The effectiveness and efficacy of exoskeletons in construction

Internship accompanying Seminar Paper

Rieke Meyer

School of Public Health University of California, Berkeley

University of Applied Sciences Upper Austria, Linz

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Abstract

Construction workers have a higher incidence of work-related musculoskeletal disorders of the shoulder than most other industry sectors. Arm support exoskeletons (ASEs) are one possibility to augment a worker's capacity to meet the high physical demands of certain tasks. Construction work is often complex and includes additional risks compared to other industry sectors: despite evidence that exoskeletons can reduce muscle activity around assisted joints, potential unintended consequences of wearing an ASE in this complex environment have not been adequately studied. The purpose of this study was to evaluate the usability and safety of three commercially available passive ASEs while users performed tasks in a simulated construction environment. Forty individuals (28 male, 12 female) completed four different tasks while using each of the ASEs. The tasks included: 1) donning and doffing; 2) maneuvering through constrained spaces; 3) ambulating on a balance beam and around cones; and 4) climbing stairs and a ladder. Wearing any of the exoskeletons significantly increased the task completion time and number of errors (contacts, snags, etc.) when maneuvering in the constrained spaces; however, there was less impact while ambulating or climbing ladders and stairs.

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1. Introduction

1.1. Background

According to the US Department of Labor the incidence and severity of work-related musculoskeletal disorders (WMSDs) were higher in construction than most other industry sectors. The most frequently impacted body regions are back and shoulders. Shoulder injuries are often severe, requiring a median of about 25 lost workdays [3]. The World Health Organization (WHO) defines musculoskeletal disorders (MSDs) as impairments in muscles, bones, joints, nerves, tendons, cartilage, spinal discs, and connective tissues leading to function and participation problems. These are often associated with pain and the loss of mobility. Worldwide, these disorders are among the most common reasons for the need of rehabilitation. Also, other diseases may co-exist or the people with MSD are at higher risk to develop other health issues [18]. MSDs are major health issues for construction workers, especially due to the many risk factors that exist [6]. The work environment and job performance, as well as whether the impairment is exacerbated or prolonged by working conditions, contribute significantly to the classification of work-related musculoskeletal disorders (WMSDs) [4]. These disorders, especially in the back, neck, and lower and upper limbs can be extremely expensive if not treated properly and in a timely manner [19]. In construction the primary cause of non-fatal injuries are WMSDs, which include sudden or continuous stresses on the musculoskeletal system. These may then impair the ability of the workers job performance and in worst case even cause permanent disability [16]. According to studies one of the main causes is overexertion [6, 17]. Overall, there are different categories of risk factors for WMSD, physical, psychosocial and individual risk factors. Physical factors include intense and awkward body movements as well as extreme body postures, vibration exposure, kneeling, contact stress, static force, environmental risk, prolonged standing, sitting, bending, twisting, carrying and lifting heavy objects. Monotonous work, an isolated working environment and pressure for a high-performance count as psychosocial factors. Individual risk factors are gender, age, anthropometry, physical activity, strength and experience. Construction workers are more susceptible to developing WMSD as the tasks require use of various body parts, constant movement in awkward positions, and repetitive and forceful use of back, shoulders, upper and lower extremities [6, 2]. Several studies have demonstrated an association between musculoskeletal disorder risk and the physical requirements of work tasks in construction. Especially muscle fatigue, discomfort, non-neutral postures and overhead work increase the risk of developing WMSDs [1, 2, 5].

An exoskeleton is a wearable device that enhances the physical capabilities of its user. Exoskeletons can be classified as “passive” or “active”. Active exoskeletons have an external power source, usually batteries and motors. Passive exoskeletons do not have an external power source; supportive forces are generated by springs or dampers storing energy from the user’s movement in the direction of gravity and releasing it during movements opposing gravity. Through augmenting a worker’s capacity, arm support exoskeletons (ASEs) have been proposed as one approach to prevent shoulder WMSDs by reducing muscle activity associated with frequent or sustained reaches, non-neutral postures, and over-shoulder work, such as many tasks required in construction. Exoskeletons are already in use for monotonous over-shoulder tasks in auto assembly, but construction work is often complex, involves varied tasks and includes additional hazards compared to other sectors [5]. Repetitive manual handling of tools and materials, often performed in non-optimal posture, and a fast pace of work in an often unstructured or unpredictable work environment increases risks in the performance of tasks. Exoskeletons offer the potential to prevent WMSDs, for example by reducing physical strain and fatigue. But the use of exoskeletons can also have negative effects. Their use can lead to riskier working postures to take advantage of the device’s support, which in turn can have negative impact on other parts of the body. The expected benefits of exoskeleton adaption and use in construction include an increased productivity through the ability to perform tasks more effectively and easily, and a decrease of musculoskeletal disorders. There may also be an opportunity to use exoskeletons as a support for people with physical disabilities or injuries to continue working. On the other side there are still perceived barriers and uncertainties, which can be divided into three groups: usability (i.e., comfort, device weight, easy to use), safety (i.e., falls, false sense of safety) and exoskeleton technologies (i.e., effectiveness, awareness). In order to advance the possible use of exoskeletons in constructions, it is necessary to evaluate short- and long-term consequences of exoskeleton technologies with regard to health and safety, work performance, usability and acceptance. The determination of the task or job specific advantages and limitations of an exoskeleton must be considered. Altogether, this should lead to the development of training areas for the use of exoskeletons [13].

1.2. Reason and goals of study

As previously described the incidence and severity of WMSD of the shoulder are higher in construction than most other industry sectors. To minimize the medical problems, the idea is to support and enhance a person's physical activity by a certain selection of exoskeletons through mechanical interaction with the body, as studies have shown an association between WMSD risk and physical requirements of different tasks at work [1, 6, 17]. Arm support exoskeletons (ASEs) have been proposed as one approach to augment a worker's capacity to meet the high physical demands of a task, as well as to prevent shoulder WMSDs by reducing muscle activity associated with especially with over-shoulder work and non-neutral postures, such as many tasks required in construction. Though studies have shown that the use of exoskeletons reduce some muscle activity around the assisted joints, the unintended consequences of wearing an ASE have not been adequately studied. An exoskeleton is a wearable device that enhances the physical capabilities of its user. Passive exoskeletons, which do not have an external power source like active ones, have springs or dampers storing energy from the user's movement in the direction of gravity and releasing it during movements opposing gravity to generate supportive forces. Exoskeletons are already in use for monotonous over-shoulder tasks in auto assembly and other industries. Construction work is often complex, involves varied tasks and includes additional hazards. Although reducing muscle activity and fatigue to prevent WMSDs may be a benefit of exoskeleton use, there may be potential unintended safety consequences including snags, trips or falls. Therefore, the purpose of the study was to investigate the usability and safety of three different commercially available passive ASEs while donning and doffing the devices, maneuvering in constrained spaces, and while ambulating and climbing stairs and a ladder.

The study includes using a within-subject full-factorial laboratory-based study including 40 participants, where half of them were experienced construction workers, to assess the usability and safety of three passive ASEs for different tasks. The effects of the exoskeletons during simulation of construction environments need to be varied for example in space and posture to determine the impact on performance, usability and physical demands. The goals of the study can be divided in three aims. The first aim is to explore the exoskeletons regarding the safety and usability of the exoskeletons in constructions activities when they are engaged versus unengaged and wearing no exoskeleton. The second aim compares the different types of exoskeletons to one another and to wearing no exoskeleton while again looking into the various tasks. The last aim is a comparison within exoskeletons for a sensitivity analysis. Therefore, the question is answered if there is a difference when a certain exoskeleton is on versus off using a pairwise comparison.

