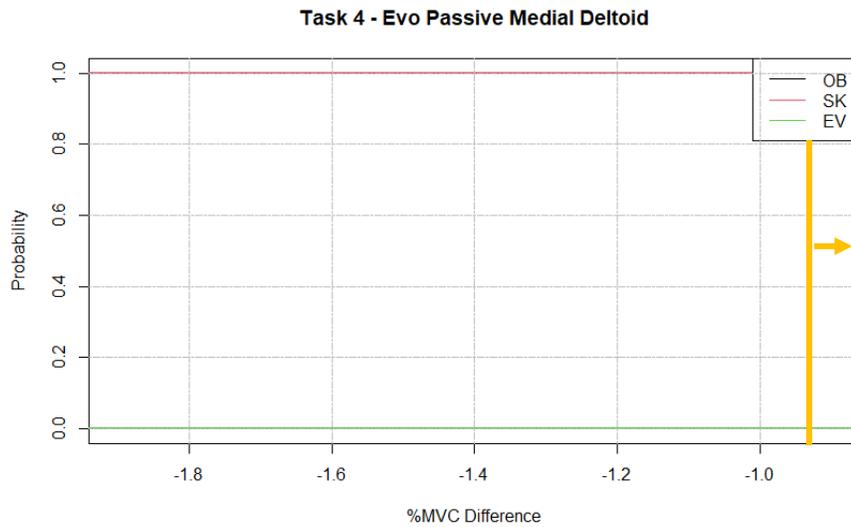


Figure 29: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo passive medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (0.1%-0.4%, vertical bars; (Figure 30)) of the passive medial deltoid, during the utilization of the Skelex exoskeleton, (Figure 30), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0% - 35%
- Paexo 23% - 100%
- Skelex 0% - 42%

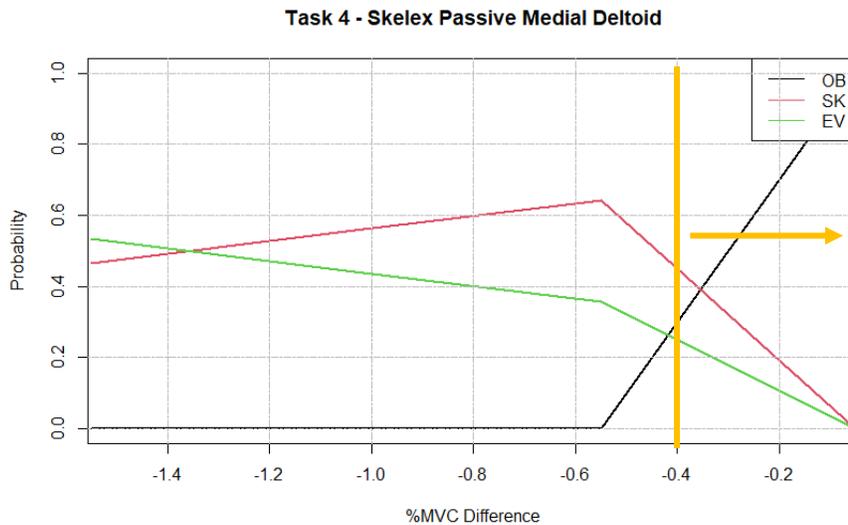


Figure 30: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex passive medial deltoid muscle.

Table 11. Task 4 - Summary of the exoskeletons probabilities

Representative Muscle - Exoskeleton	Active Medial Deltoid - Skelex	Active Medial Deltoid - Evo	Passive Medial Deltoid - Evo	Active Medial Deltoid - Paexo	Active Anterior Deltoid - Skelex	Passive Medial Deltoid - Skelex
Evo	90% - 100%	20% - 40%	0%	0%	65% - 100%	0% - 35%
Paexo	0%	0%	0%	100%	0%	23% - 100%
Skelex	0% - 10%	60% - 80%	100%	0%	0% - 35%	0% - 42%

Task 5: Standing Squeeze Riveting on Stringer 1

The muscle activity in the left anterior deltoid was significantly reduced by 15.29% during the utilization of the Evo exoskeleton, 14.59% during the utilization of Paexo exoskeleton, and 17.50% during the utilization of the Skelex exoskeleton. The left medial deltoid was significantly reduced by 10.72%, 7.90%, and 9.33% during the utilization of the Evo, Paexo, and Skelex, respectively. The trapezius was significantly reduced by 8.82% and 5.82% during the utilization of the Evo and Skelex, respectively.

The muscle activity in the right anterior deltoid was significantly reduced by 10.68% during the utilization of the Evo exoskeleton, 8.64% during the utilization of Paexo exoskeleton, and 5.74% during the utilization of the Skelex exoskeleton. The right medial deltoid was significantly reduced by 9.11%, 8.57%, and 9.14% during the utilization of the Evo, Paexo, and Skelex, respectively. The trapezius was significantly reduced by 6.50% during the utilization of Evo, (Table 8). From the pairwise comparison there was a significant difference between the exoskeletons depending on the muscle, (see Table 9, 10, and 11).

Table12. Task 5 - Absolute %MVC Difference from No-Exoskeleton on both the left and right sides of the body for the three exoskeletons tested.

Left Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-15.29*	-10.72*	-8.82*
Paexo	-14.59*	-7.90*	-3.64
Skelex	-17.50*	-9.33*	-5.82*
Right Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-10.68*	-9.11*	-6.50*
Paexo	-8.64*	-8.57*	1.87
Skelex	-5.74*	-9.14*	-7.58

The * indicates a significant reduction compared to the No-Exoskeleton condition

Table 13. Task 5 - Pairwise Comparison for the left anterior deltoid computed from SPSS for the three exoskeletons conditions.

Condition (I)	Condition (J)	Mean Difference (I_J)	Significant
Evo	Paexo	-0.007	1.000
	Skelex	0.022	0.170
Paexo	Evo	0.007	1.000
	Skelex	0.029*	0.001
Skelex	Evo	-0.022	0.170
	Paexo	-0.029*	0.001

The * indicates a significant difference at the 0.016 level.

Table 14. Pairwise Comparison for the right anterior deltoid computed from SPSS for the three exoskeletons conditions.

Condition (I)	Condition (J)	Mean Difference (I-J)	Significant
Evo	Paexo	-0.020	0.029
	Skelex	-0.049*	0.000
Paexo	Evo	0.020	0.029
	Skelex	-0.029*	0.009
Skelex	Evo	-0.049*	0.000
	Paexo	0.029	0.009

The * indicates a significant difference at the 0.016 level.

Table 15. Pairwise Comparison for the left medial deltoid computed from SPSS of for the three exoskeletons conditions.

Condition (I)	Condition (J)	Mean Difference (I-J)	Significant
Evo	Paexo	-0.028*	0.001
	Skelex	-0.014	0.328
Paexo	Evo	0.028	0.001
	Skelex	0.014	0.238
Skelex	Evo	0.014	0.328
	Paexo	-0.014	0.238

The * indicates the mean difference is significant at the 0.016 level

For Task 5, the left and right medial deltoid left and right anterior deltoid, and left and right trapezius are representative of the full model. Summary of the probabilities in (Table 16). Based on the %MVC muscle activity difference contained within a 95% confidence interval (9%-13%, vertical bars; (Figure 31) of the left medial deltoid, during the utilization of the Evo exoskeleton, (Figure 31), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 100%
- Paexo 0%
- Skelex 0%

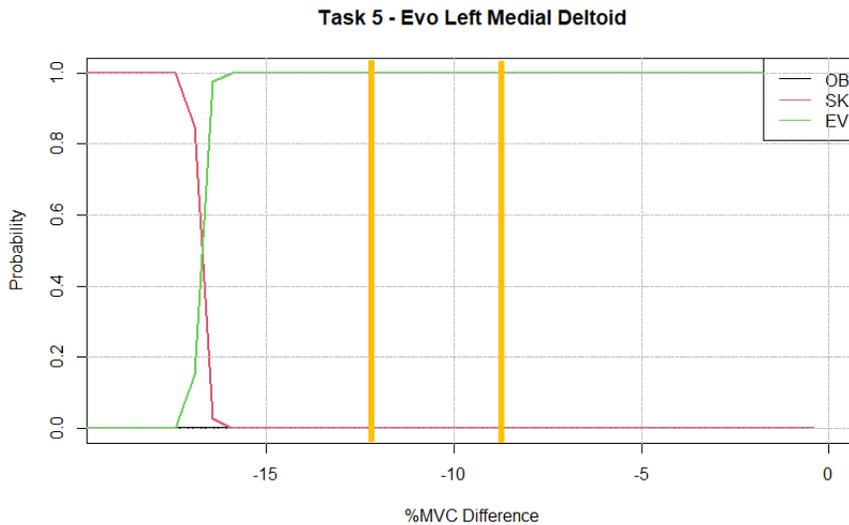


Figure 31: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo left medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (6%-10%, vertical bars; (Figure 32) of the left medial deltoid, during the utilization of the Paexo exoskeleton, (Figure 32), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 85% - 98%
- Skelex 2% - 15%

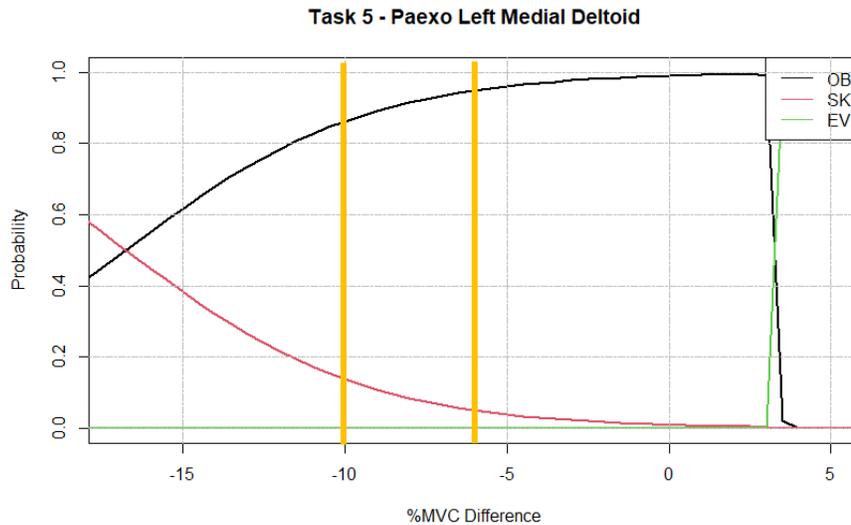


Figure 32: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Paexo left medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (6%-12%, vertical bars; (Figure 33)) of the right medial deltoid, during the utilization of the Evo exoskeleton, (Figure 33), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0% - 100%
- Paexo 0%
- Skelex 0% - 100%

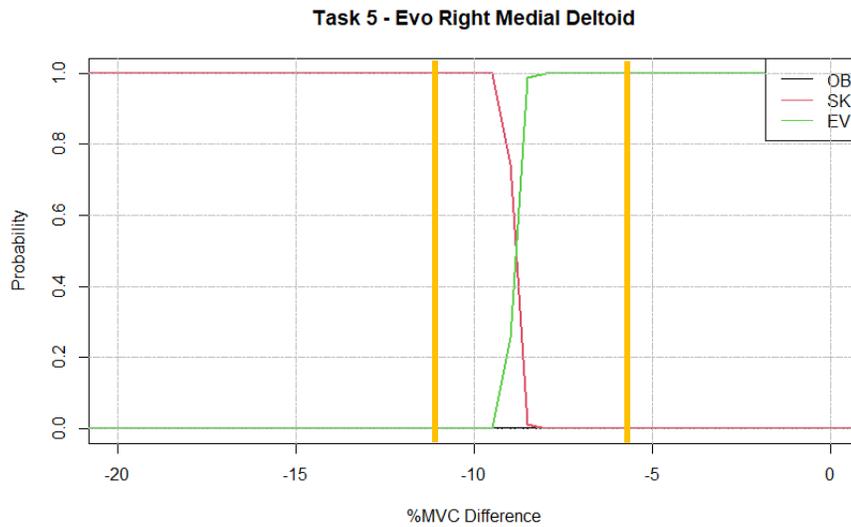


Figure 33: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo right medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (6%-11%, vertical bars; (Figure 34) of the right medial deltoid, during the utilization of the Paexo exoskeleton, (Figure 34), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 80% - 95%
- Skelex 5% - 20%

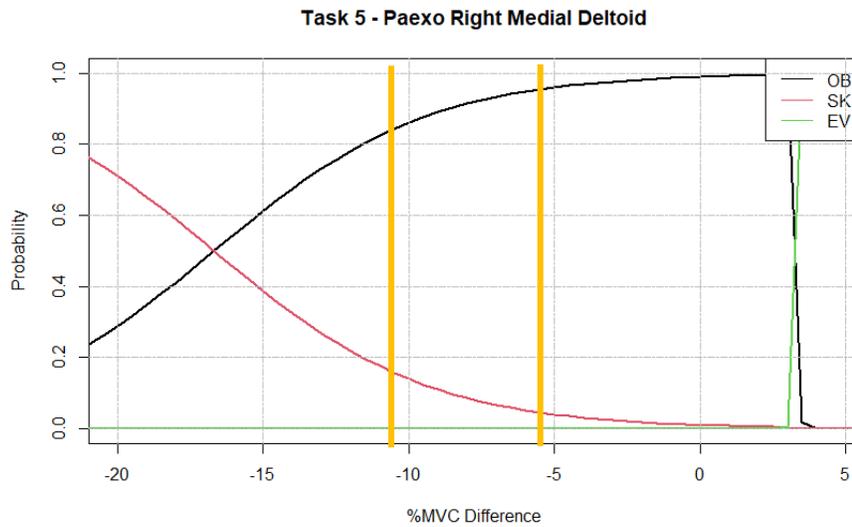


Figure 34: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Paexo right medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (12%-19%, vertical bars; (Figure 35)) of the left anterior deltoid, during the utilization of the Evo exoskeleton, (Figure 35), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 0%
- Skelex 100%

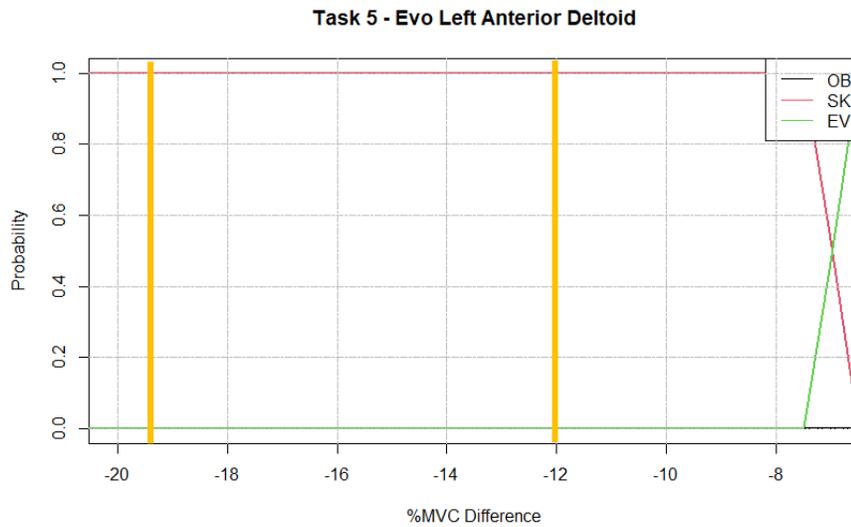


Figure 35: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo left anterior deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (13%-22%, vertical bars; (Figure 36) of the left anterior deltoid, during the utilization of the Skelex exoskeleton, (Figure 36), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 100%
- Skelex 0%

