THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

# Development, application, and reliability of methods for ergonomic workload assessments in production evaluation and workstation design

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## SUMMARY

Ergonomics assessments of conditions for humans at workstations and in manufacturing processes are necessary to prevent work-related musculoskeletal disorders and enhance efficiency and quality. Many methods can be used for this from systematic observations to direct measurements and simulation. Investigations of the accuracy and reliability of many methods as well as comparisons between them have been performed, but there is still need for further work as well as development of new methods.

The inter- and intra-rater reliability of the OCRA checklist was studied through eleven ergonomists' risk-assessments of ten video-recorded work tasks on two occasions. The statistical analysis included several parameters of reliability of which Cohen's linearly weighted kappa was the primary measure. The inter-rater agreement of the OCRA checklist was 39%, and the weighted kappa was 0.43; the intra-rater dittos were 45% and 0.52. This indicated that the OCRA checklist is a moderately reliable tool.

A risk assessment approach for digital human modelling (DHM) was developed. The approach included a reference database of epidemiological relationships between directly measured exposure and related musculoskeletal disorders. For illustration, a case in manual assembly was simulated; exposures were calculated and compared to the reference data to indicate the risk of WMSDs. The application and detailed assessment would be helpful to prioritise among different design solutions.

A 3D digital prototype laparoscopic robotic console was ergonomically evaluated using the DHM tool IMMA with 12 manikins representing anthropometries of the Swedish and US population. Work-ranges of the console and the manikins were calculated, compared and ergonomically assessed using the Swedish standards and a US checklist for computer work. The assessment criteria related to the adjustable ranges of the screen height, height of the armrest, adjustable range of the pedals were not fulfilled. The DHM tool IMMA provides the possibility for a pre-production assessment of static work tasks.

**Keywords:** Ergonomics, Risk assessment, Reliability, Systematic Observation, Direct measurement, Simulation, Digital Human Modelling, Workplace Design, Work-related Musculoskeletal Disorders, Biomechanical Exposure

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# LIST OF PAPERS

This thesis is based on the following papers, referred to in the text by their Roman numerals.

I.     Rhén, I.-M., Forsman, M., 2020. Inter- and intra-rater reliability of the OCRA checklist method in video-recorded manual work tasks. Applied Ergonomics 84, 103025.

II.     Rhén, I.-M., Forsman, M., Örtengren, R., Högberg, D., Keyvani, A., Lämkull, D., Hanson, L., 2018. Ergonomic risk assessment in DHM tools employing motion data-exposure calculation and comparison to epidemiological reference data. International Journal of Human Factors Modelling and Simulation 6, 31-64.

III.     Fan, X., Rhén, I.-M., Kjellman, M., Forsman, M., 2018. Ergonomic Evaluation of a Prototype Console for Robotic Surgeries via Simulations with Digital Human Manikins, Congress of the International Ergonomics Association. Springer, pp. 351-363.

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# 1. INTRODUCTION

## 1.1 Systematic work environment management

According to the International Ergonomics Association, ergonomics is defined such as "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimise human wellbeing and overall system performance" (IEA, 2021). Briefly, ergonomics is generally described such as "the process of designing or arranging workplaces, products and systems so that they fit the people who use them". In recent years, the concept "human factors" has become frequent as a synonym to ergonomics.

Ergonomics applications are commonly based on anthropometric, physiological and psychological principles for construction and design of products, processes and systems. The field is interdisciplinary and includes knowledge within e.g., anatomy, physiology, biomechanics, engineering, industrial design, anthropometry and visual design, in order to adapt, optimize, assess and evaluate human performance (Bridger, 2008; IEA, 2021; ISO, 2011).

Within ergonomics research, human behaviour, physical as well as cognitive and organizational, is studied in relation to the design of devices, equipment and processes, to prevent unnecessarily tiring workloads and to ensure a safe and productive workplace. To ensure that e.g. tasks, environment and information fit the user and to investigate limitations and opportunities in the work and in the work environment, ergonomists or human factor specialists consider job activity as well as user demands, equipment -in terms of physical design such as size and tangibility, and how information is accessed and presented.

The enforcement of existing health and safety regulations and guidance on good practice may largely prevent or reduce the occurrence of work-related musculoskeletal disorders (WMSDs). There are several relevant European directives regarding occupational safety and health, including Directive 89/391 (Commission, 1989), which provides a general framework for risk identification and prevention. There are also European standards regarding i.a. ergonomics principles and requirement for the design of work systems and work environments (CEN).

Since Sweden is a member of the European Union, Sweden's Work Environment Act is based on the EC Directive on the introduction of measures to encourage improvements in the safety and health of workers (89/391 /EEC). The act requires that all employers must have a work environment policy and manage the work environment in a systematic way (SWEA, 2001).

Thus, the systematic work environment management may be described as a method to obtain a better work environment, and is based on the employers', the employees' and the safety representatives' regular work to map risks, i.e. the likeliness, for work-related ill health and accidents and their collaboration for risk-prevention. The general aims are to prevent employees from suffering from work-related ill health, accidents or injuries because of their work, and to create a pleasant and creative work environment that contributes to productivity and personal development.

In practise, the systematic work environment management involves the four following steps:

1. *Examination:* by examining and compiling information about the physical, psychological and social working conditions, work and tasks associated with risk of ill health, accidents and incidents are identified.

2. *Risk assessment*: the identified risks are assessed with regard to the probability of ill health or that accidents may occur, and the consequence thereof.

3. *Actions:* in cases of unacceptable risks, actions are taken in order to eliminate or reduce the risk or to otherwise provide an opportunity to manage the risk.

4. *Control*: in the follow-up of the actions carried out, the effect of the actions is controlled. If the effect is not as desired, or if new risks have been identified, additional or new actions may be needed.

The systematic work environment management is generally illustrated as a wheel (see Figure 1) because of the ongoing process. The work should be followed up annually and performed in situations of operational changes, in the event of serious situations at the workplace, or when an employee has been injured or suffer from ill health because of work-related issues. The risk-assessment and the prioritizing of actions should be documented in writing. The employer is responsible for the follow-up control of the work, which include the evaluation of actions undertaken to reduce risks as well as the evaluation of the systematic work environmental management at the workplace.
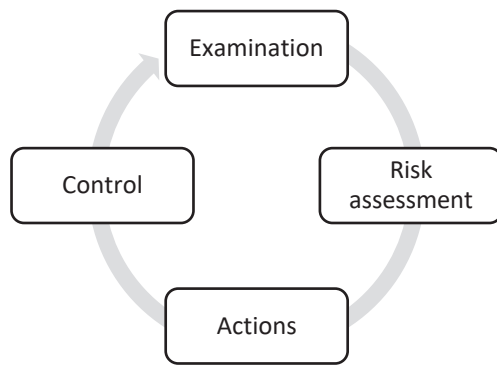
**Figure 1.** The systematic work environment management's ongoing process

## 1.2 Work-related musculoskeletal disorders

Work-related musculoskeletal disorders (WMSDs) are one of the leading causes of ill health, sick leave, early retirement and productivity loss in Europe (European Union member states). More than a third of the working population report work-related ill health, of which just over half is due to WMSDs (EU-OSHA, 2019). For the individual, the consequences of WMSDs include reduced quality of life and income loss while business sector and society are primarily faced with direct costs, such as compensation for care and medication, and indirect costs for production loss (EU-OSHA, 2010). Costs arising from loss of productivity due to WMSDs are estimated at up to 2% of Gross National Product, of which costs for e.g. back pain, which is a common work-related musculoskeletal disorder, amount to more than EUR 12 billion per year (Stephen et al., 2009).

Musculoskeletal disorders include a range of degenerative and inflammatory conditions that primarily affect muscles, tendons, cartilage, nerves and bursa (Hagberg, 1995; Putz-Anderson, 2017), which may result in functional impairment and pain, primarily in the back, neck and the upper limbs. If such disorders are caused or aggravated primarily by the work or by the work environment, they are characterized as work-related musculoskeletal disorders (WMSDs) (EU-OSHA, 2019).

## 1.3 Risk factors for WMSDs

Certain work activities and environments have been shown to significantly contribute to WMSDs. For example, work sectors such as the construction, forestry and fishing, report higher prevalence of WMSDs than e.g., recreation, art and financial sectors (EU-OSHA, 2019; Van Rijn et al., 2010).

Risk factors well associated with the WMSDs development and aggravation have been shown to be primarily of biomechanically stressful nature, such as awkward postures, high muscular load, repetitive movements (Bernard, 1997; Buckle and Devereux, 2002; Da Costa and Vieira, 2010; Kuorinka et al., 1995; Punnett, 2014) and vibrations (Charles et al., 2018), although an association to psychosocial stress (Bongers et al., 1993; Devereux et al., 2002; Gerr et al., 2014; Hauke et al., 2011) and organizational work factors, such as opportunity for rest allowances, variation in work performance and recovery time, have turned out to interact in the development of WMSDs (Mathiassen, 2006; Srinivasan and Mathiassen, 2012).

Below, primary risk factors for biomechanical exposure are described more in detail together with examples of dose-response associations.

### 1.3.1  Awkward postures

An awkward posture may be defined such as a posture where the joint deviate widely from a relaxed neutral position. Work in such positions means that the joint, together with surrounding structures such as muscles, cartilage and nerves, being loaded in an unfavourable way (Mackinnon and Novak, 1994). Work in awkward postures is often accompanied with static exposure, i.e. when the muscles are tensed over longer periods in order to maintain a certain posture, which affects the possibility for muscular relaxation. The lack of alteration between muscular contraction and relaxation, which normally act as a circulation pump, has a negative effect on the peripheral blood circulation, which in turn may lead to e.g. muscle weakness and nerve pain.

- Numerous studies confirm the association between extended time in trunk flexion or rotation and low back pain (Coenen et al., 2016; Da Costa and Vieira, 2010; Griffith et al., 2012; Ribeiro et al., 2012) or/and pain in the neck and the shoulders (Mayer et al., 2012; SBU, 2012).

- Prolonged neck flexion or rotation has been associated with an increased risk of neck pain (Ariëns et al., 2002; Coenen et al., 2016; Palmer and Smedley, 2007) and Petit et al. (2014) specified an association between disorders of the neck and neck flexion >4 hours a day for women.

- Prolonged work with elevated arms, often defined such as hand above shoulder level, has been related to pain in the neck and the shoulder (Coenen et al., 2016; Hanvold et al., 2015; Mayer et al., 2012; van der Molen et al., 2017; Van Rijn et al., 2010). In a prospective study of 3710 French workers, Petit et al. (2014) found that sustained or repeated arm abduction >60° and >90° >2 hours/day, were strongly associated with neck disorders, while Roquelaure et al. (2011), using the same material, identified an association between sustained or repeated arm abduction (≥2 h/day) >90° (men) and >60° (women) and the risk of rotator cuff syndrome. Van Rijn et al. (2010), in turn,

concluded from a systematic review, an association between upper-arm flexion ≥45° in 15% of the work time and subacromial impingement syndrome.

- Work in non-neutral positions of the elbow, such as extended elbows, has been reported as an elevated risk for nerve entrapment in the forearm and radial tunnel syndrome (van Rijn et al., 2009a). In a prospective study, Herquelot et al. (2013) found an association between elbow flexion/extension in combination with hard perceived physical exertion (>2 hr/day) and the development of elbow pain and lateral epicondylitis. Seidel et al. (2019) confirm such an association, by concluding, from a systematic review, that forearm supination ≥45° and ≥5% of time in combination with forceful lifting, is a risk factor for the development of lateral or medial epicondylitis as well as neuropathy of the elbow.

- Extended work with flexion/extension of the wrist has been proven as an increased risk of carpal tunnel syndrome (Da Costa and Vieira, 2010; Roquelaure et al., 2020; Spahn et al., 2012; Van Rijn et al., 2009b). Such exposure >2 h/day in combination with perceived physical exertion has also been reported as a risk for elbow pain and lateral epicondylitis (Herquelot et al., 2013).


