



Doctoral Thesis in Technology and Health

Beyond the Force: Redefining load exposure assessments of nutrunners for improved power tool ergonomics

AVA MAZAHERI



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Academic Dissertation which, with due permission of the KTH Royal Institute of Technology, is submitted for public defence for the Degree of Doctor of Philosophy on Friday the 6th of October 2023, at 1:00 PM in lecture hall T1, Hälsovägen 11C, Huddinge, Sweden.

Doctoral Thesis in Technology and Health
KTH Royal Institute of Technology
Stockholm, Sweden 2023

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Cover page photo: Vikas Tavanandi

TRITA-CBH-FOU-2023:38
ISBN 978-91-8040-696-3

Printed by: Universitetservice US-AB, Sweden 2023

THESIS FOR DOCTORAL DEGREE (Ph.D.)

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Summary

Reaction force exposure from handheld tightening tools (also known as nutrunners) constitutes an acknowledged contributor to musculoskeletal disorders among assembly operators, and are today not regulated by explicit limits. The research presented in this thesis aimed at contributing to the development of recommended exposure limits for, and assessments of, reaction loads from handheld right-angle and pistol-grip tightening tools.

In order to address the thesis objectives, four research studies were conducted. A literature review was conducted to provide an overview of the current state of knowledge within the topic area. Knowledge gaps were identified by mapping available publications and based on those suggesting directions for further research. Thereafter, two psychophysically based experimental studies were conducted where acceptability limits related to load exposure from handheld tightening tools were derived for right-angle and pistol-grip tightening tools. Finally, an automotive manufacturer's approach to evaluating and managing the use of handheld tightening tools was outlined by means of an interview study.

As found through the literature review, four of the forty included publications had stated exposure limits (general recommendations) or acceptability limits (load acceptance as assessed by study participants) for reaction load exposure from handheld tightening tools. However, some of the reported limits did not consider relevant physical parameters, and some did not comply with modern power tool technologies. Based on this, it was suggested that researchers should emphasize physical quantities relevant to the reaction load such as impulse, express exposure limits in terms of reaction load relevant parameters (and not only the tightening torque), and further study modern power tool technologies.

The experimental studies resulted in acceptability limits for right-angle and pistol-grip tightening tools expressed as screw-joint tightening torque (i.e. a task-related factor), where acceptable tightening torque limits were higher for the inertia-controlled tightening program compared to the continuous drive tightening program, in both studies. In addition, corresponding acceptable reaction load levels (i.e. the exposure) were derived, indicating load levels resulting from the tool use that the study participants assessed as acceptable for an 8-hour workday. It should be noted that the experimental times on which the acceptability limits are based were limited, and that the acceptability limits therefore should not be prescribed to full workdays.

From the interview study, three main topic categories were identified based on the interviewees' responses: 'A holistic approach', 'Information and knowledge availability' and 'Negotiating criteria'. Within the studied automotive organization, a comprehensive approach to ergonomics assessments is incorporate, where both objective and subjective evaluations form the basis for addressing physically demanding tool use situations. Further, it was found that there are different instances where the employees lack sufficient knowledge related to the tools, and which can influence the employment of handheld tightening tools.

In addition, it was found that criteria such as safety and quality could in some situations compete with ergonomics efforts.

In conclusion, the findings from this thesis can contribute to the development of recommended exposure limits and evaluation methods for reaction load exposure from handheld tightening tools. Policymakers could utilize the insights presented in this thesis to form general guidelines directed at power tool manufacturers as well as tool using organizations. Through standardized guidelines, reaction loads from handheld tightening tools, which is one of the contributors to MSDs within assembly work, can be managed and reduced.

Keywords

Power Tools, Nutrunners, Work Related Musculoskeletal Disorders, Risk Assessment, Load Exposure, Assembly Work

Sammanfattning

Kraftexponering från handhållna åtdragningsverktyg (även kallade mutterdragare) bidrar till belastningsskador bland montörer, och är idag inte reglerade med explicita exponeringsgränser. Syftet med avhandlingen var att bidra till ett underlag för utveckling av rekommenderade exponeringsgränser för, och utvärdering av, reaktionskrafter från handhållna åtdragningsverktyg (vinkeldragare och pistolverktyg).

Fyra forskningsstudier har genomförts inom ramen för denna avhandling. Först genomfördes en litteraturstudie där kunskapsläget inom ämnesområdet sammanställdes och kunskapsluckor identifierades. Baserat på utfallen föreslogs riktning för fortsatt forskning. Sedan genomfördes två experimentella studier baserade på psykofysiska metoder där acceptansgränser relaterade till reaktionskraftsbelastning härleddes för både vinkelverktyg och pistolverktyg. Slutligen undersöktes en fordonstillverkarens tillvägagångssätt vid utvärdering av handhållna åtdragningsverktyg via en intervjustudie.

Genom litteraturstudien framkom att fyra av det 40 inkluderade publikationerna hade uttryckt exponeringsgränser eller acceptansgränser för reaktionskraftsexponering från handhållna åtdragningsverktyg. Genom granskning av publikationerna konstaterades att gränsvärdena av olika anledningar vara otillräckliga. Baserat på de identifierade behoven föreslogs det att man inom vidare forskning bör fokusera mer på de mindre undersökta fysikaliska parametrar som är relevanta för reaktionskraftsexponeringen, så som impuls, samt att exponeringsgränser bör uttryckas i termer av exponeringen i sig och inte enbart i termer av åtdragningsmoment (dvs. moment i skruvförbandet). Dessutom föreslogs att moderna verktyg bör studeras vidare då de teknologiskt skiljer sig från traditionella luftdrivna åtdragningsverktyg.

De experimentella studierna resulterade i acceptansgränser för vinkelverktyg samt pistolverktyg uttryckta i åtdragningsmoment, där de accepterade momentnivåerna var högre för det ”tröghets-kontrollerade” åtdragningsprogrammet än det ”segdragande” åtdragningsprogrammet i båda studierna. Dessutom härleddes motsvarande reaktionskraftsnivåer (dvs. exponeringen från verktyget). Acceptansgränserna speglade de belastningsnivåer som studiedeltagarna bedömde vara acceptabla med avseende på hållbar arbetsbelastning över en arbetsdag. Det bör påpekas att de experimenttider som ligger till grund för de framtagna acceptansgränserna var korta och att acceptansgränserna därför inte bör tillämpas på hela arbetsdagar.

Genom intervjustudien konstruerades tre övergripande teman baserade på intervjuerna med studiedeltagarna: ”Ett holistisk tillvägagångssätt”, ”Informations- och kunskaptillgång”, och ”Förhandlingskriterier”. Inom den studerade organisationen tillämpas en ergonomiutvärdering där både objektiva och subjektiva utvärderingar ligger till grund för beslut kring fysiskt belastande användning av handhållna verktyg. Vidare uppmärksammades att det förekommer ett flertal tillfällen där de anställda saknar adekvat kunskap kring handhållna verktyg, och att detta i sin tur kan påverka vilka och hur verktyg används. Dessutom noterades att kriterier som säkerhet och kvalitet i vissa situationer kan hamna i konkurens med ergonomiinsatser.

Resultaten från den här avhandlingen kan bidra till att utveckla rekommenderade exponeringsgränser och utvärderingsmetoder för reaktionskrafter från handhållna åtdragningsverktyg. Beslutsfattare kan nyttja de insikter som presenteras i denna avhandling till att utforma riktlinjer riktade till både verktygstillverkare, och till de organisationer inom vilka handhållna verktyg frekvent används. Genom standardiserade riktlinjer kan reaktionskrafter, samt exponeringen för reaktionskrafter från handhållna åtdragningsverktyg reduceras. Därmed bör avhandlingen på sikt kunna bidra till en minskad förekomst av belastningsskador orsakade av monteringsarbete.

Nyckelord

Monteringsverktyg, Mutterdragare, Arbetsrelaterade Muskuloskeletal Besvär, Riskbedömning, Belastningsexponering, Monteringsarbete

Preface

The industry-driven need for the research presented in this thesis implies that the findings, partly, are intended for actionable knowledge. Therefore, a statement of my personal view on the role of research in practical action is warranted.

As we within the scientific domain try to address the ‘why’ behind the more practically oriented ‘how’, we need to be humble to the idea that practice is informed by various types of knowledge. Science-based knowledge can be regarded as *one type* of knowledge, meaning that other types of knowledge, such as practical, experiential, and tacit knowledge may as well guide actions. The lack of systematic documentation or hypothesis-tested theories need not necessarily be a barrier for actions and decisions.

Before incorporating research findings into practice, it may be appropriate to adapt the findings to the relevant context. In e.g. experimental studies, our desire to increase the internal validity of our findings by controlling variables implies that results derived from a particular study likely will not be directly applicable to contexts differing from the study’s context. Therefore, research results should be evaluated and balanced against e.g. practical feasibility, expected gain, and context-bound values.

As stated by Hansson (2008), it is important to distinguish theoretical rationality from practical rationality. While theoretical rationality concerns ‘what to believe’, practical rationality revolves around ‘what to do in order to achieve practical aims’. With research, we can provide support for or against the adoption of a policy. It is however the policymakers’ role to base their choice of a particular policy on research and ‘the consideration of other things’ as expressed by Robinson et al. (2013), thus stretching beyond the role of the researcher.

In this thesis, my co-authors and I have built on previous research about load exposures from handheld power tools. There are inherent challenges to establishing exposure limits which we with confidence can state will protect humans from adverse health effects. Nevertheless, the outcomes of the research presented in this thesis, and the insights derived thereof, can contribute to more well-grounded decisions and a practice informed by research-based knowledge, alongside other types of knowledge.

Ava Mazaheri

Stockholm, August 2023

Acknowledgements

Among the many people who have contributed to my PhD journey, the first person I want to thank is Associate Professor Linda Rose. In the role as my main supervisor, you have from day one believed in me and showed what it means to be passionate about one's job. And espresso. Following on the supervisor-track, I want to thank my co-supervisors, Micke, Professor Mikael Forsman and Dr. Romain Haettel. To both of you, your calm and collected energy has been crucial throughout this work and is truly contagious.

A warm thank you to my colleagues at the Division of Ergonomics at KTH Royal Institute of Technology. To the senior colleagues at the department, Associate Professor Andrea Eriksson, Associate Professor Catherine Trask, Professor Mats Ericson, Dr. Malin Håkansson, I have so much enjoyed our intellectual and though-provoking conversations. To my doctoral student colleagues at the department, Ellen Jaldestad, Carin Hellström, Inga Mikhaltchouck, Ellinor Rydhamn Ledin, Anna Klara Stenberg Gleisner, Karin Andersson, Helena Franzon, Katarina Olofsson Hallén, nobody 'gets it' like you do. Fredrik Häggström, thank you for the much needed guidance throughout the administrative steps of my doctoral studies. Dr. Farhad Abtahi, I have very much appreciated your input on electromyography-related matters. Dr. Liyun Yang, thank you for your support throughout the initial and final steps of my PhD. To Professor Jörgen Eklund, I don't think I've ever left a conversation with you without feeling inspired and motivated.

To the organization with which I conducted my research studies; I would like to thank Lena Nord-Nilsson, Eigil Holm, Manuela Retting, Kristin Ores, and Kjell-Daldorph Nielsen. In addition, I want to pay great gratitude to the employees of the organization participating in my research studies. I'm just going to give in to the cliché and state that without you, the research presented in this thesis would not have been possible.

Dr. Per Näsman, thank you for magically removing my anxiety around the topic of Statistics. You are what comes to my mind when someone tries to describe 'a fantastic teacher'. To Professor Patrick Neumann, who, despite making a late entrance into my PhD journey, has made my intellectual machinery (a.k.a. my brain) work on heavy-duty mode. For this I'm grateful, as I'm aware that growth and comfort do not coexist.

I would like to acknowledge the funder of this PhD project, the industrial company Atlas Copco Industrial Technique. To my colleagues at the Industrial Design and Ergonomics team at the company, Frida Graf, Oscar Lundin, Henrik Sohlman, Jonas Axelsson, Tobias Larsson, Apurba Pawar, Daniel Hassila, Erik Ebberstein, Daniel Liss Nadjalin, I have learned so much from you. You truly balance premium quality skills and knowledge with kindness and empathy. Thank you to my managers, current and former, Toni Fredäng, Francisco 'Paco' Lindoro, and Ola Stray, who believed in me when I needed it the most. Vikas Tavanandi, thanks for designing the cover of my thesis. Hanako Arambula Hayasaka and Daniele Polsoni, thank you for always just bringing sensational vibes. Olof Liliengren, thanks for posters and prints. From Atlas Copco, I would also like to devote a special thanks

to Lakshman Kulasinghe for always making sure that I had what I needed to conduct my work in the lab. You are simply the best. Azad Akbari and Rickard Gunsjö, thank you so much for your help with mechanical designs. Karolina Majstrovic, I'm super thankful for your help with coding in the early phases of my PhD journey. Further, a thank you to my fellow industrial PhD students at the company, Mayank Kumar, Jonas Millinger, Lifei Tang, Nils Dressler, and Sofia Olsson. Sofia, you have been, and continue to be, my 'ride or die'. Thank you to research assistants Lina Kluy and Sarah Wickbers for helping me conduct the experimental studies, and most importantly, helping me keep my sanity in check through some of the most stressful times. I'm also very grateful for Folke for acting as my stress relief. He's a dog so he won't be able to read this, but *knowing* does not always come from *reading*.

To my friends, thank you all for making sure I had tons of fun throughout the second half of my twenties that after all have been ongoing in parallel with my doctoral studies. My parents, Leyla and Masoud, merci for everything you have done for me. My sis, Nila, you know that I always have the best time with you – you even make queuing fun. Finally, Erik, thank you for being by my side through this – I'm always excited for the next day with you.

Appended papers

- I. Mazaheri, A. & Rose, L.M. “Reaction Load Exposure from Handheld Powered Tightening Tools: A Scoping Review” *International Journal of Industrial Ergonomics* 81 (2021): 103061.
- II. Mazaheri, A., Forsman, M., Haettel, R. & Rose, L.M. “Reaction Force Exposure for Tightening Tool Users: A Psychophysical Based Experimental Study of Electric Right-Angle Nutrunners” *Applied Ergonomics* 103 (2022): 103776–103776.
- III. Mazaheri, A., Forsman, M., Haettel, R. & Rose, L.M. “Reaction Force Exposure for Tightening Tool Users: A Psychophysical Based Experimental Study of Electric Pistol-Grip Nutrunners” Submitted for publication.
- IV. Mazaheri, A., Trask, C.M. & Neumann, W.P., “The influence of different roles and organizational priorities on assembly ergonomics: Assessing nutrunners at an automotive manufacturing company” Manuscript.

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Author contributions

Paper I: Mazaheri and Rose conceptualized and designed the study, and analyzed and interpreted the collected data. Mazaheri conducted the data collection and manuscript drafting. Rose critically reviewed the manuscript content. Mazaheri and Rose gave final approval of the version upon journal submission.

Paper II: Mazaheri, Forsman, Haettel and Rose conceptualized and designed the study. Mazaheri and Forsman conducted the data acquisition. Mazaheri analyzed all collected data with support from the other authors and drafted the manuscript. Forsman, Haettel and Rose critically reviewed the manuscript content. Mazaheri and Rose gave final approval of the version upon journal submission.

Paper III: Mazaheri, Forsman, Haettel and Rose conceptualized and designed the study. Mazaheri conducted the data acquisition. Mazaheri analyzed all collected data with support from the other authors and drafted the manuscript. Forsman, Haettel and Rose critically reviewed the manuscript content. Mazaheri and Rose gave final approval of the version upon journal submission.

Paper IV: Mazaheri, Trask and Neumann conceptualized and designed the study. Mazaheri drafted the interview guide with input from the other authors and conducted the interviews. Mazaheri, Trask, and Neumann analyzed the collected data and Mazaheri drafted the manuscript. Trask and Neumann critically reviewed the manuscript.

Acronyms and Concepts

AL	Acceptable Load (acronym used in Paper II)
APDF	Amplitude Probability Distribution Function
CS	Company Standards (acronym used in Paper IV)
DELT	Deltoid
ECU	Extensor Carpi Ulnaris
EMG	Electromyography
EU	European Union
FCU	Flexor Carpi Ulnaris
HJ	Hard Joint
ISO	International Organization for Standardization
MJ	Medium Joint
MRI	Magnetic Resonance Imaging
MSD	Musculoskeletal Disorder
MVE	Maximum Voluntary Electrical Activation
OEL	Occupational Exposure Limits. Regulatory values for a concentration of some agent in relation to a specified reference period
QS	Quick Step (Tightening program by Atlas Copco)
SD	Standard Deviation
SDG	(United Nations) Sustainable Development Goal
SJ	Soft Joint
TRAPZ	Trapezius
TRI	Triceps Branchii
TT	Turbo Tight® (Tightening program by Atlas Copco)

Acceptability limits	Study specific acceptable limits relating to some physical parameter, as assessed by study participants
Exposure limits	Limit values relating to some physical exposure defined by decision-makers (whether on a corporate, national or international level)
Limit values	The term used in Paper I instead of ‘Exposure limits’
Reaction Load	The collective name for the various physical parameters (reaction force, reaction torque, impulse, displacement and jerk) which the tool user is exposed to when using handheld tightening tools
Tightening program	Programmable setting of the power tool determining the torque buildup mode

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I am rooted, but I flow

- Virginia Woolf

1 Introduction

Corporate businesses compete by various strategic metrics, such as price, product quality, and customer experience. Yet another metric that could position organizations in a competitive advantage, and that is being increasingly invested in, is that of sustainability (Pratono et al., 2019). While being a multifaceted term, one aspect of sustainability concerns occupational health (ILO, n.d., Gualtieri et al., 2020). One of the industries heavily focusing on sustainable working conditions is the assembly industry, where manual labor and high physical demands are common. The highly assembly-focused automotive industry accounts for one of the highest incidences of musculoskeletal disorders (MSDs) (Ferguson et al., 2012).