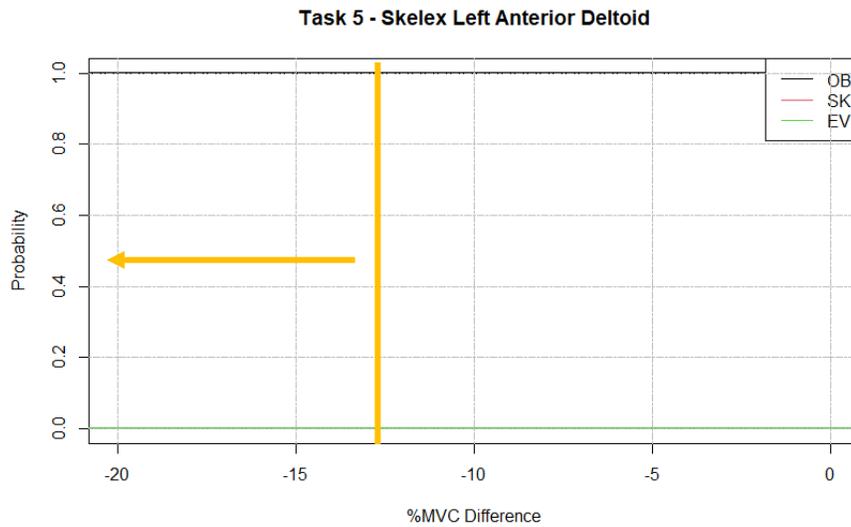


Figure 36: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex left anterior deltoid.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (6%-12%, vertical bars; (Figure 37) of the left trapezius, during the utilization of the Evo exoskeleton, (Figure 37), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 100%
- Paexo 0%
- Skelex 0%

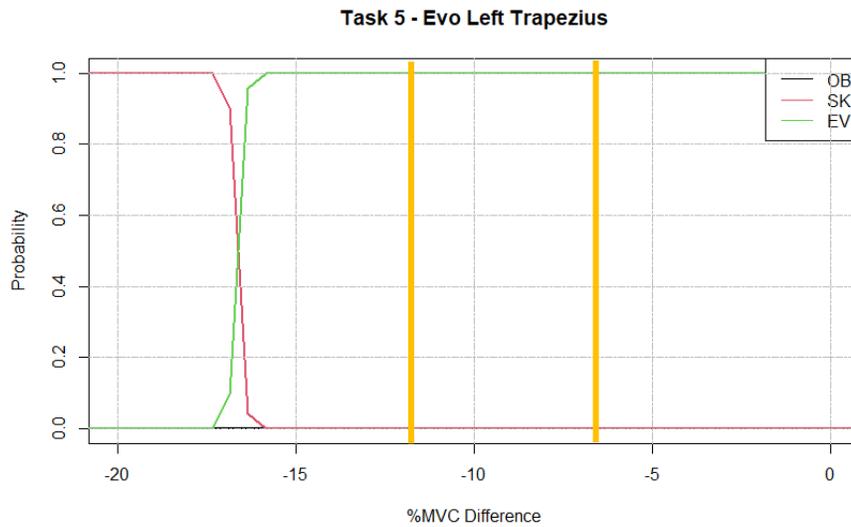


Figure 37: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo left trapezius.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (2%-9%, vertical bars; (Figure 38))of the left trapezius, during the utilization of the Skelex exoskeleton, (Figure 38), the probability ranges associated with a subject selecting a particular exoskeleton are:

- Evo 0%
- Paexo 100%
- Skelex 0%

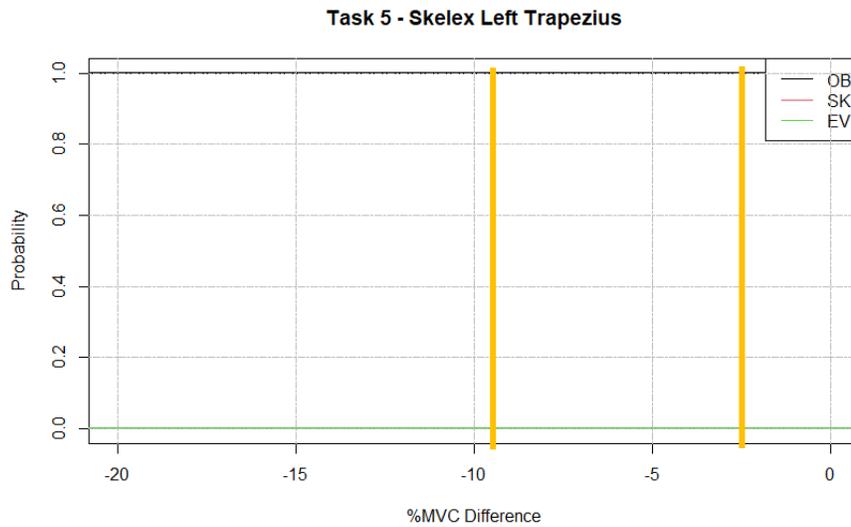


Figure 38: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex left trapezius muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (1%-14%, vertical bars; (Figure 39) of the right trapezius, during the utilization of the Skelex exoskeleton, (Figure 39), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 100%
- Skelex 0%

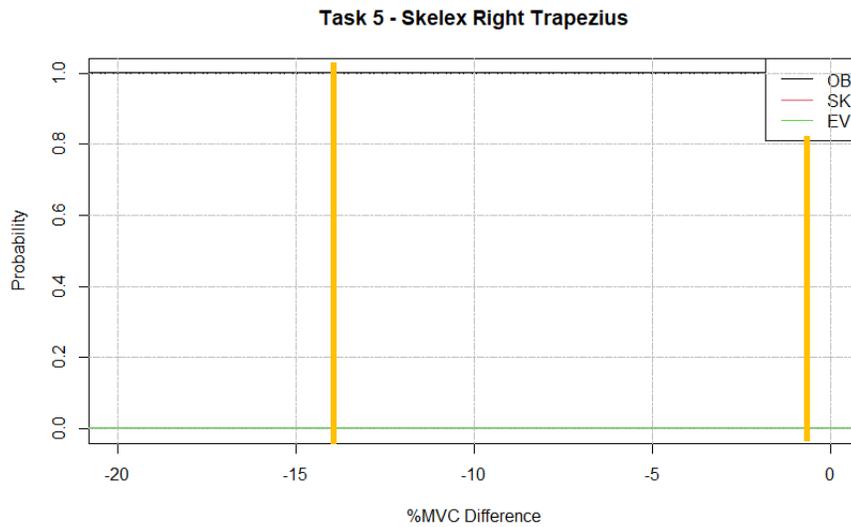


Figure 39: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex right trapezius muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (2%-10%, vertical bars; (Figure 40)) of the right anterior deltoid, during the utilization of the Skelex exoskeleton, (Figure 40), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 100%
- Skelex 0%

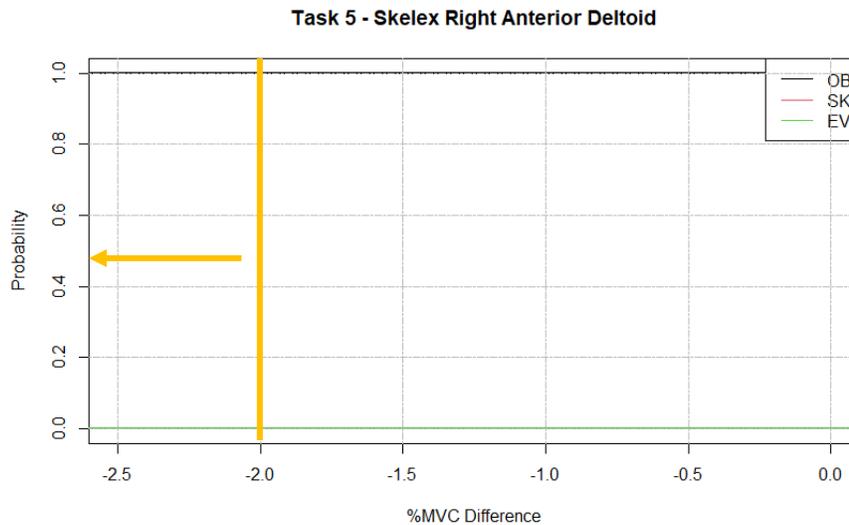


Figure 40: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex right anterior deltoid muscle.

Table 16. Task 5 - Summary of the exoskeletons probabilities

Representative Muscle - Exoskeleton	Left Medial Deltoid - Evo	Left Medial Deltoid - Paexo	Right Medial Deltoid - Evo	Right Medial Deltoid - Paexo	Left Anterior Deltoid - Evo	Left Anterior Deltoid - Skelex	Left Trapezius - Evo	Right Trapezius - Skelex	Right Anterior Deltoid-Skelex
Evo	100%	0%	0% - 100%	0%	0%	0%	100%	0%	0%
Paexo	0%	85% - 98%	0%	80% - 95%	0%	100%	0%	100%	100%
Skelex	0%	2% - 15%	0% - 100%	5% - 20%	100%	0%	0%	0%	0%

Task 6: Standing Squeeze Riveting on Stringer 3

The muscle activity in the left anterior deltoid was significantly reduced by 5.23% during the utilization of the Evo exoskeleton, 5.11% during the utilization of the Paexo exoskeleton, and 6.58% during the utilization of the Skelex exoskeleton. The left active medial anterior deltoid was significantly reduced by 2.49%, 1.83%, and 3.10% during the utilization of the Evo, Paexo, and

Skelex, respectively. The trapezius was reduced by 4.38%, 4.56% during the utilization of Evo, and Skelex.

The muscle activity in the right anterior deltoid was significantly reduced by 2.31% during the utilization of the Evo, 3.82% during the utilization of the Paexo, and 2.90% during the utilization of the Skelex. The right medial anterior deltoid was significantly reduced by 2.35%, 2.339%, and 3.05% during the utilization of the Evo, Paexo, and Skelex, respectively. The trapezius was significantly reduced by 3.43% during the utilization of the Evo, (Table 12). From the pairwise comparison there was a significant difference between the exoskeletons depending on the muscle, (see Table 13 and 14).

Table 17. Task 6 - Absolute %MVC Difference from No-Exoskeleton on both the left and right sides of the body for the three exoskeletons tested.

Left Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-5.23*	-2.49*	-4.38*
Paexo	-5.11*	-1.83*	-2.97
Skelex	-6.58*	-3.10*	-4.56*
Right Side			
	Anterior Deltoid	Medial Deltoid	Trapezius
Evo	-2.31*	-2.35*	-3.43*
Paexo	-3.82*	-2.39*	1.97
Skelex	-2.90*	-3.05*	-2.19

The * indicates a significant reduction compared to the No-Exoskeleton condition

Table 18. Task 6 - Pairwise Comparison for the right anterior deltoid computed from SPSS for the three exoskeletons conditions.

Condition (I)	Condition (J)	Mean Difference (I-J)	Significant
Evo	Paexo	0.015*	0.004
	Skelex	0.006	0.976
Paexo	Evo	-0.015*	0.001
	Skelex	-0.009	0.289
Skelex	Evo	-0.006	0.976
	Paexo	0.009	0.289

The * indicates a significant difference at the 0.016 level.

Table 19. Task 6 - Pairwise Comparison for the left medial deltoid computed from SPSS for the three exoskeletons conditions.

Condition (I)	Condition (J)	Mean Difference (I-J)	Significant
Evo	Paexo	-0.007	0.316
	Skelex	0.006	0.329
Paexo	Evo	0.007	0.316
	Skelex	0.013*	0.007
Skelex	Evo	-0.006	0.329
	Paexo	-0.013*	0.007

The * indicates a significant difference at the 0.016 level.

For Task 6, the left anterior deltoid and right medial deltoid are representative of the full model. Summary of the probabilities in (Table 20). Based on the %MVC muscle activity difference contained within a 95% confidence interval (2%-4%, vertical bars; (Figure 41) of the right medial deltoid, during the utilization of the Skelex exoskeleton, (Figure 41), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 25% - 58%
- Skelex 42% - 75%

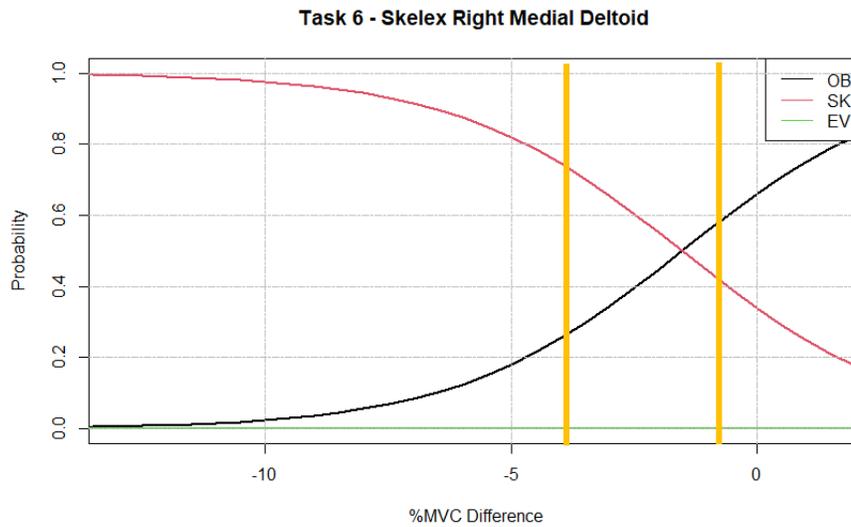


Figure 41: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex right medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (1%-4%, vertical bars; (Figure 42)) of the right medial deltoid, during the utilization of the Paexo exoskeleton, (Figure 42), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 20% - 50%
- Paexo 10% - 38%
- Skelex 40% - 42%

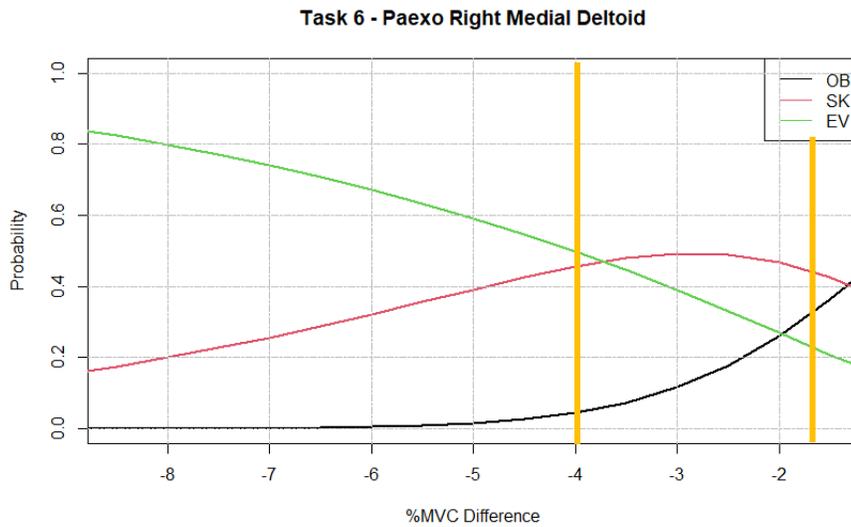


Figure 42: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Paexo right medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (1% - 4%, vertical bars; (Figure 43)) of the right medial deltoid, during the utilization of the Evo exoskeleton, (Figure 43), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 0%
- Skelex 100%