## 1.3.2 Considerable muscular force

Physically demanding work such as manual material handling (including lifting, carrying, pushing and pulling) require high tension of muscles often related to a certain location of the body. In general, the work is dynamic, i.e. the muscle length and hence the power exerted alter during the contraction. However, both acute overload such as single peak load, as well as cumulative load, i.e. prolonged repeated loads or continuous long-term loads with few rest periods, may imply unfavourable load on muscles, tendons and their attachment to the skeleton resulting in potential organ damage and degenerative diseases (Seidler et al., 2009).

There is a proven increase in the risk of pain in the back, neck, shoulders, elbows and wrists due to physically demanding work and work including manual handling (Bonfiglioli et al., 2013; Burt et al., 2011; Burt et al., 2013; Coenen et al., 2014; Da Costa and Vieira, 2010; Garg et al., 2012; Mayer et al., 2012; Roquelaure et al., 2011; SBU, 2012, 2014; Seidler et al., 2009; van Rijn et al., 2009a).

- Hoogendoorn et al. (2002) demonstrated an association between number of lifts >25 kg and sick leave due to low back pain while Skovlund et al. (2020) showed that physical high demands of the back such as bending/twisting for more than a quarter of the workday was associated with lower work ability among workers with musculoskeletal pain.

- Force requirements such as lifting ≥50 kg/h at or above shoulder level has been associated with an elevated risk for neck, shoulder and arm pain (Andersen et al., 2007) while handling loads >20 kg at least 10 times a day, or force requirements >10% maximal voluntary contraction (MVC) have been associated with subacromial impingement syndrome of the shoulder (van Rijn et al., 2010).

- The handling of loads >20 kg at least 10 times a day also has been associated with lateral and medial epicondylitis of the elbow (van Rijn et al., 2009a). Repeated handling of loads >5 kg (2 times/min) for at least 2 hours a day has been revealed as a risk for medial epicondylitis of the elbow, while the handling of tools >1 kg, has been associated with both lateral and medial epicondylitis. In addition, an association has been shown between handling of load >1 kg and radial tunnel syndrome (van Rijn et al., 2009a).

- Forceful hand exertions ≥1 hour/day have been related to the development of impingement syndrome (Van Rijn et al., 2010) and a general hand force >4 kg has been associated with carpal tunnel syndrome (CTS) (Spahn et al., 2012; Van Rijn et al., 2009b). Van Rijn et al. (2009a) demonstrated an association between powerful grips >1 h/day and medial epicondylitis while Roquelaure et al. (2020) showed that holding tools/objects using a pinch grip was related to the risk of developing carpal tunnel syndrome.

### 1.3.3  Repetitive movements and high movement velocities

Repetitive work can be described as movements of similar character, which are performed over and over. The duration of each work moment is short or highly repeated, defined by Silverstein et al. (1986) such as a cycle time <10 seconds or as performing the same movement > 50% of the cycle time. High joint angular velocity is an exposure that is closely related to repetitive work (Nordander et al., 2008).

Performing the same movements means a repeated use of the same structures, e.g. muscles, nerves and tendons, which if the work goes on for a long time, may lead to overuse injury of the involved structures (Barbe et al., 2003). Moreover, repetitive work that requires hand-finger precision may cause increased and static tension in the arm and neck-shoulder region to stabilize the arm. The lack of recovery and variation may be a risk for WMSDs. Another consequence of precision-work is the requirement for good eyesight, which can lead to an extended forward-bent head position with neck problems as a result.

Repetitive movements and high velocities as risk factors for WMSDs are predominantly related to disorders of the upper limb and the neck (Andersen et al., 2007; Nordander et al., 2008). However, several studies have also shown a correlation between high trunk motion

velocities and low-back pain (Andersen et al., 2007; Davis and Marras, 2000; Fathallah et al., 1998). Some risk levels have been identified:

Working with repetitive shoulder movements has been associated with neck disorder and chronic neck pain (Palmer and Smedley, 2007) as well as impingement (van Rijn et al., 2010) and rotator cuff syndrome of the shoulder (defined for repetitiveness ≥4h/day (Roquelaure et al., 2011).

- Repetitive arm movements >2 h/day has been reported as a risk factor for lateral and medial epicondylitis of the elbow (van Rijn et al., 2009a).

- Carpal tunnel syndrome, which is the most frequently reported disorder from hand/wrist repetitiveness (Latko et al., 1999; Palmer and Smedley, 2007; Spahn et al., 2012; van Rijn et al., 2009b), has been associated with repetitive work with cycle time <10 seconds, or repeating the same movements >50% of cycle time. Another reported effect of hand/wrist repetitive work (≥2 hours/day) is impingement syndrome of the shoulder (van Rijn et al., 2010).

- High velocity is an effect of high repetitivity, which has been shown as a risk factor for WMSDs (Lund et al., 2019; Nordander et al., 2008). Recently, quantitative dose-relationship has been demonstrated between velocity of the head, upper arm and the wrist and work-related complaints and diagnoses of neck/shoulder and elbow/hands (Balogh et al., 2019). For example, a median wrist flexion/extension velocity above 20 degrees per seconds over a full work days has been related to an increased risk of WMSDs (Arvidsson et al., 2021; Balogh et al., 2019).

## 1.3.4 Combined physical exposures

It is difficult to distinguish between single triggering factors for WMSDs and multiple factors. Rarely, one single exposure occurs without influence of other exposures (Barbe et al., 2013; Gallagher and Heberger, 2013). Moreover, a combination of physical workloads has been associated with an increasingly higher risk of long-term WMSDs (Andersen et al., 2016). For example, evidences suggest a possible interdependence between force and repetition and the risk of WMSDs. Repetitive work in combination with low-forces seems to lead to a moderate increase in WMSDs risk, while the combination repetitiveness and high-forces highly increases the risk (Gallagher and Heberger, 2013). Similarly, the combination of repetitive work and forceful grip has been associated with e.g. carpal tunnel syndrome (Kapellusch et al., 2014). Other exposure combinations have been identified for repetitive work and neck flexion and the associated chronic neck pain (Palmer and Smedley, 2007). Biomechanical factors combined with psychosocial factors in turn have shown to increase the risk of developing WMSDs multiple times (Devereux et al., 2002; dos Santos Leite et al., 2019). Although interactions between different risk exposures have been demonstrated, risk factors

in the physical work environment are typically evaluated individually which means that the combined effect of the exposures is rarely considered. However, today, there are few dose-response associations stated between such combined exposures and the development of ill health (Andersen et al., 2016).

Vibrations are mechanical oscillating movements of fixed objects which can be transferred to the human while e.g., standing, sitting or lying on a vibrating surface (whole-body vibrations) or when working with vibrating tools (hand-arm vibrations). In whole-body vibrations, the repeated shocks may affect discs, joints, tendon- and muscle attachments of the spine, with degenerative changes as a result, while hand-arm vibrations primarily involve a risk of peripherally vascular damage which can result in an impaired hand function. Exposure to whole body vibrations and hand-arm vibrations are significantly associated with risk of musculoskeletal disorders of the spine and neck/shoulders respectively hand/arms (Charles et al., 2018; Engholm and Holmström, 2005; Johanning, 2015; Merlino et al., 2003; Van Rijn et al., 2010). However, generally, subjects that are exposed to vibrations are also often simultaneously exposed to a number of other risk factors for WMSDs, such as long-term static or awkward postures (Antle et al., 2018; Charles et al., 2018) or heavy lifting (Palmer et al., 2012), which makes it difficult to discriminate the importance of covariating factors in the WMSDs development.

### 1.3.5  The multifactorial and complex aetiology of WMSDs

The aetiology of WMSDs is multifactorial. Although mechanisms for WMSDs can be described as a result of tissue overexertion resulting in injury or damage (Chaffin et al., 2006), it is difficult to distinguish the effects of work-related exposure from similar exposure at leisure-time (Hämmig et al., 2011).

Physical activity relates to body movements that are produced by skeletal muscles with increased energy consumption as a result. High physical activity at leisure-time is associated with improved health and reduced risk of mortality due to positive effects on e.g. heart, vessels, skeletal muscles, blood fats and blood pressure (Holtermann et al., 2018; Warburton et al., 2006). As a paradox, high physical activity at work is associated with ill health and mortality (Coenen et al., 2017; Holtermann et al., 2018).

However, although there has been an increase in sedentary jobs and a decrease in physically demanding jobs, the development of WMSDs has continued since the 1980s (Lim et al., 2016). Sedentary work generally relates to inactivity of larger muscle groups such as the core and legs, and higher muscle activity of the upper extremities. Hence, even though a work task may lack cardiovascular activity, certain smaller body regions such as forearm and finger muscles may become overloaded. For example, sedentary computer work involves long and

static work postures for the neck, shoulder and wrists as well as repetitive work for the wrist and fingers. Although the muscle activity in the working muscles is low, computer work is associated with a high prevalence of upper limb pain and WMSDs (Coenen et al., 2019; Juul-Kristensen and Jensen, 2005; Thorn et al., 2007).

A general theory regarding biomechanical exposure and physiological response imply that monotonous work lacks exposure variation and thus the opportunity for relaxation. The continuous muscle activation imply that specific motor units in the muscles may become overloaded (Sjogaard and Sogaard, 1998; Sjøgaard et al., 2000; Thorn et al., 2007). Hence, since excessive, high or prolonged physical exertion are risks of injury or illness, variation in physical intensity, duration and repetitiveness as well as sufficient time for recovery, are important factors suggested to avoid WMSDs and promote musculoskeletal health. However, it is difficult to provide general recommendations about appropriate variation (Mathiassen et al., 2003). In addition, individual factors such as age, BMI, smoking (Hogg-Johnson et al., 2008; Nilsen et al., 2011), privacy life (Bongers et al., 2006), genetics (Cheng et al., 2020; Meng et al., 2020) and pathophysiological phenomena (Visser and van Dieën, 2006) have been reported to influence the risk of developing WMSDs (Widanarko et al., 2014).

The fact that the development of WMSDs often takes place over a long period of time as a result of everyday microscopic wear and tear of the soft tissues, makes the cause-effect association complex (Coenen et al., 2014; Seidler et al., 2009). Biomechanical exposure caused by awkward postures, repetitive work, or heavy lifting, may not be potentially harmful if occasional or irregular occurrence or with moderate amplitude. On the contrary, certain motion and physical load are needed to maintain wellbeing (Thivel et al., 2018; Winkel, 1987).

## 1.4  Risk assessment of work-related physical exposure

Effective prevention strategies to proactively tackle the WMSD's include ergonomic risk assessments (Hignett, 2003). By careful examination of potential risk factors such as exposure to harmful biomechanical and psychosocial aspects of the work and the workplace, the risk assessment aims to identify significant risks of musculoskeletal disorders.

In order to characterize the dimension of the exposure, each risk factor should be associated with the three main quantitative characteristics: the exposure's intensity/amplitude, the frequency and the duration (Kourinka et al., 1995). The intensity, *"how much?"* measures the size of the risk factor, which, if it is posture-related, refers to the size of the joint angle, and if related to musculoskeletal load, the weight of the object handled. The frequency, "*how often?"*, measures the presence of the risk factor which relates to e.g. repetitiveness, number of work cycles, task variation, occurrence of micropauses, in view of time needed for tissue recovery. The duration, "*how long?",* measures the exposure time of the risk factor. In the

risk assessment of a work situation, the term "exposure dose" refers to a measure of the accumulated exposure. The dose is calculated by a combination of the exposure's intensity, frequency and duration.

However, although there are a numerous of systematic methods available, a recent study in Swedish occupational health (OHS) ergonomists showed that the use of systematic methods in ergonomic risk assessments is lacking. Still, the identification and assessment of physical exposures mainly is based on the ergonomists' experience and expertise (Eliasson et al., 2019).

## 1.5 Systematic methods for risk assessment of WMSDs

There are numerous of assessment methods and procedures aiming to identify and quantify the exposure or the risks of WMSDs. However, no single method covers all purposes, - instead, a method may be more or less suitable for the study's approach and objective. Thus, the choice of method should be based on the objective with its use, the characteristic of the work, who will use the method and the resources for collecting and analysing data (Bhattacharya and McGlothlin, 1996; Takala et al., 2010).

