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Evaluating the Effect of the Spineband Neck Flexion Exoskeleton on Muscle Workload and Work Posture among Floor Layers

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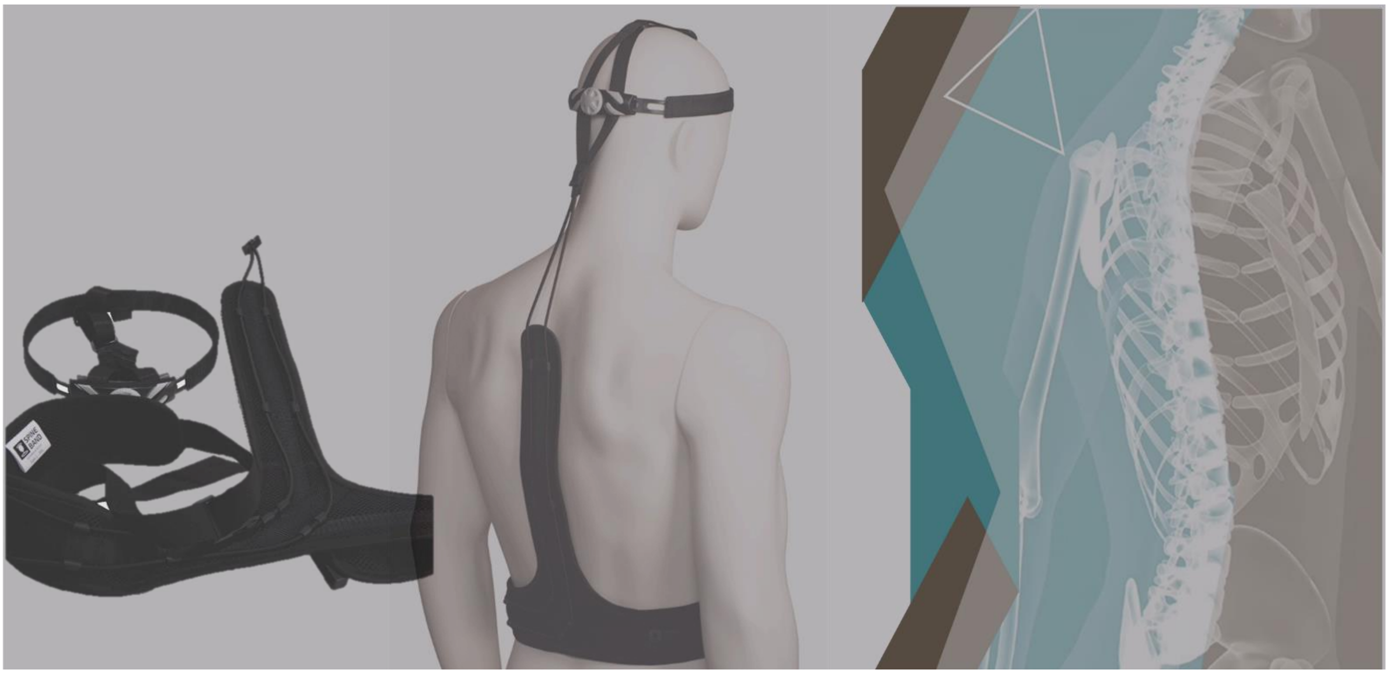

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Evaluating the Effect of the Spineband Neck Flexion Exoskeleton on Muscle Workload and Work Posture among Floor Layers

Utvärdering av effekten av spineband exoskelett på golvläggares muskelbelastning och arbetsställning

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Master's Thesis

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Abstract

With the advancement of technology, innovative control measures have been introduced to mitigate the risk of work-related musculoskeletal disorders (WMSDs). Among these measures, wearable passive exoskeletons have emerged as promising solutions for addressing WMSDs. Previous studies have demonstrated the effectiveness of wearable passive exoskeletons for improving awkward postures and reducing muscle workload in tasks involving neck extension, limbs, and back. However, the effectiveness of newly developed industrial exoskeletons designed for neck flexion remains uncertain.

This study aimed to evaluate the neck exoskeleton's effects on muscle activities and work postures, by comparing the working conditions of floor workers wearing and not wearing these devices. Six subjects were recruited for field measurements. Muscle activity of the neck extensors, as well as the forward inclination angle of the head and trunk, were assessed during the measurements. Data comparison between wearing and not wearing the neck flexion exoskeleton was conducted using the related samples Wilcoxon signed-rank test. Spearman's rank correlation coefficient was utilized to analyze the correlation between different parameters while wearing the neck flexion exoskeleton.

The results showed that compared to not wearing the exoskeleton, wearing the neck flexion exoskeleton significantly reduced muscular activity at the 10^{th} percentile (p=0.028), 50^{th} percentile (p=0.028), and 90^{th} percentile (p=0.028). Wearing the neck flexion exoskeleton also reduced the 10^{th} percentile (p=0.028) and 90^{th} percentile (p=0.046) of the head angle, and the neck angle at the 50^{th} percentile (p=0.028) and 90^{th} percentile (p=0.028). Additionally, the trunk angle was significantly higher with the exoskeleton at the 50^{th} percentile (p=0.046) and 90^{th} percentile (p=0.027).

The correlation analysis when wearing the exoskeleton revealed a negative correlation between neck angle and trunk angle at the 10^{th} percentile (r=-0.829, p=0.021). Additionally, a significant negative correlation was found between neck angle and trunk angle at the 90^{th} percentile (r=-0.943, p=0.002), as well as between head angle and trunk angle at the 90^{th} percentile (r=-0.829, p=0.021). Moreover, a strong negative correlation was observed between RMS and head angle at the 50^{th} percentile (r=-0.771, p=0.036) and 90^{th} percentile (r=-0.829, p=0.021).

In conclusion, the results show that wearing neck flexion exoskeletons during actual work tasks among floor layers reduces neck extensor muscle activity, excessive neck flexion, and forward head inclination, and it may lead to an increase in forward trunk inclination, without influencing work efficiency.

Keywords: Passive Exoskeleton, Work-related Musculoskeletal Disorders, Physical Workload, Muscle Activity, Work Posture

Sammanfattning

Med den tekniska utvecklingen har innovativa lösningar införts för att minska risken för arbetsrelaterade besvär i rörelseapparaten (WMSD). Bland dessa lösningar har bärbara passiva exoskelett framträtt som en möjlighet för att minska risken för WMSD. Tidigare studier har visat att bärbara passiva exoskelett är effektiva för att minska belastningen vid besvärliga arbetsställningar och minska muskelbelastningen vid arbetsuppgifter som involverar nackextension, extremiteter och rygg. Dock är effektiviteten av nyligen utvecklade industriella exoskelett designade för nackflexion fortfarande osäker.

Denna studie syftade till att undersöka effekten av ett nackflexionsexoskelett, med avseende på muskelbelastning och arbetsställningar hos golvarbetare. Sex försökspersoner rekryterades för fältmätningar. Muskelaktiviteten hos nackextensorerna, samt framåtlutningsvinkeln av huvudet och bålen, mättes under arbetet. Statistisk jämförelse mellan att bära och inte bära nackflexionsexoskelettet utfördes med hjälp av Wilcoxon signed-rank test för relaterade prover. Spearman rangkorrelationskoefficient användes för att analysera korrelationen mellan olika parametrar när nackflexionsexoskelettet bars.

Resultaten visade att exoskelettet signifikant minskade muskelaktiviteten ; vid 10:e percentilen (p=0.028), 50:e percentilen (p=0.028) och 90:e percentilen (p=0.028). Vidare minskade även huvudvinkeln signifikant, 10:e percentilen (p=0.028) och 90:e percentilen (p=0.046) av, liksomnackvinkelns 50:e percentilen (p=0.028) och 90:e percentilen (p=0.028). Bålvinkeln, däremot, var signifikant högre med exoskelettet både vid 50:e percentilen (p=0.046) och 90:e percentilen (p=0.027).

Korrelationsanalysen avslöjade en negativ korrelation mellan nackvinkel och bålvinkel vid 10:e percentilen (r=-0.829, p=0.021) när exoskelettet bars. Dessutom var det en signifikant negativ korrelation mellan nackvinkel och bålvinkel vid 90:e percentilen (r=-0.943, p=0.002), samt mellan huvudvinkel och bålvinkel vid 90:e percentilen (r=-0.829, p=0.021) när exoskelettet bars. Dessutom observerades en stark negativ korrelation mellan muskelaktivitet och huvudvinkel vid 50:e percentilen av de båda måtten (r=-0.771, p=0.036) och vid 90:e percentilen (r=-0.829, p=0.021) när exoskelettet bars.

Sammanfattningsvis visar resultaten att användning av nackflexionsexoskelett under faktiska arbetsuppgifter bland golvläggare minskar nackextensorernas muskelaktivitet, nackflexion och framåtlutning av huvudet, samt ökar framåtlutningen av av bålen utan att påverka arbetseffektiviteten.

Nyckelord: Passivt exoskelett, Arbetsrelaterade muskuloskeletala besvär, Fysisk arbetsbelastning, Muskelaktivitet, Arbetsställning

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Stockholm, May 2024

Qing Xia

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List of abbreviations

aEMG	Average Electromyography
CoG	Center of Gravity
DOF	Degree of Freedom
ECG	Electrocardiography
EEG	Electroencephalography
Env	Environment
EMG	Electromyography
Equip	Equipment
EXO	Exoskeleton
iEMG	Integrated Electromyography
IMU	Inertial Measurement Unit
LBD	Low Back Disorder
MSD	Musculoskeletal Disorder
MVC	Maximum Voluntary Contraction
MVE	Maximum Voluntary Electrical Activity
NMQ	Nordic Musculoskeletal Questionnaire
Org	Organization
RMS	Root Mean Square
ROM	Range of Motion
sEMG	Surface Electromyography
WMSD	Work-related Musculoskeletal Disorder

1 Introduction

1.1 Background

Musculoskeletal discomfort affects most European workers, which might impair their performance at work (Badarin et al., 2022). Prolonged, awkward working postures are a significant contributor to musculoskeletal pain among workers (Harms-Ringdahl, 2012). According to earlier studies, over 45 % of European Union workers claimed to spend at least 25 % of their working hours in uncomfortable postures (Harms-Ringdahl, 2012). According to Steinberg et al. (2017), the greatest cost of lost productivity was caused by musculoskeletal disorders (MSDs) associated with uncomfortable postures, contributing to absenteeism and sick leave (Strömberg et al., 2017). Absenteeism and sick leave may raise healthcare expenditures for both the government and employees and lower the financial returns on investment for businesses and employers (Strömberg et al., 2017). Among the factors that led to absenteeism, cervical MSDs were a significant cause of absenteeism in various working populations (Sun et al., 2017). With work-related neck disorders leading to absenteeism and economic loss from different levels (individual, organizational, and social), neck MSDs remain an occupational health issue that cannot be ignored.

Neck disorders associated with degenerative disorders have occurred primarily in occupations that involve prolonged physical demand, such as health professionals, construction workers, agricultural workers, and manual material handling workers (Sun et al., 2017). Among construction workers, especially floor layers, the neck region was one of the highest-risk areas for acquiring MSDs (Dale et al., 2015; Visser et al., 2013). Previous studies showed that over 90 % of floor layers were over the neck action level with physical exposures (McGaha et al., 2014), and above 50 % of them claimed MSDs, especially the cervical region (Dale et al., 2015). Prolonged kneeling with awkward neck flexion postures was one of the main biomechanical causes of neck MSDs among floor layers (Dale et al., 2015; Visser et al., 2013), which could decrease the quality of life and increase economic loss (Dale et al., 2015). Thus, the floor layer was one of the most affected occupational categories with a high risk of neck MSDs due to awkward neck postures.

Recently, there were not many effective risk reduction strategies to lower the risk of neck MSDs among floor layers, common practice in workplaces is to recommend frequent breaks (Faucett et al., 2007) or job enlargement (Gichuki & Munjuri, 2018). However, these two measures cannot fundamentally reduce the biomechanical load on the cervical region at work, and they are difficult to widely apply in the actual workplace due to economic loss. Therefore, there is an urgent need to find effective measures to reduce the risk of neck MSDs among floor layers at work.

Wearable exoskeletons showed great potential in different settings, including healthcare (B. Chen et al., 2016) and industry (de Looze et al., 2016), and possibly be an effective control measure to address neck MSDs and long-term problems (van der Vorm et al., 2015). Wearable exoskeletons, as an emerging technology, can improve posture, mobility, and physical activity aimed to prevent employees from musculoskeletal disorders caused by awkward postures during working activities (Lowe et al., 2019).

However, most of the current research on industrial exoskeletons has focused on the back and limb exoskeletons. Several studies showed that back and limb exoskeletons could affect muscle workload. Back exoskeleton usage might result in decreased trunk muscle activity (van Sluijs et al., 2023; Luger et al., 2021; Luger et al., 2023) but increased lower limb muscle activity (Luger et al., 2021; Luger et al., 2023). Furthermore, when using upper limb exoskeletons, the activation of several shoulder muscles was decreased (Iranzo et al., 2020; Ojelade et al., 2023). These results imply that whereas exoskeletons may lessen muscle activity in some body regions, they may also have a negative effect on other regions of muscles during work tasks. Thus, the impacts of muscle activity varied between different body parts (Ojelade et al., 2023).

Additionally, studies conducted recently revealed that the effects of limb and back exoskeletons on posture varied depending on the type of task. Regarding back exoskeletons, on one hand, various studies showed that they had no discernible impact on posture variation during work tasks (Kim et al., 2020; van Sluijs et al., 2023); on the other hand, some research suggested that the back exoskeleton could reduce trunk movement (Luger et al., 2023) and effectively transfer the movement to the lower extremities (Luger et al., 2021). According to research conducted by Iranzo et al. (2020) and Ojelade et al. (2023), upper extremity exoskeletons had a notable impact on postures, resulting in a decrease in certain joints and an increase in others (Iranzo et al., 2020; Ojelade et al., 2023). These demonstrate that different exoskeletons contribute differently to improved posture alignment in different job activities and that the posture of the targeted body part can only be enhanced when the exoskeleton and the tasks are compatible.

Currently, the research on the neck exoskeleton is limited to the research on neck extension exoskeletons. Previous research demonstrated that the use of the neck exoskeleton reduced the muscle activity of the neck region during overhead movements without affecting work performance (Garosi et al., 2022; Rossini et al., 2022). However, the shoulder muscle activity increased (Garosi et al., 2022). Additionally, Giovanelli et al. (2022) indicated that the neck extension exoskeleton could reduce the joint angle effectively (Giovanelli et al., 2022). These results suggest that the neck extension exoskeleton could improve the target muscle activity and neck posture. However, little attention has been paid to industrial neck flexion exoskeletons in previous research.

The newly developed neck flexion exoskeleton Spineband (Spineband AB, Sweden) was evaluated in this project. The company Spineband AB developed this product intending to prevent people from experiencing neck pain and tension headaches caused by awkward neck flexion. The Spineband works by applying external forces along the trunk to relieve the pressure placed on the spine by the weight of the head. Spineband's effectiveness in reducing neck muscle activity was validated by professionals. Additionally, the Spineband received the CE mark in 2020, which indicates that this product is suitable for healthcare. However, although the neck flexion exoskeleton is a potential solution for reducing work-related musculoskeletal disorders (WMSDs), its effectiveness in improving working posture, and reducing muscle activities remains unclear in the actual work environment among floor layers.

