UMEÅ UNIVERSITY

RISK ASSESSMENT OF HAND-INTENSIVE WORK USING RATINGS AND TECHNICAL MEASURES:

Sex and Gender Considerations

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The important thing is not to stop questioning. Curiosity has its own reason for existing.

— Albert Einstein

Table of Contents

ABSTRACT iii

SVENSKT ABSTRAKT v

ABBREVIATIONS vii

INVESTIGATED MEASUREMENTS viii

ORIGINAL PAPERS ix

Thesis at a glance x

INTRODUCTION 1
Theoretical framework 3
Sex and gender 3
Indirect methods: rated hand activity and hand force 4
Direct methods: wrist velocity and muscle activity 6
Biological differences 8
Theoretical perspectives on the perception of physical exertion 9

AIM 13
Overall aim 13
Specific aims of the studies 13

MATERIALS AND METHODS 14
Study design and methodological foundation 14
Participants 15
Data collection 17
Rated hand activity and hand force 19
Technical Measurement System 20
Statistical analysis 22
Ethical considerations 25

RESULTS 26
Workers 26
Wrist angular velocity and muscle activity measures 26
Ratings – HAL and Borg CR-10 28
Correlations – ratings and technical methods 30

DISCUSSION 31
HAL ratings and wrist velocity 31

Borg CR-10 ratings and muscle activity (sEMG) 32
Strengths and limitations 35
Implications for clinicians and future research 36

CONCLUSION 39

Acknowledgements 40

REFERENCES 43

ABSTRACT

Background In ergonomic risk assessment of hand-intensive work, observational methods are typically used to rate risk exposure. However, it remains unclear whether women and men performing identical work tasks are rated differently with respect to the established risk exposures: hand activity/repetitivity and hand force. To better understand these ratings, measured wrist joint angular velocity and measured forearm muscle activity could be examined in parallel.

Aim The aim was threefold: (1) to investigate whether hand activity (Hand Activity Level, HAL) and hand force (Borg CR-10) are rated differently between women and men performing identical work tasks; (2) to compare technically measured wrist angular velocity and measured forearm muscle activity between female and male workers; and (3) to examine the correlations between these ratings and their corresponding technical data.

Methods Fifty-nine workers (29 women, 30 men), organized into 28 female–male pairs, participated. Each pair performed identical hand-intensive tasks across different real-world workplaces. Data were collected on workers' measured wrist joint angular velocity (°/s) using inertial measurement units and on flexor and extensor carpi radialis (FCR, ECR) muscle activity and recovery, expressed as a percentage of maximal voluntary electrical activation (%MVE), via surface electromyography. Workers' self-rated hand activity level (HAL) and hand force (Borg CR-10). All tasks were video recorded. Additionally, two mixed-gender pairs of experienced ergonomists (n = 4) and 54 individual ergonomists (27 women, 27 men) video-rated the workers' tasks using the HAL and Borg CR-10 scales. Analyses included sex-based comparisons of all variables and correlations between ratings (self and ergonomist-rated) and technical measures. In Paper I, differences in HAL and Borg CR-10 ratings between female and male workers were compared using self-ratings and ratings from mixed-gender ergonomist pairs. Paper II examined correlations between wrist angular velocity and HAL, and between forearm muscle activity and Borg CR-10. Paper III compared measured wrist angular velocity and muscle activity between women and men. Paper IV analyzed individual ergonomist ratings in 27 female–male pairs with similar professional experience to determine whether female and male workers were rated differently (HAL, Borg CR-10.

Results No significant sex differences were found in wrist velocity (Paper III) or HAL ratings, whether self-rated, rated by ergonomist pairs, or individual ergonomists (Papers I and IV). Self-rated HAL (tau = 0.23–0.31, p = 0.002–0.005) and ergonomist pair ratings (tau = 0.32–0.41, p = 0.001) correlated significantly with wrist velocity. Measured FCR and ECR muscle activity were significantly higher in women than men (p = 0.004–<0.001) (Paper III). Similarly, ergonomist-rated hand force (Borg CR-10) was significantly higher for female workers, both in pair ratings (women: 3.9 ± 2.7; men: 3.1 ± 1.8, p = 0.01) and individual ratings (mean difference 0.35, p < 0.001) (Papers I and IV). In contrast, workers' self-rated hand force did not differ significantly between women and men (Paper I). Measured FCR and ECR muscle activity and ergonomist-rated hand force correlated significantly in 4 of 6 variables (tau = 0.32–0.41, p = 0.01–<0.001), and for recovery time in FCR only (tau = –0.47, p = 0.001) (Paper II). In contrast, self-rated hand force did not correlate significantly with measured muscle activity (Paper II).

Conclusions Measured wrist velocity and HAL ratings show no systematic differences between women and men performing identical work tasks. Women's higher measured muscle activity and higher ergonomist-rated hand force (Borg CR-10) indicate that these methods detect sex differences. Therefore, when ratings are used, ergonomist-rated hand force should be prioritized. In contrast, self-rated hand force using the Borg CR-10 does not detect sex differences and may underestimate women's hand force. Therefore, self-ratings should be avoided in risk assessments aiming to capture sex-based differences. Due to limitations in subjective ratings, technical measures should be preferred when possible. When tasks are identical, women should be prioritized in assessments of hand force or muscle activity to ensure protection for all workers. These strategies may help detect sex differences in hand force and improve precision in risk assessment. This can support the protection of both women and men in hand-intensive work from musculoskeletal disorders and promote a sustainable working life.

Keywords: Risk assessment, hand activity, force, IMU, sEMG, sex, gender

SVENSKT ABSTRAKT

Bakgrund Vid ergonomisk riskbedömning av handintensivt arbete används vanligen observationsmetoder med skattning av exponering. Det är dock oklart om kvinnor och män som utför identiska arbetsmoment skattas olika vad gäller de etablerade riskexponeringarna handaktivitet/repetitivitet och handkraft. För att öka förståelsen av dessa skattningar kan handledshastighet och underarmens muskelaktivitet mätas parallellt.

Syfte Syftet var tredelat: (1) Att undersöka om handaktivitet (Hand Aktivitets Nivå, HAL) och handkraft (Borg CR-10) skattas olika mellan kvinnor och män som utför identiska arbetsuppgifter; (2) att med tekniska mätningar jämföra handledens vinkelhastighet och underarmens muskelaktivitet mellan könen; samt (3) att undersöka sambandet mellan dessa skattningar och motsvarande tekniska mätvärden.

