Aalborg University

Sports Technology

Department of Health Science and Technology (HST)

The kinematic effect of an upper and lower-limb exoskeleton and the evaluation of biomechanical risk factors: A proof of concept study

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Abstract

Purpose: Musculoskeletal disorders(MSD) is the most common work-related health problem in Europe (De Kok et al. 2019). The passive occupational exoskeletons, is beneficial to reduce the occurrence of MSD. We aimed to assess an upper and lower-limb exoskeletons kinematic effect on two dynamic work tasks performed at a production site at Siemens Gamesa Renewable Energy A/S.
Method: The kinematic data was acquired from previous projects at Siemens Gamesa. We developed and performed an automated RULA assessment, with the purpose to evaluate potential risk factors. We also developed a test battery to standardize a catalog of work tasks, in which the industrial working facilities could compare their work tasks to, and ease the implementation of exoskeletons.
Results: The study found no significant kinematic differences when using the BackX exoskeleton, but several tendencies showed changes in the full-body kinematics. Several significant kinematic differences and even more tendencies were found for the ShoulderX exoskeleton.
Conclusion: In general, the study found that the joints interact with each other and transfer load regarding the movements performed when wearing the exoskeletons. From a biomechanical point of view, the changes of wearing an exoskeleton could impose a potential risk for work-related disorders for both the back and shoulder.

Project boundaries

The study was exposed to the Covid-19 situation hitting Europe, and due to the increased measures from the government, the study was unable to proceed as first planned. The study tested upon several workers at Siemens Gamesa Renewable Energy A/S (Siemens), and used this data to create a test battery. The study used data from previous tests performed at Siemens and chose to further investigate the kinematic tendencies that occur when applying an exoskeleton to the dynamic work at Siemens Gamesa. The changes were made to secure that the study underlines the curriculum set for 10th semester Sports Technology students at Aalborg University.

Signatures

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Contents

1 Introduction

1.1 Work-related musculoskeletal disorders (MSD)

According to the European Agency for Safety and Health at Work (EU-OSHA)(De Kok et al. 2019), musculoskeletal disorders(MSD) remain the most common work-related health problem in Europe. The agency reported that three out of five workers filed MSD complaints, back pain accounted for 43% and upper limb for 41%. These two body parts are the most prevalent regions of MSD, furthermore 58% did experience more than one MSD at the same time [1]. Back and shoulder pain is difficult to identify (Hartvigsen et al. 2018), but both are often referred to as strain or stress in the ligaments and joints. (Dionne et al. 2008), (Maroto, Bone, and Dale 2014). These disorders are in general, derived from bad posture and working in awkward positions as well as heavy physical work, lifting, and repetitive work (De Kok et al. 2019). The occurrence of MSD is accompanied by medical treatment, lost workdays, and decreased productivity, which result in an economic loss for both workers and companies (Mehdizadeh et al. 2020).

The occurrences of MSD vary between sociodemographic factors, such as gender and age, with the female workers having a higher prevalence rate for MSD than male workers. The occurrences of MSD increases significantly with age for both groups (De Kok et al. 2019). The prevalence of work-related MSD showed a decrease from 2010 to 2015 due to the establishments of new preventive methods to reduce the risk for MSD, such as ergonomic equipment, awareness on unhealthy working positions, and work task rotation. Though a reduction was shown, the work-related MSD still provides a severe and widespread problem among European workers (ibid.).

[1] These numbers were extracted from 31,612 workers in 2015

1.1.1 Exoskeletons to reduce the occurrence of MSD

A steady-state will eventually occur at different high risk work tasks which ergonomic equipment and changes in kinematics will be unable to prevent. The exoskeletons is, therefore, an exciting technology with great potential to assist a worker's physical capacity. A Study by Kim, Moore, et al. (2019) investigated the potentials of exoskeleton technologies to enhance safety, health, and performance in an industrial setting and found the exoskeletons beneficial for tasks involving " *heavy material handling, overhead work, use of heavy tools, or repetitive tasks and specifically, suggested for tasks included: carrying and lifting*"(ibid.), (Lowe, Billotte, and Peterson 2019).

Besides the beneficial use of exoskeletons, some limitations could appear when implementing exoskeletons at a company, the limitations are both managerial and production-based. The managerial limitations concern the cost-benefit, how the purchase of exoskeletons affects the financial of a firm, and how the exoskeletons repay the cost. (Kim, Moore, et al. 2019) In regards to the implementation of exoskeletons in a company, no international safety standards are present for the industrial application of exoskeletons, and is, therefore, a barrier for large scale implementation (Looze et al. 2015). An exoskeleton has several parts hanging outside the skeleton, and these parts could get snagged or caught when working and harm the workers. (Kim, Moore, et al. 2019). Another major barrier for large scale implementing, mentioned in ASTM F48 standards, is the extend to which industrial exoskeletons should be considered as mandatory, aligned with traditional personal protective equipment(PPE), or only be used as reinforcement for the workers in areas whereas hazards cannot be eliminated or substituted (Lowe, Billotte, and Peterson 2019). The use of exoskeletons as protective equipment generates production-based limitations which mainly is the acute effect when transitioning from static lab-tested situations to the dynamic working procedures in the industry (ibid.).

1.1.2 Overview of occupational exoskeletons and their effect

A narrative was conducted to address the missing gaps in the literature and to provide an overview of the current knowledge concerning the effect of occupational exoskeletons based on biomechanics and performance. The full narrative includes 26 relevant studies dated from 2006 to 2020 and contains studies for both anthropomorphic[2] and nonanthropomorphic occupational passive lower and upper limb exoskeletons, see appendix figures 8.18, 8.19, 8.20, 8.21.

The "new" believe in the technology of exoskeletons, has caused a growth in publications to validate the acute effect of the "with" and without" exoskeleton conditions (Nussbaum et al. 2019). The occupational exoskeleton is, in particular, developed to assist the physically demanding work tasks performed by the workers and thus reduce muscular load, which is considered a predominant risk factor for the occurrence of MSD(ibid.). This is expressed by a common main focus on EMG measurements and the investigation of the muscle activity under similar working conditions (Theurel and Desbrosses 2019). The majority of the studies included in the narrative found a significant decrease in muscle activity. The decrease for lower body exoskeletons ranges from 11-61% for the thoracic erector spinae(TES) and lumbar erector spinae(LES) muscles. The decrease for upper body exoskeletons ranges from 3.4-62%. The muscles tested upon was typically generalized as the "shoulder muscles", with muscles such as the Anterior Deltoid and Medial Deltoid also referred to this category. A study by Dahmen and Hefferle (2018) concluded that a study specific exoskeleton was beneficial regarding the aim of the study, without mentioning the potential adverse effects. It should also be mentioned that exoskeletons is a commercial product and the developers are stakeholders, therefore, can the research be biased by their interest to promote their product. The narrative findings, reveal that kinematic data are considered as additional investigations concerning the priority of the EMG measurements (11 out of 26 studies include kinematic measurements). One of the studies which investigated kinematics of upper limb exoskeletons found a reduction in shoulder flexion and abduction (Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Jia, et al. 2018), while

[2]The anthropomorphic exoskeleton follows the ergonomics of the human body

(Maurice et al. 2019) and (Schmalz et al. 2019) found an increase in shoulder flexion and abduction. Furthermore found (Theurel, Desbrosses, et al. 2018) an increase in elbow flexion see fig. 1.1.

Passive occupational exoskeletons for upper body						
	Name of exoskeleton	Reference	Main findings (Kinematics)	n	Research type	Citations
1	Prototype (EksoVest)	Kim, S. Nussbaum, M. (2018)b	Max. shoulder flexion and abductions angles were reduced by roughly 2.6% and 10%, respectively.	27	**Laboratory**	32
2	EXHAUSS Stronger	Theurel, J. Desbrosses, K. (2018)	With exo induced a higher elbow flexion and a smaller flexion and rotation of the shoulder.	8	**Laboratory**	35
3	PAEXO (Ottobock)	P. Maurice et al. (2019)	Arm abduction increase from 7.9 to 9.9 degrees. In general the exoskeleton affects the shoulder movements by increasing the degrees at start	12	**Laboratory**	1
4	PAEXO (Ottobock)	Schmalz, T. Schändlinger, J. (2019)	increased shoulder abduction in T1 & T2 (6° & 8°). During T2 semi-static task, mean elbow flexion increased (7°).	12	**Laboratory**	0

Figure 1.1: Compressed literature for passive upper limb exoskeleton studies.

In line with the kinematics for upper limb exoskeletons, have the kinematic investigations for lower limb exoskeletons found a wide variability among their kinematic findings. (Ulrey and Fathallah 2013a) found an increase in hip flexion and a decrease in lumbar flexion (ibid.), on the contrary found (Axel S. Koopman et al. 2019) a decrease in hip flexion and no difference for lumbar flexion, while (Bosch et al. 2016) found an increase in lumbar flexion. Three studies found no difference for any kinematics (Abdoli-E, Agnew, and Stevenson 2006), (Graham, Agnew, and Stevenson 2009), (Baltrusch, Dieën, A. S. Koopman, et al. 2020) and (Baltrusch, Dieën, Bruijn, et al. 2019) found a reduction in stride length when walking, see fig. 1.2.

Passive occupational exoskeletons for lower body						
	Name of exoskeleton	Reference	Main findings (Kinematics)	n	Research type	Citations
1	PLAD	Abdoli-Eramaki, Agnew, and Stevenson (2006)	No major kinematic differences were found when the lift assist device was worn for both posture and accelerations	9	**Laboratory**	111
2	PLAD	Graham et al. (2009)	The subjects did not change their trunk inclination angles when wearing the PLAD.	10	**Field**	76
3	BNDR	Ulrey and Fathallah (2013b)	Hip flexion increased by 11% and decrease in lumbar flexion of 9.0%	18	**Laboratory**	23
4	Laevo v1	Bosch et al. (2016)	A systematic difference in trunk flexion angle occurred: more trunk flexion, by about 5%, was measured in the condition with the exoskeleton	18	**Laboratory**	96
5	Laevo V2	Koopman et al. (2019)	Hip flexion was reduced with 9 degrees compared to without condition. No significant differences in lumbar flexion were found between device conditions.	11	**Laboratory**	18
6	Laevo V2	Baltrusch et al. (2019)	The average range of motion of the center of mass (COM) did not show a significant difference between the exoskeleton conditions. A reduction in stride length was found for the with condition	13	**Laboratory**	5
7	SPEXOR	Baltrusch et al. (2020)	Kinematics did not change signifcantly	11	**Field**	0

Figure 1.2: Compressed literature for passive lower limb exoskeleton studies.

Applicable for both lower and upper limb kinematic findings, was the investigations based on different kinds of experimental setups, and it is not easy to compare the findings and draw a conclusion on the impact on kinematic modifications, occupational exoskeletons may provide for the workers. To our knowledge, does previous research not provide a comprehensive analysis of a full-body kinematic analysis with and without exoskeletons across multiple work tasks.

1.1.3 Field vs. Laboratory testing

An interesting tendency seen in the narrative was that only two lower limb exoskeleton studies were categorized as a field study. The field studies were conducted at an automotive manufacturing facility (Graham, Agnew, and Stevenson 2009) and at a luggage handling company (Baltrusch, Dieën, A. S. Koopman, et al. 2020). The same tendency was seen for the passive upper limb exoskeletons, whereas only one out of twelve studies were made as a field study. The field study was conducted at an agriculture manufacturing facility, (Gillette and Stephenson 2019). As recommended in a study by Nussbaum et al. (2019), was there a need for large-scale field studies to quantify the on-site benefits and limitations of the occupational exoskeletons, and the studies should include aspects, such as, broad range of workers, different tasks and diverse occupational sectors.

The laboratory studies included in the narrative were primarily based on different static or quasi-static work task simulations, such as assembly work, manual handling, holding, carrying, or general locomotor skills such as forward bending, lifting/lowering and arm elevation. The wide range of different ways to measure the exoskeleton outcomes makes it difficult to estimate the actual effect among all types of occupational exoskeletons and, therefore, not comparable to each other. There was a clear consensus between researchers and experts that the occupational exoskeletons area requires a golden standard test method, which also was mentioned in the ASTM F48 standards. Another recommendation for future work was to focus on the establishment of standards of work tasks to provide a baseline for testing and evaluating exoskeletons. The standard test methods would be useful for researchers, developers, and buyers of exoskeletons, to validate the performance of the system (Lowe, Billotte, and Peterson 2019), (Bostelman and Hong 2018). To establish a standard test method to determine and compare the benefits as well as limitations of an exoskeleton, was it necessary to make an ergonomic mapping to determine physical work-related capabilities of the different work tasks for each occupational sector. A categorizing of these standard test methods would also provide knowledge for companies to understand the extent of how different exoskeleton designs could affect and help in different work tasks. The lack of knowledge for practical on-site implementation has so far been an obstacle for large scale implementation of exoskeletons in the occupational sector (Dahmen and Hefferle 2018).

1.2 Research question

How does a field-based pilot study affect the full-body kinematic motions of an industrial worker using a passive lower/upper-limb exoskeleton?

Method 2

2.1 Test overview

The general theme of the study was to understand and analyze work tasks at the Siemens production, and from that, create a test battery for standardized tests, to investigate the potential effects of using exoskeletons in the industry. The Covid-19 pandemic in Denmark and Siemens meant that we had to change the way of acquiring data. The study used data from two ninth semester projects, from Aalborg University, that tested two different work tasks concerning two different segments (shoulder and back). Both data sets were previously acquired at Siemens. We could, therefore, continue to create a test battery for future testing and to analyze the existing kinematics. To understand the experimental setup, the study wanted to create a test battery, as the topic of field-based exoskeleton tests was mostly undiscovered.
In this chapter, the reader will experience how we continued the idea of developing a test battery, however it was not possible to construct and test upon as intended.

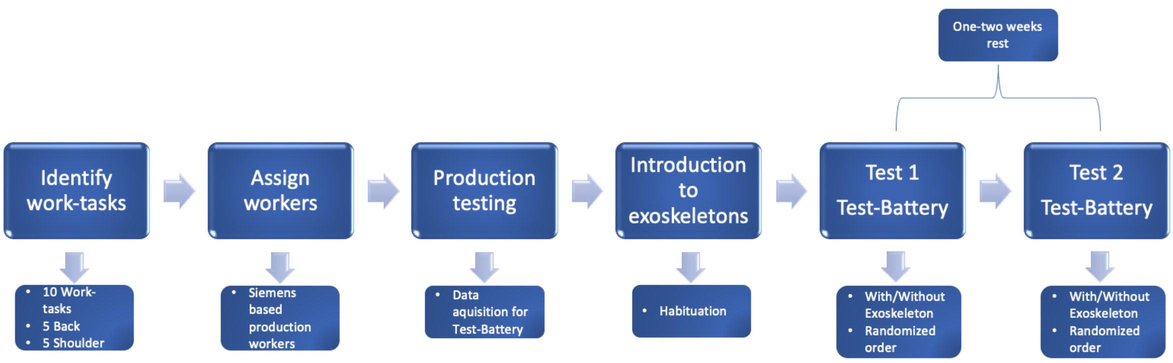


Figure 2.1: Show the intended testing procedure.

2.2 Workers

Concerning the before mentioned ninth semester tests, the workers used to acquire data were recruited from Siemens and were averagely employed for more than three years.

2.3 Equipment

2.3.1 BackX

The BackX S (SuitX, San Francisco) used in this study is a passive lower-limb exoskeleton designed to reduce gravity-induced forces in the lower back; it uses gas-powered springs without any electronic components. The spring accumulates mechanical energy when contracting the exoskeleton, and release the power when extending. The exoskeleton has two functions, "STANDARD" and "INSTANT." Standard initiates the exoskeleton at 30° and above; from 0-30°, does the standard function makes walking with the exoskeleton possible. The Instant function initiates immediately and makes the exoskeleton hard to use while walking. (Gaardahl and Wulff 2019) [1] The components used in the BackX is shown below in picture 2.2

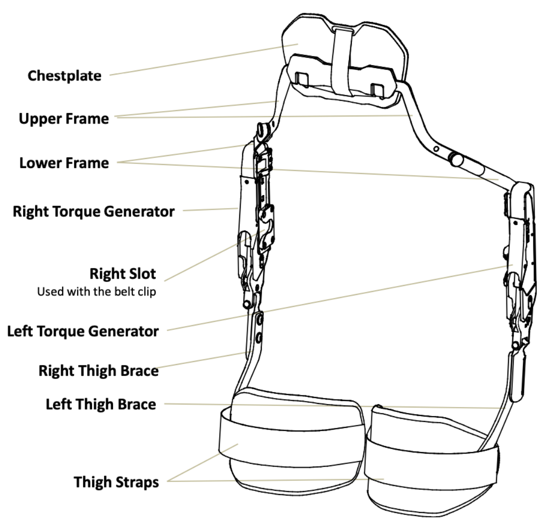


Figure 2.2: Show the BackX S V3 models components (Bionics 2017a)

[1] (Bionics 2017a)

2.3.2 ShoulderX

The ShoulderX V3 (SuitX, San Francisco) used in this study is a passive upper limb exoskeleton designed to reduce gravity-induced forces at the shoulder. The ShoulderX uses a gas-powered spring and no electronic components. The spring compresses and accumulates the mechanical power when arms is below 60°, and release a non-linear gradually-increasingly power when arms are between 60-120°. The ShoulderX is either turned on or off and, the support is changed to the workers individually support requirements at a given task[2]. The figure 2.3 illustrates the components used on the ShoulderX.

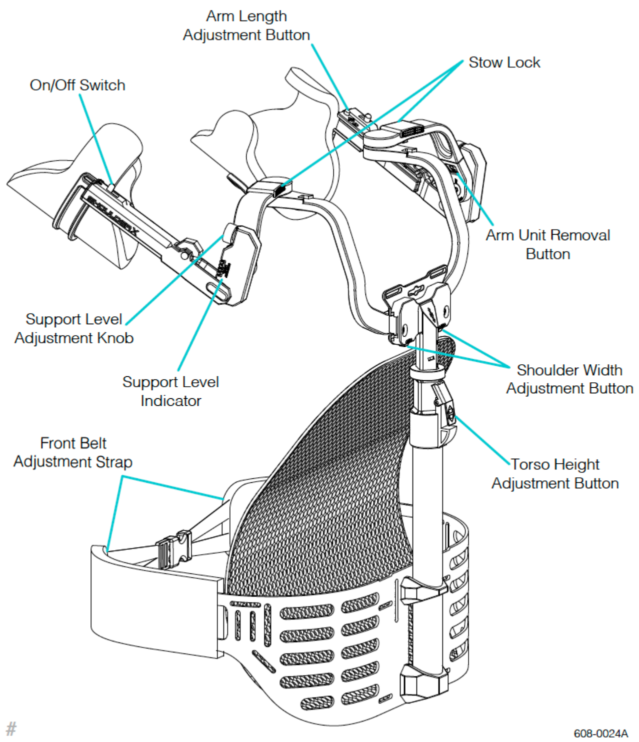


Figure 2.3: Show the ShoulderX V.3 components (Bionics 2017b)

2.3.3 Kinematics

The study used Xsens Awinda and Xsens Analyze (Enschede, Netherlands) to measure and analyze the workers kinematic movements, The Xsens Awinda system consists of 17 sensors, also called inertial measurement units(IMU), distributed on

[2](Bionics 2017c)

the body according to pre-attached labels. An IMU consists of accelerometers, gyroscopes, and magnetometers. The study used the software's standardized calibration tool "N-Pose + Walk," which initiated a 5 seconds pose "N-Pose" and hereafter a 5 seconds walk followed by a 180° turn and a return to the before-mentioned N-pose see figure 2.4 to calibrate the system.

The study used Matlab to extract z, y, and x directions from every joint, to conduct a full-body kinematic analysis.

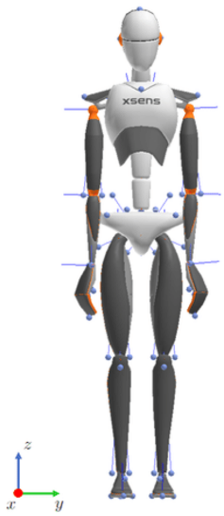


Figure 2.4: Show the Xsens Awinda N-Pose (Schepers, Giuberti, and Bellusci 2018)

2.4 Ergonomic mapping

The ergonomic mapping works as a condition to develop a test battery for different work tasks in the occupational sector and to inform the consumers about the areas of potential exoskeleton implementation. This study developed an automated evaluation tool to obtain a broad and precise sample across several work tasks. The tool was a guideline to develop the test included in the test battery, see section 2.5.

2.4.1 Tool for ergonomic analysis

One of the most cited methods of ergonomic analysis is the Rapid Upper Limb Assessment(RULA) (Vignais et al. 2013). The RULA assessment is a subjective survey method to investigate the exposure of individual workers concerning upper limb disorders. The RULA assessment facilitates information about the muscular effort in a given work task. There is no need for special equipment to conduct the assessment, but the raters need training to judge the correct posture for each body part included in the assessment (McAtamney and Nigel Corlett 1993). These low-cost and practical observational methods are beneficial to identify workplace exposures in a given work task (Vignais et al. 2013). However, the disadvantages of the observational methods are the raters' lack of accuracy and consistency; furthermore, is the method time-consuming (Seo, Yin, and Lee 2016). An automation would be advantageous to address the weaknesses of observational methods and to obtain a large sample of precise and quantitative epidemiological data. Different technologies are used to develop an automated version of the RULA assessment. This study has used IMU due to the benefits of not interfering with the workers natural motion of work.

2.4.2 Automated ergonomic analysis

It was not possible to completely adapt the automated RULA assessment to the original version, due to the lack of precise thresholds descriptions needed for a complete adaption (Vignais et al. 2013). When adapting the automated RULA assessment, the positions were rewritten to understand the joints used in our study. A limitation of the original version was not knowing the time spent at each exposure level. The limitations arise because the RULA assessment was based on the analysis of manual handling tasks in static postures to estimate a global score of different local scores. It was not possible to isolate the local scores from the original scoring system, and track them through a dynamic task. The calculations of a global score can be considered as a weakness to obtain a more comprehensive ergonomic evaluation, according to Vignais et al. (ibid.). To specify anatomical areas, we chose the back and shoulder local scores and excluded the global scoring. The local scoring was adapted to a 4x5 risk matrix, see section 2.4.3.

Ratings of the automated RULA

Rating of the back flexion (+)/extension (-) score ranges from 1 to 4, whereas 1 was equal to sitting or well supported in an upright position equivalent to 0 °; 2 for 0-20 °; 3 for 20-60° and 4 for 60° or more (Gaardahl and Wulff 2019). The score of 1, equivalent to the upright position of 0 °, was not noticeable for the automated RULA assessment of measuring time spent in the given position; therefore, where the score of 1 extended to +/- 10 °. The extended threshold was aligned with the natural forward and backward sway of a person to maintaining balance equilibrium in an upright position (Moffat, Bohmert, and Hulme 2009). Furthermore if the back was rotated or side-bent the score would increase by 1 (McAtamney and Nigel Corlett 1993), see appendix 8.9. The thresholds for back rotation and bent must be subjectively chosen, and applying this to the new scoreboard was questionable. To fulfill the automation, we chose to develop specific thresholds. The rating of the back rotation was divided into a ranging score from 1-4, whereas the score of 1 was equivalent to +/- 5 °; 2 for a 5-15 °; 3 for 15-25 ° and 4 for 25 ° or more. Due to a lack of relevance, we chose to exclude the additional side-bent score; the back rotation was described instead.

The shoulder flexion (+)/extension (-) score ranges from 1 to 4, whereas a score of 1 was equal to +/- 20 °; 2 for more than -20° or an angle between 20° and 45°; 3 for 45-90° and 4 for 90° or more. If the shoulder was abducted/adducted or raised, would the score be increased by one (ibid.), see appendix 8.9. Neither was the thresholds for shoulder abduction and shoulder raise described in the original RULA assessment. The thresholds for arm abduction/adduction were similar to the shoulder flexion/extension, except for the score of 1, which ranges from 0-20 °, due to the limitations of motion in the negative direction. Similar to the additional side-bent for the back were shoulder raise excluded.

2.4.3 Risk matrix

The risk matrix was, in general, used to define the consequence and probability of a risk occurring. The final score was reached by multiplying rows and columns, which gave a relative value, used to prioritize actions regarding the defined ranges of risk levels (Torghabeh, Hosseinian, and Ressang 2013). A "standard" risk matrix is non-existent in the literature due to the possibility of fitting matrix sizes and risk levels after the specific context. The opportunity to freely tailor the risk matrix makes it compatible to fit the automated RULA assessment. The risk matrix made for the automated RULA assessment consists of a 4x5 table, whereas the rows refer to the Consequence (RULA score), and the columns refer to the probability (Percentage time spent in the given position), see table 2.1. The full scoreboard for the relative value of multiplying the rows and columns for the Bi-axial and Uni-directional work tasks can be seen in the appendix. 8.10, 8.11 and the belonging action risk level is seen at table 2.2.

Consequence				**Probability**		
Row	RULA score	Exposure		**Column**	% time spent	Frequency
1	1	Neutral risk		**1**	0,00 - 20,00	Never
2	2	Low risk	**x**	**2**	20,01 - 40,00	Seldom
3	3	Medium risk		**3**	40,01 - 60,00	Often
4	4	High risk		**4**	60,01 - 80,00	Almost
				5	80,01 - 100,00	Always

Table 2.1: *Have been adapted from Torghabeh, Hosseinian, and Ressang (2013).* The table Show the consequence(rows) and probability(columns) of the risk matrix for the automated RULA assessment.