1.2 Aim

This project aimed to evaluate the effect of the novel neck flexion exoskeleton, Spineband, in the actual work setting among floor layers:

1. Evaluating the neck exoskeleton's effects on muscle activities.
2. Evaluating the neck exoskeleton's effects on work postures.
3. Exploring the correlation between muscle activities and work postures.

1.3 Delimitations

This project focused on evaluating the effect of the neck flexion exoskeleton among floor layers, and other occupations were excluded. The ergonomic evaluation of the effect of the neck flexion exoskeleton is limited to the following dimensions: neck muscle activities, and head and trunk postures. Evaluations of other ergonomic dimensions were not considered. All evaluations were carried out during the actual work of floor layers.

2 Theoretical Framework

2.1 Work-related Musculoskeletal Disorders

A prevalent occupational health issue, work-related musculoskeletal disorder (WMSD) encompasses a range of inflammatory and degenerative illnesses affecting muscles, tendons, ligaments, joints, and nerves (Punnett & Wegman, 2004). The most significant type of work-related sickness, WMSDs, accounted for almost one-third of occupational disorders in the US, the Nordic area, and Japan (Punnett & Wegman, 2004). The lower back, neck, shoulders, forearms, and hands are the body areas most often afflicted by WMSDs (Punnett & Wegman, 2004). Working population studies showed that 20–30 % of individuals had upper body WMSDs (Punnett & Wegman, 2004).

2.1.1 Factors related to WMSDs

WMSDs are musculoskeletal disorders brought on directly by work tasks and workplace conditions (Govaerts et al., 2021). Karsh's integrated model of WMSDs in Figure 1. showcased the complexity of the elements contributing to WMSDs, which extended beyond work activities and settings (Karsh, 2009). Karsh's integrated model found that social context, work organization, work environment, physical work demands, psychological work demands, and individual factors all contributed to WMSDs (Karsh, 2009), consistent with previous studies and epidemiological investigations (Punnett & Wegman, 2004).

The development direction of WMSDs might be influenced by the context of society (Karsh, 2009). The risk of WMSDs could be decreased by organizational culture and political climate support for WMSD prevention (Karsh, 2009). Unsuitable work cycles, such as excessively long daily or weekly working hours and excessive night shifts, might raise the risk of WMSDs when it came to work organization (Younan et al., 2019). Uncomfortable work postures were created by unsuitable work environments, such as low workbenches and seats without backrests, which raised the risk of WMSDs (Joudakinia et al., 2021; Du et al., 2022).

Additionally, improper temperature, and humidity, which made outdoor job duties more difficult, substantially elevated a worker's risk of experiencing WMSDs (Baek et al., 2023). Awkward postures, repeated motions, lifting or carrying frequently, and prolonged overexertion were the primary physical risk factors for WMSDs (Govaerts et al., 2021; Y. Lee & Park, 2007).

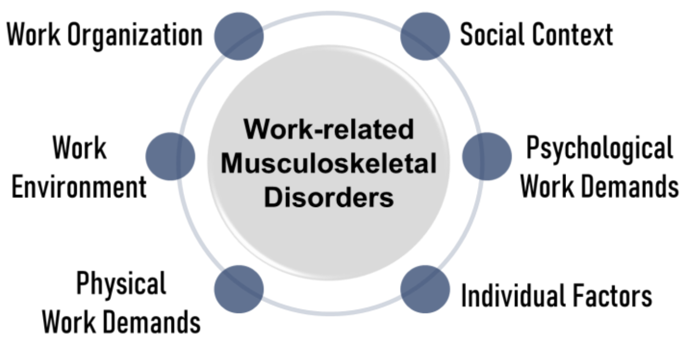

Figure 1. Karsh's integrated model of WMSDs

Furthermore, psychological factors including stress, subjective discomfort, perception of fatigue, etc., could potentially affect the development of WMSDs (Karsh, 2009). Individual factors analysis revealed that the following factors were associated with work-related WMSDs: lack of ergonomic knowledge, gender, work experience, weight, health status, and exercise status (Younan et al., 2019; Karsh, 2009). Thus, the multiple causes of WMSDs pose challenges for the development of interventions for WMSDs.

2.1.2 Economic and social impact of WMSDs

Widespread WMSDs might lower workers' quality of life and result in financial losses in several nations (Punnett & Wegman, 2004). Previous research demonstrated that in the US, Canada, Finland, Sweden, and the UK, musculoskeletal problems constituted the primary cause of absenteeism or disabilities (Punnett & Wegman, 2004). In Europe, almost half of workers lost work due to WMSDs. Additionally, it was estimated that 60 % of workers with WMSDs were permanently disabled.

Causes of negative effects at the individual, organizational, and societal levels included absenteeism and disability as a result of WMSDs (Govaerts et al., 2021). WMSDs resulted in reduced quality of life and increased healthcare expenses for workers (Govaerts et al., 2021). Employees' WMSDs-led absenteeism and sick leave could lower the productivity and profits of organizations (Dembe, 2001). Additionally, the provision of medical care services, economic costs to the employer, and payment of workers' compensation payments all raised the organizations' financial expenses (Dembe, 2001). Furthermore, WMSDs increased the government fiscal expenditure on health care. With WMSD cost totaling 2 % of EU GDP, around €240 billion, WMSDs had a detrimental socioeconomic impact on the European Union (Govaerts et al., 2021). Therefore, it is crucial to find suitable interventions to reduce WMSDs, which can reduce economic losses and negative social impacts.

2.1.3 WMSDs in the cervical region

Among WMSDs, neck disorders have a high incidence in various occupational groups (Sun et al., 2017). The cervical region had the most significant average 12-month prevalence of worker self-reported symptoms (28 %), according to self-reports from the Netherlands, Belgium, and Denmark (Buckle & Jason Devereux, 2002). Additionally, neck WMSDs caused absenteeism in workers across various industries (Sun et al., 2017), resulting in substantial financial losses that much exceed the indirect costs of lost productivity, worker replacement, training, and absenteeism (Buckle & Jason Devereux, 2002).

Neck WMSDs not only caused financial losses but also reduced the health status and quality of life of employees (Punnett & Wegman, 2004). WMSDs in the cervical region included a variety of inflammatory and degenerative disorders in different occupations (Sun et al., 2017). Long-term static neck flexion work and repeated neck flexion tasks could cause pain-related neck WMSDs, highly prevalent in professions including dentistry and computer workers (Sun et al., 2017). A previous study suggested that dentists had a higher risk of neck-related WMSDs, which could be related to their awkward neck postures (Zhou et al., 2021). Chen et al. presented that office workers had the highest rate of neck pain of any occupation because they needed to sit with prolonged awkward neck flexion to perform computer operations (Chen et al., 2018).

Additionally, physical labor-related work demands might result in degenerative neck WMSDs, which were prevalent among construction workers, agricultural workers, and health professionals with awkward neck flexion tasks (Sun et al., 2017). Previous research indicated that between 60 and 90 percent of surgeons suffered from neck pain and discomfort (Khansa et al., 2018). Therefore, neck MSD is a nonnegligible health issue among populations.

2.1.4 Neck-related WMSDs among floor layers

According to an earlier study, 91 % of floor workers were exposed to physical stressors at caution levels daily, including the cervical region (McGaha et al., 2014). One of the main causes of the high prevalence of musculoskeletal problems among floor layers was prolonged exposure to improper neck posture (McGaha et al., 2014). Dale et al. (2015) demonstrated that 51 % of the floor layers reported having musculoskeletal issues, with the neck being the most often affected (Dale et al., 2015). Additionally, neck-related WMSDs among floor layers resulted in increased healthcare expenditures and health insurance costs, leading to organizational-level economic losses (Dale et al., 2015). Thus, finding effective approaches is therefore crucial to substantially reducing WMSDs caused by awkward neck flexion among floor layers.

2.2 Occupational Exoskeletons

The definition of an occupational exoskeleton is a wearable device intended to improve posture, mobility, or body activity (Lowe et al., 2019). There are two types of industrial exoskeletons: passive and active. Active exoskeletons run on electricity, while passive exoskeletons rely on mechanical principles to give users physical support (Lowe et al., 2019). Therefore, the employment of passive exoskeletons offers the advantage of not being constrained by time limits imposed by power sources, in contrast to active exoskeletons. Due to this benefit, passive exoskeletons may have more potential for use in the industrial field to reduce WMSDs caused by awkward postures.

2.2.1 The biomechanical principle

Industrial exoskeletons are typically developed as non-anthropomorphic passive exoskeletons designed for augmentation purposes (H. Lee et al., 2012). This type of exoskeleton aims to mitigate the negative effects of loads on the user for specific tasks (H. Lee et al., 2012). Non-anthropomorphic exoskeleton joints do not align with human joints, meaning they cannot replicate all degrees of freedom of all joints and only act on specific degrees of freedom at target joints (H. Lee et al., 2012). Therefore, although industrial passive exoskeletons simplified structure for easier task execution, they also imposed limitations on movement at non-target joints due to the simplification of joints and degrees of freedom (H. Lee et al., 2012).

Additionally, due to the simplified design of non-anthropomorphic passive exoskeletons, it could be determined whether they were uniarticular or multi-articular exoskeletons based on their attachment points at the upper and lower ends. Uniarticular exoskeletons only affect the movement of a specific joint, while multi-articular exoskeletons could have interactive effects on different joints and might have the possibility to change movement patterns (Van Dijk & Van Der Kooij, 2014).

Industrial exoskeletons that function passively store and transfer the energy produced by human motion, releasing it as needed, using materials, springs, or pulley systems (Bosch et al., 2016; Van Dijk & Van Der Kooij, 2014). When the target part of the human body moves in the desired direction, the spring of the passive exoskeleton is stretched, storing elastic potential energy, thereby aiding in maintaining the movement in that desired direction and releasing the potential energy to assist in the movement when it reverses (Bosch et al., 2016) to decrease the muscle activation as well as the muscle force.

Nevertheless, there are variations in the target muscles' activation level when the movement pattern changes in different directions under some conditions. While wearing exoskeletons, the muscles that are supported by the exoskeleton are shortened and contracted concentrically as the body part moves from the goal direction to the opposite direction. According to the sliding filament theory of muscle excitation-coupling, myofilament overlap increases as a result of the incremental shortening of muscle fibers during concentric contraction (Hunter, S. K. & Brown, D. A., 2010). Under this condition, the muscles need fewer engaged muscle fibers to produce the same amount of force (Hunter, S. K. & Brown, D. A., 2010). As a result, there is less total muscle activation.

Without the support of exoskeletons, targeted muscles are usually extended and contracted either eccentrically or isometrically as the body part moves in the direction of the objective. Myofilament overlap decreases as a result of the increasing stretching of muscle fibers during these kinds of contractions (Hunter, S. K. & Brown, D. A., 2010). Under this condition, a greater number of engaged muscle fibers could produce an equivalent amount of force from the muscles. Consequently, there is an overall increase in muscle activation (Hunter, S. K. & Brown, D. A., 2010). Thus, the direction of movement affects how exoskeletons influence the target muscles.

Furthermore, the variation in the center of gravity (CoG) of a body part due to changes in posture can significantly influence both the torque of the body part and the corresponding muscle torque. When the body is in a neutral position, the gravity point of the body part aligns with the axis line, resulting in a minimal lever arm and thus minimal torque (Hunter, S. K. & Brown, D. A., 2010). Consequently, muscles require little additional force to maintain balance, leading to relatively low muscle force and activity (Hunter, S. K. & Brown, D. A., 2010). As the body deviates from this neutral position, the lever arm of the body part increases, consequently increasing the torque (Hunter, S. K. & Brown, D. A., 2010). This necessitates additional torque from related muscles to maintain balance, resulting in increased muscle force and activation. However, when wearing exoskeletons, they apply an external torque to reduce the torque produced by the related muscles, thereby reducing the muscular load. Therefore, as the CoG of a body part shifts away from the line of gravity, the torque exerted by related muscles and exoskeletons adjusts to counteract the torque generated by the body part's gravity (Hunter, S. K. & Brown, D. A., 2010).

2.2.2 The effect on muscle activities

Prior studies on neck exoskeletons showed that using them decreased the level of muscle activation in the neck region during overhead motions (Garosi et al., 2022; Rossini et al., 2022). Rossini et al. demonstrated that the novel neck extension exoskeleton could decrease neck muscle activity by over 80 % (Rossini et al., 2022). Garosi et al. (2022) illustrated that the neck extension exoskeleton could reduce sternocleidomastoid muscle activities during overhead tasks. However, Garosi et al. (2022) also presented that the neck extension exoskeleton could increase trapezius muscle activities during the same task. These imply that neck extension exoskeletons effectively reduced muscle activities in the target area, but resulted in increased muscle activities in non-target areas.

Additionally, prior studies demonstrated that upper limb exoskeletons could successfully lower muscle activity in the targeted region among different tasks. Previous studies presented that shoulder muscle activities could be reduced during plastering activities, overhead works, and vertical aircraft squeeze riveting tasks under the assistance of arm exoskeletons (De Bock et al., 2023; de Vries et al., 2021; Jorgensen et al., 2022; Kong et al., 2023; Ojelade et al., 2023).

Nevertheless, upper limb exoskeletons may potentially negatively impact muscles in non-target regions, similar to neck exoskeletons. Van Der Have et al. (2022) illustrated that the shoulder exoskeleton could reduce should and elbow muscle activity during high-lifting tasks without influencing any other muscles; however, the muscle activity of the shoulder and knee region increased during a low-lifting task.

For back exoskeletons, previous research indicated that they could effectively reduce muscle activity in the back and hip regions. During static sorting tasks, the back exoskeleton could reduce hip extensors' muscle activity according to Bär et al. (2024). Van Sluijs et al. (2023) demonstrated that the back exoskeleton could effectively reduce muscle activities in back and hip regions to over 20 % during forward bending and lifting tasks. These suggest that the same kind of exoskeletons might have a relieving effect on muscle activity in different regions.

Back exoskeletons were also demonstrated in earlier research to successfully lower muscular load in the target region during a variety of tasks. Alemi et al. (2022) presented that using back exoskeletons could reduce trunk muscle activities during repetitive lifting tasks. Additionally, trunk muscle activities could be significantly decreased during simulated surgical tasks according to Tetteh et al. (2022). Furthermore, Kang & Mirka (2023) illustrated that trunk muscle activity was decreased during simple posture-maintenance tasks by wearing a back exoskeleton. The above shows that, for various kinds of jobs, back exoskeletons are effective in lowering muscle activity.

However, previous study also demonstrated that, during industrial tasks, the back exoskeleton could reduce the muscle activity of erector spinae, and biceps femoris, but increase the muscle activity of rectus abdominis, gastrocnemius, trapezius at the same time (Luger et al., 2023). This implies that exoskeletons for the back, like those for the neck and upper limbs, can potentially increase muscular demand in non-target regions.

Additionally, Theurel & Desbrosses (2019) demonstrated that the coordination between agonist and antagonist muscles in target regions might also be hampered by using exoskeletons, implying that if agonist muscle activity decreases, antagonist muscle activity may increase in response.

In conclusion, for certain tasks, exoskeletons can successfully lessen the muscular load in specific muscles. However, for particular jobs, they may raise the muscular demand in other muscles.

2.2.3 The effect on work postures

During dynamic and static neck extension tasks in a sitting posture, Giovanelli et al. found that the neck extension exoskeleton could efficiently decrease the joint angle in the cervical region (Giovanelli et al., 2022).

