THE BIOSERVO IRONHAND AS A PREVENTIVE MEASURE FOR MUSCULOSKELETAL DISORDERS OF THE UPPER EXTREMITIES

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1 Introduction

Industries with high physical demands, have been dealing with higher injury rates for years now, forcing employees to take days off from work and employers to find solutions to compensate for the missing work force. Lower back pain or Carpal tunnel syndrome are injuries that appear to have a high prevalence in the working population. Those injuries are classified as musculoskeletal disorders (MSDs). According to the Occupational Safety and Health Administration, an injury or illness is considered work-related if an exposure or event in a certain work environment caused or contributed to the resulting condition or significantly aggravated a pre-existing condition[2]. Due to the physical demands many jobs pose to employees and the risk factors that are associated with the development of MSDs; the term work-related musculoskeletal disorder has been introduced. For simplification, whenever this paper uses the term MSDs, it refers to work-related MSDs if not noted otherwise. Therefore, creating ergonomic and health preserving work environments has become a topic of interest for many employers. Work-station adjustments or exercise programs are methods used to decrease injury risks[3, 4]. Those work-related MSDs come with high cost for industry. The Bureau of Labor Statistic published, that every third day away from work in 2018 was due to MSDs[5]. According to Liberty Mutual in 2022 overexertion involving outside sources and other exertions such as awkward postures accounted for 28.67% of all costs with a total amount of 16.64 billion US dollars and therefore rank among the most common causes of workplace injuries[6]. Additionally, employees struggling with health-issues show a decrease in productivity at work [7] as well as a decrease in work quality and diminished morale [8].

Common body parts affected by such injuries include the shoulder, lower back, or wrist. An analysis of workers' compensation claims for Washington State from 2006 to 2015 done by Howard showed that of the claims related to MSDS 42.2% were for upper extremity injury[9]. The distal upper extremity involves upper arm, elbow, lower arm, wrist, hand, and fingers. On average, disorders of the hand and wrist have found to cause the longest absences from work compared to other parts of the body[5].

This brief literature review shows the relevance of addressing this problem not only for economic but also health-preserving reasons. In the following chapter MSDs will be explained further including theories for their development and potential risk factors to better understand the problem to be solved.

1.1 Musculoskeletal Disorder

The World Health Organization (WHO) defines musculoskeletal disorders (MSDs) as impairments of muscles, bones, joints, and adjacent connective tissues which compromise function and participation of those tissues. They are often unspecific, and the exact cause is hard to diagnose. Examples for MSDs include carpal tunnel syndrome, trigger finger, rotator cuff syndrome, lower back pain, tendonitis, or epicondylitis. Symptoms include stiffness, fatigue, numbness, and swelling loss of strength [8]. While it is possible for such injuries to be caused by one traumatic event like a fall causing tear of a ligament or fracture of a bone, it is way more common for such injuries to develop over time. The exact causes for their development haven't yet been fully understood. However, there are some theories that try to explain the physiological mechanisms that cause the symptoms mentioned above:

Dose-Response Model

One possible cause for their occurrence is believed to be micro traumas caused by high physical demands which, when exposed to further stress, form into scar or fibrose tissue. Armstrong et al. presented a dose-response model to explain the occurrence of MSDs. Activities performed by a person cause internal forces to act on the persons' tissue. These forces are referred to as dose. This dose causes the body to respond by means of physiological and biomechanical mechanisms. The experience of muscle fatigue or pain is one of those responses. When exposed to high physical demands, or high doses, tissues experience micro traumas as well as metabolic changes well known from the development of muscle soreness after exercising. Multiple studies in animal models have found inflammation to play a major role in tissues exposed to repetitive and/or high-force motion[10]. In case of insufficient recovery time, meaning the tissue is exposed to further stress, more dose, instead of reparation and adaption to increase the capacity to withstand stress, degenerative tissue changes take place [1]. Muscle contractions for example cause tendons to stretch and subsequently causes compression of the tendons' internal structures. At a certain level of lengthening, tendons experience severe decreased blood flow, fibrillar tearing and inflammation. Muscles on the other hand experience an increase in internal pressure during contraction, which might also cause insufficient blood flow and subsequent rupture of muscle structures. Again, with sufficient recovery time, those defects can be repaired and adapt to the level of stress they have been exposed to. Otherwise, degenerative changes take place such as formation of fibrose or scar tissue or a decrease in muscle cross-sectional area. As force generation is strongly dependent on the number of motor units recruited and the cross-sectional area of a muscle, both effects would result in a loss of strength and loss of motor function [11] as well as chronic inflammation resulting in pain. Research shows that muscles can adapt faster than tendons which poses a risk for tendons to develop degenerative tissue changes. Muscles, tendons, ligaments, and connective tissue have viscos-elastic mechanical properties that change due to tissue reorganization. As a result, those tissues are not only less efficient in their ability to generate or transmit forces but also at a higher susceptibility to experience further damage due to their reduced exposure threshold. When occurring due to work-related exposures, the same tasks would then require a higher level of force as the workers maximum strength decreases whereas the requirements of the task would remain unchanged. To prevent MSDs, inflammation and tissue changes need to be prevented.