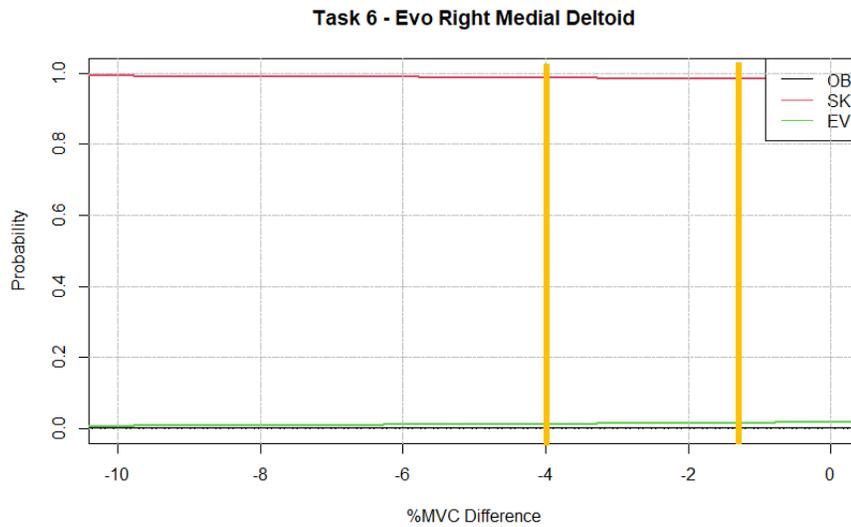


Figure 43: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo right medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (2% - 4%, vertical bars; (Figure 44)) of the left medial deltoid, during the utilization of the Skelex exoskeleton, (Figure 44), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 25% - 50%
- Skelex 50% - 75%

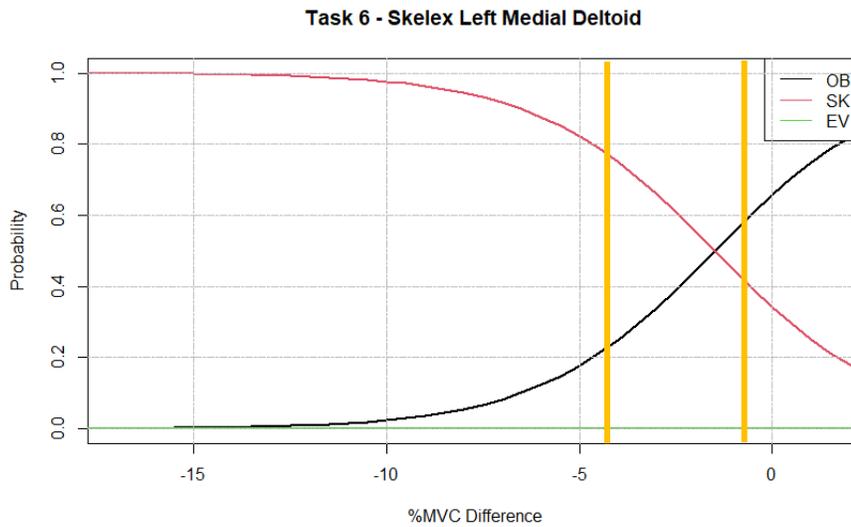


Figure 44: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex left medial deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (5%-9%, vertical bars; (Figure 45)) of the left anterior deltoid, during the utilization of the Skelex exoskeleton, (Figure 45), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 5% - 25%
- Skelex 75% - 95%

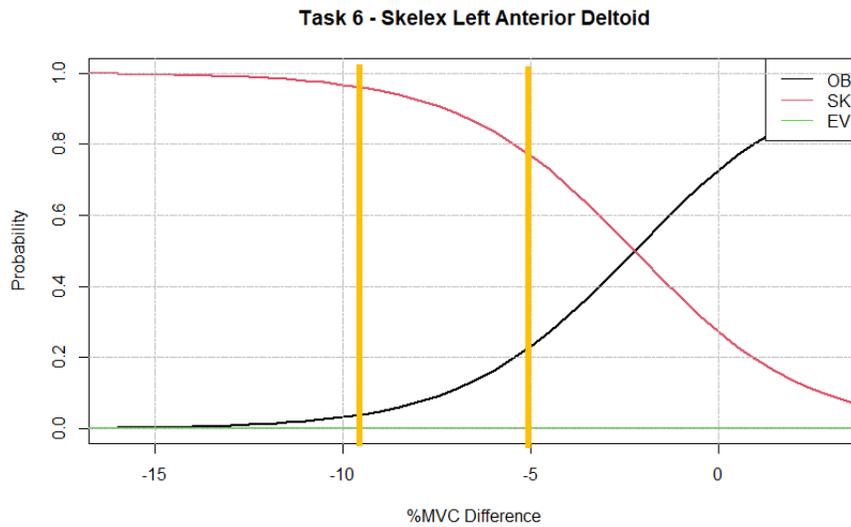


Figure 45: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Skelex left anterior deltoid muscle.

Based on the %MVC muscle activity difference contained within a 95% confidence interval (4%-7%, vertical bars (Figure 46)) of the left anterior deltoid, during the utilization of the Evo exoskeleton, (Figure 46), the probability ranges associated with selecting a particular exoskeleton are:

- Evo 0%
- Paexo 1% - 4%
- Skelex 96% - 99%

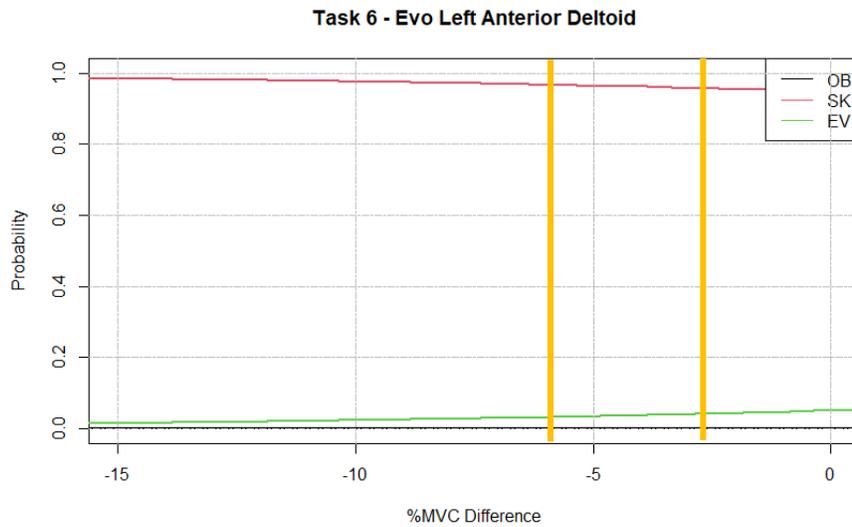


Figure 46: The probability of selecting a specific exoskeleton with respect to %MVC muscle activity reduction, vertical bars represent the 95% confidence interval of the Evo left anterior deltoid muscle.

Table 20. Task 6 - Summary of the exoskeletons probabilities

Representative Muscle - Exoskeleton	Right Medial Deltoid - Skelex	Right Medial Deltoid - Paexo	Right Medial Deltoid - Evo	Left Medial Deltoid - Skelex	Left Anterior Deltoid - Skelex	Left Anterior Deltoid - Evo
Evo	0%	20% - 50%	0% -	0%	0%	0%
Paexo	25% - 58%	10% - 38%	0%	25% - 50%	5% - 25%	1% - 4%
Skelex	42% - 75%	40% - 42%	100%	50% - 75%	75% - 95%	96% - 99%

CHAPTER 5

DISCUSSION

Previous research has demonstrated the potential for passive shoulder exoskeletons to reduce the risk of WMSDs. However, the potential for passive shoulder exoskeletons to reduce the risk of WMSDs is dependent on the workers willingness to utilize them. A secondary issue is that the passive shoulder exoskeleton needs to provide some benefit associated with reducing the risk of WMSDs. Therefore, the objectives of this study were to 1) determine if there is a significant difference between the %MVC reduction on the muscles activity level when using three different exoskeletons while performing the simulated manufacturing aircraft tasks, 2) identify the probability of selecting a specific exoskeleton, and 3) assess the correlation between exoskeleton selection preference and %MVC reduction. One important finding from this study was that exoskeletons showed a significant benefit when utilized compared to not wearing an exoskeleton. A second important finding from this study was that work height significantly affected the perceived benefit from exoskeletons. A third important finding from this study was that participants are likely not to select the exoskeleton that provides them with the greatest reduction in percent muscle activity for the muscles studied.

5.1 Exoskeleton Effect on Muscle Activity

For all tested tasks (1-6), the use of any exoskeleton did significantly reduce the %MVC muscle activity compared to the No-Exoskeleton condition for at least one muscle. In particular, tasks requiring overhead arm elevation, such as Task 1 , Task 3, and Task 5 (i.e., standing sealing on stringer 1, seated sealing on stringer 1, and standing squeezing on stringer 1), showed a greater reduction in the anterior deltoid muscle ranging from a minimum of 10% to a maximum of 17.5% when compared to tasks working at shoulder level the reduction ranged from a minimum of 5% to

a maximum of 8%. These results of a larger reduction of the muscle activity at overhead work versus shoulder height are consistent with the results presented in previous passive shoulder exoskeleton studies on overhead drilling [38] and overhead work [44]. Moreover, the active side muscles showed a greater reduction in %MVC muscle activity than the passive side muscles in sealing tasks. This result is because during sealing tasks the passive side was at total rest. Likewise, during squeezing riveting tasks, the left side showed greater reduction mostly because it was holding the tool, even though, the right side was also held in an overhead position to initiate the riveting. The decrease in the passive side and right side suggests that the exoskeleton is benefiting the whole body to some extent. Supporting this, a study by Kim et al. found differences in the muscle activity reduction between dominant and non-dominant arm side depending on the task and work height [56].

Muscle activity increased (below 2% increase) in the passive trapezius and anterior deltoid during Task1 and Task 3 (i.e., standing sealing on stringer 1 and seated sealing on stringer 1), when participants used the Paexo. A similar finding of unexpected muscle activity increase was observed in previous studies examining the Paexo exoskeleton. In a study by Schmalz *et al.* (2019) they looked at the metabolic rate (oxygen consumption and heart rate) and mean muscular fatigue index (MFI) using EMG, during a simulated drilling overhead task. They found that metabolic rate was significantly different when using the exoskeleton, as well the MFI decreased for all the muscles except for the trapezius [57]. Another study, by Fritzsche *et al.* (2021) simulated a drilling overhead task and investigated the biomechanical effects of wearing the Paexo. The results showed a significant reduction in muscle activity when using the Paexo, but a non-significant increase in the infraspinatus, biceps, and triceps brachii muscle activity was observed [58]. Since the increase

in muscle activity was relatively small and not significant in our study, the results can be considered as not particularly relevant.

For almost every sealing task and muscle studied, the pairwise comparison analysis did not identify a significant difference between the %MVC muscle activity reductions provided by each exoskeleton. Therefore, there is not enough information to indicate a significant difference in the means. Except for Task 3 (i.e., seated sealing on stringer 1), the pairwise comparison analysis showed that the Evo exoskeleton had a greater reduction in the %MVC muscle activity compared to Skelex and Paexo. The greater reduction could be due to the design of the Evo exoskeleton [46]. In the Evo exoskeleton, the maximum support torque was 115° and this also was the maximum support angle. Unlike Skelex and Paexo the maximum support angle occurred at $\geq 90^\circ$. Another potential reason could be due to force increment. Each exoskeleton had a different force increment, the lowest force setting for Evo was (2.2 kg - 3.1 kg) and had 3 different support levels (1st level = 2.2-3.1 kg, 2nd level = 3.1-4.0kg, and 3rd level = 4.0-5.4 kg). Whereas the Skelex had a lowest force setting of 0.5 kg, and a maximum of 3.5 kg, and 4 different support levels depending on the participants' body weight. Lastly, the Paexo had a continuous adjustable support knob that can change the level of support to counterbalance the arm weight. However, the Evo was the least preferred exoskeleton for sealing and squeezing tasks, (Figure 14, 15). In addition, it was noticeable from the subjective feedback the Evo had the least comfortable fit compared to Skelex and Paexo, see Figure 13.

For all sealing tasks except Task 1 - standing sealing on stringer 1, and all rivets squeezing tasks, the trapezius %MVC muscle activity reduction was significant in at least one exoskeleton condition. A potential reason could be due to the task characteristics. For Task 1, the height was adjusted to be 25.4 cm above the participant's acromion process while standing, and the participant

sealed the bottom side of stringer 1. Whereas in Task 3 (i.e., seated sealing on stringer 1), the height was adjusted to be 45 cm above the acromion process while sitting, and then participants sealed the bottom side of stringer 1. This different height of both tasks that were performed on the same stringer could have contributed to the trapezius significant activation. Based on the trapezius anatomy, it is partly responsible for elevation and stabilization of the shoulder, and it activates with forward exertion and overhead tasks [59].

5.2 The Relationship Between Preference and Performance

The following sub-sections will discuss the relationship between preference and performance for each task incorporating the results for probability, %MVC, ranking results, and comfortable fit, during the task described below by task activity, i.e., sealing or riveting squeezing.

Sealing Tasks:

All sealing tasks had a varied probability of the participant selecting an exoskeleton depending on the representative muscle. For example, in one representative probability plot for seated upper stringer sealing (Task 3), the Evo had the highest probability of selection at the lower limit of the 95% confidence interval, whereas Paexo had the highest probability of selection at the upper limit of the 95% confidence interval, and Skelex had a 0% probability of selection (Figure 23). In a second representative probability plot for the same task (Figure 24), the Skelex had the highest probability of selection at the lower limit of the 95% confidence interval, whereas Evo had the highest probability of selection at the upper limit of the 95% confidence interval, and Paexo had a 0% probability of selection. These varied probability plots outcomes were true for Tasks 2, 3, and 4 (i.e., standing sealing on stringer 3, seated sealing on stringer 1, and seated sealing on stringer 3, respectively) with the exception of Task 1 – standing sealing on stringer 1. In Task 1, a participant had a high probability of selecting the Skelex 64% to 80%, whereas Evo and Paexo had

lower probabilities, 1% to 25%, and 0% to 35%, respectively, (Figure 16). From the ranking survey, participant preference rated the Skelex the highest, then Paexo the second, and the Evo the third, for sealing tasks. Based on the absolute %MVC muscle activity difference from the No-Exoskeleton condition, (Table 4), all three exoskeletons significantly reduced the %MVC muscle activity compared to the No-Exoskeleton condition. The pairwise comparison analysis for Task 1 did not identify a difference between the %MVC muscle activity reductions provided by each exoskeleton. In this case, Task 1, because there were no differences identified within-exoskeleton differences, the participants would likely benefit from all the exoskeletons tested. As it was noted from the subjective feedback, the Skelex was the most preferred exoskeleton and was rated as having the most comfortable fit

For sealing Tasks 2, 3, and 4 (i.e., standing sealing on stringer 3, seated sealing on stringer 3, and seated sealing on stringer 4, respectively), the probability that a participant would select a particular exoskeleton was dependent upon the representative muscle used in the multinomial logistic regression analysis. All of the exoskeletons showed an associated significant reduction in %MVC muscle activity reduction for both the active anterior and medial deltoid for all three tasks when compared to the No-Exoskeleton condition. The active trapezius muscle exhibited similar results for most of the tasks. For Task 3, there was a significant difference in the %MVC muscle activity reduction for the active anterior and medial deltoid muscles for the three exoskeletons compared to the No-Exoskeleton condition. The pairwise comparison analysis identified a significant difference in the %MVC muscle activity reduction for the active anterior and medial deltoid muscles associated with wearing the Evo, However, based on the multinomial logistic regression analysis, all three exoskeletons had a high probability of selection. In this case, the participants may not select the exoskeleton that provided the greatest reduction in %MVC muscle

activity, i.e., Evo. For Tasks 2 and 4, the pairwise comparisons indicated that there was no significant difference between the exoskeletons %MVC muscle activity reductions. Similar to Task 3, all three exoskeletons had a high probability of being selected. However, because there were no significant differences between the %MVC muscle activity reduction values associated with exoskeletons in the pairwise comparisons, it is expected that all of the exoskeletons will have a similar impact on reducing the active anterior and medial deltoid %MVC muscle activity.