For back exoskeletons, the results showed that the use of different back exoskeletons had different effects on posture for different tasks. Some studies showed that the use of back exoskeletons could effectively improve the awkward postural angle of the back and transfer the postural changes to the lower extremities (Luger et al., 2023; Luger et al., 2021). Luger et al. (2021) indicated that using a back exoskeleton could affect postural changes in different styles of lifting tasks. When the back exoskeleton was used for lifting tasks, both hip and knee flexion angles increased significantly (Luger et al., 2021). This indicated that the back support exoskeleton can effectively transfer the load from the lower back to the passive movement of the legs (Luger et al., 2021). Additionally, Luger et al. (2023) also evaluated the effects of using a back exoskeleton on posture for three simulated industrial tasks, including pallet box lifting, fastening, and lattice box lifting. The results showed that the use of the back exoskeleton reduced trunk flexion in pallet box lifting (Luger et al., 2023). However, using the back exoskeleton significantly increased knee and hip flexion on pallet box lifting, fastening, and lattice box lifting (Luger et al., 2023).

However, other studies presented that using back exoskeletons had no significant effect on improving posture during some work tasks (Kim et al., 2020; van Sluijs et al., 2023). The effects of utilizing a back exoskeleton on lumbar mobility, knee flexion, and hip flexion during a simulated manual assembly work were studied by Kim et al. (2020). The outcomes demonstrated that the task's working posture was not significantly affected by the back exoskeleton (Kim et al., 2020). According to van Sluijs et al. (2023), in simulated tasks of lifting and torso leaning forward, the back exoskeleton did not affect lower limb posture. The results showed no significant difference in the angle of movement of the largest and smallest knee and hip joints when participants performed the simulated tasks (van Sluijs et al., 2023). This suggests that hip and knee ranges of motion (ROM) are not affected by whether or not the back exoskeleton is worn.

For the upper extremity exoskeleton, previous studies showed that upper extremity exoskeletons had a significant effect on the change of the upper extremity posture angle during overhead movements, with a decrease in the motion of some upper extremity joints and an increase in the motion of others (Iranzo et al., 2020; Ojelade et al., 2023). Iranzo et al. (2020) evaluated the effects on overhead tasks using pneumatic screwdriver arms with or without the use of an upper limb exoskeleton. The results showed significant differences in specific joint movements with or without the use of the upper limb exoskeleton, but the changes in joint angles were all less than 5° (Iranzo et al., 2020). With the support of the upper limb exoskeleton, lateral flexion and rotation of the lumbar spine, lateral flexion of the neck, and internal and external rotation of the shoulder were reduced (Iranzo et al., 2020). However, the rotation of the neck and the movement of the elbow joints increased (Iranzo et al., 2020). Additionally, Ojelade et al. indicated that when performing the overhead task using the upper limb exoskeleton, participants were in different shoulder positions (Ojelade et al., 2023). The results showed that the use of the upper limb exoskeleton increased the shoulder abduction angle, increased the shoulder elevation angle, and decreased the shoulder flexion angle (Ojelade et al., 2023). These suggest that although the upper limb exoskeletons had a significant effect on posture, the actual posture angle changed little. The upper limb exoskeleton reduced the angle of some joints while increasing the angle of others, which had the potential to transfer the risk of MSDs in some upper limb joints to others.

Similarly, Theurel & Desbrosses noted that using exoskeletons may increase joint angles in non-target regions as a compensatory tactic (Theurel & Desbrosses, 2019). This implies that exoskeletons have a complex effect on joint angles; that is, whereas they might support one degree of freedom (DOF) in a single joint, they might also negatively affect adjacent joints and restrict movement in other degrees of freedom within that joint.

In conclusion, the effects of exoskeletons on work postures vary depending on types of exoskeletons, and specific job tasks. Passive exoskeletons could decrease target body part joint mobility but might potentially have negative impacts on non-target regions.

2.2.4 The effect between muscle activities and work postures

D'Anna et al. (2021) investigated the correlations between angle variations of different upper body parts during seated and standing neck flexion tasks, as well as the correlations between neck posture and neck muscle activity. For both postures, there was a positive correlation between the 50^{th} percentile of elbow flexion-extension angle and neck angle; likewise, there was a positive correlation between the 50th percentile of gaze angle and the neck angle (D'Anna et al., 2021). Furthermore, in the standing posture, there was a significant and direct proportional correlation between the RMS value at the 10^{th} percentile and the neck angle at the 50^{th} percentile (D'Anna et al., 2021). These findings suggest that there may be correlations between motion angles of different upper body parts, and between cervical flexion angles and neck muscle activation during neck flexion tasks.

2.3 Evaluation of Exoskeleton

Recent theoretical models for assessing exoskeletons have focused on three key elements: target tasks, subjective evaluation, and objective evaluation (Golabchi et al., 2022; Hoffmann et al., 2022; Zhang et al., 2023). The integrated evaluation framework of the exoskeleton is presented in Figure 2. While target tasks, subjective indicators, and objective performance indicators might result in a comprehensive assessment of exoskeletons, this project primarily focused on objective evaluation, omitting the subjective evaluation component.

Firstly, the exoskeleton's possibilities of being effective are increased by the choice of target tasks. Then, Zhang et al.'s integrated evaluation approach illustrated the importance of considering muscle activity and kinematics indicators for overall exoskeleton evaluation (Zhang et al., 2023). These two indicators could not only estimate the muscle effort but also characterize the kinematic state for two-dimensional evaluation (Zhang et al., 2023). Thus, in this project, occupations including target tasks were first determined as the starting point of the exoskeleton evaluation, followed by evaluating the effect based on objective evaluations only.

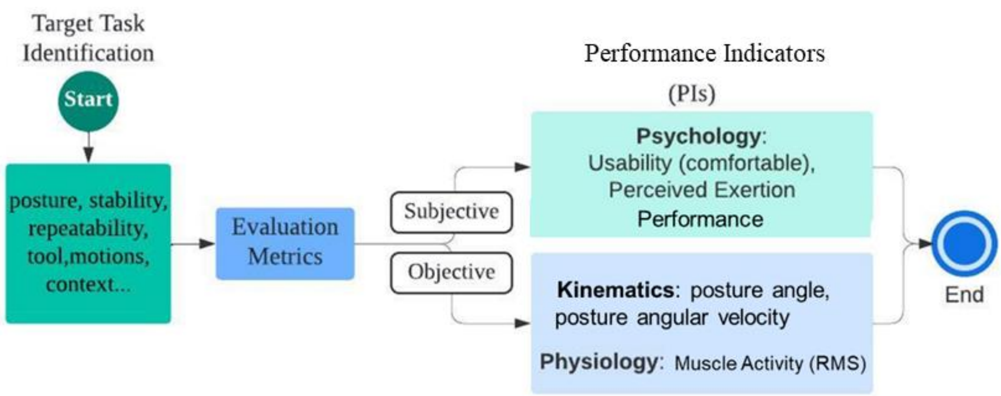

Figure 2. Integrated evaluation framework of exoskeleton

2.3.1 Target tasks identification

The target task was highlighted as crucial to assessing exoskeletons in both Hoffmann et al.'s Harmonized Evaluating Methodology and Golabchi et al.'s Framework for Exoskeleton Evaluation. Golabchi et al. (2022) suggested that target tasks should prioritize posture, stability, tool use, and repeatability. Additionally, Hoffmann and colleagues expounded on the idea that the evaluation of exoskeletons had to consider various task patterns, highlighting the critical amalgamation of primary and secondary tasks (Hoffmann et al., 2022).

2.3.2 Muscle activity measurements

The measurement of muscle activity traditionally involves two methods: intramuscular electromyography and surface electromyography (sEMG). Intramuscular EMG measures precise muscle activity by inserting electrodes into the muscle, but it is complex to operate and requires high environmental requirements (Merletti & Farina, 2008). However, sEMG, due to its high adaptability, is used as the primary tool for measuring muscle activity related to work tasks and is widely applied in the field of ergonomics (Gazzoni et al., 2016).

The method termed sEMG records the electrical signals produced by muscular contraction and relaxation by applying electrodes to the surface of the muscle (Gazzoni et al., 2016). sEMG is commonly measured for estimating muscle effort in human-exoskeleton interaction with the following recommended parameters: RMS, aEMG, and iEMG (Zhang et al., 2023).

However, unstable skin electrode contacts and other physiological variables might interfere with sEMG (Gazzoni et al., 2016). Additionally, noise, artifacts, and interference in industrial settings might potentially have an impact on sEMG signal detection (Boyer et al., 2023; Gazzoni et al., 2016). Consequently, while employing sEMG, confounding variables had to be taken into account (Gazzoni et al., 2016).

2.3.3 Kinematic measurements

Currently, wearable motion capture technology with inertial measurement units (IMUs) and optical motion capture systems are the two most commonly used techniques for human motion measurement (Yang et al., 2019). Optical motion capture has the advantage of high accuracy but is limited to laboratory settings (Nagymáté & Kiss, 2018). However, in the field of ergonomics, body posture is a key issue in work risk assessment (Yang et al., 2019) within actual work settings. Thus, wearable motion capture technology with IMUs, due to its usability and convenience, is widely used in the measurement of actual working postures (Lind et al., 2023).

Wearable motion capture devices are defined as devices that are worn on the body to continually track a person's movements without disturbing or limiting their activities (Lind et al., 2023). Joint angle and joint angular velocity are two common metrics to evaluate the kinematic condition (Zhang et al., 2023).

However, the limitation of wearable motion capture devices is their lower accuracy compared to optical motion capture systems. The wearable motion capture devices used in this study were validated and compared with optical motion capture systems (Yang et al., 2019). Additionally, the wearable motion capture devices used in this study were also validated for wearing fabric, comparing them placed in cloth and directly on the skin (Hoareau et al., 2023). Validation results indicate that the wearable motion capture device used in this study provided acceptable accuracy in measuring sagittal plane forward inclination angles (Hoareau et al., 2023).

2.3.4 Evaluation from a systematic perspective

A guiding theory for systematic analysis of human-machine-organization interactions is the Extended Framework for Humans, Technology, and Organization (HTO) (Eklund, 2003). The four fundamental components are the human, technology (exoskeleton), organization, and environment (Eklund, 2003). Then, the expended Exoskeleton Performance Interaction Framework developed by ASTM is added to the Extended Framework for HTO (ASTM F3474-20, 2023) in Figure 3.

According to Theurel & Desbrosses (2019), the outcomes of interactions between humans and exoskeletons may vary based on the type, equipment, intensity, and duration of the tasks involved, which indicates that the performance of exoskeletons will be influenced by tasks, individual factors, organizational factors.

Additionally, Moeller et al. (2022) demonstrated that exoskeletons have a different effect in real-world work conditions than they do in lab settings. Furthermore, exoskeletons may not be suitable for all workplaces (Moeller et al., 2022). These suggest that the performance of exoskeletons is also influenced by environmental factors. Thus, it is vital to evaluate the performance of exoskeletons from a systematic perspective.

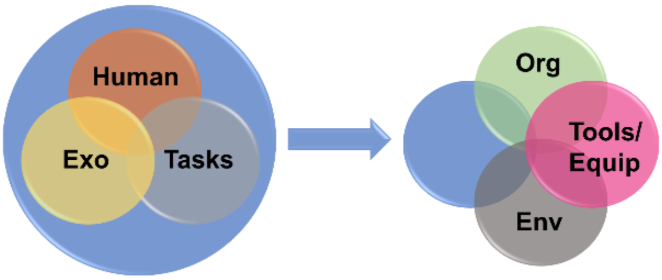

Figure 3. Expended Exoskeleton Interaction Framework (adapted from ASTM)

3 Method

3.1 Technology Roadmap

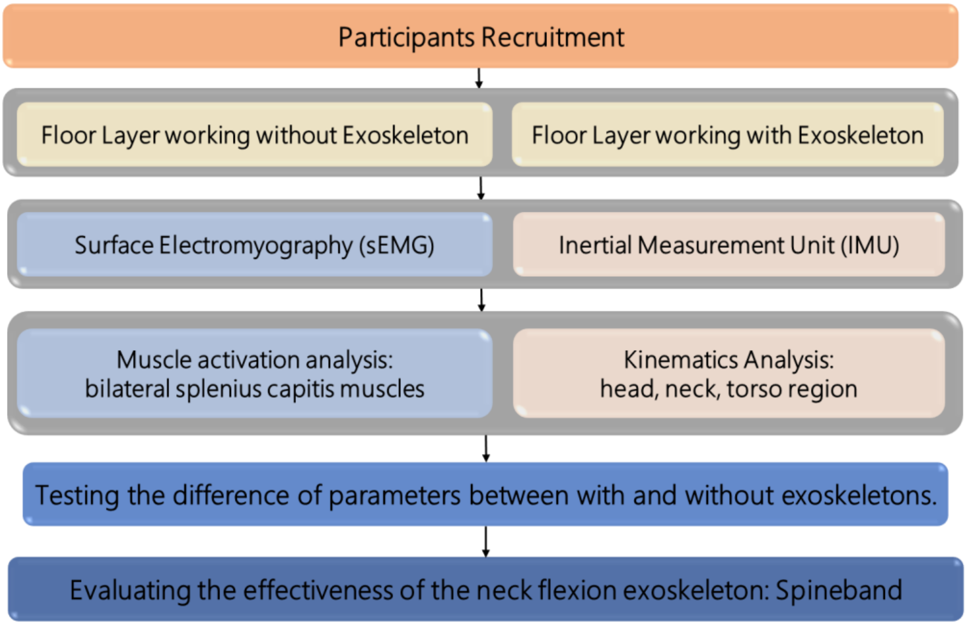

Figure 4. Technology Roadmap

3.2 Subjects

3.2.1 Basic information

Table 1. Participants Basic Information

No	Age (year)	Height (cm)	Weight (kg)	Sex (M/F)	Pain and Discomfort History		
					7 days (NMQ)	24 hours (Borg CR10)	3 months (NMQ)
1	28	194	83	M	Yes	6	1-7 days
2	24	182	90	F	Yes	3	8-30 days
3	23	168	80	M	Yes	3	1-7 days
4	50	173	65	M	Yes	3	> 30 days
5	30	184	93	M	Yes	1	0 day
6	61	184	118	M	Yes	6	Almost everyday
mean±SD	36.0±16.0	180.8±9.7	88.2±17.6			3.7±2.0	

All basic information was obtained from the survey document before measurements. The survey is presented in Appendix 2. Table 1 presents the basic information of the 6 total samples with the pain and discomfort history. The pain and discomfort history were acquired from three questions according to the Nordic Musculoskeletal Questionnaire (NMQ) (Dickinson et al., 1992), and Borg CR10 scale (Williams, 2017):

1. *"Have you had any discomfort (pain, ache, discomfort) in the neck at any time in the last seven days?"* (Dickinson et al., 1992)
2. *"How much discomfort you have experienced in the last seven days?"* (Williams, 2017)
3. *"How many days in the last 3 months have you had problems with the neck?* (Dickinson et al., 1992)

Table 2 shows participants' experience of working and Spineband. The Spineband size was decided based on the percentile of height of each participant. Participants under the 50th percentile of height were assigned to 'XS-M'; participants above the 50th percentile of height were assigned to 'L-XL'. The participants' experience of working and using Spineband was obtained from the following two questions:

1. *"How long have you worked as a floor layer?"*
2. *"Have you used Spineband before?"*

Table 2. Participants' Experience of Working and Spineband

No	Spineband Size	Using Experience (hour)	Working Experience (year)
1	L-XL	1	6
2	L-XL	10	1.5
3	XS-M	80	6
4	XS-M	1	4
5	L-XL	10	11
6	L-XL	10	31
mean±SD		18.7±30.4	9.9±11.0

3.2.2 Sample size estimation

Since this study was an exploratory measurement, the features of the analytical variables were unknown and there was no prior research. Thus, the sample size estimation was not done based on statistics. According to the actual situation, a total of 6 volunteers were recruited.