One of the main tasks of an assembly operator is to join the product components of e.g. an automotive engine. This is typically achieved by using handheld powered tightening tools (also known as nutrunners), applying torque to screw-joints (e.g. nuts and bolts) (Ku et al., 2007). Depending on the type of tightening tool, these tools expose the users to vibrations and reaction loads (commonly referred to as reaction force or reaction torque) (Forsman et al., 2002, Joshi et al., 2012). With the rise of programmable and ‘smart’ power tools, there are possibilities to precisely customize the torque-buildup patterns of the tools, which in turn also influence the tool use experience for the operator (Steingraber et al., 2021).

Both vibrations and force exposure are acknowledged contributors to MSDs (Charles et al., 2018). By EU law, it is required that employers regulate their employees exposure to vibrations by complying with the EU Directive 2002/44/EC (EUR-Lex, 2002). Power tool manufacturers today systematically measure and declare the vibration levels of their products by following the ISO 28927-2 standard (ISO, 2009). However, for reaction load exposure, there are no corresponding regulations or guidelines to adhere to.

Tool using organizations (e.g. automotive manufacturers) have for many years turned to their suppliers, i.e. the power tool manufacturers, for guidance about exposure recommendations for reaction loads. However, power tool manufacturers have lacked well-grounded and generally acknowledged recommendations or standards to refer to. Therefore, there is a need for a standardized assessment method for power tool manufacturers to evaluate the reaction loads of their handheld tightening tools, as well as recommended exposure limits for reaction loads complying with modern tightening tool technologies.

The field of power tool ergonomics has been extensively researched throughout the recent decades. Related specifically to handheld tightening tools, analytic biodynamics models of tool use have been developed and used (Lin et al., 2001, Lin et al., 2003, Radwin et al., 2016) and physiological responses following tool use have been studied (Kihlberg et al., 1993, Forsman et al., 2002, Steingraber et al., 2021). Moreover, subjective assessments (Freivalds and Eklund, 1993, Oh and Radwin, 1998, Lin et al., 2012), as well as psychophysical approaches have been utilized to investigate reaction load exposure (Kihlberg et al., 1995, Moore and Wells, 2005, Valencia et al., 2022). Despite the existing body of knowledge, there are no generally adopted practices for evaluating reaction loads from handheld tightening tools.

By offering employee-centric and ergonomic working conditions, employers can retain their staff (and thereby valuable knowledge) for longer, while sustaining their reputation as an attractive workplace for future employees (Neumann and Dul, 2010). In addition, prioritizing occupational health can support business goals and thus overall organizational performance (Dul and Neumann, 2009).

2 Thesis aim and included papers

The overall aim of this thesis was to contribute to the development of recommended exposure limits for, and assessments of, reaction loads resulting from use of electric handheld tightening tools. The anticipation is that such recommendations and assessments can serve tool manufacturers and tool using organizations when evaluating the health risks associated with tightening tool use. Prospectively, the purpose of this thesis is to contribute to reduced MSD risks among assembly operators.

This thesis is composed of the four journal articles listed below, in which the overall thesis aim is addressed through different perspectives.

- **Paper I:** The purpose of the first paper was to investigate existing literature related to reaction load exposure from handheld tightening tools. More specifically, the aims were to, *i*) list which physical properties of reaction load that have been assessed in previous research, *ii*) investigate reported relationships between reaction load exposure and MSDs, *iii*) map any existing recommended or derived exposure limits related to reaction loads, and *iv*) present knowledge gaps related to the topic and propose means of addressing them.
- **Paper II:** The aim of the study reported in the second paper was to derive acceptability limits for reaction load exposure resulting from electric right-angle tool use, as assessed by assembly operators. The findings from the study are intended to contribute to the future development of exposure limits for electric right-angle tightening tools.
- **Paper III:** The study reported in the third paper was a replication of the second study but pertained to pistol-grip tools. The aim was to derive acceptability limits for reaction load exposure resulting from electric pistol-grip tool use, as assessed by assembly operators. This, to contribute to the future development of exposure limits for electric pistol-grip tightening tools.
- **Paper IV:** The aim of the study reported in the fourth paper was to explore an automotive manufacturer's practice when evaluating and managing reaction load exposure from handheld tightening tools. By understanding the practical context, decision-makers could be more purposeful when designing exposure recommendations and assessment methods for reaction loads from tightening tools.

3 Theoretical background

3.1 Work-related musculoskeletal disorders

Musculoskeletal disorders (MSDs) are physical damages to the human body's musculoskeletal system, influencing muscles, tendons, joints, nerves and supporting structures of the body (Anderson et al., 1997). These disorders are typically a result of sudden or repetitive exposure to physical loads such as forces, weights, vibrations and adverse body postures (National Institute for Occupational Safety and Health, 1997). MSDs can result from a combination of factors and need not necessarily be caused by physical loads alone (Punnett, 2014). Organizational and psychosocial work-environment factors, as well as sociodemographic and individual factors, can all influence musculoskeletal health (EU-OSHA, 2019). The consequences of MSDs typically manifest as pain, limited mobility and functional impairment (World Health Organization, 2022). According to the World Health Organization, MSDs negatively influence well-being and limit the ability of societal participation. Globally, MSDs are the most common reason for need of rehabilitation, and it has been estimated that approximately 1.71 billion people (in 2019) had some variant of musculoskeletal medical conditions (Cieza et al., 2020).

Many cases of MSDs emerge from the working conditions in professional occupations, where there is a discrepancy between the physical demands of the work tasks and the employees' physical capabilities and limitations (Korhan, 2019). In a report about work-related MSDs in the European Union (EU) (EU-OSHA, 2019), released by the European Agency for Safety and Health at Work, three out of five employees reported MSD complaints. The most commonly reported types of work-related MSDs were pain in the back (43%) and upper limbs (41%).

Apart from the employee's personal suffering resulting from MSDs, there are substantial economic consequences associated with MSDs. The total economic impact resulting from MSDs is difficult to estimate. As described by Rose et al. (2013), the costs can be divided into visible costs (by the authors referred to as 'direct costs'), i.e. costs related to absenteeism, insurance and compensations, and, hidden costs (by the authors referred to as 'indirect costs'), e.g. losses in productivity, quality deficiencies and personnel turn-over. It has been estimated that US businesses in 2018 spent 58.6 billion USD on serious, non-fatal workplace injuries, of which 68.9% were attributed to MSDs (Liberty Mutual Insurance, 2021). Further, estimations show that the economic burden on the Swedish society as a result of MSDs, in 2012, was approximately 9.9 billion EUR (circa 2.8% of Sweden's GDP) (Ahlberg, 2014).

3.2 Industrial assembly work

In the EU, industrial assembly work constitutes a significant part of the overall employment scene (Landau et al., 2008). Albeit some parts of the assembly process are automated, current automation technologies, such as robots, lack the flexibility, resilience, and problem-solving skills of human operators (Dencker et al., 2009, Fletcher et al., 2020).

Assembly work is typically characterized as a physically demanding type of job. Assembly operators' work tasks typically involve force exertions, repetitive work, adverse and static body postures, forceful hand-arm movements and heavy lifting, which all are factors identified as causes of MSDs (Fredriksson et al., 2001, Gallagher and Heberger, 2013), in particular when combined (Bano et al., 2015).

In addition to the physical demands of the various work tasks, assembly work induces cognitive load on the operators (Biondi et al., 2023). Cognition involves e.g. attention, perception, memory, decision-making and problem solving (IEA Council, 2000). The scientific discipline of cognitive ergonomics is in turn concerned with how these capacities interact with the different elements of a work setting and how they influence performance outcomes (Wollter Bergman et al., 2021). As mapped by Wollter Bergman et al. (2021), the cognitive demands present in automotive assembly work are related to time, decision-making activities, complexity of the products and the production system, and stimuli occurring in the work environment. The work tasks in a given work cycle can be precision-demanding, for example when mounting and mating product components and connectors (Andrews et al., 2008, Wollter Bergman et al., 2021). High variation of assembly components can induce cognitive load due to high memory demands, whereas tasks with too little variation can be experienced as understimulating and thereby lead to declined attention (Young et al., 2015).

The assembly workforce is not a homogenous group, but rather constituted of individuals with diverse characteristics. One demographic shift observed in various industries is related to the substantial increase of aging workforce (Thun et al., 2011). While some performance-related improvements can be associated with experienced employees, there are physical capacities which tend to deteriorate with age (Silverstein, 2008). Changes in cardiovascular function, muscular strength, vision and auditory system are linked to aging (Flower et al., 2019). It should however be noted that overall physical fitness, regardless of age, has shown higher correlations to work capabilities compared to age alone (Davis and Dotson, 1987). The Organization for Economic Cooperation and Development (OECD) expect that the percentage of their member-nations' population older than 50 years will increase from 37% in 2020 to 45% in 2050 (OECD, 2021). In 2016, 18.6% of the US working population were above the age of 65. Therefore, due to these demographical differences and changes, there are profound incentives for investing in improved working conditions and meeting the future needs of employees.

3.3 Handheld tightening tools

Assembly operators' main task is to assemble product components of e.g. motor vehicles. There are different means of joining product components, such as gluing, riveting, welding and tightening screw joints (e.g. threaded fasteners) (Haettel, 2019). Since the tightening process is reversible and allows for convenient disassembly, it is one of the most common means of joining product components (Pai and Hess, 2002, Moses et al., 2009). Screw joint tightening is accomplished by applying torque to a screw joint using various fixtured and handheld tools.

Some of the handheld tools are manual and rely on muscular force from the operator to produce a torque output (e.g. manual torque wrenches), whereas others require external powering sources such as compressed air, hydraulics or electricity (e.g. nutrunners) (Oh and Radwin, 1998, Lin et al., 2006). The latter are referred to as power tools and are commonly used in assembly and manufacturing industries (Oh and Radwin, 1997, Lin and McGorry, 2009, Xu and Lin, 2015). They contribute to the assembly process through increased operator capacity and tightening accuracy (Freivalds and Eklund, 1993, Potvin et al., 2004) and can produce torque outputs far beyond what humans manually can produce through muscular force alone.

Traditionally, pneumatic power tools have been the standard tool type in assembly industries (Potvin et al., 2004), dating back to the late nineteenth century when the pneumatic drill was invented (Geiger and Ster, 2015). Throughout the past decades, there has been a shift in manufacturing and assembly industries where electric tools have become increasingly prevalent, and today dominate many production settings (Steingraber et al., 2021). Pneumatic power tools require installations of extensive air compressor systems in the production facilities, which are inherently energy inefficient due to the sequences of power losses in the energy conversion process (Pourmovahed et al., 1993, Odum et al., 2014). Therefore, electric tools are the more sustainable alternative from an energy-efficiency point of view. In addition, the use of compressed air results in noise emissions from pneumatic tools, whereas electric tools normally are associated with low noise levels (Rempel et al., 2019). However, the incorporation of a motor and electrical components in electric tools leads to increased tool weight compared pneumatic tools, and a lower power-to-weight ratio (Pourmovahed et al., 1993). Further, in terms of costs, electric tools generally constitute a more expensive initial investment than pneumatic tools (Ibid.).

Handheld tightening tools also differ in terms of tool handle configurations, and can be either in-line, right-angle or pistol-grip (Freivalds and Eklund, 1993) (Figure 1), intended for different applications.



Figure 1. Different tool handle configurations. From left: Pistol-grip, right-angle, and inline tool. © Atlas Copco Group

Ideally, the choice of tool handle configuration should allow for the wrist and forearm to be in neutral alignment (Lindqvist, 2022). In-line tools (also known as straight tools) are mainly suitable when performing low-torque tightenings on a horizontal surface, and result in dorsal and palmar flexion of the operators' wrist (Ibid.). Likewise, right-angle tools are appropriate for horizontal workspaces (Freivalds and Eklund, 1993), and are capable of producing high torque levels (Lindqvist, 2022). Using a right-angle tool subjects the operator to a pull-motion when counteracting the resulting reaction force from the tool. Pistol-grip tools are suitable for tightenings on vertical workspaces. Working with a pistol-grip tool induces forearm pronation and supination (Lindqvist, 2022). In practice, however, workspace and application factors, such as accessibility and required tightening torque, may influence the choice of tool handle configuration.

In addition to differences in powering mechanisms and tool handle configurations, electric and pneumatic tools differ in terms of operating mechanisms. In principal, pneumatic tools shut off through a mechanical clutch once an approximate predefined tightening torque level has been achieved (Potvin et al., 2004) and therefore have rather low torque precision. Electric tools on the other hand, either cable or battery powered, can incorporate transducers for continuous monitoring of various parameters and conditions which need to be fulfilled before finalizing the tightening procedure (Ibid.). Further, many of today's electrically powered tightening tools incorporate software which enables customized and traceable tightening procedures, where factors such as tightening torque, tightening angle and tool speed can be precisely controlled (Persson et al., 2021).

The different modes of torque build-up in tightening tools are called *tightening programs* (sometimes referred to as tightening algorithms or tightening strategies). As described by Persson et al. (2021), the conventional torque-buildup methods are referred to as *continuous drive* tightening programs, where torque in the screw-joint typically is built up according to predefined tool speeds. An example of a continuous drive tightening can be seen in Figure 2.

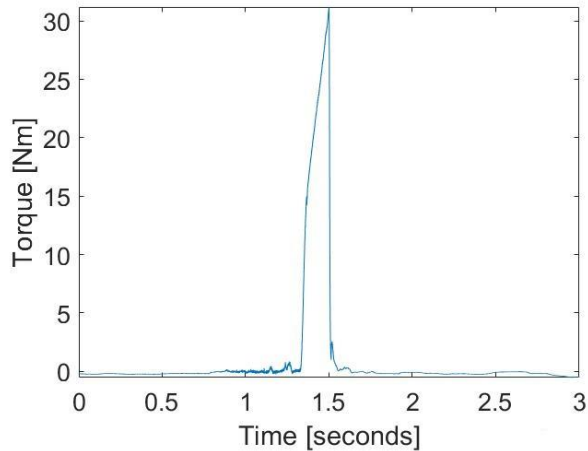


Figure 2. Example of torque buildup curve of a continuous drive tightening program.

Torque-buildup methods where drastic speed variations are utilized are referred to as *highly dynamic* tightening programs. Impact, pulse or inertia-controlled tightening programs (described below) are all highly dynamic tightening programs (Ibid.).

Impact tightening tools can be pneumatic or electric, and they make use of mechanical impact for torque-buildup. Impact tools have a motor which accelerates a rotary hammer to hit a rotary anvil in the tool (Wallace, 2015). By rapidly repeating this process, a pulse like series of torque output is obtained (Skoog, 1970, Wallace, 2015). An example of an impact tightening can be seen in Figure 3. Relatively low torque is required to accelerate the rotary hammer (motor torque), in relation to the high resulting tightening torque outputs, where some can achieve over 1000 Nm (Atlas Copco Industrial Technique, n.d.-a). The impact tools' high power-to-weight ratio makes them ideal for high torque applications. In terms of operator exposures, impact tools generate low reaction torques, but result in considerable vibration and noise emissions.

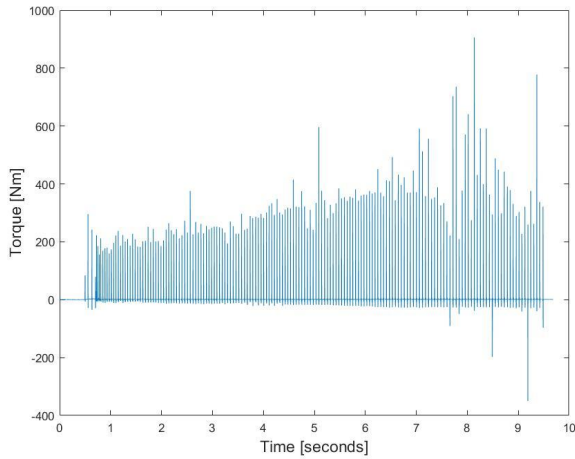


Figure 3. Example of a torque buildup curve of an impact tool.

Pulse tightening tools can be either pneumatic or electric, and, unlike impact tools, generate pulses by hydraulic means. Pulse tools are equipped with a hydraulic pulse-unit, which creates oil pressure between the inertia body and a rotary anvil (Persson et al., 2021). Thanks to the pulse shaping hydraulic mechanism, pulse tools result in controlled and smooth pulses. Pulse tools generate low reaction torques but instead lead to vibration emissions. However, the oil content in hydraulic pulse tools leads to damped vibrations and lower noise emissions compared to impact tools (Haettel, 2019). An example of a pulse tightening can be seen in Figure 4.