Metod Femtionio arbetstagare (29 kvinnor, 30 män), i 28 kvinna–man-par deltog. Varje par utförde identiska handintensiva arbetsmoment på sina ordinarie arbetsplatser. Tekniska data samlades in på arbetstagarnas uppmätta handledsvinkelhastighet (°/s) med rörelsesensorer samt på muskelaktivitet och återhämtning i flexor och extensor carpi radialis (FCR, ECR), uttryckt som procent av maximal viljestyrd elektrisk aktivering (%MVE), via yt-elektromyografi. Arbetstagarna självskattade handaktivitet (HAL) och handkraft (Borg CR-10). Alla arbetsmomenten videofilmades. Därtill video-skattade ergonomer arbetsmomenten med HAL- och Borg CR-10, i två kvinna-man par av erfarna ergonomer (n = 4) samt individuella skattningar av 54 ergonomer (27 kvinnor, 27 män). Analyserna inkluderade könsskillnader i samtliga variabler samt korrelationer mellan skattningar (självskattningar respektive ergonomskattningar) och tekniska mätningar. I Artikel I jämfördes om kvinnor och män skattades olika, baserat på arbetstagarnas självskattningar samt ergonomers par-skattning av HAL och Borg CR-10. Artikel II undersökte korrelationen mellan handledens vinkelhastighet och HAL, samt mellan underarmmuskelaktivitet och Borg CR-10. I Artikel III jämfördes kvinnor och män avseende mätt handledshastighet och mätt muskelaktivitet. Artikel IV undersökte om kvinnliga och manliga arbetstagare skattades olika (HAL, Borg CR-10) av ergonomer med liknande erfarenhet.

Resultat Inga signifikanta skillnader observerades mellan könen i handledsvinkelhastighet (Artikel III). Inga signifikanta skillnader

observerades heller mellan kvinnor och män i skattad HAL, oavsett om arbetstagarna skattade sig själva, skattades av ergonompar eller enskilda ergonomer (Artikel I och IV). Handledshastighet korrelerade signifikant med HAL, både självskattad (tau = 0.23–0.31, p = 0.002–0.005) och skattad av ergonompar (tau = 0.32–0.41, p = 0.001) (Artikel II). Däremot var uppmätt muskelaktivitet i FCR och ECR signifikant högre hos kvinnor jämfört med män (p = 0,004–<0,001) (Artikel III). Även ergonomer skattade handkraft (Borg CR-10) signifikant högre hos kvinnor, både i parvisa skattningar (kvinnor, män: 3,9 ± 2,7 respektive 3,1 ± 1,8, p = 0,01) och i individuella skattningar (medelskillnad 0,35, p = <0,001) (Artikel I och IV). Signifikanta korrelationer fanns mellan uppmätt muskelaktivitet i FCR och ECR och ergonompars skattade handkraft i 4 av 6 variabler (tau = 0,32–0,41, p = 0,01–<0.001), och för tid i återhämtning i FCR (tau = –0,47, p = 0,001) (Artikel II). Självskattad handkraft visade ingen signifikant skillnad mellan kvinnor och män (Artikel I), och självskattad kraft korrelerade inte signifikant med uppmätt muskelaktivitet (Artikel II).

Slutsatser Mätt handledshastighet och HAL-skattningar visar inga systematiska skillnader mellan kvinnor och män som utför identiska arbetsuppgifter. Kvinnors högre muskelaktivitet och högre handkraft skattad av ergonomer (Borg CR-10) visar att dessa metoder detekterar skillnader mellan kvinnor och män. Därför bör handkraft skattas av ergonomer. Självskattad handkraft med Borg CR-10 fångar däremot inte könsskillnader och riskerar att underskatta kvinnors handkraft. Självskattningar bör därför undvikas vid riskbedömning. På grund av begränsningar i subjektiva skattningar bör tekniska mätmetoder användas när det är möjligt. När arbetsuppgifterna är identiska bör kvinnor prioriteras i bedömningar av handkraft eller muskelaktivitet för att säkerställa skydd för alla arbetstagare. Strategierna kan detektera kvinnors högre handkraft och förbättra precisionen i riskbedömningar. Detta kan bidra till att skydda kvinnor och män i handintensiva arbeten mot belastningsbesvär och främja ett hållbart arbetsliv.

Nyckelord: Riskbedömning, handaktivitet, kraft, IMU, sEMG, kön, genus

ABBREVIATIONS

ECR	extensor carpi radialis
sEMG	surface electromyography
FCR	flexor carpi radialis
HAL	Hand Activity Level
HA TLV	American Conference of Governmental Industrial Hygienists Hand Activity Threshold Limit Value
IMU	inertial measurement unit
MSD	musculoskeletal disorder
MVE	maximal voluntary electrical activation

INVESTIGATED MEASUREMENTS

The following four measures were investigated in this thesis:

Objective variables measured with technical devices:

Wrist joint angular velocity
Measurement of the wrist joint velocity in flexion-extension as °/s using two inertial measurement units.

Muscle activity
Surface electromyography measurement of the relative muscle activity generated by electrical signals in the muscles.

Subjective variables measured as rated constructs:

Hand Activity Level
A numeric scale (0–10) for rating the hand activity (repetitivity) in a hand-intensive task (Latko et al., 1997).

Borg CR-10
A numeric scale (0–10) for rating the perceived exertion of hand force in a hand-intensive task (Borg, 1982).