The automated RULA assessment was developed to measure a dynamic work situation, which, due to more than one relative risk value, gives a time factor challenge. Because of the missing link to the action level table, 2.2 was the multiple risk values unable to give an overall picture of the work task. To overcome the challenge and obtain an average risk, was a summation equation with respect to the factor of time made, see fig. 2.5.

Number of risk values detected

$$\textbf{\textit{Average relative risk}} = \sum_{i=1}^{n} \frac{(Risk_i + \sqrt{Time\ factor})}{n}$$

Risk values

Figure 2.5: Show the summation equation.

The values for Risk_i and *Time factor* has been found by the matrix for Automated RULA assessment, the sum shall be rounded upwards or downwards to the nearest integer number:

$$Risk_i = Percentage\ time\ spent(columns) \times RULA\ score\ (Rows)$$

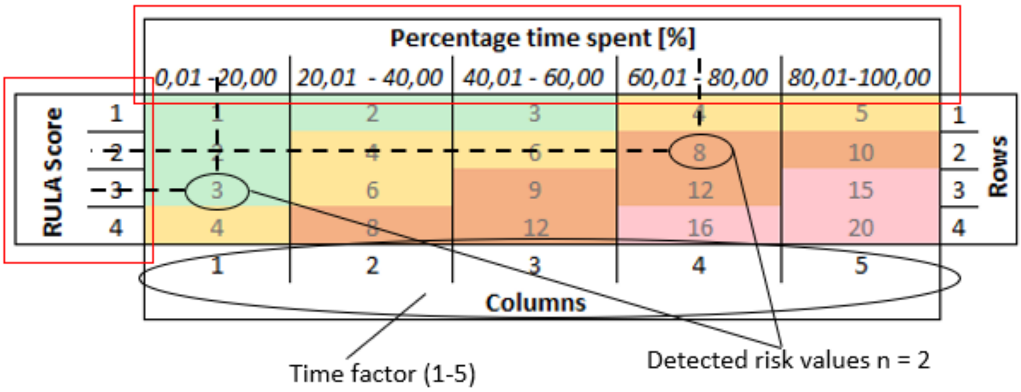


Figure 2.6: show how to find the Risk_i and *Time factor* and contains an example of relative risks obtained with the Automated RULA assessment.

$$\textbf{\textit{Average risk}} = \sum_{i=1}^{2} \frac{3+\sqrt{1}}{2} + \frac{8+\sqrt{4}}{2} = 7$$

Figure 2.7: Show an example of the summation equation, with values from fig.2.6

Risk levels for automated RULA assessment

Risk	Action
1 - 3	Acceptable working position, a slight to marginal risk for injuries. - No risk reduction needed
4 - 7	Tolerable working position, a minor risk for injuries. - Further control measures needed
8 - 14	Unacceptable working position, a very likely risk for injuries. - Future implementing of new methods to reduce risk (exoskeletons)
15 - 20	Intolerable working position, a major risk for injuries - Stop working, eliminate risk or implement new methods to reduce risk (exoskeletons)

Table 2.2: *Have been adapted from Torghabeh, Hosseinian, and Ressang (2013).* The table show the average relative risk in relation to the action levels. **Notice**: This study have chosen to suggest the workers use of exoskeleton if they reach the 3rd and fourth action level.

2.4.4 Ergonomic production analysis

The automated RULA assessment gave an overview of the workers exposure to different work tasks at the Siemens production. The intention was to test upon several aspects of e.g, service, grinding, assembling, and a wide range of manual material handling tasks. The overview should differentiate the workers exposure in each work task, and select the most critical working postures for the test battery, see section 2.5. Due to the COVID-19 pandemic was the testing limited to only two types of work tasks. The two tasks were manual handling of bi-axial and unidirectional fiberglass mats. To extract kinematic data for the kinematic analysis, where the two same tasks used, see section 2.6. The description of each task and the belonging local RULA score is seen at figure 2.8, 2.9 and figure 2.10, 2.11.

1. Phase - Standing still with both feet in frontal direction, while grabbing the mat from the crane.
2. Phase - Sideways walking, while transferring the mat to a specific location.
3. Phase - Bending downwards and correcting the position of the mat at mold' edge.
4. Phase - Stepping backward with the remaining mat.
5. Phase - Making final adjustment before bending down to release the mat.

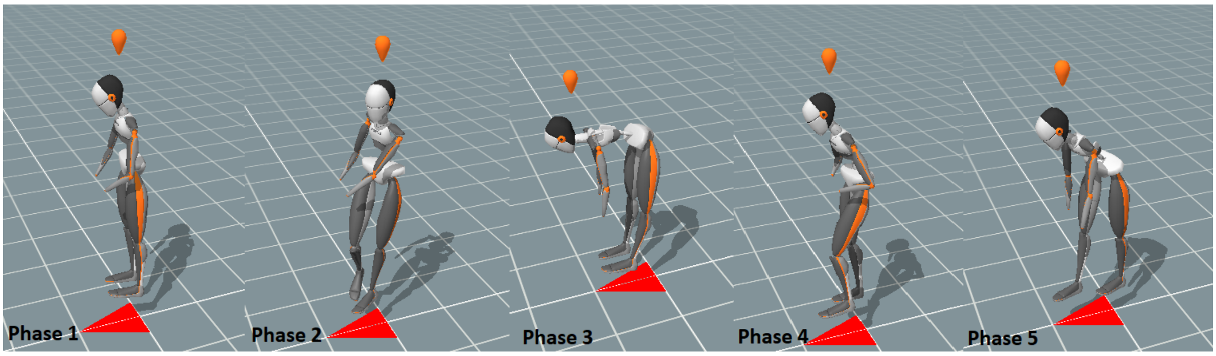


Figure 2.8: Show the different phases of bi-axial fiberglass manual handling work task. The work task description was animated due to the confidential safety protocol at Siemens.

1. Phase - Standing still with both feet in frontal direction, while grabbing the mat from the crane.
2. Phase - Sideways walking, while transferring the mat to a specific location.
3. Phase - Adjusting the mat in line with the previous mats.
4. Phase - Releasing the mat at the correct position.
5. Phase - Bending down and make sure the mat follows the curvature of the mold .

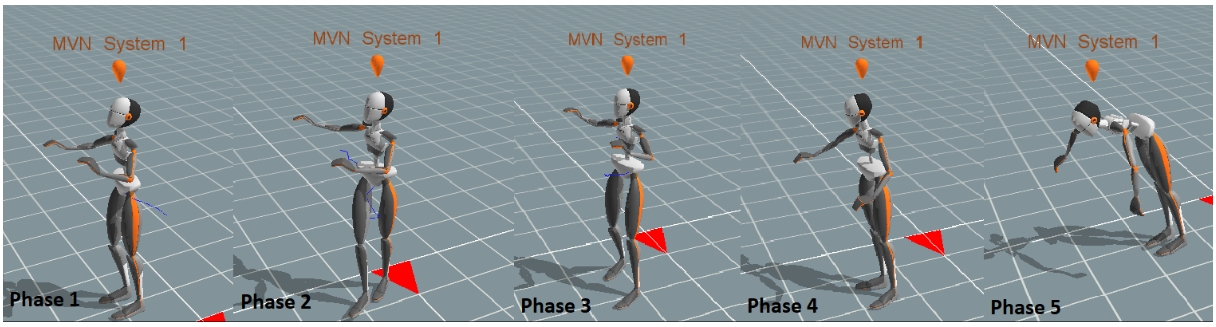


Figure 2.9: Show the different phases of the uni-directional manual handling work task. The work task description was animated due to the confidential safety protocol at Siemens.

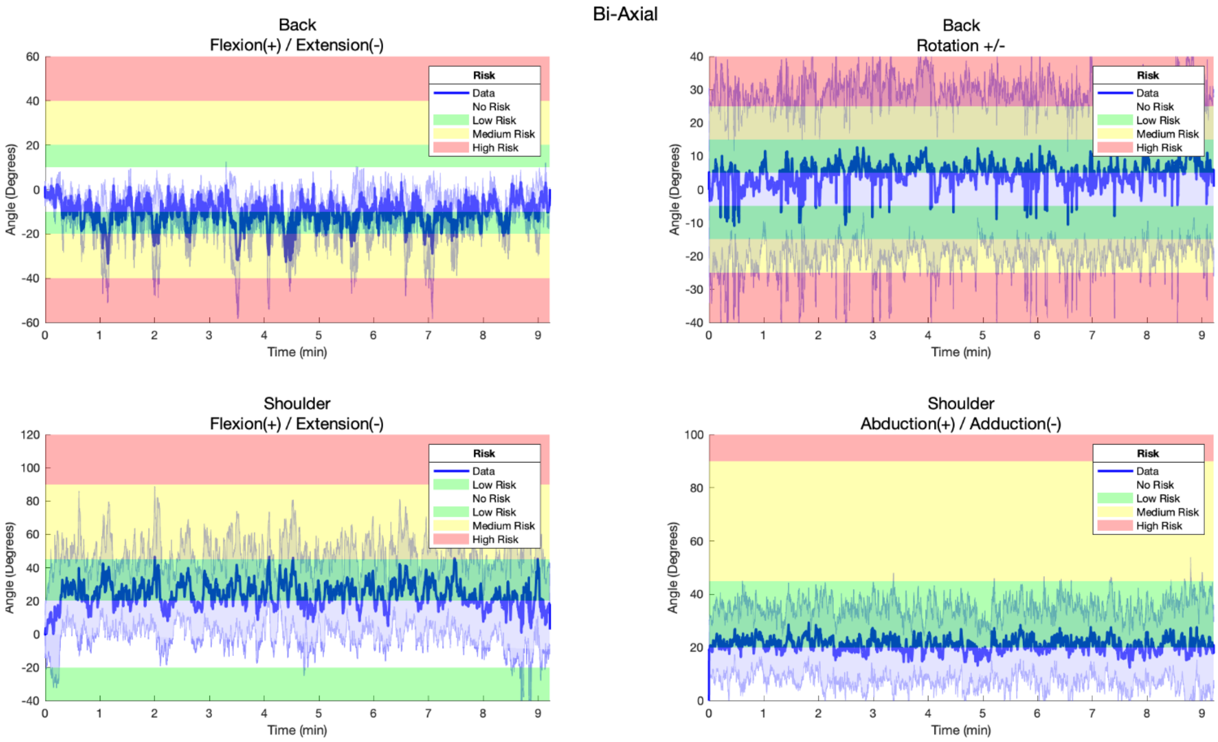


Figure 2.10: Show the raw Bi-axial data output from Matlab, displayed by mean and standard deviation.

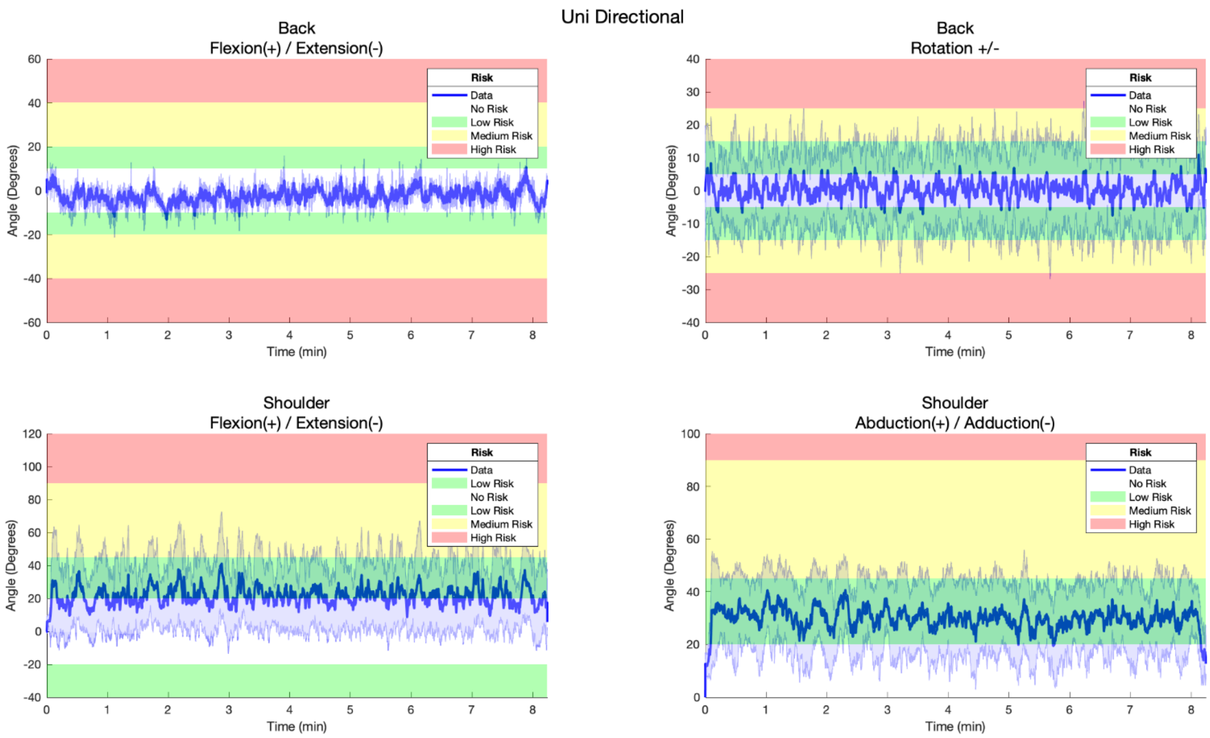


Figure 2.11: Show the raw Uni-directional data output from Matlab, displayed by mean and standard deviation.

Calculated RULA matrix scoreboard		
Work task	Type of movement	Average risk
Bi-axial	Back Flexion (+) / Extension (-)	5
	Back Rotation +/-	5
	Shoulder Flexion (+) / Extension (-)	7
	Shoulder Abduction (+) / Adduction (-)	7
Uni-directional	Back Flexion (+) / Extension (-)	5
	Back Rotation +/-	5
	Shoulder Flexion (+) / Extension (-)	9
	Shoulder Abduction (+) / Adduction (-)	7

Table 2.3: Show the average relative risk for the Bi-axial and Uni-directional work task.

In general, was the average relative risks from table 2.3 categorized as tolerable working positions for both work tasks. Only the shoulder flexion/extension for the Uni-directional work task, see fig. 2.11 was categorized as an unacceptable working position. It was recommended to conduct new methods for future implementation to reduce the potential risk 2.2. Derived from the raw data output, the back rotation for the Bi-axial work task, see fig. 2.10, had high standard deviations, indicating that for some workers could the work tasks be a risk factor. The two-movement types would, therefore, be included in the test battery.

2.5 Test battery

As mentioned in section 1.1.3, was future work recommended to establish a test battery containing several standardized tests to provide a baseline for the evaluating of different exoskeletons. We used the approach from Müglich, Sinn-behrendt, and Bruder (2015) as a framework to assess the physical work-ability in the industrial sector with respect to the workplace demands. The test battery included a wide range of physical work-related capabilities, to cover the majority of industrial work tasks (ibid.). Each test includes at least one or several capabilities. The physical work-related capabilities can be used as support for future research, to select a proper test for their investigation. The figure 2.17 and 2.20 show the physical work-related capabilities involved in each test. The tests are divided into quasi-dynamic and dynamic work tasks, to isolate the differences between the two kinds of work situations. The performance outputs were made, with respect to the work from Bostelman and Hong (2018), who used the industrial/response robot test method to categorized performance metrics. The performance outputs used for the test in the test battery are as followed: *Task duration, speed, accuracy/resolution, control force, vertical and horizontal maneuvering (ibid.)*

2.5.1 Quasi-dynamic Lower limb task

The test was developed to reflect a kneeling working position, with far bi-lateral reach. Typically are similar work tasks seen in the construction industry (masonry, carpentry, paving, etc.), in this specific case, the workers at Siemens were sitting on their knees and applying balsa wood onto the glass fiber mats.

As illustrated in figure 2.12, the workers are supposed to sit kneeling on the foam pad, and in chronological order, ranging from one to eight, move dumbbells into the correct position, as fast and accurate as possible. The dumbbells must be handled with both hands to obtain the largest rotation of the trunk; furthermore, are the dumbbells placed opposite the starting position to make the movements bi-lateral. The weight of the dumbbells is based on the EU-OSHA guidelines for the recommended weight of lowering below mid-leg height, which is 5 kg for men and

3 kg for women, see fig. 8.17 in appendix. The outcome measure was movement time (s), which is defined by time from touching the first dumbbell to placing the last dumbbell. The second outcome measure is the number of crossings, which is defined by the number of times the dumbbells touch the edge of the drawn circles.

The anthropometric measurements of the vertical grip reach were used to determine whether the workers had to use the red/blue reach points, see fig. 2.12. Workers with a vertical grip reach between 181,20 to 196,50 cm should use the red circles, and the workers with vertical grip reach above 196,50 cm should use the blue circles. The 5th and 50th percentile for women was used to calculate values for the red and blue maximum reach points. The vertical grip reach was used as a general cutoff value because all segments involved in the calculations of the maximum reach is involved, see section 2.5.2 underneath.

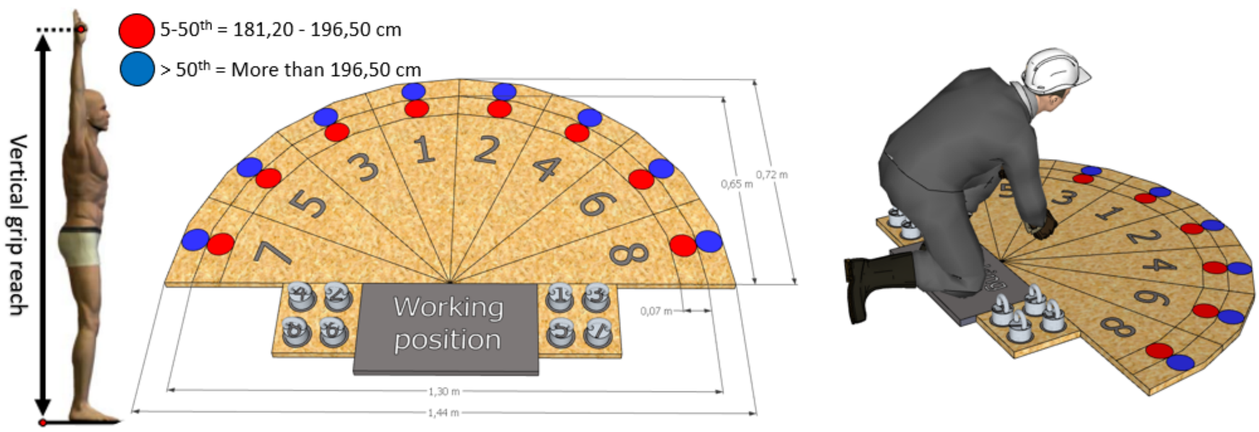


Figure 2.12: Show the technical drawings of the quasi-dynamic Lower limb task, including an illustration of the vertical grip reach measure, which is defined by the vertical distance between the standing surface and the center of a gribbed dowel (Gordon et al. 1988)

2.5.2 Maximum reach

The maximum reach in a kneeling position was calculated based on the Pythagorean theorem, $c = \sqrt{a^2 + b^2}$, with anthropometric measurements from the ANSUR database (Gordon et al. 1988). The length a; was found by subtracting the Acrominal height and Lateral femoral epicondyle height, minus the length of thigh link distance, see illustration 1, 2, and 3 at figure 2.13: the length b; was found by the vertical grip reach down, see illustration 4 at figure 2.13.

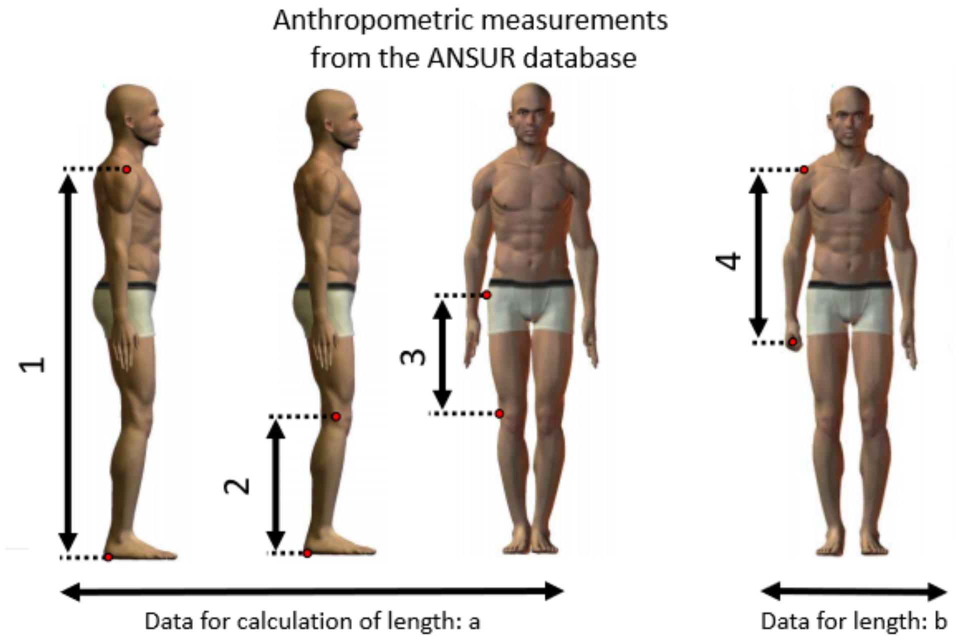


Figure 2.13: **1:** Vertical distance between the standing surface and the acromion landmark **2:** Vertical distance between the standing surface and the lateral femoral epicondyle landmark **3:** Vertical distance between the thochanterion landmark and the femoral epicondyle landmark **4:** Vertical distance between the acromion landmark and the center of a gribbed dowel (Gordon et al. 1988).

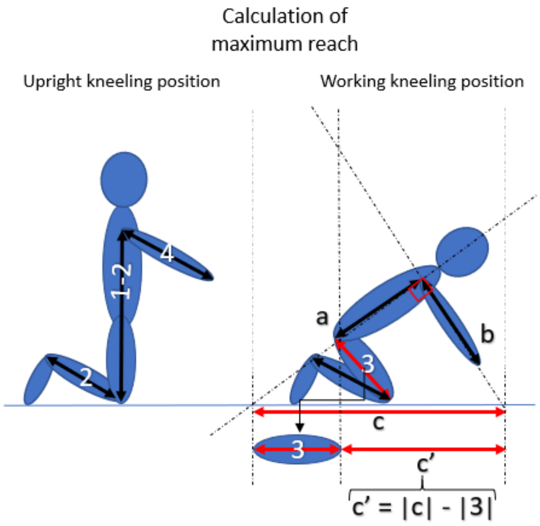


Figure 2.14: Illustrates the calculation of the maximum reach in a kneeling position.

2.5.3 Quasi-dynamic upper limb task

A multi-functional test rack was developed to test how the exoskeletons affect the upper extremities during real-time working conditions which include, drilling, assembly, and screwing tasks at different individual height levels. Below are the technical drawings and procedures found.

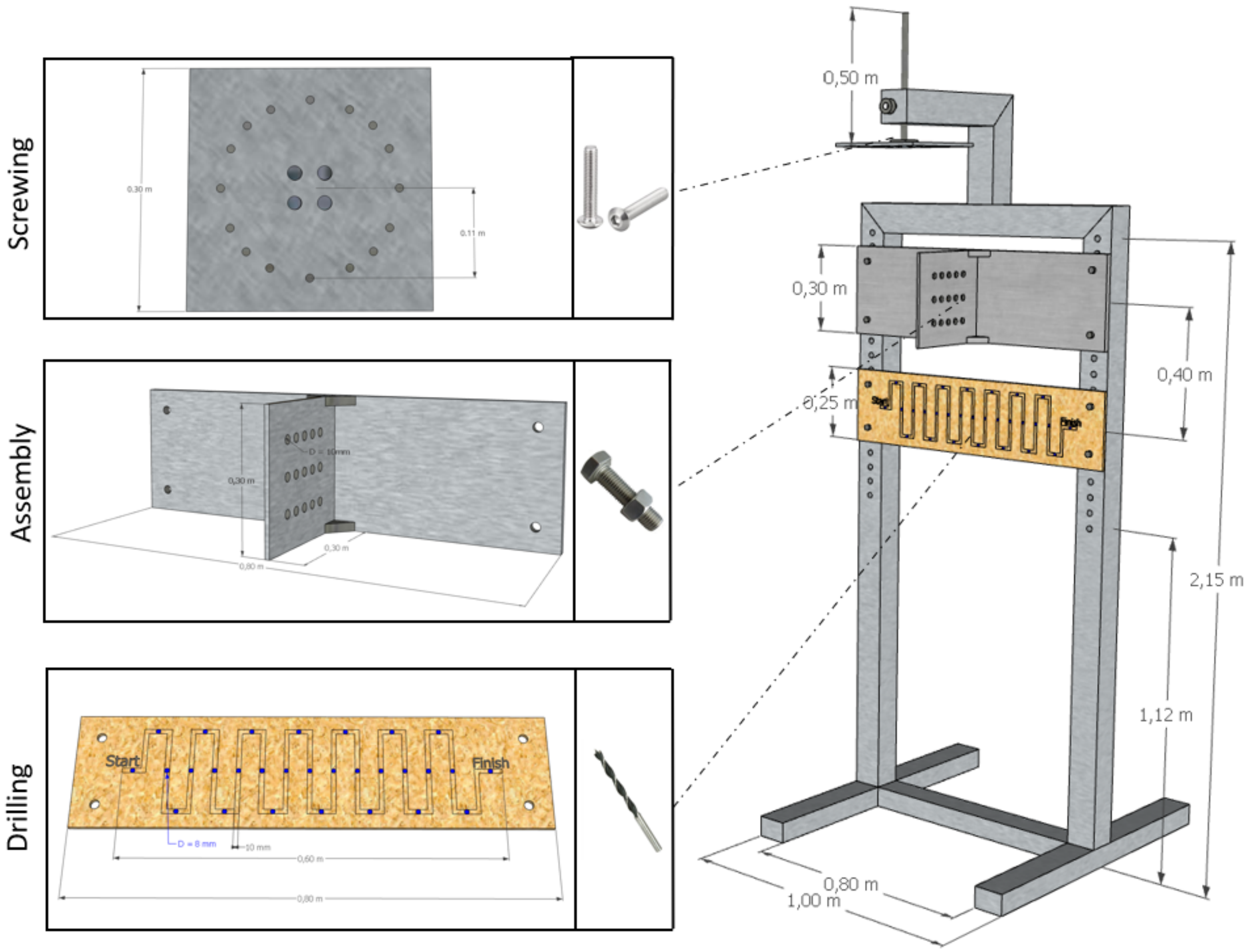


Figure 2.15: Show the technical drawing of the testing rack, including the test items for each level.