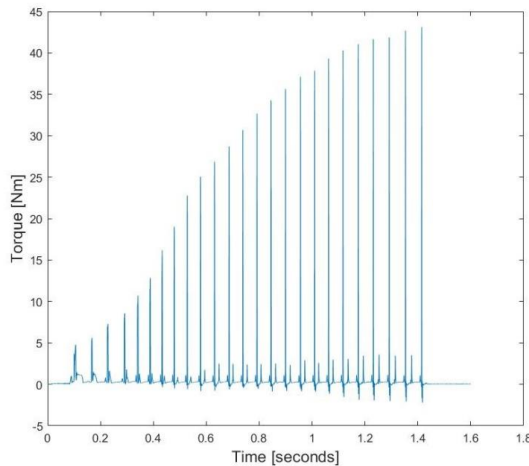


Figure 4. Example of torque buildup curve of a hydraulic pulse tightening program.

Electric tightening tools can also be operated through inertia-control, where the tool speed is regulated in real-time based on continuous torque-rate ($\delta\text{Torque}/\delta\text{Angle}$) measurements (Persson et al., 2021). The energy required is optimized to allow for the speed to reach zero as the target tightening torque is reached (Elsmark, 2010). This results in a rapid tightening procedure where the inertia of the tool impedes the movement of the tool handle and thus leads to a short duration force exposure for the operator (Persson et al., 2021). In addition, such rapid tightening programs result in short tightening times which in turn promotes increased productivity (Atlas Copco Industrial Technique, n.d.-c). An example of an inertia-controlled tightening can be seen in Figure 5.

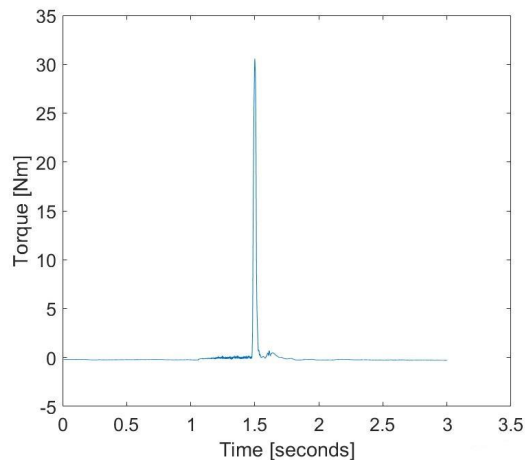


Figure 5. Example of torque buildup curve of an inertia controlled tightening program.

3.4 Working with handheld tightening tools

3.4.1 Reaction load

When conducting a screw-joint tightening, the operator holds the tool with the tool socket placed on the head of the screw-joint. As the operator activates the tool by engaging the tools' trigger, the *rundown* phase of the tightening begins and the screw-joint starts to rotate (Kumar et al., 2022). This is followed by the *rundown complete point*, or *snug point*, where resistance starts to develop in the joint and torque buildup is initiated (Lin et al., 2006, Kumar et al., 2022). The torque in the joint builds up as a function of the rotational angle of the joint (Lindqvist, 1993). The rotational angle required for the screw-joint to reach the desired tightening torque signifies the stiffness of the joint (Atlas Copco Industrial Technique, 2015).

The tightening procedure results in movement of the tool handle, where the operator needs to exert a force in the opposite direction of the movement (Lin et al., 2010b) in order to maintain control over the tool movement and ensuring the quality of the tightening. As the tightening procedure comes to an end, i.e. when the target tightening torque is reached, the

conserved mechanical energy in the system is released in the form of a rapid and/or forceful displacement of the tool handle (Kihlberg et al., 1993, Forsman et al., 2002). The tool reaction, which could be characterized by different physical quantities, is in this thesis collectively referred to as *reaction load* (otherwise commonly referred to as reaction force, reaction torque or torque reaction).

Reaction force is associated with right-angle tools, where the tool handle motion is linear, whereas reaction torque is associated with pistol-grip and in-line tools, where the tool handle undergoes a rotational movement. Likewise, linear and angular tool handle displacements are coupled to right-angle and pistol-grip/in-line tools, respectively. Traditionally, in studies investigating reaction loads from tightening tools, reaction force/torque and handle displacement have commonly been assessed (Kihlberg et al., 1993, Lindqvist, 1993, Kihlberg et al., 1994, Armstrong et al., 1999, Potvin et al., 2004, Ku et al., 2007, Lin et al., 2007). Another physical parameter related to the reaction load is the impulse of the reaction force or torque, obtained through the time integration of the reaction force or torque (Freivalds and Eklund, 1993). Not only does the impulse parameter account for the peak of the reaction force or torque, but also the duration of the reaction force or torque. It is therefore suggested that the impulse more holistically reflects the reaction load which the operator is exposed to, compared to the peak reaction force or torque alone (Freivalds and Eklund, 1993). Reaction force and impulse are shown in Figure 6. Further, the velocity of the tool handle and its first time derivative, acceleration, have also been assessed in various studies, albeit to a lesser extent than the aforementioned parameters.

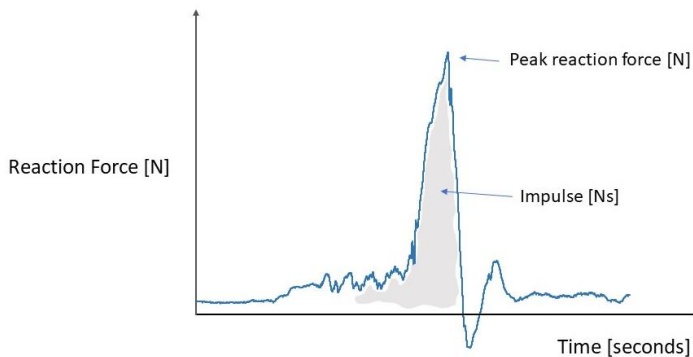


Figure 6. Example of a reaction force signal, with peak reaction force and impulse marked.

3.4.2 Eccentric muscle work

When a tool operator counteracts the displacement of the tool handle, i.e. the reaction load, she or he exerts eccentric muscle work (Oh and Radwin, 1998, Armstrong et al., 1999), meaning that the muscle is forced to lengthen in order to produce force (Hody et al., 2019). Other means of muscle contraction are concentric (muscle-shortening) and isometric (constant muscle length) (Radák, 2018).

Eccentric muscle contractions occur when a force applied to the muscle overpowers the force developed by the muscle and lead to mechanical energy being absorbed by the muscle (Hody et al., 2019). Common everyday situations where humans exert eccentric muscle force is when walking downhill or when running, where the eccentric contraction has a shock-absorbing and elastic energy storing function (LaStayo et al., 2003, Gault and Willems, 2013).

Eccentric muscular work, especially when exerted as a part of an unaccustomed movement, gives rise to delayed-onset muscle soreness which has been linked to muscle damage and inflammation (Smith, 1991, Lewis et al., 2012, Heiss et al., 2018). The body responds to the damage by administering immune system cells (macrophages and lymphocytes), which in turn act to form new muscle fibers and thus promote muscle growth and increased muscle strength (Klossner et al., 2007, Donatelli et al., 2017). The muscle soreness typically appears within 24 hours following the eccentric action, culminates after 24 to 72 hours, and successively diminishes within five to seven days (Hody et al., 2019). If sufficient recovery time is not allowed and the muscle is subjected to intense physical activity during the recovery phase, there is a risk of further damage to the muscle (Nicol et al., 2006).

Many of the physically demanding work tasks that assembly operators repetitively perform involve eccentric muscle work, such as operating handheld tightening tools. Therefore, working with these tools has been recognized as a risk factor for MSDs (Lin et al., 2007, Xu and Lin, 2015).

3.5 Existing regulations

In order to prevent and reduce the prevalence of work-related health-problems, authorities and organizations take measures to, first of all, eliminate, and if not possible, reduce the exposures occurring in occupational settings (Schenk et al., 2008, NIOSH, 2023). Health-promoting efforts can e.g. constitute appropriate choice of equipment and work-task design, physical aids, use of personnel protective gear, as well as work-staff rotations (NIOSH, 2023). Some of these efforts are enacted through laws and legislations whereas others are formed by the individual organizations (Berlin et al., 2009, Arvidsson et al., 2021).

The EU provides directives related to health and safety at work. These are legally binding for all EU member states and are transposed into national laws (EU-OSHA, 2021b). In the case of machinery, the EU Machinery Directive 2006/42/EC specifies safety requirements for design, construction and use of machines (EU-OSHA, 2021a) such as power tools. The

directive targets manufacturers, importers and distributors of machinery (Sveriges Riksdag, 2021). In addition, there is the Council Directive 2009/104/EC related to health and safety requirements when using work equipment (EUR-Lex, 2009). More specifically, vibration exposures, which are commonly associated with handheld power tools, are regulated through the Directive 2002/44/EC (EUR-Lex, 2002).

An example of a regulatory authority on a national level is the Swedish Work Environment Authority, who provide a provision related to prevention of musculoskeletal disorders; AFS 2012:2 (Swedish Work Environment Authority, 2012). The AFS 2012:2 provision covers several of the commonly occurring work exposures and conditions contributing to MSDs, such as posture, repetitive work, manual handling, as well as psychosocial and organizational factors (Swedish Work Environment Authority, 2012). The provision does however not provide specific numerical exposure limits, but instead guidance expressed in general terms.

One provision directed at power tool manufacturers (as well as distributors and importers) is AFS 2008:3 (Swedish Work Environment Authority, 2008) where product requirements on power tools are stipulated. The provision enacts the EU Machinery Directive¹ (Swedish Work Environment Authority, 2020). In addition, there is a provision dedicated to the *use* of work equipment, AFS 2006:4 (Swedish Work Environment Authority, 2006), which is based on Directive 2009/104/EC. Vibration emissions from power tools are in Sweden regulated by the AFS 2005:15 provision (Swedish Work Environment Authority, 2005). As stated in the provision, the daily exposure action value for hand-arm vibrations is 2.5 m/s^2 , and the corresponding limit value is 5 m/s^2 (over an 8-hour reference period).

Further, in the ISO 11148-6:2012 standard (ISO, 2012), risk-reducing efforts for reaction load exposure from non-electric handheld tightening tools are outlined. The standard provides tightening torque limits for the different tool handle configurations (e.g. 10 Nm for pistol tools and 60 Nm for angle tools). For tightening torque levels exceeding the stated limits, the standard recommends to use a 'second handle' or a reaction bar. However, unlike directives, which are mandatory, compliance with standards is voluntary (ISO, n.d.). For electric power tools, which today are more commonly used than non-electric tools, there are no corresponding standards. Nor are there legislative directives or national provisions addressing reaction load exposure from such tools. As a result, industrial organizations, such as automotive production companies, develop their own, company-specific, evaluation models and limits for exposures occurring in their facilities (Hagg, 2003, Berlin et al., 2009), such as handheld power tools.

¹ The EU Machinery Directive 2006/42/EC is valid at the time of writing, but will be repealed by Regulation 2023/1230 (EUR-Lex, 2023)

4 Delimitations

As described in the theoretical background, handheld tightening tools come in a variety of shapes, powering mechanisms and tightening modes. The tool types focused on in this thesis were electric right-angle and pistol-grip tools operated with continuous drive and inertia-controlled tightening programs. Pneumatic tools were excluded from the thesis as assembly industries today increasingly shift towards electric power tools. Furthermore, pulse-based tightening tools were not studied as they typically do not result in reaction load but are rather associated with vibration exposure.

5 Methods

To address the research aim, first, a literature review was conducted where available knowledge was synthesized, and knowledge gaps were identified. Based on the outcomes of the literature review, directions for continued research were proposed. Secondly, an experimental study was conducted where acceptability limits for reaction load exposure from handheld right-angle tightening tools were derived. Following the right-angle tool study, a similar experimental study revolving around handheld pistol-grip tightening tools was conducted. Finally, an interview study was conducted in order to explore practitioners' perspectives on handheld tightening tool use in industrial automotive assembly.

5.1 Research paradigms

The research presented in this thesis should be assessed in the light of the methods and research paradigms undertaken, i.e. the assumptions and theories underpinning the research approach. The findings of the presented work are inevitably influenced by the theoretical lens through which the research topics have been formed, observed, and studied.

The literature study consists of a systematic examination of available publications and is based on the researcher's interpretive description of the existing literature. The chosen search strategy (e.g. researcher-defined inclusion and exclusion criteria) for the literature selection process implies that the work was given a direction regarding what was considered relevant data to the review study (Thorne, 2016).

The experimental studies are associated with a post-positivist research philosophy. The researcher's influence on framing the research questions, designing the studies, collecting, and analyzing the data, has inherently shaped the particular studies. While recognizing the unattainable state of objectivity, the post-positivist stance seeks to elaborate on possible influences and biases which may have affected the research (Clark, 1998).

For the interview study conducted, a mainly pragmatist perspective was undertaken. Given the industry-driven need for the research presented in this thesis which, in part, intended to promote action, constructive knowledge was needed (Goldkuhl, 2012). According to the pragmatist epistemology, knowledge is considered to act as an instrument for change (Dewey, 1931).

5.2 Study I – Literature study

The literature study was conducted in the form of a scoping review, where at the time available and relevant publications within the topic area of reaction load exposure from handheld tightening tools were reviewed.

Publications to consider for inclusion in the review were identified through data base searches (Scopus, PubMed and ScienceDirect) and other sources (the researchers' own networks). Synonyms corresponding to key concepts (e.g. power tool, reaction load, subjective assessments) were formulated and combined into search strings. Titles and abstracts of the publications resulting from the data base searches were read and benchmarked against the defined inclusion criteria: 1) studies pertaining to prototyped and real handheld tightening tools, 2) models (e.g. mathematical ones) simulating powered handheld tightening tools, 3) studies examining physiological responses to reaction load exposure from handheld powered tightening tools, or, 4) studies investigating the combined influence of tightening tool use and work pace. If satisfying the inclusion criteria, the corresponding full text publications were subsequently assessed based on the defined exclusion criteria: publications with a primary focus on trigger force, handle design and anthropometrics, grip force, manual handling, vibrations, or evaluation and development of measurement methods were excluded from the review. Besides the inclusion and exclusion criteria, it was required that the publications were available in digital format, written in English, and published between 1985 and 2019. The PRISMA approach was used for reporting the publication-selection process (Moher et al., 2009).

The publications ultimately qualifying for inclusion in the qualitative synthesis were thematically analyzed with respect to the objectives of the review, i.e. to map which physical properties of reaction load (e.g. peak reaction force, impulse, tool handle displacement) that have been assessed, reported relationships between reaction load exposure and physiological changes, and reported recommendations or threshold values for reaction load exposure. Information related to these topics were systematically extracted from the included publications and reported in tabular format. In addition, information regarding the included publications' study designs were organized in tabular format.

5.3 Study II and Study III – Experimental studies

Two experimental studies, with similar study designs, were conducted in a lab setup. The first experimental study (Study II) pertained to electric right-angle tools, and the second experimental study (Study III) pertained to electric pistol-grip tools. The studies were conducted at separate occasions.

5.3.1 Participants

Experienced assembly operators ($n = 17$ for Study II and $n = 20$ for Study III) from a Swedish automotive manufacturer voluntarily participated in the experimental studies. An ethics approval was obtained from the Swedish Ethical Review Authority, with diary number 2019-04956. Prior to the experiments, all participants were informed both verbally and in written form about the goals of the studies, the experimental procedure, potential risks, and the requirements for partaking in the studies. With this information at hand, they gave their written informed consent for participating in the experiments. The participants of both studies predominantly used right-angle tools in their jobs on a daily basis, and pistol-grip tools less frequently.

5.3.2 Study design

Both studies were factorial design studies. In Study II, three factors were incorporated (tightening program, joint stiffness, and work pace), whereas in Study III, two factors were incorporated (tightening program and joint stiffness). The assessed factors (independent variables) and responses (dependent variables) are reported in Table 1.

Table 1. The independent and dependent variable of Study II and Study III.

	Independent variables	Dependent variables
Study II	Tightening program (Turbo Tight® and Quick Step) Joint stiffness (Hard, 0.8 Nm/° and medium, 0.3 Nm/°) Work pace (5 tightenings/min and 8 tightenings/min)	Tightening torque [Nm] Peak reaction force [N] Impulse [Ns] Tool handle displacement [cm] Jerk [m/s^3] Electromyography [%MVE] Discomfort ratings
Study III	Tightening program (Turbo Tight® and Quick Step) Joint stiffness (Hard, 0.1 Nm/° and soft, 0.02 Nm/°)	Tightening torque [Nm] Peak reaction torque [Nm] Impulse [Nms] Tool handle displacement [°] Jerk [m/s^3] Electromyography [%MVE] Discomfort ratings

For both studies, it was hypothesized that operating the tools with the highly dynamic tightening program on the hard screw-joints would result in lower physical load for the operators, and thus higher acceptable tightening torque levels, compared to the continuous drive tightening program on the softer screw-joints.

The participants were instructed to conduct screw-joint tightenings with a right-angle tool (Study II, tool model Atlas Copco ETV STR61-70-13) and a pistol-grip tool (Study III, tool model Atlas Copco SRB31-20-10). The stiffness of the screw-joints on which the tightenings were conducted were either on the harder or the softer end of the joint stiffness classification scale (ISO, 1994).

In both experimental studies, the tool speed settings were varied through two different tightening programs: the TurboTight® (TT) and Quick Step (QS) tightening programs by the power tool manufacturer Atlas Copco. The QS tightening program is a continuous drive program, representing a conventional means of operating a programmable tightening tool. The QS program behaves in a stepwise manner, where a defined initial speed ('first speed') is sustained up until a first defined torque level ('first torque', typically 50% of the target torque). Once the 'first torque' is reached, the speed instantly drops to another, typically much lower, speed ('final speed') which is maintained until the target torque level is reached (Atlas Copco Industrial Technique, n.d.-b). The tool handle undergoes no or low acceleration, meaning that most of the reaction load is transferred to the tool operator. The TT tightening program is an inertia-controlled tightening program, where joint stiffness is dynamically read by the tool throughout the tightening process (Atlas Copco Industrial Technique, n.d.-c). Based on the joint-stiffness readings, energy required to reach the target torque is calculated, and tool speed is dynamically regulated throughout the tightening process (Ibid.). As the TT program operates under very high speed, large portions of the reaction load is absorbed by the tool itself thanks to inertial effects of the tool mass (Atlas Copco Industrial Technique, n.d.-b).

