Efficiency assessment of passive exoskeletons for manual handling tasks

By

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

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Abstract

Work-related musculoskeletal disorders (WMSDs) have been reported as a major issue among construction workers, and governments have spent billions of dollars on the problem. However, the number of case reports is still growing steadily year by year. Multiple factors can lead to WMSDs, but the two main ones are awkward body posture during work and unsafe workloads on specific parts of the body. In total, the factors that produce unsafe joint moments will have a high risk of leading to WMSDs. Currently, the most commonly used methods to assess ergonomic risks in real-world scenarios are scoring methods based on body posture, including rapid upper limb assessment (RULA), rapid entire body assessment (REBA), and Ovako working posture analysis system (OWAS).

This thesis investigated the ergonomic risks of WMSDs among construction workers in drainage departments who need to deal with manhole covers, and the efficiency of the passive trunk-support exoskeleton for manhole cover lifting tasks with i) manual lifting, ii) lifting with a jake tool, and iii) lifting with a lever tool. To assess the risk from the factors that lead to WMSDs, muscle activity and body posture were both measured during the in-field trial. For data collection, we performed an in-field experiment on 20 able-bodied construction workers from drainage management departments. During the experiment, the workers used the jake tool and lever tool to lift a 125 lb manhole cover and lifted a 40 lb manhole cover manually. Meanwhile, a passive exoskeleton with two modes, standard mode and instant mode, was applied to the above-mentioned working scenarios. Data on muscle activity was collected by the surface electromyogram (sEMG)

sensors and normalized by maximum voluntary contraction (MVC). Data on body posture was collected by the inertial measurement unit (IMU) and presented as REBA scores. Also, questionnaires were used to collect the participants' feedback on the difficulty of the tasks and confidence in the exoskeleton.

Furthermore, we observed the issue that the sEMG signal will sometimes be larger than the MVC signal collected by conventional methods during the in-field tests, especially for low back muscles. To fix the problem, we proposed a new dynamic MVC method for low back muscles which is more valid for dynamic tasks. Inspired by the working scenario at the time point when the problem occurred, we designed the dynamic MVC collecting procedure, which let the participants lift a 45 lb weight while standing with elbow and knee joints locked, using only the trunk. Also, to collect the maximum signal, external force against the lifting direction was applied, and sEMG data for low back muscles were collected. To investigate the validity of the methods, a duplicated test similar to the in-field test was carried out and normalized by the dynamic MVC method and four other conventional MVC methods for the low back. Finally, we found that the sEMG data normalized by the dynamic MVC method is significantly lower than the data normalized by conventional methods (P-values for Wilcoxon signed-rank test < 0.05) and all the data less than 100%, which proved the validity of the dynamic MVC method.

After fixing the problem, ergonomic risk assessment tests were carried out. The normalized sEMG data and REBA scores for different situations were compared and tested by the Wilcoxon signed-rank test. We observed that the lever tool performed best in the manhole cover lifting task, with significantly lower muscle load on the low back, shoulders, and lower limbs, and lower REBA scores than the data for the task using the jake tool method (P-values for Wilcoxon signed-rank test < 0.05). Meanwhile, the efficiency of the passive exoskeleton varied with different body postures; tasks using the jake and lever tools (especially for lower back and lower limb) had good efficiency, while the manual-only task had lower efficiency.

In summary, this thesis proposed a novel dynamic MVC method, assessed the ergonomic risk for manhole cover lifting tasks and provided specific recommendations for the tasks based on the results.

Preface

This thesis is an original work by Xun Wang. The research project, of which this thesis is part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Evaluation of the impact of upper-limb, lower-back, and lower-limb exoskeletons on safety and performance of industrial workers" No. Pro00109264, June 11, 2021.

Parts of this thesis were presented as a poster at the 23rd Annual Alberta Biomedical Engineering Conference 2022 (Banff, Canada).

Dedicate to

My mom

My dad

And

My best friends

Acknowledgments

I would first like to thank my supervisor Dr. Hossein Rouhani and my co-supervisor Dr. Mahdi Tavakoli. Their patience in my study and support during my time at the University of Alberta encouraged me a lot to finish this thesis.

Also, I would like to thank Karla Beltrán Martínez, Maryam Shakourisalim, and Zenab Estaji, who provided a lot of help with the data collection and analysis. Thanks also to all the members of the Neuromuscular Control and Biomechanics Laboratory for all the help and suggestions. I can always learn new things from them. Without their help, this work couldn’t be finished.

Finally, I would like to thank my parents for their guidance and support during my graduate study. And, thanks to my friend Diwei Wu who is willing to spend time with me even overseas. Lastly, thanks to Xi Wang, who always listens to my complaints.

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Chapter 1 Introduction

1.1 Background

Work-related musculoskeletal disorders (WMSDs) are a major problem in physically demanding work environments. In the construction and utility maintenance sectors, many workers suffer from lower back pain [1], painful knees and other injuries related to long-term work shifts and the heavy load of physical work. In order to help workers prevent WMSDs and reduce the ergonomic risk factors during activities, fundamental methods have been suggested, such as reducing hours for working shifts and providing training and new tools. However, workers are globally at a high risk of WMSDs. Construction workers in Africa and East Asia have a 41% to 76% chance of suffering from WMSDs within their 3- to 12-month working period [2]. Another study found that workers in the USA had a similar risk, and about 77% of workers had at least one of WMSDs symptoms within 12 months [3].

Among many WMSD symptoms, the most prevalent is located in the low back area, with 60% of workers experiencing such symptoms [4]. Thus, low back pain (LBP) can be the most critical WMSD. In 1998, the US government spent $26.3 billion in direct health care costs on LBP care and the number has grown steadily [5]. LBP has led not only to increased costs, but also to large amounts of disability and lost work [6].

To alleviate this issue, apart from reducing the obvious risks of WMSDs and LBP, ergonomic assessment methods have been provided to evaluate working conditions and risk levels in a more systematic way. The methods can be separated into different categories based on the applied parameters. Rapid entire body assessment (REBA), rapid upper limb assessment (RULA), and new ergonomic posture assessment (NERPA) methods are based on body posture and joint angle and have a high correlation coefficient (around 0.7) to the WMSDs level [7]. Furthermore, as muscle activity is highly related to working loads and muscle fatigue, and is one of the main WMSDs risk factors [8], the percentage of maximum voluntary contraction (MVC) can also be applied to evaluate the ergonomic risks during the tasks [9]. Other methods based on parameters like oxygen consumption, heart rate, etc. can provide further information, but just for additional description in most studies [10, 11]. Through ergonomic analysis using the above-mentioned parameters, and by informing the user about the outcome, the risk of WMSDs can be reduced by improving working posture and reducing muscle load.

Meanwhile, as well as improving job design, more and more employers are beginning to consider introducing exoskeletons as personal protective equipment (PPE) in different industry sectors to prevent WMSDs [12]. To target different working scenarios, many types of passive and active exoskeletons were designed, including upper limb-shoulder support, trunk support, lower limb support, and full-body support exoskeletons [13]. So far, many studies have revealed that the use of exoskeletons during particular tasks can be helpful in preventing WMSDs [14, 15]. In short, the capability of exoskeletons to reduce muscle fatigue and extend the work duration for a number of industrial tasks has been proven, but further studies of more work scenarios are still needed.

1.2 Study objective

The study aimed to address a real-world need in drainage departments of utility maintenance sectors. Because of the high risk of work-related injuries and LBP in this industry sector, the goal of this project was to investigate the efficiency of different tools and the application of a passive exoskeleton in reducing the risk of WMSDs in the manhole cover lifting task and to recommend strategies for workers to perform this task with a lower risk of WMSDs. Data were collected from the perspective of muscle activity and body posture, and the ergonomic risk was analyzed based on these two forms of collected data. Meanwhile, to address the muscle activity normalization to analyze the collected data, we also proposed a novel MVC collecting procedure for low back muscles. The study goals are the following:

1) Design a set of experimental procedures and a questionnaire for the in-field ergonomic risk assessment.
2) Propose a novel MVC collecting procedure for data on low back muscles and compare its performance with conventional MVC procedures.

3) Analyze the data collected from in-field tests and investigate the ergonomic risks of different working conditions.

4) Provide recommendations for the task with the minimum ergonomic risk for the in-field work scenarios.

1.3 Thesis structure

This thesis is divided into five chapters (Figure 1). Chapter 1 presents the background and description of the study objective. Chapter 2 includes a literature review, including state-of-the-art measuring software and hardware for both body posture capture methods and human muscle activity measure technology, as well as methods for ergonomic risk assessment. Chapter 3 presents the proposed novel MVC collecting procedure. Chapter 4 presents an ergonomic risk assessment test for manhole cover lifting tasks. Chapter 5 includes discussions, conclusions, and future perspectives.

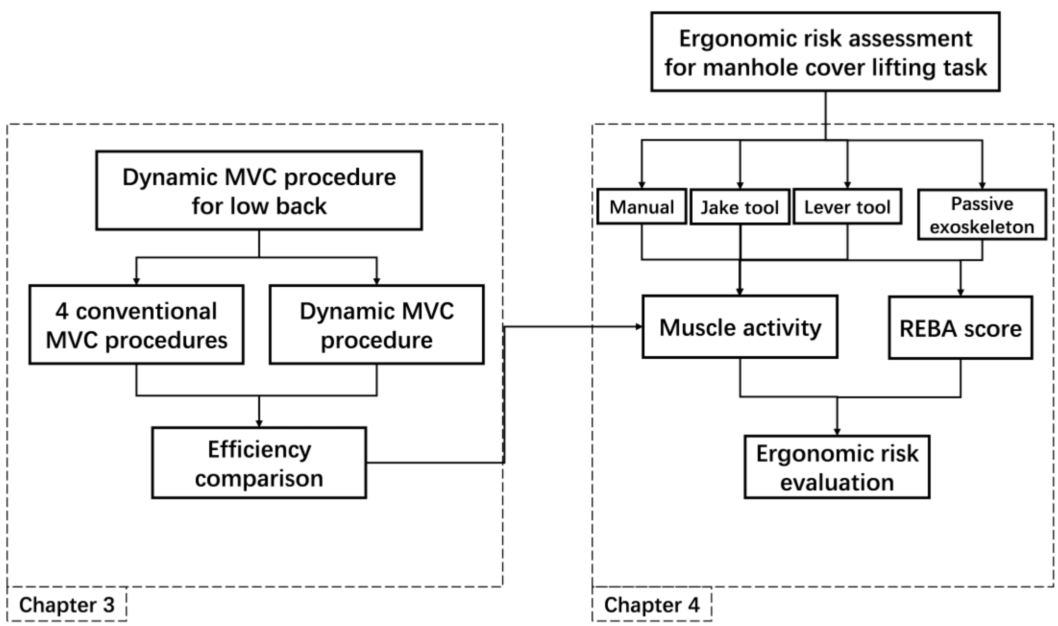


Figure 1. Thesis structure

Chapter 2 Literature review

2.1 Motion capture technology

The human body can be considered as having several rigid segments for its motion assessment, and the joint angles can be measured by measuring the two connected segments' orientation. Body posture, and its associated ergonomic risk, can be assessed based on the calculated joint angles. The motion capture methods include optical-based and inertial sensor-based methods, with the former having higher accuracy.

2.1.1 Optical capture system

Optical motion capture systems are widely applied in entertainment, biomechanics, ergonomics, and sports [16]. The performance and application of optical motion capture systems depend on motion capture technology, the number of cameras, and whether markers are used [17]. In most in-lab conditions, a multi-camera, marker-based system is applied for accurate and robust motion capture.

Despite being a more accurate system, it is not easy to set up and apply an optical motion capture system outside the lab or in specific places. Usually, the setting of an optical motion capture system requires i) a capture room with adequate space, a minimum sharp shadow cast on the floor, and sufficient illumination; ii) a specialized body suit or markers placed on anatomical landmarks; and iii) a proper number of synchronized cameras, depending on the motion range and room space [18]. With such complicated required resources, the optical motion capture system can be applied only in an ideal environment; it is not suitable for outdoor motion capture tasks such as our study condition.

2.1.2 Inertial measurement unit (IMU)

IMU is a widely used device that measures the velocity and orientation of a rigid IMU is a widely used device that measures the velocity and orientation of a rigid body, and is used, for example, in aircraft navigation. Currently, with the development of micro-electromechanics, IMUs have been introduced in a wider application field as attractive, small volume, low cost devices with high processing efficiency and low power consumption [19, 20]. An IMU usually contains accelerometers and gyroscopes, and some of the sensors also include magnetometers. With the data obtained from IMU sensors, the motion of the IMU itself as well as the rigid body attached to it can be calculated.