All adjustments on the testing rack are individual, and the lowest adjustments correspond to the 5th percentile for women, and the highest adjustments correspond to 95th percentile for men. The mounted plates can be adjusted with 5 cm, and the upper assembly plate can be adjusted with 50 cm, see fig. 2.15. Before the test starts, the workers must go through 3-5 practice trials for each level to get familiarized with the test. The workers should to avoid fatigue have at least 1 min rest between each test and 5 min rest between each level of testing, (Garnacho-Castanö V. et al. 2019). Described underneath are the purpose and specific standardization for each level.

Drilling task

The drilling task was developed to reflect the use of a hand tool, combined with hand to eye coordination. The use of hand tools, such as: screwdrivers, angle grinders, welding/painting guns, air tools, etc. in combination with precision work, is a general interaction in manufacturing, construction, and production areas. The test has furthermore been developed to challenge fine motor skills by adding time and error restrictions.

The workers should follow the pattern and drill a hole at each blue marker, see fig. 2.15. The task should be performed as fast as possible by using their dominant arm without disrupting the drawn lines on the template. The pattern consists of 29 markers, which should be drilled with a cordless screwdriver[3] and an 8mm wood drill on a 12mm plywood plate. The outcome measure for this test is movement time (s), defined by time from the drill touches the plywood to end of the last drilled hole. The second outcome is the number of errors, which is defined by the number of times the drawn lines are disrupted. The workers should stand one thumb tip reach length from the testing rack, see fig. 2.16. The first mounted plate should be placed centered 40 centimeters below eye level, see fig. 2.16.

Assembly task

The assembly task requires fine motor skills to avoid errors; an example could be errors in an assembly line, where the errors could result in lost time for the entire assembly line. The test involves a time penalty for a dropped bolt/nut. Furthermore, are the test more challenging due to the requirement for left/right-hand coordination, which challenges the psychomotor skills (Mishra, Barrans, and Crinela 2009).

[3] The weight of the wireless screwdriver should be around 2,00 kg +/- 0,25 kg https://www.bosch-presse.de/pressportal/de/en/the-new-generation-of-bosch-cordless-screwdrivers-for-professionals-44829.html

The workers should assemble 15 M8x30mm Hex bolts and nuts by hand, on a 30x30cm plate placed in the sagittal plane. The 15 holes have a diameter of 10 mm, and the nuts should only be hand-tightened. The nuts are collected from a box at hip level next to the workers dominant arm, and the bolts are collected next to the workers non-dominant arm. The outcome measure from the test is movement time (s), defined as the time from collecting the first bolt/nut to dropping the last bolt/nut. The number of errors is defined by the number of bolt/nuts dropped on the floor; the errors result in a 5 second time penalty (Test responsible, must collect and return the eventual lost bolt/nuts), see full size in appendix 8.13. The workers should stand one thumb tip reach from the testing rack, see fig. 2.16. The second mounted plate is placed centered with the eye level.

Screwing task

As a continuation of the assembly task is the screwing task developed to challenge the fine motor skills, and challenge the musculoskeletal effort in an overhead working position. We have chosen to use a cordless screwdriver to add a more extensive load on the working muscles, which could result in a speed/accuracy trade-off. The combination of overhead work and holding a tool have been associated with an increased prevalence of work-related MSD on the shoulder joint (Van Rijn et al. 2010) and therefore, an important task to include in the test battery.

The workers should screw 16 M4x20mm Hex socket screws in the pre-drilled thread as fast as possible by using their dominant arm. Each screw is collected from a box at hip level next to the worker. The test is conducted in reverse by unscrewing the 16 socket screws and drop them in a box. The outcome measure from the test is movement time (s), defined as the time from collecting the first screw to dropping the last screw. The number of errors is defined by the number of screws dropped on the floor, each error results in a 5 second time penalty (Test responsible, must collect and return the eventually lost screws), see full size in appendix 8.13. The height should be set in relation to the height of the vertical grip reach, fig. 2.16. The workers should use the same wireless screwdriver as used in the drilling task.

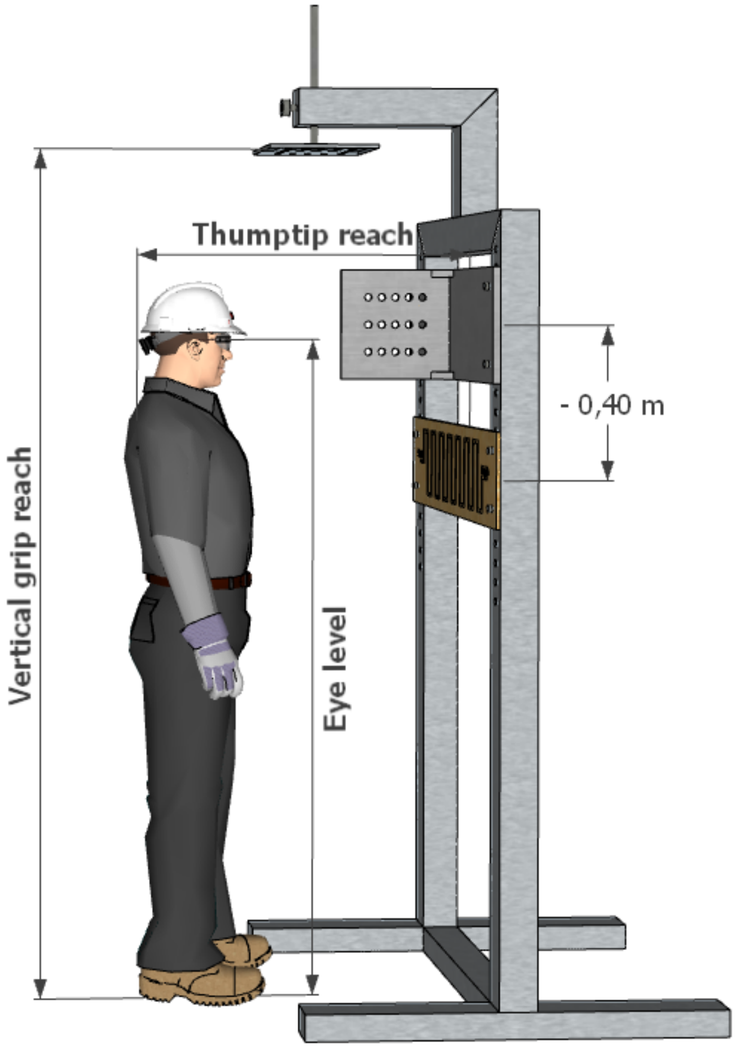


Figure 2.16: *The thumbtip reach* is the horizontal distance from a back wall, with the arm stretched forward to the tip of the thumb. *Eye height* is the vertical distance from the standing surface to ectocanthus landmark. *Vertical grip reach* Vertical distance between the standing surface and the center of a gribbed dowel(Gordon et al. 1988).

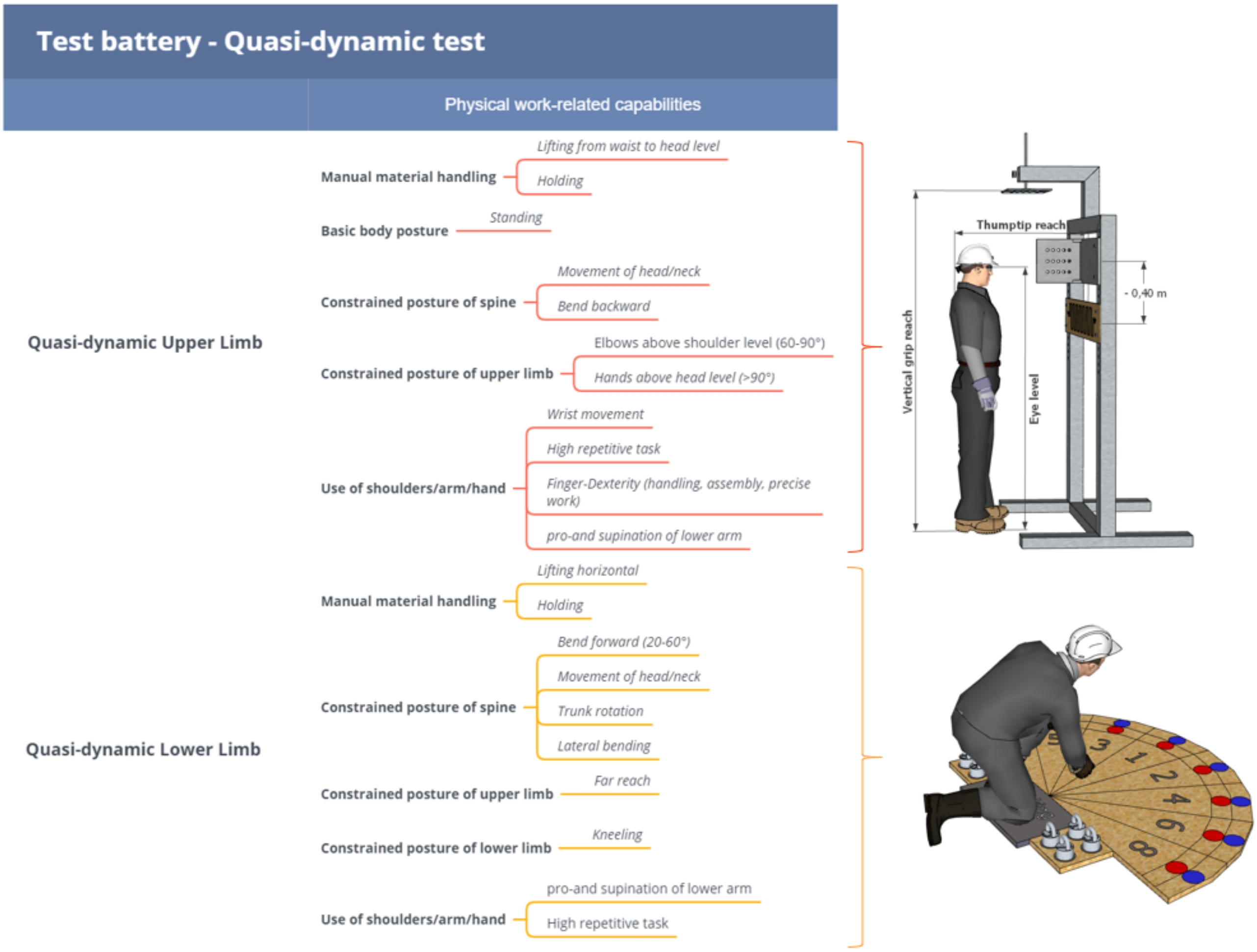


Figure 2.17: Show the physical work-related capabilities involved in the Quasi-dynamic upper and lower limb test.

2.5.4 Dynamic Lower/upper limb

This test is developed to reflect the manual handling tasks of bi-axial and uni-directional fiberglass mats at Siemens, see section 2.4.4 and fig. 2.8, 2.9. Different from the quasi-dynamic test, have these tests been made from a specific work task, and the body motions are not restricted. Despite the more free movements do, the test still involve several aspects, which can be generalized in the industrial sector. The test includes walking, lifting, elevation, back/shoulder flexion, and holding. The test is, furthermore, developed without any predefined performance outcome measures, but the ecological validity of the test is prioritized instead. The study manually extracted the actual working cycle to increase the ecological validity of the test, (*later segmented into Lifting, Walking, and Laydown in section 2.6*). The extracted frames were divided with 60, to derive frames to seconds. With more than 200 working cycles with and without an exoskeleton, have the average time for a single cycle been estimated to take 14,25 seconds. The average cycle should be used as a metronome sound with 14 beats per minute with a 5-second buffer applied to get back to the starting position. The walking length of the test varies in actual production due to the specific number of each mat. Based on multiple physical measures, was the general length estimated to 3 meters for both tests. The test aims to transfer the five dumbbells from one station to another, and secure the dumbbells to be placed within the marked areas. The dumbbells must be carried with both hands to imitate the handling of fiberglass mats. The actual weight of the fiberglass mats was unknown due to the confidential policy at Siemens. We have chosen to follow the EU-OSHA guidelines for the maximum weight of lifting and lowering, see fig. 8.17. The maximum weight for lifting above shoulder level and lowering below lower leg is 5 kg, which is chosen for the dumbbell weight, there are no weight differences between gender due to the alignment with the real working setting. Seen underneath is the individual differences between each test.

Upper limb

To imitate manual handling above the shoulder, is the testing rack from figure see 2.15 used, with an added shelf. The shelf height is individually adjusted, in the same sense as the procedure used in the assembly task.

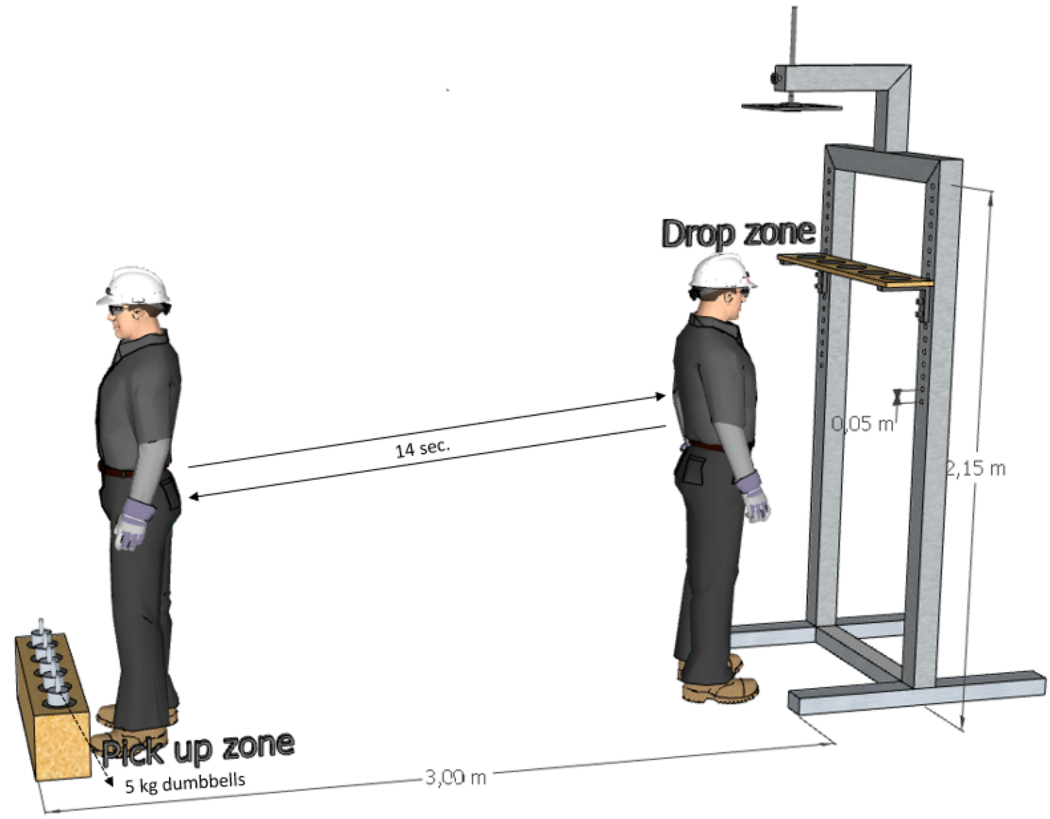


Figure 2.18: Show the material handling setup for upper limb.

Lower limb

The curvature of the blade mold was at the rod end elevated, which is imitated by applying a 1-meter ramp before object laydown. To ensure a strong flexion with a back angle of more than 60° when positioning the dumbbells, is the testing rack adjustable for the individual buttock height[4]. The highest possible adjustment of the rod barrier is based on the 95th percentile for men, and the lowest adjustment is based on the 5th percentile for women.

[4]The vertical distance between a standing surface and the level of the buttock point(Gordon et al. 1988)

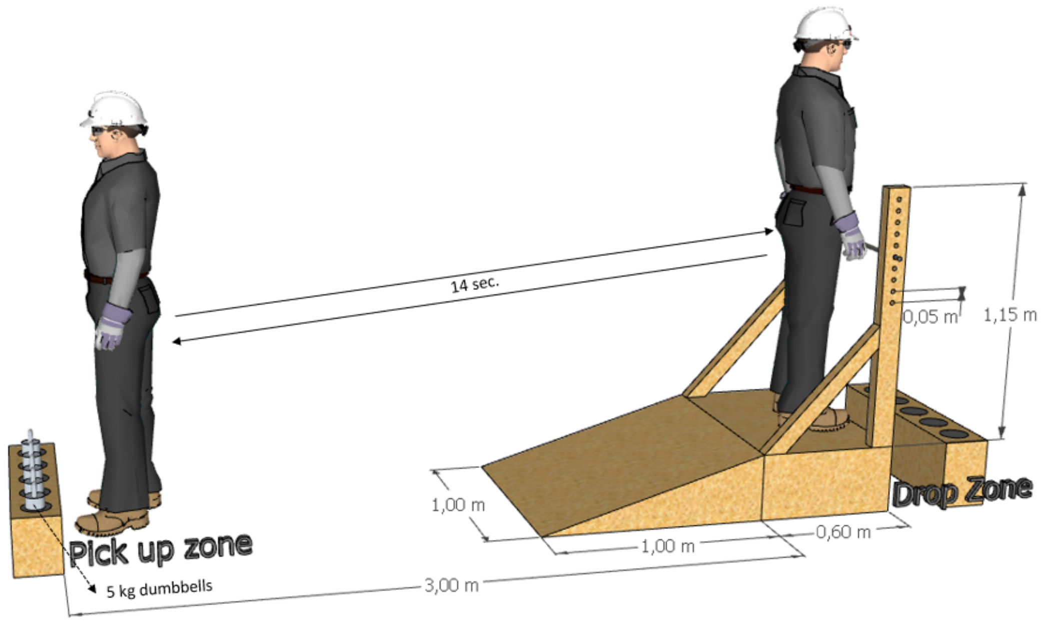


Figure 2.19: Show the material handling setup for lower limb

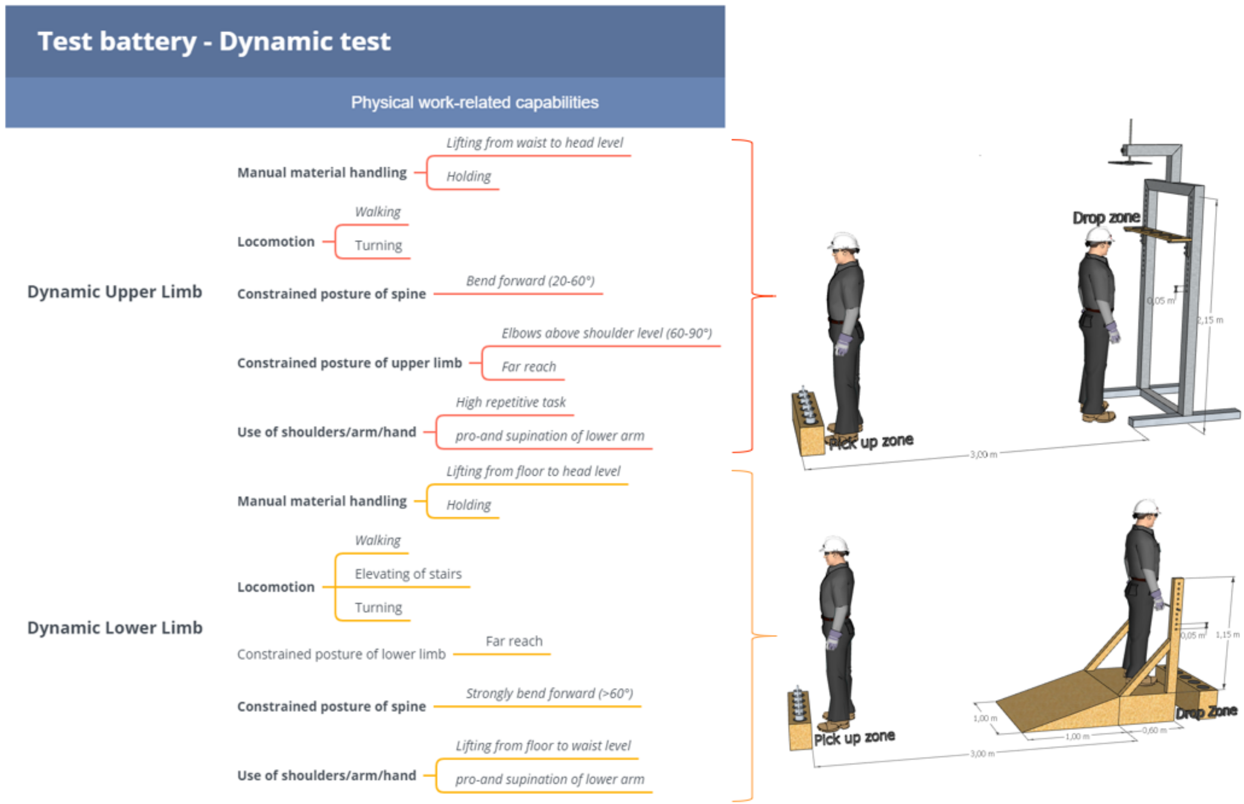


Figure 2.20: Show the physical work-related capabilities involved in the Dynamic upper and lower limb test

2.6 Kinematic analysis

The purpose of the kinematic analysis was to extract data from the Xsens MVN Analyze system and analyze the data to perform statistics. The MVN Analyze collected data produced by the Xsens Awinda system, furthermore made it possible to analyze the data directly in the program, and choose the desired data to extract, see figure 2.22. The work tasks were divided into three cycles, Lifting, Walking, and Laydown, see table 2.4. These phases were the main focus when investigating the kinematic measures of the full-body analysis.

Table 2.4: Explain start and end of the three phases.

Phase	Start	End
Lift	When touching the mat on top of the crane	When walking starts
Walk	When walking starts	When walking stops
Laydown	When walking stops	When the mat have been placed and adjusted

The cycles were manually derived from the Xsens Analyze original file. Each file was a test consisting of upwards of 25 repetitions. The first five repetitions were skipped, and the following five were chosen to ensure that the extracted data was similar; this was done for every test, both with and without the exoskeleton. The cycles were manually derived by frames due to the dynamic motions of the work tasks and meant that the cycles all had different sizes and had to be resized to generate a total mean value of the mean length. The Lifting and Laydown cycles, would be consistent due to the small variation in motions. For the Walking cycle, a variation would appear, as the steps taken for every worker would be different; therefore, a normal gait cycle with regular steps, would not be displayed.

The joints chosen and axes for the kinematic analysis is shown in table 2.5 and 2.21. All left and right joints were gathered to a mean joint angle.

Table 2.5: Show the joints used with axes and the corresponding movements.

Joints	Z-Axes (Transverse)	X-Axes (Sagittal)	Y-Axes (Frontal/Coronal)
Back	Flexion/Extension		Left/Right Rotation
Shoulder	Flexion/Extension	Abduction/Adduction (x-axes)	
Knee	Flexion/Extension		Left/Right Rotation
Ankle	Flexion/Extension		Left/Right Rotation
Elbow	Flexion/Extension		Left/Right Rotation

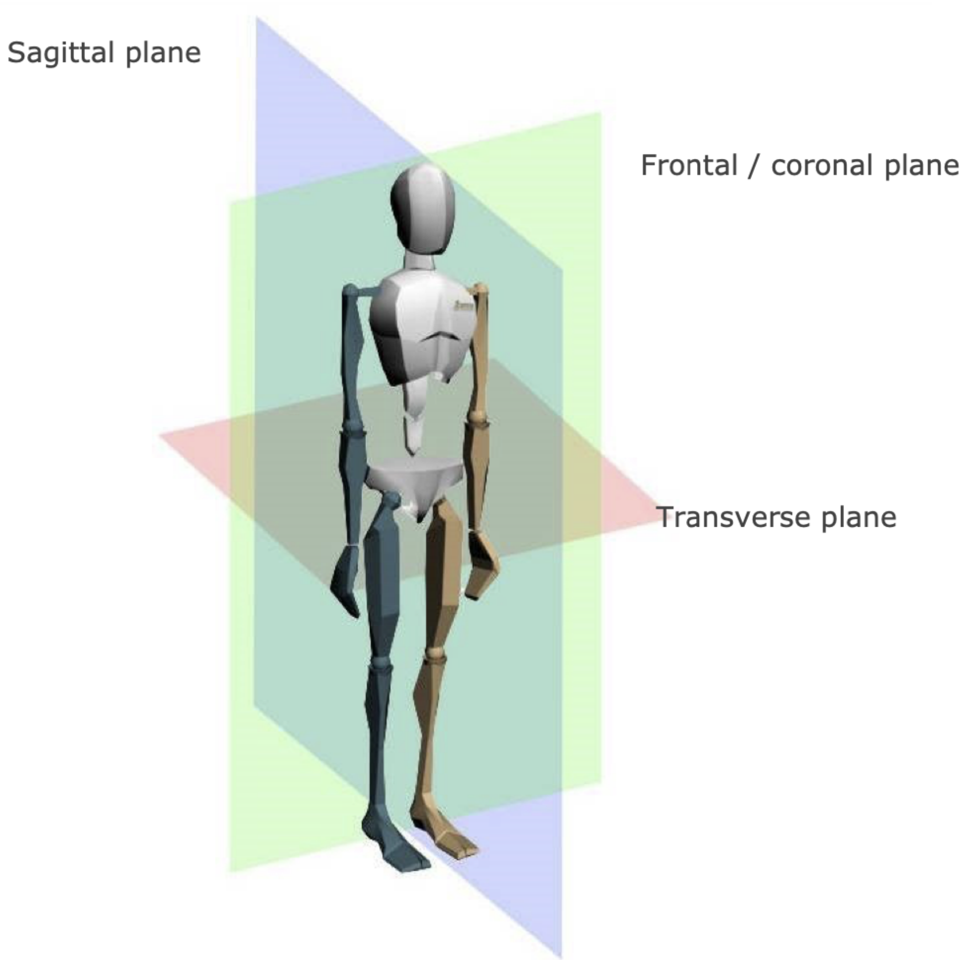


Figure 2.21: Show the Xsens MVN Analyze body planes (XSENS 2015).