3.2.3 Inclusion and exclusion criteria

Inclusion criteria:

1) with work experience and proficient in independently completing work tasks.
2) with work-related neck disorder.

Exclusion criteria:

1) without neck-related disorders unrelated to occupational activities.
2) no history of neck surgery.

3.2.4 Ethical considerations

Swedish Ethical Review Authority permission number 2022-06827-02 was granted for the ethical aspects of this study. Written and verbal informed consent was acquired from each participant regarding participation and recording.

3.3 Measurement Procedure

This experiment adopted a randomized crossover design, where the order of testing for subjects wearing and not wearing exoskeletons was randomized. The environments and tasks for the two repeated tests on subjects were kept as similar as possible without affecting the subjects' actual work. During the testing without wearing exoskeletons, subjects did not remove the exoskeletons but only disconnected the head ring and the main body of the exoskeleton. Each testing session was expected to last for 1 hour. However, to ensure task similarity, the duration of each measurement session varied between 30 and 60 minutes based on the actual working conditions.

Before the testing began, subjects first signed informed consent forms and filled out questionnaires regarding basic information. Subsequently, subjects wore exoskeletons and all measurement equipment. Then, subjects performed three maximal neck muscle contraction tests.

The participants were instructed to stand in a neutral position and to cross their hands behind their heads. They were then asked to exert backward force with their heads horizontally, aiming to achieve maximal muscle contraction of splenius capitis muscles. After that, these subjects completed daily work tasks lasting 30 to 60 minutes under the condition of wearing or not wearing exoskeletons according to the generated random sequence. Finally, subjects completed another 30 to 60 minutes of daily work tasks under the other condition.

All subjects completed the data collection. The first subject's measurement under the condition of wearing the exoskeleton had the first 30 minutes’ data excluded due to incorrect settings of the exoskeleton.

3.3.1 Setting of the Exoskeleton: Spineband

The Spineband Active is a passive neck flexion exoskeleton developed by the Spineband company in Sweden. The purpose of the Spineband Active is to reduce the muscle load in the neck region, as well as control the posture of the upper body. The Spineband Active consists of three parts: the main body of the exoskeleton worn on the torso, the adjustable head ring, and the back accessory. The Spineband Active works by adding a rubber band in the back aligned with the vertical line as a spring to assist the neck extensor, applying an additional force that helps the neck extend to relieve the muscle load on the neck extensor. The setting is shown in Figure 5.

During the measurements, the main body of the exoskeleton was tightly attached to the waist, and two back accessories were applied to connect the exoskeleton to the belt to secure the lower attachment. The head ring was worn tightly on the head aligned with the horizontal line to secure the upper attachment.

Figure 5. Setting of Neck Flexion Exoskeleton: Spineband

3.4 Procedure for Data Collection and Processing

3.4.1 Surface electromyography

Biosignalplux is an integrated biological signal acquisition device that can record various biological signals such as electrocardiography (ECG), electroencephalography (EEG), electromyography (EMG), etc, which is widely used in the field of ergonomics. Researcher Kit (Biosignalsplux, Portugal) surface EMG collection module (Figure 6) was applied for measurement and analysis of muscle activities in this project, with a 16-bit resolution, and a 2000 Hz sample frequency.

EMG data were obtained from neck extensors (bilateral splenius capitis muscles) during measurements (Dalager et al., 2020). Two pairs of Ag/AgCl electrodes (Ambu Neuroline 720, Ambu A/S, Ballerup, Denmark) were put at the horizontal level between C3 to C4 on the muscle belly of splenius capitis muscles as testing electrodes (Dalager et al., 2020), and one electrode was put right above C7 as grounding electrode. Figure 5. shows how the three electrodes were positioned by SENIAM guidelines. Skin abrasion was performed before placing the electrodes to improve the accuracy of the data (Boyer et al., 2023). The participants' EMG data were recorded throughout the whole workflow both with and without the exoskeleton.

Figure 6. Biosignalsplux Body Sensing Equipment

MATLAB 2022a (The MathWorks Inc., USA) was employed to process the data. Outliers were cleared before. Data preprocessing was done first (Figure 7). The original signal was sampled and converted into microvolts, applying the following formula:

$$\boldsymbol{EMG_{mV}}=\frac{\left(\frac{ADC}{2^n}-\frac{1}{2}\right)\cdot VCC}{G_{EMG}}.$$

Next, the bandpass filter (fourth-order Butterworth filter) was applied to filter the raw EMG signal from 20 to 400 Hz (Bodin et al., 2019). Then baseline removal was applied to the signal. After that, the signals were rectified to obtain the preprocessed signal values by performing full-wave rectification. Finally, EMG applied RMS-transformed (16Hz) (Bodin et al., 2019).

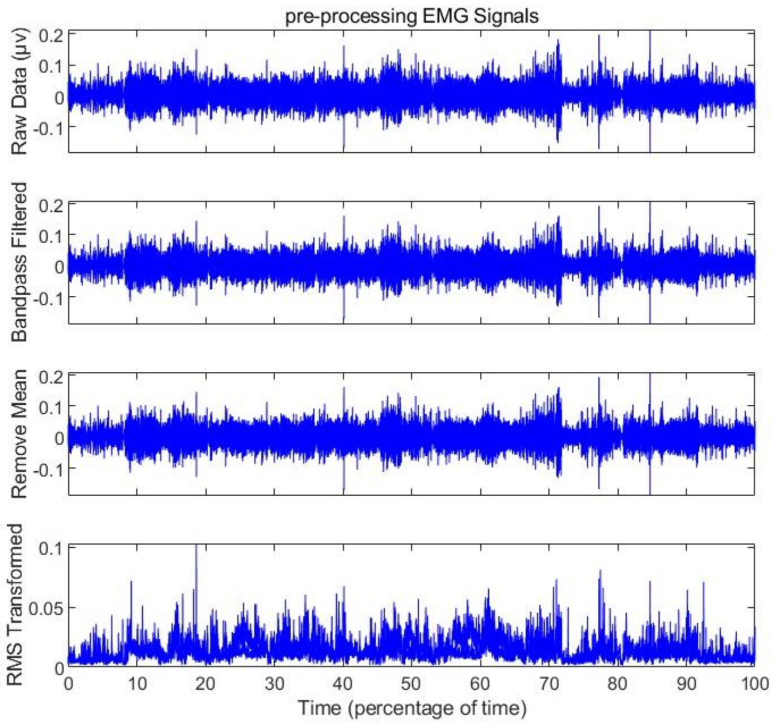

Figure 7. Pre-processing steps of EMG signals (data from subject 4 with exo)

The EMG signals were then normalized using the root mean square (RMS) of three maximum voluntary contractions (MVCs) to get normalized EMG data. The maximum 1-sec RMS value during the MVCs was used to construct the maximal voluntary electrical activity (MVE) (Bodin et al., 2019). The subjects' MVE was recorded as they exerted their maximum muscular contraction for three seconds against a manual resistor. The measurements of MVE were taken with a one-minute interval between each two measurements. The lowpass filter (6Hz) was applied to plot the normalized EMG data's linear envelop curves. The following were the further processed key parameters:

RMS (10^th^, 50^th^, 90^th^ Percentiles) This parameter represented the level of muscle activation, with higher values indicating greater muscle activation (Zhang et al., 2023). Percentiles were used to measure the distribution of this parameter. The x^{th} percentile indicated that ***x*** percent of the data was less than or equal to this value (Fan et al., 2024). The static, mean, and peak muscle activity were represented by the 10^{th}, 50^{th}, and 90^{th} percentiles, respectively (Garcia et al., 2023).

$$\boldsymbol{RMS}=\sqrt{\frac{1}{N}\sum_{i}^{N}\boldsymbol{EMG}(\boldsymbol{i})^{2}}$$

(***i*** represented the start time of the EMG signal, and ***N*** represented the end time of the EMG signal.)

3.4.2 Kinematics

In this project, postures were measured and analyzed using the inertial measurement units (IMU) —— Movesense (Wergonic, Sweden) developed by Wergonic (Figure 6). The sampling frequency in this project was 12 Hz. The Movesense was part of smart workwear, utilized to monitor posture changes during work, including the head, torso, and both arms, to assess posture-related risks in the workplace. Risk management reports were also generated via a smartphone app connected to Movesense.

Figure 8. Inertial Measurement Unit: Movesense

IMU data was obtained from head and trunk measurements. The IMU, which measured head movement, was placed in the middle of the forehead of the Spineband's head ring. The IMU, which measured trunk movement, was placed in the back measuring pocket of the Wergonic T-shirt, located directly below the C7. Figure 8. shows the IMU placement for the head and trunk. IMU data of the subjects were captured during the whole measurements, both with and without the exoskeleton.

By using the Wergonic phone application, the sagittal inclination angle and velocity for the head and trunk were pre-computed following the processing procedures outlined in Fan et al. (2021). MATLAB 2022a (The MathWorks Inc., USA) was then employed to calculate the processed data. First, the head data was corrected for quadrant alignment. Then, outliers were removed from the data. The post-processed data was applied to plot the curves. The following were the further processed key parameters:

Head Angle (10th,50th,90th Percentiles) This parameter measured the angle between the sagittal inclination line of the head and the line of gravity (Lindegård et al., 2012).
Neck Angle (10th,50th,90th Percentiles) This parameter referred to the relative angle between the sagittal inclination line of the head and the trunk (Lindegård et al., 2012).
Trunk Angle (10th,50th,90th Percentiles) This parameter recorded the angle between the sagittal inclination line of the trunk and the line of gravity (Fan et al., 2024).
50th Percentile of the Sagittal Inclination Velocity (head, trunk) The corresponding inclination angles' derivatives were used to compute the angular velocity. This parameter reflected the central tendency of the angular velocity (Fan et al., 2024).

Percentiles were used to measure the distribution of these parameters. The x^{th} percentile indicated that the x percent of the data was less than or equal to this value.

3.5 Data Analysis

The sEMG and kinematic parameters were applied to statistical analysis. The distribution of the data could not be ascertained because of the small sample size (Bodin et al., 2019). Consequently, the equality of parameters between wearing and not wearing exoskeletons was compared using the Related Samples Wilcoxon signed-rank test (Bodin et al., 2019). The one-tailed Spearman rank correlation coefficient was applied to test the relationship between parameters under the exoskeleton condition (D’Anna et al., 2021). The absolute value of the correlation coefficient r approaching 1 indicated a higher degree of correlation. The statistical significance level of 0.05 was set in all tests. The SPSS 27.0 (SPSS Inc., Chicago, USA) was used to process the data.

4 Results

4.1 Muscle Activity of Cervical Region

4.1.1 Muscle activity throughout the entire workflow

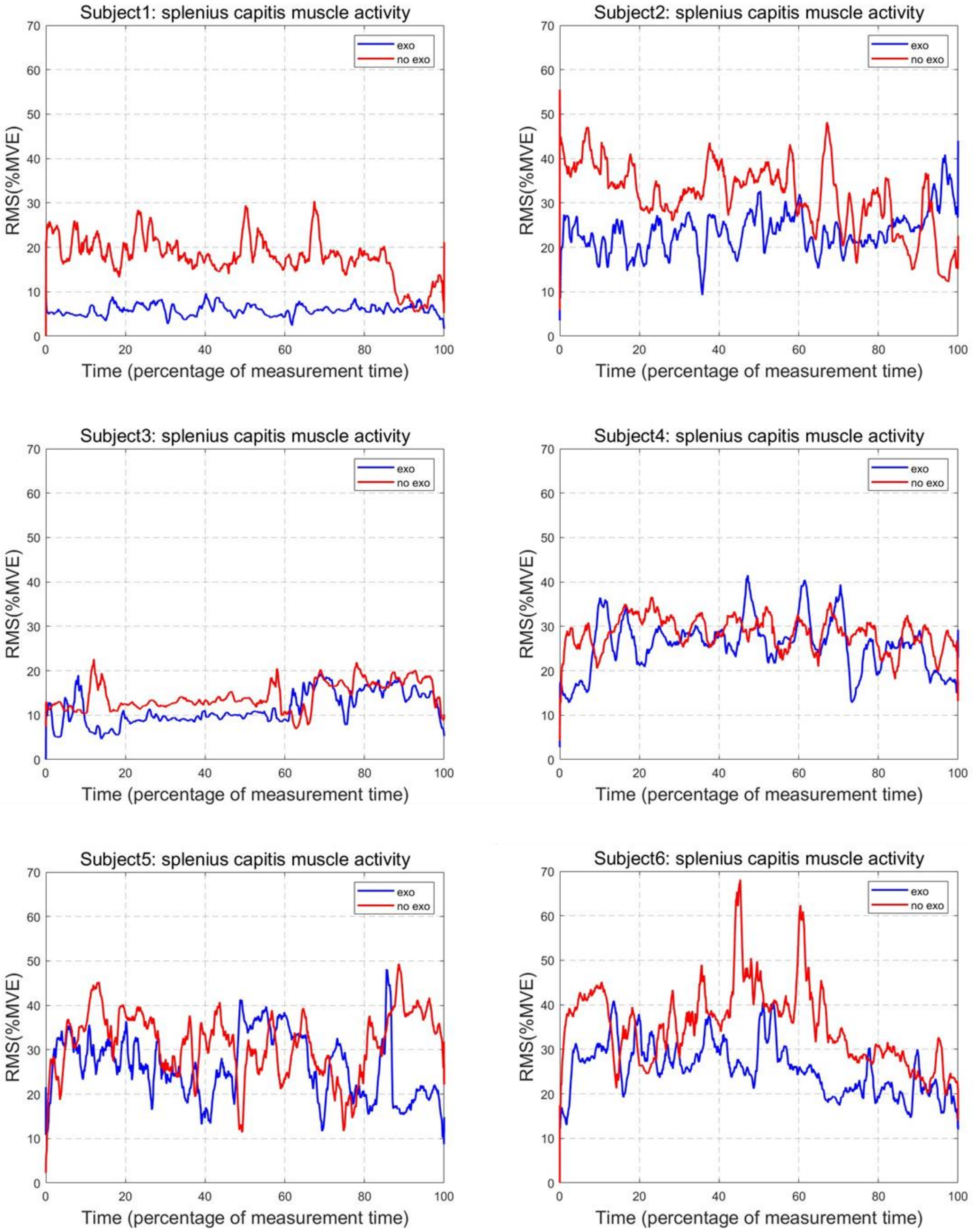

Figure 9. The muscle activity throughout the entire workflow

Six subjects' muscle activity changes over the whole floor-laying workflow are shown in Figure 9, both with and without the neck flexion exoskeleton. The overall trend of the muscle activity curves was lower when all participants wore the exoskeleton than when they did not.

For more than 90 % of the time, the splenius capitis muscle activity curves in the first, second, third, and sixth subjects with the exoskeleton on were lower than that without the exoskeleton. For more than 60 % of the time, the splenius capitis muscle activity curves in the fourth, and fifth subjects while wearing the exoskeleton were lower than that of the ones without the exoskeleton.