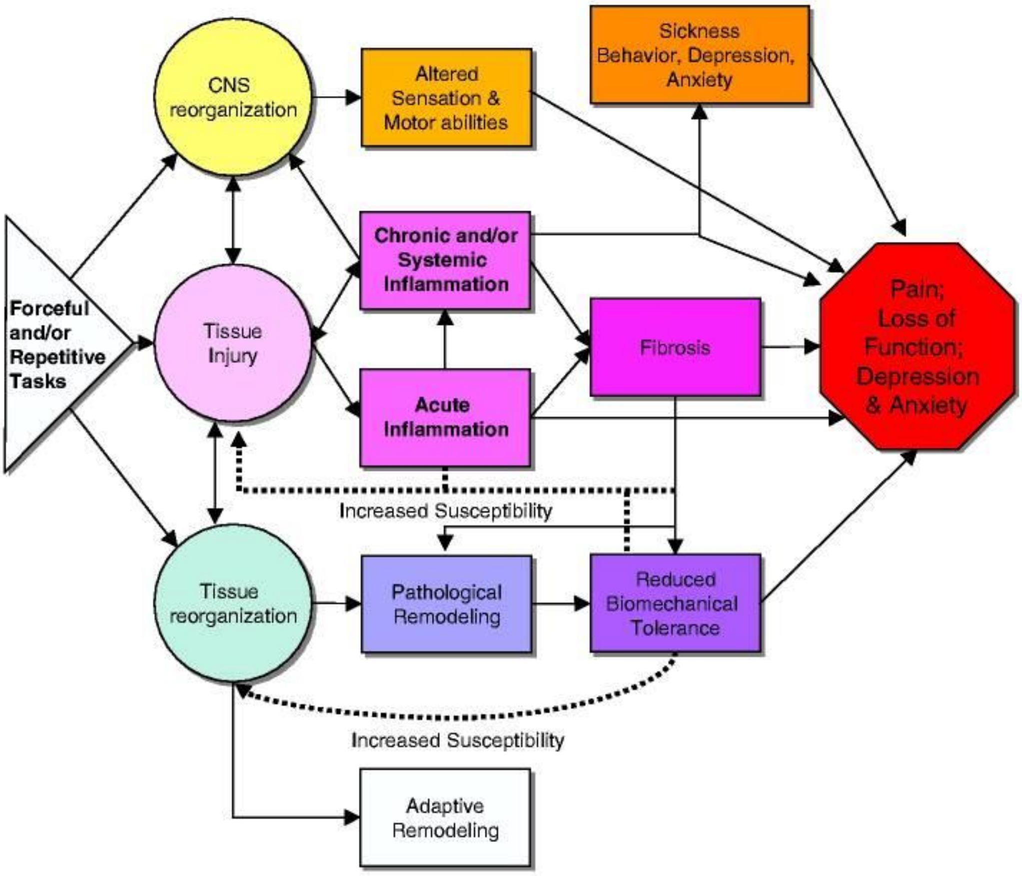

Fig. 1: Schematic for MSD causation [1]

Differential Fatigue Theory

Another theory is the so-called Differential Fatigue Theory which believes that altered muscle kinematics, in fatigued muscles, especially for repetitive and asymmetric tasks eventually lead to joint loadings which differ from the biomechanical optimum for the individual. Industrial tasks do not take the workers individual capabilities into account but loading muscles and joints disproportional. In addition, due to the repetitive nature of industrial tasks, antagonistic and anti-antagonistic muscles are often exposed to asymmetrical amounts of loading. As a short-term effect, different muscles experience different rates and levels of fatigue. More fatigued muscles have a decreased capacity to generate force compromising their ability to stabilize a joint. As the human body adjusts to the load it is exposed to, muscle disbalances develop and connective tissue changes may develop. According to this theory, this will also alter joint stability and in combination with fatigued muscles, this may cause unnatural loading patterns and even alter movement biomechanics. As the wrist is a very complex joint, to understand the relevance of this theory for wrist health, wrist anatomy needs to be understood. When studying wrist anatomy, one will learn that there is a relationship between grip and wrist activities. During hand grip, the flexor muscles in the forearm create grip strength by controlling the movements of the fore, middle, ring, and little fingers and simultaneously the extensor muscles in the forearm work to straighten the wrist. Studies have shown that wrist flexion strength is increased with increasing grip force proving the interaction. As the finger flexor tendons are located on the same side as the wrist flexor tendons, a contraction of the finger flexors creates a momentum for the wrist flexors. Therefore, reduced required grip force would create a smaller momentum on wrist flexors and extensors, preventing them from fatiguing rapidly. The wrist is mainly stabilized by a complex ligament apparatus. When a load is acting on the wrist, flexors and extensors are activated to keep the wrist in the desired position. Accumulation of fatigue in the wrist flexors and extensors due to grip intensive task would therefore result in a potential decrease in risk stability and control. Referring to this theory, to prevent MSDs, an intervention, reducing the rate of accumulation of fatigue in those muscles, needs to be found to protect the wrist [12].

Most likely, a combination of those theories along with additional events happening on the metabolic level is responsible for the symptoms patients experience. However, no matter if it is the tendon that experiences compression, inflammation or unideal joint loadings, the patient will experience discomfort and pain which can be managed by a reduction in work intensity.

While the physiological events causing those disorders need to be investigated further[13], there is a high consensus on risk factors for their development. Multiple studies have shown a relationship between high physical demands and the prevalence for MSDs. Risk factors include exposure to repetitive motion, high forces, vibration, or unnatural postures[2, 14, 15]. Many occupational groups are exposed to one or more of those risk factors. Epidemiologic studies found MSDs to be highly prevalent in meat processing, letter carrying, office works and manufacturing industries of various products, supporting the work-relatedness of MSDs[16-20]. Multiple studies have investigated the effect of personal factors such as age and have found little association between those and the development of MSDs compared to the factor occupational exposure[21, 22]. If exposed to one or more of those risk factors, employees experience an accumulation of localized muscle fatigue and discomfort. A study investigating gender differences in the prevalence of MSDs found women to be more prone to develop those types of injuries even when compensating for household work, exercise, and personal recovery. They also found them to have a higher level of muscle activity in relation to personal maximal strength hypothesizing that due women being naturally weaker than man when performing the same tasks, they are exposed to higher intensities [23].When monitoring the development of neck pain in harvesters and researchers, [24] Ostensvik found harvesters to have a higher level of trapezius muscle activity as well as a higher prevalence for developing neck pain. These findings support the assumption of muscle activity, as a parameter for intensity of a task, being a major risk factor for the development of MSDs. Furthermore, studies have shown EMG muscle activity to be higher in individuals with a history of MSDs [25] showing the reduced ability to generate force and the resulting higher levels of exposure when continuing to perform the same task.

The previous overview explains the growing interest in finding preventive measures in order to support employees. To do so, the first step is to understand the magnitude of risk posed by certain jobs. For this purpose, risk assessment models have been implemented. Used to quantify risks posed by jobs and/or tasks those assessments provide guidance to employers and ergonomists.

1.2 Risk Assessments

To identify and quantify the risk for development of MSDs, different methods have been established over the years. As the risk factors for such disorders are known, most assessment models use parameters related to those risk factors and estimate the risk posed by a certain task according to the magnitude of those risk factors. The Hand Activity Level Threshold Limit

Value (HAL-TLV) and the Distal Upper Extremity Tool (DUET) are among the most common methods used to assess upper-extremity risk. HAL-TLV uses ten-point scales for the magnitude of force related to a persons' maximum strength and the hand activity level or frequency of the activity performed. DUET is used to calculate a score for a number of tasks with different intensities, again using a ten-point perceived exertion scale to identify how "hard" the task feels.

A more sophisticated risk assessment model is the Revised Strain Index (RSI). Additionally, to looking at the intensity of exertion in relation to a persons' strength and the frequency of exertion, the RSI also takes the duration of work per day as well as wrist posture and duty cycle, meaning the amount of recovery time in between exertions into account. However, it becomes clear that all the above assess the intensity of the task by comparing the required force for a task to a persons' maximum strength. Research shows, that below 15% of a persons' maximum strength, endurance time is nearly infinite but decreases non-linear at higher levels of required force. For grip endurance, Rhomert discovered a relationship between an individuals' ability to maintain grip force and the percent of maximum grip strength known as the Rhomert's' formula. This formula links endurance time to the intensity of a task and illustrates the magnitude by which even a slight increase in required force may influence intensity of a task.

When aiming for a reduction of risk, it makes sense to find ways to decrease one or more of those risk factors. As industrial settings aim for high productivity, frequency or duty cycle are parameters that are difficult to adjust. However, methods to reduce the intensity of exertion can be applied. One possibility which has been developed recently is the use of exoskeletons to support employers.