As seen in figure 2.22, the joints were calculated by measuring the angle between two segments or sensors; this was seen for all joints except Back/Hip. We wanted to measure the flexion of the lower back, but there was no corresponding output to this angle; therefore, the study chose to measure the hip joint flexion, as this joint used the thigh and pelvis sensors to create an angle corresponding to the lower back. The study subtracted knee flexion to ensure that only back flexion was measured, as this joint added to the flexion created for the hip. This calculation gave the overall lower back flexion angle. We also wanted to analyze the back rotation, which was generated by adding the rotation of the five spine joints, T1C7, T9T8, L1T12, L4L3, and L5S1, giving the overall back rotation angle.

The finished data output was used to calculate statistics explained in the following section.

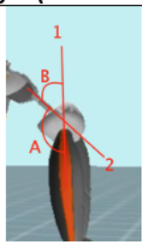
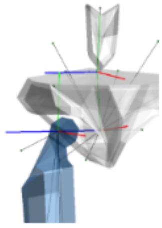
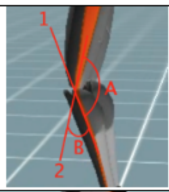
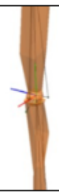
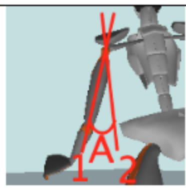
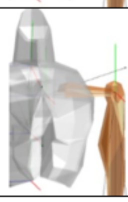
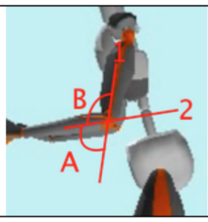
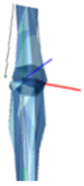
Joint	Description	Angle (Illustration)	Axes (Illustration)
Hip	1: The pelvis sensors vertical line 2: The thigh sensors vertical line A: The desired angle B: The Xsens angle		
Knee	1: The lower leg sensors vertical line 2: The thigh sensors vertical line A: The desired angle. B: The Xsens angle		
Shoulder (Flexion)	1: The Shoulder segments vertical line 2: The forearm sensors vertical line A: The Xsens and the desired angle		
Shoulder (Abduction /Adduction)	1: The forearm sensors vertical line 2: The shoulder segments vertical line A: The Xsens and desired angle		
Elbow	1: The Upper arm sensors vertical line 2: The forearm sensors vertical line A: The Xsens angle B: The desired angle		

Figure 2.22: Show the extracted joints, their angles and axes. (XSENS 2015)

2.7 Statistics

The statistical analysis was performed in Matlab using the open-source Statistical 1D Parameter Mapping (SPM1d) package [5]. The SPM1d method calculates the relationship between the t-value and the critical thresholds for a continuous time series. The method allows us to identify the cluster length (0-100%), where the critical thresholds were exceeded. The statistical test provides exact information about where in, Lifting, Walking, and Laydown, the kinematic differences occur.

A test for normality was performed from the SPM1d normality test package, and the results indicated that the majority of data was not normally distributed. All statistical tests were performed as non-parametric to avoid incorrect interpretation of the data. We chose to perform a non-parametric two-tailed paired t-test to test for the difference in a repeated sample. The repeated sample was segmented into two conditions (with and without exoskeleton). The data output was displayed on two graphs, the first graph containing mean and standard deviation for both with and without the exoskeleton. The second graph illustrates results from the statistical t-test which includes the critical alpha threshold at $\alpha = (0.05)$, the respective t*-critical value, the potential probability value (p-value) and the belonging intervals, see fig. 2.23 below.

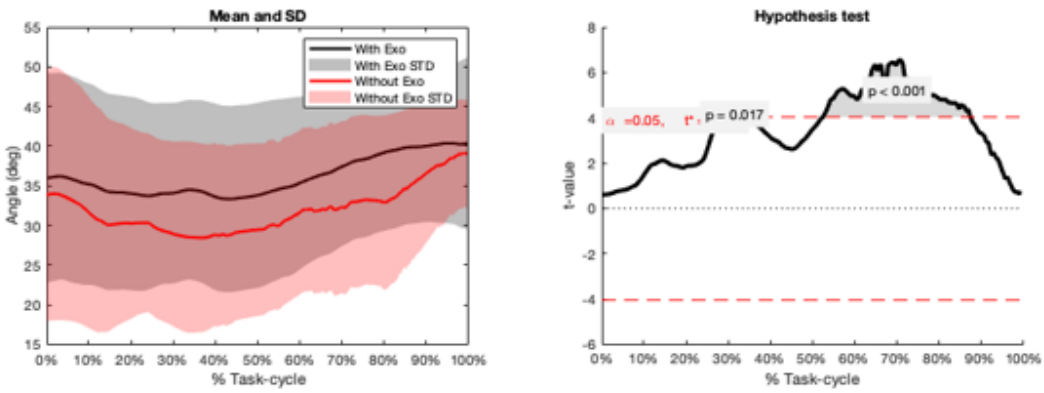


Figure 2.23: Example of statistical 1D parameter mapping.

[5] http://spm1d.org/index.html

Results 3

BackX results, correspond to the Bi-axial work task and ShoulderX results correspond to the Uni-directional work task. Full overview of the results with belonging hypothesis was seen in appendix 8.1.

3.1 BackX

The results in fig. 3.1 and fig. 3.2 in the Bi-axial work task show no significant differences.

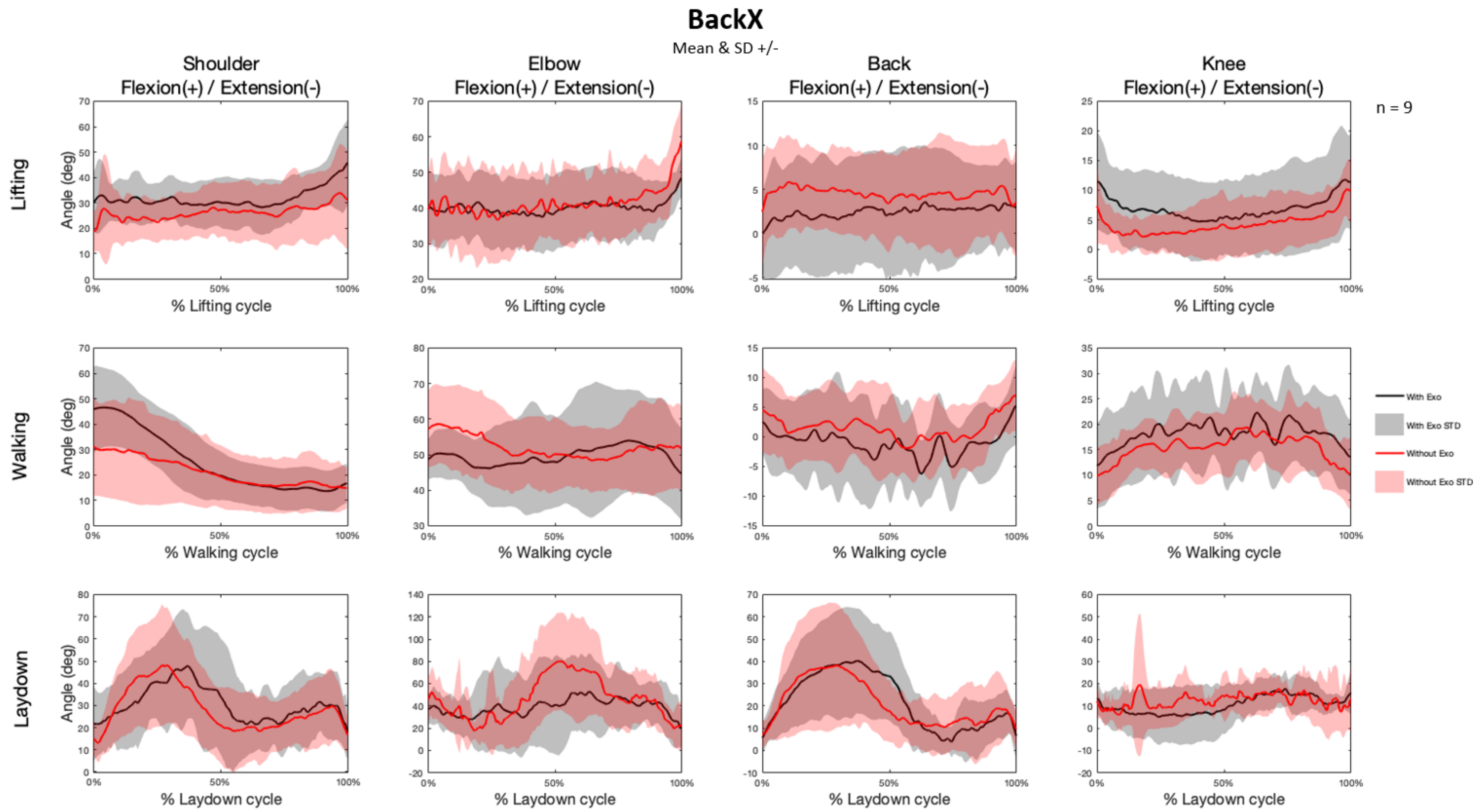


Figure 3.1: Show the mean and standard deviation for Flexion / Extension of Shoulder, Elbow, Back and Knee at Lifting, Walking and Laydown. The x-axis illustrate the work tasks from 0-100%. The y-axis illustrates the mean angle in degrees.

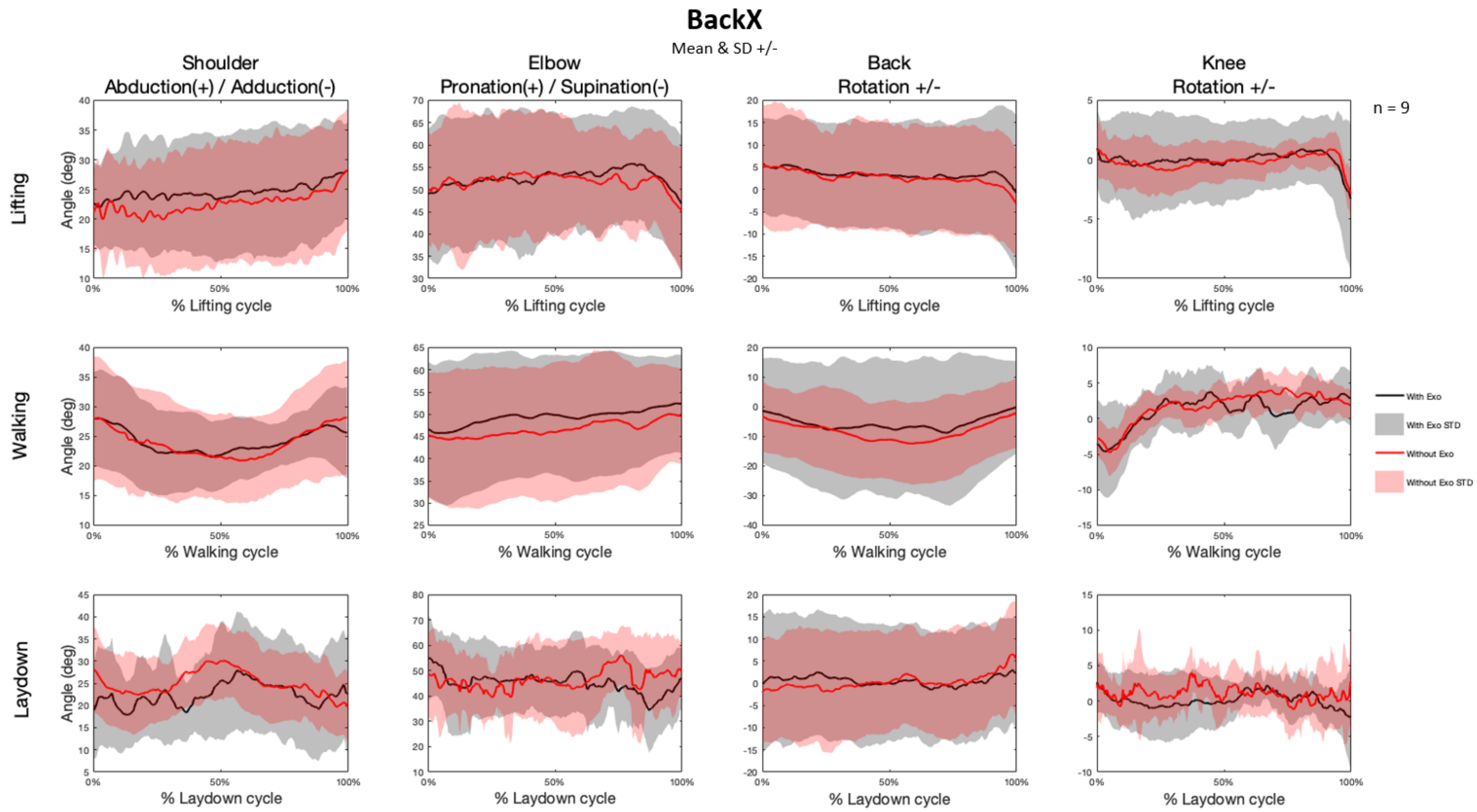


Figure 3.2: Show the mean and standard deviation for Shoulder abduction/adduction, Elbow pronation/supination, Back and Knee rotation at Lifting, Walking and Laydown. The x-axis illustrate the work tasks from 0-100%. The y-axis illustrates the mean angle in degrees.

3.2 ShoulderX

The results in fig. 3.3 show four significant clusters for shoulder flexion/extension at the Lifting cycle (12-23%, p=0.015 ; 61-67%, p=0.018 ; 68-69%, p=0.014 ; 87-99%, p=0.014 ; 99%, p=0.024).

The results in fig. 3.4 show four significant clusters for elbow pronation/supination at the Lifting cycle (73-75%, p = 0.019 ; 78-79%, p = 0.021 ; 85-96%, p = 0.002 ; 97-100%, p = 0.014)

The results in fig. 3.4 show four significant clusters for elbow pronation/supination at the Walking cycle (0-11%, p = 0.001 ; 12-20%, p = 0.008 ; 22-55%, p = <0,001 ; 58-59, p = 0.021)

The results in fig. 3.4 show one significant clusters for elbow pronation/supination at the Laydown cycle (76-77%, p = 0.01)

The results in fig. 3.4 show two significant clusters for shoulder abduction/adduction at the Lifting cycle (30-34%, p = 0.017 ; 53-88%, p = <0.001)

The results in fig. 3.4 show two significant clusters for knee rotation at the walking cycle (81-85%, p = <0.001)

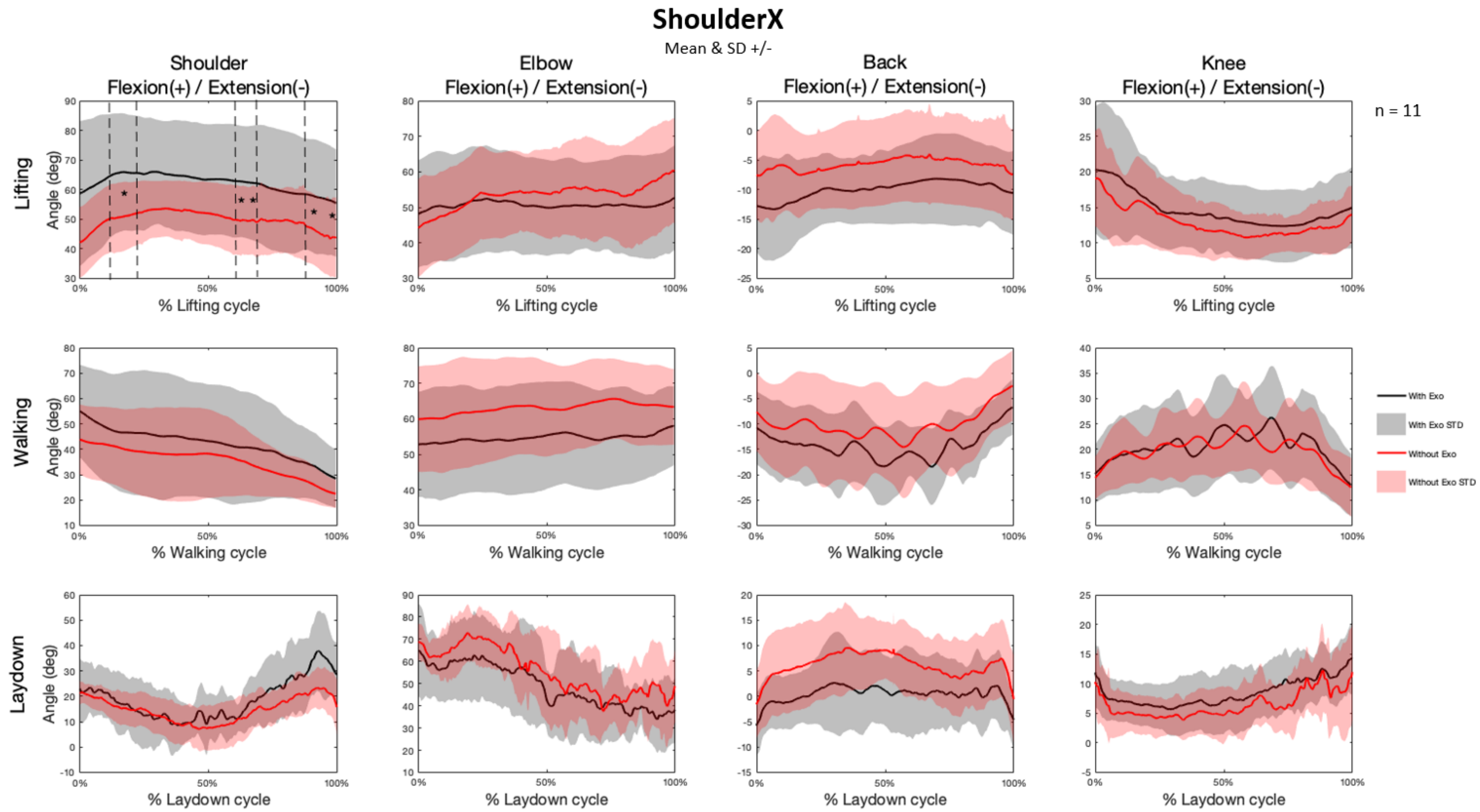


Figure 3.3: Show the mean and standard deviation for Flexion / Extension of Shoulder, Elbow, Back and Knee at Lifting, Walking and Laydown. The x-axis illustrate the work tasks from 0-100%. The y-axis illustrates the mean angle in degrees.

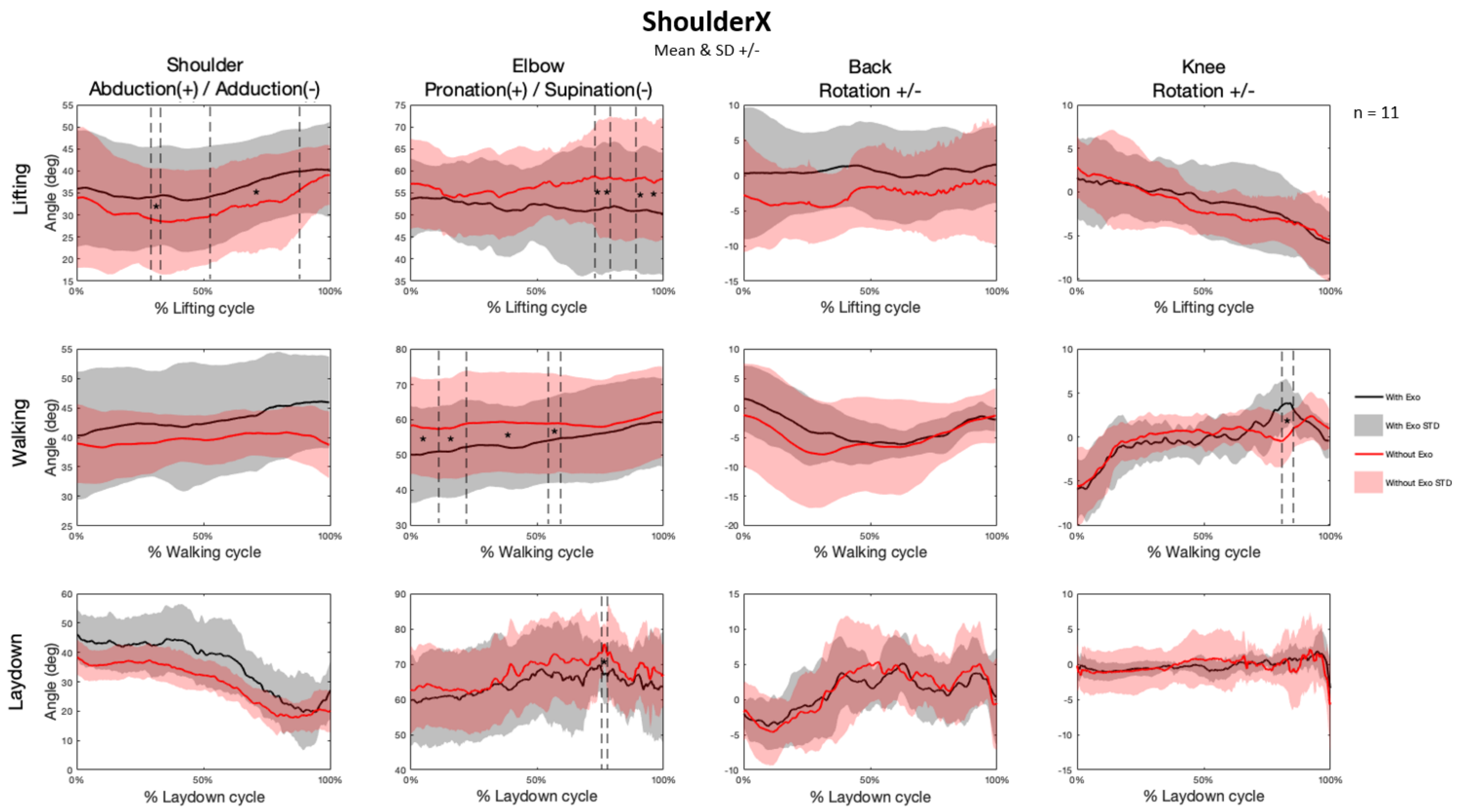


Figure 3.4: Show the mean and standard deviation for Shoulder abduction/adduction, Elbow pronation/supination, Back and Knee rotation at Lifting, Walking and Laydown. The x-axis illustrate the work tasks from 0-100%. The y-axis illustrates the mean angle in degrees.

Discussion 4

The purpose of the discussion was to understand biomechanical changes during the Bi-axial and Uni-directional work tasks and compare these changes with the use of the BackX and ShoulderX exoskeleton.

4.1 BackX

4.1.1 Interaction between Back and Shoulder

The shoulder joint showed no significant difference in ROM when using the BackX exoskeleton, though a small general difference indicating an increase in shoulder flexion was seen during the Lifting cycle see fig. 3.1. When Lifting the mat, the workers had to keep the mat stretched to ensure that it did not fall into the mold. Without the exoskeleton, the workers tend to increase back extension and increase shoulder flexion to withhold the stretching. When wearing the exoskeleton, the workers tended to position themselves close to a 0° upright position and decreased the shoulder flexion to withhold the stretch again.

4.1.2 Biomechanical changes of the lower limbs

As mentioned above, the back showed general tendencies that the workers experienced a difference in flexion and extension see fig. 3.1. The general difference was not comparable with the literature, and the discrepancy could emerge from the different test setups and movements (field vs. laboratory). The majority of the studies included in the narrative, see section 1.2, have been performed as laboratory tests, either static or quasi-static. The laboratory test restricts the body motions, which lowers the data variance. The complexity of a field study otherwise enlarges the variance, due to the complexity of performing the actual work task. To obtain similar accuracy for the results in a field study would it require a substantially larger sample size.

Comparing our study with similar field studies discover that sample size was a general issue as the studies did not find any significant differences while wearing exoskeletons. Our study had a sample size of n=9 for the BackX and n=11 for ShoulderX while Graham, Agnew, and Stevenson (2009), using the PLAD exoskeleton, and Baltrusch, Dieën, A. S. Koopman, et al. (2020), using the SPEXOR exoskeleton, respectively had a sample size of n=10 and n=11.