Squeezing Riveting Tasks:

For both riveting squeezing Tasks 5, and 6 (i.e., on stringer 1 and on stringer 3, respectively) all of the exoskeletons showed an associated significant reduction in %MVC muscle activity when compared to the No-Exoskeleton condition. From the ranking survey, participants preferred the Skelex the most, followed by the Paexo, and then the Evo, for riveting squeezing tasks. Based on the pairwise comparisons, there was a significant difference between exoskeletons %MVC reductions for the bilateral anterior and medial deltoid muscles. For Task 5, upper stringer riveting, Skelex provided the greatest reduction in the left anterior deltoid (17.50%), which was significant compared to Paexo (14.59%), whereas Evo provided the greatest reduction in the right anterior deltoid (10.68%), which was significant compared to Skelex (5.74%). For the left medial deltoid, Evo provided the greatest reduction (10.72%), which was significant compared to Paexo (7.90%). For the lower stringer riveting, Task 6, the right anterior deltoid had the greatest reduction associated with Paexo (3.82%), which was significant compared to Evo (2.31%). For the left medial deltoid, the greatest reduction was associated with Skelex (3.10%) which was significant compared to Paexo (1.83%). In these cases, there was a significant difference between exoskeletons %MVC reduction to at least one exoskeleton. However, the significant difference was small (less than 5% difference), which could be not meaningful. The participants' probability

of selection varied depending on the representative muscle. All three exoskeletons had a high probability of being selected. Since the significant difference differs based on the muscle examined, whatever the participant selects, they will significantly benefit from any of the three exoskeletons.

Overall, there is no clear trend in the probability of selection and exoskeleton muscle activity reduction associated with the height of the activities performed in this study. With respect to the overhead activities, namely Tasks 1, 3, and 5 (i.e., standing sealing on stringer 1, seated sealing on stringer 1, and squeeze riveting on stringer 1, respectively), there were both significant reductions in %MVC muscle activity and differences in exoskeleton benefit for at least one muscle, but not for all cases. There was no significant difference between exoskeleton benefits for Task 1, standing overhead sealing. The overhead stringer in Task 1 was set to be 25.4 cm above the acromion whereas the overhead stringer was positioned 45 cm and 50 cm above the acromion for Task 3 and 5, respectively. The extra shoulder flexion/abduction associated with the higher stringer positions may have led to greater benefit from the exoskeletons. Moreover, the extra shoulder flexion/abduction may have caused a greater %MVC muscle activity reduction for Tasks 3 and 5, compared to Task 1. This outcome is somewhat comparable to a study reported by Kim and Nussbaum (2019), which used a passive exoskeleton during a simulated overhead drilling task and wiring task, on two heights levels (overhead and shoulder level). They found that task height significantly affected muscle activity reduction. The normalized mean EMG reduction of the anterior deltoid ranged from 16.6% to 59.9%, which showed the greatest reduction on the overhead task [60].

In contrast to overhead work in Tasks 1, 3, and 5, there was a significant reduction in %MVC muscle activity for all the shoulder height tasks, Tasks 2, 4, and 6 (i.e., standing sealing

on stringer 3, seated sealing on stringer 4, and squeeze riveting on stringer 3, respectively). However, only in task 6 was there a significant difference between exoskeletons conditions (i.e., %MVC muscle activity reduction). In Task 6, the participants utilized a squeeze riveting tool (weigh = 2.7 kg), and in Task 2 and 4, utilized a sealing tool (weigh = 0.024 kg). The difference in the tool weight could explain the significant difference between the exoskeleton conditions. Supporting this interpretation, a study by Alabdulkarim and Nussbaum (2019) examined three different passive exoskeletons designs and different tool masses on muscle activity reduction during overhead tasks. They found the tool mass and the exoskeleton design significantly affected all muscles tested in the study, and they reported an interaction between tool mass and exoskeleton design on the peak anterior deltoid muscle loading [38].

Nonetheless, anecdotally participants tended to prefer an exoskeleton based on comfort regardless of the associated benefit. The Skelex was repeatedly preferred, and based on the comfortable fit ranking, it was the comfortable exoskeleton. A consistent finding of lack of corresponding between preference and performance was found in a previous study which investigate the relationship between metabolic cost and the optimal timing for supplying a hip power using an exoskeleton to assist participants during locomotion. Participants tested nine different assistance timing conditions, and in each condition they were asked if they prefer the new assistance timing condition over the previous assistance timing condition. The participant's preference of assistance timing did not indicate a corresponding to the reduction of metabolic cost [61]. A possible explanation for this lack of association could be participants were unable to sense the muscle reduction or solely preferred exoskeleton based on other factors such as comfort. In a study by Hensel and Keil (2019) they found that participant acceptance was strongly influenced by the level of discomfort when using an exoskeleton [62]. Therefore, a user preference may not

be an effective method in determining how useful an exoskeleton is, rather user preference may assess the degree of exoskeleton comfort.

5.3 Limitations

This study has two main limitations. First, participants were asked to rank their preference for sealing tasks and squeezing tasks once only after they completed the whole experiment. This could lead to confusion between the three different exoskeleton and tasks. In addition, the tasks were different. Sealing tasks consisted of 4 different tasks requiring different posture and height, 2 tasks on an upper stringer and 2 on a lower stringer and they performed these tasks seated and standing. Based on the literature review, task characteristics affect muscle activity. Here, there is a difference between each sealing task. Similarly, for the riveting squeezing task, Task 5 was on an upper stringer and Task 6 was on a lower stringer. These differentially should be taken into consideration, and a separate ranking survey should be conducted immediately after each task. However, this method will require a longer time, which we did not have as the participants had to work.

A second limitation was not considering a potential confounding variables such as gender and years of experience. In this study, gender was not considered as a confounding variable, but possible interaction between preference and exoskeleton muscle reduction could occur. One gender might be able to identify and prefer the exoskeleton that provides the greatest reduction. In addition, the variability in years of experience was quite large, one subject had a total of 6 years of experience and another subject had a total of 45 years of experience. Participants with years of manufacturing work experience might be able to identify the ideal exoskeleton for a specific task.

CHAPTER 6

CONCLUSIONS

All three exoskeletons showed great muscle reduction for both sealing and riveting squeezing tasks when compared to the No-Exoskeleton condition. For almost every task, the muscles bilaterally showed a %MVC muscle activity reduction, suggesting the exoskeleton is benefiting the whole body to some degree. In particular, the deltoid muscle activity was significantly reduced through all examined tasks. The tasks characteristic such as height, significantly affected the muscle activity reduction. Higher tasks resulted in a greater muscle activity reduction.

The most prominent finding from this study was that there was no relationship between the %MVC muscle activity reduction and probability of selection. The probability of selection was very random, no trends or relationships were observed. Only in one task, participants were certain about choosing a specific exoskeleton, whereas in the remaining tasks all three exoskeletons had a probability of being selected. In half of the investigated tasks, there was no significant difference between the exoskeleton muscle activity reductions.

It was noted from the preference ranking that participant liked the Skelex the most for both sealing and riveting squeezing tasks. Comfort was seen as a potential driving force in participants' preference, as the Skelex was the comfortable exoskeleton compared to Evo and Paexo.

This study provides information exoskeleton benefit and lack of relation between exoskeleton muscle activity reduction and user preference that may be useful in future studies for those who are considering identifying muscle exoskeleton benefits solely based on user preference.

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APPENDICES

APPENDIX A

R-Code for computing the probability in Task 2

```
#Loading and checking the data
```

```
#LOAD DATA
```

```
library(readxl)
```

```
Task2_PassiveActive <- read_excel("Task2_PassiveActive.xlsx")
```

```
require(nnet) # installing a package to run multinom
```

```
#First step determine which has the lowest residual deviance in each
```

```
model_____*****  
*****
```

```
#_____EV
```

```
MODEL_____
```

```
#ADELT
```

```
multinom(formula = Preferred_EKSO ~ EV_Active_Adelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 27.0549
```

```
multinom(formula = Preferred_EKSO ~ EV_Passive_ADelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 28.46033
```

```
#MDELT
```

```
multinom(formula = Preferred_EKSO ~ EV_Active_MDelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 26.10473 #LOW
```

```
multinom(formula = Preferred_EKSO ~ EV_Passive_MDelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 31.01624
```

```
#TRAP
```

```
multinom(formula = Preferred_EKSO ~ EV_Active_Trap, data = Task2_PassiveActive)
```

```
#Residual Deviance: 27.59467
```

```
multinom(formula = Preferred_EKSO ~ EV_Passive_Trap, data = Task2_PassiveActive)
```

```
#Residual Deviance: 29.89583
```

```
#_____OB
```

```
MODEL_____
```

```
#ADELT
```

```
multinom(formula = Preferred_EKSO ~ OB_Active_Adelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 30.73365
```

```
multinom(formula = Preferred_EKSO ~ OB_Passive_ADelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 28.10915
```

```
#MDELT
```

```
multinom(formula = Preferred_EKSO ~ OB_Active_MDelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 28.08683 #LOW
```

```
multinom(formula = Preferred_EKSO ~ OB_Passive_MDelt, data = Task2_PassiveActive)
```

```
#Residual Deviance: 31.22934
```

```
#TRAP
```

```

multinom(formula = Preferred_EKSO ~ OB_Active_Trap, data = Task2_PassiveActive)
#Residual Deviance: 29.10709
multinom(formula = Preferred_EKSO ~ OB_Passive_Trap, data = Task2_PassiveActive)
#Residual Deviance: 30.49311

#_____SK
MODEL_____
#ADELT
multinom(formula = Preferred_EKSO ~ SK_Active_Adelt, data = Task2_PassiveActive)
#Residual Deviance: 27.50438 #LOW
multinom(formula = Preferred_EKSO ~ SK_Passive_ADelt, data = Task2_PassiveActive)
#Residual Deviance: 29.03994
#MDELT
multinom(formula = Preferred_EKSO ~ SK_Active_MDelt, data = Task2_PassiveActive)
#Residual Deviance: 27.65655
multinom(formula = Preferred_EKSO ~ SK_Passive_MDelt, data = Task2_PassiveActive)
#Residual Deviance: 31.39243
#TRAP
multinom(formula = Preferred_EKSO ~ SK_Active_Trap, data = Task2_PassiveActive)
#Residual Deviance: 31.20289
multinom(formula = Preferred_EKSO ~ SK_Passive_Trap, data = Task2_PassiveActive)
#Residual Deviance: 28.60151

#2nd step building the models by adding one muscle at a
time_____*****
*****_____

#_____EV
MODEL_____

mMDelt.EV=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt, data =
Task2_PassiveActive) ### this is our starting model based on `decidingâ EV_Active_MDeltâ
was best single parameter model

### : ACTIVE/PASS ADelt , PASSIVE MDelt, ACTIVE/PASS Trap

### fit the following five models and compute p value
EV1=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Active_Adelt, data =
Task2_PassiveActive)
### test statistic
TEV1 = mMDelt.EV$deviance - EV1$deviance
### and p value
1 - pchisq(TEV1,1) # P-value = 0.08578785

EV2=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt, data =
Task2_PassiveActive)

```

```

### test statistic
TEV2 = mMDelt.EV$deviance - EV2$deviance
### and p value
1 - pchisq(TEV2,1) # P-value = 0.004881342 #LOW

EV3=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_MDelt, data =
Task2_PassiveActive)
### test statistic
TEV3 = mMDelt.EV$deviance - EV3$deviance
### and p value
1 - pchisq(TEV3,1) # P-value = 0.6398192

EV4=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Active_Trap, data =
Task2_PassiveActive)
### test statistic
TEV4 = mMDelt.EV$deviance - EV4$deviance
### and p value
1 - pchisq(TEV4,1) # P-value = 0.01718535

EV5=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_Trap, data =
Task2_PassiveActive)
### test statistic
TEV5 = mMDelt.EV$deviance - EV5$deviance
### and p value
1 - pchisq(TEV5,1) # P-value = 0.5178187

#Current model _____ 1 _____
mMDelt.EV=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt,
data = Task2_PassiveActive) ### this is our model
### : ACTIVE ADelt , PASSIVE MDelt, ACTIVE/PASS Trap

### fit the following five models and compute p value
EV1=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt +
EV_Active_Adelt, data = Task2_PassiveActive)
### test statistic
TEV1 = mMDelt.EV$deviance - EV1$deviance
### and p value
1 - pchisq(TEV1,1) # P-value = 0.04731339

EV2=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt +
EV_Passive_Trap, data = Task2_PassiveActive)
### test statistic
TEV2 = mMDelt.EV$deviance - EV2$deviance
### and p value
1 - pchisq(TEV2,1) # P-value = 0.001937302 #LOW

```

```
EV3=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt+
EV_Passive_MDelt, data = Task2_PassiveActive)
```

```
### test statistic
```

```
TEV3 = mMDelt.EV$deviance - EV3$deviance
```

```
### and p value
```

```
1 - pchisq(TEV3,1) # P-value = 0.1688754
```

```
EV4=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt+
EV_Active_Trap, data = Task2_PassiveActive)
```

```
### test statistic
```

```
TEV4 = mMDelt.EV$deviance - EV4$deviance
```

```
### and p value
```

```
1 - pchisq(TEV4,1) # P-value = 0.00488164
```

```
#Current model _____2_____
```

```
mMDelt.EV=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt
+ EV_Passive_Trap, data = Task2_PassiveActive) ### this is our model
```

```
### : ACTIVE ADelt , PASSIVE MDelt, ACTIVE Trap
```

```
EV1=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt +
EV_Passive_Trap+ EV_Active_Adelt, data = Task2_PassiveActive)
```

```
### test statistic
```

```
TEV1 = mMDelt.EV$deviance - EV1$deviance
```

```
### and p value
```

```
1 - pchisq(TEV1,1) # P-value = 0.3775726
```

```
EV2=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt +
EV_Passive_Trap+EV_Active_Trap, data = Task2_PassiveActive)
```

```
### test statistic
```

```
TEV2 = mMDelt.EV$deviance - EV2$deviance
```

```
### and p value
```

```
1 - pchisq(TEV2,1) # P-value = 0.4353831
```

```
EV3=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt +
EV_Passive_Trap+ EV_Passive_MDelt, data = Task2_PassiveActive)
```

```
### test statistic
```

```
TEV3 = mMDelt.EV$deviance - EV3$deviance
```

```
### and p value
```

```
1 - pchisq(TEV3,1) # P-value = 0.3291541
```

```
#will not go pass that, will stop EV model at EV_Active_MDelt + EV_Passive_ADelt +
EV_Passive_Trap
```

```
# _____OB
```

```
MODEL_____
```

```
mMDelt.OB=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt, data =
Task2_PassiveActive)
### : ACTIVE&PASSIVE ADelt, MDelt, ACTIVE Trap
```

```
OB1=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt + OB_Active_Adelt, data =
Task2_PassiveActive)
### test statistic
TOB1 = mMDelt.OB$deviance - OB1$deviance
### and p value
1 - pchisq(TOB1,1) # P-value = 0.2348328
```

```
OB2=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt +OB_Passive_ADelt, data =
Task2_PassiveActive)
### test statistic
TOB2 = mMDelt.OB$deviance - OB2$deviance
### and p value
1 - pchisq(TOB2,1) # P-value = 0.01067955 #SMALLEST
```

```
OB3=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt +OB_Passive_MDelt, data =
Task2_PassiveActive)
### test statistic
TOB3 = mMDelt.OB$deviance - OB3$deviance
### and p value
1 - pchisq(TOB3,1) # P-value = 0.3100791
```

```
OB4=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt +OB_Passive_Trap, data =
Task2_PassiveActive)
### test statistic
TOB4 = mMDelt.OB$deviance - OB4$deviance
### and p value
1 - pchisq(TOB4,1) # P-value = 0.4964922
```

```
OB5=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt +OB_Active_Trap, data =
Task2_PassiveActive)
### test statistic
TOB5 = mMDelt.OB$deviance - OB5$deviance
### and p value
1 - pchisq(TOB5,1) # P-value = 0.1456815
```

```
#Current model _____ 1 _____
```

```
mMDelt.OB=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt +OB_Passive_ADelt,
data = Task2_PassiveActive)
#TEST P MDELT, A ADELTA, A&P trap
```

```

OB1=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt, data = Task2_PassiveActive)
#### test statistic
TOB1 = mMDelt.OB$deviance - OB1$deviance
#### and p value
1 - pchisq(TOB1,1) # P-value =0.02524017 #SMALLEST