1.3 Exoskeletons

An exoskeleton is defined as a wearable device aimed to enhance the physical capabilities of its user. Exoskeletons can be classified as 'passive' when not using any kind of external power source. Instead, supportive forces are generated by use of springs or dampers storing energy from the users' movements and releasing it during movements that require support. 'Active' Exoskeletons on the contrary are externally powered devices providing additional power to the human body. Both types claim to decrease physical exposure on the users' body and therefore prevent injuries or disorders like lower back or shoulder pain in jobs with high physical demands. In multiple studies exoskeletons have been shown to reduce muscle activity in those muscle groups which are supposed to be supported. Studies investigating passive lower back exoskeletons found reduced levels of perceived discomfort when wearing the device during a series of tasks. Findings were consistent for passive and active exoskeletons and whether the tasks were static or dynamic[26]. In a study by Xiloyannis et al. a delayed onset of muscle fatigue when performing a dynamic task with the powered exosuit compared performing the same movement unpowered was found[27]. In a study investigating the effectivity of a passive arm support exoskeleton during plastering activities, de Vries et al could observe a reduction in muscle activity when using the exoskeleton for all observed tasks. Moreover, a reduction in perceived exertion (RPE) was found for all except of one task[28]. The effects on muscle activity in a laboratory and field setting during farming tasks with and without a passive back exoskeleton has been investigated by Thamsuwan et al. Decrease in lower back muscle activity was found in both settings showing the potential to decrease muscular loads[29]. As the technology is relatively young and the effects on the human body are still not fully understood more research is needed. This is why this study focuses on a specific hand exoskeleton and its' effect on pinch grip endurance time and muscle activity. So far, no literature is available investigating the effects this exoskeleton, but it is already commercially available and in use.

General Motors has provided some of their employees with the Ironhand® and have reported an increase in comfort and decrease in perceived exertion during their work shifts[30]. However, if the devices aren't fully understood, it is impossible to know, if the intervention is good enough to turn a "hazardous" task into a "safe" task. It is therefore necessary to investigate the effect and usefulness of exoskeletons with the goal of finding ways to quantify their effect on exertion.

1.4 Structure and goals

This project intended to investigate the effects of one specific exoskeleton on the Score of the risk assessment model Revised Strain Index (RSI). In multiple stages, a final experiment was designed and performed. The exoskeleton of interest, the Bioservo Ironhand® and its' mechanisms of mode of operation will be explained in the following chapters. During the initial stage of the project, experimental setups were tested. However, the design of experiments and the Ironhand® itself, showed limitations that made it necessary to adjust the experimental setup. As it was more complicated than expected to investigate the Ironhands® effect on actual risk scores, the focus was shifted towards understanding the potential of the Ironhand® during specific tasks that worked well with the design of the Ironhand®. Therefore, the final experiment uses a set of tasks to investigate the exoskeletons' effect on pinch grip endurance time and fatigue by means of EMG muscle activity and pre- and post-pinch-strength for a repetitive task. The following chapters will present the experiments used for data collection as well as data processing methods and statistical methods to interpret the results. Comparison of with and without pinch grip endurance time and the Rhomert's' formula will be used to assess the magnitude of support the Ironhand® provides during pinch grip. Thereby, the potential of the exoskeleton to reduce intensity of exertion can be investigated. The Revised Strain Index will be introduced and the results from the analysis of the endurance time will be used to calculate the risk scores with and without the Ironhand® to make a first attempt on answering the initial question. As explained previously, the mechanisms for the development of MSDs are yet to be fully understood, however there is a common believe that accumulation of fatigue plays a major role. Therefore, in this study, fatigue will be assessed by comparing pre- and post-pinch-grip-strength after a fatiguing cyclic task. A study performed by De Luca found an increase in EMG amplitude to be an indicator for localized muscle fatigue during repetitive lifting tasks[31]. Moreover, the amplitude of normalized EMG signals is believed to be related to the magnitude of force that is applied during a task which is why EMG analysis will be the third parameter of investigation in this study. A study investigating EMG muscle activity during a repetitive lifting task with varying weights could find higher levels of EMG muscle activity with increased load [32]. Lower amplitudes would be equivalent to lower applied forces and thereby a slower accumulation of fatigue. Referring to the risk assessment models mentioned previously, lower normalized muscle activity would be an indication for a decrease in magnitude of intensity of exertion and could therefore show, that exoskeletons have a potential of reducing the accumulation of fatigue in the muscles which would help to reduce the risk for MSDs. A study performed by Ostensvik found a relationship between higher levels of muscle activity of the trapezius muscle and the risk for neck pain[24], however there is little literature on if lower measured EMG amplitude does in fact indicate a lower risk for MSDs. This study does not attempt to prove this relationship, but as previous research indicates, the assumptions made in this study are reasonable and justify the use of this widely spread method for investigation.