Four main categories of methods for risk assessments, which are of different level of objectivity and precision, may be identified: subjective judgment, systematic observation, direct measurement (technical measurements), and digital human modelling (DHM) (Burdorf and van der Beek, 1999; David, 2005; Duffy, 2008; Kourinka et al., 1995); the last mentioned one can be used before the work or the workstation exist to predict the workload (Fan et al., 2018; Hanson et al., 2009a; Lämkull et al., 2009). The four categories of methods are described below.

### 1.5.1 Subjective judgement

Subjective assessments are based on the employee's perceived and thereby self-rated exposure and can be studied through interviews, surveys or diaries. The investigation, which is performed in a written manner, is carried out by questions and answers of different degree of standardization (Karwowski and Marras, 2003). A well-used method to analyse musculoskeletal symptoms, is the Nordic musculoskeletal questionnaire (Kuorinka et al., 1987). The questionnaire is based on the localization of symptoms and question if you have been ill at any time in the last 12 months and within the last seven days, and if you at any time during the last 12 months not have been able to perform your work because of the inconvenience. Methods based at subjective assessments are inexpensive, easy to apply, especially when it comes to collect data from a larger sample, and can be used to study various of work situations (Silverstein et al., 1997). However, a disadvantage is that the

worker exposure perception has proven to be exaggerated and unreliable (Hansson et al., 2001b; Spielholz et al., 2001).

## 1.5.2 Systematic observations

Systematic observations (Takala et al., 2010) refer to structured risk-assessments based on observations and scorings of exposure following a checklist-based approach. The assessment is generally accomplished by an OHS-ergonomist who rate the level of exposure for a number of risk items even though some methods include, to a certain extent, self-ratings from the observed worker (e.g., perceived exertion).

The scorings, which are performed according to predefined exposure ranges, are combined to an overall score, which in turn is compared to a risk index to characterize the risk of WMSDs. For interpretation of the WMSD's risk level, several methods reflect the risks according to the colours in a typical traffic light system (red, yellow, green) corresponding to high risk, medium risk, minor/negligible risk for WMSDs for all/most workers, several workers, few/none workers (Armstrong, 2007; Karhu et al., 1977; McAtamney and Nigel Corlett, 1993; Occhipinti, 2008).

With the benefit of being easily accessible and relatively uncomplicated to use, methods based on systematic observation, e.g. the widespread Rapid Upper Limb Assessment (RULA) (McAtamney and Nigel Corlett, 1993), Strain Index (SI) (Steven Moore and Garg, 1995), Ovako Working Posture Analysing System (OWAS) (Karhu et al., 1977), may be seen as affordable. Further advantage is that checklist-based approaches allow for a quick summary of the exposure through an overall risk score. However, since the observations require skilled observers and are time-consuming, cost-effectiveness might be influenced. Moreover, although the observations often are seen as objective, observations are indeed more objective than subjective judgment, observer subjectivity may affect accuracy, precision and ability to discriminate among exposure levels. Even though a number of observation-based methods for ergonomic risk assessment are available, research have shown that several of the methods are lacking in reliability and validity (Takala et al., 2010).

## 1.5.3 Direct measurements

Direct measurements provide reliable, valid and accurate exposure information through continuous sampling of e.g. posture- and muscle force data. By lightweight devices such as inclinometers (body posture assessment), electro-goniometers (wrist posture registration) and electromyography-devices (muscle force measurement), attached to the body, whole day measurements are feasible (Balogh et al., 2009; Forsman et al., 2015; Hansson et al., 2001a; Hansson et al., 2006). In recent years, such instrumentation has become easy to use and

reasonable in price (Dahlqvist et al., 2016), making costs for postural assessments with e.g. inclinometer use, comparable to the cost of observation-based assessment (Trask et al., 2014). Recently stated action limits, based on quantitative exposure-response relationship between physical exposures recorded by direct measurement methods, and disorders and complaints of the neck and the upper limb (Nordander et al., 2013) allow for risk prediction of WMSDs. Nevertheless, still the measurements and data analysis are complicated and require experienced and skilled practitioners to be applicable in OHS.

### 1.5.4  Digital human modelling

During the last decades, digital modelling of real humans and their behaviour has advanced from research to application in industrial engineering (Alexander and Paul, 2014; Lämkull et al., 2008; Sundin and Örtengren, 2006). By simulation and visualisation of human work, digital human modelling (DHM) tools such as Jack (Blanchonette, 2010), Ramsis (Seidl, 1997) and IMMA (Intelligently moving manikins) (Hanson et al., 2014; Högberg et al., 2016), enable modelling and assessment of e.g. anthropometry, forces, motion and muscular effort, which allow for rapid and efficient virtual testing and comparison of alternative product and workstation design concepts. For biomechanical risk assessment, widespread risk assessment methods are generally implemented in the tools. Hence, physical ergonomics conditions can be objectively verified and evaluated from the early design phase and throughout the product development process, and the material used as support for decisions so that ergonomic issues may be dealt with proactive solutions (Chang and Wang, 2007; Demirel and Duffy, 2007; Högberg et al., 2018; Lämkull et al., 2009).

Sick leave and compensation due to deficient production ergonomics are major costs for the manufacturing industry, and an association between ergonomically problematic tasks and product quality deficiencies has been identified (Zare et al., 2016). Hence, in the automotive industry, virtual ergonomics and simulation has become a commonly applied technology to facilitate a faster and more cost-efficient design process. Virtual ergonomics, allowing for proactive ergonomics workplace design, i.e. the preventive evaluation of products and processes already in the planning stage of production, has thus become important in the prevention of WMSDs (Fritzsche et al., 2014).

## 1.6  Ergonomic risk assessments in production and pre-production

Today, there are several systematic methods for ergonomic risk assessment of the existing work. But, to make ergonomic-related changes in already existing products, work and work environment is often difficult and costly. Thus, preventive work where ergonomics is considered at early stages of work- and workplace design as well as product development, are

advantageous. However, typically, ergonomics is considered too late in workplace design or the product development processes (Broberg, 1997). For example, when strategic design decisions are taken, the majority of the financing resources are dedicated. Any design modification thereafter will rise the costs drastically. Hence, although major ergonomic-related issues may be identified, only minor ergonomic-related changes are possible (Miles and Swift, 1998) to perform. It is therefore important with an early integration of ergonomics into the design- and product development process, and accurate and precise risk assessment methods are needed.

## 1.6.1  Field-assessments within OHS

Within OHS, prevention strategies for WMSDs generally means that the risk assessment is carried out in existing production/work. Typically, the assessment is performed by an ergonomists practitioner which either on-site at the workplace or by video-recordings, observe and rate the exposure.

However, previous studies have shown significant discrepancies in the results when replicating such assessments (Bao et al., 2009; Brodie and Wells, 1997; Takala et al., 2010). Takala et al. (2010) concluded that several of the existing methods are insufficiently tested for validity (to which extent the method measures what it claims to measure) and reliability (the similarity in results under consistent conditions), which are important factors for a correct ergonomic analysis.

Since the ability to obtain the same result in repeated measurement, i.e., the reliability, indirectly is related to the validity (poor reliability means poor validity), the reliability of a method, both in terms of inter-rater reliability, i.e., the consistency of results between different raters, and intra-rater reliability, i.e., the reproducibility of results within the same rater, is of high importance when choosing methods.

### *OCRA (OCcupational Repetitive Actions) checklist method*

The OCRA (OCcupational Repetitive Actions) methods, OCRA checklist and OCRA index (Colombini, 1998; Colombini, 2002; Occhipinti, 1998; Occhipinti and Colombini, 2006, 2007) are included in ISO (2007) and CEN (2007) standards as reference methods for upper limb repetitive assessment and are internationally widely used for the risk assessment of upper limb repetitive work. The risk levels of OCRA's different items are based on epidemiological research, and the final risk score has been shown to significantly predict WMSD incidences. In general, the two OCRA methods are more comprehensive than most other methods, and the OCRA checklist may take relatively long time to perform (Eliasson et al., 2015).

The more straightforward version of the OCRA methods, OCRA checklist, is generally recommended for the initial screening of the repetitive work and has been used within several fields for upper limb ergonomic assessments, such as high fashion clothing production (Forcella et al., 2012), poultry slaughterhouse (Reis et al., 2016), and animal facility operators (Occhionero et al., 2016).

However, the method has not previously been tested for intra-rater reliability, and only one study has previously tested the inter-rater reliability of the method. The lack of reliability-tests of the OCRA-method makes it difficult to motivate the usage of the method over other methods.

## 1.6.2  Pre-production digital human modelling

Within engineering and design, the use of DHM tools allows WMSD prevention strategies to be considered in the early product or production development process, this by virtual testing and comparison of alternative workstation designs, i.e., before a physical workplace exists. Enabling such early assessments implies that costs for redesign, which increase as production approaches, can be kept down (Fritzsche et al., 2014).

Today, observation-based methods such as RULA (McAtamney and Corlett, 1993), OWAS (Karhu et al., 1981), OCRA (Colombini and Occhipinti, 2006) and EAWS (Schaub et al., 2013) are incorporated into the DHM tools and are generally used for biomechanical risk assessment. However, since observation methods are developed for risk classification through observation, the assessment categories are rather rough. Thus, the DHM tool's ability to quickly provide large amounts of detailed information regarding kinematics, postures, movements and physical workload, is not fully utilized.

In the increasing real-life direct measurements of physical load, such detailed exposure data, which is similar to that obtained with DHM, can easily be assessed. Thus, even minor differences in design concepts can show an effect in simulation-obtained exposure data. Therefore, similar assessment strategies, and exposure action limits (Arvidsson et al., 2021), as in direct measurements may also be appropriate for interpretation of the simulated physical load in DHM tools.

While in DHM using the same strategies for exposure calculations as in real-life measurements, similar conclusions also could be drawn regarding risks for WMSDs, this advantageously by using conclusions from exposure-response relationship from direct measurements in epidemiological studies regarding physical load and the development of WMSDs. However, even though knowledge about such relationships still is limited, physical exposure and related complaints of the wrist has during the recent years, carefully been studied within various occupational sectors. For example, in half-day measurements, wrist posture, wrist extensor muscular activity and wrist movements (i.e., angular velocity and

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angular repetitivity) have been measured using direct measurement methods such as electro-goniometers, electromyography and data loggers. Simultaneously, related complaints were assessed by questionnaires, and diagnoses of the wrists and forearm were clinical examined, which enabled the establishment of an exposure-response relationship (Balogh et al., 2019). In risk management work, it would be valuable to use a database with exposures and linked complaints from different types of work. Hence, such a database was formed and used in Paper II.

## 1.7 Rationale for this thesis

To enable sound decisions regarding risk exposure assessments, detailed, reliable and valid methods as well as dose-response relationships based on epidemiology are required.

At present, OHS practitioners often use observation-based methods to estimate the biomechanical load and risks of WMSDs. One well known such method is the OCRA checklist method that is recommended by ISO and CEN standards for risk assessment of the upper limb. However, the method lacks when it comes to reliability testing and has not been tested for intra-rater reliability, which is of particular importance in evaluations of interventions.

Including ergonomic principles already in the planning and design of workplaces can prevent shortcomings in quality and WMSDs among the workers. Design and production engineers generally use virtual simulations to evaluate various design proposals of work and work environment, this already in the design development stage. However, today's ergonomics assessments within DHM tools are predominantly based on methods for observation, which do not make use of the possibility of all the detailed information the DHM tool may generate.

## 1.8 Aim of the thesis

The aim of this thesis was to increase the knowledge of relevant risk assessment methods for the prevention of WMSDs, both in early work- and workplace design and product- and production development stages as well as in existing work- and work environment.

The specific aims were:

- To study the inter- and intra-rater reliability of the ISO-standard recommended method, OCcupational Repetitive Actions (OCRA), aimed for assessment of upper limb repetitive exposure (Paper I).

- To develop an ergonomic risk assessment approach inspired by direct measurement methods and knowledge found in epidemiological studies, including a database with registered exposures in different occupations for comparison purposes (Paper II).