ORIGINAL PAPERS

This thesis is based on the four papers listed below and they will be referred to through-out the text by their Roman numerals:

I. Dahlgren, G., Liv, P., Öhberg, F., Slunga Järvholm, L., Forsman, M., Rehn, B., 2022. Ratings of hand activity and force levels among women and men who perform identical hand-intensive work tasks. Int J Environ Res Public Health 19, 16706. https://doi.org/10.3390/ijerph192416706

II. Dahlgren, G., Liv, P., Öhberg, F., Slunga Järvholm, L., Forsman, M., Rehn, B., 2023. Correlations between ratings and technical measurements in hand-intensive work. Bioengineering 10, 867. https://doi.org/10.3390/bioengineering10070867

III. Dahlgren, G.; Liv, P.; Öhberg, F.; Slunga Järvholm, L.; Forsman, M.; Rehn, B. Are there sex differences in wrist velocity and forearm muscule activity when performing identical hand-intensive work tasks? (In manuscript)

IV. Dahlgren, G.; Liv, P.; Öhberg, F.; Slunga Järvholm, L.; Forsman, M.; Rehn, B. Do female and male ergonomists rate female and male workers' hand activity and force differently in identical regular industrial tasks? (Submitted)

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Thesis at a glance

Paper I	28 female-male pairs of workers 2 female-male pairs of ergonomists
Aim	To investigate hand activity and force ratings in identical tasks
Methods	Comparison of female and male workers in identical tasks: workers' self-rated and ergonomist pair-rated hand activity (Hand Activity Level [HAL]) and force (Borg CR-10).
Results	No gender differences were found in hand activity. Ergonomist-rated force was higher in female workers. Self-rated force showed no gender difference.
Conclusions	The observed difference between women and men in force ratings highlights the need for objective measurement methods.
Paper II	59 workers (29 women and 30 men) 2 female-male pairs of ergonomists
Aim	To investigate the correlation between hand activity and force ratings (by both workers and ergonomists) and the corresponding technical methods
Methods	Rated hand activity (HAL) and measured wrist angular velocity (°/s), hand force (Borg CR-10) and muscle activity (percentage of maximal voluntary electrical activation [%MVE]) correlations
Results	Hand activity correlated significantly with measured velocity (°/s). Force correlated significantly only for ergonomist ratings, and not for self-ratings.
Conclusions	Hand activity aligns with velocity, and can be used for screening. Ergonomist-rated force is preferred; self-rated should be avoided. Technical measures should be preferred over ratings for work risk assessment, when possible.
Paper III	28 female-male pairs of workers
Aim	To investigate measured wrist joint angular velocity (°/s) and measured muscle activity (%MVE) in identical tasks comparing women and men
Methods	Objectively measured wrist angular velocity (°/s), and muscle activity (%MVE)
Results	Measured wrist angular velocity showed no sex differences. Women had higher measured muscle activity and lower muscular recovery than men.
Conclusions	Female workers' higher muscle load during identical tasks should be recognized.
Paper IV	26 female and 26 male ergonomists 28 female-male pairs of workers
Aim	To investigate whether female and male ergonomists rate hand activity and hand force differently in female and male workers
Methods	Ergonomists' individual ratings of hand activity (HAL) and hand force (Borg CR-10)
Results	Hand force was significantly higher in female workers, while hand activity did not differ by worker sex.
Conclusions	Ergonomists rate hand force systematically higher in female than male workers. Ergonomist-rated hand activity does not differ between female and male workers.

INTRODUCTION

Two colleagues, a woman and a man, repeat the same movement 8,000 times a day. Neither of them keeps count, but their wrists do, through pain and strain. For millions of workers like them, hand-intensive work such as assembly, sorting, food processing, warehousing or cleaning is a daily reality; about one-third of employees in the USA and the EU perform such tasks in their jobs (CEDEFOP, 2020; U.S. Bureau of Labor Statistics, 2023). When hand activity is frequent, repetitive, high in velocity, and/or combined with high hand force or muscle activity, these exposures are well-established risk factors for work-related musculoskeletal disorders (MSDs) and diagnoses such as carpal tunnel syndrome (Arvidsson et al., 2021; Hassan et al., 2022).

MSDs are the most common work-related health problem in the EU, affecting workers in all sectors and occupations. These disorders not only harm workers' health and quality of life, but also generate significant costs for businesses and society through absenteeism, lost productivity, medical expenses, disability, and compensation claims (de Kok et al., 2019; Greggi et al., 2024). Of all workers in the EU with a work-related health problem, 60% identify MSDs as their most serious issue (de Kok et al., 2019).

While work-related MSDs affect both women and men, women are disproportionately affected (Andorsen et al., 2014; de Zwart et al., 2001; Nordander et al., 2013, 2009; Wijnhoven et al., 2006). For example, 27% of female workers report elbow or hand disorders, compared to only 19% of male workers (Balogh et al., 2019). Carpal tunnel syndrome exemplifies this disparity, with women facing a 2–4 times higher risk. In Sweden, 69% of carpal tunnel surgeries in 2015 were performed on women (Atroshi et al., 2011; Giersiepen and Spallek, 2011; Linde et al., 2022; Mondelli et al., 2002; Tabatabaeifar et al., 2020), and occupational factors are estimated to cause 42% of first-time cases (Tabatabaeifar and Dalbøge, 2024). Carpal tunnel syndrome is recognized as an occupational disease in the EU (Giersiepen and Spallek, 2011), and serves as a sentinel condition for harmful mechanical strain on the hands, with strains that often extend to the elbows and shoulders (Tabatabaeifar et al., 2020).

Sex and gender differences in work-related MSDs may partly be explained by different exposure related to occupational segregation, where women and men work in different occupations (Biswas et al., 2021; Migliore et al., 2021), hold different job titles within the same occupation (Carranza et al., 2023), or perform different tasks under the same title (Eng et al., 2011;

Wuytack et al., 2023). These differences may also be influenced by organizational factors related to the distribution of how work is distributed between the sexes (Hagberg et al., 1995; Quinn and Smith, 2018). Even when women and men share the same task, differences in task exposure may persist.

For example, in identical work tasks performed by women and men, women exhibit higher relative muscle activity than men (Kim et al., 2024; Meyland et al., 2014; Nordander et al., 2008). Higher muscle activity is theoretically linked to muscular fatigue and tissue damage (Gallagher and Barbe, 2022), and has also been empirically associated with an increased risk of MSDs when exceeding proposed action limits for work exposure (Arvidsson et al., 2021).

Preventing work-related MSDs in hand-intensive work relies heavily on early identification and management of risk (Lewis et al., 2002; Tabatabaeifar et al., 2017). In Sweden and other countries, occupational health and safety regulations require risk assessment within a systematic work environment management process. This risk assessment plays a central role, with the primary aim of identifying hazardous exposures that may lead to work-related MSDs. The outcome of the risk assessment is the foundation for guiding risk-reducing actions to protect all workers from ill-health, and so it is essential for the assessment to account for differences among workers, including sex/gender, to ensure effective protection for all workers.

Workplace risk assessment is typically conducted using observational methods and task ratings of risk exposures. The work task is performed by the worker and observed by an ergonomist, who may also film the task for additional video-based assessment afterward. The risk assessment typically involves the worker, workplace representatives, and a trained external ergonomist.