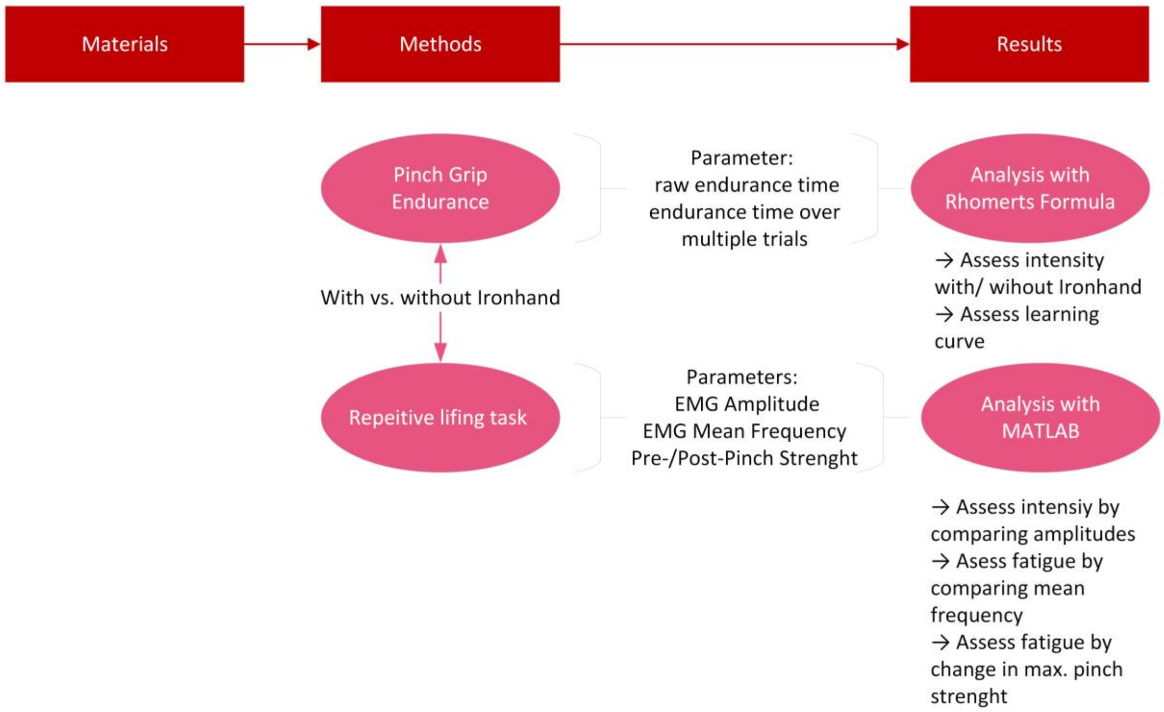

Fig.2: Structure and goals of this paper

2 Material and Methods

A literature review using Google Scholar was performed to understand the relationship between occupational requirements and the development of MSDs of the wrist. Furthermore, possibilities to measure muscle fatigue have been investigated and experiments measuring muscle fatigue of the wrist have been searched for and reviewed. To narrow down the research question and to understand more about the mechanisms of use of exoskeletons as well as possible problems, occupational exoskeletons have been investigated. Key words like occupational exoskeletons, work-related musculoskeletal disorders of the wrist, muscle fatigue and Electromyography (EMG) have been searched for and possibly relevant articles have been skimmed. References used in all articles have been checked to find additional articles to help design the experiments. It was found that cyclic tasks combined with a pre- and post-test of strength and the acquisition of EMG data to investigate muscle activity give information about the level of muscle fatigue. Therefore, studies using cyclic tasks to induce muscle fatigue have been searched for and reviewed.

2.1 The Bioservo Ironhand®

The exoskeleton of interest for this study is the Bioservo Ironhand®. It is a powered glove which is supposed to increase grip strength and grip endurance shown in figure 1.

Fig. 3: The Bioservo Ironhand®

Using resistance-based sensors, as soon as the user starts gripping an object, the powered glove applies additional force. This is performed by tendons sewed into the glove and a servo motor, pulling those tendons back and therefore flexing the fingers, when the sensors are activated. The amount of force can be defined separately for each individual finger or task. Bioservo provides an app which allows the user to define individual settings and safe them as modes of operation. For each user, the Ironhand® is calibrated to his or her maximum strength. Proportional to these measures, each finger can be set to a certain percentage of force that should be applied by the Ironhand®. The Ironhand® also provides the possibility to define a locking tendency for each finger, meaning the user must actively pull his fingers off a tool. Hereby, endurance for static tasks is increased. Moreover, the Ironhand® comes with a function called "Smart Assist" which learns from the users' movements in order to learn and react even quicker. The company Bioservo claims, that by reducing the needed grip force to complete tasks, less fatigue will accumulate in the lower arm muscles responsible for gripping and therefore the glove will help preventing MSDs caused by overuse. The Ironhand® even provides automatic risk assessments by gathering data throughout the use of the Ironhand® Hand-Activity-Level Threshold limit value (HAL-TLV) and the Distal Upper Extremity Tool (DUET) are used to perform the risk assessments.

2.2 Electromyography

The System used for EMG data collection was a Biometrics DataLink DLK900 Base Unit and PC Software Version 8.51. The data was collected at a sampling rate of 1000Hz. Five bipolar electrodes (Biometrics Sx230 1000 Surface EMG Sensor) have been used for the data collection. The first electrode was placed above the muscle belly of the extensor carpi ulinaris (ECU) by measuring the distance between lateral epicondyle to radial and ulnar styloid processes and placing the electrode at about 10% of the distance according to figure 4. To ensure correct placement, participants were asked to make a fist which helps to identify the muscle belly of the ECU above which the electrode should be placed. Electrode number four has been placed on the flexor digitorum superficialis (FDS) measuring the distance between medial epicondyle of the humerus and radial styloid process, placing the electrode at about 10% as well[33]. The remaining three electrodes have been placed circular around the forearm. Two electrodes have been placed on the ulnar side between ECU and FDS electrode and one electrode has been placed on the radial side. Distances between electrodes have been kept constant. Before Application, all electrodes were cleaned using alcohol wipes. Prior to sensor applications, the participants skin was prepped by shaving and cleaning the skin with alcohol.

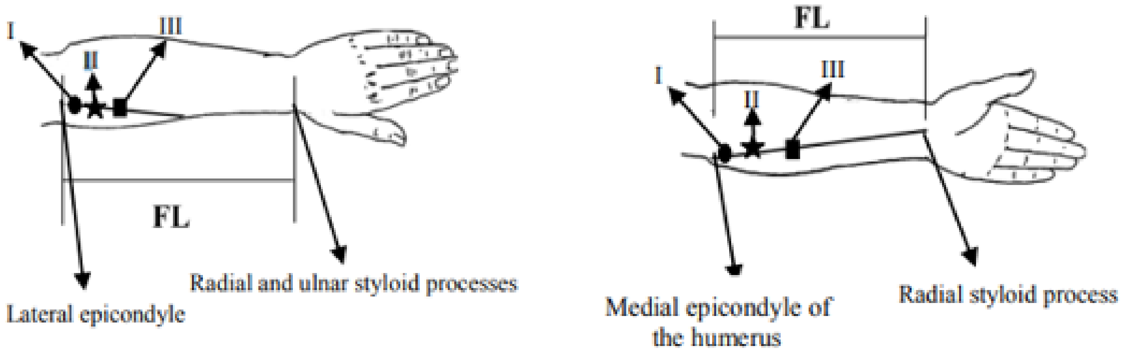

Fig. 4: Electrode placement for flexors and extensors of the lower arm, ideal placement marked by star in position II

2.2.1 Participants

This pilot study included ten healthy participants (eight females and two males) ranging in age from 22 to 42. They were all recruited using convenience sampling. All participants were right-handed. All participants have been screened for a history of musculoskeletal disorders within the last six months as well as for neurological disorders. Furthermore, full pain-free range of motion was screened for visually to avoid interference with the data collection. Demographical data such as age, height, body weight and gender were collected.

2.2.2 Study Design

For both tests, individual settings have been defined for the Ironhand®. As no data is available on how to choose settings, several settings have been tested and for each task a setting were chosen based on comfort. For the Endurance Test, the locking tendency has been increased whereas it was set relatively low for the cyclic lifting test to avoid an increase in accumulation of fatigue by requiring the participants to use high forces to let go of the object.