The results can then be used to make statements about the usability regarding the ease of use, comfort and physical effort during the tasks, as well as the safety including risks of certain predefined errors and sense of safety. A self-reported survey is used, and the questions can be categorized in four categories: 1) usability; 2) comfort; 3) preference and 4) system usability scale (SUS), which is predefined questionnaire for measuring the usability. After analyzing the collected video data and the survey data the results can be compared with each other for a better understanding and evaluation of the usability of the exoskeletons in construction. The analysis of the projection photos supports the evaluation. These are photos taken in different positions to study the influence of the exoskeleton on the extension of the body dimensions regarding their design and profile.

2. Methods

2.1. Participants and study design

Forty participants were included in this within-subjects, full-factorial laboratory-based study. Half of the participants were experienced construction workers. All were over 18 years (18-67), 28 (70%) of which were male. Participants with prior chronic pain at shoulder or back were excluded. Participants had a mean (SD) height of 175.5 (9.8) centimeters, mass of 78.1 (13.05) kilograms, and BMI of 25.4 (3.9) kg/m^2. Written informed consent was obtained prior to starting the study, and the study protocol was approved by the Institutional Review Board of University of California, San Francisco. The independent variables were the exoskeletons. There were six different testing conditions for all tasks. A repeated measures design was used in which participants completed six trials of the obstacle course.

2.2. Independent variables

2.2.1. Exoskeletons

An exoskeleton is a wearable device, which contains various joints and links. The goal of using an exoskeleton is to enhance the physical capabilities of its user. Exoskeletons can be classified as “active” or “passive”. Active exoskeletons use external power sources, usually batteries and motors, that require external re-charging. These exoskeletons are mostly used in therapeutic applications for example in hospitals. Passive exoskeletons do not have an external power source; supportive forces are generated by springs or dampers storing energy from the user’s movement in the direction of gravity and releasing it during movements opposing gravity. The usage of passive exoskeletons is usually divided in military and civil or industrial usage. The industrial exoskeletons can support particular sports or can be used for sitting, so-called mobile chair exoskeletons. Different types of mobile chair are often used in assembly lines. The last two types are back and arm support exoskeletons. Back support exoskeletons are for supporting the lower back during daily work with heavy objects. To support arm strength and skill arm support exoskeletons have been developed. These are used especially in auto assembly [11].

For the study three different passive arm support exoskeletons (ASEs) from three companies (SuitX, Ottobock, EksoBionics) have been investigated. These ASEs were selected to represent diverse design approaches among current commercially available systems.

2.2.1.1. V3 shoulderX

Figure 1: Arm support exoskeleton V3 shoulderX (SuitX) [12].

The V3 shoulderX (SuitX) (Figure 1) is a passive shoulder support exoskeleton with an On- and Off-state. It weighs 3.17 kg and no batteries required for the use. As a support for the corresponding shoulder joint, the load of the raised arms is transferred to the hip. The arms are held by arm shells with skin-friendly material. By lifting the arms up the support increases and decreases by lowering them, to allow to reach for tools without working against the exoskeleton and to rest the arms in different positions. This support is adjustable. The exoskeleton frame fits most people and is featured with adjustable height, waist, shoulder and arm size [12]. In a study it has been shown that the exoskeleton reduces muscle activity during static and repetitive overhead task while using light and also heavier tools [15].

2.2.1.2. Ottobock Paexo Shoulder

Figure 2: Arm support exoskeleton Ottobock Paexo Shoulder (Ottobock).

The Ottobock Paexo Shoulder (Ottobock) (Figure 2) with permanent On-state is used for relieving the shoulder joint and upper arms. The exoskeleton weighs 1.9 kg and does not need any energy supply. It is designed for supporting people while carrying out a physically challenging task with raised arms. If the exoskeleton is fitted well on the user, according to the biomechanical principals the joint at the shoulder should mimic the movement of the user's body. The level of support can be adjusted according to the user's need. To support the weight of the arm, arm shells are used with a skin-friendly material. At the hip, ball joints are used for a free movement of the upper body. The transfer from the shoulder and arm to the hip is done via a passive actuator, the exoskeleton is fixed with a pelvic belt [10]. Support torque is an adjustable percentage of the arm weight. The reduction in shoulder muscle activity is followed by an increase in endurance and task productivity as well as a decrease in physical workload of the shoulder [8].

2.2.1.3. EksoBionics EVO

Figure 3: Arm support exoskeleton EksoBionics EVO (Evo) [7].

The EksoBionics EVO (Evo) (Figure 3) is spring-loaded and also a passive shoulder-support exoskeleton with an On- and Off-state. The company claims as benefits that the user's torso, arms and waist can move without restriction, so that there is an increased range of motion. It should also reduce the worker's fatigue, increase productivity, improve health and endurance, prevent injuries at the workplace especially, shoulder injuries, elevate worker moral and retention as well as enhance workmanship and output in real time. The device does not require batteries and weighs about 4.2 kg [7]. The exoskeleton transfers the weight of the arms from shoulder, neck and upper body to hip and body center to reduce physical stress and prevent injuries during special task, for example overhead work. It has different ranges of sizes and power to accommodate needs and to reduce the user's fatigue by supporting strength and persistence. The user should become more efficient and suffer less often from injuries. The company promises 5 to 15 pounds of lift assistance and by lifting the arm up the 15 pounds (6.8 kg) assistance should be reached in a height range of 152.4 cm to 193.04 cm [14].

Overall, there were six testing conditions for each participant, including Ottobock, SuitX (on and off), Evo (on and off) and no exoskeleton. The order of the six testing conditions was fully randomized.

The *On* level of support was set to provide support sufficient to "float" the participants' arms while in 90° of flexion at the shoulders and elbows. The order of the six testing conditions was fully randomized.

2.3. Dependent variables

The dependent variables of this study included time completing each task and the number of errors while performing the tasks. GoPro Cameras were used to record the participants going through the prepared obstacle course. This video data was used to calculate the time required to complete each task and the number of errors while performing each task. Multimedia Video Task Analysis® (University of Wisconsin, Madison, IL) was used to analyze the collected data. The errors for the analysis were predefined. Errors included body contacts with fixed objects, by the head, hands, lower body and upper body, exoskeleton contacts, snags, trips and rebalance in the tasks.

Additional dependent variables of interest perceived safety and usability while performing each task. Self-reported sense of safety and balance, physical effort, and exoskeleton interference was evaluated using 0 to 10 scales. Participants also answered questions of the system usability scale (SUS) to obtain a global overview of their subjective evaluation of usability. An overall opinion of each exoskeleton, including an overall grading of the ASEs was also asked, called user-friendliness.