The orientation information is calculated according to the acceleration and angular velocity and is updated every second. However, the updating procedure is an open loop procedure; therefore, the calculated orientation error accumulates by the time when only acceleration and angular velocity are used [21]. Methods to calibrate the data and reduce the measurement error include: i) introducing calibration sensors like magnetometers and temperature sensors to compensate for the drift due to accumulated error and temperature changes, and ii) applying algorithms like Kalman filtering and novel calibration algorithms [22, 23].

Even when the orientation data are calibrated for human motion during a task, they cannot be translated directly into physiologically meaningful parameters. To analyze the body kinematics in the anatomical planes for ergonomic risk assessment, a sensor-to-body calibration is needed for further data translation [24].

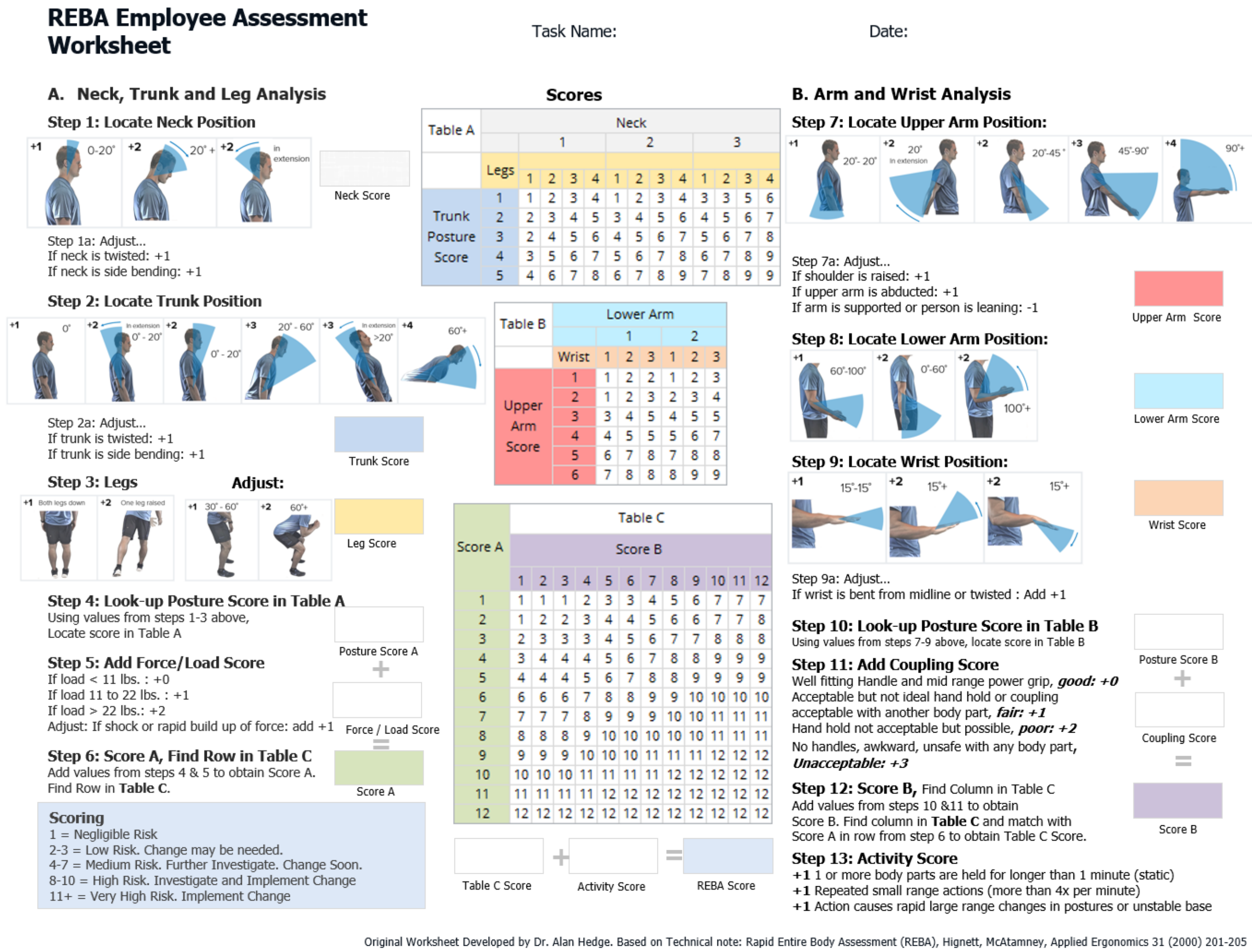
2.1.3 Sensor-to-body calibration

Sensor fusion algorithms are used conventionally to accurately obtain the IMU orientation used to calculate body joint angles for applications such as ergonomic risk assessment [19, 20, 25, 26]. However, to obtain anatomically meaningful joint angles using IMUs, the sensor coordinate system must be converted into an anatomical coordinate system. This procedure is called “sensor-to-body calibration.” Functional calibration is an approach to sensor-to-body calibration that uses several repeatable movements around a known axis of joint rotation [27]. Favre et al. introduced a functional calibration procedure to calibrate the sensor orientation through knee abduction/adduction movement. Nazarahari et al. also proposed a functional calibration procedure by using several groups of abduction/adduction and flexion/extension movements for lower limbs [26, 28] and obtained the calibration matrix using a combination of gravity vector and angular velocity data.

2.1.4 Posture-based ergonomic risk analysis

One of the main factors leading to WMSDs is awkward body posture; therefore, ergonomic risk can be evaluated according to the body joint angles and the total body postures. There are many scoring systems designed for ergonomic risk assessment including RULA, REBA, and OWAS [29].

RULA is an ergonomic tool for a rapid assessment of neck and upper limb loading in mainly sedentary tasks. The risk under this tool ranges from 1 (low risk) to 7+ (high risk) [30]. REBA is an extension of RULA, used to rapidly evaluate the ergonomic risk of WMSDs for the entire body during a physical task, and the risk ranges from 1 (low risk) to 11+ (high risk) [31]. Commonly, a worksheet like the following in Figure 2 and Figure 4 provide a clear look at the scoring systems and will be applied in actual tasks.



REBA Employee Assessment Worksheet

Task Name:

Date:

A. Neck, Trunk and Leg Analysis

Step 1: Locate Neck Position

+1 0-20° +2 20°+ +2 in extension

Neck Score

Step 1a: Adjust…
If neck is twisted: +1
If neck is side bending: +1

Step 2: Locate Trunk Position

+1 0° +2 in extension 0°-20° 0°-20° +3 20°-60° +3 in extension >20° +4 60°+

Step 2a: Adjust…
If trunk is twisted: +1
If trunk is side bending: +1

Trunk Score

Step 3: Legs **Adjust:**

+1 Both legs down +2 One leg raised +1 30°-60° +2 60°+

Leg Score

Step 4: Look-up Posture Score in Table A
Using values from steps 1-3 above,
Locate score in Table A

Posture Score A

+

Step 5: Add Force/Load Score
If load < 11 lbs. : +0
If load 11 to 22 lbs. : +1
If load > 22 lbs.: +2
Adjust: If shock or rapid build up of force: add +1

Force / Load Score

=

Step 6: Score A, Find Row in Table C
Add values from steps 4 & 5 to obtain Score A.
Find Row in **Table C.**

Score A

Scoring
1 = Negligible Risk
2-3 = Low Risk. Change may be needed.
4-7 = Medium Risk. Further Investigate. Change Soon.
8-10 = High Risk. Investigate and Implement Change
11+ = Very High Risk. Implement Change

Scores

Table A	Neck	1				2				3			
	Legs	1	2	3	4	1	2	3	4	1	2	3	4
Trunk Posture Score	1	1	2	3	4	1	2	3	4	3	3	5	6
	2	2	3	4	5	3	4	5	6	4	5	6	7
	3	2	4	5	6	4	5	6	7	5	6	7	8
	4	3	5	6	7	5	6	7	8	6	7	8	9
	5	4	6	7	8	6	7	8	9	7	8	9	9

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

Table C: Score A \ Score B	1	2	3	4	5	6	7	8	9	10	11	12
1	1	1	1	2	3	3	4	5	6	7	7	7
2	1	2	2	3	4	4	5	6	6	7	7	8
3	2	3	3	3	4	5	6	7	7	8	8	8
4	3	4	4	4	5	6	7	8	8	9	9	9
5	4	4	4	5	6	7	8	8	9	9	9	9
6	6	6	6	7	8	8	9	9	10	10	10	10
7	7	7	7	8	9	9	9	10	10	11	11	11
8	8	8	8	9	10	10	10	10	10	11	11	11
9	9	9	9	10	10	10	11	11	11	12	12	12
10	10	10	10	11	11	11	11	12	12	12	12	12
11	11	11	11	11	12	12	12	12	12	12	12	12
12	12	12	12	12	12	12	12	12	12	12	12	12

Table C Score + Activity Score = REBA Score

B. Arm and Wrist Analysis

Step 7: Locate Upper Arm Position:

+1 20°-20° +2 20° in extension +2 20°-45° +3 45°-90° +4 90°+

Step 7a: Adjust…
If shoulder is raised: +1
If upper arm is abducted: +1
If arm is supported or person is leaning: -1

Upper Arm Score

Step 8: Locate Lower Arm Position:

+1 60°-100° +2 0°-60° +2 100°+

Lower Arm Score

Step 9: Locate Wrist Position:

+1 15°-15° +2 15°+ +2 15°+

Wrist Score

Step 9a: Adjust…
If wrist is bent from midline or twisted : Add +1

Step 10: Look-up Posture Score in Table B
Using values from steps 7-9 above, locate score in Table B

Posture Score B

+

Step 11: Add Coupling Score
Well fitting Handle and mid range power grip, ***good: +0***
Acceptable but not ideal hand hold or coupling acceptable with another body part, ***fair: +1***
Hand hold not acceptable but possible, ***poor: +2***
No handles, awkward, unsafe with any body part, ***Unacceptable: +3***

Coupling Score

=

Step 12: Score B, Find Column in Table C
Add values from steps 10 &11 to obtain Score B. Find column in **Table C** and match with Score A in row from step 6 to obtain Table C Score.

Score B

Step 13: Activity Score
+1 1 or more body parts are held for longer than 1 minute (static)
+1 Repeated small range actions (more than 4x per minute)
+1 Action causes rapid large range changes in postures or unstable base

Original Worksheet Developed by Dr. Alan Hedge. Based on Technical note: Rapid Entire Body Assessment (REBA), Hignett, McAtamney, Applied Ergonomics 31 (2000) 201-205

Figure 2. REBA score worksheet, adopted from [32]

Score	Level of MSD Risk
1	negligible risk, no action required
2-3	low risk, change may be needed
4-7	medium risk, further investigation, change soon
8-10	high risk, investigate and implement change
11+	very high risk, implement change

Figure 3. REBA score risk level, adopted from [32]