Endurance Test

To investigate the Ironhands' effect on pinch grip endurance, participants were set up with the Ironhand® by putting on the backpack and adjusting the straps. They were asked to put on the glove and the wrist strap has been tightened. All participants were using the Ironhand® for the first time during this experiment. The Ironhand® was switched on and was calibrated by applying a maximum grip to a cylindrical object three times with a rest period in between trials according to the devices' manual. After calibrating, the Ironhand® was switched off again and the participants were asked to grasp a cylindrical jar with a weight of 96oz with a three-finger grip using thumb, index, and middle finger. The time was stopped for how long participants could hold the object for. The experiment was repeated on a different day, following the same protocol but keeping the Ironhand® switched on. To account for possible fatigue due to the calibration protocol and due to the anti-slip materials for better grip that the glove is made of, to avoid bias, the experiment has been done with a switched on and switched off Ironhand®, rather than with and without. For two participants, the experiment with the Ironhand® switched on was repeated five times to get a first impression on the learning curve for operating with the Ironhand®.

Cyclic lifting Test

To investigate the Ironhands'® effect on muscle fatigue, a repetitive task was chosen. To prepare participants for the experiment, they were asked to put on the backpack before placing the EMG electrodes on the right arm. The skin was prepared by shaving and cleaning it with alcoholic wipes. Five electrodes were placed on the right forearm. The first electrode was placed on the muscle belly of the MUSCLE, participants were asked to make a fist identify the muscle belly. The other four electrodes were placed circular around the forearm. The neutral electrode was placed on the wrist of the left arm. To normalize the data acquired during the experiment, a MVC measurement was performed. A maximum grip exertion was followed by a series of four resisted hand maneuvers: pushing upwards from neutral, downwards from neutral, outwards from neutral, and inwards from neutral Each maneuver lasted approximately three seconds.

After this initial measurement, participants performed a maximum pinch strength measurement was performed. Participants were seated with their shoulder neutral, the elbow flexed at 90° and the wrist neutral, holding the force sensor with three fingers and pressing it for about 3 seconds followed by a 20 second rest period. This was repeated two more times.

Subsequently, participants put on the glove and the Ironhand® was calibrated using the same protocol described previously. The Ironhand® was switched off again to perform the first trial of the repetitive lifting task. Participants were asked to use the same three-finger grip to lift the same 96oz cylindrical object placed on a table from left to right over a distance of 45cm. To ensure proper lifting, a 3cm high box was placed in between. The task was performed for 2.5 minutes to the beat of a metronome set to 40 beats per minute. EMG signals were recorded during the task. Participants were encouraged verbally and were given instructions to not compensate for accumulating fatigue by altering their upper body movements or stance.

After completing the 2.5 minutes of exercise, the glove of the Ironhand® was taken off and participants performed the post-pinch-strength-test, following the same protocol described previously. They were asked to rate their perceived exertion using the BORG-10 scale.

The experiment was repeated on a separate day with the Ironhand® being switched on to support the participant. Additionally, to rating perceived exertion, participants were asked to describe their experience when using the Ironhand® briefly.

2.2.3 Data Analysis

Endurance Test – Rhomert's Curve

The times, participants were able to hold onto the weight during the endurance test was analyzed by means of the Rhomert's Curve. The Curve provides a relationship between grip endurance and the percentage of one's maximum voluntary contraction (MVC) that is held by the individual. The Rhomert's formula is defined as follows:

$$T_{sec} = -90 + \left(\frac{126}{P}\right) - \left(\frac{36}{P^2}\right) + \left(\frac{6}{P^3}\right)$$

T_{sec} defines the time of endurance and P the decimal percentage of maximum force applied. The relationship is non-linear and results in curve shown in figure 5.

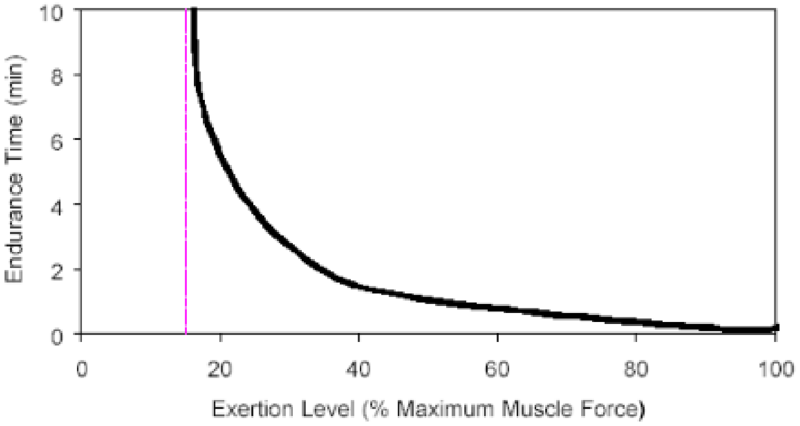

Fig. 5: Rhomert's Curve – endurance time as a function of percentage MVC

This curve has been used to evaluate the intensity of the task with and without the Ironhand®. The times have been inserted into the equation and percentages of MVCs have been determined.

Endurance Test – The Revised Strain Index

With the data from the analysis by means of the Rhomert's Curve, the RSI for the repetitive task was calculated for all participants to see the influence of the reduction in intensity on the resulting RSI score. The RSI is the multiplication of five multipliers: the posture multiplier PM, the intensity multiplier IM, the total duration multiplier HM (referring to the **h**ours per day), the frequency multiplier EM (referring to **e**fforts per minute), and the duration per exertion multiplier DM. The wrist posture (P) is neutral during the exercise and the total duration (H) is <0.05 h. The equations to calculate the RSI for those parameters are shown below:

$$IM = 30 * I^3 - 15.6 * I^2 + 13 * I + 0.4 \qquad for\ 0 < I < 0.4$$

$$IM = 36 * I^3 - 33.3 * I^2 + 24{,}77 * I - 1{,}86 \qquad for\ 0.4 < I < 1$$

$$EM = 0.1 + 0.25 * E$$

$$DM = 0.45 + 0.31 * D$$

$$HM = 0.2 \qquad for\ H < 0.05h$$

$$HM = 0.042 * H + 0,09 * log_e(H) + 0.477 \qquad for\ H > 0.05h$$

$$PM = 1$$

Cyclic lifting Test – EMG Analysis

EMG data has been collected during the repetitive task. MATLAB was used for data processing. To prepare the data for analysis, the MVC measurement performed prior to the experiment has been used. The data was bandpass filtered with 10 Hz to 450 Hz chosen as passband frequencies. Subsequently, the signal was RMS filtered with a window size of 150 samples. Then, the signal was normalized with the maximum values acquired for each electrode during the MVC measurement. The mean amplitude and mean frequency for the sum of all electrodes as well as for all individual channels was calculated.

Cyclic lifting Test – Pre- and Post-Pinch-Strength

Pre- and Post- Pinch-strength data was analyzed with MATLAB. The maximum value for each trial was determined and the average the three trials for each pre- and post-test has been used for analysis.

3 Results

3.1 Endurance Test

3.1.1 Endurance Times with Rhomert's Curve

The endurance times for the Control and the Ironhand® condition are shown in table 1. Analysis was performed by means of a paired T-Test with alpha set to α = 0.05. The analysis showed a p-value of p = 0.0216 and therefore statistical significance.