In Study II, tightenings were conducted at a frequency of either five or eight tightenings per minute in order to study how work-pace influenced the dependent variables. In Study III, it was decided to keep the work-pace constant, i.e. at five tightenings per minute. This was based on the outcomes of Study II, where the different repetition frequencies did not show an influence on the dependent variables (potential reasons are discussed in Paper III). The work paces were chosen after conversations with representatives from the Swedish and North American automotive industry and reflect an approximate average of common repetitions frequencies of screw-joint tightening. The experimental conditions for both studies are listed in Table 2.

Table 2. The combinations of independent variables constituting the experimental conditions of Study II and Study III. TT = Turbo Tight®, QS = Quick Step®, HJ = Hard joint, MJ = Medium joint, SJ = Soft joint.

	Experimental condition no.	Tightening program	Joint Stiffness	Work-pace [tightenings per minute]
Study II	1	TT†	HJ	5
	2	TT	HJ	8
	3	QS	HJ	5
	4	QS	HJ	8
	5	QS	MJ	5
	6	QS	MJ	8
Study III	1	TT	HJ	5
	2	QS	HJ	5
	3	QS	SJ	5

†The Turbo Tight® tightening program is mainly suitable for use on hard joints due to its dynamic mechanical properties (Atlas Copco Industrial Technique, n.d.-c). Therefore, TT was only combined with the hard joints in the two studies.

The orders of the experimental conditions were randomized. In Study II, each participant was assigned to four (out of six) experimental conditions, and in Study III, each participant was assigned to all (three) experimental conditions.

Within each experimental condition, the participants conducted screw-joint tightenings in three sets of trials: three 8-minute trials for Study II (total of 24 minutes per experimental condition) and three 4-minute trials for Study III (a total of 16 minutes per experimental condition). Between each trial, the participants rested for two minutes.

5.3.3 Psychophysics approach

A psychophysics approach was used to derive exposure levels which the participants assessed as physically sustainable when working with a tightening tool throughout an 8-hour workday.

For each of the experimental conditions, the participants started to conduct screw-joint tightenings at a predefined tightening torque level (30 Nm in Study II and 4 Nm in Study III), and were asked to assess the perceived load level at the particular tightening torque in relation to the following question: ‘Would you accept to work with a tool that results in such a reaction load’? Based on their assessment of whether the load exposure would enable a physically sustainable workload, they expressed to the research leader whether they wanted to try a higher, lower or unchanged load level. The research leader adjusted the load level by increasing or decreasing the tightening torque (5 Nm per increment/decrement in Study II and 1 Nm per increment/decrement in Study III). At the new load level, the participants would again assess the exposure and express to the research leader whether they wanted a load

level change. Between the trials, i.e. during the two-minute resting time, the research leader changed the tightening torque level in a direction unknown to the participant. Thereby, the new trial was initiated at a load level different from the one that the previous trial had ended. This way, the participant's most recent perception of the load exposure was disoriented. The goal was that the participants, by the end of the third trial, would converge to a load level which they assessed as acceptable to them, and which would enable a sustainable load exposure from the tightening tool. The study participants were blinded to all numerical values (e.g. tightening torque levels) and compositions of the experimental conditions.

The psychophysics approach has previously been used by e.g. Snook and Ciriello (1991) to form guidelines for maximum acceptable forces and weights of manual handling tasks. The approach has also been used to derive maximum acceptable forces for repetitive ulnar deviations (Snook et al., 1997). Related to power tools, Kihlberg et al. (1995), Moore and Wells (2005), and Valencia et al. (2022) have adopted the psychophysics approach to derive acceptability limits for handheld tightening tool use.

5.3.4 Subjective ratings of perceived discomfort

The participants of both Study II and Study III subjectively rated their perceived discomfort associated with each one of the experimental conditions. Their perceived discomfort was rated between each trial, i.e. during the resting time, as well as after the final trial. Each participants performed three rounds of rating per experimental condition. Six upper body regions (the wrists and hands (grouped as one region), neck, shoulders, elbows, upper part of the back, and lower part of the back) were rated according to Borg's CR10 scale (Borg, 1990) on a modified body map (Kuorinka et al., 1987). In addition to the specified body regions, the participants also subjectively rated their perceived *overall* discomfort using Borg's CR10 scale.

5.3.5 Measurement equipment

In both Study II and Study III, tightening torque was measured with a torque transducer (Atlas Copco BLM, Paderno Dugnano, Italy) between the tool head's outgoing shaft and the threaded screw-joint.

In Study II, the reaction load was measured in two different ways depending on the tightening program (Figure 7). For the QS conditions, a simulated tool handle with an integrated force and torque transducer (ATI Industrial Automation, Apex, North Carolina, USA) was attached to the right-angle tool, similar to the measurement handle used by Valencia et al. (2022). For the TT conditions, the simulated tool handle was not used, but instead, data from the attached accelerometer (Piezoelectric CCLD Accelerometer, Type 4508, Brüel & Kjaer, Naerum, Denmark) was used as a means of obtaining the reaction load. As the TT program takes advantage of high speed in combination with the tool's inertia for reducing the reaction load, the simulated tool handle, weighing 1.25 kg, was undesirable.

Instead, a light-weight measurement method was needed in order to keep the overall system's inertia intact.

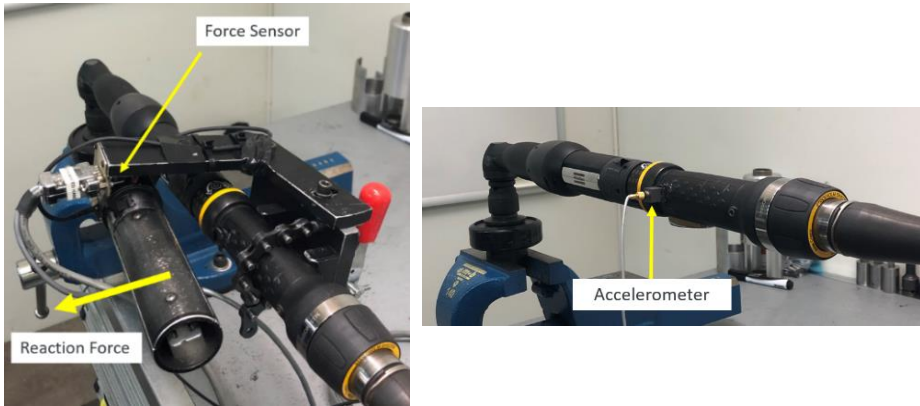


Figure 7. Measurement equipment used in Study II. The measurement handle (left) was used for measuring reaction load when operating the tool with the QS program, and the accelerometer (right) was used for measuring reaction load when operating the tool with the TT program.

The reaction load resulting from operating the tool with the TT program was calculated based on the measured acceleration of the tool handle (Equation 1 and Equation 2). The accelerometer was attached to the tool throughout both the QS and TT conditions, but the reaction load calculations² based on acceleration were only used for the TT condition. For both QS and TT, the tool handle displacement was obtained by double-integrating the acceleration signal, and the jerk was obtained through the time derivative of the acceleration signal. As the tool handle undergoes no or low acceleration when operated with the QS program, the added mass of the simulated tool handle (and thus increased inertia of the system) does not substantially contribute to absorbing the reaction load.

² The accelerometer method used for obtaining reaction force in Study II contains uncertainties (error estimation is reported in Paper II). The reaction force values obtained through the calculations (Equation 1 and Equation 2) were systematically higher than the reaction force values obtained with the reference force transducer used during the development work of the accelerometer method (i.e. the simulated tool handle).

For the TT conditions, Equation 1, describing the sum of all torques acting on the tool, was utilized for calculating the reaction torque:

$$I \cdot \ddot{\Theta} = \text{Torque}_{\text{reaction}} - \text{Torque}_{\text{joint}} \quad (1)$$

where I is the tool inertia [kgm^2], $\ddot{\Theta}$ is the angular acceleration of the tool handle [rad/s^2], $\text{Torque}_{\text{reaction}}$ is the reaction torque [Nm], and $\text{Torque}_{\text{joint}}$ is the screw-joint's tightening torque [Nm]. The $\text{Torque}_{\text{reaction}}$ was then converted to reaction force through Equation 2:

$$\text{Force}_{\text{reaction}} = \text{Torque}_{\text{reaction}} / \text{Distance}_{\text{hand}} \quad (2)$$

where $\text{Force}_{\text{reaction}}$ is the reaction force [N] and $\text{Distance}_{\text{hand}}$ is the distance between the tool head shaft and the operator's right-hand placement on the tool handle [m].

In Study III, reaction torque and reaction angle were measured with a simulated tool handle equipped with a torque and angle transducer (Atlas Copco BLM, Paderno Dugnano, Italy) attached to the rear part of the pistol-tool (Figure 8). The tool trigger was mechanically extended.

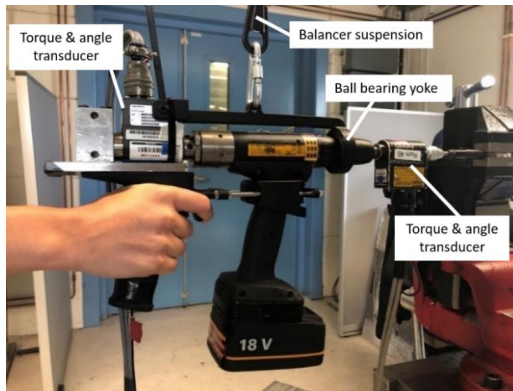


Figure 8. Measurement equipment, setup and simulated tool handle used in Study III.

The jerk motion was measured with an accelerometer (Piezoelectric CCLD Accelerometer, Type 4508, Brüel & Kjaer, Naerum, Denmark) attached to the simulated tool handle.

A tool balancer (Atlas Copco WP-05-4, Stockholm, Sweden) was used to suspend the tool. This, to relieve the participants from the additional weight of the simulated tool handle and measurement equipment (1.03 kg). In order to counteract the upward force applied by the tool balancer on the rotational movement of the tool during tightening, a custom-made suspension yoke with an incorporated ball-bearing was used when suspending the tool.

In both Study II and Study III, muscular activity of right upper extremity muscles was measured throughout the experiments, using Myoware™ Muscle Sensors (Advancer Technologies, Raleigh, USA). In Study II, electromyography (EMG) signals were collected from the flexor carpi ulnaris (FCU), extensor carpi ulnaris (ECU), triceps brachii (TRI) and trapezius (TRAPZ) muscles. In Study III, EMG signals were collected from the flexor carpi ulnaris (FCU), extensor carpi ulnaris (ECU) and the medial deltoid (DELTA) muscles. Surface electrodes were placed along the long axis of the muscles. In order to normalize the EMG signals, maximum voluntary electrical activation (MVE) was recorded prior to the experiments (for details, see Paper II and Paper III).

5.3.6 Data analyses

For both Study II and Study III, the tightening torque levels accepted by the study participants were extracted. All other dependent variables (Table 1) corresponding to the accepted level were subsequently extracted. Descriptive statistics of the data were then obtained (mean and standard deviation).

The collected EMG signals were normalized to each participant's maximum voluntary electrical activation (MVE) levels. Histograms and amplitude probability distribution functions (APDF) of the normalized EMG signals were created (example graphs are reported in Paper III). Static, mean and peak muscular activity levels were extracted from the APDFs, represented by the 10th, 50th and 90th percentiles of the APDF, respectively (Jonsson, 1982). EMG results were reported both in relation to the acceptable load levels, as well as in relation to a constant tightening torque (i.e. 30 Nm in Study II and 5 Nm in Study III) for the sake of comparison.

Inferential statistics were obtained through the non-parametric Kruskal-Wallis test and the Dunn-Bonferroni post-hoc test. As the collected data were not close to a normal distribution, a non-parametric statistical method was chosen. Mean values were compared to investigate the effects to tightening program, joint stiffness and work-pace (only Study II) on the dependent variables. Test statistics (p-values) below the critical value 0.05 were considered to be statistically significant. The statistics software SPSS (IBM SPSS® Statistics 28, New York, USA) was used for the statistical analyses.

5.4 Study IV – Interview study

A qualitative single-case study design was chosen for Study IV, where selected employees of a Swedish multinational automotive manufacturer were interviewed. The study objective was addressed by exploring the following research questions:

1. How are ergonomics assessments of handheld tightening tools conducted in a production organization?
2. What are the challenges when conducting ergonomics assessments of handheld tightening tools?
3. How should handheld tightening tools be assessed in order to satisfy the practitioners' and organization's needs?

5.4.1 Study participants

Employees (n = 14) of the case company were interviewed. The participants were chosen based on the criteria that they, as a part of their professional role, would come in contact with the organization's ergonomics assessment approach (a company-specific standard) for handheld tightening tools. Participants of various professions were included in order to obtain different perspectives on the topic. The participants' specific professions were the following: Ergonomist (n = 5), tightening technician (n = 1), tightening specialist (n = 1), quality technician (n = 1), manager of local production systems (n = 1), ergonomics coordinator (n = 3), back-office process technician (n = 1), and ergonomics assessment specialist (n = 1). Through the researchers' networks, initial study participants were recruited. Additional participants were identified through referral by some of the interviewed participants.

5.4.2 Interviews

A semi-structured interview guide was developed, where a set of prompt questions were phrased. The interview guide was divided into three sections: One section was directed at the participants mainly involved with the *development work* of the organization's company standard for handheld tightening tools. The other section was directed at the participants mainly involved with *applying* the company standard for handheld tightening tools. A third section, applicable to all participants, included questions around prospective thoughts and reflections regarding improved assessments of handheld tightening tools.

The interview questions revolved around incentives for changing the assessment method, input retrieval for the assessment method, other professional roles in the organization which the participants are connected to, potential situations and requirements conflicting with ergonomics efforts related to handheld tightening tools, and role-specific or organizational priorities that could influence the implementation of ergonomics efforts for handheld tightening tools. In addition, questions around perceived usability, utility and improvement potential of the assessment method were phrased. The full interview guide is reported in Paper IV.

5.4.3 Data analyses

The audio recordings of the interviews were transcribed, and thereafter imported to NVivo 14 (2023, Release 14.23.0) for analysis. The interview transcripts were inductively coded (Lauri and Kyngäs, 2005), where the content of the interviews were given headings such as ‘communication’ or ‘quality requirements’. The codes were thematically analyzed (Braun and Clarke, 2006), and commonalities and patterns in interviewee responses were explored. Upon organization and grouping of the codes, overarching themes and associated subcategories were constructed.

6 Results

6.1 Study I – Literature study

Data-base searches and additionally identified documents resulted in a total of 306 publications candidating for review. After removal of duplications and eligibility evaluations, a remainder of 40 publications were included in the qualitative synthesis.

6.1.1 Assessed physical properties of the reaction load

The physical properties of reaction load exposure from handheld tools identified in the included publications were peak reaction force/torque, tool handle displacement, impulse, tool handle velocity/acceleration, power, and energy/work. The frequency at which these parameters were reported in the reviewed publications, as well as assessed tool types, are reported in Table 3.

Table 3. Proportion of tool powering mechanisms, tool types, and studied physical properties identified in reviewed literature.

Powering	No. of studies
Pneumatic	26 (65%)
Electric	12 (30%)
Tool Type	
Pistol-grip	29 (73%)
Right-angle	24 (60%)
In-line	9 (23%)
Physical property	
Peak reaction force/torque [N or Nm]	28 (70%)
Tool handle displacement [cm or degrees]	28 (70%)
Impulse [Ns or Nms]	9 (23%)
Tool handle velocity/acceleration [m/s or m/s ²]	6 (15%)
Power [Watt]	2 (5%)
Energy/work [Joule]	2 (5%)

A majority of the reviewed studies assessed reaction force/torque and tool handle displacement. Albeit tool handle velocity and acceleration were measured in 15% of the publications, no reporting of the time derivative of acceleration, i.e. jerk, was found. As described in 3.4.1, jerk is suggested to be associated with the subjective sensation of control and discomfort.

6.1.2 Reported relationships between load exposure and physiological changes

In three of the 40 reviewed publications, short-term physiological changes in human tissue resulting from reaction load exposure were reported. The changes were regarded as potential risk factors for MSDs.

By assessing magnetic resonance imaging (MRI) scans of upper extremities, Chourasia et al. (2009) reported prevalence of edema as a result of exposure to reaction force from a simulated power tool. Edema is regarded as a precursor to developing MSDs (Foley et al., 1999). Further, Lin et al. (2010a) studied changes in blood volume and oxygenation in the forearms as a result of tightening tools use, by means of near-infrared spectroscopy. Blood deoxygenation has previously been linked to reduced force producing capabilities of the muscles (Murthy et al., 2001). A greater average increase in deoxygenation change was observed for the flexor muscle in the case when the study participants used the tightening tool without resting. In addition, as decreases in local blood volume were observed, the exposure to reaction torque was linked to reduced grip force. The third study reporting on physiological changes following tightening tool use was Sesto et al. (2005), where MRI scans of the forearm were studied for the occurrence of edema. In addition, mechanical properties of the forearm (mass, damping and stiffness) were evaluated. A statistically significant increase in the MRI marker for edema was observed for the extensor muscle one day after exposure to the reaction torque, whereas MRI scans of the non-exposed arm showed no indication of edema. Further, the simulated tool use resulted in a 53% and 58% decreased in mechanical stiffness and effective mass of the forearm, respectively.