The above results present that for all participants, the overall activities of the splenius capitis muscles decreased when wearing the exoskeleton compared to when not wearing it.

4.1.2 Muscle activity characteristics between without and with exoskeleton

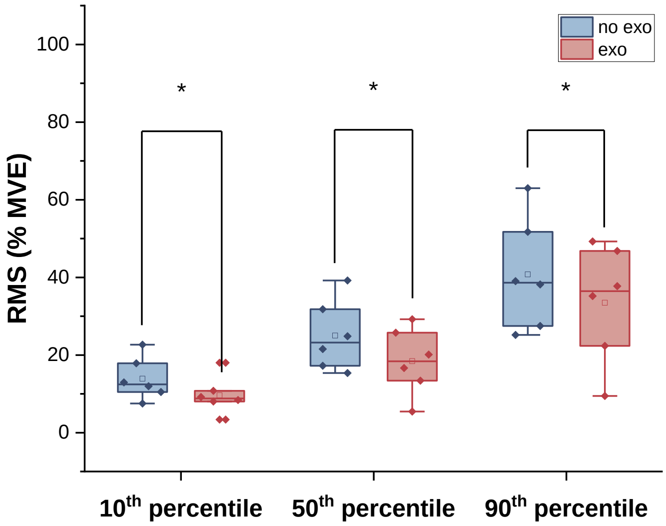

Figure 10. Muscular activity without and with exoskeleton

As shown in Figure 10, the results of the RMS without exoskeleton condition were significantly higher than those with exoskeleton condition in the 10^{th} percentile (p=0.028), 50^{th} percentile (p=0.028), and 90^{th} percentile (p=0.028).

4.2 Kinematics of Neck and Trunk

4.2.1 The kinematics throughout the entire workflow

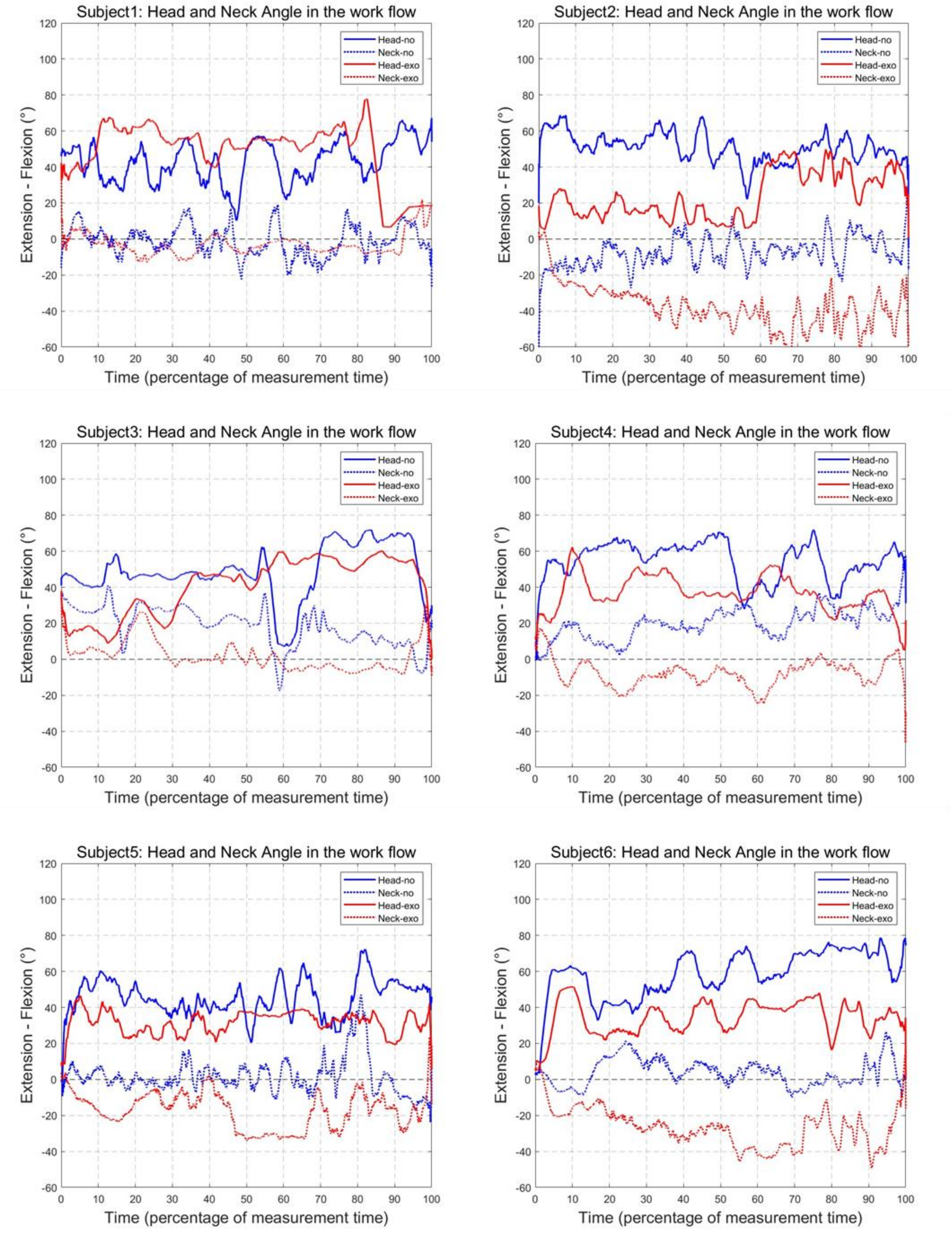

Figure 11. The kinematics of head and neck throughout the entire workflow

Figure 11 illustrates the head and neck angle variations among six participants throughout the entire workflow of laying floors under both conditions, with and without the neck flexion exoskeleton. Head angle curves under the exoskeleton condition consistently remained lower than those without the exoskeleton for over 80 % of the workflow duration, except for the first participant. This result shows that when wearing the exoskeleton, most of the participants exhibited reduced degrees of the head forward inclination angles during the workflow period compared to when not wearing the exoskeleton. Additionally, peak head angle values were consistently lower with the exoskeleton compared to without it, except for the first participant. This result presents that for most participants, the maximum degrees of the head forward inclination angles while wearing the exoskeleton were less than that when not wearing it.

Similarly, neck angle curves under the exoskeleton condition were also consistently lower than those without the exoskeleton, including over 90 % of the workflow duration. However, according to the first participant's curve, the trend in neck angle curves remained similar between both conditions, but the curve under with exoskeleton condition was flatter. The aforementioned findings demonstrate that, for the majority of participants, wearing the exoskeleton during the workflow period decreased their degree of neck flexion angles in comparison to not wearing it. Moreover, peak neck angle values were consistently lower with the exoskeleton across all participants. This result presents that when wearing the exoskeleton, the maximum degrees of neck flexion angles for all participants were less than that when not wearing it.

Furthermore, under the exoskeleton condition, neck angle curves decreased below the zero-horizontal line (extension) among all participants. Notably, during the workflow, the neck angle curves remained below the zero-horizontal line for over 90 % of the time among the second, fourth, fifth, and sixth participants. In contrast, under the condition without the exoskeleton, the curves generally remained near or above the zero-horizontal line. The above results present that when wearing the exoskeleton, neck angles for most of the workflow period were in extension position for all participants; whereas without wearing the exoskeleton, neck angles were in flexion or relatively neutral position.

Six participants' trunk angle variations during the floor-laying workflow are shown in Figure 12. The peak trunk angles while wearing the exoskeleton were higher in all subjects compared to those not wearing the exoskeleton. Additionally, it was found that in the first, third, and fourth subjects, the trunk angle curves while wearing the exoskeleton were higher than not wearing the exoskeleton for over 70 % of the time; however, the trunk angle curve variations in the second, fifth, and sixth subjects were similar between wearing and not wearing the exoskeleton conditions. The above results show that when wearing the exoskeleton, the maximum trunk angles for all participants were greater than when not wearing the exoskeleton, and showed an overall increasing trend.

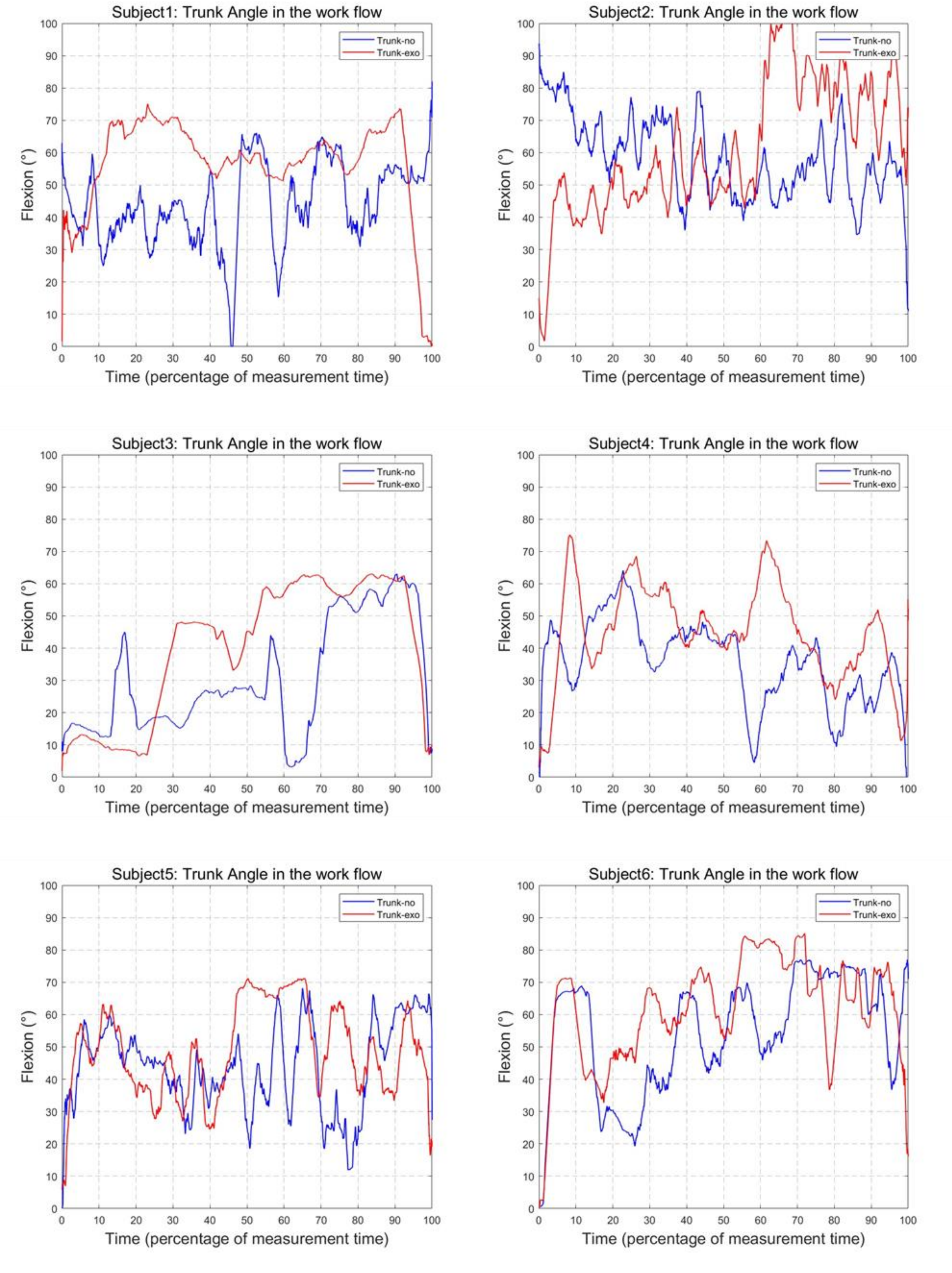

Figure 12. The kinematics of trunk throughout the entire workflow

4.2.2 Kinematic characteristics between without and with exoskeleton

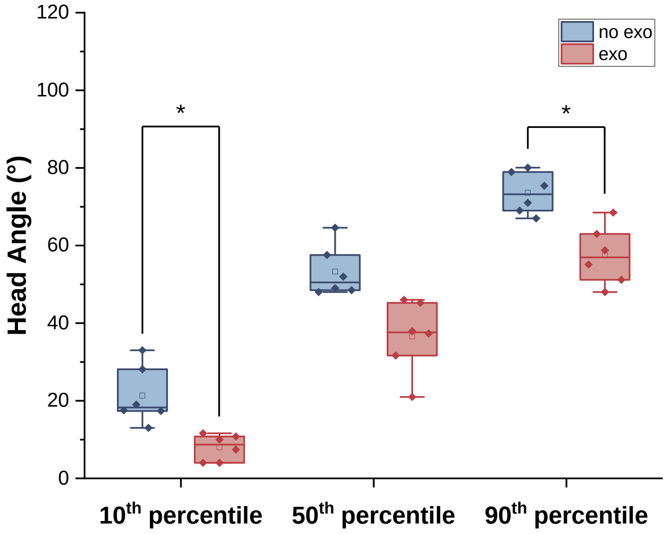

Figure 13. Head Angle without and with exoskeleton

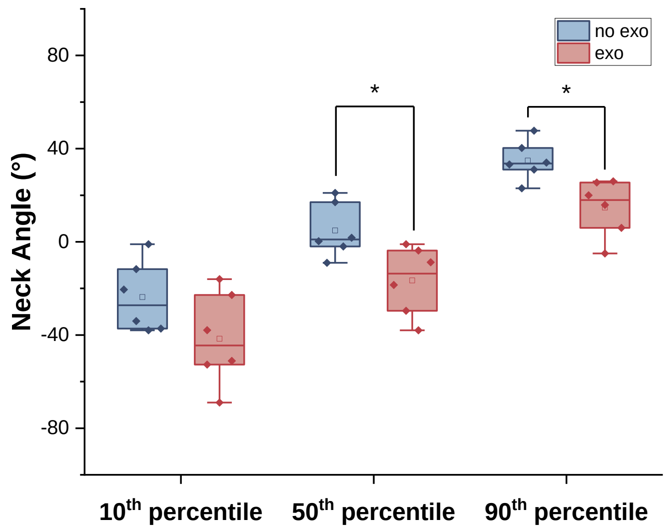

Figure 14. Neck Angle without and with exoskeleton

As presented in Figure 13, the 10th percentile (p=0.028) and the 90th percentile (p=0.046) of the head angle without exoskeleton condition were significantly higher than with exoskeleton condition. Comparably, in Figure 14, the neck angle without the exoskeleton condition was significantly higher in the 50th percentile (p=0.028) and 90th percentile (p=0.028) than it was in the exoskeleton condition. However, there was no significant difference between with and without exoskeleton conditions of the 50th percentile of the head angle (p=0.075), and the 10th percentile of the neck angle (p=0.093).