- To evaluate a prototype laparoscopy robotic console at the pre-production stage, using a new DHM model together with a US checklist and the Swedish standards, which are relevant for visual display unit work, as references (Paper III).

# 2. METHODS

## 2.1 Observation based workload assessment (Paper I)

The study was performed within the frame of a larger research project aiming to evaluate six commonly used observation-based methods for ergonomic risk assessment of hand-intensive repetitive work regarding validity, reliability and usability (the "OBS project").

Eleven female professional OHS-ergonomists, also licensed as physiotherapists, were educated within in the OCRA checklist method and given exercises with the same structure as the final risk assessments. To determine inter- and intra-rater reliability, each ergonomist did risk-assessments individually at two separate occasions (assessment and reassessment) of ten video-recorded manual work tasks with varying level of upper limb activity. The tasks included grocery- and cashier work, meat deboning and netting, engine assembly, lavatory- and stair cleaning, post sorting, and hairdressing. The assessments were performed by watching video clips (length 2-3 minutes) of the tasks on individual laptops and by given information regarding risk factors that could not be read from the videos. The risk level ratings were performed according to the OCRA checklist general procedure (Occhipinti and Colombini, 2006) which includes the assessment of six primary risk factors: Frequency, Force, Postures, Additional risk factors, Recovery and Duration. The risk factor Posture include the assessment of five subcomponents: Shoulder/arm, Elbow, Wrist, Handgrip and Movement similarity. Each risk factor, which include several items to consider, is scored with a numerical value according to predefined exposure intervals. By combining the scores for each risk factor, an overall risk score is obtained. The risk of developing WMSDs is evaluated by OCRA's five risk classification criteria, and a colour system illustrate the risk, i.e. acceptable risk: green, very low risk: yellow, medium-low risk: Light red, medium risk: dark red, high risk: purple.

The statistical analysis was performed only for the right limb assessed, which also in all cases were the dominant limb. In some of the risk assessments performed, scorings for a few individual items were missing. Therefore, in the statistical analysis, the median score of the other ergonomists' assessments, for that specific rating, substituted each of these missing scorings.

For the assessment of reproducibility, i.e. the level of consistency between and within ergonomists ratings, statistical parameters were calculated for the overall risk levels of each work task assessment and for each risk factor. In the percentage agreement, which was calculated, the effect of chance is not taken into account. Therefore, other statistical parameters were also studied. Since the most assessment variables in the OCRA checklist are of ordinal character, Cohen's linearly weighted kappa (Cohen, 1968; Warrens, 2013), which appropriately discriminates between minor and major differences in ratings, was used as the primary measure for reliability. However, a number of other reliability measures such as Cohen's kappa (Cohen, 1960), Intraclass correlation coefficient (ICC) 2.1 (Shrout and Fleiss, 1979) and Kendall's coefficient of concordance (KCC) (McDowell, 2006), were also calculated to enable comparison with other similar studies of reliability.

For the interpretation of statistical outcomes of reliability, Landis and Koch's (1977) recommendations: 0.21-0.4: fair, 0.41-0.6: moderate, 0.61-0.8: substantial, 0.81-1: almost perfect and 1: perfect was used for kappa values; for percent agreement, McHugh's (2012) proposal of ≥80% as acceptable was used; the ICC and KCC coefficients were interpreted using general guidelines stated by Cicchetti (1994) and Koo and Li (2016), i.e.: ICC <0.50: poor, 0.50–0.75: moderate, 0.75–0.9: good, and >0.90: excellent.

## 2.2 Digital human modelling and direct assessment of workload (Paper II)

As part of a research project aiming to develop a new digital human modelling tool (Intelligently moving manikins, IMMA), this study concerned the development of an assessment module regarding physical workload and the risk of WMSDs.

A literature search formed a reference database of epidemiological associations between directly measured exposure of the wrist and related musculoskeletal disorders, with respect to different occupations and work situations. Single or combined key words such as wrist assessment, upper limb biomechanical exposure, ergonomic assessment, exposure-response relationship, WMSDs, ergonomic evaluation, epidemiological studies and physical workload were used for search in the databases PubMed, Scopus, Google scholar and ScienceDirect.

Exposure variables, measurement method, measurement results and if any, exposure-response associations, were noted for relevant publications, this in order to identify exposure variables directly measured to assess physical workload along with exposure and response data in different occupations and work situations.

As a test case, the assembly of a central electronic module (CEM), -a manual task in the assembly of automobiles associated with unfavourable load of the wrist joint and related to risk for WMSDs, was simulated using the DHM tool IMMA (Hanson et al., 2014; Högberg et

al., 2016). The task's 7.5-s long initial part, which includes the operator grasping and placing the CEM under the dashboard (a hidden position with a limited view), was studied with respect to flexion-extension and ulnar-radial deviation angles of the right wrist joint. In IMMA, wrist angle exposure was computed at 25 Hz to create time curves, which were exported to Excel for calculation of velocity, mean power frequency (MPF, the centre of gravity of the power spectrum) and motion pause, this in order to predict risk of WMSDs associated with the workload. By the use of a digital family consisting of five male and five female manikins, anthropometric diversity was covered in the simulation.

## 2.3 Digital human modelling in workstation design (Paper III)

The study was performed as a part of the research project as described in Paper II and as the same time as a contribution to the development of the IMMA-tool.

In this study, the design of a prototype console aimed for laparoscopic surgery and its adjustment ranges was virtually simulated and ergonomically assessed, in order to evaluate if the adjustment ranges of the console allowed for an ergonomically proper working posture with reference to anthropometric diversity.

A three-dimensional virtual model of the prototype console was imported to the DHM tool IMMA where two manikin families were created. The two families, which represented anthropometrics of the US (Gordon, 1989) and the Swedish (Hanson et al., 2009b) populations, included six manikins each, with three females and three males with statures corresponding to the median, the 5th, and the 95th percentiles of the underlying female/male populations.

The work in the console is intended to be performed in a seated position using a chair with adjustable sitting height, although with a lower limit of 43 cm above floor. Therefore, each manikin was positioned accordingly as well as according to recommendations for a proper ergonomic sitting posture: torso and neck vertical and in-line, thighs horizontal and lower legs vertical (OSHA, 2021; Woo et al., 2015).

For the ergonomic assessment, an ergonomic checklist and standard criteria related to computer work were used, this since specific ergonomic standards within laparoscopy and surgical procedures are lacking, and since the work posture in the console is similar to that in computer work.

Swedish standards for computer workstations (Arbetsmiljöverket, 1998), which in parts refers to the more general regulation regarding physical workload ergonomics (Arbetsmiljöverket, 2012), was used for the assessment of simulated geometries of the Swedish population, and an American checklist for computer workstation (OSHA, 2018), recommended by the US Department of Labor, was used for the assessment of the simulated geometries of the US

population. Since the Swedish standards was written in Swedish, it was first translated into English. Then, to facilitate the ergonomics evaluation, the text was condensed and framed as a table. For this study, irrelevant sections and paragraphs of the checklist and standards, such as e.g. lighting and visual conditions, the design of the work chair, software and peripheral equipment, were not considered in the assessment.

For measurements in the virtual environment, landmarks such as reference points and reference planes, were established. Moreover, six pairs of distance-related measures, each a pair representing one measure related to the prototype and one measure related to the manikin, were defined to enable quantification of the adjustability of the prototype with reference to anthropometric diversity of the manikin family. The six distance-related measures were:

1. Height of 3D monitor – Height of manikin eyes
2. Height of top of armrest – Height of manikin elbow
3. Height of bottom of armrest – Height of manikin thigh
4. Distance of foot control – Distance of manikin feet to reference point
5. Proximal work depth of hand control – Proximal work depth of manikin
6. Lateral work depth of hand control – Lateral work range of manikin

The ergonomics evaluation of the prototype, which was based on whether the adjustment ranges allowed for an ergonomically proper working posture, was performed by studying the correspondence between console-related measures and the manikin-related measures within each pair or the six defined distance-measures, and assess the possibility to adopt a proper work posture according to the criteria found in ergonomic standards and checklist.

The measurements were all static.

# 3. RESULTS

## 3.1 Inter- and intra-rater reliability (Paper I)

### 3.1.1 Inter-rater agreement and reliability

All OCRAs overall risk-levels were represented among the ratings in the first assessment: 27% were scored as acceptable risk (green), 16% as very low risk (yellow), 16% as low risk (light red), 33% as medium risk (dark red), and 8% as high risk (purple). The overall risk level ratings differed between work tasks and between raters. Within six of the ten work tasks, the ratings represented four out of the OCRAs five risk levels for each task. For example, all raters agreed in rating of the work task "engine assembly" (green) while the work task "hair dressing" included ratings covering the whole risk interval. The result of the intra-rater risk-level agreement is presented in Table 1.

**Table 1.** Overall risk level for each work task and rater as well as the work task percentage agreement of the first assessment session

| Rater | Grocery work | Meat netting | Post sorting | Post handling | Meat cutting | Engine assembly | Hair-dressing | Lavatory cleaning | Cashier work | Stair cleaning |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Dark red | Dark red | Green | Yellow | Purple | Green | Light red | Yellow | Dark red | Dark red |
| 2 | Light red | Dark red | Yellow | Dark red | Purple | Green | Dark red | Dark red | Dark red | Dark red |
| 3 | Green | Light red | Green | Light red | Purple | Green | Light red | Yellow | Dark red | Dark red |
| 4 | Green | Light red | Light red | Green | Dark red | Green | Purple | Green | Dark red | Dark red |
| 5 | Yellow | Yellow | Green | Green | Dark red | Green | Purple | Yellow | Yellow | Dark red |
| 6 | Green | Green | Yellow | Dark red | Purple | Green | Dark red | Yellow | Light red | Dark red |
| 7 | Green | Light red | Dark red | Light red | Dark red | Green | Dark red | Dark red | Light red | Light red |
| 8 | Yellow | Yellow | Yellow | Yellow | Dark red | Green | Purple | Yellow | Dark red | Light red |
| 9 | Light red | Yellow | Yellow | Dark red | Dark red | Green | Dark red | Green | Dark red | Light red |
| 10 | Green | Dark red | Green | Light red | Dark red | Green | Dark red | Green | Yellow | Dark red |
| 11 | Green | Light red | Green | Dark red | Purple | Green | Green | Green | Purple | Dark red |
| % | 31 | 22 | 29 | 20 | 45 | 100 | 25 | 31 | 31 | 56 |

The colours illustrate the OCRA risk levels: Green: acceptable risk, Yellow: very low risk, Light red: medium-low risk, Dark red: medium risk, Purple: high risk

The inter-rater percentage agreement of the OCRA overall risk levels was 39%. At risk factor level, the agreements were about 45% for the risk factors: Force 42%, Recovery 45%, Additional factors 45% and Duration 48%. The percentage agreements for the other risk

factors were lower, Frequency 23% and Posture 20%. The percentage agreements for the five subcomponents of the risk factor Posture showed: Shoulder/arm 54%, Elbow 37%, Wrist 49%, Handgrip 43% and Movement similarity 61%.

The weighted kappa was 0.43 for the overall risk level and between 0.25 and 0.40 for the risk factors (Force 0.40, Recovery 0.40, Additional factors 0.29, Duration 0.39, Frequency 0.35 and Posture 0.25). The weighted kappa for Posture subcomponents spread between 0.03 and 0.35 (Shoulder/arm 0.28, Elbow 0.03, Wrist 0.14, Handgrip 0.25, and Movement similarity 0.35). All parameters of inter-rater agreement and reliability are presented in Table 2.