2.4. Test protocol

2.4.1. Fitting process

The passive arm support exoskeletons used in this study have different linked segments combined with a passive energy storage device for accommodating a wide range of users. For all ASEs diverse adjustments can be made to set the fit and level of support. To have a good fit of the ASE it is important that the disturbance with the range of motion of the user is as minimal as possible and the load of the arms is transferred to the hips. To obtain these goals it is required to have unique adjustments for each ASE in combination with the anthropometry of each participant. Therefore, each participant of the study provided height, weight, and sex in advance, so that the settings for the exoskeletons could be predicted and the ASEs adjusted. This data is inserted in a prepared excel file, which calculates the different needed settings for each exoskeleton using the population coefficients derived from ANSURII data and Plagenhoef et al. (1983). For preparing the Evo exoskeleton four different values beside the level of support are needed. These are the shoulder breadth (inner or outer), spine length (range from 1 to 10), arm cup size (S, M, L, XL) and waist (range from 1 to 10). The SuitX requests three different values, which are shoulder breadth (range from 1 to 4 by 1.25"/ 3.175 cm), spine length (range from 1 to 8 by 1" / 2.54 cm) and arm length (range from 1 to 7 by 0.5" / 1.27 cm). The Ottobock requires only two other values in addition to the level of support. These are the hip width (range from 1 to 10 by 0.5" / 1.27 cm) and spine length (range from 0 to 5 constant). For calculating the level of support a similar approach was used to predict the participants full support for the arm in 90 degrees of shoulder and elbow flexion. This position is the so-called "floating" and was later used during the fitting process as "float" test to assess the level of support. The exoskeletons are tried on by the participant before the donning and doffing part (this describes the putting on and taking off of the exoskeleton) to evaluate the fitting process. Important is that the waist belt is sitting on the anterior superior iliac spine. During this process, attention is also paid to certain fitting characteristics, related to the spine length and the position of the arm cups, which are different for the exoskeletons. The Evo has to be positioned at 60 % of the arm from shoulder to elbow, the SuitX at 70 % and the Ottobock at 80 % to give the user the full amount of support with the exoskeleton in the "float" position.

2.4.2. Procedures

After initial familiarization and training, the participants donned/doffed the exoskeleton (first part of the study, described in the flow chart in Figure 4). Subsequently, participants walked through an obstacle course (second part of the study, described in the flow chart in Figure 5) with different constraints designed to evaluate maneuvering in a constrained space. Specifically, the constrained space task consisted of stepping through a narrow aperture (86 cm diameter), walking through a 50 cm wide and 244 cm long passage way, then bending over and walking under a scaffolding (150 cm height and 179 cm long, area of exit left 56 cm long, right 72 cm) into a standard frame-only construction with open floor joists (244 cm long with a 37 cm opening). The third "ambulation" task required participants to walk on a narrow beam (10 cm wide and 274 cm long) then around cones (outside distance 190 cm) in a figure-eight pattern. The fourth task required the participants to climb up and down stairs (five steps) and a ladder (244 cm height, last step for participants 4th step at a height of 117 cm).

Each task was repeated three times except for the figure-eight task which was repeated six times.

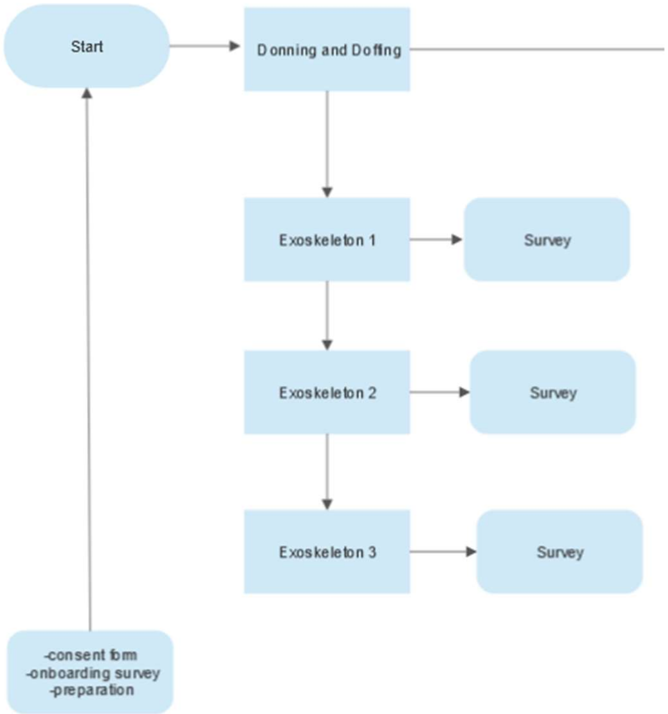

Figure 4: First part of the study. Participants had to don and doff each exoskeleton three times after practice. After completing the task, a self-reported survey was filled out.

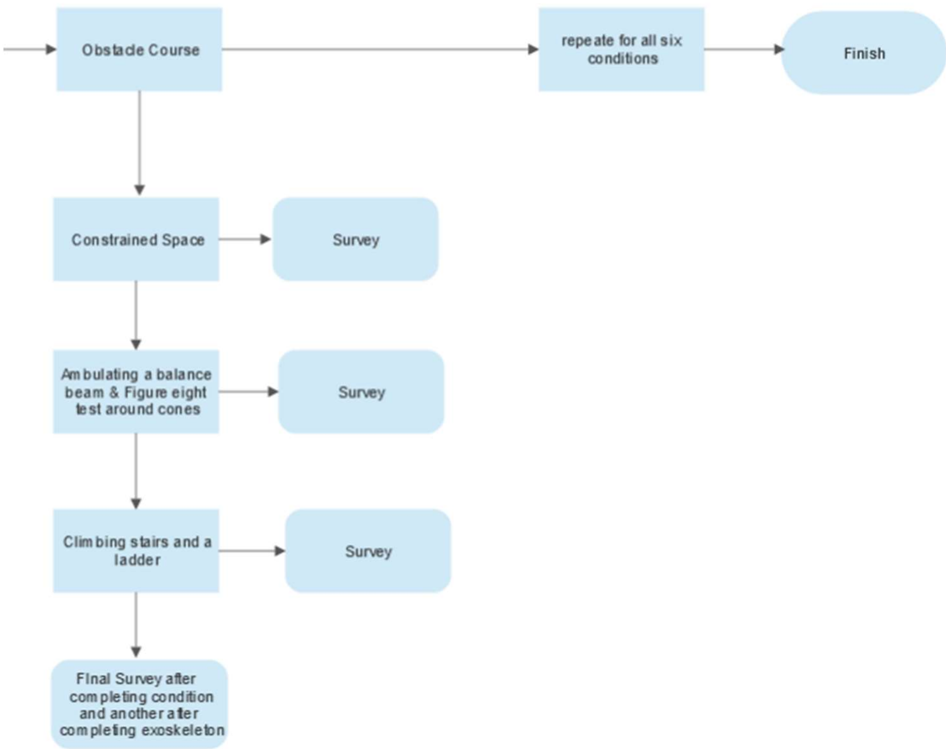

Figure 5: Second part of the study, obstacle course. After each task per condition, the participants filled out a self-reported survey and another survey in the end after completing the conditions to give an overall opinion of each exoskeleton including an overall grading of the exoskeletons.

After completing all tasks in all different exoskeleton conditions, participants completed a final survey regarding their overall opinion of each exoskeleton including an overall grading of the exoskeleton with letters (A to F) where A grades received five points and F grades received one point. The mean of scores across subjects was obtained as an exoskeletons overall rating.

The different survey questions can be categorized in four categories, which are: 1) usability; 2) comfort; 3) preference and 4) System Usability Scale (SUS). The usability includes intense of the physical effort, exoskeleton interference, feeling of restriction in movements, feeling of balance and safety. Category comfort contains questions to general discomfort and specified to the upper body regions, comfort in wearing and pressure on body. If the exoskeleton stayed in position, how likely the participant would use it and recommend it, as well as overall feeling towards the exoskeleton are collected in the category preference. The SUS is a predefined questionnaire that provides an overview of the subjective evaluation of usability. Thereby it is using the aspects effectiveness, satisfaction, and efficiency.