6.1.3 Reported limit values for reaction load exposure

Out of the 40 reviewed publications, four presented limit values³ relevant to reaction load exposure from handheld tightening tools (Table 4). The limit values for the three first listed publications in Table 4 have been derived based on psychophysical assessments.

³ At the time of writing Paper I, the term ‘limit values’ was used for what in this thesis is referred to as ‘exposure limits’ (see Acronyms and Concepts for definition of the term).

Table 4. Identified limit values and associated tool types, physical parameters and exposure durations.

Publication	Tool type	Physical parameter	Limits values	Exposure duration
Kihlberg et al. (1995)	Pneumatic right-angle tool	Tool handle displacement Impulse	< 3 cm 1 Nms	'A whole working day'
Moore and Wells (2005)	Electric in-line tool	Tightening torque	1.09 Nm at 25% duty cycle, 0.9 Nm at 50% duty cycle and 0.73 Nm at 83% duty cycle	5 h
Valencia (2018)	Electric right-angle tool	Tightening torque	‡ <u>60° joint</u> ATC: 43 Nm QS: 47 Nm TT: 81 Nm ‡ <u>450° joint</u> ATC: 45 Nm QS: 41 Nm TT: 48 Nm	'A whole working day'
ISO 11148-6:2012 (ISO, 2012)	Pneumatic/Hydraulic/Gas Fuel/ Liquid Fuel Pistol-grip/right-angle/in-line Tool	Reaction torque	¥ In-Line tools: 4 Nm Pistol-grip tools: 10 Nm Right-angle tools: 60 Nm	None reported

‡ Valid at a repetition rate of 3 tightenings/min. For other repetition rates and details, see full publication.

¥ According to the standard, if the torque limits are exceeded, it is recommended to use a second handle for in-line and pistol-grip tools, and a reaction bar for right-angle tools.

The limit value for tool handle displacement expressed by Kihlberg et al. (1995) reflects acceptability for 90% of the included study participants, whereas the limit value for impulse reflects acceptability for 95% of the participants (an impulse of approximately 4 Nms were accepted by 50% of the participants). The limit values for tightening torque reported by Moore and Wells (2005) reflect average acceptability among the participants, whereas the limit values reported by Valencia (2018) accommodate for the physical capability of 75% of the female population.

6.2 Study II – Right-angle tool study

Comparing the different work-paces (i.e. 5 tightenings/min and 8 tightenings/min), load acceptability did neither differ largely nor significantly (potential reasons for this are elaborated on in Paper II). Therefore, the experimental conditions with tightening program and joint stiffness in common, but different work-pace, were merged. As an example, data collected from TT-HJ-5/min and TT-HJ-8/min were merged into a single pool of data, thus composing TT-HJ. All results related to Study II will hereinafter be reported for the three resulting experimental conditions, i.e. TT-HJ, QS-HJ, QS-MJ.

6.2.1 Acceptable load levels

The highest acceptable tightening torque levels were obtained for the TT-HJ condition, where the participants, in average, accepted a tightening torque level of 36.4 Nm. The other assessed physical quantities related to the reaction load, corresponding to the acceptable load levels, are reported in Table 5. As instructed to the participants, the acceptable load levels are supposed to reflect the maximum load reaction load level which the participants assessed would enable a sustainable physical workload throughout an 8-hour workday.

Table 5. Average accepted load levels for right-angle tools derived from Study II, with standard deviations in parentheses. TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, MJ = Medium Joint.

Experimental condition	Tightening Torque [Nm]	Peak reaction force [N]	Impulse [Ns]	Displacement range [cm]	Jerk range [m/s ³]
TT-HJ	36.4 (12.5)	55.8 (13.3)	2.9 (0.6)	3.5 (1.6)	29 800 (5224)
QS-HJ	31.3 (4.7)	63.1 (26.6)	12.0 (8.9)	3.7 (0.9)	19 313 (1902)
QS-MJ	31.9 (14.4)	74.0 (37.7)	15.8 (12.3)	3.4 (0.8)	18 461 (7948)

The experimental condition with the highest acceptable tightening torque levels, i.e. the TT-HJ condition, conversely resulted in the lowest corresponding peak reaction force and impulse among the experimental conditions. On the other hand, the TT-HJ condition resulted in the highest jerk exposure, at the acceptable load level. The high jerk levels imply that the motion of the tool handle changes rapidly, something which the operator needs to counteract. Results from the statistical analysis, comparing the mean acceptable load levels and corresponding muscular activity levels, are reported in Table 6.

Table 6. Results from the statistical analysis performed in Study II. The ‘*’ symbol indicates statistically significant differences between the compared means of the experimental conditions ($\alpha = 0.05$). TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, MJ = Medium Joint.

Measured parameter	TT-HJ : QS-HJ	TT-HJ : QS-MJ	QS-HJ : QS-MJ	p-value	Kruskal-Wallis H	Effect size (ϵ^2)
Tightening torque				p > .05	2.50	-
Peak reaction force				p > .05	1.24	-
Impulse	*	*		p = .000	23.58	-0.421
				p = .000	-29.458	-0.526
				p > .05	-5.875	-
Jerk	*	*		p = .006	9.89	0.396
				p = .001	12.53	0.501
				p > .05	2.64	-
Tool handle displacement				p > .05	2.29	-
FCU muscular activity				p > .05	3.46	-
ECU muscular activity				p > .05	4.41	-
TRI muscular activity	*	*		p = .023	-11.40	-0.248
				p = .002	-15.34	-0.333
				p > .05	-3.94	-
TRAPZ muscular activity				p > .05	1.31	-

6.2.2 Electromyography

At the acceptable load levels, the TT-HJ condition resulted in considerably lower peak muscular activity levels for the ECU and TRI muscles compared to the other experimental conditions. This indicates that operating the tool with the TT program, and on a hard joint, is associated with less muscular demands (assessed in terms of %MVE) for those specific muscles. The peak muscular activity levels for all experimental conditions and studied muscles at the acceptable load levels are reported in Table 7.

Table 7. Average EMG levels at the acceptable load levels for Study II, with standard deviations in parentheses. TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, MJ = Medium Joint, FCU = flexor carpi ulnaris, ECU = extensor carpi ulnaris, TRI = triceps brachii, TRAPZ = trapezius.

Experimental condition	Accepted tightening torque [Nm]	FCU [%MVE]	ECU [%MVE]	TRI [%MVE]	TRAPZ [%MVE]
TT-HJ	36.4 (12.5)	20.2 (15.4)	49.4 (24.8)	14.4 (9.2)	11.4 (5.9)
QS-HJ	31.3 (4.7)	33.2 (22.2)	61.1 (30.2)	30.8 (26.9)	14.7 (8.5)
QS-MJ	31.9 (14.4)	20.9 (11.8)	64.3 (29.9)	34.3 (23.1)	12.5 (7.0)

At the acceptable tightening torque level, only the TRI muscle showed a statistically significant reduction in muscular activity when working with the TT-HJ condition compared to the two other experimental conditions.

The muscular activity levels are also reported in relation to a constant tightening torque level of 30 Nm for the sake of comparison, in Figure 9, and do thereby not correspond to the acceptable load levels.

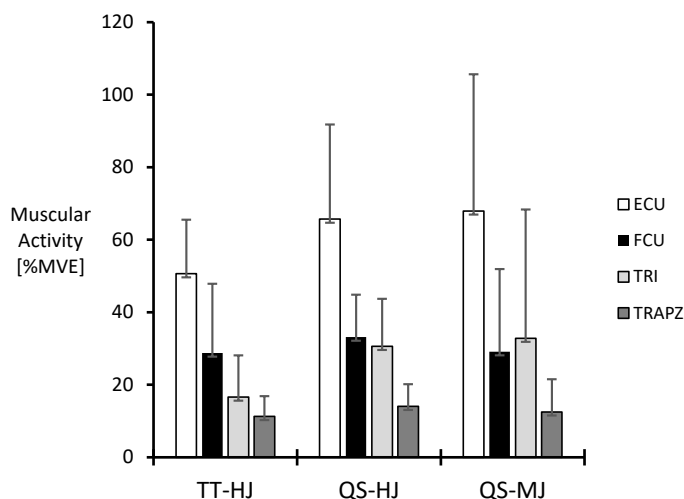


Figure 9. Average EMG levels at 30 Nm tightening torque, with standard deviation bars. TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, MJ = Medium Joint, FCU = flexor carpi ulnaris, ECU = extensor carpi ulnaris, TRI = triceps brachii, TRAPZ = trapezius.

Among the four muscles studied, the ECU muscle resulted in the highest muscular demands, whereas the TRAPZ muscle resulted in the lowest muscular demands. This was the case for all three experimental conditions.

6.2.3 Subjective ratings of perceived discomfort

At the acceptable load levels, the participants in average, rated their overall sensation of discomfort as being ‘weak’ to ‘moderate’ according to Borg’s CR10 scale (Borg, 1990). More specifically, the TT-HJ condition was, in average, rated as 2.6 (SD = 1.4), the QS-HJ was, in average, rated as 2.7 (SD = 1.3), and the QS-MJ condition was, in average, rated as 2.3 (SD = 1.2). The differences in mean subjective ratings of discomfort between the three experimental conditions were not statistically significant. Among the six rated body regions, the discomfort ratings were the highest in the wrists and hands region (grouped as one region), where the participants, in average, rated the sensation of discomfort as 2.5 (SD = 1.7, $p < 0.05$), whereas the discomfort ratings of the lower back region were the lowest (1.4, SD = 1.1).

Table 8. Average accepted load levels for pistol-grip tools derived from Study III, with standard deviations in parentheses. TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, SJ = Soft Joint.

Experimental condition	Tightening Torque [Nm]	Peak reaction torque [Nm]	Impulse [Nms]	Angular displacement [degrees]	Jerk [m/s ³]
TT-HJ	10.5 (2.6)	1.2 (0.6)	0.3 (0.2)	9.3 (4.4)	34 689 (15 295)
QS-HJ	5.3 (1.4)	3.5 (1.3)	1.1 (0.5)	29.0 (11.8)	14 382 (5 826)
QS-SJ	4.0 (1.5)	3.4 (1.2)	0.9 (0.8)	22.2 (10.5)	6 720 (3 425)

Similar to the findings from the right-angle tool study (Study II), the TT-HJ condition, while resulting in the highest acceptable tightening torque level among the experimental conditions, resulted in the lowest peak reaction torque level, i.e. 1.2 Nm, at the acceptable load level. When operating the tool with the QS tightening program, the mean acceptable peak reaction torques were 3.5 Nm and 3.4 Nm, for the hard and soft joints, respectively. Further, the TT-HJ condition resulted in the lowest mean impulse exposure and tool handle displacement compared to the other two experimental conditions. However, the TT-HJ condition resulted in the highest jerk exposure, whereas the QS-SJ resulted in the lowest jerk exposure.

Table 9. Results from the statistical analysis performed in Study III. The ‘*’ symbol indicates statistically significant differences between the compared means of the experimental conditions ($\alpha = 0.05$). TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, MJ = Medium Joint.

Measured parameter	TT-HJ : QS-HJ ^a	TT-HJ : QS-SJ ^b	QS-HJ : QS-SJ ^c	p-value	Kruskal-Wallis H	Effect size (ϵ^2)
Tightening torque	*	*	*	$p^a < .001$	15.00	0.254
				$p^b = .000$	35.70	0.605
				$p^c = .019$	20.70	0.351
Peak reaction torque	*	*		$p^a < .001$	-29.70	-0.503
				$p^b < .001$	-27.45	-0.465
				$p^c > .05$	2.25	-
Impulse	*	*		$p^a < .001$	-32.65	-0.553
				$p^b < .001$	-21.80	-0.369
				$p^c > .05$	10.85	-
Jerk	*	*	*	$p^a = .025$	14.60	0.248
				$p^b < .001$	33.85	0.574
				$p^c = .001$	19.25	0.326
Tool handle displacement	*	*		$p^a < .001$	30.2	0.512
				$p^b < .001$	21.55	0.365
				$p^c > .05$	-8.65	-
FCU muscular activity				$p > .05$	3.14	-
ECU muscular activity				$p > .05$	4.23	-
DELTA muscular activity				$p > .05$	3.98	-

6.2.4 Electromyography

At the acceptable load levels, the TT-HJ resulted in lower normalized muscular activity levels for the FCU and ECU muscles compared to the other two experimental conditions, despite the acceptable tightening torque being nearly double that of the QS-conditions. The average electromyography levels corresponding to the acceptable tightening torque levels, for the three experimental conditions, are reported in Table 10. The differences in mean muscular activity levels between the three experimental conditions were not statistically significant. This was the case for all three assessed muscles.

Table 10. Average EMG levels at the acceptable load levels for Study III, with standard deviations in parentheses. TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, SJ = Soft Joint, FCU = flexor carpi ulnaris, ECU = extensor carpi ulnaris, DELT = deltoid.

Experimental condition	Accepted tightening torque [Nm]	FCU [%MVE]	ECU [%MVE]	DELT [%MVE]
TT-HJ	10.5 (2.6)	20.0 (21.9)	31.1 (22.3)	11.2 (17.3)
QS-HJ	5.3 (1.4)	26.4 (9.0)	41.2 (20.2)	13.5 (11.9)
QS-SJ	4.0 (1.5)	22.4 (6.0)	43.3 (20.4)	10.8 (4.2)

Overall, the electromyography values reported in relation to the acceptable load levels were associated with high standard deviations. This may pinpoint the large variations of muscular activity measured for the different study participants. For the sake of comparison, the average normalized muscular activity levels are also reported in relation to a constant tightening torque level, i.e. 5 Nm (Figure 10).

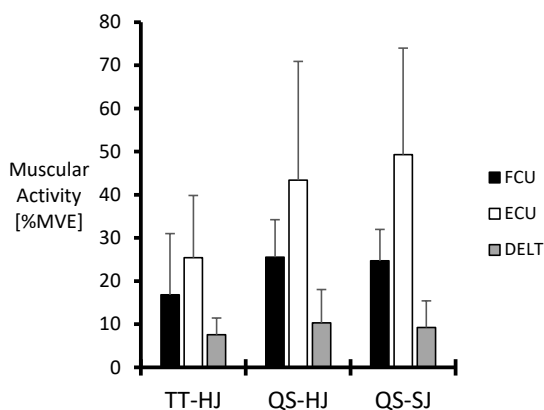


Figure 10. Average EMG levels at 5 Nm tightening torque, with standard deviation bars. TT = Turbo Tight®, QS = Quick Step, HJ = Hard Joint, SJ = Soft Joint FCU = flexor carpi ulnaris, ECU = extensor carpi ulnaris, DELT = deltoid.

At the constant tightening torque level, the ECU muscle resulted in the highest muscular demands among the three assessed muscles. This was the case for all three experimental conditions. Potential reasons are discussed in Paper III. Conversely, the DELT muscle resulted in the lowest muscular demands, indicating low involvement in counteracting the exposure from the tool, in the particular work posture.

6.2.5 Subjective ratings of perceived discomfort

For the three experimental conditions, the subjective ratings of perceived overall discomfort (i.e. not connected to any particular body region) ranged between 1.9 (TT-HJ, SD = 1.4) and 2.5 (QS-SJ, SD = 1.9) on Borg's CR10 scale. The values correspond to a 'weak' to slightly more than 'weak' sensation of discomfort according to the scale (Borg, 1990). The reported numbers represent the mean discomfort rating at the time when the participants just had finished each experimental condition.

Similar to the findings of the right-angle study (Study II), the wrists and hand region (grouped as one region), in average, received the highest discomfort ratings among the assessed body regions. When operating the tool under the QS-SJ and QS-HJ conditions, the participants, in average, rated the discomfort in the wrists and hands as 2.7 (SD = 1.8) and 2.6 (SD = 2.9) on Borg's CR10 scale. Differences in discomfort ratings among the experimental conditions, as well as among the rated body regions, were not statistically significant.

6.3 Study IV – Interview study

The findings from the study concerned the organization's overall approach to evaluating handheld tightening tools with respect to ergonomics, and the perceived challenges when doing so. Overall, the participants were content with the function of the evaluation approach but acknowledged that handheld tightening tools were challenging to evaluate from an ergonomics point of view. Based on the thematic analysis of the interviews, three main themes were identified: 1) A holistic approach, 2) Information and knowledge availability, and 3) Negotiating criteria. In addition, the participants' suggestions for improved means of evaluating the exposure from handheld tightening tools were reported.

6.3.1 A holistic approach

As a basis for evaluating the physical exposures from handheld tightening tools, a company specific standard for ergonomics assessments was used within the studied organization. In addition to handheld tightening tools, the standard addressed common operator tasks which could constitute occupational health risks such as lifting and adverse postures. For handheld tightening tools, there were tightening torque limits stipulated for two categories of tool types: smart tools and clutch tools. The tightening torque limits for smart tools were more liberal (i.e. higher) than those of clutch tools. In the standard, tightening torque limits were further distinguished based on tool handle configuration, i.e. right-angle, pistol-grip and inline tools. The torque limits were graded according to a 'traffic light system' (green, yellow and red) indicating the MSD risk and whether actions are needed or not. In addition to the tightening torque level, repetitions of tightenings per hour were taken into account.