**Table 2.** Statistical parameters of inter-rater reliability of the risk factors and overall risk level

| Statistics | % | Kw | K | ICC | KCC |
|---|---|---|---|---|---|
| **Frequency** | 23 | 0.35 | 0.14 | 0.63 | 0.75 |
| **Force** | 42 | 0.40 | 0.23 | 0.51 | 0.66 |
| **Posture** | 20 | 0.25 | 0.12 | 0.40 | 0.54 |
| **Additional factors** | 45 | 0.29 | 0.21 | 0.40 | 0.54 |
| **Recovery** | 45 | 0.40 | 0.33 | 0.50 | 0.52 |
| **Duration** | 48 | 0.39 | 0.35 | 0.48 | 0.52 |
| **Overall risk level** | **39** | **0.43** | **0.21** | **0.62** | **0.65** |

%: percentage agreement, Kw: weighted kappa, K: Cohens kappa, ICC: intraclass correlation, KCC: Kendall's coefficient of concordance

## 3.1.2 Intra-rater agreement and reliability

Ten raters repeated the assessments. The agreement of the OCRA overall risk level compared to the first assessment session was 45%. The intra-rater agreement of the overall risk level varied between work tasks (changes in risk level agreement are presented in Table 3), e.g., in the work task "engine assembly", all raters agreed in their previous rating, while in the work task "meat netting" only one rater agreed with her former rating.

At risk factor level, the agreements spread between 33% (Frequency) and 59% (Duration): Recovery 40%, Force 48%, Additional factors 57% and Posture 36%, the latter including the subcomponents: Shoulder/arm 70%, Elbow 64%, Wrist 63%, Handgrip 49% and Movement similarity 73%.

The weighted kappa was 0.52 for the overall risk level and for risk factors ranging from 0.41 to 0.61: Force 0.50, Recovery 0.41, Additional factors 0.46, Duration 0.61, Frequency 0.52 and Posture 0.46 where the weighted kappa for the Posture subcomponents spread between 0.03 and 0.35 (Shoulder/arm 0.28, Elbow 0.03, Wrist 0.14, Handgrip 0.25, Movement similarity 0.35). All parameters of the intra-rater agreement and reliability are presented in Table 4.

**Table 3.** Changes in risk level, per work task, for the individual raters. Grey (filled) cells indicate an agreement between the first and second assessment sessions

| Rater | Grocery work | Meat netting | Post sorting | Post handling | Meat cutting | Engine assembly | Hair-dressing | Lavatory cleaning | Cashier work | Stair cleaning |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | -1 | -1 | +3 | +1 | -1 | 0 | +2 | +2 | -1 | 0 |
| 2 | 0 | -1 | 0 | 0 | 0 | 0 | +1 | -3 | +1 | +1 |
| 3 | +1 | +1 | +1 | +1 | -1 | 0 | +1 | +1 | -1 | 0 |
| 4 | 0 | -1 | -2 | 0 | 0 | 0 | 0 | 0 | -1 | 0 |
| 5 | -1 | -1 | 0 | 0 | 0 | 0 | -1 | +1 | 0 | -1 |
| 6 | 0 | +2 | -1 | -1 | 0 | 0 | 0 | +1 | 0 | -1 |
| 7 | 0 | +1 | -2 | -1 | +1 | 0 | +1 | -1 | -1 | +1 |
| 8 | -1 | -1 | 0 | 0 | 0 | 0 | 0 | +1 | -2 | 0 |
| 9 | -2 | +1 | 0 | -2 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | +1 | +1 | 0 | 0 | 0 | 0 | +2 | -2 |

Filled squares indicate matched ratings. The numbers describe the difference in risk level steps between the first and second assessment session. + (plus) indicates an increase in risk level, and – (minus) indicates a decrease in risk level

**Table 4.** Statistical parameters of intra-rater agreement and reliability for the risk factors and for the overall risk level

| Statistics | % | Kw | K | ICC | KCC |
|---|---|---|---|---|---|
| **Frequency** | 33 | 0.52 | 0.24 | 0.78 | 0.91 |
| **Force** | 48 | 0.50 | 0.30 | 0.68 | 0.87 |
| **Posture** | 36 | 0.46 | 0.26 | 0.65 | 0.83 |
| **Additional factors** | 57 | 0.46 | 0.32 | 0.58 | 0.80 |
| **Recovery** | 40 | 0.41 | 0.30 | 0.52 | 0.81 |
| **Duration** | 59 | 0.61 | 0.50 | 0.69 | 0.82 |
| **Overall risk level** | **45** | **0.52** | **0.29** | **0.72** | **0.85** |

%: percentage agreement, Kw: weighted kappa, K: Cohens kappa, ICC: Intraclass correlation, KCC: Kendall's coefficient of concordance

# 3.2 Exposure quantification and risk assessment in digital human modelling (Paper II)

## 3.2.1 Risk factors, measurement and quantification

Four risk factors for WMSDs of the arm and the wrist were identified in the literature and selected for quantification of simulated exposure in DHM:

- *Postures*
  Relationships have been identified for example between work in non-neutral wrist postures and carpal tunnel syndrome as well as lateral and medial epicondylitis; the latter especially while wrist angles are in flexion-extension direction, in combination with force or repetitive activities. Similarly to studies of human work postures, where postures are measured with sensors attached to the body and where a sufficient

registration rate is 20 Hz, simulated exposure from digital human manikins were studied. For quantification, the amplitude probability function was found usable to describe the percentage distribution of wrist postures in flexion-extension and ulnar-radial deviation, using the 50th percentile (mean) as well as the 10th and the 90th percentiles as peak.

- *Velocity*
Angular velocity of the wrist joint are variables found to interact in the development of cumulative trauma disorders (CTD). The absolute angular velocity was quantified. Similar as to the study of wrist postures, the registration rate of 20 Hz as well as the amplitude probability function (10th, 50th and 90th), were used to describe the velocity.

- *Repetitive motions*
Repetitive motions of the wrist such as high-speed arm movements and short work cycles are well-documented risk factors for work-related disorders of the hand, wrist and elbow. Repetitiveness, quantifiably by the Mean power frequency (MPF) and here obtained by fast Fourier transform (FFT) in order to compute the power spectrum of the angles during the whole duration of the task were used for assessment of wrist angular flexion-extension and ulnar-radial deviation.

- *Motion pause*
Motion pause of the wrist joint, definable by wrist joint angular velocity < 1 °/s in a sequence of at least 0.5 s (Balogh et al., 2009; Thomsen et al., 2002) was here calculated as the percentage of time using this definition in a function (developed for this) in MATLAB (MATLAB, 2016).


### 3.2.2 The reference database

A reference database was compiled by summarising epidemiological exposure and response data for the wrist from studies of different occupational groups. Characterised in terms of group mean values, the exposure was presented according to the 10th, 50th and 90th percentile for flexion-extension and ulnar-radial deviation angles of the wrist, the 50th percentile for the absolute angular velocity of flexion-extension and ulnar-radial deviation, MPF and motion pause. Thereto, for each group, the proportion of workers with wrist-related complaints during the past 7 days or 12 months and if available, type of diagnose as well as percentage of subjects with diagnosed disorder was described.


### 3.2.3 The risk assessment approach

A simple framework for ergonomics risk assessment within DHM tools was developed. The approach is based on the availability of a reference database such as the one described above.

A general assessment procedure is illustrated in Figure 2, here exemplified and below described, by a test case where the wrist is assessed.
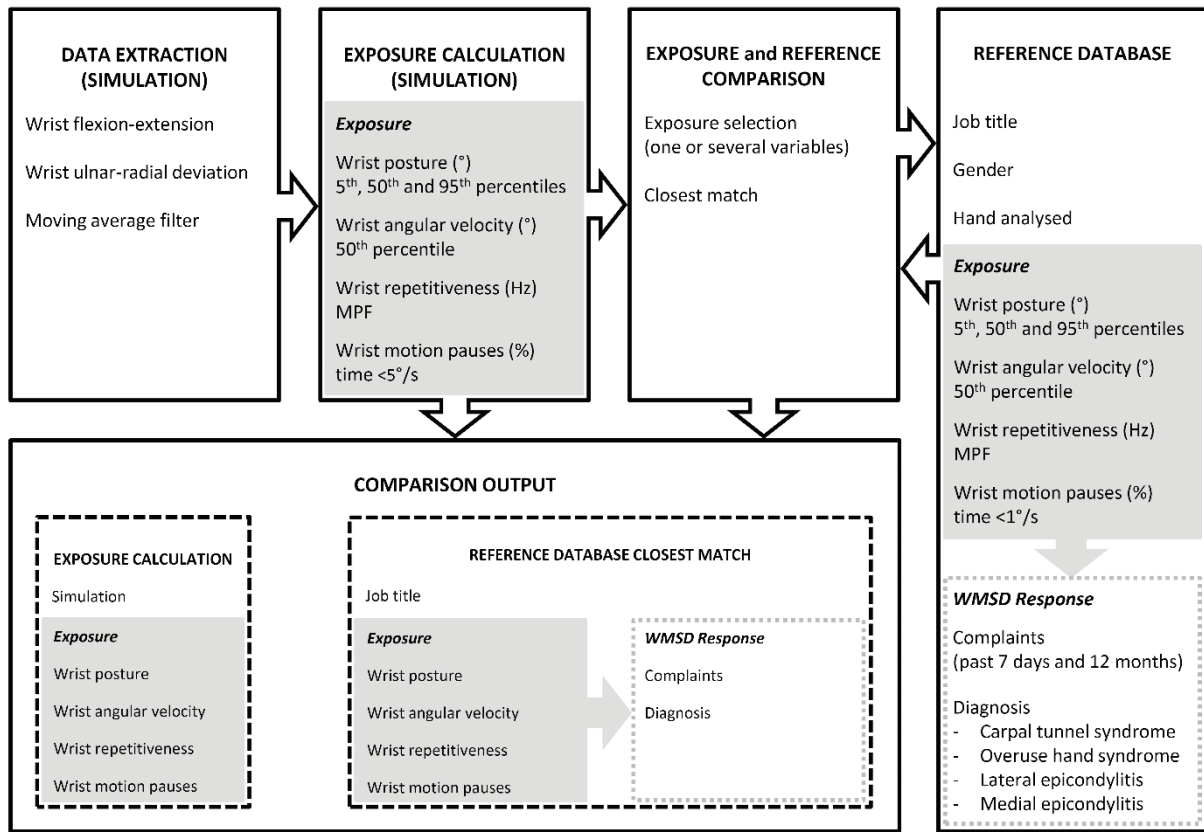


**Figure 2.** Risk assessment approach flowchart

Briefly, the risk assessment procedure includes the following steps:

- *Data extraction*
  Simulated motions of the manikin's wrist (i.e. wrist angular flexion-extension and ulnar-radial deviation) are sampled by a frequency of 25 Hz, and filtered by 5 Hz,

- *Exposure calculation*
  Wrist exposure is calculated and described for flexion and deviation according to measures such as: $10^{th}$, $50^{th}$ and $90^{th}$ percentiles of posture, $50^{th}$ percentile angular velocity, MPF and time percentage motion pause,

- *Exposure and reference comparison*
  One or more measures are compared to corresponding one in the *Reference database,* Automatically, the best matched exposures (i.e. simulated exposure to reference exposure) are identified,

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- *Comparison output*
    As output, the exposure outcome from the simulation is presented for each exposure variable studied along with corresponding values from the closest exposure match in the reference database; its job title, the amplitude and the WMSDs response.

### 3.2.4  The test case

In the test case, the exposure measures of the right wrist were quantified for each subject of the manikin family. Mean values of exposures in flexion-extension direction showed that the 90th percentile posture was 25°, the 50th percentile of the absolute angular velocity 10.3 °/s, the MPF of the angle was 0.58 Hz, and the motion pause less than 0.05% of the simulation.

Different best job matches were found for different exposure variables. The best matched jobs in the database were for posture (90th percentile) "cleaning" and "daily nursery work", for the angular flexion-extension velocity (50th percentile): "varied office", and for repetitiveness: "sorting parcels".

These matched occupational groups and their reported complaints during the seven past days may predict the risk for WMSDs. Based on matched postures, 24% to 46% of the workers performing this work for a longer time, can be expected to report wrist pain. Moreover, 4% to 20% of these workers will probably be diagnosed with one or more CTDs of the wrist.

## 3.3  Evaluation of a prototype design (Paper III)

The prototype console was possible to evaluate by virtually positioning the digital manikins in the 3D digital prototype inside the DHM tool. In the comparison of the adjustment ranges of the console to the ergonomic-based and anthropometric-related work areas of the manikins, some critical design issues were revealed.