```

```

OB2=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Active_Trap, data = Task2_PassiveActive)
#### test statistic
TOB2 = mMDelt.OB$deviance - OB2$deviance
#### and p value
1 - pchisq(TOB2,1) # P-value = 0.1831467

```

```

OB3=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt +OB_Passive_ADelt
+OB_Passive_Trap, data = Task2_PassiveActive)
#### test statistic
TOB3 = mMDelt.OB$deviance - OB3$deviance
#### and p value
1 - pchisq(TOB3,1) # P-value = 0.1281037

```

```

OB4=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt +OB_Passive_ADelt
+OB_Active_Adelt, data = Task2_PassiveActive)
#### test statistic
TOB4 = mMDelt.OB$deviance - OB4$deviance
#### and p value
1 - pchisq(TOB4,1) # P-value = 0.1110818

```

#Current model _____2_____

```

mMDelt.OB=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt, data = Task2_PassiveActive)
#TEST A ADELTA , A&P TRAP ,

```

```

OB1=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Adelt, data = Task2_PassiveActive)
#### test statistic
TOB1 = mMDelt.OB$deviance - OB1$deviance
#### and p value
1 - pchisq(TOB1,1) # P-value = 0.1350256

```

```

OB2=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap, data = Task2_PassiveActive)
#### test statistic
TOB2 = mMDelt.OB$deviance - OB2$deviance
#### and p value

```

1 - pchisq(TOB2,1) # P-value = 0.007416266 #LOW

```
OB3=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Passive_Trap , data = Task2_PassiveActive)
```

test statistic

```
TOB3 = mMDelt.OB$deviance - OB3$deviance
```

and p value

1 - pchisq(TOB3,1) # P-value = 0.009053884

#Current model 3

```
mMDelt.OB=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap, data = Task2_PassiveActive)
```

#TEST active delT ,P TRAP

```
OB1=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap+OB_Active_Adelt, data =
Task2_PassiveActive)
```

test statistic

```
TOB1 = mMDelt.OB$deviance - OB1$deviance
```

and p value

1 - pchisq(TOB1,1) # P-value = 0.00217945 #LOW

```
OB2=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap+OB_Passive_Trap, data =
Task2_PassiveActive)
```

test statistic

```
TOB2 = mMDelt.OB$deviance - OB2$deviance
```

and p value

1 - pchisq(TOB2,1) # P-value = 0.002182578

#Current model 4

```
mMDelt.OB=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap+OB_Active_Adelt, data =
Task2_PassiveActive)
```

#TEST P TRAP

```
OB1=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap+OB_Active_Adelt+OB_Passive_T
rap, data = Task2_PassiveActive)
```

test statistic

```
TOB1 = mMDelt.OB$deviance - OB1$deviance
```

and p value

1 - pchisq(TOB1,1) # P-value = 0.9871989

#will stop after OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap+OB_Active_Adelt. will not add
passive trap

_____ SK

MODEL _____
mADelt.SK=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt, data =
Task2_PassiveActive)
TEST P ADELTA, A&P MDELTA TRAP

SK1=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt + SK_Passive_ADelt, data =
Task2_PassiveActive)
test statistic
TSK1 = mADelt.SK\$deviance - SK1\$deviance
and p value
1 - pchisq(TSK1,1) # P-value 0.05189416

SK2=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_MDelt, data =
Task2_PassiveActive)
test statistic
TSK2 = mADelt.SK\$deviance - SK2\$deviance
and p value
1 - pchisq(TSK2,1) # P-value 0.000125413 #LOW

SK3=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt + SK_Passive_MDelt, data =
Task2_PassiveActive)
test statistic
TSK3 = mADelt.SK\$deviance - SK3\$deviance
and p value
1 - pchisq(TSK3,1) # P-value 0.5561161

SK4=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_Trap, data =
Task2_PassiveActive)
test statistic
TSK4 = mADelt.SK\$deviance - SK4\$deviance
and p value
1 - pchisq(TSK4,1) # P-value 0.7649321

SK5=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Passive_Trap, data =
Task2_PassiveActive)
test statistic
TSK5 = mADelt.SK\$deviance - SK5\$deviance
and p value
1 - pchisq(TSK5,1) # P-value 0.0051664

#Current model _____ 1 _____

```
mADelt.SK=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_MDelt,
data = Task2_PassiveActive)
# TEST P ADELTA, A&P TRAP P Mdelt
```

```
SK1=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_MDelt +
SK_Passive_ADelt, data = Task2_PassiveActive)
#### test statistic
TSK1 = mADelt.SK$deviance - SK1$deviance
#### and p value
1 - pchisq(TSK1,1) # P-value 0.01749838 #LOW
```

```
SK2=multinom(formula = Preferred_EKSO ~
SK_Active_Adelt+SK_Active_MDelt+SK_Passive_Trap, data = Task2_PassiveActive)
#### test statistic
TSK2 = mADelt.SK$deviance - SK2$deviance
#### and p value
1 - pchisq(TSK2,1) # P-value 0.551115
```

```
SK3=multinom(formula = Preferred_EKSO ~
SK_Active_Adelt+SK_Active_MDelt+SK_Passive_MDelt, data = Task2_PassiveActive)
#### test statistic
TSK3 = mADelt.SK$deviance - SK3$deviance
#### and p value
1 - pchisq(TSK3,1) # P-value 0.7741664
```

```
SK4=multinom(formula = Preferred_EKSO ~
SK_Active_Adelt+SK_Active_MDelt+SK_Active_Trap, data = Task2_PassiveActive)
#### test statistic
TSK4 = mADelt.SK$deviance - SK4$deviance
#### and p value
1 - pchisq(TSK4,1) # P-value 0.8054336
```

```
#Current model 2
mADelt.SK=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_MDelt +
SK_Passive_ADelt, data = Task2_PassiveActive)
# TEST A&P TRAP P Mdelt
```

```
SK1=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_MDelt +
SK_Passive_ADelt+SK_Active_Trap , data = Task2_PassiveActive)
#### test statistic
TSK1 = mADelt.SK$deviance - SK1$deviance
#### and p value
1 - pchisq(TSK1,1) # P-value 0.3387052
```

```
SK2=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_MDelt +
SK_Passive_ADelt+SK_Passive_Trap, data = Task2_PassiveActive)
```

```

#### test statistic
TSK2 = mADelt.SK$deviance - SK2$deviance
#### and p value
1 - pchisq(TSK2,1) # P-value 0.00750751 #LOW

SK3=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+SK_Active_MDelt +
SK_Passive_ADelt+SK_Passive_MDelt, data = Task2_PassiveActive)
#### test statistic
TSK3 = mADelt.SK$deviance - SK3$deviance
#### and p value
1 - pchisq(TSK3,1) # P-value 0.05015672

#Current model_____3_____

mADelt.SK=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+ SK_Active_MDelt +
SK_Passive_ADelt+SK_Passive_Trap, data = Task2_PassiveActive)
# TEST A TRAP P Mdelt

SK1=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+ SK_Active_MDelt +
SK_Passive_ADelt+SK_Passive_Trap+SK_Active_Trap , data = Task2_PassiveActive)
#### test statistic
TSK1 = mADelt.SK$deviance - SK1$deviance
#### and p value
1 - pchisq(TSK1,1) # P-value 0.9700386

SK2=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+ SK_Active_MDelt +
SK_Passive_ADelt+SK_Passive_Trap+SK_Passive_MDelt, data = Task2_PassiveActive)
#### test statistic
TSK2 = mADelt.SK$deviance - SK2$deviance
#### and p value
1 - pchisq(TSK2,1) # P-value 0.9675435 #LOW

# nothing will be added , the model has SK_Active_Adelt+ SK_Active_MDelt +
SK_Passive_ADelt+SK_Passive_Trap

#3rd step plot the
probabilities
_____
*****
_____

#EV CANDIDATE MODEL

model_EV=multinom(formula = Preferred_EKSO ~ EV_Active_MDelt + EV_Passive_ADelt +
EV_Passive_Trap, data = Task2_PassiveActive)
summary(model_EV)

EV_C.OB = coefficients(model_EV)[1,]

```

```

EV_C.SK = coefficients(model_EV)[2,]

summary(Task2_PassiveActive$EV_Passive_ADelt)
EV_Passive_ADelt_Test = seq(-5,1,by=0.5) # From,to,by

summary(Task2_PassiveActive$EV_Active_MDelt)
EV_Active_MDelt_Test = seq(-17,1,by=0.5) # From,to,by

summary(Task2_PassiveActive$EV_Passive_Trap)
EV_Passive_Trap_Test = seq(-13,12,by=0.5) # From,to,by

EV_mean.Active_MDelt = mean(Task2_PassiveActive$EV_Active_MDelt)
EV_mean.Passive_ADelt=mean(Task2_PassiveActive$EV_Passive_ADelt)
EV_mean.Passive_Trap=mean(Task2_PassiveActive$EV_Passive_Trap)

#par(mfrow=c(3,1)) # Suplots_____

#Plotting passive adelt
#Linear
EV_eta.OB_1 = EV_C.OB[1] +
EV_C.OB[2]*EV_mean.Active_MDelt+EV_C.OB[3]*EV_mean.Passive_Trap+EV_C.OB[4]*E
V_Passive_ADelt_Test
EV_eta.SK_1 = EV_C.SK[1] +
EV_C.SK[2]*EV_mean.Active_MDelt+EV_C.SK[3]*EV_mean.Passive_Trap+EV_C.SK[4]*E
V_Passive_ADelt_Test

# now we can compute the probability curves
EV_P.OB_1 = exp(EV_eta.OB_1)/(1 + exp(EV_eta.OB_1) + exp(EV_eta.SK_1))
EV_P.SK_1 = exp(EV_eta.SK_1)/(1 + exp(EV_eta.OB_1) + exp(EV_eta.SK_1))
EV_P.EV_1 = 1/(1 + exp(EV_eta.OB_1) + exp(EV_eta.SK_1))

#PLOT
plot(NA,xlim = c(-4,0),ylim = c(0,1), xlab = '%MVC Difference', main='Task 2 - Evo Passive
Anterior Deltoid',
      ylab = 'Probability')
lines(EV_Passive_ADelt_Test,EV_P.OB_1,col=1,lwd=2.0)
lines(EV_Passive_ADelt_Test,EV_P.SK_1,col=2,lwd=2.0)
lines(EV_Passive_ADelt_Test,EV_P.EV_1,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

#lty = 2, # Grid line type
#col = "gray", # Grid line color
#lwd = 2) # Grid line width

#Plotting Active_MDelt

```

```

#Linear
EV_eta.OB_2 = EV_C.OB[1] +
EV_C.OB[2]*EV_mean.Passive_ADelt+EV_C.OB[3]*EV_mean.Passive_Trap+EV_C.OB[4]*E
V_Active_MDelt_Test
EV_eta.SK_2 = EV_C.SK[1] +
EV_C.SK[2]*EV_mean.Passive_ADelt+EV_C.SK[3]*EV_mean.Passive_Trap+EV_C.SK[4]*E
V_Active_MDelt_Test

# now we can compute the probability curves
EV_P.OB_2 = exp(EV_eta.OB_2)/(1 + exp(EV_eta.OB_2) + exp(EV_eta.SK_2))
EV_P.SK_2 = exp(EV_eta.SK_2)/(1 + exp(EV_eta.OB_2) + exp(EV_eta.SK_2))
EV_P.EV_2 = 1/(1 + exp(EV_eta.OB_2) + exp(EV_eta.SK_2))

#PLOT
plot(NA,xlim = c(-15,0),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Evo Active
Medial Deltoid',
      ylab = 'Probability')
lines(EV_Active_MDelt_Test,EV_P.OB_2,col=1,lwd=2.0)
lines(EV_Active_MDelt_Test,EV_P.SK_2,col=2,lwd=2.0)
lines(EV_Active_MDelt_Test,EV_P.EV_2,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

#Plotting Passive_Trap_Test
#Linear
EV_eta.OB_3 = EV_C.OB[1] +
EV_C.OB[2]*EV_mean.Passive_ADelt+EV_C.OB[3]*EV_mean.Active_MDelt+EV_C.OB[4]*
EV_Passive_Trap_Test
EV_eta.SK_3 = EV_C.SK[1] +
EV_C.SK[2]*EV_mean.Passive_ADelt+EV_C.SK[3]*EV_mean.Active_MDelt+EV_C.SK[4]*
EV_Passive_Trap_Test

# now we can compute the probability curves
EV_P.OB_3 = exp(EV_eta.OB_3)/(1 + exp(EV_eta.OB_3) + exp(EV_eta.SK_3))
EV_P.SK_3 = exp(EV_eta.SK_3)/(1 + exp(EV_eta.OB_3) + exp(EV_eta.SK_3))
EV_P.EV_3 = 1/(1 + exp(EV_eta.OB_3) + exp(EV_eta.SK_3))

#PLOT
plot(NA,xlim = c(-12,10),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Evo Passive
Trapezius',
      ylab = 'Probability')
lines(EV_Passive_Trap_Test,EV_P.OB_3,col=1,lwd=2.0)
lines(EV_Passive_Trap_Test,EV_P.SK_3,col=2,lwd=2.0)
lines(EV_Passive_Trap_Test,EV_P.EV_3,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)

```

```

grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

#OB CANDIDATE MODEL

model_OB=multinom(formula = Preferred_EKSO ~ OB_Active_MDelt
+OB_Passive_ADelt+OB_Passive_MDelt+OB_Active_Trap+OB_Active_Adelt, data =
Task2_PassiveActive)
summary(model_OB)

OB_C.OB = coefficients(model_OB)[1,]
OB_C.SK = coefficients(model_OB)[2,]

summary(Task2_PassiveActive$OB_Active_MDelt)
OB_Active_MDelt_test = seq(-18,2,by=0.5)

summary(Task2_PassiveActive$OB_Passive_ADelt)
OB_Passive_ADelt_test = seq(-8,1,by=0.5)

summary(Task2_PassiveActive$OB_Passive_MDelt)
OB_Passive_MDelt_test = seq(-5,8,by=0.5)

summary(Task2_PassiveActive$OB_Active_Trap)
OB_Active_Trap_test = seq(-12,15,by=0.5)

summary(Task2_PassiveActive$OB_Active_Adelt)
OB_Active_Adelt_test = seq(-23,1,by=0.5)

OB_mean.Active_MDelt = mean(Task2_PassiveActive$OB_Active_MDelt)
OB_mean.Passive_MDelt = mean(Task2_PassiveActive$OB_Passive_MDelt)
OB_mean.Passive_ADelt = mean(Task2_PassiveActive$OB_Passive_ADelt)
OB_mean.Active_Trap=mean(Task2_PassiveActive$OB_Active_Trap)
OB_mean.Active_Adelt=mean(Task2_PassiveActive$OB_Active_Adelt)

#par(mfrow=c(5,1)) # Suplots _____

#Plotting Active_MDelt
OB_eta.OB_1 = OB_C.OB[1] + OB_C.OB[2]*OB_mean.Active_Trap +
OB_C.OB[3]*OB_mean.Active_Adelt + OB_C.OB[4]*OB_mean.Passive_ADelt+
OB_C.OB[5]*OB_mean.Passive_MDelt+ OB_C.OB[6]*OB_Active_MDelt_test
OB_eta.SK_1 = OB_C.SK[1] + OB_C.SK[2]*OB_mean.Active_Trap +
OB_C.SK[3]*OB_mean.Active_Adelt + OB_C.SK[4]*OB_mean.Passive_ADelt
+OB_C.SK[5]*OB_mean.Passive_MDelt + OB_C.SK[6]*OB_Active_MDelt_test

### now we can compute the probability curves
OB_P.EV_1 = 1/(1 + exp(OB_eta.OB_1) + exp(OB_eta.SK_1))
OB_P.SK_1 = exp(OB_eta.SK_1)/(1 + exp(OB_eta.OB_1) + exp(OB_eta.SK_1))