Tab. 1: Raw endurance times – without vs. with the Ironhand®

Participant	***Control Endurance time [sec]***	***Ironhand Endurance time [sec]***
1	88	107
2	72	93
3	92	123
4	271	464
5	69	101
6	71	94
7	83	111
8	85	126
9	76	98
10	319	495
MEAN	**122.6**	**181.2**

The results of the analysis with the Rhomert's Curve are displayed in table two below. The analysis shows a reduction in percentage of MVC by an average of 8.2% with a standard deviation of +/- 2.29%. It is important to note that the endurance time increased for all participants, even though all participants were first time users and did not have any experience with the Ironhand®.

Tab. 2: endurance times and equivalent percentage of MVC by means of Rhomert's Curve

Participant	Control Condition [%MC]	Ironhand® Condition [%MVC]	Reduction [%MVC]
1	57	51	6
2	63	55	8
3	56	47	9
4	29	23	6
5	62	52	10
6	63	55	8
7	59	50	9
8	59	46	13
9	61	53	8
10	27	22	5
MEAN	**53,6**	**45,4**	**8,2**

As mentioned previously, two participants have been asked to repeat the experiment with the

Ironhand® four more times to get an idea about a possible learning effect when using the Ironhand®. Figure 6 shows the results. It is interesting to see, that the graph shows increasing slopes for both participants. However, to perform a meaningful statistical analysis, more participants would be needed.

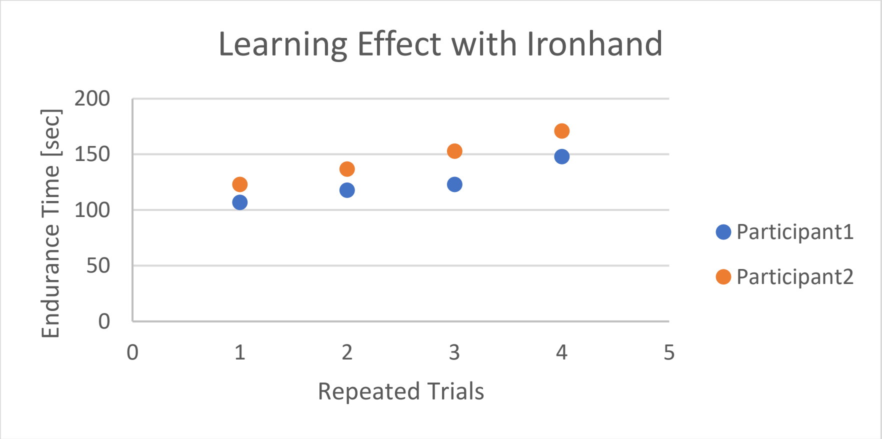

Fig. 6: Learning curve for endurance test with the Ironhand®

3.1.2 RSI Scores

By inserting the percentages of MVC determined in the previous step, the IM multiplier was calculated for all participants with and without the Ironhand by means of the equations in chapter 2.2.3. The number of efforts per minute is one due to the static nature of the task (EM). The posture of the wrist is constant and neutral (PM). The total duration multiplier (HM) is similar for all female participants but varies for the two male participants as their endurance time was more than 3 minutes (>0.05 h). The frequency multiplier was determined by inserting the endurance time of the test without the Ironhand® to compare how only the reduction in intensity with the exoskeleton influences the result. The results of the calculations are shown in table 3.

$$EM = 0.1 + 0.25 * E = 0,35$$

$$PM = 1$$

Tab. 3: Multipliers and RSI scores calculated for the Control and the Ironhand® condition

Participant	***DM (without)***	***HM (without)***	***IM (without)***	***IM (with)***	***RSI (Without)***	***RSI (With)***
1	26,39	0,2	8,107	6,887	14,976	12,722
2	22,54	0,2	9,530	7,680	15,039	12,119
3	27,24	0,2	7,890	6,164	15,047	11,754
4	47,95	0,247	3,590	2,930	14,881	12,145
5	21,73	0,2	9,277	7,078	14,109	10,765
6	22,28	0,2	9,530	7,680	14,860	11,975
7	25,27	0,2	8,556	6,700	15,135	11,851
8	25,73	0,2	8,556	5,992	15,408	10,790
9	23,58	0,2	9,030	7,274	14,905	12,006
10	51,08	0,263	3,363	2,824	15,813	13,280
MEAN					**15,017**	**11,941**

Statistical significance was found between the RSI score for with and without the Ironhand® by means of a paired T-Test (α = 0.05). The RSI score decreased for all participants.

3.2 Cyclic lifting Test

Pre- and Post-Pinch-Strength were measured with and without the Ironhand®. The results are shown in table 3.

Tab. 4: Pre- and Post-Pinch-Strength Measurements

	Control Pinch Strength		***Ironhand Pinch Strength***	
Participant	PRE [kg]	POST [kg]	PRE [kg]	POST [kg]
1	44.16	38.38	37.93	37.32
2	37.12	20.18	34.26	29.85
3	40.32	33.89	40.79	40.61
4	54.9	53.4	57.17	59.71
5	42.2	37.1	49.72	42.7
6	28.09	21.65	26.4	29.6
7	31.52	23.85	29.90	25.87
8	35.9	33.7	31.38	35.23
9	38.76	26.94	39.78	38.28
10	37.17	31.59	35.48	35.75

To analyze the Ironhands'® effect on Pre- and Post-Pinch-Strength, a repeated measures ANOVA was performed, using SPSS. No significance was found for the Box's Test of Equality, justifying the use of this analysis. Levene's Test of Equality of Error Variances showed no significance. Pairwise Comparison showed no significant difference between the groups for the Pre-Pinch-Strength. However, significant difference was found between Pre- and Post-Pinch-Strength measurements for the Control condition without the Ironhand®. No significant difference was found between time points for the Ironhand® condition. Looking at the graphic visualization of the results, a steep decline in strength is shown for the control condition whereas the slop for the Ironhand® condition is relatively flat.