### 3.3.1  The adjustability of the console

The measures for comparison between the console's adjustment ranges and anthropometry-related work areas of the manikins are illustrated in Figure 3.
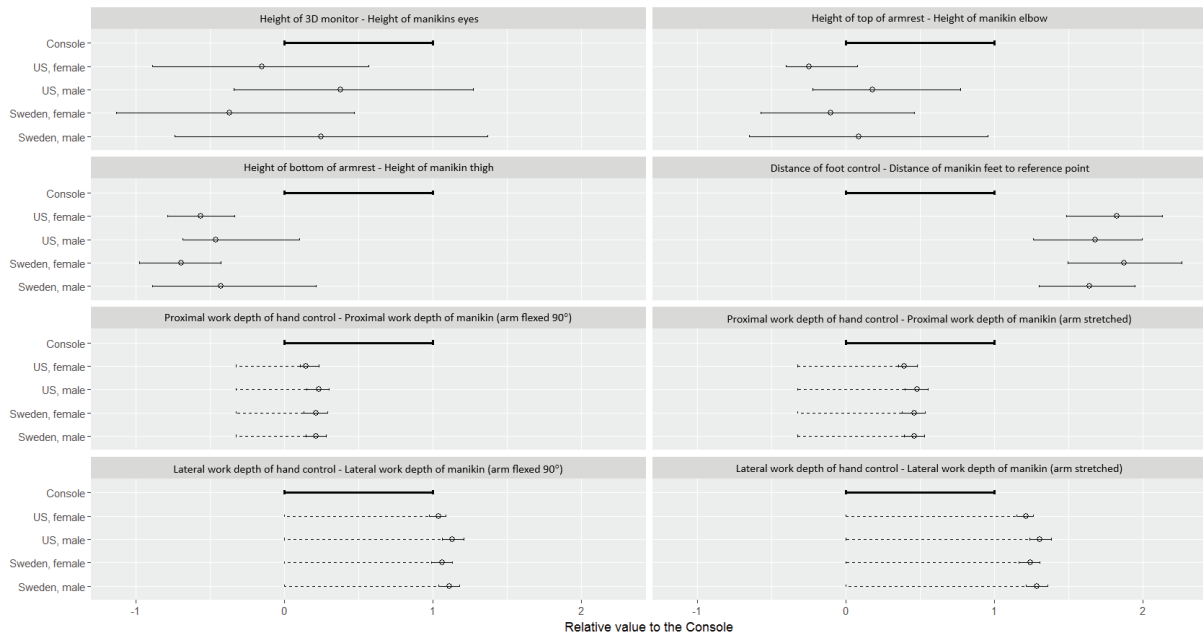
**Figure 3.** Comparison between the adjustable dimensions of the console and the work area of the manikins, when the manikins are placed in a correct ergonomic sitting position in the console, inside the 3D DHM tool

## 3.3.2 Ergonomics assessments

### *US checklist*

Assessment of the physical ergonomics according to the US checklist "Computer Workstations eTool" showed that, out of the 33 criteria, which were divided in 7 paragraphs, i.e.: Working postures, Seating, Keyboard/input device, Monitor, Work area, Accessories and General (the last one related to e.g. equipment, organisation and condition of the work station), 17 criteria (involving the paragraphs Seating, Keyboard/Input device, Accessories, and General) were not relevant for the assessment and were therefore excluded. Among the other 16 criteria, 10 were fulfilled, four were not, two criteria were difficult on the borderline difficult to assess. The criteria that were not fulfilled were all related to Working postures or the position of the Monitor.

### *Swedish standards*

The assessment using the Swedish standard included 45 criteria divided within 10 paragraphs: Screen and viewing conditions, Lighting and viewing conditions, Work postures and work movements, Work height, Work area for the hands, Work with handheld controls, Neck, Shoulder/arm, Back, Leg. Twenty-three of these criteria were not adequate for the assessment and therefore excluded in the assessment (i.e., criteria related to paragraphs such as Screen and viewing conditions, Lighting and viewing conditions, Work postures and work

movements, Work with handheld controls, Back). Of the 22 criteria seen as relevant, 11 criteria were fulfilled and 11 were not.

Detailed descriptions of the assessments using the US checklist and the Swedish standards is provided in Paper III.

In brief, the following criteria in the US checklist and the Swedish standards were not fulfilled, or only fulfilled for some of the manikins, and need to be further considered:

- *Adjustability of armrest height: The lowest position of the armrest is insufficient adjustable in height, i.e. too high for several of the manikins too use to armrest properly (i.e. the forearm at about 90 degrees to the upper arm).*

  US Checklist: The armrest is too high for all the female manikins as well as for the shortest male manikin.
  Swedish standards: Only the tallest male and female manikins as well as the average male manikin can use the armrest properly.

- *Adjustability of main monitor height: For several of the manikins, the height adjustment of the 3D monitor is insufficient, both upwards and downwards. Hence, the taller manikins need to bend their neck forward and the shorter ones need to bend their neck backward to be able to have the eyes in line with the top height of the 3D monitor.*

  US checklist: The tallest male manikin must bend his neck forward and the shortest female and male manikin as well as the average female manikin must bend their neck backward.
  Swedish standards: The tallest male manikin has to bend his neck forward and the shortest female and male manikins as well as the average female manikin have to bend their neck backward.

- *The positioning of the extra screen: The extra screen is positioned at the side of the console.*

  US checklist: The positioning of the extra screen means that the manikins have to twist their head while watching. However, the extra screen is only used for a few minutes of the working time and may therefore not be seen an issues for further consideration.

- *Ability to rest the feet on the ground: The work in the console include the use of foot pedals.*

  US checklist: Resting the feet flat on the ground is only occasionally possible since the control of the monitor requires repeated use of the foot pedals.

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- *Adjustability of foot controls*
  US checklist: The adjustability of the foot controls are insufficient. None of the manikins is able to reach the foot controls while sitting with the thighs parallel to the floor

- *Armrest support*
  Swedish standards: the design of the armrest is narrow and tilted inward, thus, does not support the whole forearms.

- *Working in a standing position*
  Swedish standards: the console does not allow working in a standing position, this because of the limited adjustability of the height as well as the fact that during surgery work, both feet are used to control the pedals.

# 4. DISCUSSION

This thesis aimed to increase the knowledge in the area of methods for ergonomic risk assessment, both in the early work- and workplace design and product- and production development, and in existing work and work environment, for the prevention of WMSDs.

## 4.1 The inter- and intra-rater reliability of the OCRA checklist (Paper I)

### 4.1.1 Consistency in ratings

The objective was to study the consistency of ergonomists observation-based assessments of different work tasks, both in terms of inter-rater reliability (the consistency between different ergonomists assessments) and intra-rater reliability (the consistency within ergonomists while repeating the assessments), when using the OCRA checklist method.

The findings in Paper I showed that the inter-rater overall percentage agreement for the five risk levels, was 39%, and corresponding Cohen's linearly weighted kappa was 0.43, which according to Landis and Koch (1977) criterion indicate a moderate reliability. The inter-rater consistency of the six risk factors, showed that Cohen's linearly weighted kappa ranged from 0.25 (Posture) to 0.40 (Duration and Force), which indicates a fair reliability (Landis and Koch, 1977).

The intra-rater reliability was higher than the inter-rater ditto. The intra-rater overall percentage agreement was 45% and Cohen's linearly weighted kappa, which was 0.52, indicated a moderate reliability. Cohen's linearly weighted kappa of the risk factors, ranged between 0.41 (Recovery) and 0.61 (Duration), which still are within the moderate range of reliability (Landis and Koch, 1977).

### 4.1.2 The inter- and intra-rater reliability of the OCRA checklist

Only one previous study has revealed results of the inter-rater reliability of the OCRA checklist. In that study (Paulsen et al., 2015), similarly designed as our and where 21 video-

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recorded cheese-manufacturing tasks were assessed by seven raters, the values of the overall risk level, shown by Intraclass correlation (ICC) was 0.80, indicating an excellent reliability, which was higher than in our study, 0.62, which represented a moderate reliability (Cicchetti, 1994).

In the study by Paulsen et al. (2015), all work tasks were within the same work area, and of a typically cyclical nature, with work cycle times between 6 and 106 s. The work tasks in our study were similar in work cycle lengths, 3 to 120 s. but within different work areas and included both more and less cyclical work. The differences in study design between the studies may have contributed to the differences in ICCs.

Our study revealed the same risk factors regarding highest and lowest reliability as did the study by Paulsen et al. The highest ICC, 0.63 in our study and 0.68 in the study by Paulsen et al, was shown for the risk factor Frequency, while the lowest ICC, which differed noticeably between the studies, i.e., 0.21 in our study compared to 0.40 in the study by Paulsen et al, was shown for the risk factor Additional factors.

Inter-rater reliability of other observation-based risk assessment methods has demonstrated varied results. Studies of the Strain Index method (Steven Moore and Garg, 1995), revealed a poor to moderate overall inter-rater reliability, shown by ICC and, the ICC-similar, quadratically weighted kappa ranging from 0.41 to 0.59 (Paulsen et al., 2015; Portney and Watkins, 1993; Spielholz et al., 2008; Stevens et al., 2004). Individual variables of the Strain Index method demonstrated ICCs ranging from 0.66 to 0.81 (Stevens et al., 2004), i.e. interpreted as moderate to good, with the posture variable, which was similar to our OCRA results for individual variables, representing the lowest value.

Moreover, the overall inter-rater reliability of the Hand Activity Level method (Hygienists, 1995), studied by quadratically weighted kappa (0.34), shows a poor overall reliability (Spielholz et al., 2008) while the Quick Exposure Check method (Li and Buckle, 1998), used in the assessment of three different tasks, demonstrate, by Kendall's coefficient of concordance, a moderate to good (0.6-0.79) overall inter-rater reliability, which comprise our result (0.65).

To my knowledge, our study was the first to study the intra-rater reliability of the OCRA method. The results show, however, a lower intra-rater reliability compared to published results of other observation methods.

In contrast to our results, where the ICCs of the exposure variables were between 0.52 and 0.78, the repeatability of the Strain Index method, which was studied by comparison of 15 raters' individual and repeated assessments of 73 video recordings within different industry job, showed, ICCs that ranged from 0.82 to 0.95 (Stephens et al., 2006). The intra-rater reliability of the Quick Exposure Check method, studied by eight raters repeated assessment of 18 video recorded industrial tasks, revealed, for the seven exposure variables, a Cohen´s

kappa ranging from 0.45 to 0.53 (Li and Buckle, 1999). All but one of those values were thus noticeably higher than the kappa values for the OCRA risk factors in our study, where Cohen's kappa ranged from 0.24 to 0.50. However, the Quick Exposure Check method's both fewer exposure levels (four) and coarser risk categories, are likely reasons for differences in kappa result (Warrens, 2012).

### 4.1.3  Aspects influencing the consistency in ratings

The lack of consistency in ratings was expected, this based on previous research (Dartt et al., 2009; David et al., 2008; Denis et al., 2002; Denis et al., 2000; Dockrell et al., 2012; Eliasson et al., 2017) where aspects such as the lack of, or differences in raters' skill as well as experience in ergonomics assessments have been argued as possible explanations for inconsistency in results. However, the complexity of the assessment material (e.g. non-cyclic vs. strict cyclic work) as well as the comprehensiveness of the method (e.g. number of items to assess and the quantity of possible options available) might rather be seen as likely reasons for the variation (Burt and Punnett, 1999; Denis et al., 2002; Denis et al., 2000).

The low consistency of the exposure variable posture, has previously been shown in other studies (Dartt et al., 2009; Ebersole and Armstrong, 2006; Stephens et al., 2006; Stevens et al., 2004). Hence, posture, and particularly deviations and postures of smaller joints, appears difficult to assess by observation (Bao et al., 2009; Dartt et al., 2009; Stetson et al., 1991).