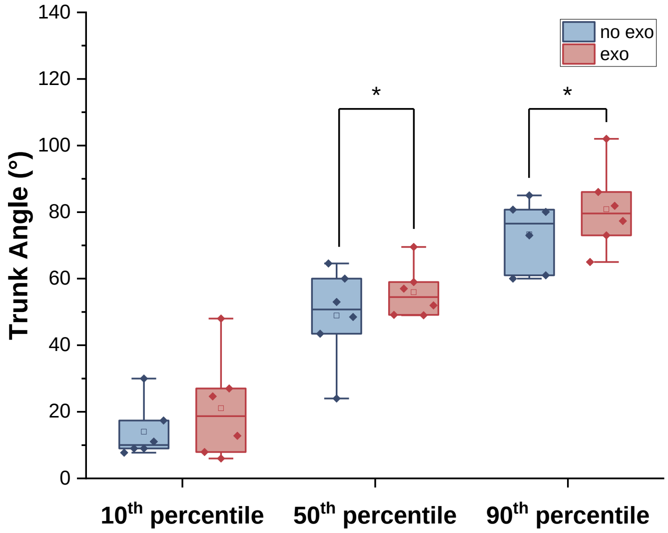

Figure 15. Trunk angle without and with exoskeleton

Figure 15 shows that the trunk angle with the exoskeleton condition was significantly higher than the trunk angle without the exoskeleton condition at both the 50th percentile (p=0.046) and the 90th percentile (p=0.027). Nevertheless, there was no significant difference (p=0.340) between the 10th percentile of the trunk angle with and without exoskeleton conditions.

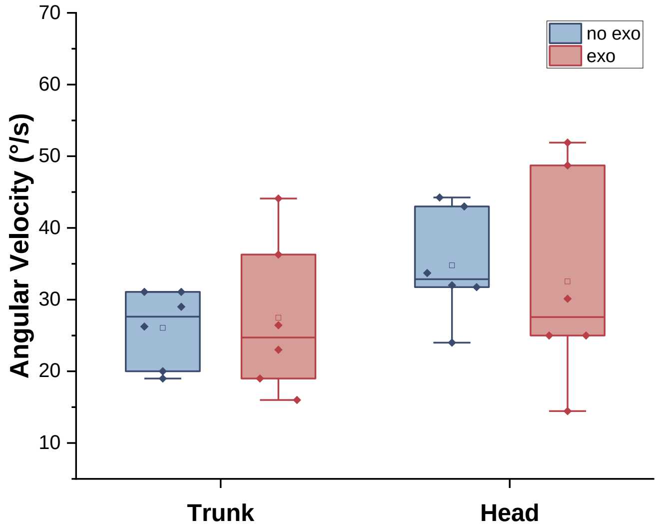

Figure 16. Angular velocity without and with exoskeleton

Additionally, there was no significant difference between with and without exoskeleton conditions of the 50th percentile of the head angular velocity (p=1.000) and the 50th percentile of the trunk angular velocity (p=0.715) in Figure 16.

4.3 Correlation Analysis under Exoskeleton Condition

4.3.1 Correlation analysis of kinematics

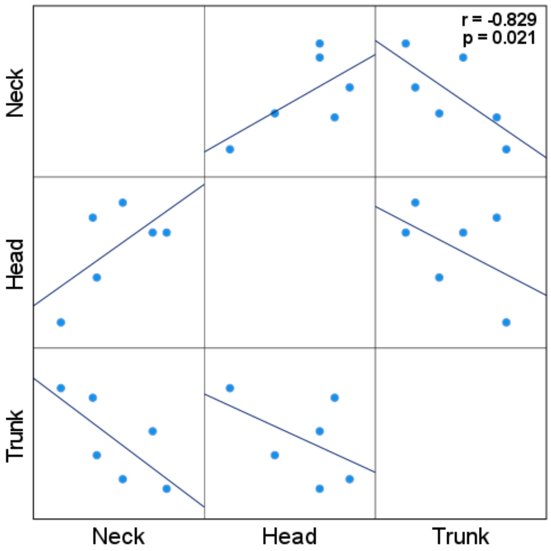

Figure 17. The 10th percentile of work posture with exoskeleton

As shown in Figure 17, under the condition of wearing the exoskeleton, the neck angle at the 10th percentile was significantly correlated with the trunk angle (p=0.021), with a correlation coefficient of r=-0.829, indicating a highly negative correlation.

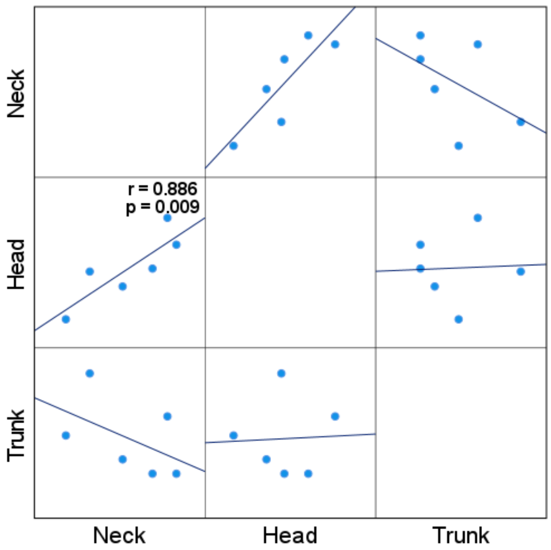

Figure 18. The 50th percentile of work posture with exoskeleton

Additionally, in Figure 18, under the condition of wearing the exoskeleton, the neck angle at the 50th percentile was significantly correlated with the head angle (p=0.009), with a correlation coefficient of r=0.886, indicating a highly positive correlation. However, no significant correlation was observed among other parameters.

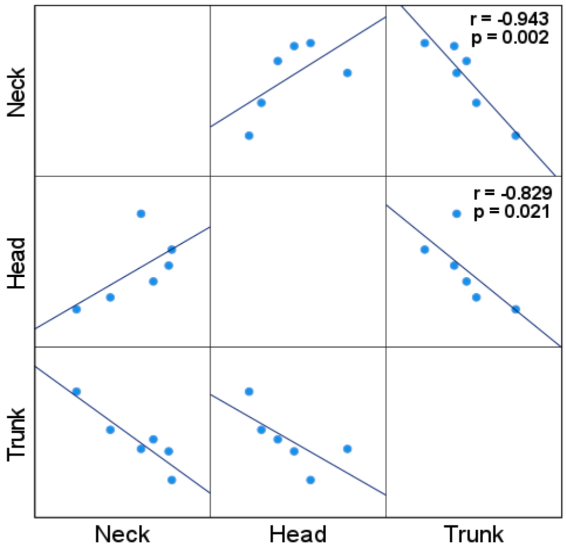

Figure 19. The 90th percentile of work posture with exoskeleton

According to Figure 19, under the condition of the exoskeleton, the neck angle at the 90th percentile was significantly correlated with the trunk angle at the 90th percentile ($p=0.002$), with a correlation coefficient of $r=-0.943$, indicating a strong negative correlation.

Similarly, under the condition of the exoskeleton, the head angle at the 90th percentile was significantly correlated with the trunk angle at the 90th percentile ($p=0.021$), with a correlation coefficient of $r=-0.829$, indicating a strong negative correlation. Nevertheless, there was no obvious association found between other parameters.

4.3.2 Correlation analysis between muscle activity and kinematics

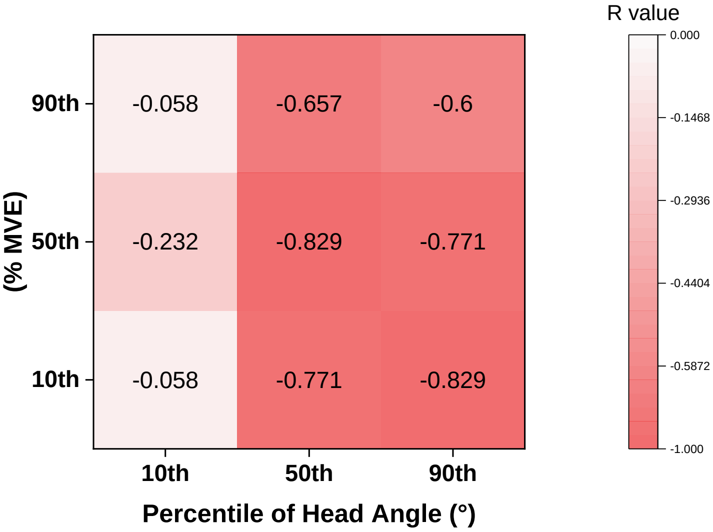

Figure 20. Correlation between muscular activity and head angle with exoskeleton

Based on Figure 20, in the case of wearing the exoskeleton, the 50th percentile of head angle was significantly negatively correlated with the 10th percentile of RMS (r=-0.771, p=0.036), and the 50th percentile of RMS (r=-0.829, p=0.021). Additionally, the 90th percentile of head angle was significantly negatively correlated with the 10th percentile of RMS (r=-0.829, p=0.021), and the 50th percentile of RMS (r=-0.771, p=0.036).

4.4 The Relationship between Neck Muscle Activity and Neck Angle

By comparing the curves in Figure 9 and Figure 11, it was observed that during the majority of the time percentage, curves of neck angle in the first and third subjects while wearing the exoskeleton were below the zero-horizontal line. Additionally, it was noted that in the second, fourth, fifth, and sixth subjects more than 50 % of the time, curves of the neck angle while wearing the exoskeleton were below the zero-horizontal line. During the same period within the percentage, curves of neck muscle activity while wearing the exoskeleton remained below curves of neck muscle activity without wearing the exoskeleton.

The results above show that using the exoskeleton changes the subjects' neck movement from flexion to extension, while also reducing the muscle activity of neck extensors.

5 Discussion

5.1 Discussion of Results

The following discussion centers on the head angle, neck angle, trunk angle, and RMS of neck extensors. Both the head angle and trunk angle refer to the forward inclination angle and are positive values. However, the neck angle is positive during flexion and negative during extension.

5.1.1 The impact of the exoskeleton on muscle activities

Through analysis of muscle activity curves, it was found that over 60 % of the participants had muscle activity curves lower than those without wearing the neck exoskeleton for over 90 % of the time when wearing the neck exoskeleton. The remaining participants also had muscle activity curves lower than those without wearing the neck exoskeleton for over 60 % of the time when wearing it. Additionally, participants 10^{th}, 50^{th}, and 90^{th} percentiles of RMS were significantly lower when wearing the neck exoskeleton compared to not wearing it. These findings indicate that wearing the neck exoskeleton effectively reduces the distribution trend in task execution of user muscle activities. These results align with previous research on neck extension exoskeletons, suggesting that neck exoskeletons could effectively reduce muscle activities at the target area (Garosi et al., 2022; Rossini et al., 2022).

Additionally, according to the proposed action level of the trapezius muscle's muscular load, the peak load levels must not exceed 20% of MVC (Arvidsson et al., 2021), which could possibly (however being another muscle) be a reference value for neck extensors here. During measurement periods among floor layers, the 90^{th} percentile of RMS exceeded this proposed action level under with and without exoskeleton conditions, but there still was a significant decrease under the with exoskeleton condition compared with the no exoskeleton condition, which suggests a reduction in muscle workload risks during tasks when wearing the exoskeleton, yet the values remain above the proposed action level. Consequently, while the neck exoskeleton appears to reduce muscle workload, whether it can eliminate the muscle workload risks in the cervical region remains unclear and requires further research.

5.1.2 The impact of the exoskeleton on work postures

Through analysis of participants' head and neck angle curves with and without wearing neck flexion exoskeleton, it was found that over 80 % of the participants spent more than 80 % of the time with their head angle curves lower when wearing neck flexion exoskeleton compared to not wearing them, and over 90 % of the time with their neck angle curves lower when wearing the neck flexion exoskeleton compared to not wearing them. Additionally, when wearing the neck flexion exoskeleton, the 10^{th} and 90^{th} percentile of head angles significantly decreased, and the 50^{th} and 90^{th} percentile of neck angles also significantly decreased. These results indicate that participants reduced head forward inclination and neck flexion when wearing the neck flexion exoskeleton compared to not wearing them, consistent with findings from Giovanelli et al.'s previous research on the neck exoskeleton (Giovanelli et al., 2022).

The aforementioned results further validate the biomechanical mechanism of passive exoskeletons (Bosch et al., 2016), which involves the exoskeleton's springs being stretched to limit and maintain movement towards the target direction when the target joint moves in a particular DOF (H. Lee et al., 2012), which controls and improves the user's posture in the target region.

Additionally, according to the proposed action levels for physical workload concerning head postures, the 10th percentile, 50th percentile, and 90th percentile of the head angle should not exceed -10°, 25°, and 50°, respectively, during an 8-hour workday (Arvidsson et al., 2021). However, measurements of floor layers without exoskeleton support showed that the 10^{th} percentile, 50^{th} percentile, and 90^{th} percentile of head angles all exceeded these proposed action levels, indicating a significant risk of physical workload on the cervical region. With the use of the neck exoskeleton, there are decreases in the 10^{th} percentile, 50^{th} percentile, and 90^{th} percentile of head angles compared to the no exoskeleton condition. The above result suggests that while the neck exoskeleton can reduce the physical workload risks on the cervical region, it remains unclear whether it can eliminate it.

Furthermore, the peak values of the trunk curves for each subject were greater when the neck exoskeleton was worn than when it was not. Half of the subjects showed a higher curve of trunk angle for over 70 % of the time with the neck exoskeleton on compared to without it. Moreover, compared to not using the neck exoskeleton, the trunk angles at the 50^{th} and 90^{th} percentiles were significantly higher when wearing the neck exoskeleton. The aforementioned suggests that although the neck exoskeleton can decrease neck flexion, it may harm trunk forward inclination, resulting in a rise in trunk angles. The notion that exoskeletons can decrease motion angles at target joints while potentially increasing angles at non-target joints is supported by this (H. Lee et al., 2012; Luger et al., 2023; Luger et al., 2021; Iranzo et al., 2020; Ojelade et al., 2023).

Besides, trunk forward inclination greater than 60° is significantly associated with low back disorder (LBD) when occurring for more than 0.3 to 1 hour per workday (Lind et al., 2020). During measurement periods of floor layers, the 10^{th} and 50^{th} percentiles of trunk angles were below 60°, indicating a low-risk physical workload for the back regions with and without exoskeleton conditions. However, the 90^{th} percentile of trunk angles exceeded 60° under both conditions during the 20 to 60-minute measurement periods and showed an increase in the exoskeleton condition. Therefore, it is unclear whether wearing a neck exoskeleton during an 8-hour workday will cause the trunk flexion angle to exceed 60° for 0.3 hour to 1 hour. However, when the forward inclination angles of the trunk increase and exceed 60°, there are arm supports in the kneeling tasks of floor layers instead of the no support situation under the proposed action level, so the increase in the forward inclination angles of the trunk may not increase the physical workload risks of LBD. Thus, further research is required for verification of the variation of physical workload risks of LBP with the exoskeleton.

However, some prior studies of back exoskeletons presented no significant effect on work posture improvements during some work tasks (Kim et al., 2020; van Sluijs et al., 2023), which did not align with the result of this project. The aforementioned implies that the neck flexion exoskeleton is effective for floor layers' work tasks, but its effect on other work tasks is unknown. Thus, further research is needed to verify whether the neck flexion exoskeleton has improvements in other work tasks or not.

According to the analysis of the correlation between head, neck, and trunk angles at the 10^{th}, 50^{th}, and 90^{th} percentiles: in the 10^{th} percentile posture, there was a significant negative correlation between neck angle and trunk angle; in the 50^{th} percentile posture, there was a significant positive correlation between neck angle and head angle; in the 90th percentile posture, there were significant negative correlations between head angle and trunk angle, as well as between neck angle and trunk angle. These results indicate that in postures with slight upper body forward inclination, compensation for neck flexion may occur through trunk forward inclination; in extremely awkward postures, compensation for forward head tilt and neck flexion may occur through trunk forward inclination. The aforementioned implications further confirm the viewpoint of Theurel & Desbrosses (2019) that exoskeletons have interaction effects on joints, and as a compensatory strategy, using exoskeletons may increase joint angles in non-target areas.