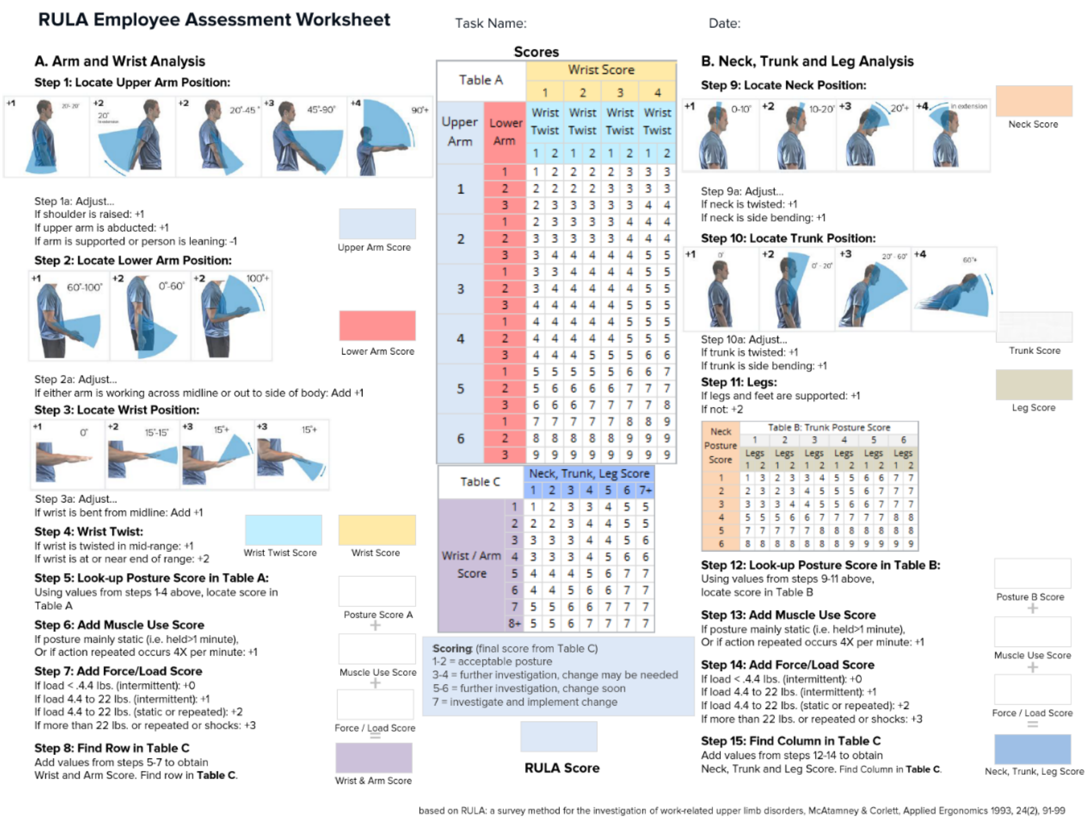


Figure 4. RULA score worksheet, adopted from [33]

Score	Level of MSD Risk
1-2	neglibible risk, no action required
3-4	low risk, change may be needed
5-6	medium risk, further investigation, change soon
6+	very high risk, implement change now

Figure 5. RULA score risk level, adopted from [33]

Range of motion (ROM) is a parameter commonly used to characterize the body's joint motions during a task and varies among different age groups, genders, body shapes, and clinical conditions [34]. As joint torque (a function of joint angles and muscle loads) is highly related to muscle fatigue and WMSDs [35], ROM can also indicate the ergonomic risk during work with fixed working loads, with lower ROM suggesting a lower risk level.

2.2 Muscle activity measurement technology

2.2.1 Surface electromyogram (sEMG)

The sEMG recorded for a muscle depends on the muscle contraction, and there is a relationship between peak-peak sEMG amplitude and muscle force [32]. Meanwhile, the effect of muscle fatigue can be reflected in the sEMG parameters, including the amplitude and frequency parameters [1, 29]. Therefore, the analysis of sEMG signals can be a valuable approach to muscle fatigue detection and thus, ergonomic risk assessment [36]. However, the sEMG signal can vary among participants and measurement conditions, and sEMG amplitude and frequency parameters may vary for identical tasks and target muscles in repeated measurement trials [37]. These variations can occur for both static and dynamic contraction [38]. Thus, the interpretation of sEMG data largely depends on the data collection and analysis procedures.

2.2.2 Data interpretation

Length of working time, body posture, and working load are the crucial factors that contribute to most muscle fatigue and WMSDs [39], with awkward body posture and unsafe working load being relatively easy to improve. As the changes in muscle activity will reflect on the sEMG signal, the ergonomic risk that comes from this factor can be evaluated through sEMG analysis. However, sEMG amplitude will be largely affected by different measurement conditions, and thus cannot be used for direct cross-participant comparisons [40]. Therefore, a proper normalization method is critical for cross-participant comparisons. Currently, the most used normalization methods include i) using the max value of the sEMG amplitude during a task as the normalization standard, and ii) using maximum voluntary contraction (MVC) data as the normalization standard. The latter is more commonly used [39]. However, as shown in a previous study carried out by

Farina et al. [38], the sEMG data collection during dynamic contraction can be more complicated compared to that during static contraction. The conventional MVC methods were not observed to be valid for low back muscles during the thesis study, as the recorded sEMG amplitudes during these conventional MVC procedures were frequently smaller than those recorded during the target task. Therefore, we proposed a novel dynamic MVC procedure for low back muscles, which will be described in Chapter 3.

On the other hand, considering different factors that lead to WMSDs, the ergonomic risk assessment experiment can be designed to investigate the impact of each factor, such as body posture and muscle activity. Usually, for able-bodied workers, higher sEMG signal amplitude can indicate higher muscle activity associated with heavier muscle loads, which might lead to a high risk of WMSDs within the workers' 6- to 12-month working period [2]. To study the ergonomic risk among construction workers doing manhole cover lifting tasks, a set of experimental procedures were designed as described in Chapter 4.

Chapter 3 A Dynamic Procedure to Detect Maximum Voluntary Contraction in Low Back

3.1 Introduction

Surface electromyography (sEMG) has an important role in ergonomic risk assessment and the diagnosis of musculoskeletal disorder (MSD) [41]. sEMG data can be interpreted based on the amplitude and frequency features of the collected sEMG signals. However, the sEMG amplitude can vary among individuals and measurement trials due to several factors, such as the location of electrode placement, the thickness of soft tissue between the muscle and the electrode, and skin preparation [42]. Therefore, to characterize the muscle activity based on the sEMG signal amplitude consistently among individuals and trials, the raw sEMG signal is usually normalized to that of maximum voluntary contraction (MVC), as a reference. The sEMG amplitude expressed as a percentage of MVC amplitude can then be used to evaluate muscle fatigue and the risk of MSD and to diagnose medical conditions [43].

For different muscles, different MVC exercises are used to record the sEMG amplitude when only the target muscle is activated under proper external force to reach the maximum contraction. This procedure could be straightforward for major muscles of the upper and lower limbs. Yet, due to the complex musculature of the low back and the presence of several layers of muscles under the skin, several muscles contribute to trunk bending. Therefore, it is extremely difficult to i) isolate the contraction of a muscle while maximizing its contraction to resist an external force, and ii) have the same group of muscles involved in the MVC task and the movement during the actual test [44]. As a result, the sEMG electrodes do not necessarily record the maximum activity of a targeted muscle during the MVC procedure [45, 46]. Currently, there are two ways to normalize the sEMG data: i) by using MVC data, and ii) by using maximum activity during the test procedure [40, 47]. When considering the first way, the back muscles are commonly separated into erector spinae and latissimus dorsi [48, 49], and the MVC will be based on the idea of maximum back extension against the manual force on a flat plane [50]. In this way, the MVC procedure only concentrates single muscles and only has a small range of motion for lumbar spine joints, thus it may perform smaller amplitudes than actual tasks due to skin formation, blood flow velocity, measured skin temperatures, tissue, structure, etc. [42]. On the other hand, when applying maximum activity during a physical task, the working load is not fixed, and the method can be efficient only when combined with other parameters (like torque and force, etc.) [51]. As a result, neither of these two methods may be valid for low back muscles in all task conditions.

Therefore, for lower back muscles (the left/right latissimus dorsi and left/right thoracolumbar fascia (part of lower erector spinae muscle), which are the muscles that are most frequently used in most physical tasks [44, 52]), we observed that the sEMG amplitude recorded during the actual task measurement is usually larger than that collected by conventional MVC exercises. Thus, to efficiently normalize the sEMG amplitude for the above-mentioned low back muscles, this study aimed to propose a set of novel dynamic MVC exercise procedures to obtain the largest possible sEMG amplitudes for muscles involved in a trunk-bending task. The validity of our proposed procedure was experimentally investigated and its results were compared with those collected by conventional MVC exercises.

3.2 Methods

3.2.1 Dynamic MVC measurement procedure

Usually, static exercises are used for MVC data collection for low back muscles; some common examples are seen in Figure 6 [44]. However, these methods do not always record a muscle activity signal higher than that found during the actual task. To illustrate this, we recorded the sEMG amplitude from the right latissimus dorsi during one of the most common MVC procedures (Figure 6 (c)) and compared it to a typical material handling task. The results are shown in Figure 7, where it is observed that the collected sEMG amplitude while performing the task is larger than the sEMG amplitude during the

MVC collection.

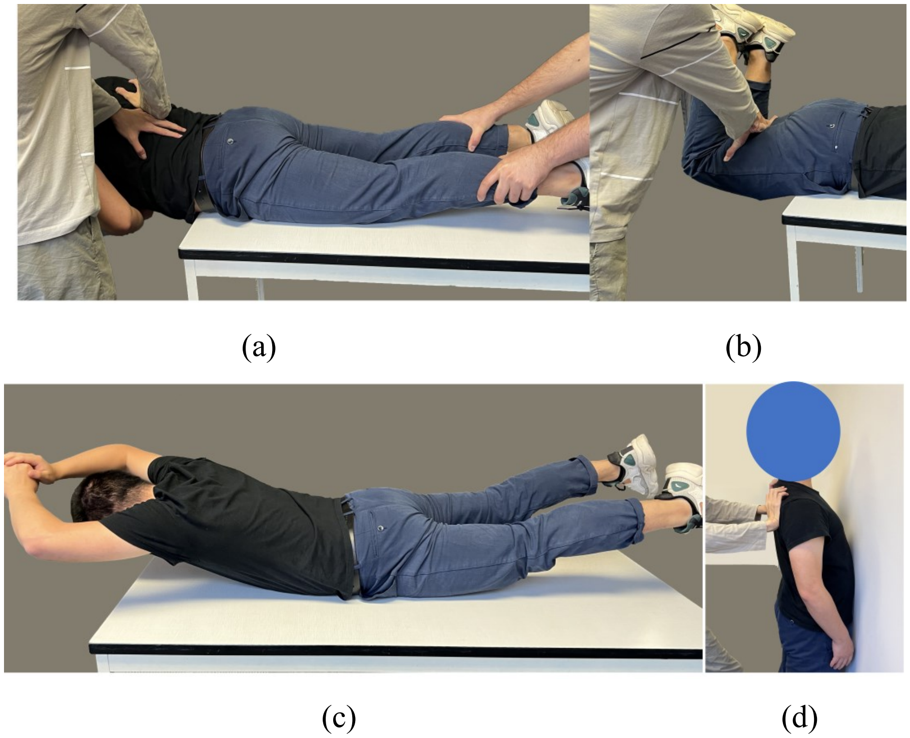


Figure 6. Four conventional MVC collecting exercises: (a) trunk bending, (b) leg bending, (c) -trunk-leg combined, (d) standing (adapted from [44]).

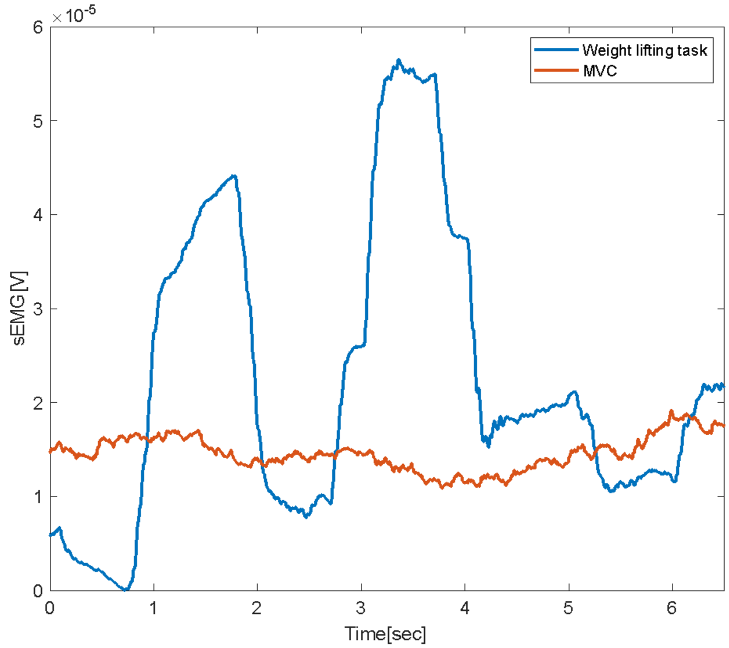


Figure 7. sEMG signal amplitude collected from a lower back muscle (right latissimus dorsi) during a weightlifting test and MVC collection.