Table 1: Procedures summary.

Task description	Task number	Used conditions	Collected data
Donning / Doffing	-	Ottobock, SuitX, Evo	Time, Survey
Constrained Space	Task 1A	Ottobock, SuitX (On, Off), Evo (On, Off), No Exo	Time, Error, Survey
Frame Construction	Task 1B	Ottobock, SuitX (On, Off), Evo (On, Off), No Exo	Time, Error, Survey

Balance Beam	Task 2A	Ottobock, SuitX (On, Off), Evo (On, Off), No Exo	Time, Error, Survey
Figure-eight around cones	Task 2B	Ottobock, SuitX (On, Off), Evo (On, Off), No Exo	Time, Survey
Climbing stairs	Task 3A	Ottobock, SuitX (On, Off), Evo (On, Off), No Exo	Time, Survey
Climbing a ladder	Task 3B	Ottobock, SuitX (On, Off), Evo (On, Off), No Exo	Time, Survey

2.5. Data analysis protocol

2.5.1. Multimedia Video Task Analysis®

For the video analysis the program Multimedia Video Task Analysis® (MVTA) is used. It was developed by Dr. Robert G. Radwin and Dr. Thomas Yen at the University of Wisconsin-Madison, cooperating with government consortium members and industry. The video is loaded into the program and then it can be analyzed. The program helps in the analysis of time and motion of activities. Different events can be identified with breakpoints, meaning the start- and endpoint. These events are defined for different records to split up the analysis. In this case the records task, error and condition were used. It is possible to analyze at any speed and also frame by frame. After the creation of the events the program can be used for time study reports, computing frequency of occurrence of each event and for postural analysis. Different interactions between the records can be done to then perform reports. There are four different types of reports: frequency report, raw time reports, duration report and time study report. For this research the time study report was used to analyze the data. This report gives information on the number of times an event has occurred and using the detailed time study it provides the information on the duration of event elements [9].

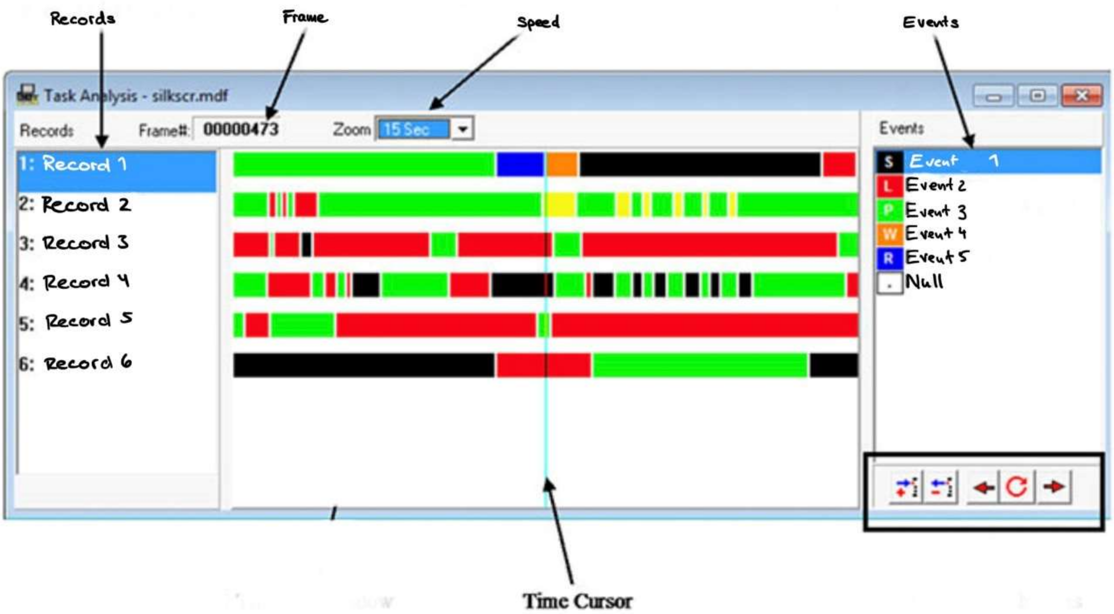

Figure 6: Multimedia Video Task Analysis (MVTA) example with left the records, in the middle the video timeline which is being analyzed and the start- and endpoints of the events are set in different colors. On the right side the events can be seen [9].

2.5.2. Video analysis

To analyze the collected data, the single videos of the different tasks are edited together in one video for each subject, using Adobe Premier Pro 2022. The analysis program MVTA can be only used for 99 events and the NULL, everything with more events will cause errors in the result data. This error occurred during the start of the analysis. To bypass this problem the solution is to analyze the tasks separately. This means that there are seven different analyses and their results. Templates were created to perform all analyses for each task 1A through 3B, including donning and doffing as one separate task. In each template there are records for task, condition, and error.

Table 2: Structure of the templates for the MVTA analysis.

Task	**Donning / Doffing**	**1A**	**1B**	**2A**	**2B**	**3A**	**3B**
Records	Task Condition	Task Condition Error	Task Condition Error	Task Condition Error	Task Condition	Task Condition	Task Condition
Events							
Task	Donning Doffing NULL	1A NULL	1B NULL	2A NULL	2B NULL	3A NULL	3B NULL
Condition	SuitX Evo Ottobock NULL	SuitX ON SuitX OFF Evo ON Evo OFF Ottobock No Exoskeleton NULL	SuitX ON SuitX OFF Evo ON Evo OFF Ottobock No Exoskeleton NULL	SuitX ON SuitX OFF Evo ON Evo OFF Ottobock No Exoskeleton NULL	SuitX ON SuitX OFF Evo ON Evo OFF Ottobock No Exoskeleton NULL	SuitX ON SuitX OFF Evo ON Evo OFF Ottobock No Exoskeleton NULL	SuitX ON SuitX OFF Evo ON Evo OFF Ottobock No Exoskeleton NULL
Error		Hand contact light and heavy Head contact light and heavy Exo contact light and heavy Rebalance Trip Lower body contact Upper body contact Snag NULL	Hand contact light and heavy Head contact light and heavy Exo contact light and heavy Rebalance Trip Lower body contact Upper body contact Snag NULL	Hand contact light and heavy Head contact light and heavy Exo contact light and heavy Rebalance Trip Lower body contact Upper body contact Snag NULL			

The task record shows as related event the selected task, for example donning, doffing and Null or 1A and Null. Eleven different errors and the Null can be found in the related events of the error record. These errors are Hand contact light and heavy, Head contact light and heavy, Exo contact light and heavy, Rebalance, Trip, Lower body contact, Upper body contact and Snag. The last record is the condition record, and it has as related events the different exoskeletons in their condition. That means there are Ottobock, SuitX On-State and Off-State, Evo On-State and Off-State and No Exoskeleton. The conditions are set for the total video to avoid any errors in the interactions.

Starting the donning and doffing analysis, it is important for the timing to start the event at a similar starting point. This was chosen for the donning as the first contact with the ASE and it ends with the arms up in 90-degree flexion in shoulder and 90-degree flexion in elbow with the wrists normally neutral. The doffing starts by the first movement in direction to start the process of taking the exoskeleton off and it ends by losing the contact to it.