Another aspect that may have influenced the consistency in ratings, is the time-points within the task chosen for consideration. It is natural that different observers choose different parts of a work sequence to assess, and even if the work sequences in the study were only 2-6 minutes long, it is difficult to know whether the assessments were based on the same time-period.

Further aspects that may have affected the consistency in results may be related to the OCRA-checklist method's comprehensive scoring procedure and presentation of final results. The method's high number of scoring options, the complicated scoring system as well as the high number of levels (five) for final risk presentation may have affected the consistency (however not the linearly weighted kappa (Warrens, 2012).

### 4.1.4  Methodological considerations

The OCRA checklist has several items with different number of levels. The levels and the final risk level are of ordinal character. Therefore the use of the linearly weighted kappa as a preferable parameter for reliability testing, since the linearly weighted kappa is neutral to the number of levels (Cohen, 1968; Warrens, 2013).

The quadratically weighted kappa, punishes, similarly as the ICC and KCC, dissimilarly in ratings exponentially, which is excessive and not suitable for this type of assessment; the kappa values of the quadratically kappa is higher than the kappa values of the linearly weighted kappa and the unweighted kappa. However, the ICC is included in many statistical software packages, which is advantageous in practise.

A strength of the study was the sample of work tasks. In addition to several job categories being represented, there was a variation in both task complexity and exposure. Another strength was the raters' experience within ergonomics assessments. A general problem in repeated tests is the change in items between the test periods. However, in the presented study, the assessment material constituted of video-files, hence, there was no risk that the situation would have changed.

The sample size of 11 raters, may be seen as a limitation of the study. But, the sample size was comparable or higher than several other studies of reliability referred to, and, with reference to the inclusion criteria of the ergonomists', it would probably have been difficult to increase the number of raters.

In general, both reliability and validity should be covered while testing a method's usefulness. Here, the focus was on reliability of the OCRA checklist method, which showed a moderate result, and since a methods validity cannot be higher than its reliability (Kerlinger, 1966), the validity would also have been limited if assessed.

The study of intra-rater reliability was based on an "arranged" approach, i.e. the repeated assessments were studied by using the same video-clip and same additional information, as in the first assessment round. In a real situation, there would have been a natural-over time-variation in the task performance, which would have affected the reliability negatively. However, the study aimed to study the reliability of raters' assessments and not other influential variations in the work or in the work environment.

## 4.2 Ergonomic risk assessment in DHM simulation (Paper II)

In this study, an alternative and new approach for applying motion data from computer manikin simulations was based on risk assessment incorporating direct measured exposure and WMSDs prevalence data in scientific literature. The usage was exemplified in a simulated work task within vehicle assembly, which in reality is associated with risk for unfavourable load of the wrist.

### 4.2.1 The application of motion data obtained from computer manikin simulations

Digital human modelling tools enable simulations of human movement through a structural model, representing the human body with defined body parts for the monitoring of movement trajectories. Hence, joint angles, angular velocities and accelerations can be used for monitoring exposure and for WMSDs risk assessment in the similar way as in direct measurements. The strategy of obtaining the same information of exposure in computer simulation such as in direct measurements of real humans, enable the possibility to handle the exposure data similarly for risk assessment. By this, the possibility to use recommendations on threshold values for risk exposure also means the possibility of objective assessment of DHM-simulated work.

### 4.2.2 Data handling strategies and the use of exposure profiles

Direct measurements, whether performed in a simulated or real context, usually means that large amounts of data are collected. In order to be useful, the data must be reduced to individual variables, which can characterize a certain exposure. In the presented approach, individual exposure variables such as posture and angular velocity, MPF and motion pause are assessed in order to give the work analysed an exposure profile, which according to recommendations regarding ergonomic epidemiology assessments, accurately will describe the overall exposure (Hagberg, 1992; Winkel and Mathiassen, 1994). Thus, the exposure profile cover information of the three main dimensions of mechanical exposure, i.e., magnitude, repetitiveness and duration. Since knowledge of the individual impact of risk factors on exposure is limited, combining factors into an overall exposure is difficult and do not support a reliable evaluation. Hence, the exposure is presented per variable.

In epidemiological occupational health research (Bovenzi, 1994; Fallentin et al., 2001; Nordander et al., 1999) attention is paid on relationships between occupational exposure profiles (a group exposure profile represents a sample of workers within the same occupation) and health outcomes. Here, the DHM tool allowed the use of a manikin family to demonstrate the within-group exposure variation (based on anthropometric variation), which to a greater extent may vary than the exposure between different occupations (Fallentin et al., 2001).

### 4.2.3 Exposure assessment using exposure and prevalence data on WMSDs

In the database presented, a common way of describing the relationship between exposure and prevalence data on WMSDs is used. However, the summarised data on exposure and outcome gives no indication of risk limits. Instead, recommended threshold limit values for the upper

limb, based on relationship between direct measured physical exposure and health outcome may be used for interpretation (Balogh et al., 2019).

Unlike the rough categorized exposure outcome while using observational methods, direct measurements provide continuous data, which while complied e.g., such as percentiles or percentage of time, may be compared to recommended threshold limit values estimating the level of risk. The advantage of direct measurements is the ability to evaluate even minor changes in the workload, which is essential in the evaluation of different actions or design proposals in the quest to improve the working conditions.

The approach presented here is based on the assumption of that simulated physical exposure is equated with real physical exposure, and that a certain exposure leads to a certain health outcome. Hence, comparing the exposure profile of the manikin or manikin family with the database, provides an opportunity to evaluate which WMSD's response the simulated task would lead to in reality.

For the method to be relevant, it is necessary to have access to comprehensive reference data. However, we believe that today's standardised methods for direct measurements of physical exposures as well as procedures for the diagnosis of WMSDs, should soon make it possible to expand the database with additional occupational groups.

### 4.2.4 The test case

In the test case, the varied level of exposure within the manikin family speaks for the importance of considering anthropometric variation. However, the task in the case was very short, and even though work cycles around one minute are common (and repeated for two hours) within the final assembly of automobiles, there is usually some recovery time included in the cycle. Hence, a relevant assessment should include the entire cycle time, and for a full-day exposure assessment, assessment from of each of the workstations rotating between during a workday, should be considered. While the test case only illustrates an assessment of a minor part of the work, the predicted risk of WMSDs cannot be used as a basis for the occupational health data from the factory.

### 4.2.5 Methodological considerations

In this study, the ergonomic assessment did not include muscular load, which is a risk factor strongly associated with WMSDs (Thomsen et al., 2007); handling physical loads as well as forceful gripping have been described as of major relevance in the development of wrist-related disorders such as carpal tunnel syndrome (Hagberg, 1992; Shiri et al., 2009; Silverstein et al., 1987). The approach did include neither vibration- nor psychosocial and

environmental factors that are of importance in the assessment of WMSDs. Instead, the emphasis was to assess biomechanical risks of WMSDs in a pre-production setting.

To program a manikin to move like a manikin is difficult, and although the movements looked human while visualised, the reality of the movement pattern has not been evaluated. For such a verification, the simulated movements should have been compared to measurements of real work movements.

Since the approach did not present an overall score, the evaluation of the ergonomic assessment, i.e. results from the assessment of separate risk factors, may be seen as too demanding non-experts. However, significant efforts are required before such an epidemiologically based overall score of a combination of different exposures can be presented.

## 4.3 Evaluation of a prototype design (Paper III)

The study aimed to assess and evaluate the ergonomics design of a robotic console prototype for laparoscopy, through digital human simulations of an American and Swedish population and with associated checklists and standards for visual unit work.

### 4.3.1 Ergonomics assessments

The evaluation of the console's adjustment possibilities to enable work with proper ergonomics showed, according to the US checklist, that almost all the relevant checklist criteria were fulfilled, and, according to the Swedish standards, that half of the requirements relevant for the study were fulfilled. Hence, there were a number of questions that were not satisfied and that had to be further reviewed.

The adjustability of several parameters made it possible to adapt the console to the individual. In addition, the design enabled opportunities for free movement as well as space around the thighs, legs and feet. While placed in the console, the manikins were allowed to work in an upright position, with the head mainly faced forward. The work could be performed within the required viewing distance, i.e., the horizontal distance between the eyes and the front of the screen, which according to the OSHA (2021) is recommended as between 50 and 100 cm and according to Swedish standards as approximately 70 cm (Arbetsmiljöverket, 1998). The armrest allowed for a relaxed working posture for the arm and shoulders, and the control handles could be used according to their designed features, allowing the user to work with a neutral wrist posture and within the inner work area (i.e. with the arms flexed, and the upper arms and elbows close to the body).

### 4.3.2 Outcomes to be considered

The height of the armrest was not adjustable enough to fit all the manikins. While placing the manikins in an ergonomic correct sitting posture, i.e., with the upper arms perpendicular to the upper body and the lower arms resting on the armrests, the armrests were too high to suit half of the manikins in the two manikin families, and thus didn't fulfil its purpose.

Nor the height of the 3D monitor was sufficiently adjustable. However, while considering a preferred viewing angle located 15-20° (not exceeding 60°) below eye-level while viewing the middle of the screen according to OSHA (2021) the user could achieve a proper working posture for the neck, despite the lack of height adjustability of the screen.

To be able to reach the foot controls, the user had to stretch her/his legs forward, which may affect the curvature of the back due to the backward tilting of the pelvis. Moreover, long-time stretching of the legs in combination with a forward bent sitting posture might affect the nervous system, resulting in back pain or long-term irritation.

Although the console was equipped with forearm support, support for the wrist was lacking. In computer mouser-work, wrist support is essential to limit the load of the wrist extensors and lower the risk for WMSDs. In the handling of the controls, such support may limit the flexibility of the controls, however, it might improve the possibility of precision work of the hand.

A noticeable limitation in the design of the console was the lack of opportunity to work in a standing position. Except the fact that both feet might be needed simultaneously when working in the console, the 3D monitor and armrests were not sufficiently adjustable in height to fit standing work. However, considering the association between long-time sitting and low back pain and diabetes (Park et al., 2018; Taylor, 2011; Åsvold et al., 2017), the ability of the console to enable switching to work in a standing position should be further investigated.

### 4.3.3 DHM as a preproduction assessment tool

The DHM tool enables objective assessments of physical ergonomics conditions already in the design phase of a product. In the present study, two manikin families represented the anthropometrical variation in the selected populations. In the present case, the early ergonomic assessment identified and clarified a number of areas for improvement, which if considered, enable for alternative design solutions to improve the product.

### 4.3.4 Methodological considerations

The methods used for evaluation of the consoles possibility to enable a proper ergonomic work posture, were actually aimed for observation-based computer work assessment. Hence, several items within the methods were not relevant for the assessment. However, since assessment methods for the specific area of interest are lacking, and since the work is similar to computer work, the chosen methods were considered suitable, i.e. relevant for ergonomics assessment of the work posture.

The data that was used for anthropometrical population measures, was not updated since 1989 (US) and 2008 (Sweden). Considering that anthropometrical measures change over time, the outcome may have minor inaccuracies due to outdated data. In reality, the work would involve a series of minor movements and different working positions. However, to include all these possible variations in the assessment would be too complicated, and therefore certain approximations were made, which meant that only typical movements and working positions required to perform the work were assessed.

A limitation of the assessment was that the manikins only were assessed in an upright sitting posture. There are also other sitting alternatives that can be considered ergonomically correct, such as "declined sitting", reminding more of a half-standing position, where the angle between the thigh and the spine is greater than 90 degrees. If the evaluation of the console was performed in a declined sitting posture, the height of the armrest (which was slightly too high within the upright sitting) would probably have been suitable. However, since there are no defined measures for a declined sitting, it would be difficult to objectively perform such assessment.

## 4.4 Overall discussion

This thesis focuses on risk assessments of work-related physical exposure, and emphasizes the reliability and level of detailed exposure quantification in order to draw correct conclusions about the risk of WMSDs in existing and planned work tasks.

Correct risk assessments are crucial to enable essential risk-reducing measures to prevent WMSDs (Hignett, 2003). Observation-based methods have long been the basis for ergonomic risk assessments, both in field-assessments within OHS and in industry-simulated assessments prior to production. However, such methods have shown deficiency in both precision and reliability and may therefore be questioned as proper for ergonomic risk assessments in all cases.