Thus, we extended the MVC procedures to dynamic tasks to explore the highest sEMG amplitude recorded from the involved low back muscles. During the dynamic MVC procedure, participants were instructed to lift a 45 lb weight using only their low back muscles, which means that they needed to keep their elbows and knees straight during the movement (Figure 3). Also, external force was applied to control the pace and ensure the muscles had the maximum contraction. A metronome working at 40 bpm was used and participants were instructed to finish each motion within each beat. The external force varied among participants based on their body strength to produce maximum muscle contraction and make the participants follow a fixed pace produced by the metronome during the MVC procedure. The participants were instructed to perform the lifting task three times, as slowly and smoothly as possible.

(a) (b)

Figure 8. Dynamic MVC procedure: (a) start posture, and (b) end posture.

3.2.2 Experimental procedure

To investigate the efficiency of the dynamic MVC measurement procedure, a set of experimental procedures were designed. The data were collected from ten able-bodied participants (6 males and 4 females, body mass: 61.2±8.7 kg, body height:171.2±48 cm, age: 23.8±1.5 y.o.). Four EMG sensors (Trigno Avanti EMG sensor, Delsys, USA) were placed on the participant's right and left latissimus dorsi and thoracolumbar fascia (Figure 9), the muscles mainly involved in weightlifting tasks [53, 54]. To measure MVC, we used four conventional procedures seen in Figure 6 (trunk bending, leg bending, trunk-leg combined, and standing posture, which are commonly used and recommended by previous studies [40, 45-47]) and our novel dynamic MVC technique.

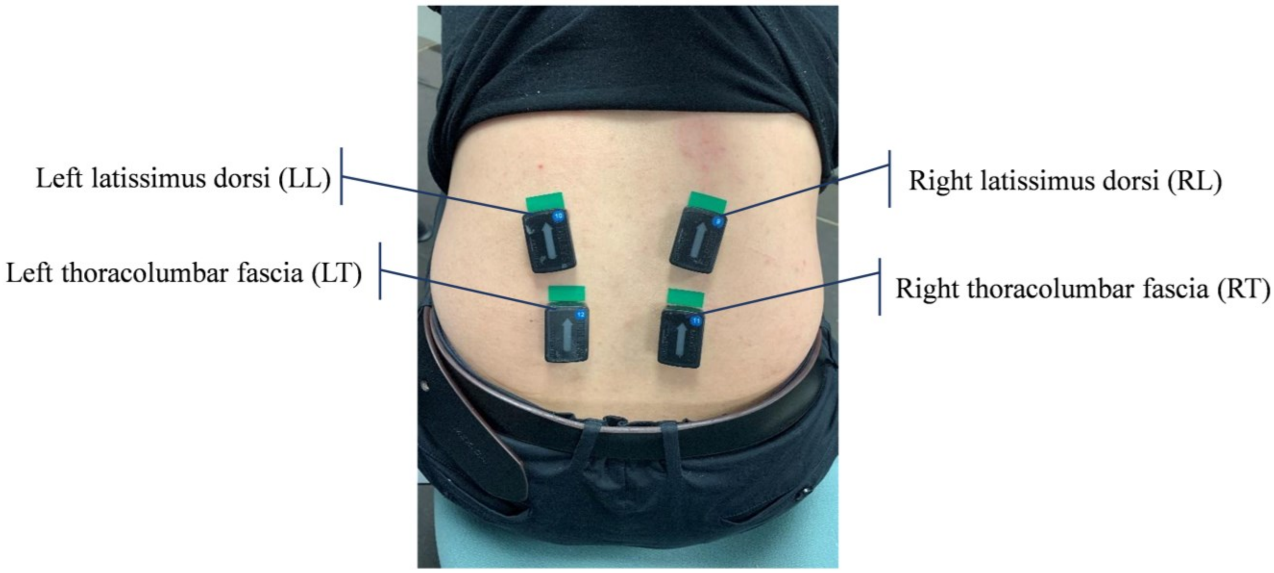


Figure 9. Placement of EMG sensor modules on lower back muscles.

Finally, the participants were instructed to perform a manual lifting task three times at their preferred pace and posture. The task consisted of lifting a 45 lb weight from the floor to the participant's chest and lowering it to the floor again. The sEMG data collected during this task was normalized by the four conventional MVC exercises and the proposed dynamic MVC procedure. Then, the normalized sEMG results for each muscle were compared together.

3.2.3 Data processing

3.2.3.1 EMG processing

The raw sEMG signal's amplitude can range within ± 5000 μV, with its energy concentrated mostly between 20 Hz to 150 Hz. The sEMG recording is usually rectified and band-pass filtered before further data interpretation [55, 56]. In this study, the data was collected at the sampling frequency of 2148.15 Hz (by EMGworks Acquisition software, Delsys, USA). The sEMG signal was processed as follows:

1. Remove the baseline error using the medium value during a quiet lying down

period.

2. Band-pass filter the EMG signal using a 4th-order Butterworth filter with cut-off frequencies of 10 Hz and 500 Hz.

3. Perform full wave rectification.

4. Smooth the results using a moving average filter with 500 sample points, 1 step length.

5. Calculate the root mean square (RMS) of the sEMG amplitude during the working period.

6. Normalize by the five different MVC procedures.

3.2.3.2 Statistical test

We hypothesized that the best MVC collection procedure records the highest sEMG amplitude and thus the lowest normalized sEMG amplitudes in the same actual lifting test and compare this to other MVC procedures. Thus, to investigate if the dynamic MVC procedure outperforms other conventional MVC collecting procedures, we used the paired Wilcoxon signed-rank test (since the distribution of the data was not normal) and compared the results normalized by the dynamic MVC collecting procedures to those normalized by conventional MVC procedures. The significant level for multiple comparisons (dynamic MVC procedure versus four conventional MVC procedures) was set to 0.05 and 0.0125 [57, 58].

3.3 Results

According to Figure 10, only the dynamic MVC procedure almost always obtained normalized sEMG amplitudes less than 100% (range from 65.81% to 70.95% according to Table 1), and also had the lowest normalized sEMG amplitudes among the five methods for all four target muscles. During the actual lifting task normalized by all four conventional MVC procedures, the sEMG amplitudes were frequently larger than 100%, which is a situation identical to that in the previous weightlifting experiments shown in Figure 7.

Table 1. Mean value and Standard deviation of normalized data

MVC test Muscles	Trunk bending	Leg bending	Trunk-leg combined	Standin g	Dynamic
Mean value	%	%	%	%	%
Left Latissimus dorsi	112.35	110.94	116.51	84.44	66.87
Right Latissimus dorsi	85.48	105.74	93.48	86.23	65.81
Left Thoracolumbar fascia	90.70	116.31	118.64	128.63	70.95
Right Thoracolumbar fascia	95.16	96.08	101.92	91.74	67.33
SD					
Left Latissimus dorsi	48.82	51.01	38.35	42.15	19.38
Right Latissimus dorsi	45.47	42.86	20.01	34.08	17.10
Left Thoracolumbar fascia	19.50	48.47	58.00	30.21	16.80
Right Thoracolumbar fascia	30.57	41.21	47.93	38.78	21.81

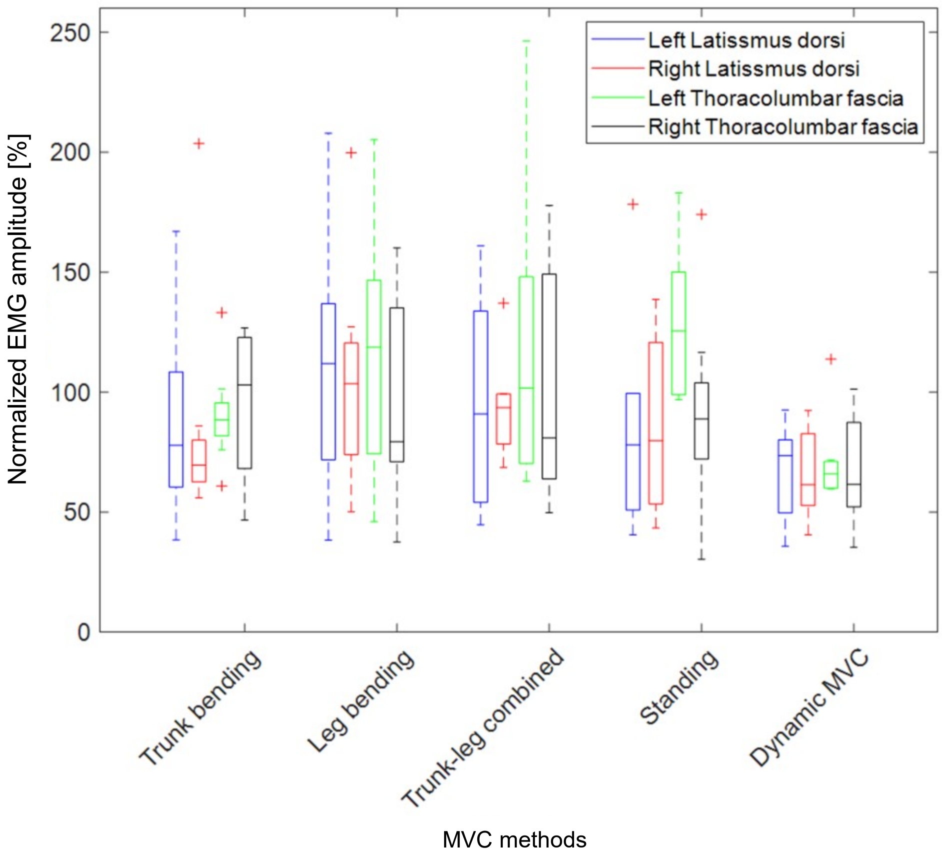


Figure 10. Differences between the sEMG amplitudes during the weight lifting test by the dynamic MVC procedure and those normalized by the four conventional MVC procedures.

According to Figure 10 and Table 2, based on the P-values for the Wilcoxon signed-rank test with dynamic MVC as a baseline, the differences are all significant between conventional MVC and dynamic MVC, with most of the P-values less than 0.05 (except for trunk bending MVC and standing MVC on the right latissimus dorsi, but the EMG amplitude for these muscles normalized by dynamic MVC showed an equal or lower level compared to that normalized by conventional MVC). On the other hand, the P-values for trunk bending MVC on the left/right thoracolumbar fascia, trunk-leg combined MVC on the right thoracolumbar fascia and standing MVC on the left thoracolumbar fascia are even less than 0.0125, which also suggests that the dynamic MVC has the best performance compared to corresponding conventional MVC methods for these muscles.

Table 2. P-values for the paired Wilcoxon signed-rank test on normalized EMG data for the duplicated task; each EMG data normalized by conventional MVCs were compared with that normalized by dynamic MVC.

Wilcoxon	Trunk bending	Leg bending	Trunk-leg combined	Standing
Left Latissimus dorsi	0.0391	0.0234	0.0391	0.0234
Right Latissimus dorsi	0.1094	0.0234	0.0156	0.0547
Left Thoracolumbar fascia	**0.0078***	0.0156	0.0391	**0.0078***
Right Thoracolumbar fascia	**0.0078***	0.0156	**0.0078***	0.0391

3.4 Discussion

The normalization of sEMG amplitude translates the raw voltage data into muscle activity relative to MVC and can provide meaningful information about muscle fatigue and MSDs [59, 60]. Due to the complex musculature of the low back, the conventional MVC measurement procedures usually fail to obtain sEMG that are larger than those collected during any weight-lifting tasks, a condition assumed for all MVC collections. This study aimed to address this challenge by defining a novel, dynamic MVC procedure for low back muscles that obtained the largest sEMG amplitudes during MVC collection and normalized sEMG amplitude during a weightlifting task, always to a value less than 100%. We also experimentally compared the performance of the proposed MVC procedure with conventional MVC procedures proposed in the literature.

We observed that the dynamic MVC procedure obtained higher sEMG amplitudes than all four other conventional MVC procedures. As a result, the sEMG amplitudes normalized by the dynamic MVC procedure were in general lower than those normalized by conventional MVC procedures for all four low back muscles that were studied (all p-values for the Wilcoxon signed-rank test were smaller than 0.05 except for trunk bending and standing as the MVC procedure for right latissimus dorsi). By calculating the differences and comparing them to 0 using the Wilcoxon signed-rank test, we observed that the sEMG amplitudes normalized by the dynamic MVC procedure were 18% to 46% lower than those normalized by conventional MVC procedures.