While this approach is well established, it has not been systematically investigated whether ratings of hand activity and hand force capture potential sex/gender differences. In particular, it remains unclear whether women and men performing identical hand-intensive tasks are rated differently. To explore this, technically measured wrist velocity and muscle activity could be assessed in parallel.

Theoretical framework

The research described in this thesis is grounded in occupational exposure assessment theory and adopts a measurement-oriented approach. The main focus is to examine whether subjectively rated risk exposures differ between female and male workers. For this purpose, rated hand activity using the Hand Activity Level (HAL) scale (Latko et al., 1997) and rated hand force using the Borg CR-10 scale (Borg, 1982) are investigated. To support this understanding, parallel objective technical measured wrist joint angular velocity and measured muscle activity are examined to correspond with the ratings. Finally, correlations between the rated and technical measures are analyzed.

To interpret the findings comparing sex and gender, two key perspectives were considered. Differences in self-ratings and observer ratings are interpreted through both biological and social lenses. Sex-based physiological factors and gendered perceptions of exertion are jointly considered to understand when and why rating differences appear, and how they relate to objective measures of physical exposure. These perspectives are further elaborated in the sections below on biological differences and theoretical models of perceived exertion.

Sex and gender

Definitions of sex and gender

The Sex and Gender Equity in Research (SAGER) guideline is used to define "sex" (categorized as female or male) in relation to a set of biological attributes in humans, and "gender" (categorized as woman and man) in relation to the socially constructed roles, behaviors, and identities of female, male, and gender-diverse participants (Heidari et al., 2016). The term "sex/gender" is also sometimes used to align with cited research (Gualtieri, 2023; Laberge et al., 2022), particularly when those sources do not clearly distinguish between biological sex and gender.

A distinction is sometimes made between the terms "female" and "male" and the terms "woman" and "man", with the former being used to describe differences related to biomechanical and physiological measures of wrist angular velocity and muscle activity, and the latter being used for subjective ratings regarding hand activity and force. However, to keep the grammar clear, this text uses "woman" and "man" as nouns, and "female" and "male" as adjectives, without intending to conflate sex and gender. Sex and gender identities other than female and male are beyond the scope of the present work.

Sex/gender in exposure and risk assessment
Although gender-inclusive risk assessment is supported by EU legislation, which stipulates that assessments must consider gender issues, differences, and inequalities (European Agency for Safety and Health at Work, 2003), the consideration of sex and gender in exposure assessment methods remains under-researched in hand-intensive work in occupational health.

In clinical practice, ergonomic risk assessment of hand-intensive work is typically conducted through observational rating methods due to their practicality, ease of use in estimating exposure levels, low cost, and adaptability to workplaces where technical measures may not be feasible (Burdorf and van der Beek, 1999; Takala et al., 2010). However, sex- and gender-specific considerations are rarely integrated into observational methods and ergonomic risk assessments. A recent scoping review on observational methods found that among six identified risk assessments for repetitive or hand-intensive work, none explicitly considered sex (Serna Arnau et al., 2023). One of these is the Hand Activity Threshold Limit Value (HA TLV), developed by the American Conference of Governmental Industrial Hygienists (ACGIH, 2022). Furthermore, although the international standard for repetitive hand-intensive work (ISO, 2007) briefly mentions individual factors such as age, gender, and health status, it does not explicitly require the systematic consideration of sex- or gender-specific differences in exposure assessment or risk evaluation.

Indirect methods: rated hand activity and hand force

Indirect, or observational, methods used in hand-intensive work risk assessment are typically based on subjective ratings of work exposures. One well-known observational method used in clinical practice for risk assessment of hand-intensive work is the HAL TLV. This applies to jobs such as manual assembly, packaging, food processing and similar tasks that involve repetitive motions and forceful exertions performed for 4 to 8 hours per day. The two rated exposures in the HAL TLV examined in this thesis are hand activity (repetitivity) by the Hand Activity Level (HAL) scale and hand force by the Borg CR-10 scale. The HAL and Borg CR-10 scales used in the HA TLV have been tested for reliability and validity across various contexts, including repeated analyses, interrater reliability studies, and comparisons with other assessment tools (Latko et al., 1997; Ebersole and Armstrong, 2006; Spielholz et al., 2008; Lowe, 2009; Wurzelbacher et al., 2010).

The Hand Activity Level (HAL) scale is a linear, standardized observational tool (0–10) developed to quantify the repetitiveness of manual tasks based on movement speed and task frequency. It provides a structured approach to rating hand activity in occupational settings.

Alternative methods for assessing hand activity in workplace risk assessment include counting repetitions per unit of time, for example, per minute or day (David, 2005; Douwes and de Kraker, 2012; Gallagher et al., 2018; Kapellusch et al., 2021; Klussmann et al., 2017).

The Borg CR-10 is a non-linear category-ratio scale (0–10). In HA TLV Borg CR-10 is used to measure perceived physical hand exertions. The Borg CR-10 scale was developed in alignment with the Rating of Perceived Exertion (RPE) scale and was intended to capture perceived exertion, as well as symptoms such as aches and pain (Borg, 1982). It has been tested for reliability and validity in work risk assessment contexts, including inter-observer agreement (gender unspecified) (Bao et al., 2010), comparisons between worker and observer ratings, and correlations with sEMG-based force measures in men (Lowe and Krieg, 2009).

Other ratings for hand force used in hand-intensive risk assessments are the visual analogue scale (0–10), the OMNI-RES (linear scale of 0–10), or load weight categories based on exertion and absolute weight classes; for example, low defined as <1kg, moderate as 1–4 kg, and high as >4kg (ACGIH, 2022; David, 2005; Douwes and de Kraker, 2012; Gallagher et al., 2018; Kapellusch et al., 2021; Klussmann et al., 2017; McAtamney and Nigel Corlett, 1993).

The HA TLV risk categories are based on the combination of rated hand activity (HAL) and hand force (Borg CR-10), and is classified as green (below the Action Limit), yellow (between the Action Limit and the Threshold Limit Value), or red (above the Threshold Limit Value). This classification system has demonstrated predictive validity for carpal tunnel syndrome in mixed populations (Harris-Adamson et al., 2015; Kapellusch et al., 2014; Violante et al., 2007; Yung et al., 2019).