However, there was no significant difference in the angular velocity of the head and trunk at the 50th percentile between wearing and not wearing the exoskeleton, indicating that wearing the neck exoskeleton may not have a negative impact on work efficiency.

5.1.3 The impact of the exoskeleton between muscle activities and work postures

Through analysis of the correlation between muscle activity and head angle, it was found that when RMS was at the 10th and 50th percentiles, there was a significant negative correlation with head angle at the 50th and 90th percentiles, respectively. These results suggest that the muscle load on the neck may be successfully reduced when the head is positioned from medium to extreme positions and the muscle activity is from static load to median load. However, the neck exoskeleton is ineffective or fails when the head forward inclination angle is slight or the muscles are under peak load.

According to the results above, the neck flexion exoskeleton's spring is stretched to store energy and starts to work when the head is tilted forward to a specific degree, which is beyond the 10th percentile of the head angle. However, when the neck muscles are operating at maximum capacity, the exoskeleton's spring is unable to maintain or resist the force of the neck muscles, which would diminish or stop the exoskeleton's operation.

Additionally, the preceding findings suggest a robust negative correlation between the strength of neck muscle activity and the head angle, affirming the biomechanical principles governing head movements (Hunter, S. K. & Brown, D. A., 2010). Specifically, as the head forward inclination angle increases, so does the distance between the head's CoG and the line of gravity. Consequently, the moment arm for the torque generated by forward head tilt enlarges, leading to an escalation in the resultant torque. Under this condition, the neck exoskeleton applies an opposing torque to counterbalance the tilt-induced torque, effectively diminishing the torque exerted by the neck extensor muscles as well as reducing their muscle activity (Hunter, S. K. & Brown, D. A., 2010).

Furthermore, when wearing the neck flexion exoskeleton, more than 60 % of participants' neck angles were below the zero-degree horizontal line more than 90 % of the time, demonstrating a shift in the neck's movement pattern from flexion to extension (Van Dijk & Van Der Kooij, 2014). Meanwhile, comparing the curves of muscle activity reveals that muscle activity is lower when wearing the neck flexion exoskeleton compared to not wearing it. These results imply that the alteration in neck movement pattern may be connected to the decrease in neck extensor activity when wearing the neck flexion exoskeleton.

Since the neck extensor muscles in the tasks of floor layers only act to resist the gravitational force of the head itself and are not subjected to other external forces, when not using the neck exoskeleton, the neck extensor muscles are in a relatively flexed position, resisting the gravitational force of the head through isometric contraction. However, when using the neck exoskeleton, the neck extensor muscles are in a relatively extended position, resisting the gravitational force of the head through concentric contraction. According to the sliding filament theory of muscle excitation-coupling, when muscles are in concentric contraction, there is a greater overlap of muscle filaments, requiring fewer recruited muscle fibers to generate the same force, thus resulting in less muscle activity (Hunter, S. K. & Brown, D. A., 2010). This may be the reason for the reduction in muscle activity caused by the change in neck movement pattern.

5.2 Discussion of Methods

5.2.1 Limitation of study design

Firstly, because this was an exploratory study, no statistical estimation of sample size was conducted, and samples were obtained based on practical circumstances. Due to the relatively small sample size, there may be insufficient statistical power (Hertzog, 2008), so increasing the sample size might be necessary.

Secondly, for muscle activity, only the muscles in the target area were evaluated, and the muscles in adjacent areas as well as the antagonists were not measured. Previous studies showed that while using exoskeletons could reduce muscle activity in the target area, it might also increase muscle activity in adjacent areas or the antagonists (Luger et al., 2023; Theurel & Desbrosses, 2019). Therefore, including the muscles in adjacent areas or the antagonists in the evaluation can further determine whether the use of exoskeletons will harm the muscle workload in non-target areas.

Finally, maintaining similarity in task completion between wearing and not wearing the exoskeleton during repeated measurements is crucial. The assessment of the neck flexion exoskeleton in this study was restricted to the evaluation of the overall tasks, ignoring variations in factors like detailed task types, working tools, and work environment (Theurel & Desbrosses, 2019; Golabchi et al., 2022). Thus, in the first subject, insufficient similarity in tasks due to differences in task tools and work environments resulted in slightly higher head angles measured when wearing the exoskeleton compared to when not wearing it, which could affect the accuracy of the results. Therefore, selecting similar tasks for evaluation under a systematic perspective in actual work conditions is essential (Eklund, 2003).

5.2.2 Limitation of the measurement settings

In this project, an adjustable head ring was chosen for fixing the upper end of the neck flexion exoskeleton, while an accessory connected with a belt was chosen for fixing the lower end. However, when the subject was in the awkward working posture of trunk forward bending with neck flexion, slight upward sliding of the forehead head ring and detachment of the accessory from the belt on the back might occur (Figure 21). The test configuration may result in structural instability or exoskeleton failure due to excessive tension created by the neck exoskeleton, which cannot be balanced by the friction force at both ends (Figure 22). The efficacy of the exoskeleton may be improved by including an integrated belt and adjustable head fixation at the top and bottom, respectively, of the neck flexion exoskeleton. Adding a soft pad under the chin could reduce the pressure on the chin from the reaction force and increase comfort.

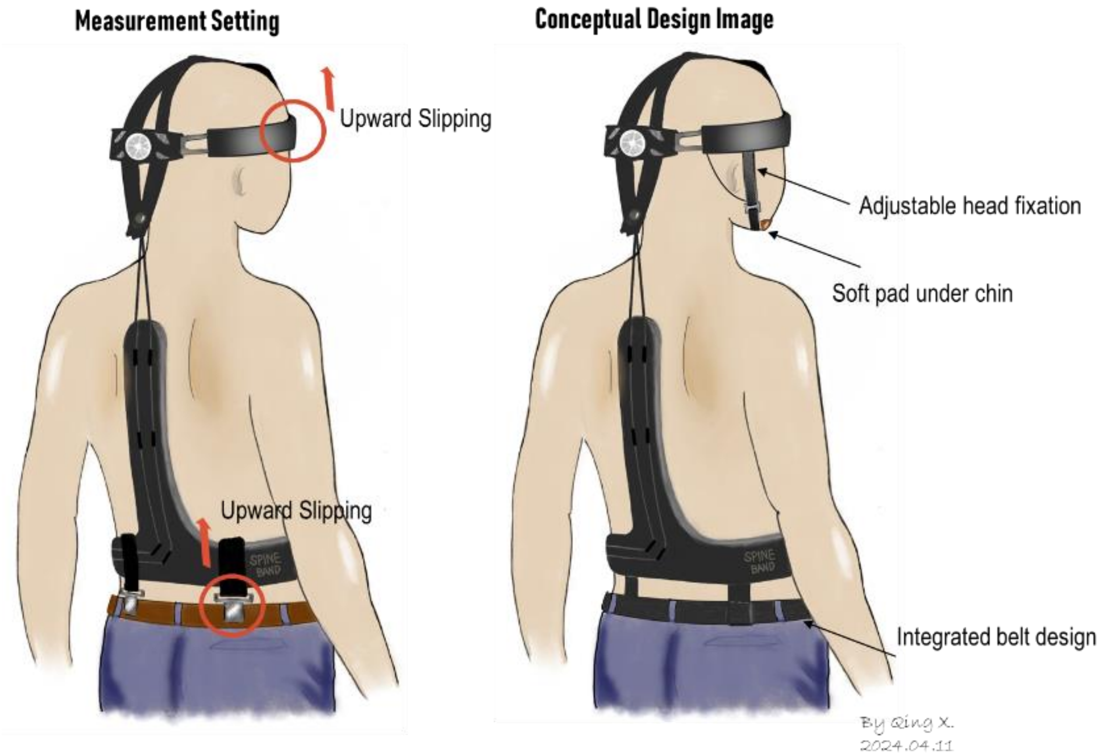

Figure 21. Setting of the neck flexion exoskeleton

Additionally, the neck flexion industrial exoskeleton used in this project was non-anthropomorphic, meaning it simplified the human joints, which might limit some non-target joint movements, such as lateral bending or rotation of the spine (H. Lee et al., 2012). Furthermore, the neck flexion exoskeleton used in this project was a multi-joint exoskeleton spanning the entire spine, so the joint movements of the spine itself affected its function on the neck (Van Dijk & Van Der Kooij, 2014). When floor layers were in an awkward trunk forward bending with neck flexion, there was a change in the physiological curvature of the spine itself; the lumbar lordosis extended straight, causing the actual length of the trunk to be greater than in the neutral position. Therefore, even if the neck is not in a relatively flexed position or is in a relatively extended position, it may still receive support from the exoskeleton tension.

Regarding the measurement devices, firstly, the IMU used in this project was validated for its acceptable accuracy in measuring sagittal plane inclination angles in previous studies (Hoareau et al., 2023). However, this setup employed two IMU systems for measuring the head and trunk, which might introduce minor time discrepancies, thus reducing the accuracy of neck angle calculations. Second, concerning the sEMG measuring devices, measurement disruptions might occur from electrode detachment due to the high probability of sweating among participants as a result of the actual working environment's temperature (Gazzoni et al., 2016). Furthermore, the accuracy of sEMG signals might be impacted by the noise produced by floor workers' equipment and by awkward postures that pull on device wires (Gazzoni et al., 2016). Therefore, the setup of the testing equipment may require more adjustments.

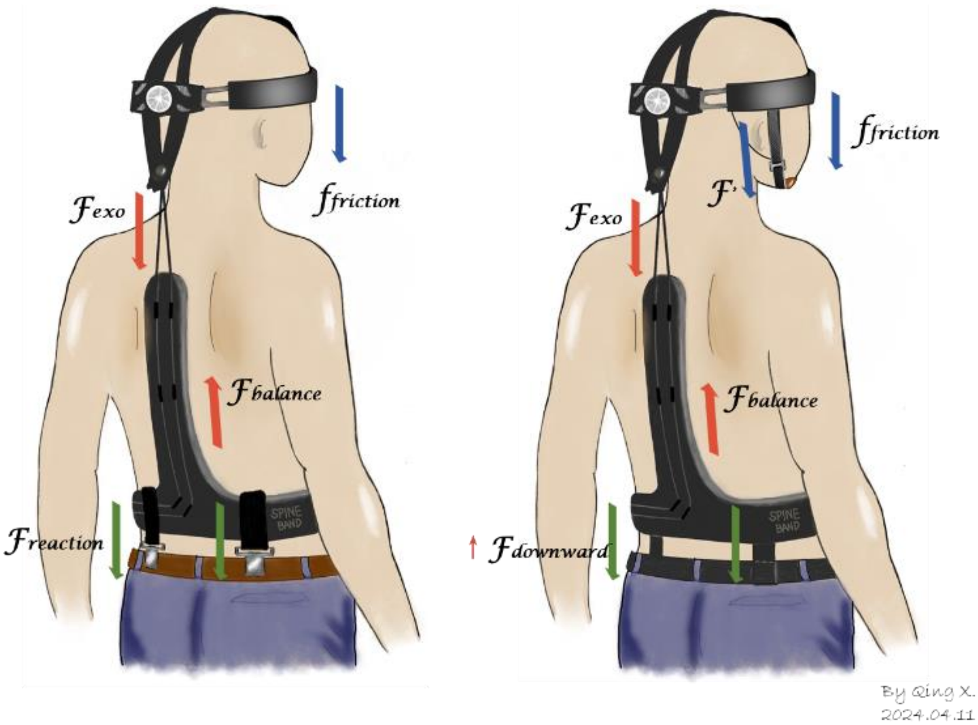

Figure 22. The biomechanic flow of the neck flexion exoskeleton

5.2.3 Limitation of measurement metrics

The evaluation of the neck flexion exoskeleton in this project only included objective factors. However, the Golabchi et al. Framework for Exoskeleton Evaluation and the Hoffmann et al. Harmonized Evaluating Methodology expanded the aspects of evaluation. From a psychological perspective, subjective evaluation could enhance objective assessment and contribute value to the evaluation results (Golabchi et al., 2022; Hoffmann et al., 2022). Additionally, prior studies extensively employed the concepts of comfort, usability, and effort perception (Golabchi et al., 2022; Hoffmann et al., 2022). Thus, the evaluation of the neck flexion exoskeleton could be more comprehensive including both objective and subjective metrics.

5.3 Future Work

In future research, further exploration and refinement of a sustainable closed-loop approach to assess the adaptability of exoskeletons and manage health risks are planned. Firstly, various tasks will be selected for testing in actual work environments to collect objective and subjective indicators, including sEMG, posture, discomfort perception, comfort, and usability. Subsequently, the collected data will be statistically analyzed to verify which indicators are important and effective for determining adaptability. Through this analysis, a deeper understanding of the impact of each indicator on adaptability will be gained. Next, the raw data will be labeled and used to train models. Attempts will be made to use predictive models based on machine learning algorithms or statistical models to predict the adaptability of exoskeletons. Finally, the predictive model will be used to obtain indicators from new subjects and continuously improve the model to enhance prediction accuracy. Additionally, risk management feedback will be provided based on detected indicators and predictive model results. The framework for sustainable occupation neck exoskeleton evaluation is presented in Figure 23.

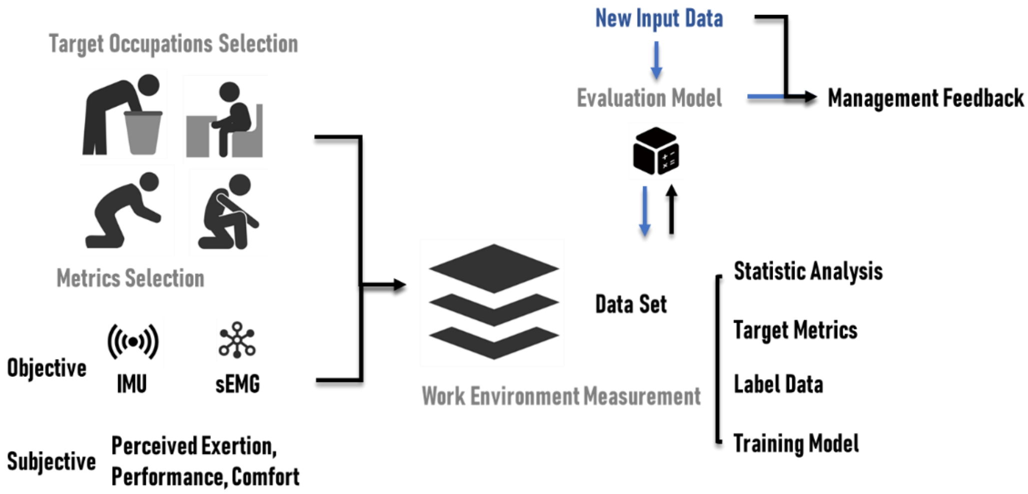

Figure 23. Framework for Sustainable Occupation Neck Exoskeleton Evaluation

6 Conclusion

This project evaluated the effectiveness of the Spineband neck flexion exoskeleton in actual work tasks performed by floor layers. The results indicate that the neck flexion exoskeleton can effectively reduce the muscle activity of the neck extensors, decreasing forward head inclination and neck flexion. According to the proposed action level (Arvidsson et al., 2021; Lind et al., 2020), physical work risks of neck extensors, head postures, and neck postures can be reduced.