Low back muscles are prone to the crosstalk effect of multiple muscles, which could be the reason for obtaining a higher sEMG amplitude during a desired task than during the MVC procedure; another reason could be due to the misplacing of the sEMG electrodes [61, 62]. For body parts such as the low back during tasks such as trunk bending, in which the EMG signal will be affected by several muscles [24], introducing an MVC procedure that isolates contraction of a single muscle could be challenging and thus it may be reasonable to use dynamic MVC procedures instead of static procedures. Such a dynamic MVC procedure is collected during motion similar to the actual trunk-bending task but with maximum voluntary muscle contraction and thus, unlike conventional MVC procedures, has the potential to overcome errors due to crosstalk and electrode misplacement [64]. Although we did not discuss it here, we also implemented the dynamic MVC procedure during the in-field weightlifting test and observed its feasibility and efficiency.

This study focused only on low back muscles. Nevertheless, the efficiency of the proposed dynamic MVC concept method should be investigated in future studies for other body parts with complex musculature. Also, the feasibility of the proposed MVC approach should be further investigated for those with a disability or limited mobility.

3.5 Limitations and future works

This study introduced a new dynamic MVC measurement procedure for low back muscles. This dynamic MVC measurement procedure showed better performance compared to conventional static MVC tests for low back muscles, which was evident from obtaining the highest level of sEMG amplitude during the dynamic MVC procedure compared to conventional MVC procedures. The proposed dynamic MVC procedure was also the only MVC procedure that always obtained normalized sEMG amplitudes less than 100%, unlike the conventional MVC procedures. The efficiency of our proposed dynamic MVC procedure should be further investigated for other skeletal muscles.

Chapter 4 The Impact of a Passive Back Exoskeleton on Reducing Overexertion and Ergonomic Risk During Manhole Cover Lifting

4.1 Introduction

Lower back pain (LBP) is a commonly reported work-related musculoskeletal disorder (WMSD), especially in physically demanding jobs [65]. Several factors can lead to WMSDs, including working with heavy objects, awkward posture in the workplace, muscle fatigue, and overexertion [66]. WMSDs can lead to limited mobility, pain, and long-term muscle, joint, or nerve injury [67, 68]. Oftentimes, work-related LBP with light symptoms can be alleviated by adjusting the awkward posture, working load, and working shift, as well as by physical therapy [1]. Yet, many physically demanding tasks inherently expose workers to work-related LBP when these work condition modifications are not feasible.

Many utility maintenance workers need to move or lift manhole covers. Manhole covers are usually made of solid metal to prevent damage, for example, from vehicle passage and even from theft or vandalism, and their weight can range from 250-300 lbs on average. At the same time, since the cover lies on the ground, workers need to lift them, which is unsafe due to their weight Therefore, workers usually use hand tools with mechanisms (such as jake or lever tools in our situation) to lift the cover, which still requires a bending posture that can overload the low back muscles, discs, and other soft tissues [69]. As a consequence, both the object weight and body posture are unsafe for utility maintenance workers, and work-related LBP is common. To address the issue, many employers have applied new tools and machines, and implemented the use of personal protection equipment (PPE) for workers' safety. Recently, both passive and powered exoskeletons have been introduced as PPE in several industry sectors [70]. Given their low cost and convenience, passive exoskeletons have received more attention than powered exoskeletons [66]. Based on working posture and working load, exoskeletons are designed to support different body parts such as the shoulder, trunk, leg, and full body [71, 72]. However, because of differences in structures and working mechanisms, the performance of different exoskeletons can vary from task to task, and the efficiency of an exoskeleton for a given task is not guaranteed. Multiple types of passive exoskeletons for different physical tasks were developed and their efficiency was tested for muscle activity reduction in the upper limbs [73], low back [74], and legs [75] during a range of industrial task scenarios. Yet, the efficiency of passive exoskeletons for most real-world industrial tasks such as those in the area of utility maintenance is unknown.

Thus, in order to explore safe approaches to performing the manhole cover lifting task, this study aimed to investigate the impact of using passive exoskeletons on reducing ergonomic risk during the manhole cover removal task using a jake tool and using a lever tool. We hypothesized that the use of a jake, a lever, and an exoskeleton would reduce the ergonomic risk and overexertion. However, the interaction between these tools and the exoskeleton might have a negative impact.

4.2 Methods

4.2.1 Manhole cover lifting scenarios in real-world workplaces

When workers lift manhole covers of a special shape (e.g., a cover on the curb), they usually lift them manually using an awkward posture, transmitting nearly all the load onto their low back (Fig. 11(a)). When heavier covers need to be handled, workers commonly use the jake tool, which is a type of tool with a combination of sledgehammer and pick bar (shown in Figure. 11(b)), to move the manhole cover. However, because of its shape and function, the worker must have a bending posture to lift and drag the cover, which increases the risk of LBP in the long term. Also, manhole covers dragged with a jake tool can weigh over 120 lbs, which can overexert the low back muscles, discs, and soft tissues above their safe ranges.

Figure 11. Workers moving a manhole cover (a) manually, (b) using a jake tool, and (c) using a lever tool.

To reduce the working load and change the working posture, a lever tool may be used, consisting of a metal bar with a pedal and an adjustable chain with a hook at the end

(Figure 11(c)). When a lever tool is used, most of the load is transmitted to the ground, and the working load on the low back muscles and the working posture are improved.

Although a lever tool is conceptually safer than manual handling or using a jake, its efficiency in reducing the ergonomic risk has not yet been assessed for this work scenario.

4.2.2 Posture-related risk assessment

REBA is used to analyze the WMSD risk in general tasks based on body posture and joint angles. A worksheet explaining how to measure this score is shown in Figure 2 [32]. Since body motion measurements take place in a real-world scenario, we used wearable IMUs instead of the camera-based motion capture system, to measure the orientation of body segments during the manhole cover lifting task [19, 25]. Thus, in this study, the IMU sensors (MTws, Xsens Technologies, The Netherlands) were applied to record the workers' body posture during the tasks and then calculate the joint angles and the REBA scores. The IMUs were placed on the body according to Figure 12. First, we used a sensor-to-body calibration procedure to obtain physiologically meaningful joint angles. For this purpose, we asked the participants to perform limb flexion-extension motions in the sagittal plane (10 times), squat (10 times), and stand still (5 seconds). Then, following Nazarahari et al., we performed a virtual alignment of the IMUs' readouts into the body's anatomical frame [20, 25, 26, 28]. Second, we obtained the 3D orientation of body segments and, subsequently, the 3D joint angles using IMUs. For this purpose, we used algorithms previously validated in [19, 20]. Then, we calculated the REBA score as described in Figure 2 using the joint angles obtained by the IMUs. We previously validated the accuracy of REBA scores obtained by IMUs in [29].

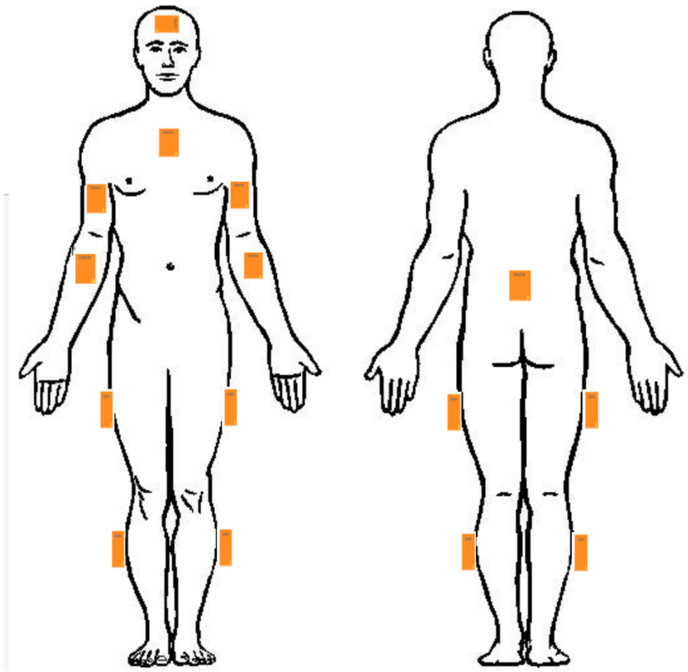


Figure 12. IMU sensor placement on the body segment. The orange boxes represent IMUs placed on the forehead, chest (over sternum), pelvis (over sacrum), upper arms, forearms, thighs, and shanks.

4.2.3 EMG data processing

To measure muscle activity during the manhole cover lifting task, we used sEMG sensors (Trigno, Delsys Inc, USA). The sensors were placed on the body according to Figure 13 and recorded at a sampling frequency of 2148.15 Hz using EMGworks acquisition software (Trigno, Delsys Inc, USA). We took the following steps to process the sEMG recordings:

(1) Remove the baseline error using the medium value during a quiet standing period since the muscle activities were compared to this posture throughout the tests.

(2) Filter the signal using a 4th-order band-pass Butterworth filter with cut-off frequencies of 10 Hz and 500 Hz, which was recommended by [56].

(3) Perform full wave rectification.

(4) Smooth the data using a moving average filter with a window length of 500.

(5) Recheck baseline error and eliminate it if needed.

(6) Normalize the sEMG amplitude by an MVC procedure for each muscle, similar to procedures in [56]

(7) Calculate the RMS of the normalized amplitude value during the working period.

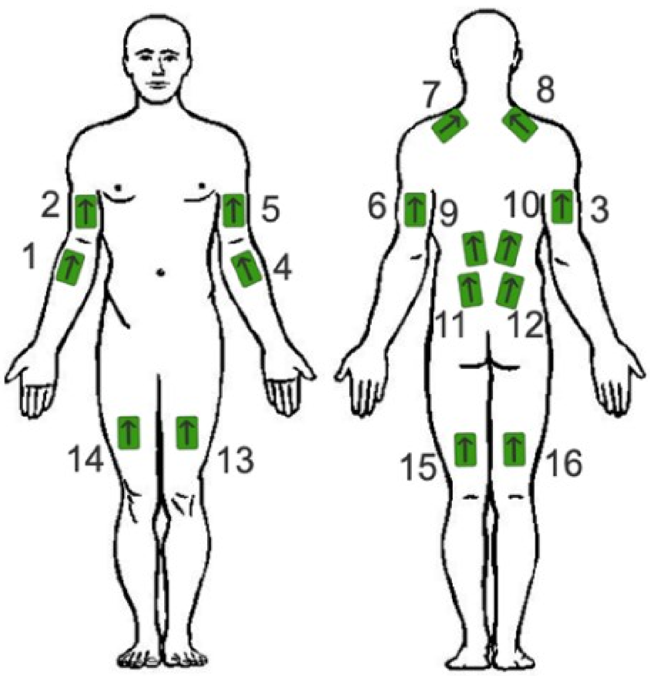


Figure 13. Surface electromyography (sEMG) sensor placement on body muscles: (1) Right brachioradialis, (2) Right biceps brachii, (3) Right triceps brachii, (4) Left brachioradialis, (5) Left biceps brachii, (6) Left triceps brachii, (7) Left trapezius middle branch, (8) Right trapezius middle branch, (9) Left latissimus dorsi, (10) Right latissimus dorsi, (11) Left thoracolumbar fascia, (12) Right thoracolumbar fascia, (13) Left rectus femoris, (14) Right rectus femoris, (15) Left bicep femoris, (16) Right bicep femoris.

4.2.4 Experimental procedure

Twenty able-bodied workers (19 males, 1 female, body mass: 78±15 kg, body height:172±9 cm, age: 37±10 y.o.) from drainage and construction departments who handle manhole cover removals as part of their daily work participated in this study.

sEMG sensing modules and IMUs were placed on their bodies and used to measure muscle activities and body posture during the task. The REBA score was obtained from body posture according to Section 2.2 above [31]. The REBA score and the RMS value of normalized sEMG amplitude during tasks with the jake or lever tool and with/without the exoskeleton were compared to evaluate the performance of the tools and the exoskeleton.

Each participant moved the manhole cover in three ways: for the light cover (40 lbs), the participants moved the cover manually, and for the heavier cover (125 lbs), the participants moved the cover once using the jake tool and once using the lever tool. Each trial was composed of two repetitions and five seconds of standing still at the beginning and end of each repetition to remove the sensors' measurement offset.

The exoskeleton used in this study was a back-support exoskeleton (BackX, SuitX, USA) with two designed modes: (i) standard mode, in which the exoskeleton is activated at a particular angle and provides more movability during non-work time, and (ii) instant mode, in which the exoskeleton is activated all the time. The participants were familiarized with the functioning of the exoskeleton prior to actual tests. All trials for moving the manhole cover manually and using the jake and lever tools were repeated two times each with both the standard mode and the instant mode of the exoskeleton (Figure 14).