High-quality evidence shows that high repetition (measured as HAL ratings) is significantly associated with an increased rate of carpal tunnel syndrome (HR: 1.87, 95% CI: 1.42–2.46), as is high hand force intensity (Borg CR-10) (HR: 1.84, 95% CI: 1.22–2.79). HA TLV exposure between the action limit and the threshold limit value is also associated with an elevated risk of carpal tunnel syndrome (HR: 1.75, 95% CI: 1.40–2.17) (Hassan et al., 2022). Additionally, HAL rating ≥4 is significantly

associated with disorders in the non-dominant hand only (OR: 2.81, 95% CI: 1.40–5.62) (Spielholz et al., 2008).

Observational methods, such as the HA TLV, have several advantages as previously described and are also suitable for larger data collections. However, they may lack precision and accuracy (Hansson et al., 2001; Spielholz et al., 2001), and there is a gap in knowledge regarding whether ratings differ between women and men (Serna Arnau et al., 2023).

Direct methods: wrist velocity and muscle activity

Direct, or technical methods can offer objective measures corresponding to hand activity (HAL) and hand force (Borg CR-10). Wrist joint angular velocity (°/s) measures biomechanical exposure related to movement speed and repetitiveness. This velocity can be recorded by inertial measurement units (IMUs) placed on the skin on each side of the joint.

SEMG provides a physiological measure of muscle activity by detecting the electrical signals generated during voluntary contractions. These signals originate from the depolarization and repolarization of muscle fiber membranes, triggered by neural stimulation at the neuromuscular junction (Hug and Tucker, 2017). The sEMG signal reflects the summed activity of multiple motor units and can be recorded non-invasively using surface electrodes placed on the skin above the muscle (Hermens et al., 2000).

Similar to the HA TLV risk categories, action levels for measured wrist joint angular velocity and forearm extensor carpi radialis (ECR) muscle activity have been proposed as indicators of risk for neck and upper extremity disorders (Arvidsson et al., 2021). For wrist joint angular velocity, a suggested action level for the 50th percentile over a workday is 20 °/s in general, or 15 °/s if the work is force-demanding or involves using vibrating tools. The risk for several diagnoses has been found to be more than twice as high in groups with high wrist or upper arm velocity, above the action limit, compared to those with low velocity, below the action limit (Arvidsson et al., 2021).
For ECR muscle activity, Arvidsson et al. (2021) define action levels based on maximal voluntary contraction (MVC), and muscle activity is expressed as a percentage of maximal voluntary electrical activation (%MVE). Normalizing sEMG this way allows comparisons between individuals, regardless of muscle strength.

Arvidsson et al. recommend for forearm ECR muscle that the normalized sEMG does not exceed 10%MVE at the 50th percentile (median load) or 30%MVE at the 90th percentile (peak load), and that recovery time, defined as sEMG activity below 0.5% MVE, accounts for at least 5% of the workday. This means that muscle activity should remain below 10% MVE for at least half of the workday (median load), below 30% MVE for at least 90% of the workday (peak load), and that that at least 5% of the day should allow the muscle to be almost completely at rest (recovery). Measured muscle activity exceeding these thresholds has been associated with more than twice the risk of several musculoskeletal diagnoses compared to exposures below the action limit (Arvidsson et al., 2021).

IMUs and sEMG offer objective, reliable, and high-resolution data that help reduce observer bias (van der Beek and Frings-Dresen, 1998). Although analysts measure wrist velocity and muscle activity through direct, technical methods, subjectivity can still arise from their choices, such as which muscles are selected and how the data are analyzed. IMUs are relatively affordable and easy to use (Baklouti et al., 2024), whereas sEMG measures require more expertise, time, and resources, although technological developments are making sEMG more accessible (Bawa and Banitsas, 2022).

Terminology and conceptual distinctions

To ensure clarity in the terminology used for work exposure measures in this thesis, the constructs hand activity (HAL) and hand force (Borg CR-10) are referred to as ratings and classified as observational methods. In contrast, wrist joint angular velocity and muscle activity are considered direct or technical measures.

HAL and Borg CR-10 ratings and their respective corresponding technical measured wrist velocity and measured muscle activity capture related but distinct dimensions of workload. Rated hand activity (HAL) and measured wrist angular velocity are not gold standards for one another, and the same holds for rated hand force using Borg CR-10 and measured muscle activity (sEMG) (Burdorf and van der Beek, 1999; Takala et al., 2010). Rather, they reflect different disciplinary perspectives.

Ratings such as hand force on the Borg CR-10 reflect perceived exertion, while corresponding sEMG data quantify the physiological response in muscle activity. These perspectives align with psychophysics (subjective ratings), occupational physiology (physiological measures), and social psychology (influences such as workplace norms and gender roles). This distinction is important because ratings may be shaped by context or

social expectations, while technical measures more directly reflect biomechanical demands. Combining both approaches allows for a more nuanced interpretation of rated measures and helps in understanding whether the observed rated differences reflect actual physical workload and biological differences or subjective perceptions in relation to gender.

Biological differences

To deepen the understanding of sex differences in measured work exposures, it is important to consider biological factors that may influence exposure measures.

Strength and *anthropometric characteristics* differ between sexes. On average, men are stronger than women, particularly in upper body strength, including hand grip strength (Haizlip et al., 2015; Miller et al., 1993). At their peak grip strength, which is typically attained between ages 25 and 39, women possess approximately 65% of the grip strength of men, and this difference persists across the lifespan (Mathiowetz et al., 1985; Wang et al., 2018)

Men also have larger anthropometric body size, on average, than women (Hanson et al., 2009; Open Ergonomics, 2022; Pheasant and Haslegrave, 2018). Research has also shown that grip strength correlates with hand circumference (Li et al., 2010; Zaccagni et al., 2020), as well as with forearm circumference and length, hand size, and overall body height (Günther et al., 2008).

A similar pattern is seen for strength relative to muscle cross-sectional area (Bruce et al., 1989; Miller et al., 1993). Women and men show no differences in strength per unit area, motor unit number, or activation. The overall strength gap is primarily due to the greater muscle mass in males resulting from testosterone-induced hypertrophy. Men have a higher proportion of “fast” type IIa and IIx muscle fibers, which are larger in cross-sectional area and generate greater force. Women, in contrast, have a greater proportion of “slow oxidative” type I fibers, which are more fatigue-resistant and support sustained, low-force activity (Haizlip et al., 2015).