Task 1A (constrained space) starts in the first movement in the obstacle course and it ends in the movement when the participant leaves an imaginary plane between the scaffolding and the wall. This frame is then the start for task 1B (frame construction), which ends when the participant stands back on the starting cross for 1A, with both feet next to each other.

The first movement to start at the balance beam starts the task 2A (balance beam) and is changed to a Null event when the participant is stepping down from the beam with both feet. Task 2A starts again with the participant's first movement to the balance beam, so Task 2A should be performed three times for each condition.

In the analysis of task 2B (figure eight around cones), the starting point is as soon as the participant makes the first movement walking an eight. After completing an eight a Null event is inserted with two frames for separating the different eights. In the end, six figure eights should be performed in each condition in task 2B.

Task 3A (stairs) starts with the first move to get on the stairs and is changed to a Null event when the participant has both feet back on the ground. The first move to get back on the stairs start task 3A again. It follows that there should be three times task 3A for each condition.

Contact with the hands on the ladder or a movement of the legs towards the ladder starts task 3B (ladder). Letting loose of it or standing on both feet in front of the ladder is a Null event until task 3B starts again which means there are supposed to be three times task 3B in each condition.

To fit the errors, it is important that only unplanned contact counts. Listening to the audio helps to identify the strength of an error and to separate it in light or heavy. If there is an accidental hand contact, an error with the intensity of this contact has to be added. Not included are the contacts at the wall of the frame and the ladder, because the participant is supposed to touch the wall and hold on to the ladder while climbing. Contacts of the helmet with the environment count as head contact and the audio is used to identify the intensity of the error. Exoskeleton contacts include any contacts of the exoskeleton with any obstacle and the intensity is decided with the audio. If the participant falls or steps down from the balance beam or in the frame construction, these errors count as trip. Also, hand contacts with the scaffold during the balance beam are counted as trip. Contacts of the lower body are lower body contact errors. If the participant has contact with the whole upper body and it is hard to specify the exact point of contact, the error is characterized as an upper body contact. The snag is selected if the exoskeleton gets stuck in the obstacle course and the participant has to change the direction of the movement. After the analysis, these different records are combined with each other to get the results from the data collection. Therefore, a time report is used.

2.5.3. MVTA data overview

The data obtained by MVTA for the participants are first pre-analyzed with MATLAB R2021 b for a first overview. Therefore, the output data for each participant is summarized in one excel workbook. This contains the mean time for donning and doffing of each ASE, which is received by an interaction between the task and condition record in the don/doff analysis. It also contains the mean time the participant needed to complete each task, for the tasks 1A through 3B. In the program MVTA, the times for each circle are separated through setting the start and endpoint, so afterwards the mean can be calculated. Additionally, the sheets for task 1A, 1B and 2A also include the number of errors per task in total and the separation of the number of errors per condition. The interaction of task and error gives the total number of errors in the task. The following interaction of that record with the conditions separates the errors into the different conditions.

The mean times for all participants in donning and doffing per condition were calculated in MATLAB, the results are shown in Figure 7. It shows that the donning overall takes longer than the doffing, independent from the ASEs. In both tasks the Evo is the ASE where the participants need the most time for donning and doffing. The Ottobock and SuitX have a similar donning time, with the Ottobock being a little bit slower overall. On average the participants were slower in doffing the Ottobock than the SuitX.

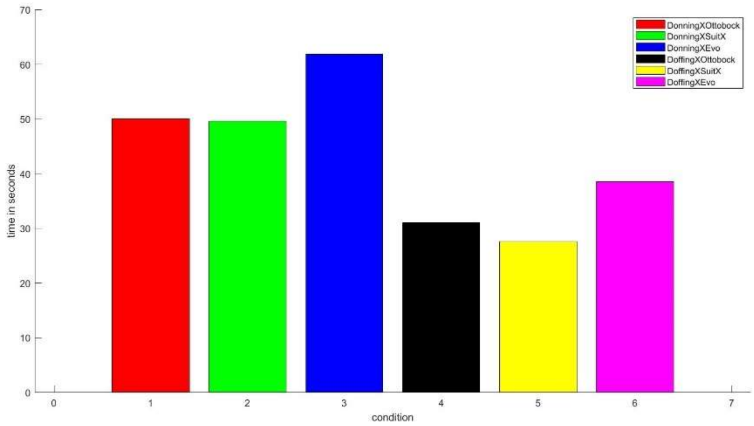

Figure 7: Donning (Ottobock, SuitX, Evo) and Doffing (Ottobock, SuitX, Evo) of ASEs.

Comparing the times, it took the participants to complete task 1A again, the mean times from all participants were added up and the mean of the population was found. The result (Figure 8) was that while there is a difference between each exoskeleton and no exoskeleton, there is not much difference between the two exoskeletons with different states in terms of On- or Off-State. The participants were slightly slower wearing the SuitX in the On-State in task 1A, than wearing it in the Off-State. For the Evo, which also has an On- and Off-State, it was the other way around as the participants were a little slower wearing the exoskeleton in the Off-State. But overall, they were faster than with the SuitX. Going through the obstacle course wearing the Ottobock, the participants were in total faster than with the other exoskeletons, although there was only a small difference to the Evo. The round of task 1A of performing the task without an exoskeleton was clearly the fastest among the participants.

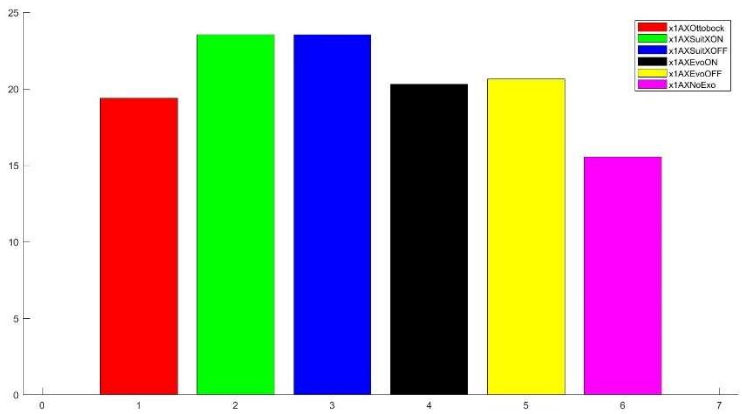

Figure 8: Comparing the mean times of duration in task 1A, this is the first part of the constrained space (Ottobock, SuitX ON, SuitX OFF, Evo ON, Evo OFF, No Exoskeleton).

To analyze the time duration in each condition and to compare them for task 1B, the mean of the population was found and shown in Figure 9. In this task the means for all the conditions were very similar and only the round of task 1B without any exoskeleton was clearly faster.

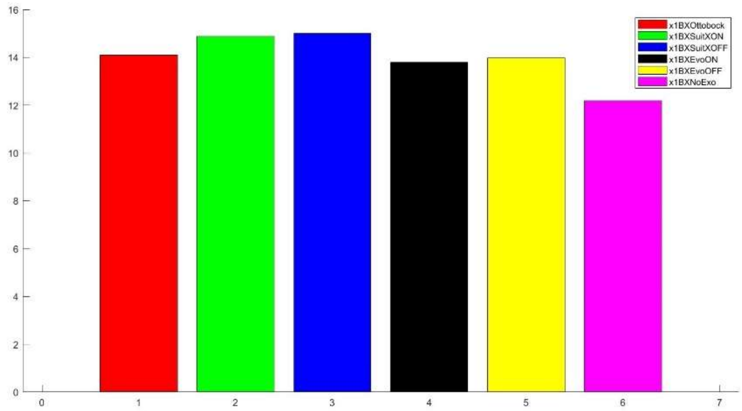

Figure 9: Comparing the mean times of duration in task 1B, second part of the constrained space, this is the frame construction (Ottobock, SuitX ON, SuitX OFF, Evo ON, Evo OFF, No Exoskeleton).