Figure 14. Lifting a manhole cover using a lever tool while wearing an exoskeleton.

Finally, to collect feedback on the exoskeleton's efficiency, a rated perceived exertion (RPE) scale (range 0-10) was used to let the workers evaluate the work intensity for the task (Figure 15). Also, a questionnaire about the impact of wearing an exoskeleton and using tools on the participants' perception of load reduction in various body parts was used at the end of the test in the form of a Yes-No response.

1 – 10 Borg Rating of Perceived Exertion Scale	
0	Rest
1	Really Easy
2	Easy
3	Moderate
4	Sort of Hard
5	Hard
6	
7	Really Hard
8	
9	Really, Really Hard
10	Maximal: just like my hardest race

Figure 15. Borg scale, adapted from [76].

4.2.5 Data analysis

The REBA scores were used to compare the ergonomic risk based on the body posture using the tools and the exoskeleton. sEMG data were used to compare the muscle activities when a tool or an exoskeleton was used. To compare the effectiveness of tools, muscle activity without wearing exoskeletons was compared. To assess the exoskeleton's effectiveness, muscle activities for the tasks with the exoskeleton working in two modes were compared with tasks without the exoskeleton for the same tool. For all paired comparisons, the Wilcoxon signed-rank test (significance level: 5%) was used given that we did not observe a normal distribution for the data [57].

4.3 Results

The normalized EMG amplitude level varied for different tools and for the two functioning modes of the exoskeleton. When the workers lifted the light cover manually, wearing the exoskeleton in both instant and standard modes impacted muscle activity compared to when the tasks were performed without the exoskeleton (Figure 16). Neither the standard nor instant modes showed a general trend in reducing or increasing muscle activity. The standard mode of the exoskeleton significantly increased the activity of the left triceps brachii by 18.7% (within groups among participants) and significantly decreased the activity of the left thoracolumbar fascia by 15.0%. Its instant mode, however, significantly decreased the activity of the right thoracolumbar fascia by 21.5% (Table 3). The use of the exoskeleton in both modes slightly improved the REBA score (Figure 17).

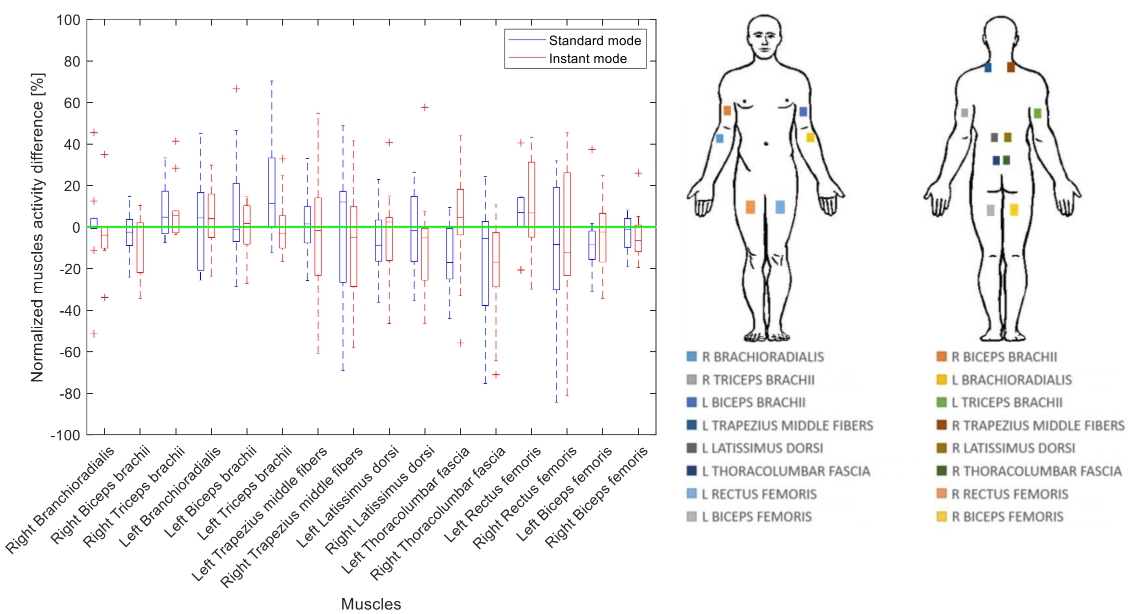


Figure 16. Boxplots (among participants) showing the relative change of muscle activity when an exoskeleton was used compared to manually lifting the manhole cover without the exoskeleton for both standard mode (blue) and instant mode (red). A positive percentage shows an increase in muscle activity when the exoskeleton was worn.

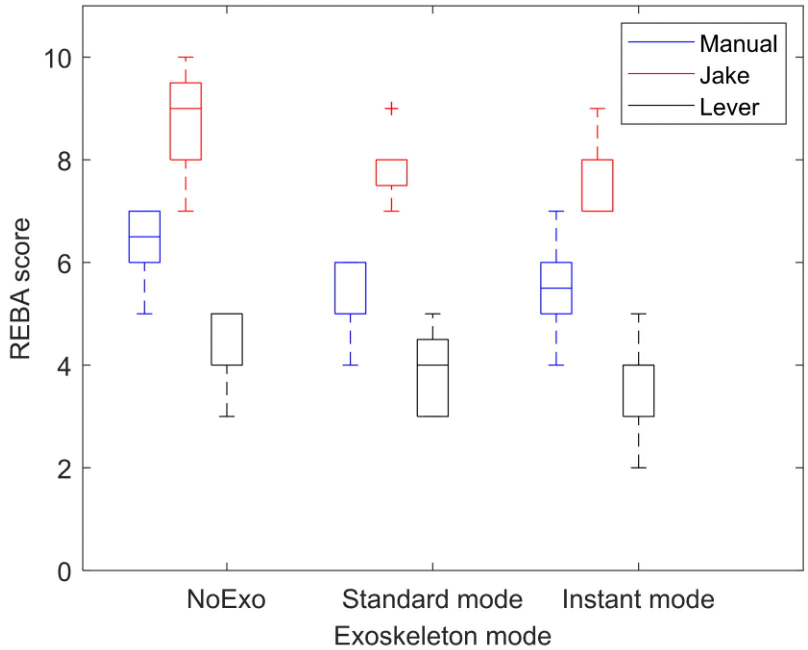


Figure 17. REBA scores for different tools and Exoskeleton mode.

Table 3. The relative change of muscle activity when an exoskeleton was used (both standard and instant modes) compared to manually lifting the manhole cover without the exoskeleton. P-values for paired comparisons between muscle activity during lifting tasks with and without an exoskeleton are also reported. A positive percentage shows an increase in muscle activity when the exoskeleton was worn. The shaded cells indicate a significant difference.

	Standard mode vs Manual		**Instant mode vs Manual**	
Muscle name	**muscle activity change (%)**	**p-value**	**muscle activity change (%)**	**p-value**
Right BRACHIORADIALIS	0.2	0.85	-3.3	0.23
Right BICEPS BRACHII	-3.7	0.43	-6.5	0.62
Right TRICEPS BRACHII	7.5	0.19	8.4	0.08
Left BRACHIORADIALIS	5.0	0.77	4.6	0.43
Left BICEPS BRACHII	8.4	0.77	-0.1	0.70
Left TRICEPS BRACHII	18.7	0.049	0.5	0.70
Left TRAPEZIUS MIDDLE FIBERS	2.6	0.70	-1.2	0.92
Right TRAPEZIUS MIDDLE FIBERS	1.0	0.77	-8.2	0.56
Left LATISSIMUS DORSI	-6.2	0.28	-2.1	0.85
Right LATISSIMUS DORSI	-2.2	0.85	-6.0	0.23
Left THORACOLUMBAR FASCIA	-15.0	0.037	2.1	0.70
Right THORACOLUMBAR FASCIA	-17.1	0.19	-21.5	0.037
Left RECTUS FEMORIS	6.0	0.32	8.1	0.28
Right RECTUS FEMORIS	-11.5	0.49	-7.2	0.70

Left BICEPS FEMORIS	-6.4	0.11	-5.2	0.43
Right BICEPS FEMORIS	-2.5	0.49	-3.6	0.28

When the task involved lifting the heavy covers, the RMS muscle activity for a jake tool was usually larger compared to when a lever tool was used (Figure 18). This larger muscle activity when a jake tool was used was significant for the left and right latissimus dorsi (24.1% and 19.4%, respectively), right thoracolumbar fascia (25.5%), left and right rectus femoris (32.8% and 28.7%, respectively), and right biceps femoris (22.4%) (Table 4). The use of a lever tool led to a much smaller REBA score compared to the use of a jake tool, indicating a smaller ergonomic risk (Figure 17).

Table 4. The relative change of muscle activity when a jake tool was used compared to when a lever tool was used. P-values for paired comparisons between muscle activity during lifting tasks with a jake and a lever are also reported. A positive percentage shows an increase in muscle activity when a lever was used. The shaded cells indicate a significant difference.

	Jake vs Lever	
Muscle name	**muscle activity change (%)**	**p-value**
Right BRACHIORADIALIS	11.29	0.43
Right BICEPS BRACHII	-6.74	0.38
Right TRICEPS BRACHII	-4.46	0.56
Left BRACHIORADIALIS	-9.10	0.43
Left BICEPS BRACHII	-1.75	0.85
Left TRICEPS BRACHII	-0.46	0.49
Left TRAPEZIUS MIDDLE FIBERS	-5.85	0.56
Right TRAPEZIUS MIDDLE FIBERS	-1.13	0.92
Left LATISSIMUS DORSI	-24.14	0.00
Right LATISSIMUS DORSI	-19.40	0.03
Left THORACOLUMBAR FASCIA	-9.74	0.49
Right THORACOLUMBAR FASCIA	-25.49	0.01
Left RECTUS FEMORIS	-32.85	0.01
Right RECTUS FEMORIS	-28.67	0.00
Left BICEPS FEMORIS	2.19	0.85
Right BICEPS FEMORIS	-22.39	0.01

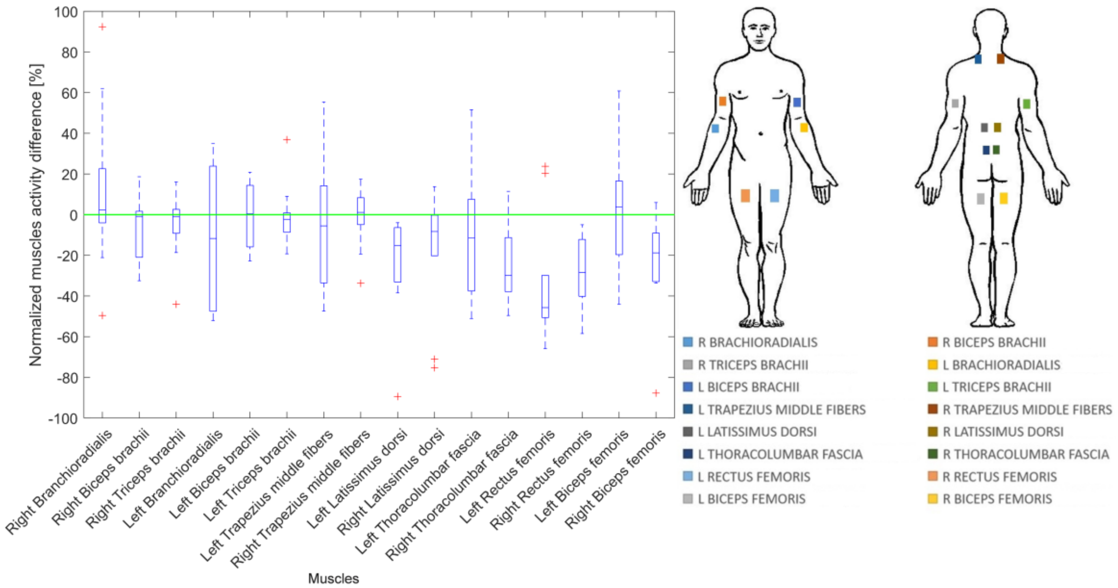


Figure 18. Boxplots (among participants) showing the relative change of muscle activity when a jake tool was used compared to when a lever tool was used. P-values for paired comparisons between muscle activity during lifting tasks with a jake and a lever are also reported. A positive percentage shows an increase in muscle activity when a lever was used.