```

```
OB_P.OB_1 = exp(OB_eta.OB_1)/(1 + exp(OB_eta.OB_1) + exp(OB_eta.SK_1))
```

```
plot(NA,xlim = c(-17,0),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Paexo Active Medial Deltoid' ,
```

```
  ylab = 'Probability')
lines(OB_Active_MDelt_test,OB_P.OB_1,col=1,lwd=2.0)
lines(OB_Active_MDelt_test,OB_P.SK_1,col=2,lwd=2.0)
lines(OB_Active_MDelt_test,OB_P.EV_1,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)
```

```
#Plotting ActiveTrap __
```

```
OB_eta.OB_2 = OB_C.OB[1] + OB_C.OB[2]*OB_mean.Active_MDelt +
OB_C.OB[3]*OB_mean.Active_Adelt + OB_C.OB[4]*OB_mean.Passive_Adelt+
OB_C.OB[5]*OB_mean.Passive_MDelt+ OB_C.OB[6]*OB_Active_Trap_test
OB_eta.SK_2 = OB_C.SK[1] + OB_C.SK[2]*OB_mean.Active_MDelt +
OB_C.SK[3]*OB_mean.Active_Adelt+OB_C.SK[4]*OB_mean.Passive_Adelt
+OB_C.SK[5]*OB_mean.Passive_MDelt + OB_C.SK[6]*OB_Active_Trap_test
```

```
#### now we can compute the probability curves
```

```
OB_P.EV_2 = 1/(1 + exp(OB_eta.OB_2) + exp(OB_eta.SK_2))
OB_P.SK_2 = exp(OB_eta.SK_2)/(1 + exp(OB_eta.OB_2) + exp(OB_eta.SK_2))
OB_P.OB_2 = exp(OB_eta.OB_2)/(1 + exp(OB_eta.OB_2) + exp(OB_eta.SK_2))
```

```
plot(NA,xlim = c(-11,11),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Paexo Active Trapezius' ,
```

```
  ylab = 'Probability')
lines(OB_Active_Trap_test,OB_P.OB_2,col=1,lwd=2.0)
lines(OB_Active_Trap_test,OB_P.SK_2,col=2,lwd=2.0)
lines(OB_Active_Trap_test,OB_P.EV_2,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)
```

```
#Plotting Active_Adelt __
```

```
OB_eta.OB_3 = OB_C.OB[1] + OB_C.OB[2]*OB_mean.Active_MDelt +
OB_C.OB[3]*OB_mean.Active_Trap + OB_C.OB[4]*OB_mean.Passive_Adelt+
OB_C.OB[5]*OB_mean.Passive_MDelt+ OB_C.OB[6]*OB_Active_Adelt_test
OB_eta.SK_3 = OB_C.SK[1] + OB_C.SK[2]*OB_mean.Active_MDelt +
OB_C.SK[3]*OB_mean.Active_Trap+OB_C.SK[4]*OB_mean.Passive_Adelt
+OB_C.SK[5]*OB_mean.Passive_MDelt + OB_C.SK[6]*OB_Active_Adelt_test
```

```
#### now we can compute the probability curves
```

```
OB_P.EV_3 = 1/(1 + exp(OB_eta.OB_3) + exp(OB_eta.SK_3))
OB_P.SK_3 = exp(OB_eta.SK_3)/(1 + exp(OB_eta.OB_3) + exp(OB_eta.SK_3))
OB_P.OB_3 = exp(OB_eta.OB_3)/(1 + exp(OB_eta.OB_3) + exp(OB_eta.SK_3))
```

```

plot(NA,xlim = c(-22,0),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Paexo Active
Anterior Deltoid',
     ylab = 'Probability')
lines(OB_Active_Adelt_test,OB_P.OB_3,col=1,lwd=2.0)
lines(OB_Active_Adelt_test,OB_P.SK_3,col=2,lwd=2.0)
lines(OB_Active_Adelt_test,OB_P.EV_3,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

```

```
#Plotting Passive_MDelt
```

```

OB_eta.OB_4 = OB_C.OB[1] + OB_C.OB[2]*OB_mean.Active_MDelt +
OB_C.OB[3]*OB_mean.Active_Trap + OB_C.OB[4]*OB_mean.Passive_ADelt+
OB_C.OB[5]*OB_mean.Active_Adelt+ OB_C.OB[6]*OB_Passive_MDelt_test
OB_eta.SK_4 = OB_C.SK[1] + OB_C.SK[2]*OB_mean.Active_MDelt +
OB_C.SK[3]*OB_mean.Active_Trap+OB_C.SK[4]*OB_mean.Passive_ADelt
+OB_C.SK[5]*OB_mean.Active_Adelt + OB_C.SK[6]*OB_Passive_MDelt_test

```

```
### now we can compute the probability curves
```

```

OB_P.EV_4 = 1/(1 + exp(OB_eta.OB_4) + exp(OB_eta.SK_4))
OB_P.SK_4 = exp(OB_eta.SK_4)/(1 + exp(OB_eta.OB_4) + exp(OB_eta.SK_4))
OB_P.OB_4 = exp(OB_eta.OB_4)/(1 + exp(OB_eta.OB_4) + exp(OB_eta.SK_4))

```

```

plot(NA,xlim = c(-4,5),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Paexo Passive
Medial Deltoid',
     ylab = 'Probability')

```

```

lines(OB_Passive_MDelt_test,OB_P.OB_4,col=1,lwd=2.0)
lines(OB_Passive_MDelt_test,OB_P.SK_4,col=2,lwd=2.0)
lines(OB_Passive_MDelt_test,OB_P.EV_4,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

```

```
#Plotting Passive_ADelt
```

```

OB_eta.OB_5 = OB_C.OB[1] + OB_C.OB[2]*OB_mean.Active_MDelt +
OB_C.OB[3]*OB_mean.Active_Trap + OB_C.OB[4]*OB_mean.Passive_MDelt+
OB_C.OB[5]*OB_mean.Active_Adelt+ OB_C.OB[6]*OB_Passive_ADelt_test
OB_eta.SK_5 = OB_C.SK[1] + OB_C.SK[2]*OB_mean.Active_MDelt +
OB_C.SK[3]*OB_mean.Active_Trap+OB_C.SK[4]*OB_mean.Passive_MDelt
+OB_C.SK[5]*OB_mean.Active_Adelt + OB_C.SK[6]*OB_Passive_ADelt_test

```

```
### now we can compute the probability curves
```

```

OB_P.EV_5 = 1/(1 + exp(OB_eta.OB_5) + exp(OB_eta.SK_5))
OB_P.SK_5 = exp(OB_eta.SK_5)/(1 + exp(OB_eta.OB_5) + exp(OB_eta.SK_5))
OB_P.OB_5 = exp(OB_eta.OB_5)/(1 + exp(OB_eta.OB_5) + exp(OB_eta.SK_5))

```

```

plot(NA,xlim = c(-7,0),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Paexo Passive
Anterior Deltoid',

```

```

ylab = 'Probability')
lines(OB_Passive_ADelt_test,OB_P.OB_5,col=1,lwd=2.0)
lines(OB_Passive_ADelt_test,OB_P.SK_5,col=2,lwd=2.0)
lines(OB_Passive_ADelt_test,OB_P.EV_5,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 7, col = "grey", lwd = 1)

```

```
#SK
```

```
MDOEL _____
```

```

_____
model_SK=multinom(formula = Preferred_EKSO ~ SK_Active_Adelt+ SK_Active_MDelt +
SK_Passive_ADelt+SK_Passive_Trap, data = Task2_PassiveActive)
summary(model_SK)

```

```
SK_C.OB = coefficients(model_SK)[1,]
```

```
SK_C.SK = coefficients(model_SK)[2,]
```

```
summary(Task2_PassiveActive$SK_Active_Adelt)
```

```
SK_Active_Adelt_test = seq(-19,0,by=0.5)
```

```
summary(Task2_PassiveActive$SK_Active_MDelt)
```

```
SK_Active_MDelt_test = seq(-18,1,by=0.5)
```

```
summary(Task2_PassiveActive$SK_Passive_ADelt)
```

```
SK_Passive_ADelt_test = seq(-5,0,by=0.5)
```

```
summary(Task2_PassiveActive$SK_Passive_Trap)
```

```
SK_Passive_Trap_test = seq(-15,4,by=0.5)
```

```
SK_mean.Active_MDelt = mean(Task2_PassiveActive$SK_Active_MDelt)
```

```
SK_mean.Passive_ADelt = mean(Task2_PassiveActive$SK_Passive_ADelt)
```

```
SK_mean.Passive_Trap=mean(Task2_PassiveActive$SK_Passive_Trap)
```

```
SK_mean.Active_Adelt=mean(Task2_PassiveActive$SK_Active_Adelt)
```

```
#par(mfrow=c(2,2)) # Suplots _____
```

```
#PLOTTING active ADelt
```

```
#### same idea, except now we will use mean.LA for everyone
```

```
SK_eta.OB_1 = SK_C.OB[1] + SK_C.OB[2]*SK_mean.Active_MDelt+
```

```
SK_C.OB[3]*SK_mean.Passive_ADelt+SK_C.OB[4]*SK_mean.Passive_Trap
```

```
+SK_C.OB[5]*SK_Active_Adelt_test
```

```
SK_eta.SK_1 = SK_C.SK[1] + SK_C.SK[2]*SK_mean.Active_MDelt+
```

```
SK_C.SK[3]*SK_mean.Passive_ADelt+SK_C.SK[4]*SK_mean.Passive_Trap+
```

```
SK_C.SK[5]*SK_Active_Adelt_test
```

```

#### now we can compute the probability curves
SK_P.OB_1 = exp(SK_eta.OB_1)/(1 + exp(SK_eta.OB_1) + exp(SK_eta.SK_1))
SK_P.EV_1 = 1/(1 + exp(SK_eta.OB_1) + exp(SK_eta.SK_1))
SK_P.SK_1 = exp(SK_eta.SK_1)/(1 + exp(SK_eta.OB_1) + exp(SK_eta.SK_1))

plot(NA,xlim = c(-18,-0.5),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Skelex
Active Anterior Deltoid',
     ylab = 'Probability')
lines(SK_Active_Adelt_test,SK_P.OB_1,col=1,lwd=2.0)
lines(SK_Active_Adelt_test,SK_P.SK_1,col=2,lwd=2.0)
lines(SK_Active_Adelt_test,SK_P.EV_1,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

#PLOTING Active_MDelt
#### same idea, except now we will use mean.LA for everyone
SK_eta.OB_2 = SK_C.OB[1] + SK_C.OB[2]*SK_mean.Active_Adelt+
SK_C.OB[3]*SK_mean.Passive_ADelt+SK_C.OB[4]*SK_mean.Passive_Trap
+SK_C.OB[5]*SK_Active_MDelt_test
SK_eta.SK_2 = SK_C.SK[1] + SK_C.SK[2]*SK_mean.Active_Adelt+
SK_C.SK[3]*SK_mean.Passive_ADelt+SK_C.SK[4]*SK_mean.Passive_Trap
+SK_C.SK[5]*SK_Active_MDelt_test

#### now we can compute the probability curves
SK_P.OB_2 = exp(SK_eta.OB_2)/(1 + exp(SK_eta.OB_2) + exp(SK_eta.SK_2))
SK_P.EV_2 = 1/(1 + exp(SK_eta.OB_2) + exp(SK_eta.SK_2))
SK_P.SK_2 = exp(SK_eta.SK_2)/(1 + exp(SK_eta.OB_2) + exp(SK_eta.SK_2))

plot(NA,xlim = c(-15,0),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Skelex Active
Medial Deltoid',
     ylab = 'Probability')
lines(SK_Active_MDelt_test,SK_P.OB_2,col=1,lwd=2.0)
lines(SK_Active_MDelt_test,SK_P.SK_2,col=2,lwd=2.0)
lines(SK_Active_MDelt_test,SK_P.EV_2,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

#PLOTING Passive_ADelt
#### same idea, except now we will use mean.LA for everyone
SK_eta.OB_3 = SK_C.OB[1] + SK_C.OB[2]*SK_mean.Active_Adelt+
SK_C.OB[3]*SK_mean.Active_MDelt+SK_C.OB[4]*SK_mean.Passive_Trap
+SK_C.OB[5]*SK_Passive_ADelt_test
SK_eta.SK_3 = SK_C.SK[1] + SK_C.SK[2]*SK_mean.Active_Adelt+
SK_C.SK[3]*SK_mean.Active_MDelt+SK_C.SK[4]*SK_mean.Passive_Trap
+SK_C.SK[5]*SK_Passive_ADelt_test

```

```

#### now we can compute the probability curves
SK_P.OB_3 = exp(SK_eta.OB_3)/(1 + exp(SK_eta.OB_3) + exp(SK_eta.SK_3))
SK_P.EV_3 = 1/(1 + exp(SK_eta.OB_3) + exp(SK_eta.SK_3))
SK_P.SK_3 = exp(SK_eta.SK_3)/(1 + exp(SK_eta.OB_3) + exp(SK_eta.SK_3))

plot(NA,xlim = c(-4,-0.5),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Skelex
Passive Anterior Deltoid',
     ylab = 'Probability')
lines(SK_Passive_ADelt_test,SK_P.OB_3,col=1,lwd=2.0)
lines(SK_Passive_ADelt_test,SK_P.SK_3,col=2,lwd=2.0)
lines(SK_Passive_ADelt_test,SK_P.EV_3,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

```

```

#PLOTING Passive Trap test
#### same idea, except now we will use mean.LA for everyone
SK_eta.OB_4 = SK_C.OB[1] + SK_C.OB[2]*SK_mean.Active_Adelt+
SK_C.OB[3]*SK_mean.Active_MDelt+SK_C.OB[4]*SK_mean.Passive_ADelt
+SK_C.OB[5]*SK_Passive_Trap_test
SK_eta.SK_4 = SK_C.SK[1] + SK_C.SK[2]*SK_mean.Active_Adelt+
SK_C.SK[3]*SK_mean.Active_MDelt+SK_C.SK[4]*SK_mean.Passive_ADelt+
SK_C.SK[5]*SK_Passive_Trap_test

```

```

#### now we can compute the probability curves
SK_P.OB_4 = exp(SK_eta.OB_4)/(1 + exp(SK_eta.OB_4) + exp(SK_eta.SK_4))
SK_P.EV_4 = 1/(1 + exp(SK_eta.OB_4) + exp(SK_eta.SK_4))
SK_P.SK_4 = exp(SK_eta.SK_4)/(1 + exp(SK_eta.OB_4) + exp(SK_eta.SK_4))

plot(NA,xlim = c(-5.,0),ylim = c(0,1),xlab = '%MVC Difference', main='Task 2 - Skelex Passive
Trapezius',
     ylab = 'Probability')
lines(SK_Passive_Trap_test,SK_P.OB_4,col=1,lwd=2.0)
lines(SK_Passive_Trap_test,SK_P.SK_4,col=2,lwd=2.0)
lines(SK_Passive_Trap_test,SK_P.EV_4,col=3,lwd=2.0)
legend('topright',c('OB','SK','EV'),lty = 1, col = 1:3)
grid(NULL,NULL, lty = 6, col = "grey", lwd = 1)

```

APPENDIX B

Probability plots that did indicate a significant reduction in %MVC muscle activity

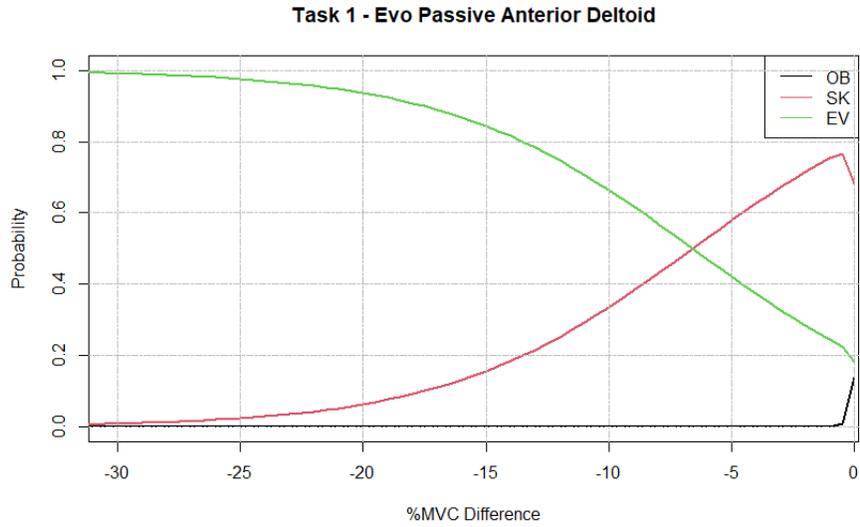


Figure 47: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Evo Passive Anterior Deltoid.