In real-life settings, the external workload of an identical repetitive task is the same for women and men in absolute terms. However, due to women’s generally lower maximal strength and smaller body size, they are likely to perform the task at a higher relative intensity (Gallagher and Barbe, 2022). This disparity is reflected in sEMG muscle activity normalized to the individual’s maximal voluntary isometric contraction. Differences in

muscle morphology and contractile properties, such as smaller muscle fiber size and cross-sectional area, suggest that women may recruit higher relative muscle activity than men when performing the same absolute workload (Haizlip et al., 2015; Miller et al., 1993). Empirical studies also demonstrate higher relative muscular load in female workers compared to males performing identical tasks (Kim et al., 2024; Meyland et al., 2014; Nordander et al., 2008). In summary, the measured relative muscle activity (sEMG) during work reflects the physiological response to the task. On average, this activity is higher in women than in men, although the difference can sometimes be in the opposite direction when comparing individuals.

Physiological sex differences can affect both the capabilities of the musculoskeletal system and the likelihood of experiencing fatigue failure injuries (Gallagher and Barbe, 2022). The *fatigue failure theory* of MSDs, as proposed by Gallagher and Barbe (2022), explains that tissues such as muscles, tendons, and ligaments can develop damage when exposed to repeated or sustained mechanical loading without sufficient recovery time. Just like materials in engineering, biological tissues have a limit to how much strain they can withstand before micro-damage accumulates. Over time, this can lead to inflammation, degeneration, or structural failure, ultimately resulting in MSDs. Physiologically, this process involves microscopic tears, reduced oxygenation, and cellular stress responses in the overloaded tissue.

Gallagher and Barbe also highlight potential sex differences, noting that women may be more vulnerable to fatigue-related damage due to differences in muscle size, fiber composition, and recovery capacity, especially under the same absolute workloads. This theory provides a biomechanical explanation for how physical workload can gradually lead to chronic injury, even at submaximal force levels. In an empirical study examining muscular activity in two industries where women and men performed identical repetitive tasks, the findings showed that female workers exhibited substantially higher relative muscular activity, and they also had a greater prevalence of upper extremity MSDs compared to their male counterparts (Nordander et al., 2008).

Theoretical perspectives on the perception of physical exertion

In contrast to directly measured exposures (e.g., muscle activity) linked to biological sex differences, rated exposures (e.g., hand force) may be shaped by more than physiology.

A review of empirical studies by Verbrugge (1989) and a theoretical analysis by Macintyre et al. (1996) suggest that differences between genders in reported health and symptoms may reflect social roles, contextual expectations, and behavior rather than objective differences alone. Applying this reasoning to workplace exposure ratings, it is possible that men and women differ in how they report physical exertion, not only due to physiological differences, but also because of gendered socialization into norms surrounding the expression of fatigue, pain, and effort. The *Social Role Theory* (Eagly and Wood, 2012) supports the idea that rating differences may be influenced by social norms; for example, men may underreport exertion to align with ideals of strength, while women may avoid high ratings to not appear weak, particularly in work environments where physical performance is culturally expected.

Besides how gender can affect ratings, another aspect is the intensity of exertion. Rating lower levels of physical exertion may be more challenging than rating higher levels. The *Dual-Mode theory* explains how perceived exertion is influenced by different factors depending on intensity level (Ekkekakis and Petruzzello, 1999). At lower intensities, perceptions are shaped primarily by psychological and cognitive factors, such as previous experiences, self-perception, situational interpretation, and social norms within the context. As intensity increases, physiological cues such as breathlessness, muscle fatigue, and discomfort become more pronounced, making subjective ratings more closely reflect the actual physical strain. In short, at low exertion intensities, how you think shapes how you feel. At high intensities, how your body feels takes over and affects your mood. This finding aligns with earlier psychophysical research. *Stevens' Power Law* (Stevens, 1957) shows that the relationship between physical stimulus and perceived intensity typically follows a non-linear, exponential pattern. For perceived muscle effort, the exponent is typically above 1, meaning perceived intensity rises faster than actual effort, especially at higher levels. But at lower load levels, the curve is flatter, and physiological sex differences in maximal strength may not be reflected in the ratings.

The Borg CR-10 scale (Borg, 1982) is a relative measure reflecting the perceived exertion of how demanding a task feels in proportion to an individual's maximal capacity. Because the scale is internally calibrated to each person's own limits, individuals with different strength or endurance levels may rate the same task similarly, especially if the task is perceived as light or the work is familiar. For example, in a study by (Jakobsen et al., 2014) involving over 200 workers in physically demanding occupations, significant correlations were found between self-reported exertion and

objective measures of muscle load. However, these correlations were weak at moderate levels of exertion. Clear threshold values were also observed, as correlations increased markedly only at Borg ratings of 4 or higher, particularly for trapezius muscle activity. This suggests that rating scales, such as the Borg CR-10, may capture differences in actual physiological load more clearly at higher intensities. This is also demonstrated in Meyland et al. (2014), who compared self-rated force (Borg CR-10) between female and male house painters in nine different tasks within a laboratory setting. Three tasks rated <4 on the Borg CR-10 scale were not rated significantly differently between sexes. Five (of six) tasks rated >4 differed significantly between sexes, with higher rated force (Borg CR-10) in females.

Moreover, other factors that can influence the rating include how the Borg CR-10 scale is used, such as the presentation of the question and whether the rating refers to a short or long duration (e.g., 15 minutes vs. 2 hours).

In this research context, physical work exposure, biological factors, and perception of exertion related to women and men are central. Biological differences, social theories, empirical findings, and the application of the Borg CR-10 scale all contribute to explaining why self-ratings and observer ratings can differ, and why sex/gender differences appear in some cases but not others. These perspectives inform how the findings in this thesis may be interpreted, particularly in relation to the Borg CR-10 scale and the different perspectives of workers and ergonomists.

Rationale

High hand activity and hand force are well-established work risk exposures for MSDs, with women being disproportionately affected. However, it remains unclear whether rated exposures in terms of hand activity (HAL) and rated hand force (Borg CR-10) differ between women and men. This is critical, as precise exposure measures in risk assessment underpin effective risk identification and the development of preventive measures that protect both women and men. To explore differences in rated exposures, corresponding objective measures (wrist angular velocity and forearm muscle activity) should be collected simultaneously. Furthermore, using female-male pairs performing identical tasks helps control for task-related variability and strengthens the basis for comparing physical exposure between women and men.