In comparison, we found a general difference, especially during lifting and walking, when wearing the exoskeleton see fig. 4.1. The cause of the difference could be the way the BackX exoskeleton works. The exoskeleton, as seen in 2.2, had a chest pad connected to the thigh pads through the torque generators. The chest pad imposed a resistance to the workers, which the workers had to push through. The resistance from the chest pad was believed to induce a startle reaction until the workers get comfortable to exceed the resistance. Otherwise, the resistance could change the workers kinematic motion, as the exoskeleton could resist the flexion caused by gravity, the exoskeleton replaces the muscular load from the lower back and induce this to the workers through the chest pad. The reduction in back flexion caused by the chest pad could reduce the shear forces on the L5–S1 joints, but also restrict the range of motion(ROM) of the torso (Ulrey and Fathallah 2013b). The study claimed that the stiffness of the exoskeleton could change the flexion of the leg joint and adversely affect the joint with a higher load (ibid.). The same tendency was seen in our study, instead of using their back, the workers showed a tendency to increase the knee flexion, see fig. 3.1, to get into the optimal position for picking up the mat and avoid getting through the resistance.

The laydown cycle did not indicate any kinematic differences. The reason could be that the workers had to bend far to place the mat correctly and were forced to bent through the resistance. This cycle experienced the best worker response to the support from the exoskeleton.

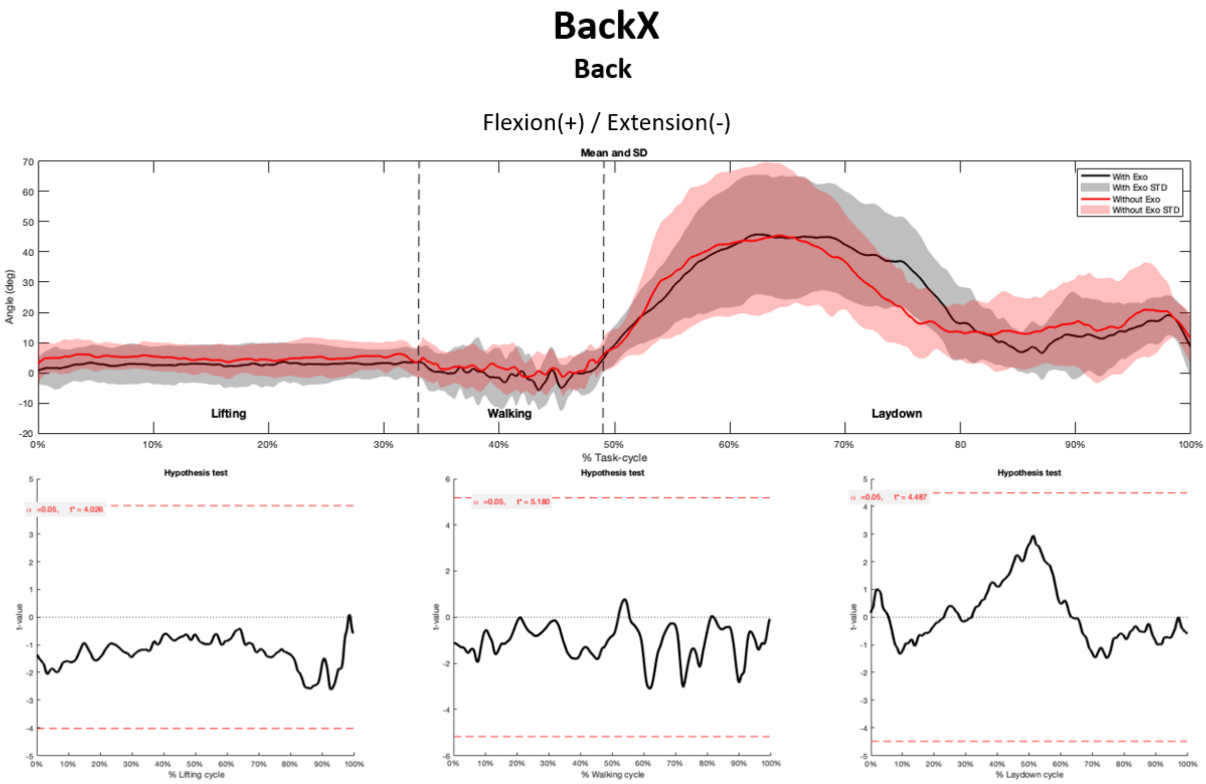


Figure 4.1: Show the overview of the complete BackX work task for back Flexion(+)/Extension(-) involving Lifting, Walking and Laydown. Below is the belonging hypothesis test. Both illustrations was created in SPM.

Regarding back rotation, we did not find any significant differences between "with" and "without" see fig.3.2. The reason for the small fluctuations seen in back rotation, could be found in the workers Walking cycle 2.6. The workers walk sideways, this meant that when grabbing the mat at the Lifting cycle, the workers did not have to turn their trunk to face the correct direction, but instead just started walking sideways until they reached the Laydown cycle.

4.2 ShoulderX

4.2.1 Biomechanical changes of the shoulder joint

A general larger shoulder flexion was seen for the 'with' exoskeleton condition in the Walking and Laydown cycle with a significant larger shoulder flexion in the Lifting cycle. The increase in shoulder flexion 'with' exoskeleton could be caused in the moment whereas the shoulder exoskeleton support initiates (20° shoulder angle), which generates an unnatural lift of the arm. Furthermore, the strength of the exoskeleton increased proportionally when it exceeded the maximum support at 60°; this could explain the significant differences seen in the Lifting cycle. The transferring between the support levels, showed a significant kinematic difference from the start of the walking cycle when the shoulder angle dropped below 60°, then the difference showed no significant difference again, see fig. 8.5.

Align with the shoulder flexion, a tendency to a larger abduction for the "with" exoskeleton condition was seen for the walking and Laydown cycle, and a significant larger shoulder abduction was seen for the Lifting cycle, see fig. 8.5. The design of the exoskeleton mostly caused a difference in kinematics. In contrast, the exoskeleton "shoulder joint" has been reconstructed as two revolute joints to allow movement in the z,x,y-direction[1]. The design of the human shoulder joint is like a ball and socket joint(Herda et al. 2003). The exoskeleton shoulder joint have restricted movement due to the revolute joint, see fig. 2.3 "stow lock", to perform both abduction/adduction and horizontal flexion/extension. The use of one revolute joint to perform two kinds of movements was solved with an extended arm on horizontal revolute joint, see fig.4.2. The consequence of the extended arm is a bigger turning radius, which forces the shoulder to be more abducted when performing a shoulder flexion, as illustrated below, see fig. 4.2.

[1]**z-direction**: vertical flexion/extension **x-direction**: abduction/adduction **y-direction**: horizontal flexion/extension) **Rotation**: Internal/external rotation of the axes occurs independently of the exoskeleton, due to free movement inside the arm cuffs.

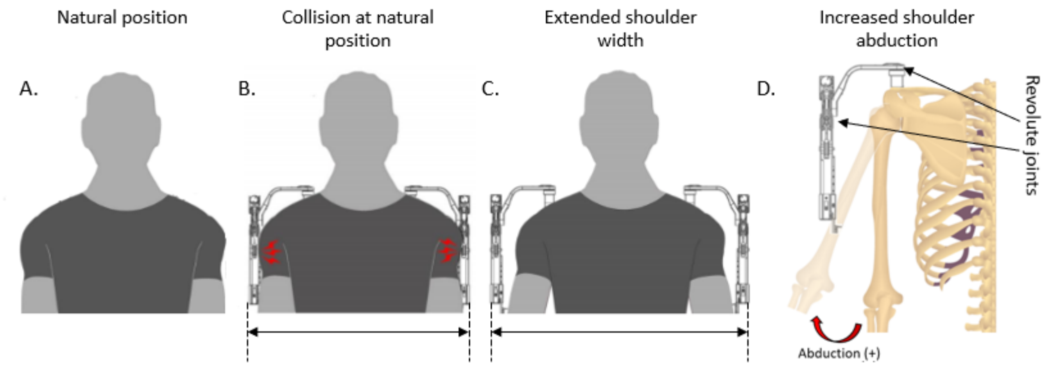


Figure 4.2: Show an illustration of how the ShoulderX exoskeleton, increases the arm abduction in a neutral position. The revolute joints provide horizontal and vertical movements. Illustration A-C have been adapted from (Bionics 2017c) and illustration D. have been adapted from (Scott Sheffield 2017)

The kinematic changes for shoulder flexion could result in an increased risk of physiological and biomechanical consequences (Grieve and Dickerson 2008). According to the RULA assessment, see section 2.4.2 is the shoulder flexion score "with exo" equal to 3, which corresponds to a medium risk 2.1, whereas the "without exo" score of 2 only corresponds to low risk. The negative physiological consequences of prolonged arm elevation could increase intramuscular pressure (IMP) and decreased limb circulation. The restricted intramuscular blood flow is a major source for the development of rotator cuff pathology, which is one of the most common shoulder injuries (ibid.). The negative biomechanical consequences emerge from a greater tissue load on the shoulder complex and can cause impingement of the shoulder (ibid.). The potential imposed risk for prolonged arm elevation is only a theoretical discretion due to the fact of not knowing the actual support from the ShoulderX exoskeleton. To compare the findings with other studies have Schmalz et al. (2019) [1] and Maurice et al. (2019)[2], likewise found a larger shoulder abduction with exoskeleton ($8^{\circ 1}$ and $2^{\circ 2}$), but still a significant decrease in muscle activity for the shoulder muscles. The decrease in muscle activity reduces the physical demand for the workers and thereby lowering the risk for the occurrence of shoulder disorders (Kim and Nussbaum 2019), (Nussbaum et al. 2019). The decrease in muscle activity could, therefore, indicate, the supposed risk from the biomechanical changes could be counterbalanced by support from the exoskeleton.

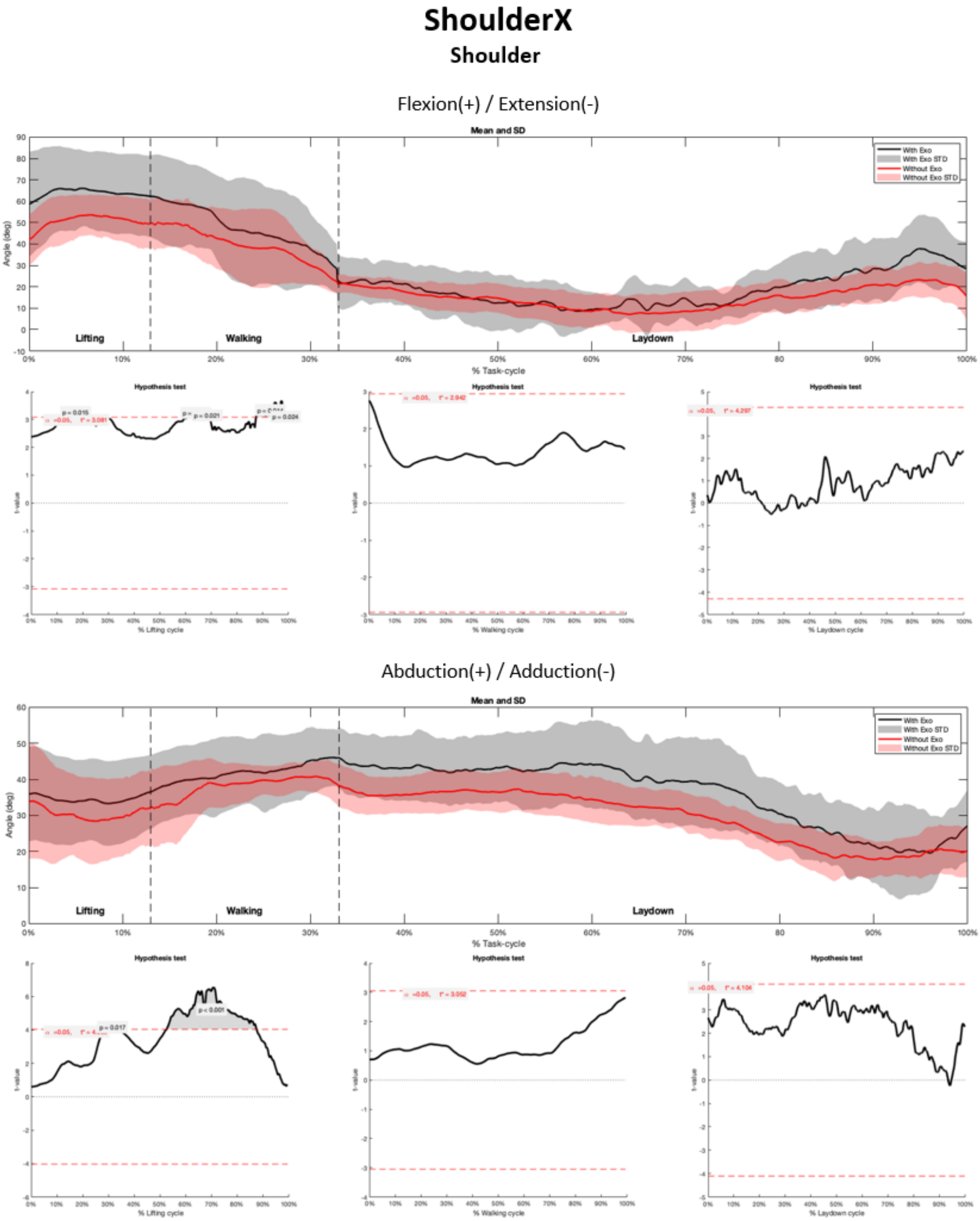


Figure 4.3: Show the entire task cycle divided in, Lifting, Walking and Laydown, with the belonging hypothesis test for shoulder flexion/extension and abduction/adduction

4.2.2 Load transfer

A comparison of flexion and extension between shoulder, elbow, and back, showed tendencies of load transfer and change in the performed motions. As mentioned above, the shoulder joint showed significant differences between with and without exoskeleton, but with the increased flexion of the shoulder joint, a generally increased extension in Lifting at around -10° and in Walking around (-15°) for the back was present see fig. 3.3. In Laydown, the back did not extend but showed the same flexion as without the exoskeleton (5°). The elbow joint showed at all three cycles a general difference that counteracts the shoulder joint, meaning that when the shoulder flexion increased, the elbow flexion decreased at around 50° for Lifting and Walking, while Laydown showed a overall general difference see fig. 3.3. To summarize, when wearing the exoskeleton, the workers increased the flexion of the shoulder, and decreased the flexion at the elbow, meanwhile the back extension was decreased, see fig. 4.4 (A). When not wearing the exoskeleton, the shoulder flexion decreased, and the elbow flexion increased, meanwhile the back extension was increased, see fig.4.4 (B). The figure amplifies the differences to show the two working positions.

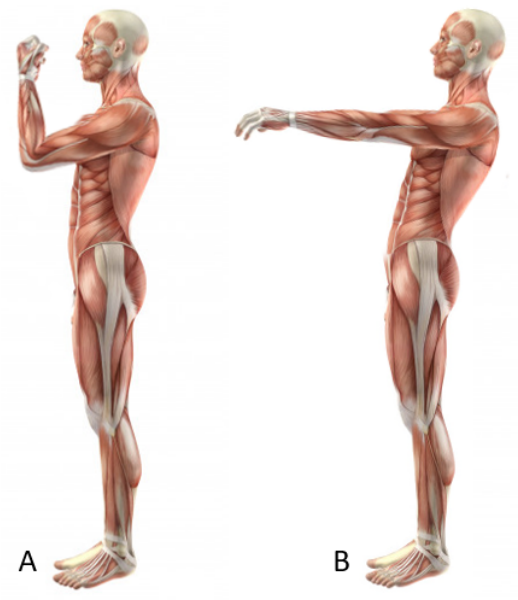


Figure 4.4: Show an illustration of the two work positions mentioned above. A: show the illustration of the position without the exoskeleton. B: show the illustration of the position with the exoskeleton.

To compare these motion with other studies, (Theurel, Desbrosses, et al. 2018) and (Kim, Nussbaum, Mokhlespour Esfahani, Alemi, Jia, et al. 2018) showed a decrease in shoulder flexion and an increased elbow flexion when wearing an exoskeleton; these studies were static performed in a laboratory setting. This supports the statement from (Nussbaum et al. 2019), that there is a need for large-scale field studies that test the dynamic motion in a real-life setting, not only static and quasi-static.

The reason for the change in kinematics was believed to be the exoskeletons' lumbar support pad, which is curved to match the natural curve in the back; therefore, the workers could have a natural feeling to follow the support leading to an increased extension. When comparing the three joints, a tendency that wearing the exoskeleton could cause the potential imposed risk to move from the shoulder to the lower back, But as mentioned in 4.2.1, this was only a theoretical assumption. As well as not knowing if the extension shown in the lower back, was enough to reduce the shear forces, as mentioned in (Dionne et al. 2008)

4.2.3 Interaction between Elbow and Shoulder

The elbow and shoulder flexion was mentioned above in comparison with the kinematic motion changes caused by the back. The shoulder abduction was presented in 4.2.1, but the elbow pronation and supination have not been mentioned. The elbow pronation and supination showed significance levels at all three cycles and with the exoskeleton a decrease in pronation would occur, see fig. 4.5.

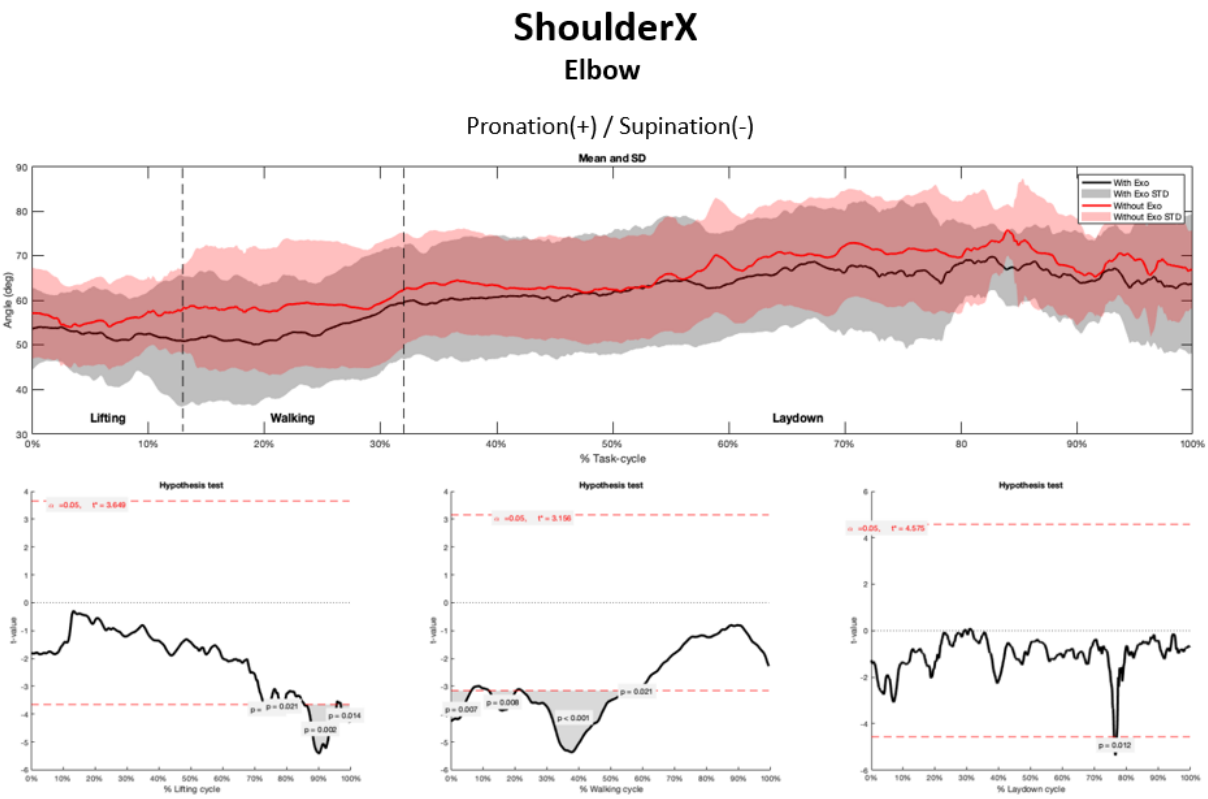


Figure 4.5: Show the entire task cycle divided in, Lifting, Walking, and Laydown, with the belonging hypothesis test for elbow pronation/supination

The shoulder abduction caused a decrease in pronation and the workers hand position when holding the mat. When holding the mat, the workers tend to hold the mat at the top and pronate their hands to obtain a firm grip see fig. 4.6(A). The hand position does not change whether the workers wear the exoskeleton or not; therefore, when a decreased shoulder abduction occurred, the workers would automatically increase their elbow pronation to maintain the correct hand position. As an increase in shoulder abduction occurred, the workers would automatically experience a decrease in pronation, as the abduction would cause their elbow pronation to be closer to the neutral hand position, see fig. 4.6(B).

Figure 4.6: A: Show the workers preferred hand position. B: Show the neutral hand position.

4.3 Study Limitations

The study experienced a few limitations which will be acknowledged.

First, the workers were already familiar with the work tasks, meaning that the workers all performed the work tasks differently.

Second, the small sample size, the aging and the gender diversity for both work tasks should be taken into account when generalizing the results to a broad population.

Third, the test only tested on the acute effects of the exoskeleton, and not how the exoskeleton affects the workers over a longer period of time.

Fourth, the study only investigated the kinematic changes of the workers; therefore, the biomechanical changes reported in the discussion are a part of other studies.

5 Conclusion

The study implemented the open-source statistical 1D Parameter Mapping (SPM1d) package and was, to our knowledge, the first to conduct a dynamic full-body kinematic test on exoskeletons. From this, we could conclude that SPM1d was a suitable tool to assess kinematic information, and in our case, dynamic movements. Comparing this to the narrative, it is clear that the literature only investigated specific joints and movements, whereas we investigated the full-body kinematics of a complete dynamic work task cycle.

The study found no significant kinematic differences when using the BackX exoskeleton, but several tendencies showed changes in the full-body kinematics. The BackX indicated a reduction in back flexion, but the stiffness of the exoskeleton could change the flexion of the leg joint and adversely affect the joint with a higher load.

The study found several significant kinematic differences and even more tendencies for the ShoulderX exoskeleton. In general, the study found that the joints interact with each other and transfer load regarding the movements performed when wearing the exoskeletons. From a biomechanical point of view, the changes of wearing an exoskeleton could impose a potential risk for work-related disorders for both back and shoulder.

Lastly, the study found the automated RULA assessment applicable to several industrial production facilities or, in general, to detect potential risk factors for the occurrence of MSD. In relation to the automated RULA assessment, could the test battery standardize a catalog of work tasks, in which the industrial working facilities could compare their work tasks to, and ease the implementation of exoskeletons.

Perspective 6

Mentioned in chapter 4 most of the literature who performed field-based testing, had a low sample size. The low sample size caused a high variance in our study and, therefore, should future tests perform a power analysis based on their specific study before recruiting subjects.

Based on this study, a power analysis[1] would illustrate the optimal sample size. The power analysis is based on a two-tailed matched paired t-test, an effect size of 0.8 to capture substantial differences, an alpha value of 0.05, and a power size of 0.95. The power analysis suggests a sample size of 23 workers to obtain optimal results.

We recommend that future studies, testing full-body dynamic work tasks on kinematics, should use the SPM1d package to obtain exact information of where statistical differences occur in a continuous time series.

There are currently no golden standards for the testing of occupational exoskeletons. The study would recommend that the work task catalog should be expanded to implement a broader selection of physically work-related capabilities found in the industrial sector.