### 4.4.1 Reliability challenges in observation-based assessments

Achieving good reliability, i.e. consistency in results, seems to be a general challenge within observation-based assessments of ergonomic risk factors (Takala et al., 2010). In accordance with the outcome of the study in Paper I, five other conventionally used observation-based methods, Hand Arm Risk-assessment Method (Douwes and de Kraker, 2009), Quick Exposure Check (David et al., 2008), Assessment of Repetitive Tasks (Ferreira et al., 2009), Strain Index (Steven Moore and Garg, 1995), and the repetitive work model by the Swedish Work Environment Authority's provisions on physical ergonomics, AFS 2012:2, which were included in the same project and studied in the same way as the OCRA method, also showed deficiencies in inter- and intra-rater reliability (Forsman, 2017; Kjellberg et al., 2015; Nyman et al., 2021). Although Forsman (2017) and Nyman et al. (2021), firstly found a higher overall reliability for the HARM-method compared to the other five methods included in the project, they also found that HARM's kappa values of individual items such as posture, repetition and movements, were low. The authors concluded that the higher overall reliability found for the HARM-method was rather due to the weighting procedure, where especially task duration, which was given to the raters, had a higher impact in the compilation of the total score, than the consistency in the ratings from the actual video. However, as mentioned in the discussion of the Paper I, there are several factors (see Paper I for a more detailed description), both related to the complexity of the assessment material as well as to the comprehensiveness of the method, that are likely to influence the degree of reliability of the assessment.

Although observation-based methods generally are structured similarly, the inter-method reliability, i.e. the consistency in results between different methods, has been found low (Chiasson et al., 2012; Forsman, 2017; Kjellberg et al., 2015; Nyman et al., 2021). Likely reasons for inconsistency in results include the fact that exposure items generally differ between methods and exposure levels vary in number and in resolution. Other reasons are that different methods use different concepts, e.g. combinations of the scorings, to achieve an overall score.

### 4.4.2 The advantages of observation methods

Although direct measurements are more reliable, observation-based methods still do have several advantages. An important aspect that speaks in favour of observation-based methods is the exception of equipment. For the study object, this means that the work can be performed as usual without equipment that interferes with or otherwise affects the work performance. For the rater, it means that the assessment can take place whenever desired, without any form of forethought regarding the preparation of equipment such as control of the equipment, charging, and study object consent, as well as space and time for application of the equipment. The simplicity of a method is highly important. The easier an assessment is to perform, the more likely it is to actually be performed (Eliasson et al., 2019; Forsman, 2017).

Another advantage of observation-based methods is the ability to cover more dimensions of the exposure, such as psychosocial and environmental exposures (e.g. stress, light and noise), which are part of the WMSDs risks. Hence, without observations, important information, even if subjective, may be lacking. Therefore, it should be considered, whenever possible, that technical measurement may be accompanied by observations for a more comprehensive ergonomic risk assessment.

Easily accessible education- and training opportunities in observation-based risk assessment have been shown to increase knowledge and provide insight about reliability in risk assessment methods and how to increase the quality of the assessments (Eliasson et al., 2021; Rose et al., 2020).

### 4.4.3  Challenges within simulation and measurement of biomechanical exposure

Digital human modelling tools still highly include ergonomics risk assessment methods developed for observation-based assessment, where the emphasis is mainly put on posture-related measures and assessment intervals are rough, while time-sensitive measures, which have been shown to be essential for the development of WMSDs, is taken into less consideration. Thus, apart from the fact that several observation-based risk assessment methods are insufficiently tested for reliability and validity (Takala et al., 2010), the use of observation-based methods within DHM, means that the tool's ability to record detailed and time-dependent data is not utilised. Hence, as indicated in both Paper I and Paper II, technical measurements and the risk measures used within these methods, should increasingly be used in the ergonomic risk assessments of real people and simulated manikins.

Technical methods have a high reliability. However, even within technical measurements, there are challenges needed to be addressed. For example, the more precise placement of the equipment is still an issue within research of physical workload (Jackson et al., 2015; Yang et al., 2018). Moreover, the calibration procedure, which is essential to obtain valid measurements, differs among researchers, and should be considered while comparing results in different studies.  Other challenges concern how to collect and analyse data. For instance, the fact that different measures are used to estimate arm inclination makes comparisons between studies as well as comparisons of study results with recommended action levels (which in turn are based on certain calculation methods, such as in Balogh et al., (2019)) difficult. For instance, today, arm inclination is estimated by either inclination velocity, which only includes velocities of inclination, i.e. elevation of the arm, or generalized velocity, which includes velocities of inclination and rotation of the arm in all of three of the sensors axes, which therefore gives higher velocity values. (Fan et al., 2021). Hence, for a correct use of the exposure action levels, also within DHM, more research is needed within this field.

### 4.4.4 Possibilities for increased precision in ergonomic assessments

Today's accessible small and wireless devices for direct measurements as well as methods for analysing physical exposure, allows for possibilities to perform correct ergonomic assessments, in many different cases.

One possibility is the ability to distinguish minor differences in exposure, which is of high importance in the risk assessment and in the evaluation of ergonomic adjustments. For example, in an ergonomics intervention study within the food industry (Forsman et al., 2012), various prototypes of biscuit boxes were evaluated by direct measurement of muscle activity in the wrist, and a small but significantly lower exposure was revealed for ones of the boxes. The authors argued that although small, the difference can increase the risk of WMSDs, and it was not possible to detect it by observation.

The possibility of registering data over time allows day-to-day variations in exposure to be covered in the assessment. The availability of water-resistant devices that contain long-life batteries, simplifies long-time work exposure registration e.g. several days, which is recommended to consider within and between day-variations (Gupta et al., 2015; Jørgensen et al., 2019; Wahlström et al., 2010).

A further possibility is that such devices, which have become inexpensive and in some cases easier to administrate, to a greater extent can be used in epidemiological studies. Such measurements, together with standardized clinical examinations, may provide objective and accurate results regarding dose-response relationships, which is part of the work to develop exposure limit values. Thereto, the possibility of using similar strategies for exposure analysis within DHM, allow for discrimination of small differences in design, which simplifies ergonomic decisions, and enables ergonomic comparisons between planned and existing workstations.

### 4.4.5 Technical measurements in combination with observations

As earlier mentioned, observations should preferably be combined with technical measurements. Nowadays, there are several low-cost and easily administrated methods available that could be useful for such supplementary measurements. For example, the smartphone together with free downloadable applications can be used to register and risk assess work postures; Exposure data is saved and analysed in the phone, which also shows the result of the measurement (Yang et al., 2017). Another simple method includes easily administrated USB accelerometer-based inclinometers, which can be used to register postures of the back, head, neck and arm. The posture data is saved in the USB accelerometer and a built in excel-based program analyse and present the result when the USB is connected to a computer (Forsman et al., 2015). More extraordinary methods that are now under development, comprise a T-shirt based system including a specially sewn T-shirt with pockets

for posture-registering sensors and sewn-in sensors for the recording of muscular load and heart rate. The system is connected to a smartphone program for automatic analysis and presentation of results (Vega-Barbas et al., 2019; Yang, 2019). In addition, the method can be used for work-technique training, by giving tactile feedback to the user as response to exposure (Lind et al., 2020).

If observation methods can be made so that it would be possible to use easy technical methods for some aspects, that would increase their reliability.

## 4.4.6  Ergonomic action levels for technical measurements

Ergonomic action level values have been requested for long time, both by practitioners and researchers within the field. In work-environment areas with exposures to chemicals, noise or vibrations, such limit values are often used to support actions. Since work-related physical exposure traditionally has been assessed through questionnaires and observations, i.e. methods that largely rely on subjective and rather rough assessments, exposure-response relationship has been difficult to state. The development of exposure-response relationships depends on reliable measurements where e.g. questionnaires may lead to bias due to the risk of overestimation of exposure, and responses, in terms of e.g. tissues concerned, becomes non-specific (Hansson et al., 2001b).

However, a research group within the division of Occupational and Environmental Medicine, Lund University in Sweden, has for many years studied work-related physical exposure and associated musculoskeletal complaints in many different occupational groups, with technical measurement methods (Nordander et al., 2016; Nordander et al., 2013) structured questionnaires (Kuorinka et al., 1987) and physical examinations (Jonker et al., 2015). In the compilation of the data collected, associations were found for velocity of the head, the upper arm and the wrist, activity of the trapezius and forearm extensor muscles, wrist posture, and several complaints and diagnoses of neck/shoulder and elbow/hand. Based on these dose-response relationships, action-levels for the upper arm and the wrist have been proposed (Arvidsson et al., 2021; Balogh et al., 2019). According to the authors, exceeding these action levels entails an increased risk of WMSDs, and in such cases preventive actions are needed.

Action levels should be highly useful and valuable in the quest of evidence-based, objective and precise risk assessments of work-related physical exposures, in both existing and planned work situations, which speaks for the benefit of technical measurements and computerised simulations to register, analyse and evaluate physical workload.

## 4.5 Future research perspectives on ergonomic risk assessments

Based on the results of this dissertation, it is proposed that future research in methods for ergonomic risk assessment should primarily focus on technical measurements and further simplification of such measurement and analysis procedures.

Technical measurements should also be used to evaluate to what extent the simulated exposure corresponds to the exposure of a real situation. Today, different sensor technologies and measurement systems are available for assessing physical exposure (Chen et al., 2020; Vega-Barbas et al., 2019; Yang et al., 2017). The suitability of instruments, measurement strategy, data analysis as well as interpretation of results is therefore difficult to conclude. An international agreement would therefore be needed so that standardized procedures for technical measurements can be established, see Weber et al. (2018).

The efforts to establish thresholds between work-related exposure and complaints should be continued. Thus, further research on dose-response associations should involve longitudinal epidemiological research with technical measurements and clinical examinations.

# 5.  CONCLUSIONS

The conclusions from this thesis work are that:

- The OCRA checklist is a moderately reliable tool with a reliability similar to other commonly used observation-based methods intended for ergonomic assessment of work-related upper limb exposure. The lowest reliability was shown for posture assessment, which also has been revealed for other methods. The intra-rater reliability was only somewhat higher than the inter-rater reliability. Hence, technical methods should be considered for pre- and post- assessments of physical exposure in intervention-studies.

- In order to take advantage of the DHM tool's ability to collect detailed information on postures and movements, direct measurements strategies should to a larger extent be used in the ergonomic risk assessment within DHM. A number of relevant quantifiable exposure measures, suitable for workload assessment of posture- and movements within direct measurements, are presented. In the proposed approach for DHM risk assessment, such measures are compared with prevalence values for WMSDs, which may give an indication of the exposure's risk of WMSDs. A direct measurement influenced approach for ergonomic assessments within DHM, will lead to detailed assessments, which should be helpful to prioritise ergonomic needs and adjustments in different design solutions, as well as the evaluation of actions regarding working conditions prior and post to intervention.

- Digital human modelling may be useful in the ergonomic evaluation of static work situations, which was exemplified by a digital prototype console with several setting options, aimed for robot-assisted laparoscopy, and where static working postures, considering anthropometric variation, were compared to ergonomic checklists for visual display unit work. A number of requirements of the checklists were not fulfilled. Design improvements considering e.g. wider adjustability ranges may hence be relevant.

- The results indicate a future potential of increased usage of DHM. If the same methodology as within field-measurements could be used to analyse and assess simulated exposure, simulated concepts may be compared to direct measurements

from already existing workstations, which may be highly useful in ergonomic workplace improvements. Methods, parameters and procedures for risk assessment of work-related physical exposure, should therefore be standardized, so that DHM simulations can be compared with standardised methods, and so that planned workstations, after they have been realized, can be compared with the real standardised measurements.

At last, generally, methods have no value if they are not used. Therefore, efforts should be made to ensure that proper methods of risk assessments in simulations and existing work are easily accessible, simple to use and inexpensive. In order to increase the usage, educational material in such methods should be offered.

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