When the workers lifted the heavy cover using a jake tool, wearing the exoskeleton in both instant and standard modes usually decreased the muscle activity compared to when the task was performed using a jake tool without the exoskeleton (Figure 19). This decrease in muscle activity was significant but around or less than 10%, and usually less than 5% in the left and right biceps brachii and triceps brachii, left brachioradialis, left biceps femoris, left rectus femoris (only standard mode), right rectus femoris (only instant mode) and right thoracolumbar fascia (only standard mode). The exoskeleton's use significantly and considerably (10% to 24%) decreased muscle activity in the left and right latissimus dorsi. However, the exoskeleton's use in standard mode significantly increased (5.9%) the activity of the right trapezius middle fibers (Table 5). The exoskeleton's use in both modes slightly improved the REBA score when the jake tool was used as well (Figure 17).

Table 5. The relative change of muscle activity when an exoskeleton was used (both standard and instant modes) together with a jake tool compared to when only a jake tool was used for lifting the manhole cover. P-values for paired comparisons between muscle activity during lifting tasks using a jake together with and without an exoskeleton are also reported. A positive percentage shows an increase in muscle activity when the exoskeleton was worn. The shaded cells indicate a significant difference.

	Jake Standard BSE		Jake Instant BSE	
	muscle activity/%	p-value	muscle activity/%	p-value
Right BRACHIORADIALIS	7.34	0.43	10.00	0.11
Right BICEPS BRACHII	-4.68	0.05	-0.49	0.00
Right TRICEPS BRACHII	-7.68	0.00	-3.49	0.00
Left BRACHIORADIALIS	-9.61	0.01	-10.29	0.00
Left BICEPS BRACHII	1.93	0.02	1.81	0.03
Left TRICEPS BRACHII	-1.62	0.01	-1.16	0.05
Left TRAPEZIUS MIDDLE FIBERS	6.11	0.92	14.21	0.56
Right TRAPEZIUS MIDDLE FIBERS	5.94	0.02	-1.61	0.19
Left LATISSIMUS DORSI	-10.17	0.01	-17.65	0.03
Right LATISSIMUS DORSI	-21.70	0.00	-23.99	0.01
Left THORACOLUMBAR FASCIA	2.26	0.85	7.30	0.63
Right THORACOLUMBAR FASCIA	-3.77	0.05	-3.62	0.11
Left RECTUS FEMORIS	-1.66	0.01	-8.04	0.28
Right RECTUS FEMORIS	-2.66	0.11	-16.41	0.05
Left BICEPS FEMORIS	-3.95	0.01	-3.27	0.00
Right BICEPS FEMORIS	-5.82	0.23	-0.49	0.13

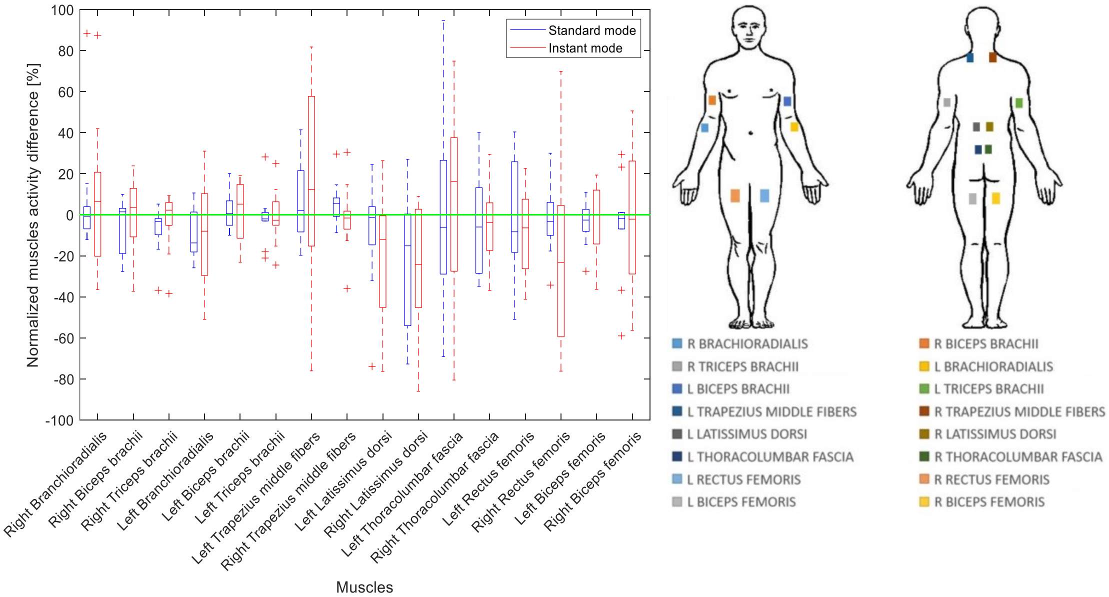


Figure 19. Boxplots (among participants) showing the relative change of muscle activity when an exoskeleton together with a jake tool was used, for both standard mode (blue) and instant mode (red), compared to when only a jake tool was used for lifting the manhole cover. A positive percentage shows an increase in muscle activity when the exoskeleton was worn.

When the workers lifted the heavy cover using a lever tool, wearing the exoskeleton in both instant and standard modes decreased the activity of some muscles and increased the activity of others compared to when the task was performed using a lever tool without the exoskeleton (Figure 20). However, this trend was significant only toward a decrease of muscle activity when an exoskeleton was used (except for the right triceps brachii (0.4%) when the exoskeleton was in the instant mode) and mostly when it was in the instant mode: left triceps brachii (3.6%), right latissimus dorsi (19.1%), left and right thoracolumbar fascia (19.2% and 9.7%), right rectus femoris (0.6%), and left and right biceps femoris (9.6% and 3.2%) (Table 6). The exoskeleton's use in both modes slightly improved the REBA score when the lever tool was used as well (Figure 17).

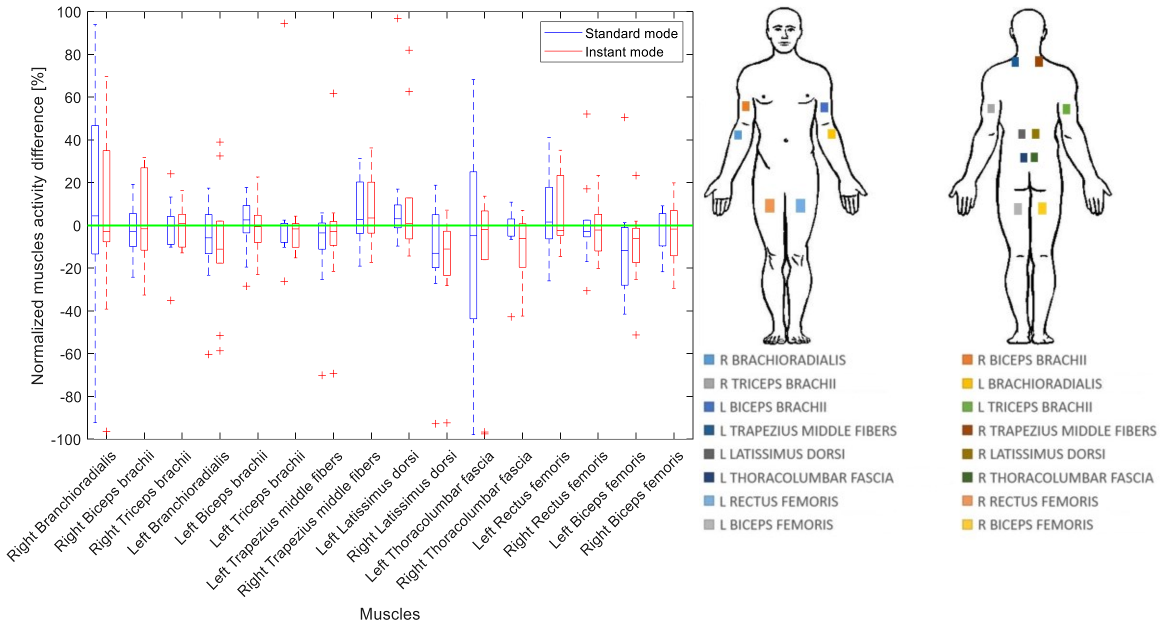


Figure 20. Boxplots (among participants) showing the relative change of muscle activity when an exoskeleton together with a lever tool was used, for both standard mode (blue) and instant mode (red), compared to when only a lever tool was used for lifting the manhole cover. A positive percentage shows an increase in muscle activity when the exoskeleton was worn.

Table 6. The relative change of muscle activity when an exoskeleton was used (both standard and instant modes) together with a lever tool compared to when only a lever tool was used for lifting the manhole cover. P-values for paired comparisons between muscle activity during lifting tasks using a lever together with and without an exoskeleton are also reported. A positive percentage shows an increase in muscle activity when the exoskeleton was worn. The shaded cells indicate a significant difference.

	Lever Standard BSE		Lever Instant BSE	
	muscle activity/%	p-value	muscle activity/%	p-value
Right BRACHIORADIALIS	8.96	1.00	1.74	0.70
Right BICEPS BRACHII	-3.04	0.08	2.51	0.43
Right TRICEPS BRACHII	-1.39	0.23	0.41	0.01
Left BRACHIORADIALIS	-8.36	0.06	-9.42	0.16
Left BICEPS BRACHII	-0.56	0.38	-0.79	0.06
Left TRICEPS BRACHII	5.17	0.08	-3.57	0.00
Left TRAPEZIUS MIDDLE FIBERS	-10.97	0.00	-4.51	0.06
Right TRAPEZIUS MIDDLE FIBERS	5.60	1.00	5.97	0.49
Left LATISSIMUS DORSI	12.32	0.70	13.34	0.49

Right LATISSIMUS DORSI	-14.76	0.05	-19.14	0.00
Left THORACOLUMBAR FASCIA	-12.04	0.49	-19.23	0.01
Right THORACOLUMBAR FASCIA	-3.60	0.04	-9.67	0.00
Left RECTUS FEMORIS	3.54	0.92	5.13	0.56
Right RECTUS FEMORIS	1.01	0.32	-0.63	0.05
Left BICEPS FEMORIS	-9.45	0.06	-9.56	0.02
Right BICEPS FEMORIS	-2.88	0.03	-3.21	0.05

Similar to the results of the REBA score and the normalized sEMG amplitude, the lever tool tended to be the most favored tool, based on the participants' feedback, while doing the task manually was the least favored approach (Figure 21). Also, results showed that around 80% of participants have high confidence that the exoskeleton can help reduce the working load on the leg and low back, but not on the shoulders and arms (Figure 22). The wearing of an exoskeleton did not affect feedback much on task difficulty or even on whether it helped reduce the task difficulty. Yet participants felt that the two exoskeleton modes reduced the workload on body parts similarly.

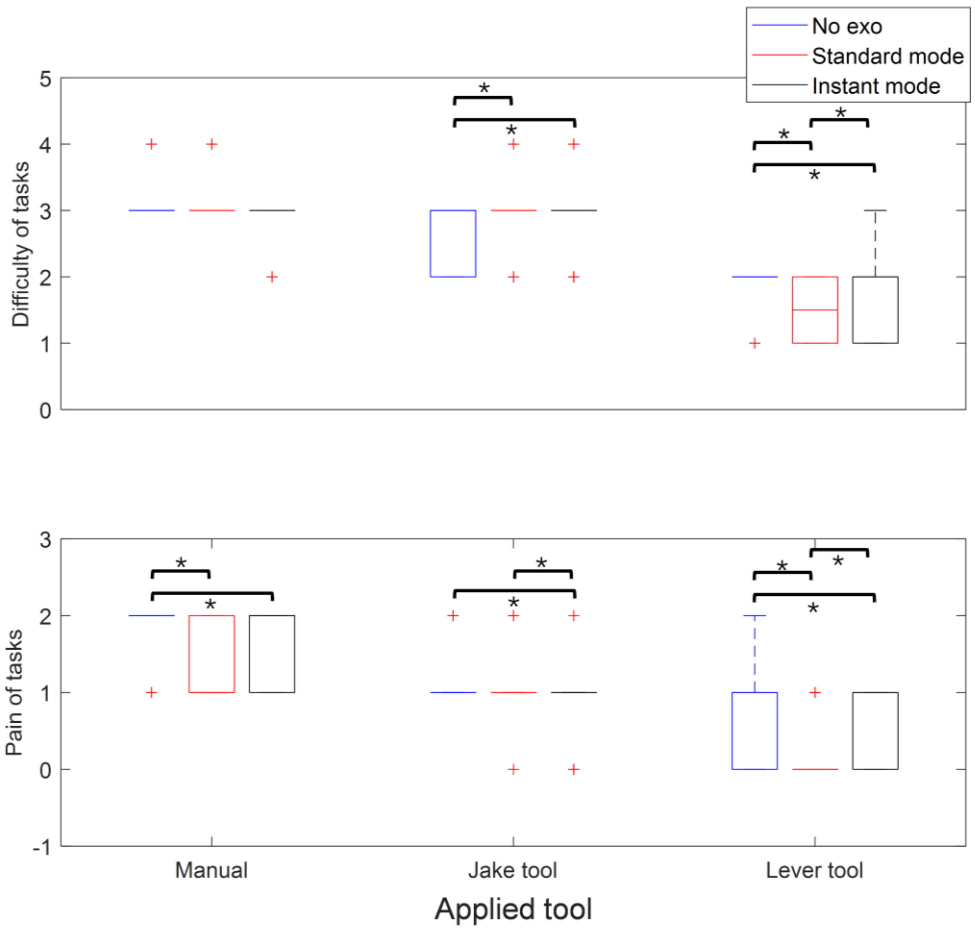


Figure 21. User feedback scores on difficulty and RPE scores on tasks using different methods with/without exoskeleton (asterisks indicate significant differences with p-values less than 5% for the Wilcoxon signed-rank test).