Although four previous studies have examined sex/gender differences in either HAL, Borg CR-10, wrist angular velocity, or muscle activity, none have compared hand activity and hand force ratings simultaneously in

identical tasks performed by female-male pairs during real-life work. The present research is therefore essential to determine whether hand activity and hand force ratings differ between women and men. In addition, it is crucial to understand the correlation between subjective ratings and objective measures in order to investigate whether one can substitute for the other in exposure assessment (Table 1).

Table 1 Studies using ratings and technical measures to compare men and women in hand-intensive work, or to investigate correlations between subjective ratings and objective measures

	Setting, task	**Duration**	**Ratings**	**Technical measures**	**Sample**
Comparisons between female workers and male workers					
Meyland et al., 2014	Laboratory; house painters, 9 tasks	Mean total: 36 min	Self-rated force (Borg CR-10)	Muscle activity (sEMG) FCR, ECR	16 women 16 men
Heilskov-Hansen et al., 2014	Field-based; house painters	Full day	-	Wrist angular velocity (goniometer)	25 women 25 men
Nordander et al., 2008	Field-based; rubber manufacturing and mechanical assembly	Median: 3 h 58 min	-	Muscle activity (sEMG) ECR	19 women 18 men
Kim et al., 2024	Laboratory; surgeons performing 3 simulated ureteroscopy tasks	-	-	Muscle activity (sEMG) FF, FE	6 women 8 men
Correlations between ratings and technical measures					
Dahlqvist et al., 2024	Field-based; assembly work, 3 stations, 3 tasks at each	Sub-samples of a full day	Worker self-rated force (Borg CR-10) Ergonomist-rated hand activity (HAL)	Wrist angular velocity (goniometer) Muscle activity (sEMG) ECR	8 men 3 women 4 ergonomists

ECR=extensor carpi radialis, sEMG=surface electromyography, FCR=flexor carpi radialis, FE=forearm extensor, FF=forearm flexor, HAL=Hand Activity Level.

AIM

Overall aim

The overall aim of this thesis was to investigate whether female and male workers' hand activity and hand force exposures differ in identical hand-intensive tasks on-site. More specifically, the aim was to examine rated hand activity (HAL) and hand force (Borg CR-10) exposures through workers' self-ratings and ergonomists' ratings (Papers I, II, IV). For understanding these ratings, their corresponding technically measured wrist joint angular velocity and measured muscle activity (Paper III) were investigated in parallel. An additional aim was to analyze correlations between these subjective ratings and objective technical measures (Paper II).

Specific aims of the studies

Paper I:
To investigate whether hand activity (HAL) and hand force (Borg CR-10) are rated differently for women and men performing identical tasks onsite, based on both workers' self-ratings and ratings by mixed-gender pairs of ergonomists; and to determine whether any significant differences between women and men in these ratings are associated with grip strength, forearm length, and finger abduction.

Paper II:
To investigate the correlation between rated hand activity (HAL) and measured wrist joint angular velocity, and between rated hand force (Borg CR-10) and measured muscle activity, in hand-intensive tasks. Both workers' self-ratings and mixed gender paired-ergonomist ratings were examined.

Paper III:
To investigate whether measured wrist joint angular velocity and measured muscle activity differ between female and male workers performing identical tasks on-site.

Paper IV:
To investigate differences in the individual ratings produced by female and male ergonomists when rating hand activity and hand force in female and male workers performing identical tasks.

MATERIALS AND METHODS

Study design and methodological foundation

This research used a quantitative, field-based observational design (Papers I–IV). Data were collected from workers performing regular hand-intensive tasks at their workplaces (Papers I–III) and video-based ratings conducted by ergonomists (Papers I, II, IV) (Figure 1). This approach enhanced the ecological validity as it reflected real-world work tasks and standard ergonomic practice. The design enabled statistical comparisons of self-ratings, observer ergonomist ratings (mixed gender pairs and individually), and corresponding technical measures. This comparative approach was a core strength, revealing differences or similarities that might otherwise have been obscured.

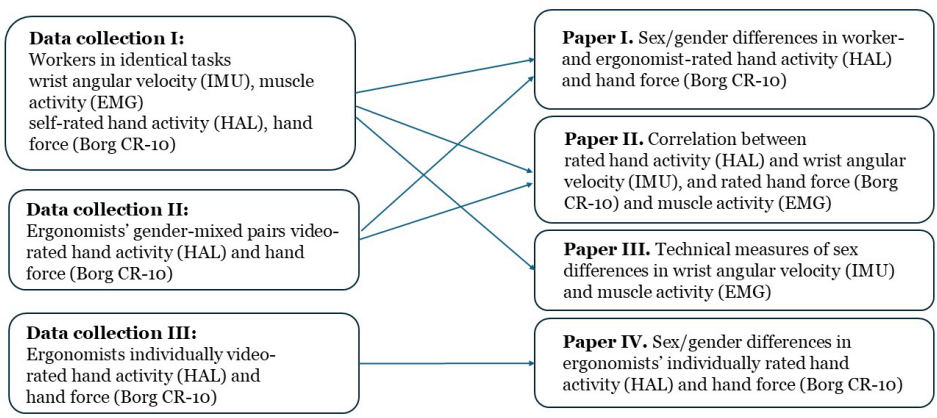

Figure 1. Data collections and their contributions to Papers I–IV.

To ensure valid comparisons of rated and technically measured exposures between women and men, each female–male pair performed hand-intensive tasks defined as identical (below). This approach minimized confounding from gender-related differences in work organization and task allocation during full-day or multi-task assessments (Biswas et al., 2021; Heilskov-Hansen et al., 2014; Migliore et al., 2021).

Definition of identical tasks
Identical tasks were defined as those with the same instructions, goals, steps, equipment, environmental conditions (e.g., lighting, noise, workspace), external workload, duration, and expected outcomes (e.g., speed, quality, accuracy). This definition ensured consistent physical work exposure between women and men, enabling valid comparisons.

Participants

The worker and ergonomist participants are described in Table 2.

Table 2. Number of workers and ergonomists in Papers I–IV.