Tab. 5: Mean values for Pre- and Post-Pinch-Strength for repetitive task

Group	***time***	***Mean***	***Std. Error***	***95% Confidence Interval***	
				Lower Bound	***Upper Bound***
Control	1	39.219	2.946	32.974	45.464
	2	32.121	3.397	24.920	39.322
Ironhand	1	38.592	2.946	32.347	44.838
	2	37.686	3.397	30.485	44.887

Tab. 6: Mean Difference, Std. Error, and p-values for between time-point analysis for Pre- and Post-Pinch- Strength

Group	***(I) time***	***Mean Difference (I-J)***	***Std. Error***	***Sig.[b]***	***95% Confidence Interval for Difference[b]***	
					Lower Bound	***Upper Bound***
Control	1	7.098*	1.427	<.001	4.073	10.123
	2	-7.098*	1.427	<.001	-10.123	-4.073
Ironhand	1	.907	1.427	.534	-2.118	3.931
	2	-.907	1.427	.534	-3.931	2.118

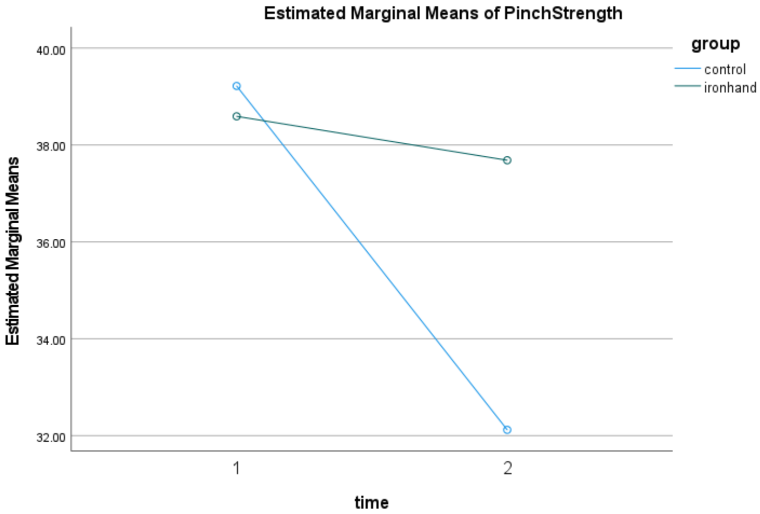

Fig. 7: Pre- and Post-Pinch-Strength Measurements – graphical visualization

No statistical significance could be found for the EMG data. Neither the comparison of the summed EMG with and without the Ironhand® showed significance during the performed paired T-Test, nor the single channels showed significance. Furthermore, no pattern could be observed regarding the change in mean frequency. For some participants, mean frequency decreased with use of the Ironhand®, for others, mean frequency increased. The processed data as a function of time show different patterns for all participants. Table 6 shows the Pre- and Post-Mean-Amplitudes.

Tab. 7: Pre- and Post-Mean-Amplitudes for EMG data without vs with the Ironhand®

Participant	Control Condition	Ironhand® Condition
1	0,2123	0,192
2	0,3064	0,2738
3	0,2187	0,2138
4	0,299	0,2328
5	0,2456	0,2596
6	0,589	0,6956
7	0,3755	0,3971
8	0,2511	0,2299
9	0,3344	0,2625
10	0,2516	0,2637
MEAN	**0,30836**	**0,30208**

4 Discussion

During the course of this project, the biggest challenge was the design of an experiment that would be suitable for investigating the potential of the Ironhand®. Due to the design of the Ironhand®, especially the placement of the sensors as well as the properties and condition of the wrist band, common tools used in biomechanical laboratories, such as hand dynamometers to assess grip strength, were not suitable. An attempt to use a model-based approach to assess the required force during a hand clipper task failed, as the model which was based on EMG data showed high variability. Many hours were spent on trying different tasks with different settings for the Ironhand® to find one that would not put too much strain on the wrist, making the wrist the limiting factor, while using the full potential of the Ironhand® by activating the sensors properly. In correspondence with the distributing company for the Ironhand® in the US, it has been reported that employees in the manufacturing department of General Motors have been equipped with the exoskeleton and many feel comfortable and supported. Participants in this study reported that the static as well as the repetitive task felt "easier" but also expressed concern about the grasping feeling unnatural and a lack of sensory feedback. The reported the glove "pulls the fingers in a direction that feels unnatural and awkward". Two participants felt highly uncomfortable while using the device, even complained they "hated" using it during the repetitive task. As the Ironhand® comes with four sizes and one design for the glove only, fitting the glove was challenging for some participants. Even the smallest size was slightly too big for some, especially short female participants. This could explain the variability in the data as well as the differences in reported comfort. The design therefore limited not only the tasks that could be included in this study but also is believed to cause variability in the data as it did not fit all participants equally well.

As with any study, the present set of experiments presents with weaknesses that were taken under consideration but have been found to be acceptable. One weakness was that a similar weight was used for all participants even though they presented with different levels of strength. To get a better understanding, the experiment should be repeated using weights that are relative to the individuals' strength as some participants had trouble performing the repetitive task for the full 2.5 minutes without compensating for fatigue by adjusting their stance or using their upper body for support. The biggest weakness was found to be the small sample size and the lack of variability in the sample. Most participants were women in their twenties, all of them students. As the device was designed for employees exposed to a high level of physical exposure, the sample does not match the intended users. Furthermore, two older males were included in the study. Their highly varying results for all tests could have caused errors in the analysis. Due to the difficulties that were faced concerning the design of the experiment and the pilot study nature of this study, it was found that even with this small sample a sufficient first impression of the tests and tasks that are suitable for further investigation of the Ironhand®, as well as a first impression of the potential of the device would be possible. Moreover, this study concentrates on the effects of the Ironhand® on muscle activity and fatigue in the forearm. To be able to confidently recommend the use of the device, the effects of the backpack or waistband that hold the powerpack of the Ironhand® and that have to be worn during use have to be investigated. It needs to be made sure, that the backpack/ waistband do not cause strain, pressure, compression or imbalances when wearing long-term. The shoulder and back have not been investigated in this project but should be brought into focus during further testing.

4.1 Endurance Test

The results of the endurance test clearly showed that the Ironhand® does decrease the intensity of the task for all participants and increased endurance in all cases. The chosen setup therefore seems to be suitable for the task. A decrease in percentage of MVC by a minimum of 6 % and a maximum of more than 10 % during first time use is very promising. Both participants that were asked to repeat the test could decrease their percentage of MVC by another 9 %. This indicates, that with further training the Ironhands® potential is even bigger. However, it is expected that after a certain training period, users reach a plateau. Furthermore, not only does repeating the task train users on how to operate the device but also on the task itself. It should therefore be investigated how the learning effect without the Ironhand® would look like in comparison. This effect will be investigated in further detail at the University of Wisconsin – Milwaukee. A hand expert who has been asked for their opinion on the Ironhand® stated, that they feel like the Ironhand® alters the interaction between muscles by isolating the flexor digitorum superficialis while putting less strain on the flexor digitorum profundus. The flexor digitorum superficialis is attached to the phalanx media and is therefore responsible for flexing the finger without flexing the most lateral joint. It is considered a reserve muscle that is activated when increased force is required for finger flexion. It also has a smaller physiological diameter compared to the flexor digitorum profundus resulting in smaller capacity to generate force[34]. As the Ironhand® flexes the fingers completely, involving all joints, this could trick the body into thinking the flexor digitorum profundus is already activated as the feedback indicates a flexion of the most lateral joint. This could prevent the flexor digitorum profundus from being fully activated resulting in altered interactions between forearm muscles and greater accumulation of fatigue in a muscle that is not normally isolated. Those effects should be investigated in further studies and possible risks should be analyzed.