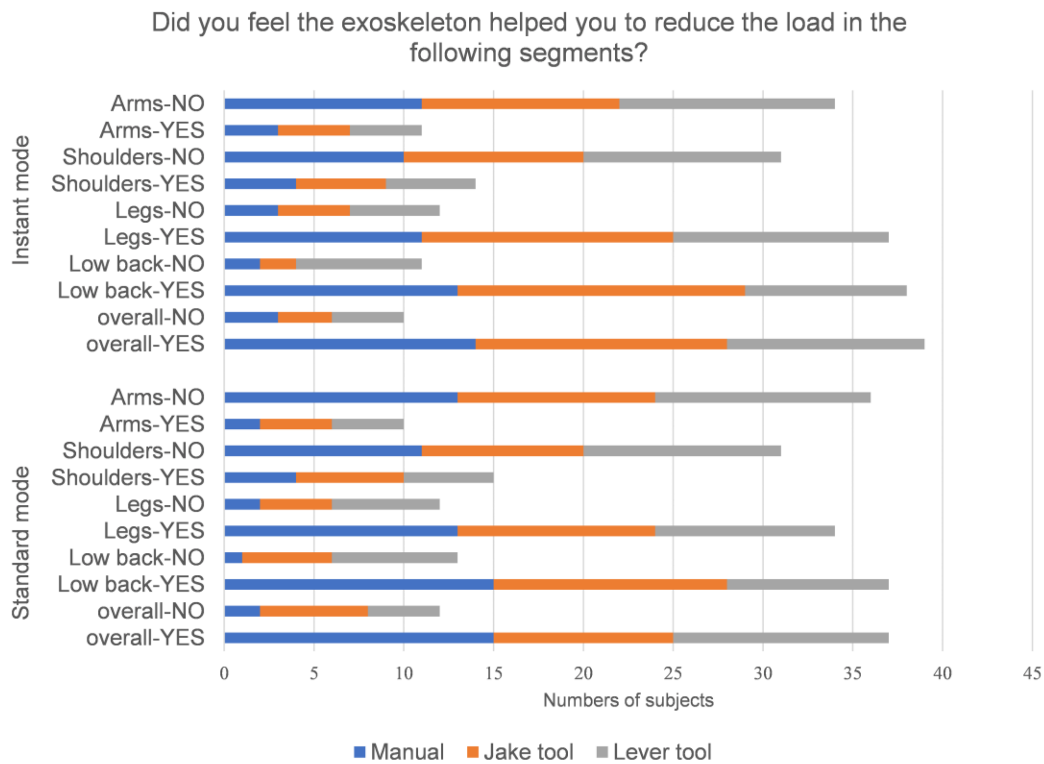


Figure 22. Subjective user feedback on the question "Do you feel the exoskeleton helped you to reduce the load in each part of your body?" The exoskeleton is compared to the condition without the exoskeleton.

4.4 Discussion

In this study, we investigated the effectiveness of passive back support exoskeletons in reducing the ergonomic risk during a manhole cover removal task, when the task was performed manually, using a jake tool, and using a lever tool. To this end, we compared the muscle activities obtained by sEMG sensors and the REBA scores obtained by IMUs in different scenarios. To our knowledge, this is the first time that the effectiveness of using a passive exoskeleton together with tools such as a jake and a lever for lifting or moving a heavy manhole cover has been investigated. It is also the first time that such physiological measurements have been conducted in a real-world environment and on real workers to assess the effectiveness of a passive exoskeleton for the use of manhole cover removals. We observed that a passive back-support exoskeleton does not equally benefit the participants when they perform the lifting task manually and when they use different tools. The body posture used for such a lifting task, with or without a tool, impacted the exoskeleton's effectiveness.

Since the manhole cover used for manual lifting or lifting using a tool had different weights, we were not able to compare the effectiveness of the jake and lever tools with manual lifting. Therefore, we only compared the effectiveness of the two tools. In general, we observed that the activities of muscles in the lower limbs and lower back areas were smaller (from 20% to 32%) when using a lever tool compared to a jake tool (Table 4 and Figure 18). Also, the workers had a body posture with a smaller ergonomic risk (characterized by the REBA score) when a lever tool was used compared to a jake tool. Moreover, when they applied a lever tool, participants felt it was easier to lift the manhole cover, which is supported by the feedback on task difficulty for different tools (Fig. 21). Thus, the lever tool was more effective than a jake tool when a passive back support exoskeleton was not used.

The application of a back-support exoskeleton was expected to improve the ergonomic risk and muscle load [77, 78]. When a passive back support exoskeleton was used to perform the manual lifting task, we did not observe much difference in most muscle activities and the REBA scores, compared to when the exoskeleton was not used (Table 3 and Figure. 16). We only observed a trend (although often not significant) that showed the exoskeleton increased the load on arms and upper trunk muscles but reduced the load on legs and low back muscles. Thus, we are not able to recommend using or not using the exoskeleton for manual lifting. Possible causes for the lack of significant effects of the exoskeleton may be: (1) the workers were not acquainted with the applied exoskeleton and their preferred body movement patterns were restricted by it, and (2) the personal habits and preferred posture for manual lifting tasks varied significantly between the workers, which might have adversely affected the exoskeleton's performance. Also, based on the workers' feedback, due to the unfamiliarity with the exoskeleton, wearing it was not comfortable and helpful compared to performing the tasks with constraints imposed by the exoskeleton.

However, when a jake or lever tool was used, the workers' body motion and posture were more consistent. Therefore, the effectiveness of a back support exoskeleton was more consistently observed in both standard and instant modes and for most muscles. The combined use of the back support exoskeleton and a jake tool reduced muscle activity for most muscles by up to 21.7% in the standard mode and up to 24.0% in the instant mode, compared to when the jake tool was used alone. Among all muscles, low back muscles benefited the most from a back support exoskeleton. Yet, assessments based on the REBA scores showed that the addition of an exoskeleton did not significantly change the body posture.

When the passive back support exoskeleton was used together with a lever tool, the reduction in muscle activity was significant, especially in the instant mode (up to 14.8% for standard mode and 19.2% for the instant mode); however, fewer muscles benefited from the exoskeleton's addition compared with the combination of the exoskeleton and the jake tool. Once again, low back muscles benefited from the exoskeleton's addition more than other muscles. Also, the addition of an exoskeleton did not significantly change the REBA score. The difference between the exoskeleton's effectiveness when combined with the jake and lever tools could be due to the participant's body posture when using these tools. Tasks involving trunk bending load the low back muscles the most and the worker would benefit from the use of a back support exoskeleton [79, 80]. Thus, the muscle activity reduction from using the exoskeleton when a jake tool was used (with a larger trunk-bending angle compared to when a lever tool is used) was larger than the muscle activity reduction when the exoskeleton was worn to perform the task with a lever tool, in which the trunk bending was minimal. In summary, we conclude that the effectiveness of a passive back support exoskeleton highly depends on the body posture in which the task is performed [81].

Also, participants' feedback on the task difficulty for different tools showed that the wearing exoskeleton change much on the feeling of difficulty and pain, and even had a significant reduction in difficulty and pain except for the difficulty of lifting the cover manually. Over 75% of participants also felt much more confident in the efficiency of the exoskeleton for reducing the working load on low back and leg segments during the manhole cover lifting task for all situations.

4.5 Limitations and future works

Some of the limitations of this study are: (1) we studied muscle activity, body posture based on REBA score, and users' feedback based on questionnaires. Other factors, such as energy expenditure, may impact the exoskeleton's efficiency and must be studied in the future; and (2) our findings and their interpretation are limited to a specific type of exoskeleton used for a specific task. In the future, the efficiency of other exoskeletons used for other real-world tasks should be investigated.

We investigated the effectiveness of using a passive back support exoskeleton for manhole cover lifting tasks both manually and together with a jake or lever tool. We found that the effectiveness of the exoskeleton highly depends on the body posture in which the exoskeleton is used. We conclude that using a lever tool should be recommended for lifting the manhole cover because of the better body posture and muscle load in this technique. Some workers prefer to use a jake tool, for example, to loosen the manhole cover before lifting it. When using either of these tools, especially a jake tool, workers can reduce the ergonomic risk and low back muscle load by using a back support exoskeleton. Due to person-specific preferred postures for lifting lighter manhole covers manually, we could not make a recommendation on the use of a passive back support exoskeleton for this task. The effectiveness of different back support exoskeletons for various tasks should be further studied in the future.

Chapter 5 Discussion and Conclusions

This thesis research investigated the ergonomic risk during in-field manhole cover lifting tasks on different tools from the perspectives of body posture and muscle activity, as well as the efficiency of using a passive exoskeleton for these tasks. This thesis research study also proposed solving the actual sEMG normalization issue by providing novel MVC methods.

In ergonomic risk assessment studies, WMSDs are frequently reported to have risk factors, such as body posture and working load. Thus, the risk level can be evaluated by collecting body motion and muscle activity data. The sEMG signal normalization is often required for muscle activity data collection, and the development of an MVC procedure is a prerequisite to data analysis such that the normalized sEMG amplitude values never exceed 100% during dynamic motion. Therefore, an MVC procedure should be established for such tasks.

To evaluate the ergonomic risk for construction workers during the manhole cover lifting tasks and to study the efficiency of passive exoskeletons applied in these tasks, a series of experiment protocols and questionnaires were designed to collect and analyze the biomechanical data. With the help of a unified experiment protocol and data analysis methods, the ergonomic risk with different tools and the utility of the exoskeleton were compared; based on the comparison results from WSMD factors, certain recommendations to reduce the ergonomic risk can be provided for construction workers. Based on the data analysis results, the use of the lever tool together with an exoskeleton is the safest combination with a minimum working load and best posture among all situations in manhole cover lifting tasks. This ergonomic risk assessment procedure, based on both body posture and muscle working load measurement, can also be considered valid for other industrial scenarios as a systematic method to evaluate the ergonomic risks as well as the application of PPE such as passive exoskeletons. Considering the complexity of manhole cover lifting tasks, differences were observed between different tools and personal habits during the data collection. Thus, the efficiency of the exoskeleton for both dynamic tasks and static tasks should be further studied in the future. Also, as there are different designs of exoskeletons targeted to different tasks, the efficiency of different exoskeleton designs on complex tasks is worth further study.

To address the problem of sEMG signal normalization for lower back muscles, we also proposed a novel MVC collecting procedure according to the relationship between body movements and muscle activity modulation. We showed that in ergonomic risk assessments, the proposed dynamic MVC procedure had better efficiency than the conventional MVC procedures for low back muscles. The proposed dynamic MVC methods are not limited to low back muscles but can also be adjusted for different muscles for specific tasks with a large range of motion and high motion frequency. For example, especially for trapezius muscles, the normalized sEMG signal during the lifting tasks was close to 100%, which may present another application of dynamic MVC procedures.

Our proposed ergonomic risk assessment and dynamic MVC procedures were only targeted to certain work scenarios. However, considering the association between different tasks, both methods should be extended to similar study topics and can be adjusted for different scenarios in future research.

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