Several participants pointed out that the content of the standard related to handheld tightening tools did not fully capture the physical demands associated with using such tools. The diversity of tasks where tightening tools are used imply that the physical demands are heavily dictated by the undertaken work posture. One ergonomist and one ergonomics coordinator pointed out that the operators often complain about the use of handheld tightening tools, but that their complaints typically did not seem to revolve around the tightening torque levels. Therefore, as a complement to the objective metrics (tightening torque and repetition frequency), the ergonomics coordinators had incorporated a routine of asking the operators to assess their subjective experience of the assembly task where the handheld tool was used. In addition to better risk capturing, the subjective assessments were said to function as a means of focusing the prioritization of which ergonomics problems to address. Several ergonomists and ergonomics coordinators highlighted that the operators' subjective experience played a key role in the ergonomics assessments, and that they wished for more systematic subjective evaluations.

6.3.2 Information and knowledge availability

To the extent possible, ergonomics principles were incorporated at different stages of the production process in the studied organization. At the product design stage, the design engineers have to consider engineering requirements of e.g. tightening torque. Based on the descriptions of the participants, the success of incorporating those principles at the different stages depends on the information, knowledge and methods available. As described by some of the participants, the design engineers typically do not have insight into what tightening tool that will be used by the assembly operators. Although not always practically achievable (due to e.g. time constraints), the design engineers do have guidelines for classifying their design with respect to ergonomics. However, the design engineers are primarily concerned with ensuring a design that fulfils engineering requirements and which complies with safety and quality requirements.

Once the final design of the product is released for production, the production staff need to ensure that the assembly operators can assemble the product in a safe and ergonomic manner. Depending on the design of the product (e.g. an engine), the production technicians have to choose suitable tools and means of assembly. For example, if the product requires high torque in the screw-joints, thereby exceeding what would be classified as 'green' according to the ergonomics standard, pulse tools can be selected, or reaction bars could be attached to the conventional continuous drive tightening tools. This way, the selection of tightening tools and additional equipment is based on what the design engineers have constructed.

In operating production, the ergonomics assessments are conducted by the assembly operators themselves. In line with the company's ergonomics standard, they collect information about tightening torque and tool type, as well as the repetition frequency of tool use. However, as brought up by several participants, information such as tool type, tool settings and screw-joint characteristics may not be evident or readily available to those conducting the assessments. Some of the interviewees expressed that there are many disclaimers in the section of the ergonomics standard about tightening tools, which sometimes complicate the assessments.

Further, modern tightening tools are programmable, and allow for customized settings of e.g. tool speed in order to achieve a particular torque buildup curve. Throughout the interviews, it was brought up that adequate competence around how to optimally select the settings of the tool is crucial. The tool settings can in turn directly reflect the resulting tightening quality, as well as the reaction load exposure for the operator. The possibility to improve ergonomics by adjusting tool settings was not well-known by all those assessing load exposure from handheld tightening tools. It also was expressed that the technicians responsible for setting up the tools may not always be knowledgeable about how to optimize tool settings with respect to ergonomics. There is therefore a need for increased knowledge around how to appropriately select tool settings with respect to operator comfort.

6.3.3 Negotiating criteria

In addition to ensuring ergonomic working conditions for the assembly operators (and staff in general), there are business critical criteria which need to be fulfilled when designing the product and deciding on means of assembly. Although the topic of ergonomics was claimed to rank high on the agenda, many participants agreed that employee safety and end-product quality held a higher priority level compared to ergonomics. Unlike quality and safety requirements, the values stated in the ergonomics standard are not strict requirements. As an example, seatbelts and steering wheels are fastened with screw-joints which are considered as ‘critical joints’, and therefore need to comply with legal requirements. As stated by some of the participants, the functional requirements on the screw-joints are uncompromisable and the assembly conditions are therefore customized around the resulting product (e.g. engine) design. Thereby, selection of tightening tool and tool settings are oftentimes dependent on the quality demands of the screw-joint.

In addition to safety and quality standards, the design engineers need to account for factors such as voltage conduction abilities and rust susceptibility of the product components. In addition, they need to design with respect to weight constraints of the construction, as well as costs.

The responsibilities of the different roles within the organization need to be fulfilled within the scope of the set business demands, such as production volumes. Overall, the participants agreed that the different perspectives, such as ergonomics, quality, and R&D, are treated respectfully and that they consistently work towards consensus and finding the best solution to satisfy the different perspectives. However, as stated by one ergonomist, it is not uncommon for ergonomics to collide with other criteria. The outcomes of how the problems are addressed can however differ between situations. The selection of a handheld tightening tool is e.g. weighed against how often the tool will be used and whether the investment thereby is economically justifiable. In contrast, the interviewed quality technician did not perceive ergonomics and quality criteria to stand in conflict and expressed that they normally manage to satisfy both perspectives.

6.3.4 Feedback for improvement

Although the studied organization’s approach to ergonomics assessments was comprehensive, there still remained uncertainties about how the use of handheld tightening tools influences the assembly operators. The interviewees therefore gave some suggestions on areas for improvement related to handheld tightening tools.

Although they took into account repetition frequency of tool use, some participants expressed that they would like to know more about appropriate tool use duration and repetition frequency specific to handheld tightening tools. The current repetition frequencies stated in the standard apply to all physical exertion tasks, and not only tool use. The interviewed tightening technician further expressed that they would like the standard to include more guidance on selection of tightening tools. This could include information about when to use

a particular tool, as well as their associated technical particularities. The technician also said that they would like to see more information about programming of the 'smart' tools, as the programming of the tools heavily can influence the experience for the tool user.

Another factor greatly influencing the reaction load of handheld tightening tools is the stiffness of the screw-joint. Some of the participants expressed that they lacked information about how to assess the ergonomics of tool use with respect to the screw-joint and that they would like to know how to assess the ergonomics based on different screw-joints. As brought up by a tightening expert, all screw-joints are unique and need to be evaluated on an individual basis. However, from a pragmatic point of view, it could be useful to know the ergonomic implication of, if not all, but at least a few commonly occurring screw-joints.

In contrast to having a highly detailed ergonomic standard which accounts for the wide variety of different tool use situations, some participants suggested that the content of the standard needs to leave room for interpretation. As consensus-based decision making is highly valued within the studied organization, the standard should be flexible enough for context-specific decisions to be made where needed.

A central part of the ergonomics assessment of handheld tightening tools are the set tightening torque limits. According to one of the ergonomists, their current limits values have been shown to be quite appropriately set for identifying potentially harmful reaction load levels. The ergonomist further emphasized the importance of pragmatic exposure limits. They speculated that stricter exposure limits, where many tasks would be classified as 'yellow' and 'red', could complicate the prioritization of which ergonomics problems to address.

One of the participants suggested that power tool manufacturers could start declaring the reaction load levels of their tightening tools in relation to a few screw-joint stiffnesses, similar to what is done with vibrations. This way, it would be easier to compare and select tools from different tool manufacturers, and non-compliant tools could be rejected.

7 Discussion

The work included in this thesis aimed at contributing to the development of recommended exposure limits for, and assessments of, reaction loads resulting from electric handheld tightening tools. In the subsequent subchapters, a compilation of the four studies included in this thesis will be presented and discussed, where findings from the studies are synthesized. Below, results and insights are discussed and positioned in a theoretical, as well as a practical, context. Further, methodological aspects which could have influenced the validity and generalizability of the results are discussed.

7.1 Tightening torque limits

As presented in the review of available publications about reaction load exposure from handheld tightening tools (Paper I), a number of exposure limits related to the exposure of interest were identified. Based on the needs identified in Paper I, acceptability limits were derived from two experimental studies (Paper II and Paper III), where two of the most commonly used tool types were investigated, i.e. handheld electric right-angle tools and handheld electric pistol-grip tools.

Based on the findings reported in Paper I, Paper II and Paper III, current tightening torque limits for handheld right-angle and pistol-grip tools are presented in Table 11 and Table 12, respectively. For the sake of comparison, torque limits for those tool types set by four automotive manufacturers are also presented in the tables (corresponding to the traffic-light classification ‘green’, i.e. indicating low MSD risk).

Table 11. A compilation of tightening torque limits for right-angle tools. The torque limits of the automotive manufacturers listed are the limits above which actions are needed. TT = Turbo Tight® (Atlas Copco), QS = Quick Step (Atlas Copco), ATC = Adaptive Tightening Control (STANLEY®).

Right-angle tools	
Tightening torque limits	Source
60 Nm	ISO 11148-6:2012 (ISO, 2012) Pneumatic/hydraulic/gas fuel/liquid fuel tools
<u>Hard joint</u> ATC: 43 Nm QS: 47 Nm TT: 81 Nm <u>Soft joint</u> ATC: 45 Nm QS: 41 Nm TT: 48 Nm	Valencia et al. (2022)‡
<u>Hard joint</u> TT: 36.4 Nm QS: 31.3 Nm <u>Medium joint</u> QS: 31.9 Nm	Mazaheri et al. (2022) (Paper II)†
26 Nm	Automotive manufacturer A
40 Nm	Automotive manufacturer B
55 Nm	Automotive manufacturer C
60 Nm	Automotive manufacturer D

‡ Valid at a repetition rate of 3 tightenings/min. For other repetition rates and details, see full publication.

† Valid at a repetition rate of 5 tightenings/min.

Table 12. A compilation of tightening torque limits for pistol-grip tools. The torque limits of the automotive manufacturers listed are the limits above which actions are needed. TT = Turbo Tight® (Atlas Copco), QS = Quick Step (Atlas Copco).

Pistol-grip tools	
Tightening torque limits	Source
10 Nm	ISO 11148-6:2012 (ISO, 2012) Pneumatic/hydraulic/gas fuel/liquid fuel tools
<u>Hard joint</u> TT: 10.5 Nm QS: 5.3 Nm	Paper III†
<u>Soft joint</u> QS: 4.0 Nm	
6.7 Nm	Automotive manufacturer A
7 Nm	Automotive manufacturer B
8 Nm	Automotive manufacturer C
9 Nm	Automotive manufacturer D

† Valid at a repetition rate of 5 tightenings/min.

As found in the interview study (Paper IV), the studied automotive manufacturer expressed their threshold limits (i.e. deciding if a task should be classified as ‘green’, ‘yellow’ or ‘red’) in relation to a tightening torque level. Similarly, other automotive manufacturers typically express their threshold limits for handheld tightening tools in terms of tightening torque (Oh and Radwin, 1998, Lidstone et al., 2021). As discussed by Lidstone et al. (2021), by simply expressing threshold limits in terms of tightening torque, many of the factors which contribute to the health-risks of using handheld tightening tools (e.g. joint type, repetition frequency, operator posture and the technological potential of the tools) are neglected. This is supported by findings of Ku et al. (2007), where tightening torque was shown to poorly correlate to predictions of reaction forces and tool handle displacements. Instead, the predictions were (with statistical significance) correlated to the individual tool, tool shape and joint stiffness.

In numerous research studies related to reaction load exposure from handheld tightening tools, e.g. Kihlberg et al. (1993), Armstrong et al. (1999), Lin et al. (2012), and Radwin et al. (2014) to name a few, reaction load has been quantified in terms of physical parameters other than merely the tightening torque. In Paper II and Paper III, the acceptability thresholds are expressed in relation to not only tightening torque, but also peak reaction force [N] (Study II), peak reaction torque [Nm] (Study III), impulse [Ns or Nms], tool handle displacement [cm or degrees] and jerk [m/s^3]. In a practical context, clarity is needed regarding which physical parameters to assess in relevance to reaction load exposure. Clarifications are also needed around which party (i.e. tool manufacturer or tool using organization) that should bear the responsibility of conducting different parts of the exposure assessment of handheld tightening tools. It should further be noted that adequate exposure assessments rely on the availability of relevant data. As found in Study IV, the data type being readily available to the employees conducting the ergonomics assessment, is the tightening torque. With this information at hand, they obtain a rough indication of the potential exposure severity. In line with their approach to ergonomics evaluations, they further refine their assessment of handheld tightening tools by including additional tool and task related factors in the assessment, such as posture, repetition frequency and tool type, as well as systematic assessments of the tool operators' subjective experience of the physical demands associated with the particular assembly task. However, within the organization, they neither measured nor evaluated the reaction load exposure, much due to knowledge-related and measurement-technical gaps.

The acceptability limits derived by Valencia et al. (2022), Mazaheri et al. (2022) (Study II), and in Study III, provide some diversification of tightening scenarios, where the limits are stated in relation to selected tightening programs, joint stiffnesses and repetition frequencies. From a feasibility and study design point of view, simplifications of the study phenomena of interest were needed (see discussion in 7.4.2) Therefore, the psychophysically derived acceptability limits correspond to load acceptability at a discrete set of conditions and may not be suitable for extrapolation to other tool and task related conditions.

As listed in Table 11 and Table 12, automotive manufacturers account for reaction loads by setting their own tightening torque limits. The torque of the screw-joint is an engineering-related matter, where the screw-joint needs to fulfil certain product functionality and security requirements. As reported in Paper IV, ease of assembly for the operator is to the extent possible considered by the design engineers, and further by the production management staff. It is in some instances possible to redesign the product in order to reduce the torque requirements of the screw joint. However, this typically comes at the expense of an increased number of screw-joints in order to ensure the mechanical durability of the assembled end product. This exemplifies the common tradeoffs of product and production design, where changes in (in this case) assembly conditions, can pave the way for new problems, and where the changes need to be balanced against production demands, resources and costs.

Regarding the only ISO standard treating the topic of reaction loads from handheld tightening tools, the tightening torque limits stated in the ISO 11148-6:2012 standard pertain to tightening tools powered by air, hydraulics, gas and liquids. They are thereby not directly applicable to today's commonly used electrical tightening tools. In order to comply with contemporary power tool technologies, an update of the ISO standard is warranted.

7.2 Evaluating reaction load exposure

In order to adequately and efficiently evaluate reaction load exposure from handheld tightening tools, three main gaps need to be addressed. More specifically, there is a need to clarify *what* physical parameters that are relevant to assess, *how* reaction loads should be measured, and *who* should bear the assessment responsibilities.

7.2.1 Physical parameters to assess

A fundamental part of targeted risk assessment revolves around translating collected data to useful metrics characterizing physical demands associated with the exposure. In the literature review reported in Paper I, physical parameters of the reaction load studied in previous research were mapped and described. It was found that in a majority of the studies (70% of the 40 included publications) reaction load from handheld tightening tools has been studied and expressed in terms of peak reaction force/torque and tool handle displacement. Less commonly assessed parameters were the impulse (23% of the studies), tool handle velocity/acceleration (15% of the studies), power (5% of the studies) and energy/work (5% of the studies).

In Paper II and Paper III, a new physical parameter was introduced, namely jerk, which had not previously been identified in other studies within the field of reaction load exposure from handheld tightening tools. While acceleration can be regarded as a consequence of static load, the jerk, being the change of acceleration, can be experienced as an increasing or decreasing force (Eager et al., 2016). This physical parameter is for example used when designing for roller coaster rider's comfort (Pendrill, 2005, Eager et al., 2016, Pendrill and Eager, 2020). Ideally, roller coasters should be designed for minimized jerk in order to allow for a smooth and pleasant ride experience. Although the human tolerance to jerk is not yet fully understood, it is acknowledged that humans need sufficient time to sense motion changes in order to regulate their muscular tension accordingly (Eager et al., 2016). As seen in Paper II and Paper III, when operating the tightening tools with the Turbo Tight® program, the jerk parameter measured was, with statistical significance, substantially higher than the other two program and joint combinations. Unlike the roller-coaster scenario, working with a power tool may not be associated with whole-body exposure to the jerk motion, but rather be concerned with upper-extremity movements.

Prior to Study II and Study III, it was hypothesized that working with the Turbo Tight® would result in substantially higher acceptable tightening torque levels due to the small

impulse resulting from inertial effects of the tool. The hypothesis was accepted in Study III (pistol-grip tools) but not in Study II (right-angle tools). In the right-angle tool study, the participants' average accepted tightening torque level was only slightly higher when working with the Turbo Tight® program (36.4 Nm), compared to the other two experimental conditions (31.3 Nm for Quick Step on the hard joint and 31.9 Nm for Quick Step on the medium joint). It is hypothesized that the high jerk motion of the tool was the factor inhibiting higher acceptable tightening torque when operating the tightening tool with the Turbo Tight® program on the hard joint, although the impulse was considerably lower (mean of 2.9 Ns compared to 12.0 Ns and 15.8 Ns for the other two experimental conditions). In the pistol-grip tool study however, despite the substantially higher jerk values of Turbo Tight (nearly 35 000 m/s³ compared to approximately 14 000 m/s³ and 7000 m/s³ for the two other experimental conditions, at the accepted load levels), the participants accepted an average tightening torque level of 10.5 Nm, to be compared to 5.3 Nm and 4.0 Nm for the other two experimental conditions. Comparing the right-angle tool study (Paper II) to the pistol-grip study (Paper III), it was seen that the expected benefits of the Turbo Tight® program on the hard joint (i.e. the ability to conduct higher torque tightenings without substantially increasing the physical load on the operator) were clearly more evident in the pistol-tool study. Two plausible reasons for this difference between the two tool types are discussed: firstly, the biomechanical advantages when operating a right-angle tool imply that higher torques can be applied to the screw-joint, whereas pistol-grip tools typically are used for lower torque applications (with the exception of pulsating tightening modes). In Study II, the participants conducted screw-joint tightenings with the right-angle tool in the range of 15 Nm up to 80 Nm, whereas in Study III, the corresponding range was 3 Nm up to 20 Nm. It is possible that the combination of high tightening torque (as is the case when using a right-angle tool) and jerk lead to an increased sensation of discomfort. Therefore, it is hypothesized that, as tightening torque increases, the discomforting effect of jerk becomes more pronounced. Secondly, the choice of screw-joints, representing two different joint stiffnesses, are likely to have influenced the outcomes (further discussed under 7.4.2).