The analysis of the RSI score showed that the determined reduction in intensity led to a significant reduction in risk. However, for none of the participants the reduction was enough to achieve an RSI score below the critical value of 10. This might be due to the very high intensity of the task. The Ironhand® is designed for tasks that are performed over the course of a work shift, meaning multiple hours. The experiment performed was high intensity and participants reached a maximum after a couple of minutes resulting in relatively high RSI scores. Further research is necessary to understand if the Ironhand® reduces the risk scores of industrial tasks sufficiently. Interestingly, when calculating the RSI score with the increased duration times, the scores are relatively similar to the scores without the Ironhand®. This makes sense as in both trials, participants reached their maximum. However, even then scores decreased slightly with the Ironhand® for all participants which indicates that intensity has a greater impact on reducing the risk for MSDs than duration per effort does. If this is true must be investigated in another set of experiments.

4.2 Repetitive Task

The results of the Pre- and Post Pinch-Strength analysis clearly indicate that participants were required to use less force while completing the task with the Ironhand® and therefore accumulated less fatigue. The decrease in Pinch strength was significantly greater without the Ironhand® whereas no difference could be found between the Pre-Test values. This indicates that participants started the experiment with the same level of force or capacity but fatigued less during the experiment with the Ironhand®. This clearly proves the potential of the device. However, no significance was found for any of the EMG data. No patterns indicating lower levels of muscle fatigue such as a decrease in amplitude and an increase in mean frequency could be found. However, this does not mean that the device is not useful but rather points out weaknesses in the methodology. EMG is known to have high variability. Muscle activity has been shown to increase with psychological stress. Especially negative stress is believed to increase muscle activity[35]. Participants that felt uncomfortable using the device could have experienced stress and therefore higher levels of muscle activity. Furthermore, even with normalization, the exact placement of the electrodes may vary influencing the recorded data(Day, 2002 #75)(Williamson, 1980 #76). Additionally, changes in impedance of the skin affect the data as well. Participants were encouraged verbally to put as much effort into the MVC measurements as possible, but forces applied may still vary. In addition, the forearm muscles are arranged in two tiers. As EMG only measures activity that reaches the skin, effects that may occur in the lower-tire muscles may not be visible. A possibility to explore this method further would be to also record EMG data during the Pre- and Post-Test to see if any effects for lower levels of fatigue can be found. However, the wrist and the interactions between muscles of the forearm are complex and will need further investigation.

Participants have reported that they did feel supported but also at times felt like they had to work against the device. While the activation of the sensors has not been recorded and investigated, participants experienced inconsistency. They reported that even if they felt like they grasped the object in the same way, they experienced different levels of support. This could also explain some of the variability in the data. If users experience lower levels of support than expected, they must compensate for the lack of force applied by means of higher levels of muscle activation, possible faster activation, resulting in higher levels of EMG amplitude. The inconsistency of the provided support might also cause a tendency to generate more force than needed to be certain that enough force is applied to lift the object. Those overshoots may also be a reason for why the expected results could not be observed in the EMG data. The different levels of support could be due to poor fitting of the gloves. As the sensors might move relative to the skin, especially if the glove does not fit the user perfectly, they are exposed to different levels of pressure when grasping an object, resulting in different levels of support. Design wise, it might be helpful to consider using a set of sensors or sensors with a larger diameter to provide a more consistent support.

5 Outlook

This study can be seen as the first step to understanding the usefulness of devices like the Ironhand®. To answer the initial question, more tasks and settings have to be evaluated to get a better understanding of the reduction in intensity the support of the Ironhand® may cause. When this is accomplished, the Ironhand® can be included into risk assessment models like the RSI to investigate, if the use of the Ironhand® is powerful enough to reduce the risk for MSDs and bring job exposures on a "safe" level. During the time working with the Ironhand® as well as due to the literature research, more and more questions arose concerning the Ironhand® itself as well as concerning the use of exoskeletons in general. In the previous chapters, it was mentioned that participants reported a loss of sensory feedback. A study investigating sensory feedback in older adults found a loss of sensory function. In the study, Bioservos' second product, the Carbonhand®, was used. The Carbonhand® uses a similar design but only covers thumb, index- and middle-finger and is supposed to be used for rehabilitation purposes. The Carbonhand® was reported to cause struggle to complete the tasks, especially when precise movements or small objects were involved[36]. Xiloyannis et al. found decreased accuracy and smoothness for movements while using a powered exosuit for the elbow. Furthermore, a decrease in speed of movement was noticed and it was speculated that users might wait for the additional support before completing the movement[27]. As the Ironhand® is supposed to be used in industrial environments with appropriate protection gear, meaning protective gloves on top of the Ironhand®, those effects could even worsen. Loss of tactile function would not only decrease performance but also pose a risk for injuries. Therefore, a study focusing on tactile function when using the Ironhand® should be performed.

As mentioned, participants have also reported that their movements felt "unnatural" when using the device. This feeling presumably refers to altered biomechanics. Further research is needed to investigate the Ironhands® effect on biomechanics and movement patterns as well as possible risks associated with such changes. Gregorczy et al. found alterations in posture and biomechanics during load carriage with and lower-body exoskeleton[37]. In another study, it was found that there is the possibility for antagonistic muscle groups to show more activity during exoskeleton use. Possibly altered centers of gravity or the additional weight of the Ironhand® could pose risks to develop imbalances between antagonistic muscle groups or by applying compression forces to the user[38, 39]. Additionally, it is necessary investigate the effects of the Ironhand® during long-term use. Longitudinal studies should be performed to assess compliance as well as effects on forearm strength. It is possible, that due to the provided support, muscle atrophy is induced as less strength is required. This would possibly expose users to even higher levels of intensity when returning to work without the device, exposing them to a greater risk for the development of MSDs. Especially studies in industrial settings should be performed in the future as those would give better insights in usability during an actual work shift with different tasks, longer use of up to eight hours and the use of different hand tools as the real-life use might differ quite a lot from the environment of laboratories.

One also needs to keep in mind that those devices come with high cost for a company. When an investment is made, managements expect profits. In a real life application this could lead to increased expectations concerning productivity which would then increase the exposure of workers by means of frequency or speed of work. A questionnaire-based study reported that expectations for the use of exoskeletons included higher productivity[40, 41]. Again, a longitudinal on-site study could help to answer those questions.

There are grand expectations when it comes to exoskeletons in industrial settings with very little research on their long-term effects. This study showed that the Ironhands'® design shows room for improvement but nevertheless has the potential to be used as a supportive measure for employees. However, MSDs are multicausal and relying on a relatively new technology for prevention should be considered carefully and investigated intensely. Exoskeletons vary a lot in their design as well as mechanisms of operation and must therefore all be investigated separately. They pose a challenge for researchers and developers but come with promising potential that should be followed-up on in the future. With sufficient evidence and technical improvements, exoskeletons like the Ironhand® could be a great tool for injury prevention in the future.

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