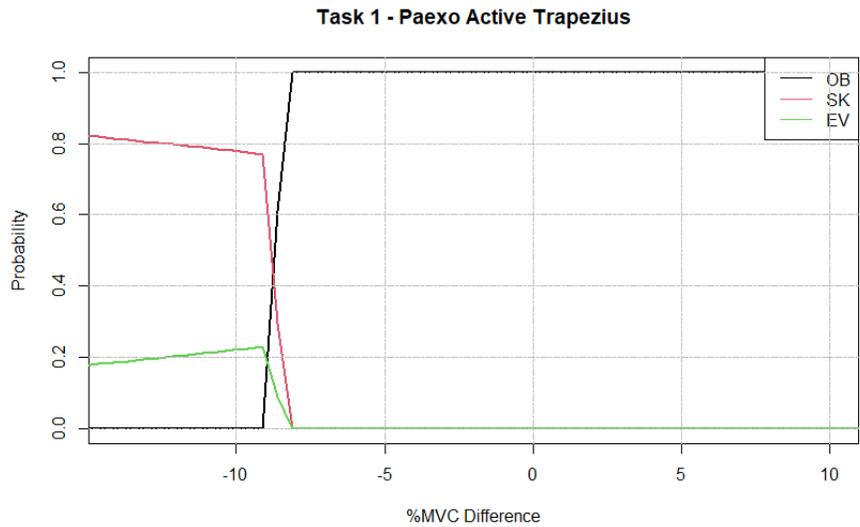


Figure 48: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Active Trapezius.

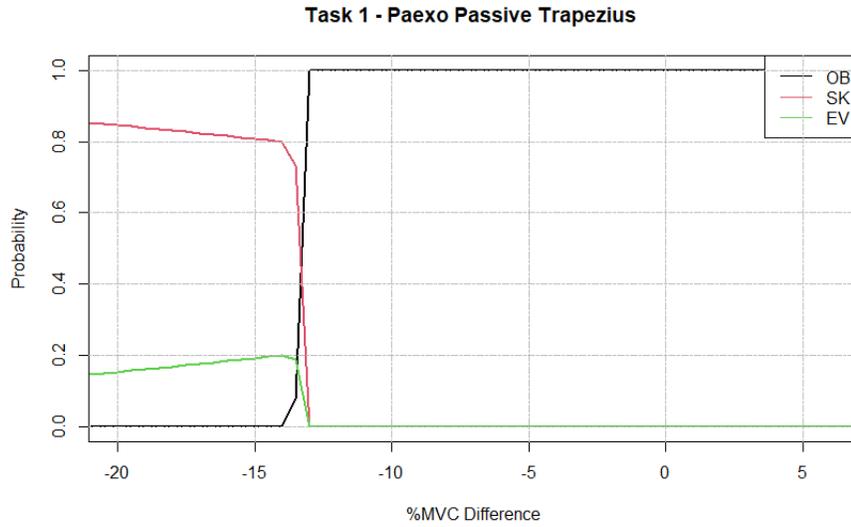


Figure 49: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Passive Trapezius.

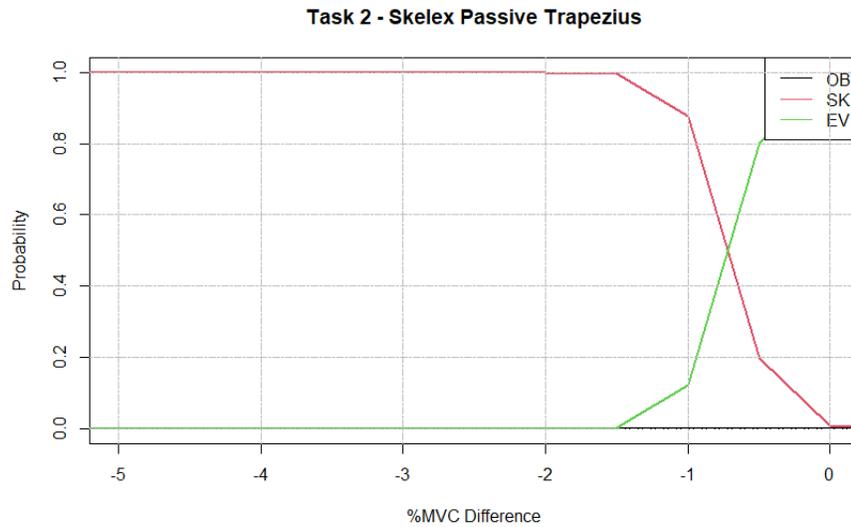


Figure 50: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Passive Trapezius

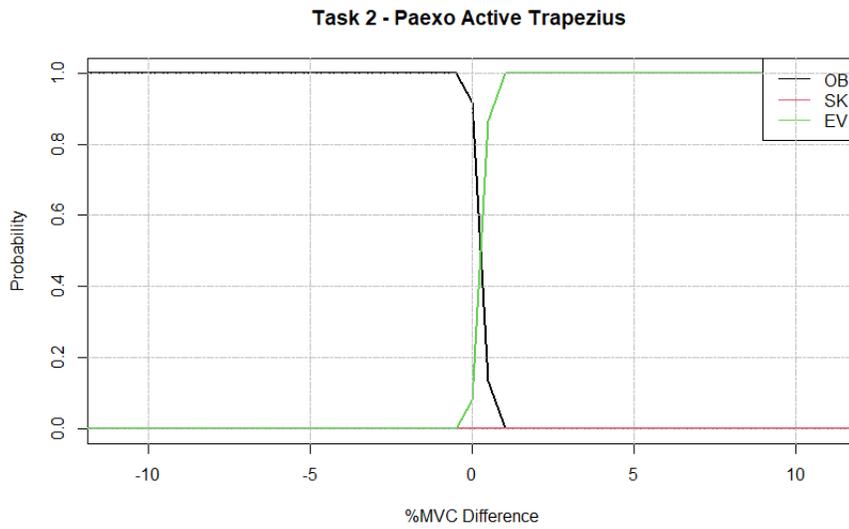


Figure 51: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Active Trapezius.

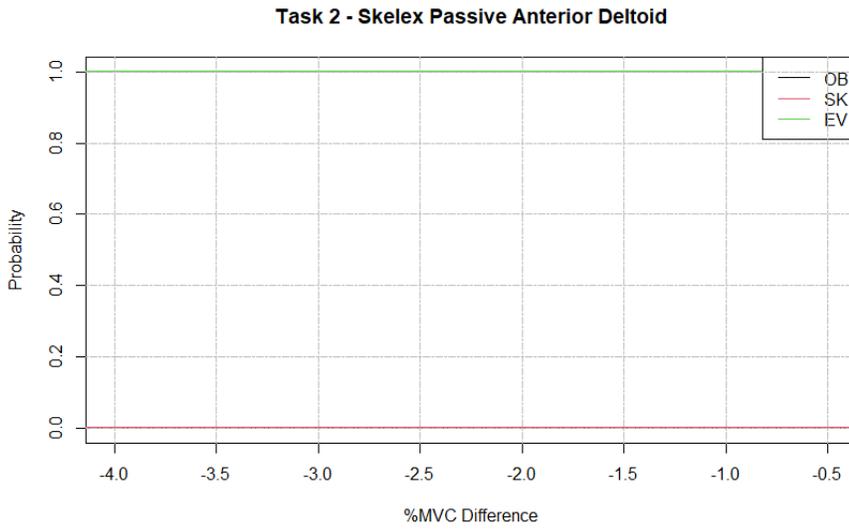


Figure 52: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Skelex Passive Anterior Deltoid.

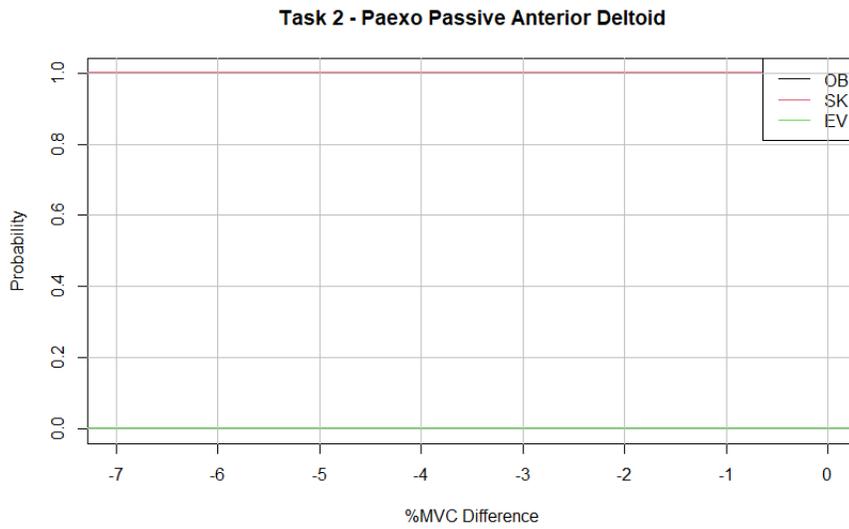


Figure 53: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Passive Anterior Deltoid.

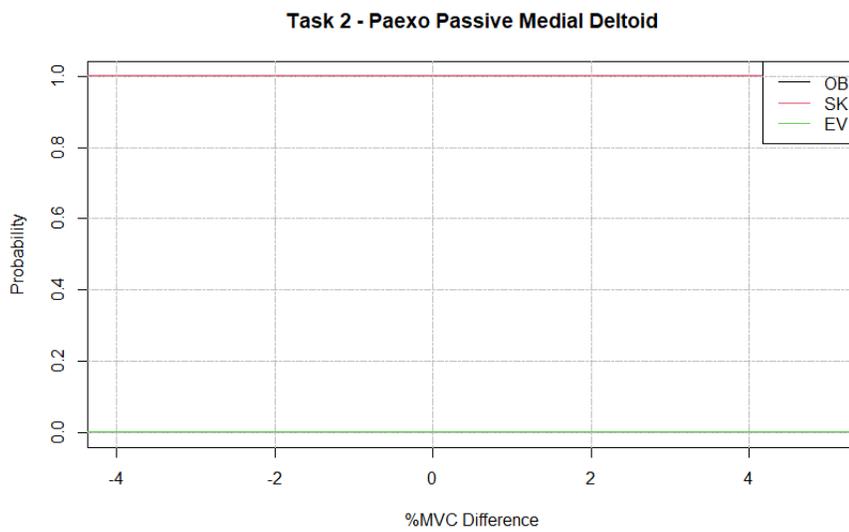


Figure 54: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Passive Medial Deltoid.

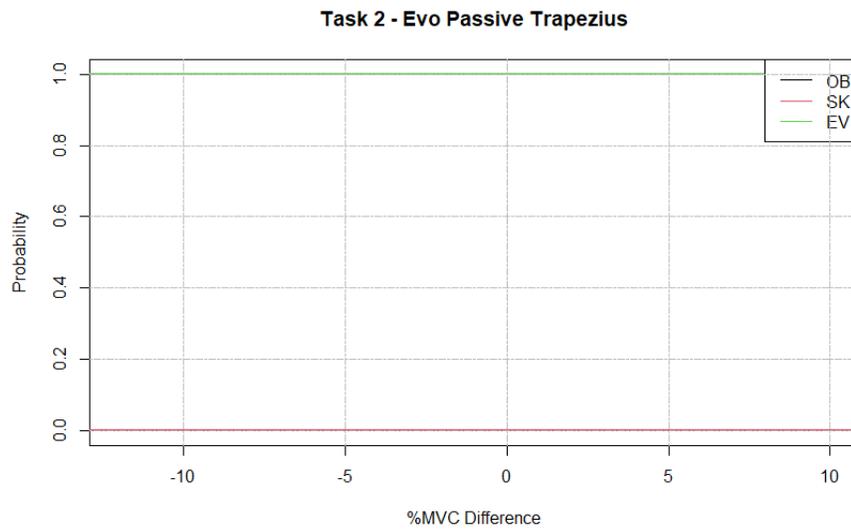


Figure 55: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Evo Passive Trapezius.

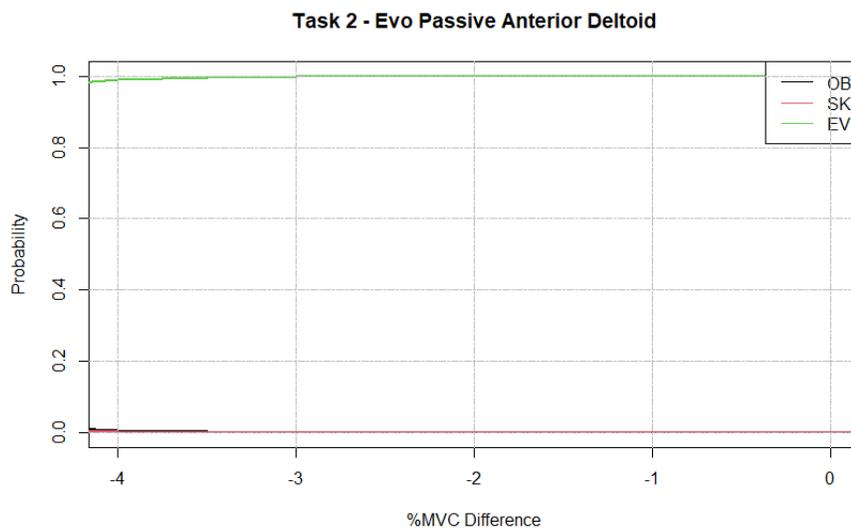


Figure 56: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Evo Passive Anterior Deltoid.