Task 2A, which was going over a balance beam, showed no obvious difference in the mean time for the participants for all six conditions (Figure 10). The SuitX in Off-State was a condition, where the participants were overall a little slower, but it is not a distinct deviation from the others.

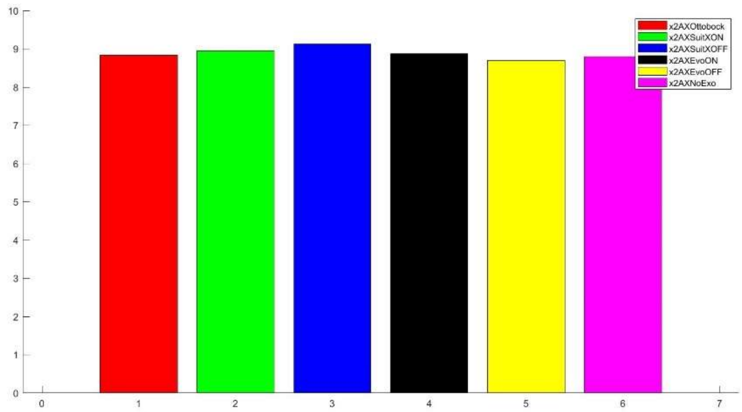

Figure 10: Comparing the mean times of duration in task 2A, the balance beam (Ottobock, SuitX On, SuitX OFF, Evo ON, Evo OFF, No Exoskeleton).

Analyzing the mean times of the population walking eights around cones (task 2B) shows very similar times for all different conditions. The participants were just slightly slower with both SuitX conditions, but not significantly. This is shown in Figure 11.

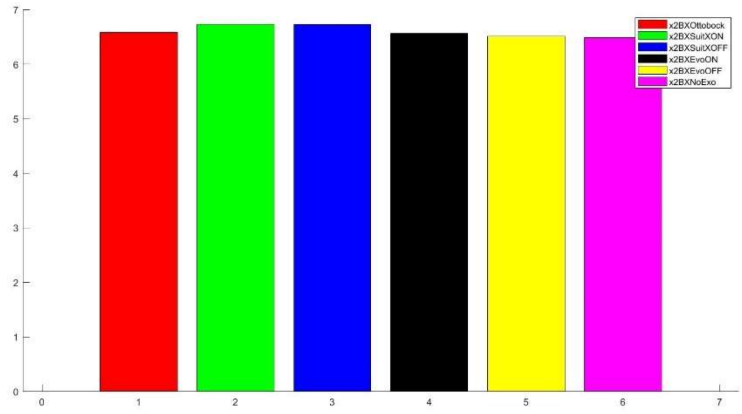

Figure 11: Comparing the mean times of duration in task 2B, walking in a figure-eight pattern (Ottobock, SuitX ON, SuitX OFF, Evo ON, Evo OFF, No Exoskeleton).

The mean time which was found for task 3A in the different conditions, pointed out that the participants were slightly faster with no ASE and the slowest with the SuitX in the Off-State (Figure 12). The other conditions are all in a similar range in between.

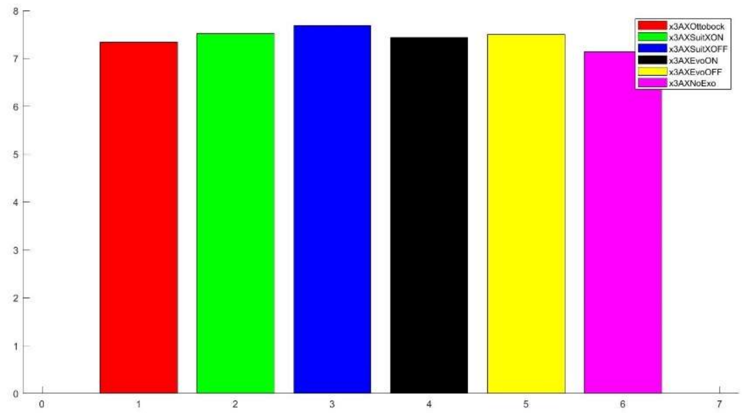

Figure 12: Comparing the mean times of duration in task 3A, walking the stairs up and down (Ottobock, SuitX ON, SuitX OFF, Evo ON, Evo OFF, No Exoskeleton).

To compare the different conditions in task 3B again the mean times from each participant were added up and the mean of the population was calculated with MATLAB. The participants were the fastest on the ladder with no exoskeleton and the Evo in Off-State, this is shown in Figure 13. They were slightly slower wearing the SuitX in the Off-State. The mean time increased further from the Evo in the On-State to the SuitX in the On-State to the Ottobock, which was the slowest in this task.

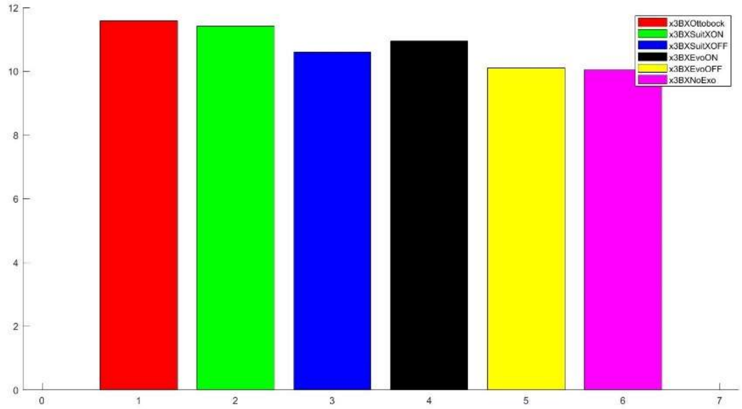

Figure 13: Comparing the mean times of duration in task 3B, climbing the ladder (Ottobock, SuitX ON, SuitX OFF, Evo ON, Evo OFF, No Exoskeleton).

For further statistical and error analysis the data of each participant has been brought together in one long excel file.

2.5.4. Projection photos

Figure 14: Anterior view and lateral view with arms in relaxed position wearing all three ASEs.

All exoskeletons additionally extend the body dimensions of the user in height from the shoulders, aside and backwards. The influence of the individually increased size of the body on mobility and possible consequences is important especially with regard to constrained spaces. Analyzes of the projections can be used to see if there are correlations between the sizes of the exoskeletons, the times required to complete the different tasks in the obstacle course and the number of errors per exoskeleton.