[1] G*Power: Statistical Power Analysis found at https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.html

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Keywords: *Passive exoskeleton, Kinematics, Industry, Biomechanics, Upper-limb, Lower-limb, RULA, Test battery, Dynamic, Quasi-dynamic*

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Appendix 8

8.1 Results for kinematic analysis

8.1.1 BackX

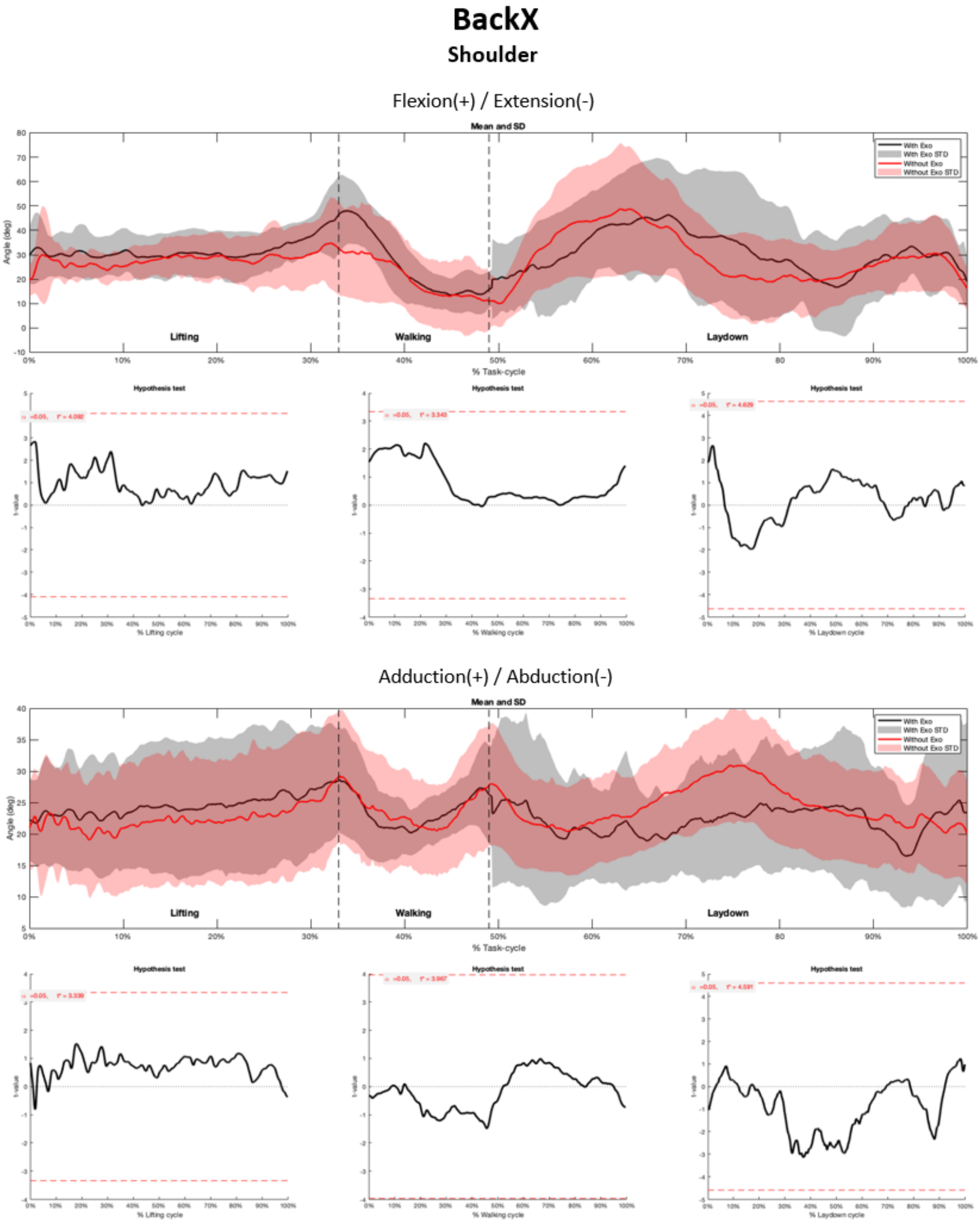

Figure 8.1

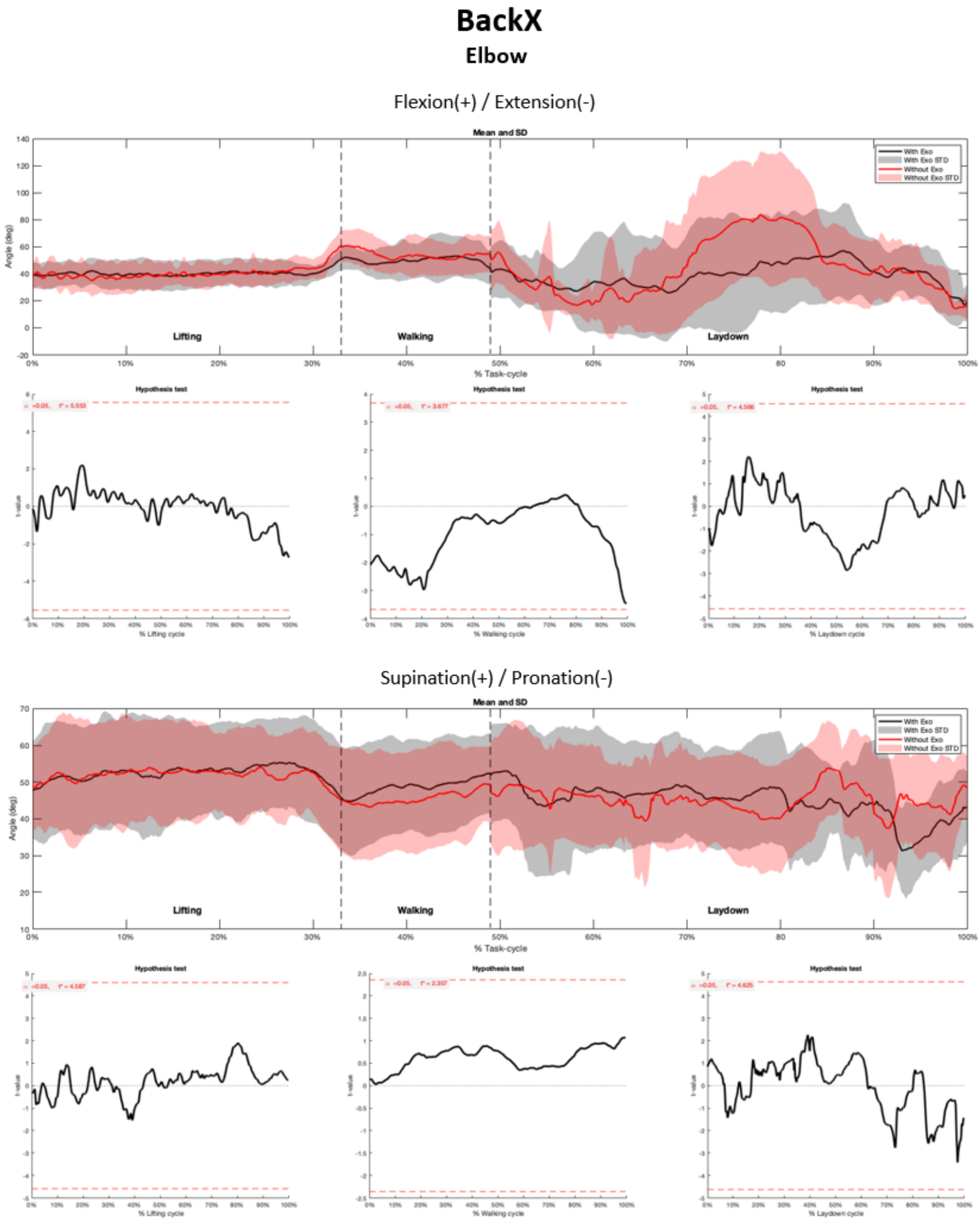
BackX
Elbow
Flexion(+) / Extension(-)
Mean and SD
With Exo
With Exo STD
Without Exo
Without Exo STD
Angle (deg)
Lifting
Walking
Laydown
% Task-cycle
Hypothesis test
t-value
% Lifting cycle
% Walking cycle
% Laydown cycle
Supination(+) / Pronation(-)

Figure 8.2

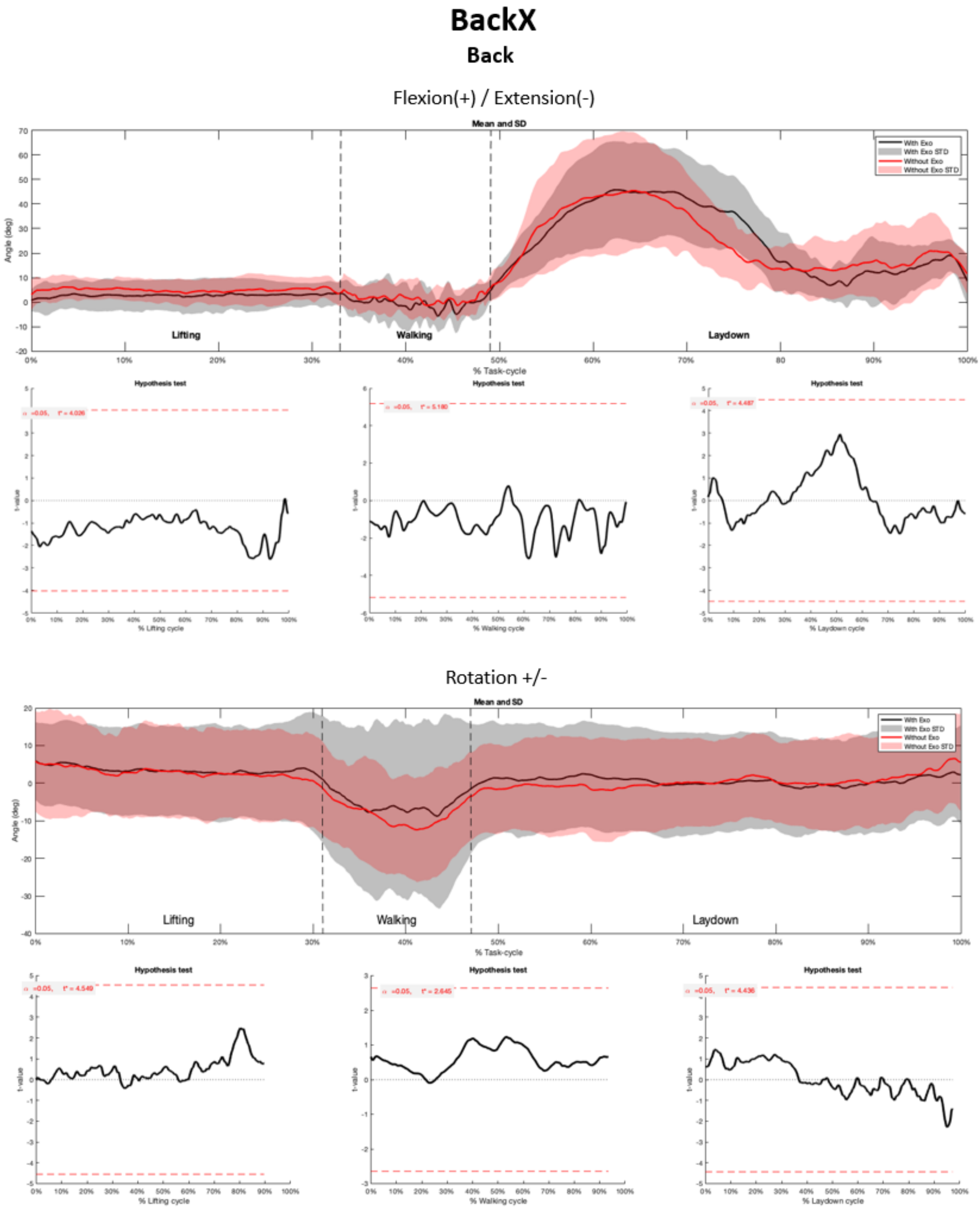
BackX
Back
Flexion(+) / Extension(-)
Mean and SD
With Exo
With Exo STD
Without Exo
Without Exo STD
Angle (deg)
Lifting
Walking
Laydown
% Task-cycle
Hypothesis test
t-value
% Lifting cycle
% Walking cycle
% Laydown cycle
Rotation +/-

Figure 8.3

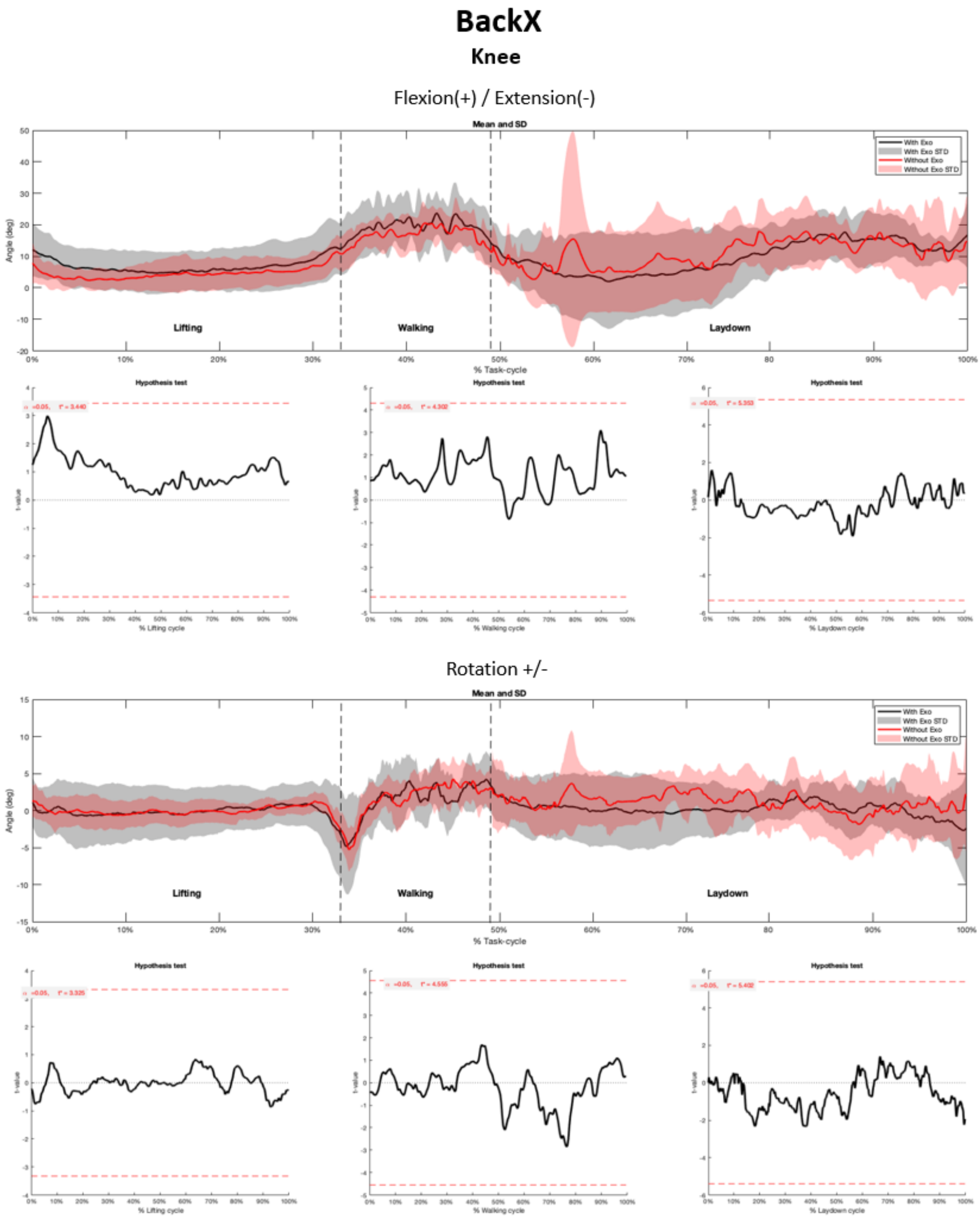
BackX
Knee
Flexion(+) / Extension(-)
Mean and SD
With Exo
With Exo STD
Without Exo
Without Exo STD
Angle (deg)
Lifting
Walking
Laydown
% Task-cycle
Hypothesis test
t-value
% Lifting cycle
% Walking cycle
% Laydown cycle
Rotation +/-
Mean and SD
Hypothesis test

Figure 8.4

8.1.2 ShoulderX

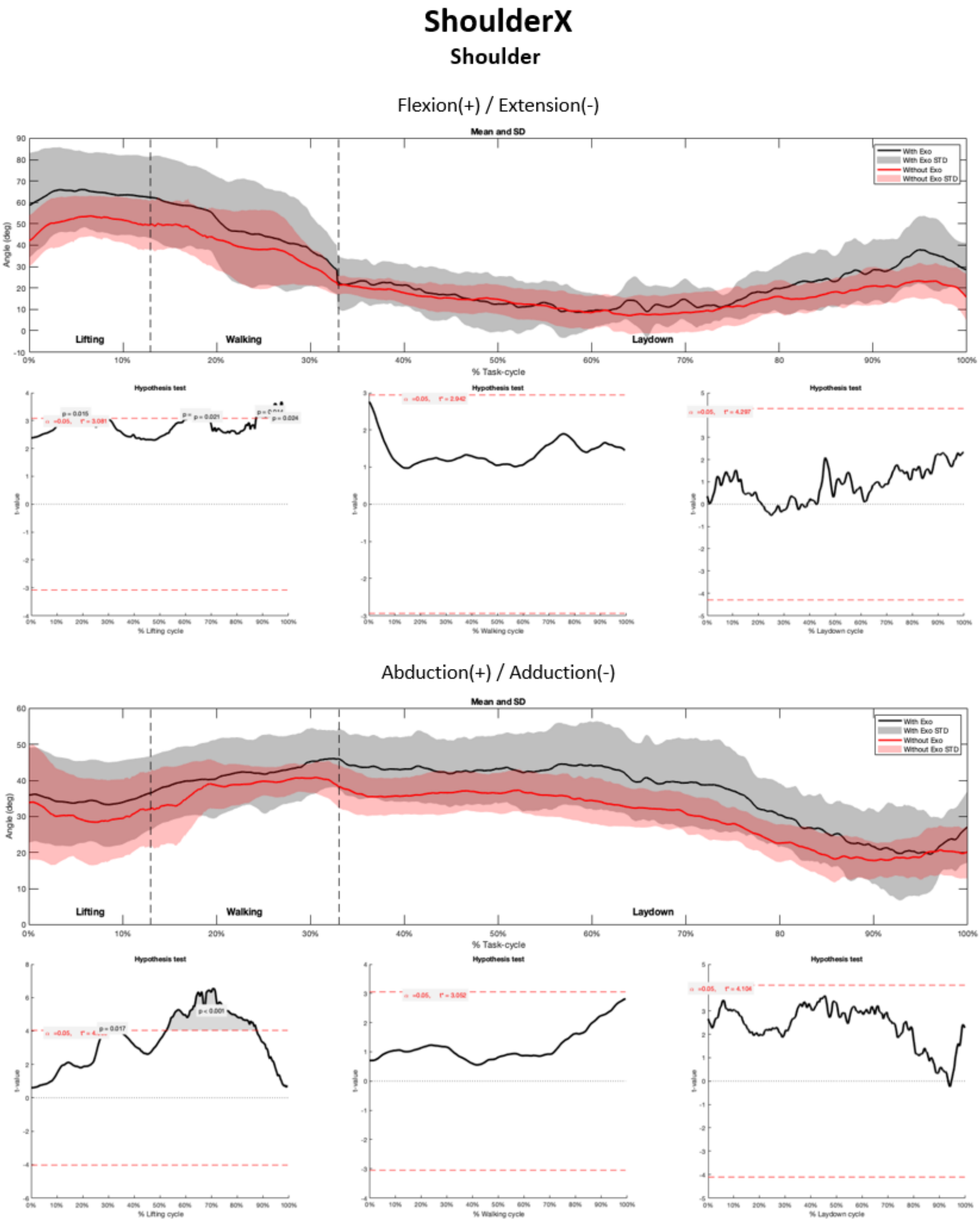

Figure 8.5

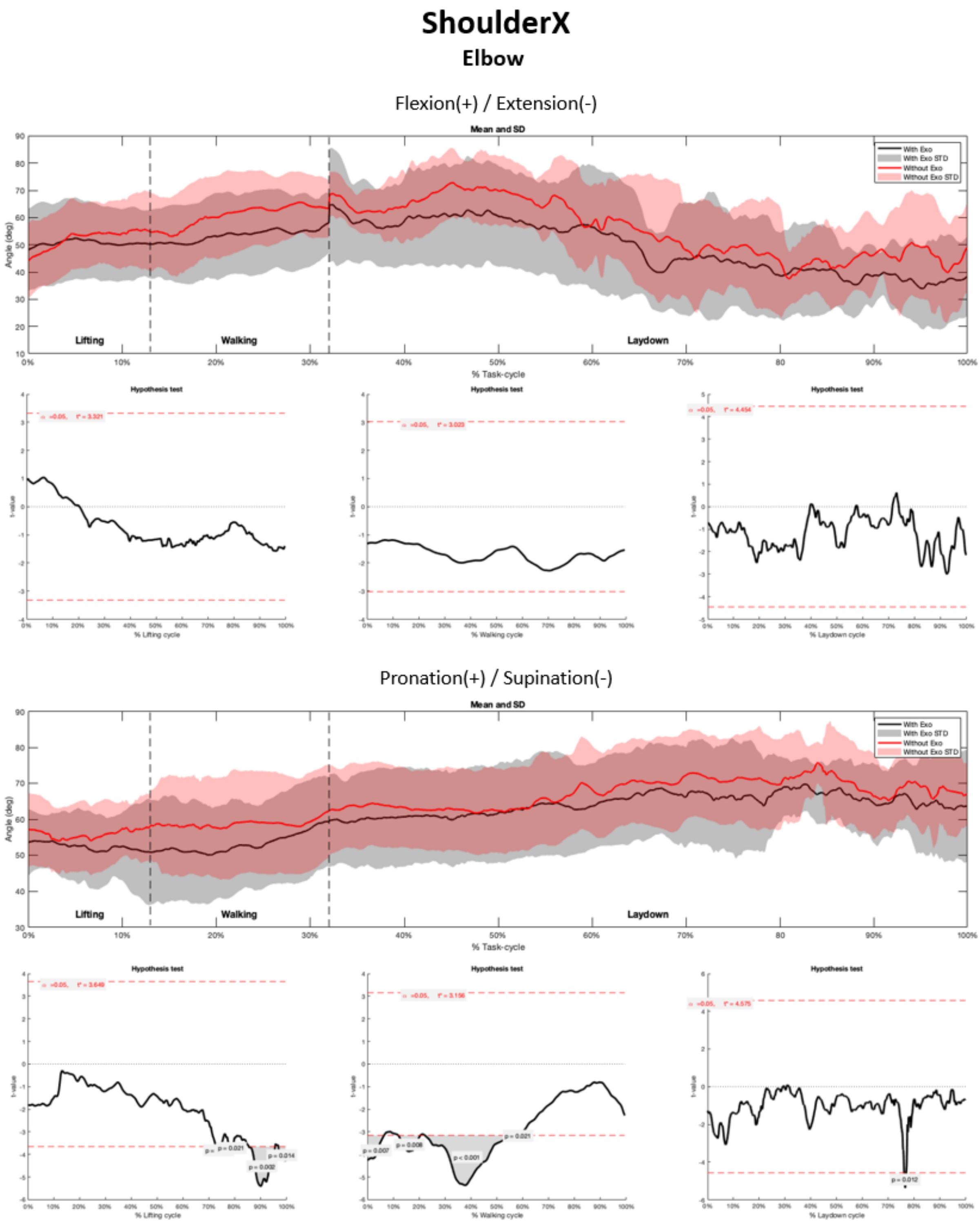
ShoulderX
Elbow
Flexion(+) / Extension(-)
Mean and SD
With Exo
With Exo STD
Without Exo
Without Exo STD
Angle (deg)
Lifting
Walking
Laydown
% Task-cycle
Hypothesis test
t-value
% Lifting cycle
% Walking cycle
% Laydown cycle
Pronation(+) / Supination(-)

Figure 8.6

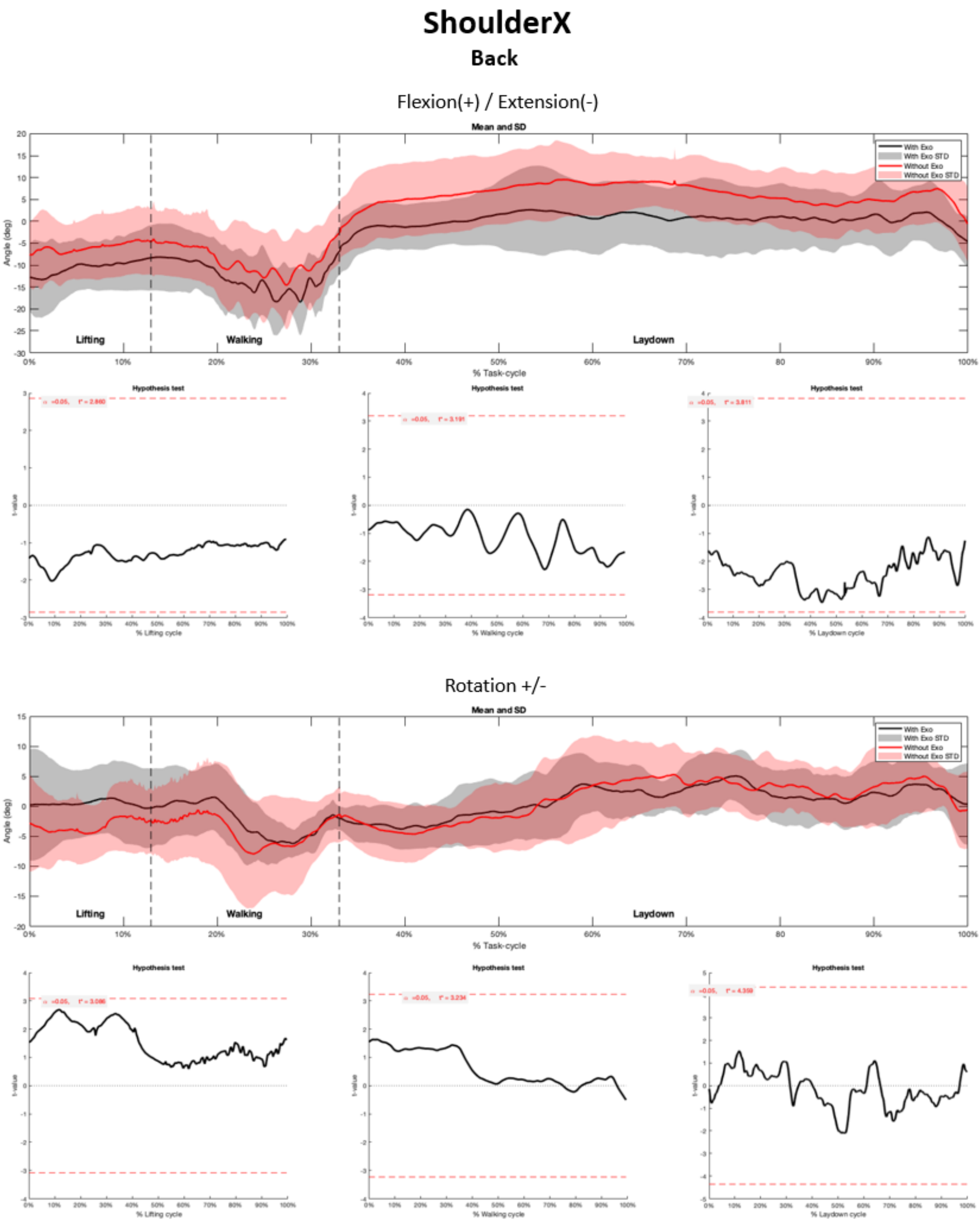
ShoulderX
Back
Flexion(+) / Extension(-)
Mean and SD
With Exo
With Exo STD
Without Exo
Without Exo STD
Angle (deg)
Lifting
Walking
Laydown
% Task-cycle
Hypothesis test
t-value
% Lifting cycle
% Walking cycle
% Laydown cycle
Rotation +/-