The impulse metric is further a valuable parameter as it reflects the duration of reaction force/torque exposure. The duration of the exposure is in turn a result of the tightening time and the inertia effects of the system (i.e. the tool). As reported in Paper I, some researchers have suggested impulse to be a suitable predictor of physical stress when using tightening tools (Freivalds and Eklund, 1993, Kihlberg et al., 1995, Lin and McGorry, 2009, Valencia et al., 2022). In Study II, the jerk parameter functioned as a complement to the impulse parameter, where, despite resulting in low impulse, operating the tool with the high-speed program (Turbo Tight®) did not yield considerably higher load tolerance among the study participants.

The peak reaction force/torque is a parameter reflecting the peak exposure at a given instance of time. From a practical point of view, simply extracting the peak value of a measured signal requires little effort compared to conducting e.g. the time integrations and derivations required to obtain the impulse and jerk of the measured signal, respectively.

However, by only investigating the peak value of the reaction force/torque, dynamic information about the exposure, i.e. force/torque variations over time, may be omitted.

As reported in Paper I, tool handle displacement (whether it be linear or angular) has been commonly assessed in previous research. As became evident in the pistol-grip study (Paper III), working with the Turbo Tight® resulted in substantially lower angular displacements of the tool handle compared to the other two experimental conditions. It is therefore possible that other parameters, such as impulse and jerk, are more firmly correlated to the perceived discomfort and required effort than the displacement of the tool handle.

7.2.2 Measuring reaction loads

In the quest of MSD prevention, the ability to measure the exposure of interest (in this case reaction loads from handheld tightening tools) greatly contributes to accurate risk assessments and load management (David, 2005). One of the practical issues related to adequate assessments of reaction load exposure from handheld tightening tools relates to the availability of satisfactory measurement methods. In the now withdrawn ISO 6544:1981 standard (ISO, 1981), the reaction torque of a tightening tool is equalized to the tightening torque (referred to as ‘installed torque’ in the standard). In studies such as Kihlberg et al. (1993), Kihlberg et al. (1995) and Lin et al. (2003), reaction torque has been measured in compliance with the ISO 6544:1981 standard. The assumption that reaction torque is perfectly proportional to the tightening torque is accurate under the condition that the motion of the tool handle undergoes no or little acceleration. In such a situation, the full installed tightening torque would be transferred to the operator. This is for example observed when tightening very soft screw-joints (i.e. long torque buildup time). However, as a disclaimer in the ISO 6544:1981 standard, it was stated that the presented means of measuring reaction loads do not account for dynamic effects of tool operation, such as tool inertia, which in turn could influence the resulting reaction load.

Further, in the ISO 6544:1981 standard it was stated that there is a lack of appropriate measurement devices ‘that can be used between the tool and the operator’ for direct measurement of the reaction load. This gap was addressed by Lin et al. (2007), who presented a force measurement system interfacing the tool operator and the tool handle. This advancement in measurement technique has enabled direct measurements of the reaction loads in power tool research studies (Lin et al., 2010b, Lin et al., 2012, Xu and Lin, 2015), as opposed to the indirect means of measuring reaction loads through tightening torque, as was stipulated in ISO 6544:1981. A further refined version of the measurement handle presented by Lin et al. (2007), was utilized in studies by Cort et al. (2021), Steingraber et al. (2021) and Valencia et al. (2022) for measuring reaction loads from electric right-angle tightening tools. The same measurement handle was used in the study reported in Paper II, where reaction force signals resulting from right-angle tool operation were collected.

In order to measure reaction torque resulting from pistol-grip tool use (Paper III), a custom-made measurement solution was constructed, consisting of a torque and angle transducer placed posterior to the tool, and in line with the tool's axis of rotation.

The use of these measurement handles enables measurements of reaction loads from handheld right-angle and pistol-grip tools. In particular, the measurement devices are appropriate for lab-studies, but may not constitute a sophisticated means of conducting large-scale measurements on tools used at running production lines. The measurement devices used in Paper II and Paper III require cable connections to external data acquisition systems and are thereby invasive to the production environment.

In addition to the notion that the measurement devices described above can interfere with the environment in which the power tools are being used, the mass of the measurement device modifies the inertia of the system. This becomes particularly pronounced when measuring reaction forces on the right-angle tool, as the mass distribution of the total system (i.e. tool and measurement handle) is concentrated at a distance perpendicular to the axis of rotation. The mass moment of inertia increases as a function of the distance of the mass from the center of the rotation (in this case the tool head) (Winn, 2010). As described in 3.3, operating a tightening tool with an inertia-controlled tightening setting, such as the Turbo Tight® program (Paper II and Paper III), leads to large portions of the reaction force being absorbed by the tool mass. Therefore, there was a need to develop a means of measuring reaction force from right-angle tools which does not substantially alter the inertia of the tool. This was in Paper II achieved by attaching an accelerometer, with negligible weight, to the tool and thereby perform an indirect measurement of the reaction force (described in 5.3.5). This novel means of measuring reaction force from handheld tightening tools does however come with its own set of challenges. As seen throughout the development work of the accelerometer method, the reaction force obtained through Equation 1 was systematically higher than reaction force measured with a reference force transducer. Equation 1 is established under the assumption that the system (i.e. the operating power tool) acts as a rigid body. Thereby, the dynamic behaviors of the system are neglected. These effects could plausibly be observed through a modal analysis of an operating tightening tool, where inherent damping effects, natural frequencies and modes shapes can be determined (Fu and He, 2001). This way, a more accurate mathematical model for reaction force calculation could be developed. In addition, the placement of the accelerometer on the tool could influence the acquired acceleration signal. It is e.g. preferable to not position the accelerometer close to the tool motor, as the motor itself gives rise to accelerations which are not directly relevant for the acceleration motion of the tool handle.

In addition to providing information about the reaction force, an accelerometer placed on the tool provides additional information about the tool motion. As reported in Paper II, the tool handle displacement was obtained by double integrating the linear acceleration, whereas the jerk of the tool handle (reported in Paper II and Paper III) was obtained by differentiating

the linear acceleration. This further demonstrates the versatility of measuring acceleration on handheld tightening tools, either by means of a single accelerometer, or by combining signals from an inertial measurement unit (IMU). This way, there is a potential to obtain a variety of reaction load relevant information from a single measurement unit.

Besides the measurement methods utilized in previous research and in the studies included in this thesis, mechanical rigs such as the one developed by Eriksson et al. (2021), and further developed by Ekman and Sernelin (2023), can enable repeatable measurements and investigations of reaction loads without the influence of a human test operator. By utilizing a mechanical rig simulating a human operator, variance introduced by humans is omitted. This could be beneficial from an engineering point of view, where the resulting exposure can be directly deduced to tool and screw-joint specific characteristics. A mechanical rig does however not provide information about the subjective experience of working with handheld tightening tools.

From a prospective point of view, appropriate means of measuring reaction loads directly, e.g. through IMUs integrated in the power tool itself, could allow for direct insight into the exposure from the tool. The exposure could be expressed in terms of e.g. peak reaction force/torque, impulse, tool handle displacement and jerk, or a combination thereof. By measuring these physical quantities, the effect of task related factors (such as joint stiffness) and tool related factors (such as tightening program) would be reflected. Task related factors such as posture and repetition frequency likely require a separate means of inclusion in the total risk assessment of handheld tightening tool use.

7.2.3 Role responsibilities

Apart from knowing *how* and *what* to assess when determining reaction load exposure from handheld tightening tools, there is a need to delineate *who* should bear the assessment responsibilities. In the subsequent subchapter, the intent is to elaborate on the division of responsibilities between tool manufacturers and tool using organizations with regards to managing reaction load exposure from handheld tightening tools.

Measurement methods and assessment scopes can take on different levels of complexity. Different measurement and assessment methods are associated with various costs of acquisition, training requirements, as well as time required to conduct the assessments and analyzing resulting data (David, 2005). This should be considered when proposing means of measuring and assessing reaction load from handheld tightening tools directed at tool manufacturers and tool using organizations, where the approaches should be aligned with the aims of the investigations. On one hand, tool manufacturers need to ensure that the products they bring to the market are designed for minimal harmful impact on the tool user. On the other hand, once the product (in this case the power tool) propagates the intended context of use, the product needs to be assessed in synthesis with the overall system with which it coexists.

As stated by the European Agency for Safety and Health at Work, organizational factors can contribute to the prevalence of MSDs (EU-OSHA, 2019). For these reasons, the management of exposures from power tools need to be targeted from both the angle of the tool manufacturer, as well as that of the tool using organization.

As exemplified in Paper IV, the employees of tool using organizations such as automotive manufacturers, need to manage occupational health-related matters with considerations of feasibility and costs. This is in line with the analogous idea that occupational exposure limits (OELs) should balance considerations of health, technical constraints and economic factors (Schenk, 2013). Thereby, means of measuring and assessing the loads, directed at tool using organizations, should be resource-efficient and stand in proportion to the available competences, potential of improvements, as well as the abilities to address any straining tool use tasks (Paper IV). As presented in Paper IV, the studied automotive production organization's main goal when assessing reaction loads from handheld tightening tools was to prioritize which problems to address. Therefore, the assessments need to result in relevant information that can facilitate the prioritization of actions (such as installing a reaction bar on the tool).

Further, conducting thorough and detailed ergonomics assessments depends on time availability. As reported in Paper IV, practitioners in a production organization need to address many different challenging situations. For this reason, and as stated by David (2005), assessment methods need to be designed for time-efficiency while also being straightforward. Until technical advancements can enable convenient and direct measurements of reaction load exposure from handheld tightening tools, tightening torque is the data type which is readily available to tool using organizations. Tool manufacturers on the other hand, possess greater opportunities to conduct in-depth measurements and assessments of reaction load exposures from handheld tightening tools. With access to targeted lab equipment and topic-specific competence, assessment methods used within a tool manufacturing organization can be more detailed, where e.g. various characteristics of the measured reaction load signals can be examined. Even without established or generally accepted exposure thresholds, the ability to measure reaction loads from handheld power tools paves the way for systematic comparisons of different tool and task related parameters such as tightening programs, specific tool speed settings and various joint stiffnesses. This could be integrated into the R&D process of developing new power tools, where engineering choices influencing the resulting ergonomics of the tool can be motivated through collected data.

In terms of test methods, evaluations of vibration emissions from power tools could inspire future approaches to systematic in-house assessments of reaction loads. In the ISO 28927-2 standard (ISO, 2009) a test method for vibrations from tightening tools is stipulated, and tool manufacturers are obliged to declare the results from their vibration tests in order to sell their products on the EU market (Haettel, 2019). According to the method, vibrations are to be measured on three individual power tools (e.g. tightening tools, grinders and drills) with tri-axis accelerometers. Further, the tests need to be conducted by three test operators in order

to account for human variance. There is potential to test reaction loads from handheld tightening tools in a similar manner. In such case, decisions around joint selection, tool settings (e.g. tightening program) and measurement equipment are needed in order to enable reaction load tests that are comparable between different tool types and manufacturers.

7.3 Towards exposure guidance

While industrial parties can take measures to reduce and manage physical loads exposures from handheld tightening tools, additional efforts can be imposed by policymakers on various levels. As described in 3.5, there are directives and standards describing general recommendations for handheld tightening tool use with respect to operator health and safety. However, they do not address exposure doses and methods for load assessment for handheld tightening tools. Describing an in-depth process for developing occupational exposure limits (OELs) for reaction loads from handheld tightening tools is beyond the scope of this thesis. Nonetheless, matters to consider in such development work are presented below.

Unlike several other occupational diseases arising from exposure to specific hazardous agents, such as chemicals or ionizing radiation, MSDs are typically a result of a combination of factors (van der Beek and Frings-Dresen, 1998). In the field of toxicology, OELs ideally relate to the so called *critical effect*, i.e. *‘the adverse effect that appears at the lowest exposure level’* (Hansson, 1997). Deciding on a critical effect for MSD is however not as apparent due to the multi-faceted nature of MSDs. The main factors contributing to MSDs are force (e.g. magnitude, direction and statics/dynamics), posture, repetition rate, task duration and recovery time (Wells, 2009, Gallagher and Heberger, 2013). Therefore, only assessing reaction load magnitude from handheld tightening tools provides a narrow picture of the total load implication for the operator when working with a handheld tightening tool. As described by some of the participants in Study IV, the physical demands associated with tightening tool use were not primarily due to the defined tightening torque limits (which in turn relate to the resulting reaction load magnitude), but rather the *use* of the tool and the task for which the tool is used (e.g. required posture). This transfers back to the inherent difficulties of determining a critical effect level for exposures such as reaction loads from handheld tightening tools. The dynamic nature of MSD risks following physical load exposure is further highlighted by Waters et al. (2015), who stated that the probability of developing ill-health changes as exposure concentration increases. They therefore suggest that occupational risks should be treated as probabilistic as opposed to binary (i.e. acceptable or unacceptable risk).

From a pragmatic point of view, in cases where risk probabilities are unknown, risks are managed by using the best available estimate and data (Hansson, 2008). This aspect of decision theory suggests a rational and objective approach to risk management, where

decisions and actions are guided by the current state of knowledge. To achieve an evidence-based practice, generated evidence needs to be combined with contextual factors as well as critical thinking (Rycroft-Malone et al., 2004, Profetto-McGrath, 2005). In such a process, the validity and reliability of evidence needs to be scrutinized. In the case of reaction load exposure from handheld tightening tools, where critical effects and numerical risk probabilities have been shown difficult to establish, current available data can guide action, taking into account potential gaps and quality deficiencies of the data. This can be achieved by applying experience-based and context-bound knowledge to the available pool of data and thus forming a practice-compliant and results-oriented approach to risk management for reaction loads from handheld tightening tools. This further sheds light on the importance of practitioner's judgement for management of occupational risks.

Besides the need for specific competence and understanding of context, quantifiable means of assessing physical load exposures are necessary, not least for the sake of comparisons and systematic evaluations of changes and interventions. Lindqvist (2022) describes an ergonomics assessment method for handheld power tools, where the load magnitude is combined with the task related factors 'speed of movement' (i.e. if the task requires fast movements or not), 'frequency of the operation', and 'total duration of the operation'. Similarly, dose calculations of vibrations exposure (e.g. from handheld power tools) combine exposure magnitudes with total exposure duration. Likewise, in order to better determine the cumulative load implications of working with handheld tightening tools, assessments need to combine the exposure magnitude (i.e. reaction load) with time-related factors such as repetition and duration, as well as accounting for postural factors which influence the overall effort required for the tool-use task.

Although this thesis revolves around reaction load exposure from handheld tightening tools, the matters described above may be stretched beyond the particular case of reaction loads, and thus be applied to other types of physical load exposures occurring in occupational settings.

7.4 Methodological considerations

The findings presented in this thesis need to be evaluated and understood in the light of the chosen methodologies and study designs. The overall aim of this thesis was to contribute to the development of recommended exposure limits for, and assessment of, reaction loads resulting from use of electric handheld tightening tools. The aim was in part addressed by mapping out state-of-the-art within the topic area and based on that proposing a direction for needed research (Paper I). Thereafter, psychophysically based studies were conducted, where human limitations related to technical characteristics of handheld tightening tools were assessed (Paper II and Paper III). Finally, the focus was shifted from tool users and tool technicalities to organizational approaches for mitigating health risks associated with tool use (Paper IV).

7.4.1 Literature review

The literature review conducted and ultimately reported in Paper I undertook the form of a scoping review. This type of literature review was chosen among a variety of means of conducting literature reviews (Grant and Booth, 2009). The purpose of the review was to provide an overview of the current state of the art and based on that propose directions for further research. Being a scoping review, the quality of the publications included in literature synthesis were not critically assessed (e.g. assessing methodological limitations), nor were evidence from the included studies synthesized and statistically evaluated (as would have been required in a meta-analysis). The purpose of the study was not to inform practice, but rather to identify knowledge gaps. It was therefore decided not to conduct a formal systematic literature review (Munn et al., 2018), but rather, the scoping review format was assessed as appropriate to satisfy the purpose of the study.

7.4.2 Experimental studies

One of the key components underpinning the approach of the experiments is the psychophysical means of gaining insight into assembly operators' capabilities and limitations when using handheld tightening tools. In the quest for deriving exposure limits for various types of physical loads, such as lifting (weights) and force exposure, psychophysical approaches have been suggested to be useful (Snook and Irvine, 1967, Garg and Badger, 1986, Garg et al., 2014, Moore and Wells, 2005, Valencia et al., 2022). Mainly, the psychophysics approach has been used to determine maximum acceptable loads in repetitive occupational tasks. In order for study participants to make informed and reliable assessments, a prerequisite is that they are sufficiently experienced or trained at the task, as well as trained at confidently being able to determine their perception of the stimulation (Karwowski and Yates, 1986). In an ideal case, the assembly operators recruited for the two experimental studies in this thesis (Paper II and Paper III) would have been given sufficient time to get accustomed to the task of making a thought-through assessment of the load acceptability. In the comparable psychophysically based study of right-angle tools by Valencia et al. (2022), the participants (who were not professional assembly operators) underwent extensive training time prior to the actual data collection (45 minutes of training per experimental condition). This certainly promoted the participants qualifications for making informed and appropriate assessments of acceptable load exposure, in relation to their own intellectual perception of what assembly work entails. Their study participants' lack of experience from real assembly work, with all the various tasks and challenges which assembly work implies, does however raise the question of transferability of study results yielded from a study sample not representing the target sample (i.e. professional assembly operators). While psychophysics studies provide insight into study participants *perception* of load exposure under the specific experimental circumstances, they do not provide information about the actual occurrence of (in this case) MSDs following exposure. As the development of MSDs typically have a slow progression, epidemiological studies may be an option for capturing occurrence of MSDs following prolonged exposure.