After checking the fit of the current exoskeleton in general, as described in the fitting process of the ASEs, the participants were asked to position themselves in different predefined positions in order to photograph them. These images are used to investigate the different design approaches of the used exoskeletons in relation to the participant's body, a predefined scale, and different anatomical landmarks. The positions were anterior view, lateral view with the arms in three different positions, the back view and the so-called inspection position. As a reference the pictures were not only taken for each ASE, but also without any exoskeleton. For the analysis the positions anterior and lateral view with arms hanging down next to the body were analyzed with Adobe Photoshop 2023. For one participant the used views can be seen in Figure 14. For simplifying the analysis, the size of the pixels per centimeter is set in the beginning according to the scale of the measuring tape seen in the picture. Thereafter 1533 pixel correspond to a logical length of 122 cm. This same setting can be used as the camera was positioned on the same mark, as well as the settings in the camera were constant during all data collection.

For body reference on the anterior view the landmark on the shoulder corner is used. Due to the fact that the participants are wearing clothes, there will be precision errors in the choice of these errors. A horizontal line is the drawn through the highest points of the exoskeleton for the condition without ASE. Likewise, vertical lines are inserted on the outermost points on the sides (left and right). It is important that no soft straps of the exoskeletons are used as reference points. The measurements were taken from the shoulder landmark to a horizontal line on each side and to vertical lines on each side. In addition, different body dimensions are measured in the picture without any exoskeleton and in all images with different ASEs. These are measurements from elbow to elbow, shoulder distances and hip distances. All measurements together give an impression on the influence of the different exoskeletons on changes in posture and body size.

For the lateral view the body reference landmarks will be set at the left ear and on top of the head. The vertical line is then drawn through the so-called marionette line of the body. To compare the extend the different ASEs give, the distance from this line to the furthest hard, not soft exoskeleton point is determined. In order to have a reference for comparing the different measurements of all ASEs, measurements must also be taken on the picture without any exoskeleton. From the marionette line to the furthest body point.

The analysis of the photos is still in process.

3. Statistical analysis

All data was tested for normality. A one-way repeated ANOVA was used to determine if there were differences in the mean times and errors in each task. Differences in survey responses across conditions were analyzed using Friedman non-parametric tests. Statistical significance was determined using a p-value of <0.05. Statistical analysis is not yet completed.

3.1. Stata

For statistical analysis the statistical software Stata 17 was used, developed by StataCorp. Stata is written in C. The software is usually used for statistics, data manipulation and visualization. To use the in MVTA generated data of mean times and number of errors, the data has to be sorted by ID in a long file. This is done with a python code with a data frame to avoid errors. The missing subjects 9, 30 and 34 are skipped to keep the participant IDs to verify the code.

3.2. Analysis of time

A first analysis of the time is done by importing the in MVTA generated data and labeling the variables. As there is missing data in reported data, it has to be replaced by a period, to avoid errors in Stata. In MVTA analysis the different tasks had to be analyzed separately, as it was not possible to have more than 99 interactions additionally to the NULL. For each combination of tasks, the detected mean times had to be added together by sorting the data by ID and condition and then generating a new variable. Combinations are: 1) donning and doffing; 2) constrained space (task 1A and task 1B); 3) balance (task 2A and task 2B) and 4) stairs (task 3A and task 3B). Mean, standard deviation, and standard error gave a first information about the statistics for the mean time in the tasks. Afterwards a repeated ANOVA was performed, followed by a Tukey's post hoc test.

3.3. Analysis of number of errors

For the statistical analysis of the number of errors in the performed tasks the in MVTA generated data was imported into Stata and the variables were labeled. As there was data missing all error rows needed to be converted from string to numeric to avoid error messages in Stata. For performing a repeated ANOVA, followed by a Tukey's post hoc test, all errors had to be summed up. This was done by generating a new column calculating a row total of the error columns for the tasks where errors were collected (1A, 1B and 2A) and for the constrained space (task 1A and 1B) only. The mean, standard deviation, and standard error for the number of errors in the constrained space, task 2A (balance beam) and the combination of the three tasks were calculated. Also repeated ANOVA and Tukey's post hoc test were performed for these three columns.

3.4. Analysis of user-friendliness

The participants of the study completed a final survey regarding their overall opinion of each exoskeleton including an overall grading of the exoskeleton with letters (A to F) after finishing all tasks with the respective ASE. For the analysis the A grades received five points and F grades received one point. In the survey data, after cleaning and labeling the data, it is possible to specify the frequencies of the grades (letters A to F) specific per ASE by sorting by the type of exoskeleton. The average and the standard deviation for each ASE were then calculated to show which exoskeleton users found most user-friendly.

4. Results

4.1. Task completion time

There were statistically significant differences in completion times between exoskeleton conditions for the donning/doffing ($p<0.005$, Figure 15) and the constrained space ($p<0.005$) tasks. Completion time increased when maneuvering in the constrained space while wearing any of the exoskeletons ($p<0.005$, Figure 16) compared to not wearing an exoskeleton. There were no statistically significant differences in completion time across conditions during the ambulation task ($p<0.60$). Wearing no exoskeleton while climbing was faster than wearing any exoskeleton, though this effect only approached statistical significance ($p<0.06$).

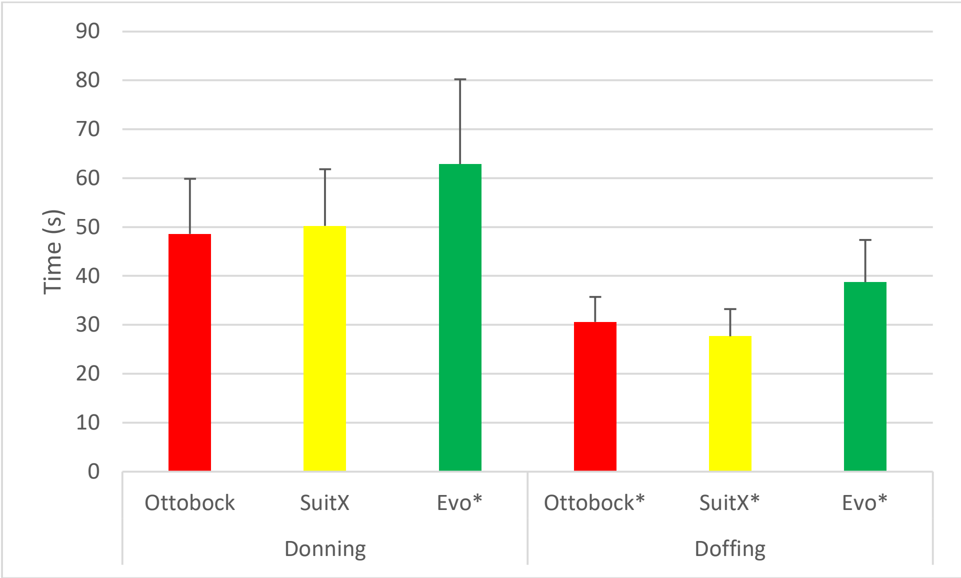

Figure 15: Mean time (seconds) for donning and doffing the exoskeleton (asterisk indicates statistical significance with p<0.05).