Figure 8.7

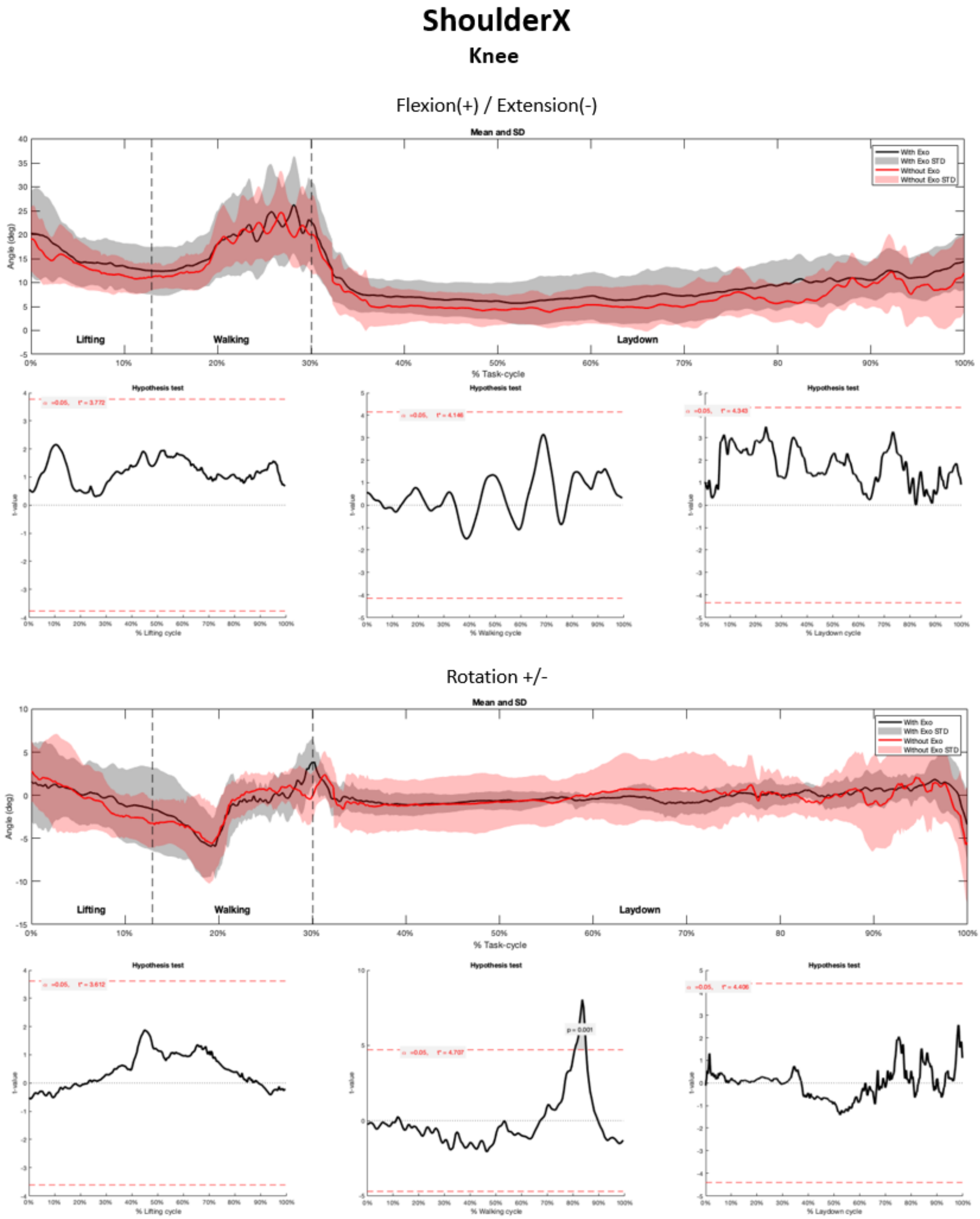
ShoulderX
Knee
Flexion(+) / Extension(-)
Mean and SD
With Exo
With Exo STD
Without Exo
Without Exo STD
Angle (deg)
Lifting
Walking
Laydown
% Task-cycle
Hypothesis test
t-value
% Lifting cycle
% Walking cycle
% Laydown cycle
Rotation +/-
Mean and SD
With Exo
With Exo STD
Without Exo
Without Exo STD
Angle (deg)
Lifting
Walking
Laydown
% Task-cycle
Hypothesis test
t-value
% Lifting cycle
% Walking cycle
% Laydown cycle

Figure 8.8

8.2 Ergonomic mapping

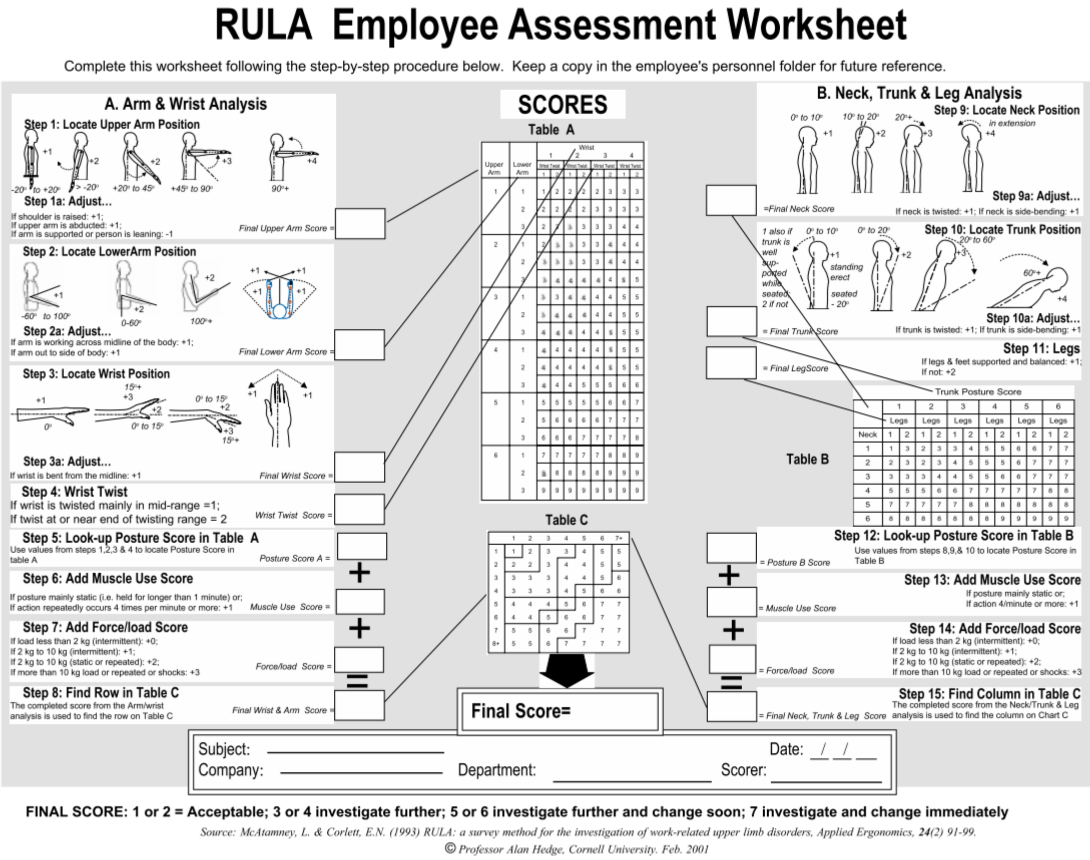

Figure 8.9: Rapid Upper Limb assessment(RULA) (McAtamney and Nigel Corlett 1993)

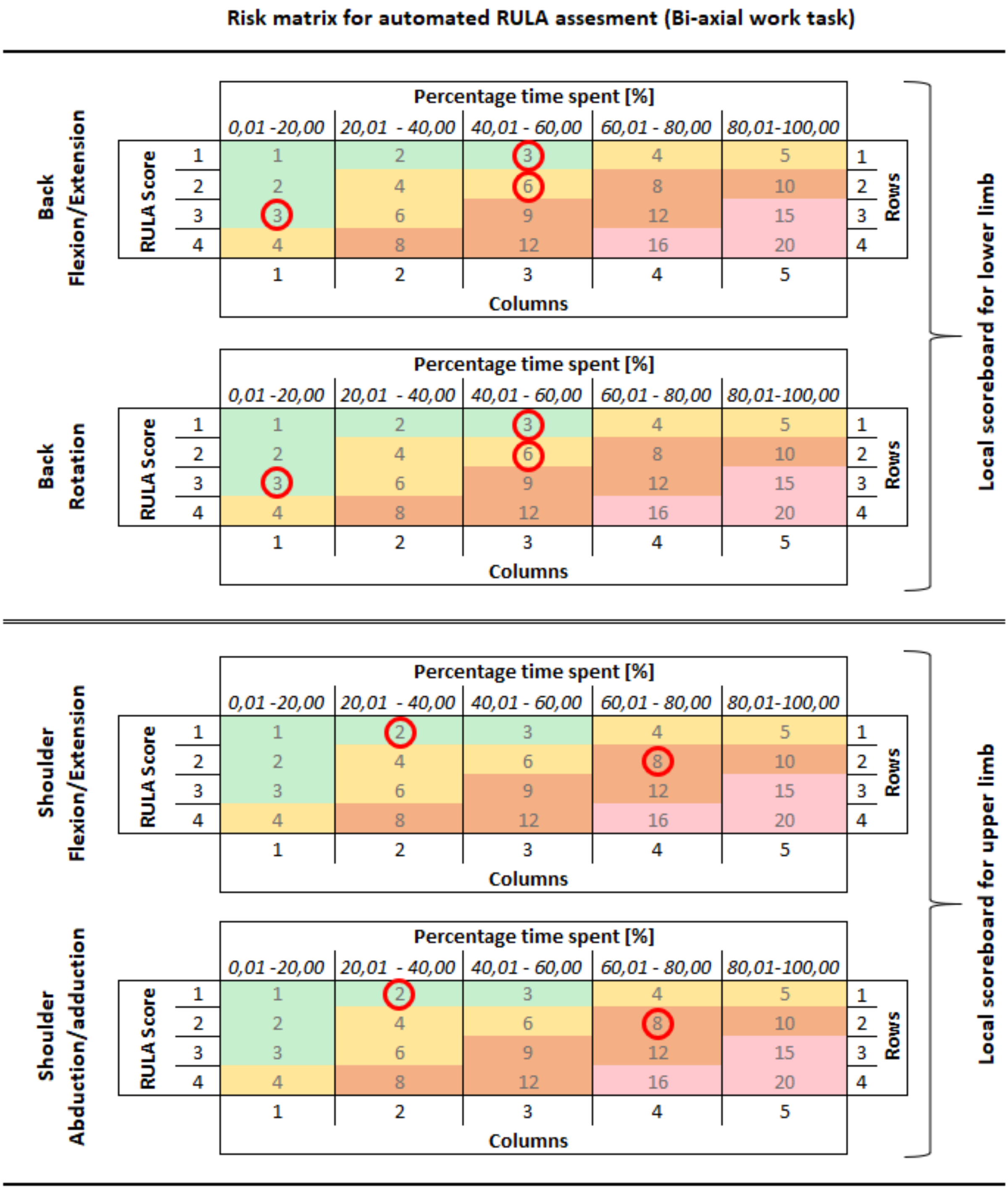

Figure 8.10: Show the risk matrix for the automated RULA assessment(Bi-axial work task). The matrix was divided in to sections, local score of back and shoulder. **Notice**: The segregation between body segments is done due to fact of knowing if the workers need a upper or lower limb exoskeletons, based on the action level suggestions, see table 2.2

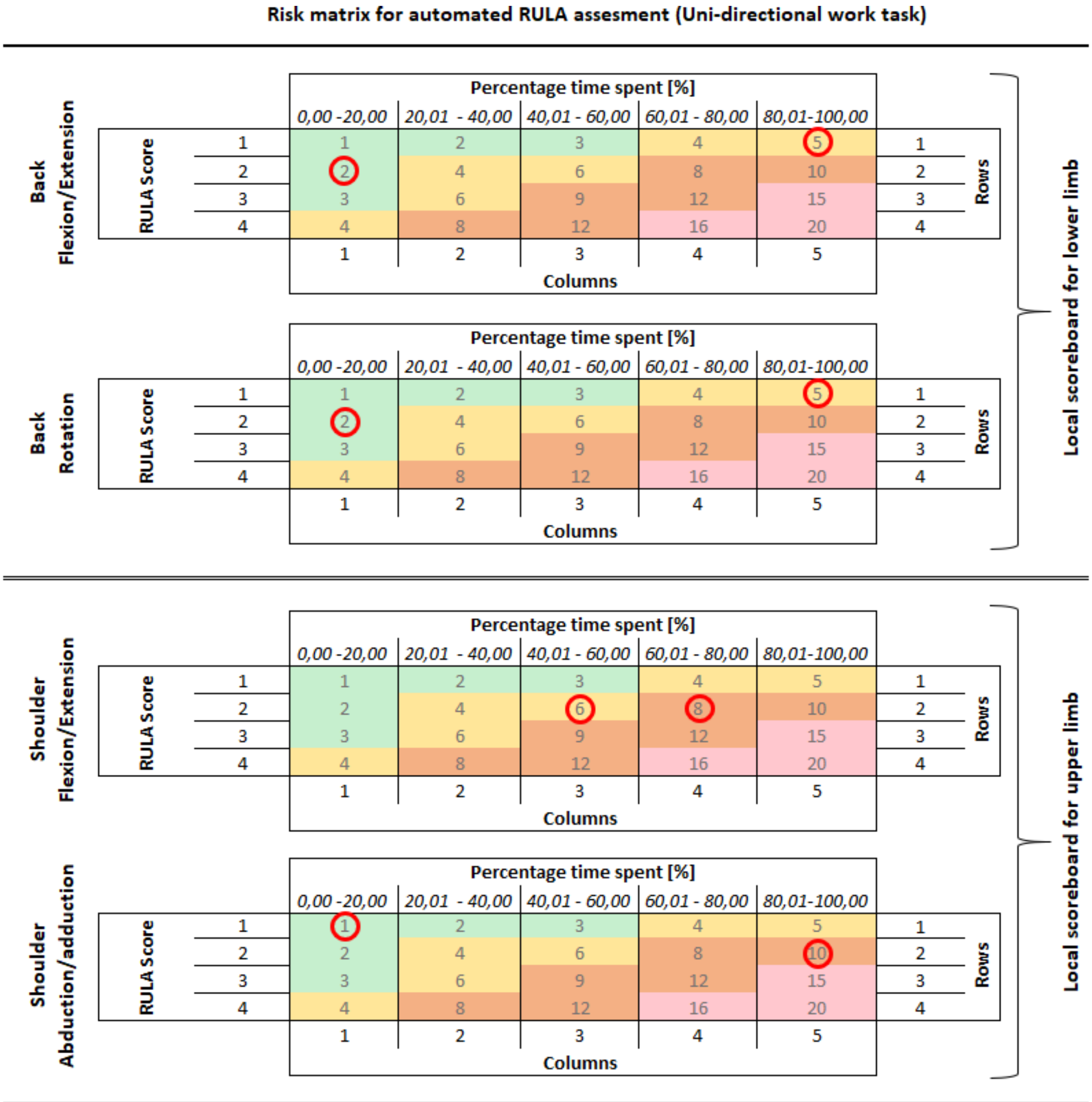

Figure 8.11: Show the risk matrix for the automated RULA assessment(Uni-directional work task). The matrix was divided in to sections, local score of back and shoulder. **Notice**: The segregation between body segments is done due to fact of knowing if the workers need a upper or lower limb exoskeletons, based on the action level suggestions, see table 2.2

8.3 Technical drawings

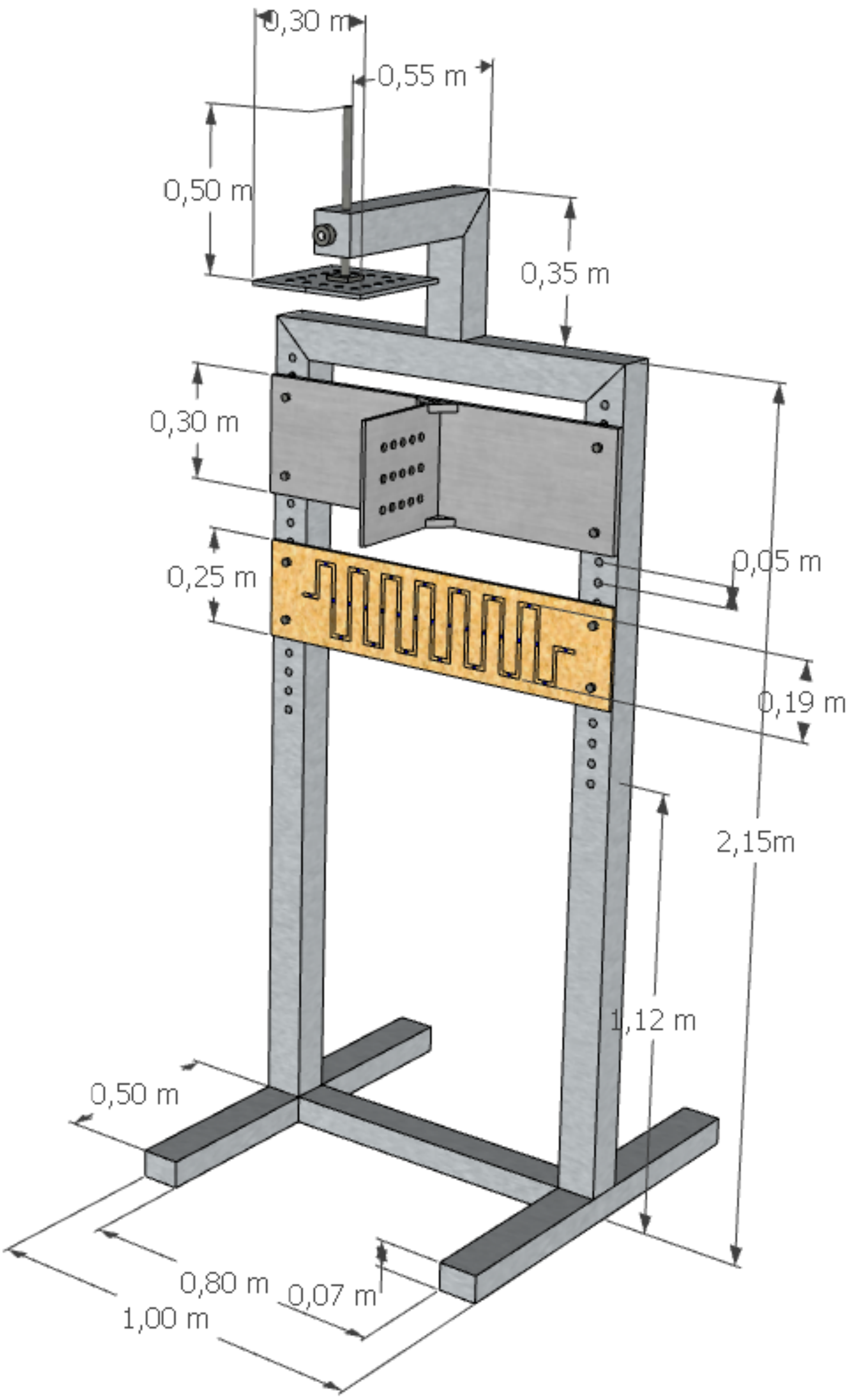

Figure 8.12: Technical drawing of test rack used for the quasi-dynamic upper limb test

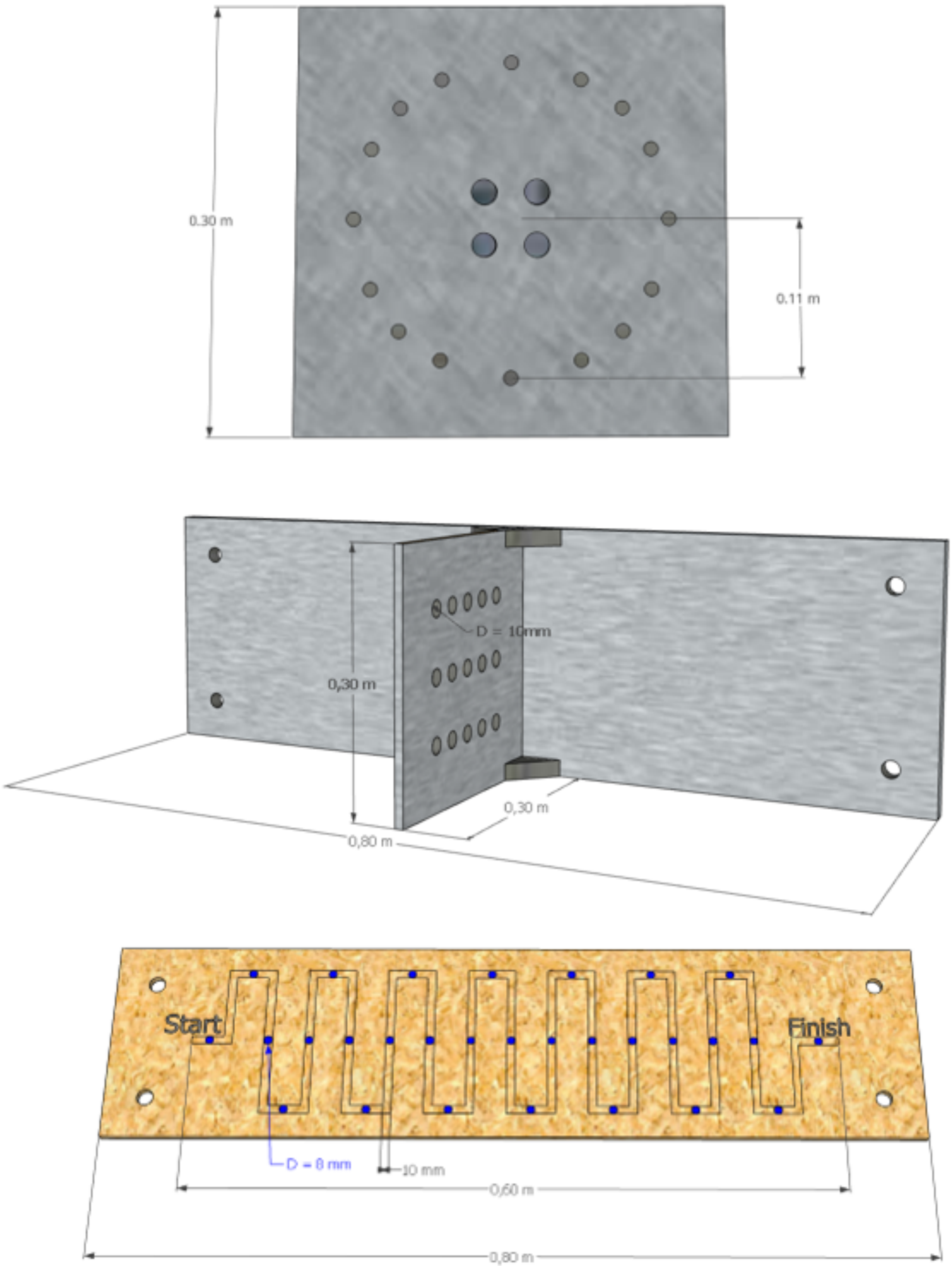

Figure 8.13: Technical drawing of all three levels used for the quasi-dynamic upper limb test