However, wearing the neck flexion exoskeleton could increase the forward inclination angle of the trunk, which yet may not increase the physical work risks among floor layers. Therefore, further validation is needed to evaluate the potential negative impact of wearing the neck flexion exoskeleton on floor layers. This project suggests that floor layers can appropriately wear the neck flexion exoskeleton during work tasks to reduce physical work risks.

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8 Appendix

Appendix 1. Letter of Consent

Projekt: Testning av exoskelettet Spineband i mattläggning

Information till forskningspersoner

Du tillfrågas här om du vill delta i det här projektet.

Vad är det för ett projekt och varför vill ni att jag ska delta?

Syftet med mätningarna är att undersöka och jämföra belastningen under arbete med resektive utan Spineband i typiska situationer för mattläggare. Mätutrustningen är liten och hindrar inte arbetet.

Du tillfrågas eftersom du arbetar som mattläggare. Resultatet av den här undersökningen blir mycket mer trovärdigt om vana mattläggare deltar.

Forskningshuvudman för projektet är KTH. Med forskningshuvudman menas den organisation som är ansvarig för projektet. Ansökan är godkänd av Etikprövningsmyndigheten, diarienummer för prövningen hos Etikprövningsmyndigheten är 2022-06827-02.

Hur går projektet till?

I experimentet jämförs belastningen under arbete med respektive utan Spineband i typiska arbetssituationer för mattläggare.

Ryggens och nackens arbetsställningar och rörelser mäts med små mätare, som både mäter och lagrar ryggens och nackens vinklar under arbetspasset. Dessa fästs på Spineband. Muskelaktivitet mäts med små självhäftande elektroder som fästs på huden på en skuldermuskel och på ländryggen.

Samtidigt med mätningarna kommer arbetet att observeras och videofilmas. Efter mätningarna kommer vi att ställa några frågor om utrustningen, ditt arbete samt om du upplevt besvär från muskler och leder.

Möjliga följder och risker med att delta i projektet

Mätapparaturen är liten. Den drivs med små 3 Volts-batterier. Mätutrustning har använts i flera andra liknande projekt och det finns inga risker kopplade till mätningarna.

Du arbetar som du brukar i ditt vanliga arbete.

Samtycke till att delta i studien

Genom att skriva under nedan bekräftar du att du har fått information om studien och att du samtycker till deltagande genom att medverka i testerna och i film/fotografier som avser användas för vetenskapliga analyser.

Jag har fått muntlig och skriftlig informationen om studien och har haft möjlighet att ställa frågor. Jag får behålla den skriftliga informationen.

☐ Jag samtycker till att delta i forskningsprojektet *Testning av exoskelettet Spineband i mattläggning*

☐ Jag samtycker till att uppgifter om mig behandlas på det sätt som beskrivs i forskningspersonsinformationen

Datum: ____

Underskrift:

____

Namnförtydligande:________________________________

Appendix 2. Survey Document for basic information of participants

survey for carpet installers

PERSONAL INFORMATION

i. **Fill in the following information.**

Gender	☐ Female	☐ Male	☐ Other
Age (y)	________	**Height (cm)**	________
		Weight (kg)	________
Work experience	**How long have you worked as carpet installer?**		________ years
	Have you used Spineband before?		How often? (approx. % use cases) _______

PAIN, ACHE, DISCOMFORT

ii. **Have you had any discomfort (pain, ache, discomfort) in the <u>neck</u> at any time in the last seven days and how much discomfort you have experienced in the last seven days in**

☐ No ☐ Yes

If yes, how strong? (fill in a number 0 – 10) [ ]

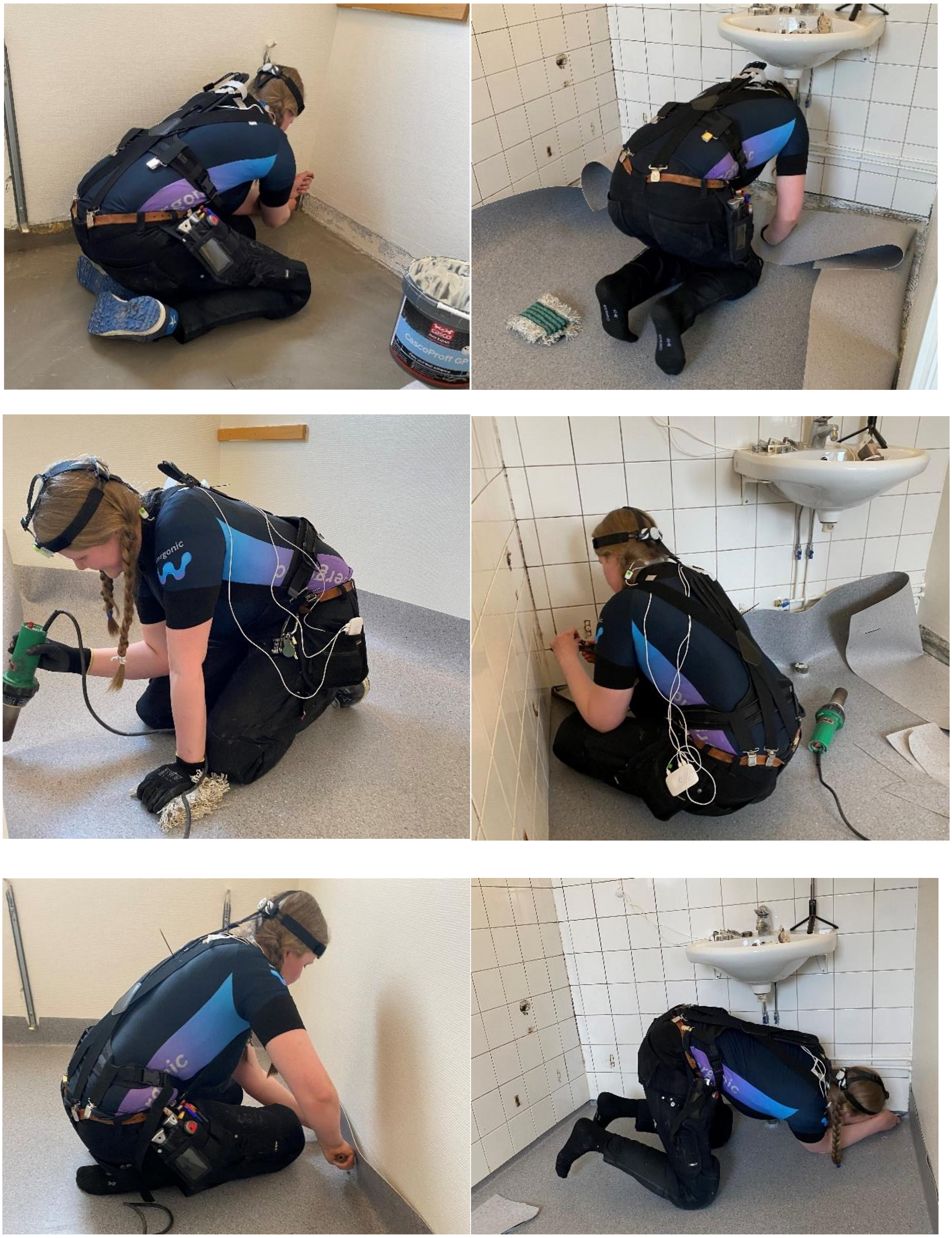
0	Nothing at all	
0.3		
0.5	Extremely weak	Just noticeable
0.7		
1	Very weak	
1.5		
2	Weak	Light
2.5		
3	Moderate	
4		
5	Strong	Heavy
6		
7	Very strong	
8		
9		
10	Extremely strong	"Maximal"
11		
∣		
•	Absolute maximum	Highest possible

iii. **How many days in the last 3 months have you had problems in the <u>neck</u>?**

0 days	**1-7 days**	**8-30 days**	**more than 30 days**	**amlost every day**
☐	☐	☐	☐	☐

Appendix 3. Work Setting Measurements

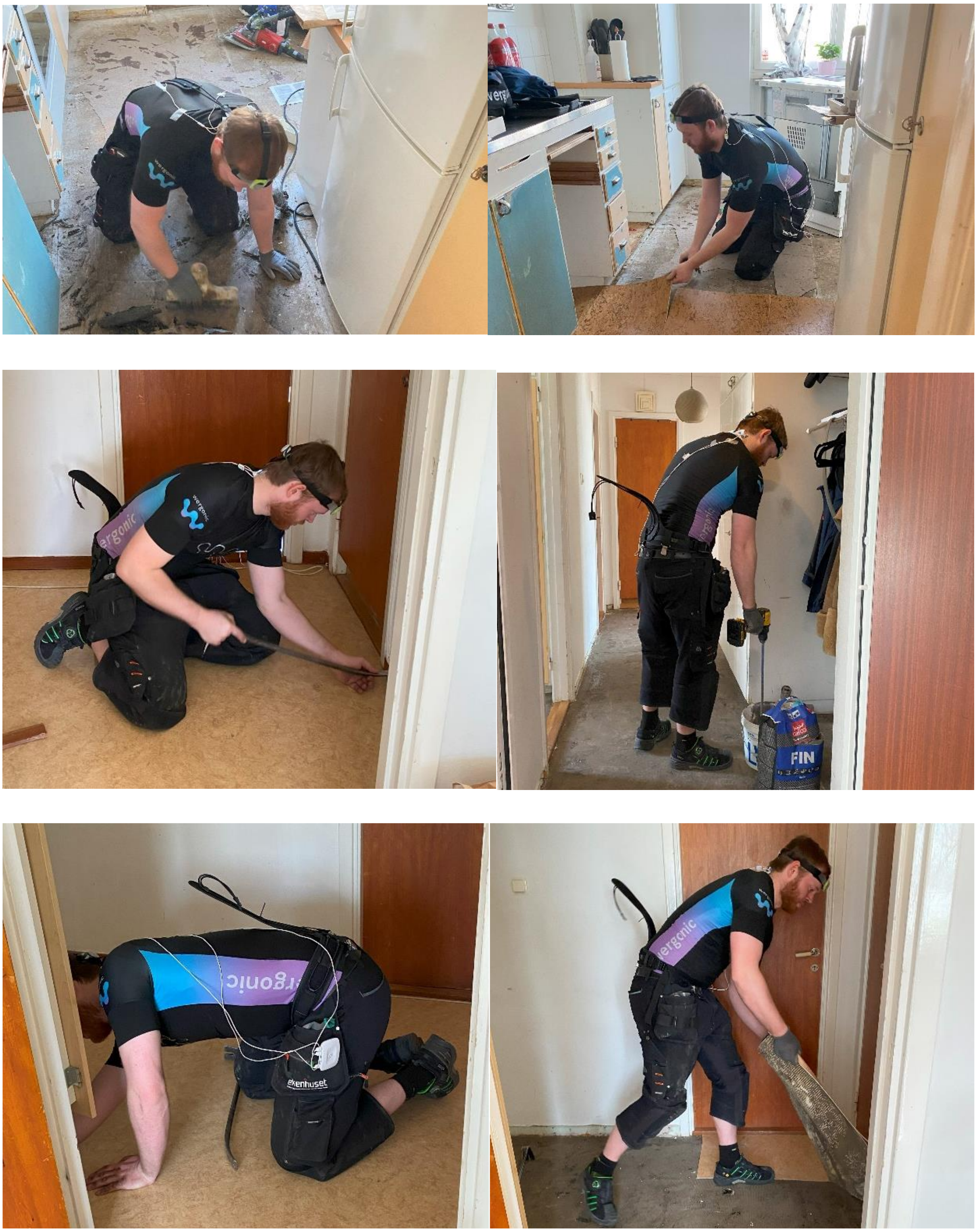
Participant 1



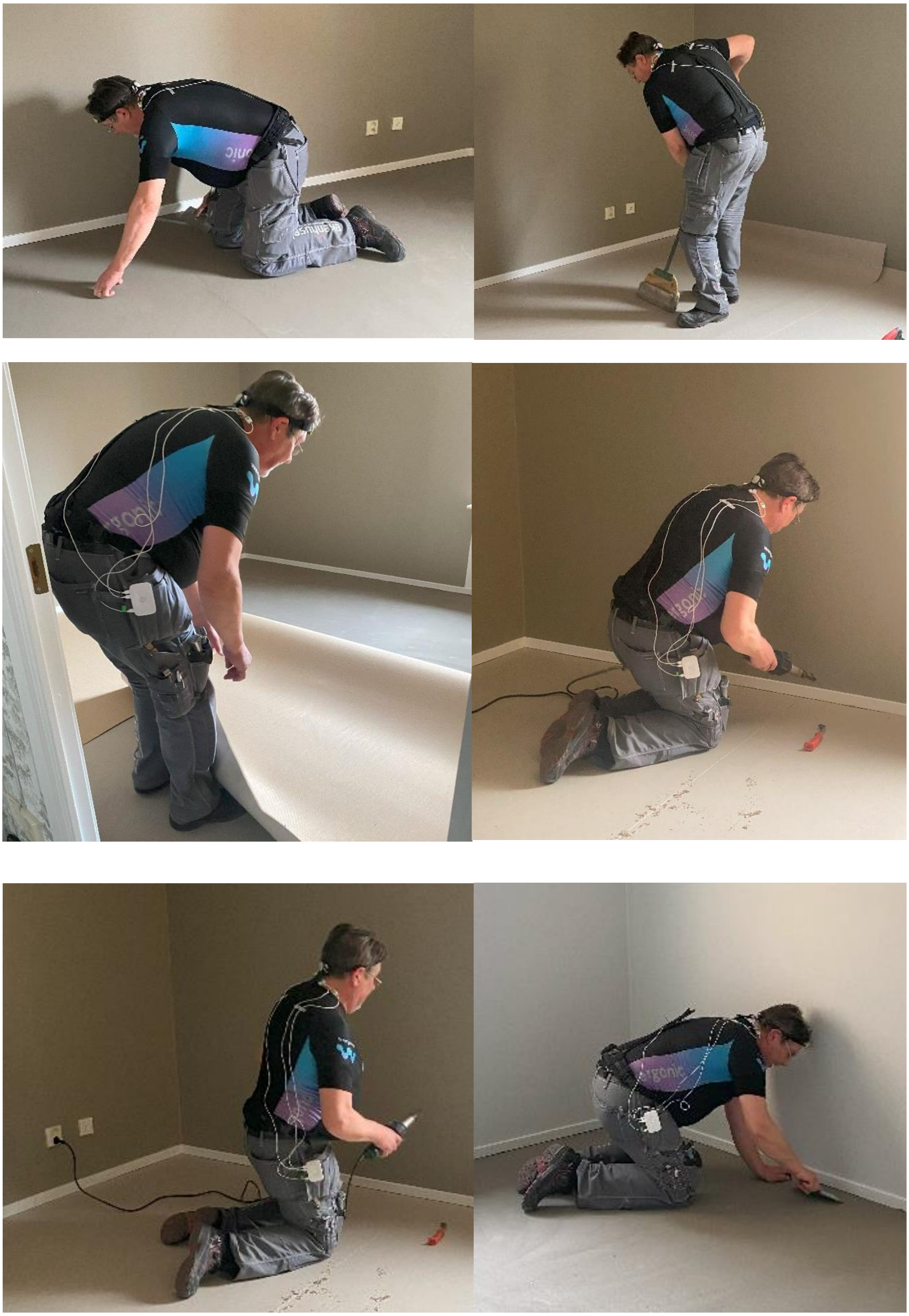
Participant 2

Participant 3

Participant 4



Participant 5



Participant 6