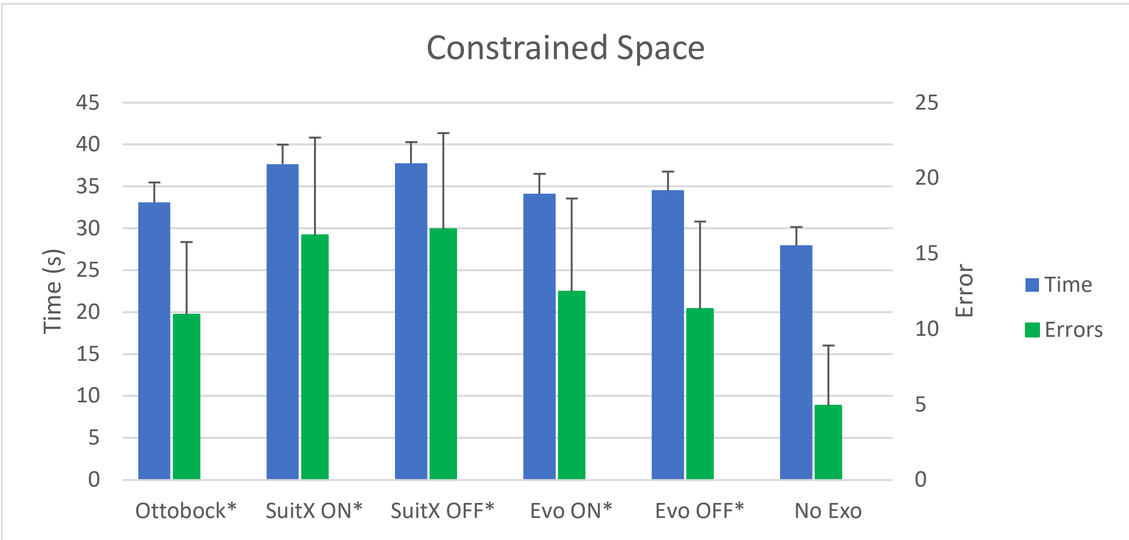

Figure 16: Mean task completion times (seconds) and number of errors in constrained space for each condition (asterisk indicates statistical significance with p<0.05).

4.2. Errors

Workers wearing any of the exoskeletons caused more errors while maneuvering in the constrained space versus wearing no exoskeleton alone ($p<0.005$, Figure 16). There were no significant effects of ASE use on errors during the ambulation task ($p<0.32$).

4.3. Survey user-friendliness

ASE user-friendliness varied between the different exoskeleton conditions and most of the results were positive (Figure 17). The SuitX (32.2 points, SD=27.6) and the Ottobock (32.2 points, SD=29.4) received the same overall exoskeleton user-friendliness score. The Evo received a slightly lower score (30.6 points, SD=29.9).

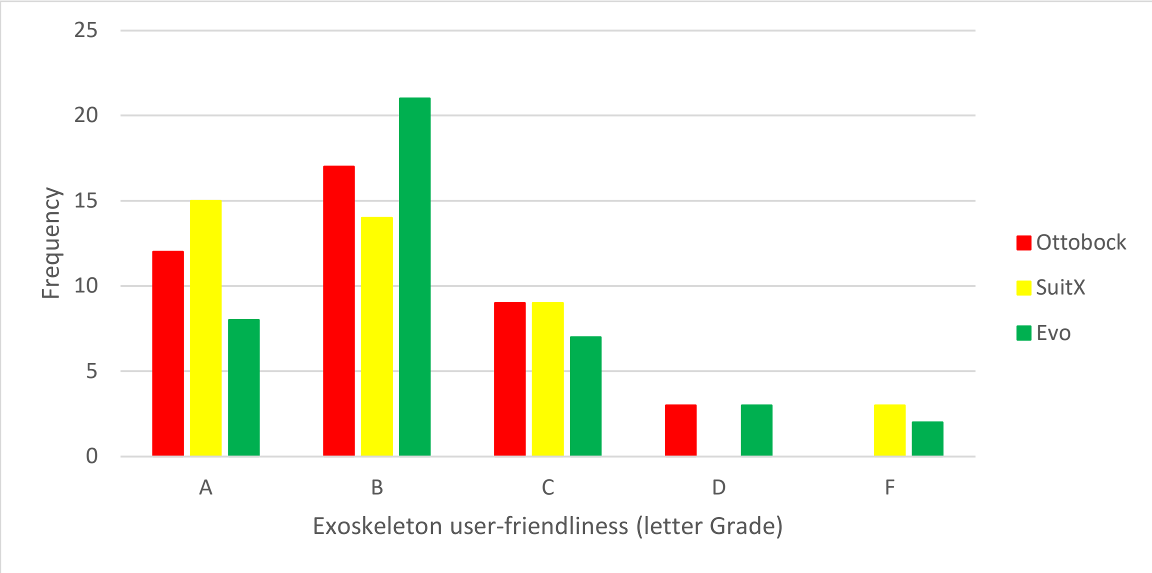

Figure 17: Exoskeleton user-friendliness across the three exoskeletons. The letters represent numeric scores (A=5, B=4, C=3, D=2, F=1).

5. Discussion

Overall, wearing any of three different ASEs had a negative impact on maneuvering in constrained spaces and climbing ladders and stairs; the ASEs had negligible impacts, in contrast, on ambulation whether turning or walking on a narrow beam. There were important differences between ASEs when maneuvering in constrained spaces as well as donning and doffing. Surprisingly, engagement of the exoskeleton in the "ON" state had little impact on the outcomes. This lack of an effect suggests that the design of the ASE, not the support torque on the arm, is the main factor impacting maneuverability.

Donning took longer than doffing for all ASEs; the time required to don and doff Ottobock and SuitX exoskeletons was similar. Participants required a mean of 14.3 seconds (22.7% of total time) and 12.6 seconds (20%) more to don the Evo than the Ottobock and SuitX, respectively. This difference is likely only important if a user were expected to don/doff an ASE multiple times throughout the day. However, doffing time is important since one may need to doff an ASE quickly if the ASE is caught on something or in an emergency. Participants required 8.1 seconds (20.9%) and 11 seconds (28.4%) more to doff the Evo versus the Ottobock and SuitX. One reason for this difference could be that the latter two ASEs have a greater resemblance to a backpack than the Evo, and thus the participants might find it easier to don/doff. More research is needed, though, to understand whether don/doff times improve with more practice.

The SuitX ASE required the most time to complete and caused the highest number of errors to move through the constrained space task, likely due to its larger profile. The Ottobock and Evo ASEs were similar, but both required more time and led to a higher number of errors while maneuvering in the constrained space versus wearing no exoskeleton. These findings indicate that caution should be used when wearing an ASE while in a constrained space or when climbing ladders or stairs, and more time may be required to perform tasks with an ASE in a constrained space or on a ladder.

Overall, the ranking of user-friendliness of the ASEs across participants showed no difference between Ottobock and SuitX in total. However, there was a difference in the distribution of the scores (Figure 17) and the Evo was rated slightly lower than the other two devices. When working in the constrained space, wearing the SuitX resulted in a slower time and more errors on average. However, this effect did not seem to have substantial negative impact on the overall ratings of the participants.

5.1. Limitations

Only three ASEs were evaluated in this study. This was a laboratory-based study with a simulated construction site environment. To gain further insight into usability and safety of ASEs for construction workers, a field study would be beneficial.

5.2. Conclusion

Overall, this study shows that wearing an ASE has adverse impact on maneuvering time and number of errors when compared to no exoskeleton in constrained spaces and while climbing, but little impact on ambulation on a narrow beam or figure-eight walking. There was minimal difference when the ASE was in on- versus off-state. This suggests that the design and profile of the exoskeleton, not the support torque, which is provided to the arm, may be more important in increasing time and errors while maneuvering in constrained spaces and climbing stairs and ladders. The further analysis of the profile picture may provide more insight and information. In the participants' overall usability ratings of the three ASEs were no major differences. The other impressions and statements from the surveys are still being evaluated.

5.3. Acknowledgement

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