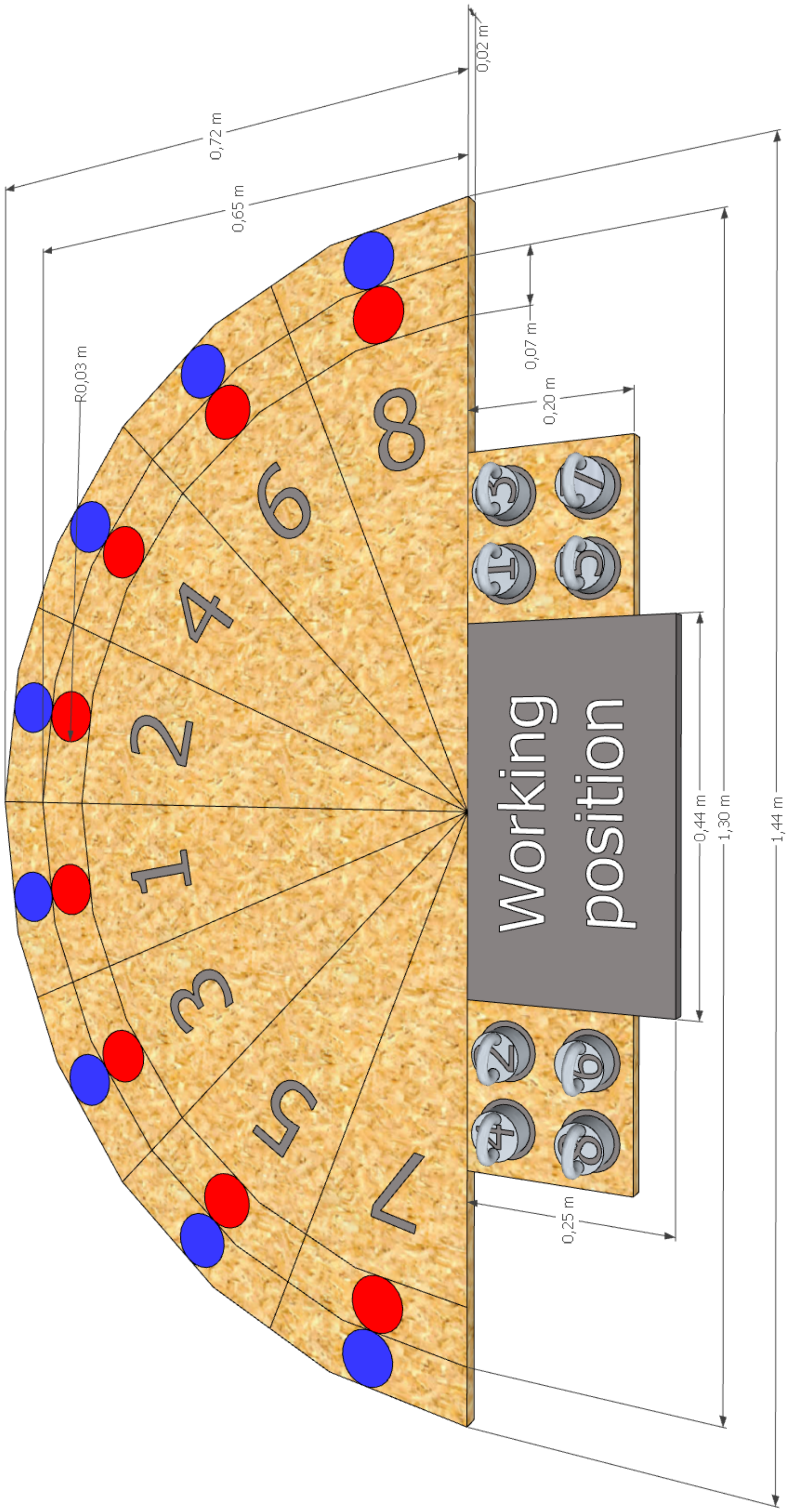

Figure 8.14: Technical drawing of quasi-dynamic lower limb test

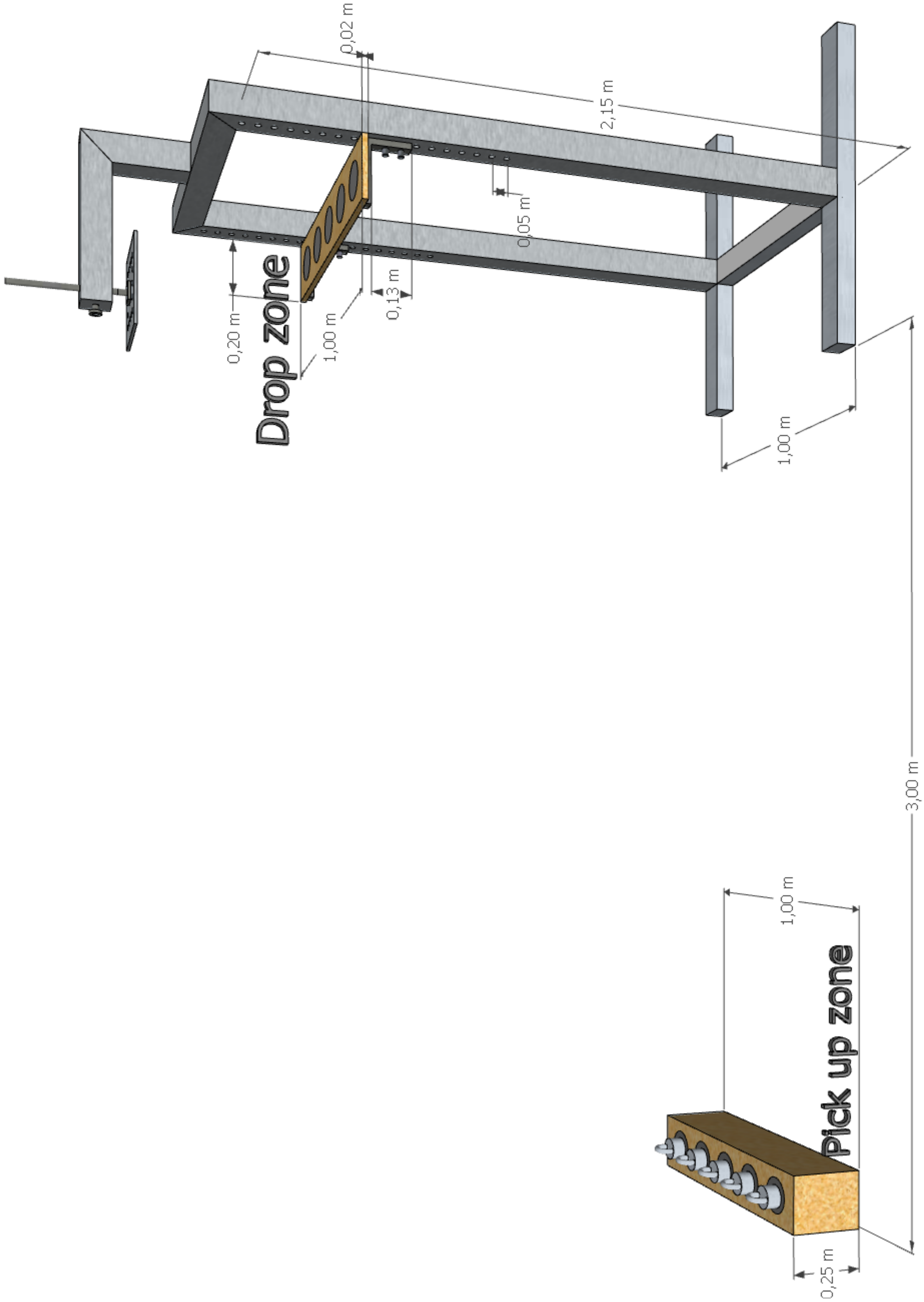

Figure 8.15: Technical drawing of quasi-dynamic upper limb test

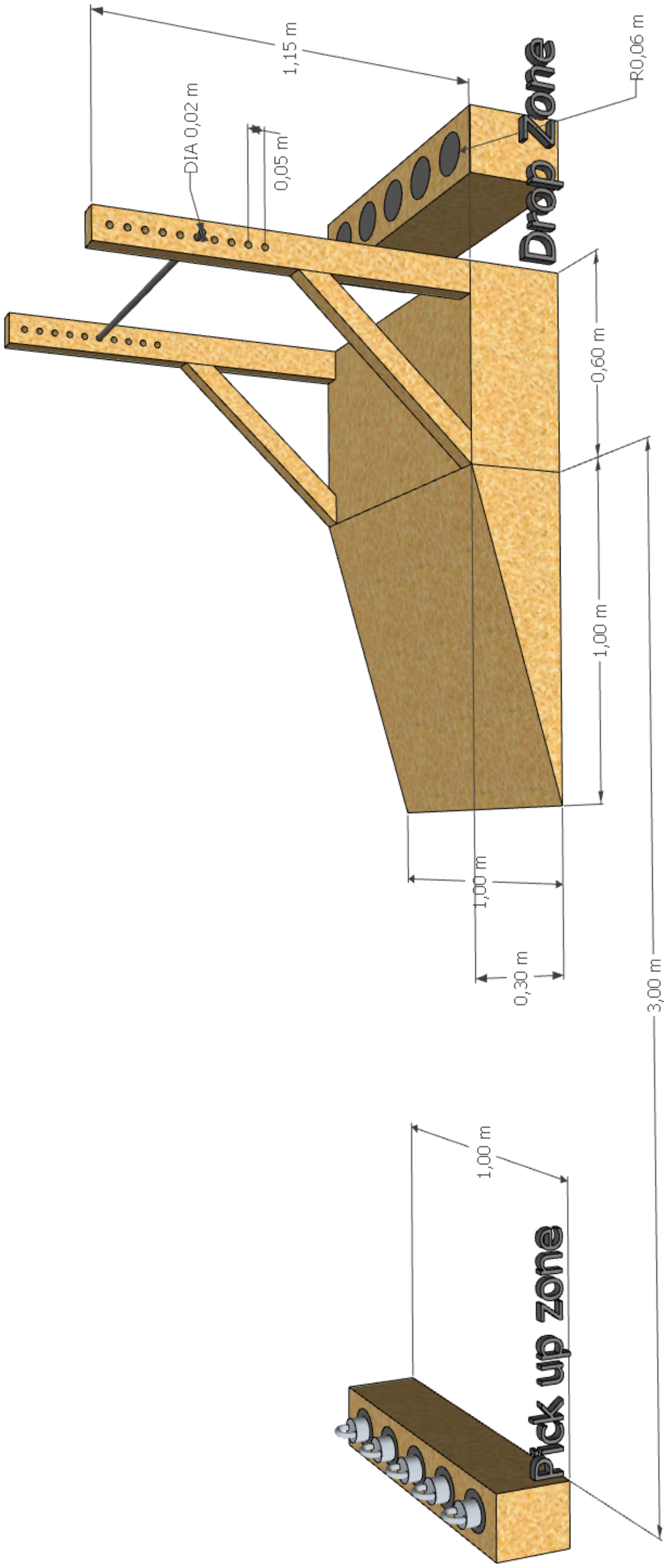

Figure 8.16: Shows the technical drawings of the dynamic lower limb test.

8.3.1 Test battery

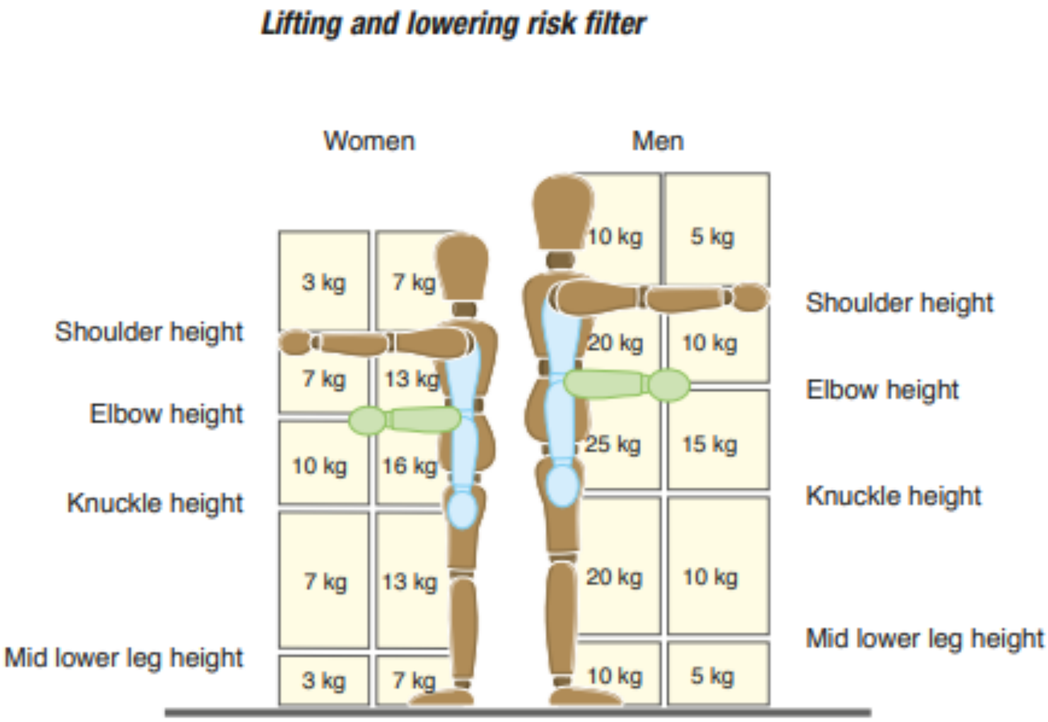

Figure 8.17: Illustration of recommended lifting/lowering loads [1]

8.4 Narrative

Passive occupational exoskeletons for lower body

	Name of exoskeleton	Reference	Title	Main findings (EMG)	Main findings (Kinematics)	Main findings (Performance)	Number of subjects	Research type	Citations
1	PLAD	Abdoli-Eramaki, Agnew, and Stevenson (2006)	*An on-body personal lift augmentation device (PLAD) reduces EMG amplitude of erector spinae during lifting tasks*	The amount of integrated electromyography reduction ranged from 14.4% to 27.6% for the lumbar and thoracic erector spinae respectively	No major kinematic differences were found when the lift assist device was worn for both posture and accelerations		9 male subjects	**Laboratory** Lifting in the sagittal plane, using freestyle, stoop, and squat postures	111
2	PLAD	Graham et al. (2009)	*Effectiveness of an on-body lifting aid at reducing low back physical demands during an automotive assembly task: Assessment of EMG response and user acceptability*	The mean percent difference across 10th, 50th and 90th percentiles for TES and LES was 27.52%.	The subjects did not change their trunk inclination angles when wearing the PLAD.		10 workers (8 male / 2 female)	**Field** Automotive assembly task. Included forward bending and static holds.	76
3	PLAD	Lotz et al. (2009)	*The effect of an on-body personal lift assist device (PLAD) on fatigue during a repetitive lifting task*	Muscular fatigue with PLAD (LES: 22% and TES:26%) Muscular fatigue without PLAD (LES: 104% and TES 88%) Muscle activation increased significantly from 20 min onward until the end of the session		The subjects were able to hold the isometric contraction 26% longer after wearing the PLAD during lifting. No significant increase in heart rate over time between conditions	10 male subjects	**Laboratory** 45-min lift trial. 20% of their maximum back extensor strength (540 repetitions)	54
4	BNDR	Ulrey and Fathallah (2013a)	*Subject-specific, Whole-body Models of the Stooped Posture with a Personal Weight Transfer*			Compression and shear forces at the L5–S1 level were reduced by 13% and 12% respectively. Internal loads in the leg joints were reduced between 10% and	18 subjects (11 male / 7 female)	**Laboratory** Static forward bending in three phases: Flexion, stoop and extension	30
5	BNDR	Ulrey and Fathallah (2013b)	*Effect of a personal weight transfer device on muscle activities and joint flexions in the stooped posture.*	Found a 23% reduction in peak LES and a 17% reduction in peak TES activity	Hip flexion increased by 11% and decrease in lumbar flexion of 9.0%		18 subjects (11 male / 7 female)	**Laboratory** Static forward bending in three phases: Flexion, stoop and extension	23
6	Laevo v1	Bosch et al. (2016)	*The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work*	Reductions in back muscle activity in the simulated assembly task, in the range of 35-38% when wearing the exoskeleton.	A systematic difference in lumbar flexion angle occurred: more lumbar flexion, by about 5%, was measured in the condition with the exoskeleton	Wearing the exoskeleton in our subject population increased endurance time from 3.2 to 9.7 min, respectively.	18 subjects (9 male / 9 female)	**Laboratory** Simulated assembly worktask and static holding (40 degrees bending)	96
7	Biomechanically assistive garment prototype	Lamers et al. (2017)	*Feasibility of a Biomechanically-Assistive Garment to Reduce Low Back Loading during Leaning and Lifting*	Reducing erector spinae muscle activity by an average of 23-43% during leaning tasks, and 14-16% during lifting tasks			8 subjects (7 male / 1 female)	**Laboratory** Sagittal plane manual handling tasks and static leaning	10
8	Laevo v1	Baltrusch et al. (2018)	*The effect of a passive trunk exoskeleton on functional performance in healthy individuals*			Wearing the exoskeleton, decreased objective performance in 7 out of 10 tasks. Tasks that involved hip flexion were perceived more difficult with the exoskeleton.	18 male subjects	**Laboratory** Test battery of 12 realistic working tasks in relation to NIOSH guidelines	34

Figure 8.18: Shows page 1 of 2 for lower limb exoskeleton studies.

9	Laevo V2	Koopman et al. (2019)	*Effects of a passive exoskeleton on the mechanical loading of the low back in static holding tasks.*	Significant reductions (11–57%) in back muscle activity.	Hip flexion was reduced with 9 degrees compared to without condition. No significant differences in lumbar flexion were found between device conditions.		11 male subjects	**Laboratory** Static forward bending in five different heights (0%-100%)	18
10	Laevo V2	Baltrusch et al. (2019)	*The effect of a passive trunk exoskeleton on metabolic costs during lifting and walking*	A significant increase in muscle activity of the m. rectus abdominus was found when walking with the exoskeleton. Muscle activity in the legs did not show any significant differences between conditions.	The average range of motion of the center of mass (COM) did not show a significant difference between the exoskeleton conditions. A reduction in stride length was found for the with condition	For walking, metabolic cost increased by 12% and 17 % for preferred walking speed. Significantly different walking speed, walks faster without the exoskeleton. (Without: 1.27m/s and with : 1.22m/s).	13 male subjects	**Laboratory** Lifting and Walking	5
11	Laevo V2.5/ BackX AC	Madinei et al. (2020)	*Biomechanical Evaluation of Passive Back-Support Exoskeletons in a Precision Manual Assembly Task: "Expected" Effects on Trunk Muscle Activity, Perceived Exertion, and Task Performance*	**BackX:** led to significant reductions in all three nEMG metrics in all the six supported conditions. **Laevo:** Significantly decrease in nEMG in only two of the six conditions		**Females:** significant increase in task completion time in both the unsupported and supported scenarios, by up to 0.7 and 1.2 s **Males:** no significant effect was found on manual sorting performance	18 subjects (9 male / 9 female)	**Laboratory** Simulated industrial assembly work, supported and unsupported at four levels: Waist, knee, ankle, below floor	0
12	Laevo V2.5/ BackX AC	Alemi et al. (2020)	*Effects of Two Passive Back-Support Exoskeletons on Muscle Activity, Energy Expenditure, and Subjective Assessments During Repetitive Lifting*	Significantly reduced peak activity of the trunk extensor muscles (by ~10%–28%). The reductions were larger in the symmetric versus asymmetric tasks		**Leavo:** Reduction in metabolic cost in the asymmetric standing (5.5%) and symmetric kneeling tasks (10.8%). **BackX:** Reductions in the symmetric standing (~12.6%) and asymmetric kneeling (~6.2%)	18 subjects (9 male / 9 female)	**Laboratory** Simulated industrial lifting/lowering task from standing and kneeling position for symmetric and asymmetric conditions.	0
13	SPEXOR	Baltrusch et al. (2020)	*SPEXOR passive spinal exoskeleton decreases metabolic cost during symmetric repetitive lifting*	The SPEXOR device reduced back muscle activity by 10–16%, indicating that less muscular efort was needed to perform the lifting task	Kinematics did not change signifcantly	Wearing the exoskeleton signifcantly decreased the net metabolic cost of lifting by 18%. The exoskeleton took over 18–25% of joint work at the hip and L5S1, but it´s was signifcant due to large variation.	11 male workers	**Field** luggage handling task (KLM): lift and lower a box of 10 kg	0
14	MeBot-EXO	W. Wei et al. (2020)	*The effects of a passive exoskeleton on muscle activity and metabolic cost of energy*	35% reduction of muscle MVE for the LTLES, a 40% reduction for the RTLES, a 61% reduction for the LTTES, a 57% reduction for the RTTES with the exoskeleton		Metabolic cost of energy during the static holding posture was significantly lower (by 22%) when wearing the exoskeleton	8 male subjects	**Laboratory** Lifts executed in the sagittal plane and static holding posture	0

Figure 8.19: Shows page 2 of 2 for lower limb exoskeleton studies.

Passive occupational exoskeletons for upper body

	Name of exoskeleton	Reference	Title	Main findings (EMG)	Main findings (Kinematics)	Main findings (Performance)	Number of subjects	Research type	Citations
1	WADE	Rashedi et al. (2014)	*Ergonomic evaluation of a wearable assistive device for overhead work*	Wade use decrease nRMS for right Anterior Deltoid (~25-50%) and increase nRMS for right iliocostalis lumborum pars lumborum (~31-88%).			12 male subjects	**Laboratory** Overhead work	53
2	Prototype (EksoVest)	Kim, S. Nussbaum, M. (2018)a	*Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I – "Expected" effects on discomfort, shoulder muscle activity, and work task performance*	The exoskeletal vest reduced the peak and median muscle activity of several shoulder muscle groups by up to ~45% and ~50%		Drilling task completion time decreased by nearly 20% with the vest, but the number of errors increased	12 subjects (6 male / 6 female)	**Laboratory** Work simulation. Repetitive drilling and light assembly	45
3	Prototype (EksoVest)	Kim, S. Nussbaum, M. (2018)b	*Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part II – "Unexpected" effects on shoulder motion, balance, and spine loading*	Reduced spine loading (up to ~30%)	Max. shoulder flexion and abductions angles were reduced by roughly 2.6% and 10%, respectively.		27 subjects (14 male / 13 female)	**Laboratory** Overhead work and shoulder work in different heights	32
4	EXHAUSS Stronger	Theurel, J. Desbrosses, K. (2018)	*Physiological consequences of using an upper limb exoskeleton during manual handling tasks*	Significant lower activity for Anterior Deltoid for with exo. No significant activity for Erector Spinae Longissimus.	With exo increased a higher elbow flexion and a smaller flexion and rotation of the shoulder.		8 subjects (4 male / 4 female)	**Laboratory** Performing three modalities of handling tasks, lifting in a sigital plane.	35
5	Robomate	Huysamen et al. (2018)	*Evaluation of a passive exoskeleton for static upper limb activities*	Reduce muscle activity in Biceps Brachii (49%), Medial Deltoid (62%) and Rectus Abdominis (13%).			8 subjects (4 male / 4 female)	**Laboratory** Overhead work. Stand upright and with arms at 90 deg.	31
6	Steadicam Fawcett Exoskeletal vest	Weston et al. (2018)	*Biomechanical evaluation of exoskeleton use on loading of the lumbar spine*	The exoskeletaldevice increased both peak and mean muscle forces in the torso extensor muscle. Peak and mean compressive spinal loads were also increased up to 52.5% and 56.8%			12 male subjects	**Laboratory** Carrying light tool 100% of stature height and heavy tool 50% stature of height	32
7	ShoulderX v2	Van Engelhoven, L. et al. (2019)	*Experimental Evaluation of a Shoulder-Support Exoskeleton for Overhead Work: Influences of Peak Torque Amplitude, Task, and Tool Mass*	Overall reductions in muscle shoulder muscle activity. 5 Nm load (22% reduction) and 10 Nm load (38% reduction)			14 male subjects	**Laboratory** static and repetitive overhead tasks using light and heavy tools	1
8	PAEXO (Ottobock)	P. Maurice et al. (2019)	*Objective and Subjective Effects of a Passive Exoskeleton on Overhead Work*	54% decrease in Anterior Deltoid with exo. 30% increase from first to last block without exo.	Arm abduction increase from 7.9 to 9.9 degrees. In general the exoskeleton affects the shoulder movements by increasing the degrees at start position.	33% lower oxygen consumption with exo, and 19% lower heart rate with exo.	12 male subejcts	**Laboratory** Overhead exercise	1

Figure 8.20: Shows page 1 of 2 for upper limb exoskeleton studies.

9	EksoVest	S. Kim and M. A. Nussbaum (2019)	*A Follow-Up Study of the Effects of An Arm Support Exoskeleton on Physical Demands and Task Performance During Simulated Overhead Work*	reduced peak and median normalized muscle activity levels, respectively, by up to 52.5% and 60.6% for the shoulder, and 29% and 16% for the lower trunk		No significant main or interaction effects were found on task completion time. Fewer drilling errors (up to 92% reduction)	12 subjects (6 male / 6 Female)	**Laboratory** Work simulation. Repetitive drilling and light assembly	6
10	Levitate (Airframe)	J. Gillette and M. Stephenson (2019)	*Electromyographic assessment of a shoulder support exoskeleton during on-site job tasks*	**Overall:** EMG amplitudes were reduced overall with the exoskeleton, but not significant. **Beginning of Shift vs. End of Shift:** EMG amplitude was significantly increased for the anterior deltoid (without condition) and not for the with condition.			6 workers (4 male/ 2 female)	**Field** Agriculture manufacturing tasks (John deere): Assembly, welding, painting and parts handling	3
11	SkelEx	A. De Vries et al. (2019)	*The Amount of Support Provided by a Passive Arm Support Exoskeleton in a Range of Elevated Arm Postures*	Reduction in EMG amplitude was highest at VE 60 degrees (mean difference of 3.4% MVC). An increase in amplitude for the LT muscle as a result of wearing the exoskeleton at the vertical arm elevation angle of 150 degrees		The supportive moment provided by the exoskeleton (0.5–6.1 Nm; up to 56% of the required moment) implied a significant reduction to the shoulder moment that needed be generated by the subject.	12 male subjects	**Laboratory** Task performed in Five different vertical arm elevation (VE) angles and three horizontal abduction(Hab) angles.	1
12	PAEXO (Ottobock)	Schmalz, T. Schändlinger, J. (2019)	*Biomechanical and Metabolic Effectiveness of an Industrial Exoskeleton for Overhead Work*	T1, mean amplitude reduction between 61% and 22%. T2, semi-static reduction between 48% and 22%.	increased shoulder abduction in T1 & T2 (6° & 8°). During T2 semi-static task, mean elbow flexion increased (7°).	No significant foundings for metabolic parameters.	12 subjects (6 male / 6 female)	**Laboratory** Overhead work. T1: screwing nuts. T2: Drilling with electrical drill.	0

Figure 8.21: Shows page 2 of 2 for upper limb exoskeleton studies.