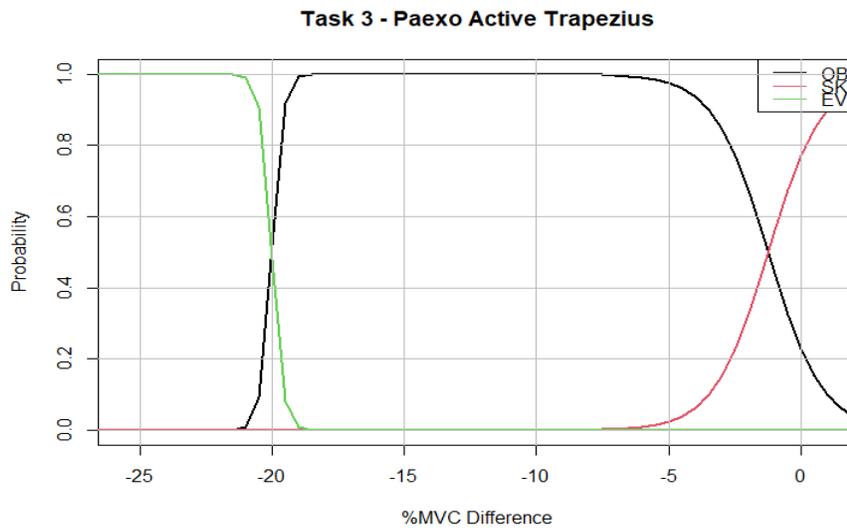


Figure 57: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Active Trapezius.

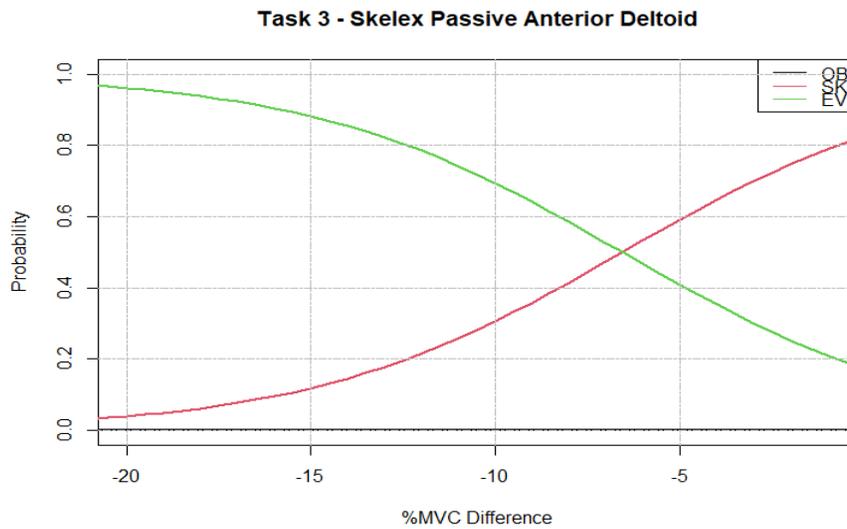


Figure 58: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Skelex Passive Anterior Deltoid.

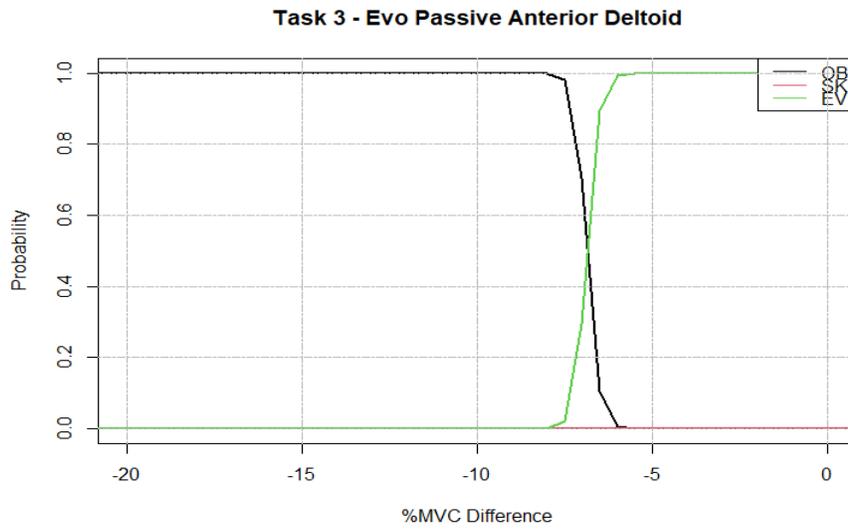


Figure 59: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Evo Passive Anterior Deltoid.

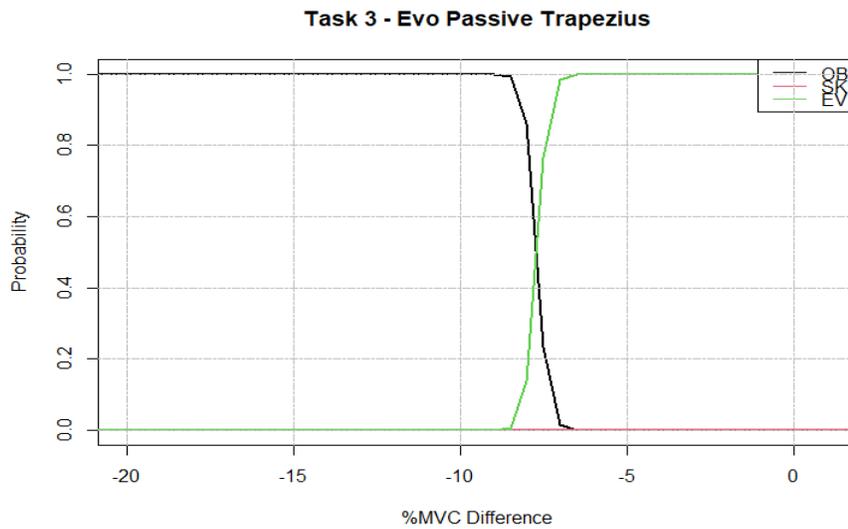


Figure 60: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Evo Passive Trapezius.

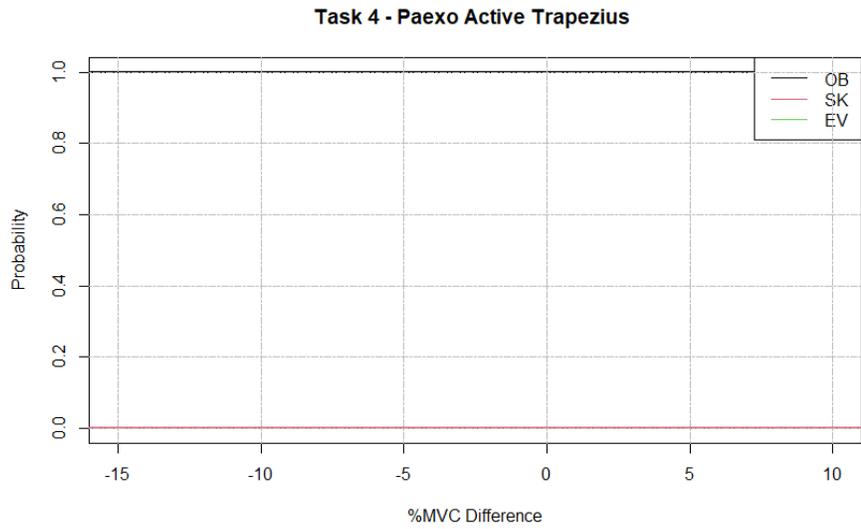


Figure 61: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Active Trapezius.

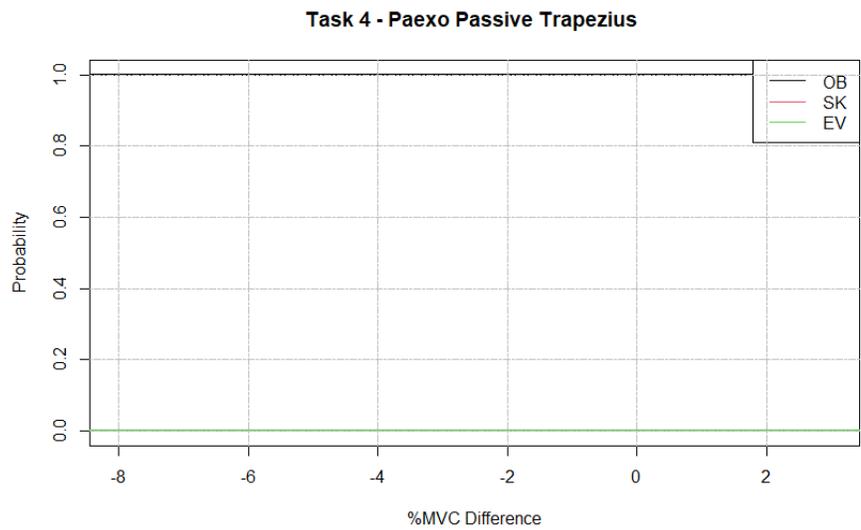


Figure 62: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Passive Trapezius.

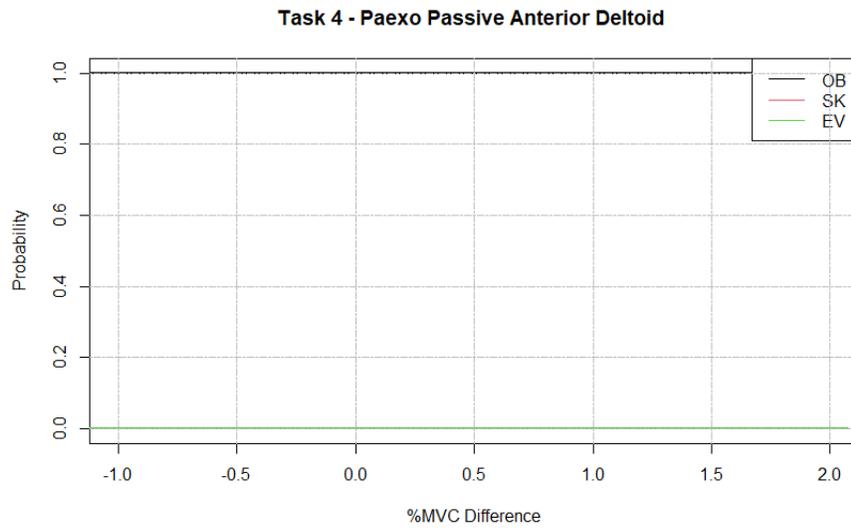


Figure 63: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Passive Anterior Deltoid.

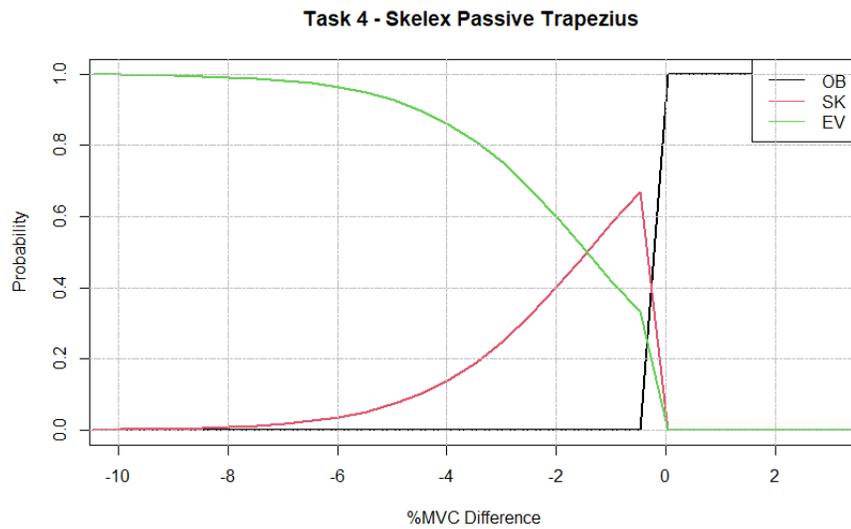


Figure 64: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Skelex Passive Trapezius.

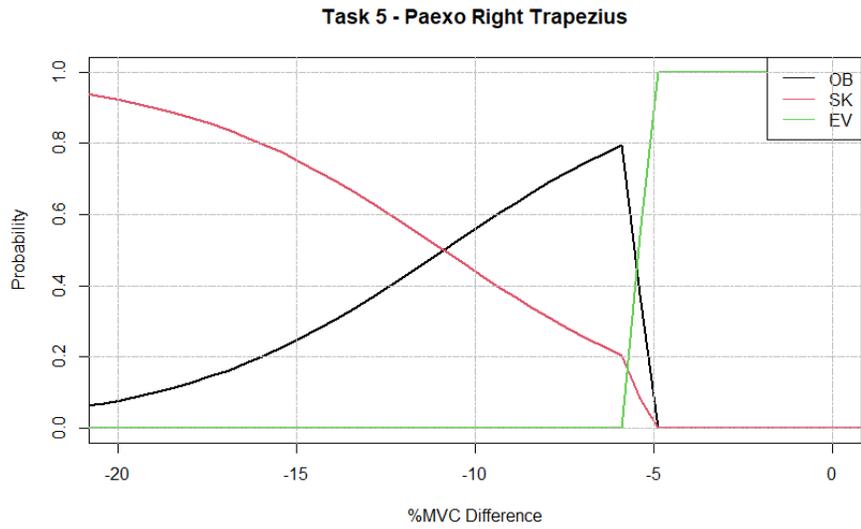


Figure 65: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Right Trapezius.

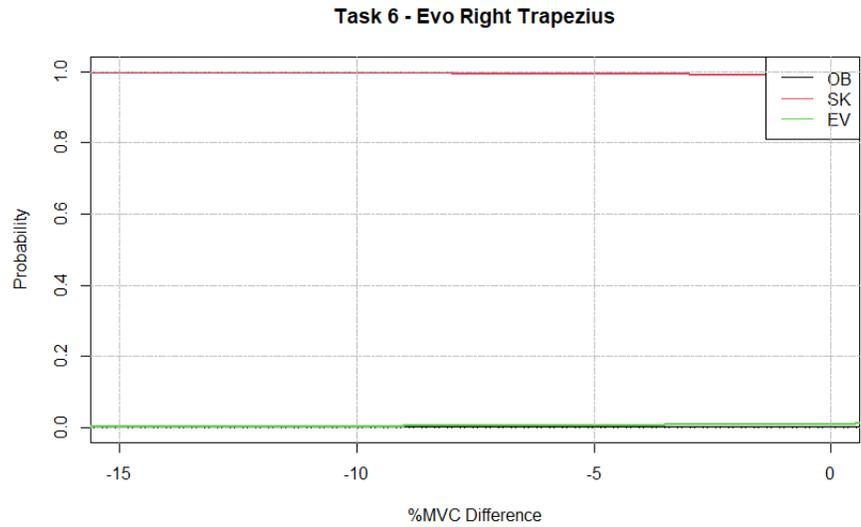


Figure 66: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Paexo Right Trapezius.

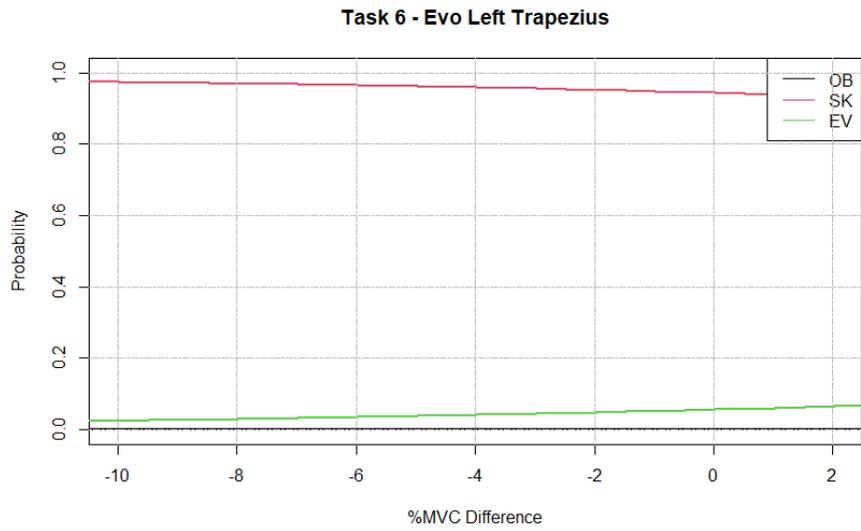


Figure 67: The probability of selecting a specific exoskeleton with respect to %MVC reduction for the Evo Left Trapezius.