However, as MSDs typically are a result of multiple factors, it may be difficult to deduce the occurrence of MSDs to a particular type of exposure.

Compared to the study by Valencia et al. (2022), the experimental times of Study II and Study III were heavily reduced to a total of 24 minutes and 12 minutes per experimental condition, respectively. These short exposure times inevitably imply certain limitations to the extrapolation potential of the derived acceptability limits. In the instructions provided to the study participants, it was stated that their task was to find a load level which they assessed would enable a sustainable physical workload throughout an 8-hour workday. Prescribing the derived load levels based on 24 minutes (Paper II) or 12 minutes (Paper III) experimental time (per experimental condition) to an 8-hour workday is a very large leap and not advised. Instead, the acceptability levels derived in Study II and Study III should be regarded as rough indications, and context and task specific circumstances need to be accounted for appropriately.

The decision to reduce the experimental time, and thus compromise the psychophysics approach in the two experimental studies (Paper II and Paper III), was a result of practical and ethical considerations. As the two studies were conducted at an automotive manufacturers' site (in a laboratory environment), there were time constraints which needed to be adhered to. The choice of attaining a high sample size (i.e. number of participants) implied that the time consumption per study participant needed to be reduced within the granted time frame. Had the number of participants been halved at the advantage of doubled experimental time, the generalizability of the study results would likely have been subject to critique. In the experimental studies included in this thesis (Paper II and Paper III), 17 and 20 participants were included, respectively. Although not enough to be considered a normally distributed sample, the number of participants contributed to higher statistical power of the collected data than had the number of participants been halved. From an ethical perspective, it was decided to not expose the assembly operators to undue strain throughout the experiments. In particular when working with the pistol-grip tool, the torque motion of the tool can rapidly be experienced as painful, especially when repeated many times.

The generalizability of study results derived by means of a psychophysics approach need to be contemplated. Assembly work entails an abundance of tasks which the operator needs to attend to while undertaking adverse postures, manual handling and managing different types of handheld tools. These working conditions, combined with the repetitiveness of the work, ultimately contribute to the risk of developing MSDs. In addition, assembly operators globally constitute a heterogeneous group spanning over a wide demographic spectrum. The large standard deviations related to acceptable tightening torque levels in the two experimental studies hint to the large fluctuations among assembly operators (and humans in general). Replicating these diversities and dynamic working conditions by experimental means is undoubtedly difficult. The monotony of the experimental task, as well as the modifications to the tool and the task are results of heavy simplifications, and therefore, it cannot be stated that the simulated task and working conditions correspond to real assembly

tasks where handheld tightening tools are used. Further, extrapolating research findings to real-world conditions typically requires principles of practical rationality to be adopted (Hansson, 2008). For example, the practical point of view can entail human judgement around (in this case) risk-acceptability, and may not be best understood by scientific means (Hansson and Aven, 2014). As suggested by Hedges (2013) and Robinson et al. (2013), due to the inherent limitations of allowing single studies to form the basis for practical recommendations, it may be wise to employ a synthesis of available research to lay the foundation for broader generalizations.

The design of the experimental studies included a combination of objective means of assessing the load exposure and subjective approaches to understanding the implications for the tool operators. This way, information that could not be deduced to objective metrics could be captured. The importance of combining objective and subjective metrics was demonstrated in Paper II, where measurements of muscular efforts (Table 7) showed reductions in muscular demand for the ECU and TRI muscles when working with the TT-HJ condition compared to the two other conditions. Despite the reduced muscular efforts, the acceptable tightening torque level was, in average, not considerably higher when working with the TT-HJ condition (5.1 Nm higher than the condition with lowest acceptable tightening torque). The large standard deviations obtained for the EMG measurements do however potentially indicate a large physiological spread among study participants, as well as the quality of the collected EMG data (e.g. due to electrode placement or electrode adhesion to the participants' skin). Regardless, the dissonance between subjective and objective means of assessing exposure to a physical load may in itself be an important bearer of information. As verbally expressed by several participants, working with the TT program on the hard joint (right-angle tools) was experienced as unpleasant (in particular at high torque levels), although the reaction force and EMG measurements overall did not show high magnitudes.

Comparing the right-angle tool study and the pistol-grip study, in which both TT and QS tightening programs were tested, the expected difference in acceptable tightening torque between the two programs was much more distinct in the pistol-grip study. From a material selection point of view, the choice of screw-joints has likely influenced the outcomes of the studies. In the right-angle study, where acceptable load did not differ much between the hard and the medium joint, the hard joint was 2.7 times stiffer than the medium joint. In the pistol-grip tool study, the difference between the hard joint and the soft joint were greater, the hard joint being 5 times greater than the soft joint. Larger contrast between the hard joint and the medium joint in the right-angle study would likely have led to larger observed differences in acceptable tightening torque levels.

The study participants recruited for the experimental studies were chosen randomly from the target population (i.e. automotive assembly operators). However, they were all employed at the same organization, implying that they primarily were accustomed to the specific

organization's ways of working, and the particular power tool they were using on a daily basis. It is plausible that studying assembly operators spanning across different organizations, as well as countries, would have influenced the outcomes of the studies. Nevertheless, the included participants represented different ages, sexes, body types and work experience level. According to the criteria stated by Shadish et al. (2002) against which the internal validity of a study can be benchmarked, the confounding factors occurring in experimental studies influence the degree of internal validity. In an effort to control potential confounding factors, an inclusion criterion for selecting participants for the experiments was that they had no current or underlying musculoskeletal issues in the hand-arm region, as this could have influence load acceptability (besides the ethical concerns). On the other hand, it is highly likely that the average assembly operator from the population experiences chronic or temporary musculoskeletal pain to some degree. Moreover, this is an example of the inherent tradeoff between internal and external validity, where highly controlled experimental conditions aggravate the generalizability of the study findings (Jiménez-Buedo and Miller, 2010). Another potential confounding factor is the measurement equipment used and the design modifications required to measure the physical parameters of interest. The additional weight of the measurement equipment, as well as its design, modified the real experience of working with the power tool. Therefore, it is possible that the acceptability levels derived from the studies, in part, reflect the subjective experience of handling the modified tool.

7.4.3 Interview study

In order to provide insight into the more practice-oriented perspective of managing physical load exposures from handheld tightening tools, a single-case study of an automotive manufacturing organization was conducted (Paper IV). The anticipation was that current approaches and challenges of tool using organizations related to managing handheld tightening tools use could provide indications of how experimentally generated knowledge could be disseminated into practice. It was decided to study one Swedish automotive manufacturer. This way, outcomes of the interviews could be tied to specific aspects of the organizations policies and approaches. Plausibly, since only one organization was studied, the structures described, and topics emerged from the collected data may not apply to other automotive manufacturing organizations. Nevertheless, the specific case organization was chosen due to their progressive approach to occupational health and production ergonomics. Case studies may not primarily be concerned with general interpretation, but the focus is rather on understanding the specific case (Stake, 2005) from which useful knowledge can be derived.

In the case organization, employees of different competences were recruited to partake in the interviews. The qualification criterion was that they, as a part of their occupation, would come in contact with the selection or management of handheld tightening tools in the production facility. The choice of interviewing employees of various competences was made in order to shed light on the study topic from various perspectives, and not only from

occupational health practitioners' perspective. The anticipation was thereby to gain insight into organizational priorities and practice which could influence the physical exposures resulting from repetitive tightening tool use. The actual users of the power tools were however not interviewed, with the reason being that they typically are not the ones who select and manage the organizational policies around occupational health. Nevertheless, as found through the interview study, the assembly operators' opinions about matters influencing their health are actively considered by e.g. ergonomics management. Therefore, it is plausible that the assembly operators could provide an additional perspective on how the physical load exposures should be managed.

The transferability of the results from the interview study can be determined by the extent to which the findings can be applied to other contexts and settings. It therefore follows that the degree of transferability highly depends on the 'receiving' context (the other setting to which the results would be applied), and its similarities to the 'sending' context (i.e. the studied case) (Erlandson et al., 1993). The transferability of the interview study (Paper IV) therefore depends on the similarities between the studied case organization and other automotive manufacturing organizations and thus needs to be assessed on a case-to-case basis.

As the interviews were conducted online via the meeting software Zoom (Zoom Video Communications, San Jose, California, USA), there were no on-site engagement between researcher and study participants. This may have influenced the interviewees trust towards the interviewer. On-site engagement and observation of the production facility and ergonomics assessments conducted could have been beneficial to the credibility of the collected data. Throughout the interview study, only one technique of data collection was used, namely semi-structured interviews. Other data collection methods, (e.g. observation-based ones) could have further complemented the portrayal of the study phenomena while contributing to validation of the interview findings. On the other hand, the level of credibility of the findings was in part increased by several interviewees providing the same or similar comments about some of the topics (e.g. the priorities between quality, safety and ergonomics) at separate occasions.

7.5 Sustainability goals alignment

The work presented in this thesis is aimed at research community, as well as the industrial community. In a larger perspective, the purpose of the research presented is to contribute to better designed and managed handheld power tools, thus enabling reduced MSD prevalence caused by power tool use. By contributing to more sustainable working conditions for assembly operators, the work from this thesis stands in line with the United Nations Sustainable Development Goals (SDGs) focused on Good Health and Well-being (SDG 3) and Decent Work and Economic Growth (SDG 8) (United Nations, 2015). This thesis adds to the knowledge and awareness around how (one type of) physical load exposures in industrial occupations can be reduced and can hopefully inspire means of addressing other types of occupational health risks.

8 Future work

As demonstrated throughout this thesis, knowledge gaps have been addressed, where new knowledge about reaction loads from handheld tightening tools has been presented. The thesis has also opened gateways to additional fields within the topic area which could be subject to further investigations and research, as presented subsequently.

Regarding measurement techniques, there is still a need for appropriate, effective, and user-friendly means of measuring reaction loads from handheld tightening tools. The less invasive the measurement method is to the study environment, the more easily can measurements be performed close to actual assembly tasks, as opposed to being constrained to laboratory environments. The measurement technologies presented in this thesis serve as a steppingstone to further technical development of measurement technologies. Moreover, standardization authorities need to define a measurement method which can be used by tool manufacturers in order to ensure systematic and comparable assessments of reaction loads.

In this thesis, the physical parameters characterizing the reaction load from handheld tightening tools were studied and presented (reaction force/torque, impulse, tool handle displacement, and jerk). From a practical, as well as theoretical, point of view, it yet remains to select the parameters which most effectively can be measured, and which provide sufficient information regarding the physical load implications for the tool users.

The acceptability levels presented in the two experimental studies of this thesis (Paper II and Paper III) are based on the characteristics of the two tightening tools utilized in the studies, and the specific screw-joints. There is a continued need to establish acceptability limits which reflect a wider variety of tool and screw-joint characteristics, e.g. experimentally, through simulations or by extrapolating available data.

In addition to future advancements of the technical aspects of reaction load exposure from handheld tightening tools, there is a need to compile the findings presented in this thesis in line with practice-compliant processes and needs. As the physical exposures associated with tightening tool use correlate to MSD risks, there is a need for organizations as well as for authorities to reach a state of consensus about *acceptable* risk and the ethical grounds on which the risk-acceptance stands, as complete elimination of risk may not be practically viable. Results from risk assessments are incorporated in the more practically oriented risk management stage, and this is where additional factors such as economic and technical feasibility need to be weighted for.

9 Practical implications

The results presented in this thesis can be directed at power tool manufacturers, power tool using organizations, and decision-makers within work-environment authorities and agencies.

Novel and state of the art measurement technologies have been used throughout the studies included in this thesis, demonstrating the benefits and drawbacks of available means of measuring reaction loads from right-angle and pistol-grip tightening tools. These measurement methods can be utilized by tool manufacturers for determining reaction loads from their tightening tools resulting from e.g. engineering choices within their product development process. The reaction load parameters suggested in this thesis, i.e. peak reaction force/torque, impulse, jerk and tool handle displacement, could be measured in laboratory settings in order to obtain detailed insight into the reaction load, and how different tool settings and screw-joints may influence the exposure. The acceptability limits derived from the studies included in this thesis could be utilized as rough reference values for measured reaction load measurements. Benchmarking should however be done carefully, as test specific conditions (e.g. screw-joint stiffness) influence the reaction load. It should also be noted that the acceptability limits were derived based on short experimental time (i.e. not corresponding to full workdays), and therefore, the exposure limits may not be appropriately extrapolated to full workdays.

When conducting laboratory measurements of reaction loads from handheld tightening tools, user diversity can be introduced into the test data by drawing inspiration from current standardized means of evaluating vibration exposure from handheld power tools (ISO, 2009), where three different test persons operate the tool, and from which an average measure is taken. By methodologically assessing resulting physical loads from handheld tightening tools, power tools manufacturers can declare the physical loads associated with their products, thus enabling their customers (e.g. within the automotive industry) to compare the ergonomics of power tools when selecting products from different power tool suppliers.

Tool using organizations typically have their own means of estimating and assessing reaction loads from handheld tightening tools. Current approaches are normally based on estimating exposure severity through the tightening torque, which does not always accurately reflect the reaction load. With further developed measurement techniques, tool using organizations can gain insight into, and compare, how different tool and task related modifications influence the reaction loads of the tools. Objective data of the reaction load need to be combined with task related parameters, such as posture, frequency of tool use, and total duration of tool use, which always should be accounted for in order to obtain a full picture of the physical demands associated with handheld tool use.

At authority and agency level, the novel insights and knowledge presented in this thesis can serve as a basis for decisions-makers to form standardized assessment procedures for the power tool industry. With increased understanding of power tool technologies and how they influence resulting physical exposures to the tool users, as well as knowledge about the practical contexts in which the tools are used, exposure guidelines and recommendations can be purposefully designed. Thereby, reaction load exposure, being a well-acknowledged cause of MSDs, can be regulated similarly to vibration exposure from handheld power tools.

By successfully implementing research findings, and considering practical feasibility, there is potential for tool manufacturers to design power tools emitting less reaction loads, while tool using organizations can gain better insight into the load levels that their assembly operators are exposed to. These combined efforts can in turn reduce exposure to one of the workload types commonly occurring in assembly settings, thereby contributing to more sustainable working conditions for assembly operators.

10 Conclusion

The research presented in this thesis aimed at contributing to the development of recommended exposure limits for, and assessments of, reaction loads from handheld right-angle and pistol-grip tightening tools. The quest for reducing MSD risks following power tool use starts by being able to measure and benchmark reaction loads, as well as considering the context in which the tool is being used.

In identified publications, exposure limits for electric right-angle and pistol-grip tools were expressed in terms of tightening torque. In addition to the task-relevant factor tightening-torque, exposure limits should also be expressed as reaction load relevant parameters. Based on the results of the experimental studies, it is suggested that reaction loads from handheld tightening tools be characterized according to the following physical parameters: reaction force (right-angle tools), reaction torque (pistol-grip tools), impulse, tool handle displacement, and, as newly proposed, jerk. It is hypothesized that the jerk parameter links to the subjective sensation of discomfort. Depending on the type of tightening (i.e. tool setting or screw-joint characteristics) the different parameters may be more or less pronounced.

Psychophysically based acceptability limits were derived for right-angle and pistol-grip tools. It should be noted that the experimental times on which the acceptability limits are based were limited, and that the limits therefore should not be administered to full workdays. Instead, they can in synthesis with previously determined acceptability limits and exposure limits, contribute to a basis for forming generally acknowledged exposure limits for reaction loads associated with such tools.

As there are inherent difficulties to replicating the variety of real assembly tasks and tool use situations in simplified and controlled experiments, there are limitations to the generalizability of the outcomes of experimental studies such as the ones presented in this thesis. Derived exposure limits cannot alone account for the probability of developing MSDs. Therefore, in practice, attention has to be devoted to the particular conditions under which assembly operators are using power tools. Factors influencing the MSD risk following power tool use, and which need to be evaluated, can be divided into tool-related factors and task-related factors. Tool-related factors of relevance include tightening program and speed settings, as well as the length and weight of the tool (which all influence the resulting reaction load). Task-related factors of relevance include tightening torque, screw-joint stiffness, posture, frequency of tool use, and total duration of tool use. In addition to these objective metrics, systematic assessments of tool users' subjective experience when using the tools need to be considered. By considering the research reported in this thesis, power tool manufacturers can measure and benchmark the reaction loads of their tightening tools. Further, policy-makers can utilize the outcomes of the thesis to form recommendations for

exposure limits and standardized assessments of reaction loads. Thereby, power tool manufacturers can compare reaction load levels between different engineering designs, while tool using organization can be more insightful in their tool selection. The collective efforts can in the long run pave the way for reduced MSDs caused by power tool use and thus more sustainable working conditions for assembly operators.

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