	Paper I	**Paper II**	**Paper III**	**Paper IV**
Workers: female–male pairs in identical tasks	28 women 28 men 11 excluded	29 women 30 men 8 excluded	28 women 28 men 11 excluded	28 women 28 men 11 excluded
Observer ergonomists: gender-mixed pair ratings	2 women 2 men	2 women 2 men	-	-
Observer ergonomists: individual ratings	-	-	-	27 women 27 men 11 excluded

Workers
The study was conducted at eight companies, where workers were measured during typical tasks involving varying levels of hand activity/repetition and hand force, to capture a range of hand-intensive physical exposures. The occupational sectors represented included warehouse work, pharmaceutical production, industrial assembly, postal service mail, postal sorting terminal work, direct mail sorting, food production, and laboratory work. A total of 67 workers met the eligibility criteria and volunteered to participate.

Ergonomist participants
The observer ergonomists in this study were Swedish registered physiotherapists with varying levels of formal ergonomics training. Two sample groups were used. Studies I and II included four ergonomists in two gender-mixed pairs, all with 15–35 years of experience. Study IV included 54 ergonomists with experience ranging from less than 2 years

to over 30 years. In total, 66 ergonomists volunteered to participate, and 54 were included based on reaching the target of an equal number of women and men.

Recruitment

Workers. CEOs and regional or site managers in 14 hand-intensive sectors were contacted, informed about the study, and asked for permission to recruit volunteer workers. Eight companies signed a letter of intent to participate. Information about the study was provided to the leaders and workers in meetings at the respective companies, and the workers were invited to participate in the study. Workers and leaders helped identify common hand-intensive tasks performed by both women and men. A key contact was appointed in each company to assist with the practical and planning aspects related to the data collection. Each location provided a quiet room near the work area for clinical examinations, technical preparations of IMUs and sEMG, and exposure rating immediately after the task.

Ergonomists. For Study I, ergonomists in occupational health settings were recruited via the local occupational ergonomics network after being informed about the study. For Study IV, ergonomists were informed about the study and recruited through three national ergonomic network meetings held in northern, central, and southern Sweden. Ergonomists and indirectly informed volunteers were invited to participate. All worker and ergonomist participants were convenience samples.

Procedure

Workers. The workers were first individually assessed for background factors and given a clinical examination. On another occasion, the individual worker was prepared with the technical devices (IMUs and sEMG) on their most active hand and forearm. The worker then performed one regular hand-intensive task on-site for 15 minutes. This duration was chosen to ensure identical task exposure and to align with previous observational and technical exposure studies (Bao et al., 2010; Spielholz et al., 2008). During the task, wrist angular velocity and muscle activity were measured. The worker was video recorded by one of the co-authors (B.R.) using a single camera during the task. Immediately after the task, the worker self-rated their hand activity (HAL) and hand force (Borg CR-10) in a quiet room near the workstation, accompanied by both a female and a male research leader (the author of this thesis, along with B.R.).

All clinical examinations, technical measures, and exposure rating questions of the workers were conducted by the author of this thesis.

Ergonomists. Ergonomists took part in a 1-hour digital group meeting (1–9 ergonomists) where they received instructions on rating hand activity (HAL) and hand force (Borg CR-10) using the HA TLV method (Studies I, II, IV). The observer ergonomists conducted video-based ratings. In Study I, ratings were completed in mixed-gender pairs in a quiet room provided by the author of this thesis. In Study IV, individual ergonomists performed ratings online at a self-chosen time and location, using secure platforms: UMU Play for video access and REDCap for data entry. The ergonomists had access to the video recordings only during the study period. The ergonomists were not informed about the workers' backgrounds, the worker gender pairing (Studies I and IV), or the ergonomist gender pairing in the analysis (Study IV). All procedures and data collection involving the ergonomists were conducted by the author of this thesis.

Data collection

Data collection was conducted in three separate periods (Figure 1). The first phase, involving workers, took place from October to December 2021 during a period of eased COVID-19 restrictions. The second phase, focused on ergonomist pair ratings, was conducted in April 2022. The final phase involved 54 ergonomists across Sweden and took place between December 2023 and January 2024. An overview of the data used in each study is provided in Table 3.

Table 3. Overview of the data used in Papers I-IV

	Paper I	Paper II	Paper III	Paper IV
Composite questionnaire: workers	✓	✓	✓	✓
Composite questionnaire: ergonomists	✗	✗	✗	✓
Nordic Questionnaire, clinical examination: workers	✓	✓	✓	✓
Worker ratings: hand activity (HAL) and force (Borg CR-10)	✓	✓	✗	✗
Observer ergonomists' ratings: hand activity (HAL) and force (Borg CR-10)	✓	✓	✗	✓
Technical measures: wrist angular velocity, muscle activity	✗	✓	✓	✗

HAL=Hand Activity Level.

Questionnaires
The workers completed a composite 43-item questionnaire covering work history (working years and daily hours), illness, sick leave (from the Work Ability Index; Ilmarinen, 2007), stress (time pressure and general stress from the Quick Exposure Check; David, 2005), and physical activity (IPAQ Short Form; Hagströmer et al., 2006). The questionnaire was used to describe the participant sample.

All participants (workers and ergonomists) self-reported their sex/gender in their respective questionnaires.

Grip strength and anthropometric measurements
Grip strength (Mathiowetz et al., 1985), forearm length, and finger abduction width of the dominant hand (Open Ergonomics, 2022) were recorded for each worker during the same occasion as the clinical examination.

Clinical Examination
The workers underwent a clinical examination for MSDs using a standardized physical clinical examination (Health Examination under Adverse Conditions; Jonker et al., 2015). For inclusion in the study, workers were also screened by asking whether they could work with their arms without difficulty. The inclusion criteria required no reported difficulties. Only workers without difficulty performing hand-intensive tasks were included, which was motivated by the debate over whether

MSDs can affect ratings, as workers with MSDs have been shown to rate exposures higher than those without (Balogh et al., 2004; Burdorf and van der Beek, 1999; Buchholz et al., 2008; Evanoff et al., 2019).

The exposure ratings and technical measures are described below.

Rated hand activity and hand force

Both workers and ergonomists rated hand activity using the HAL scale and hand force using the Borg CR-10 scale. Self-ratings capture the worker's perception of exposure during the task, while ergonomist ratings provide an external observational estimate based on visible indicators, such as motion speed and rest pauses (HAL), and observable exertion cues, including facial expressions, posture, and muscle tension (Borg CR-10). The use of both self-ratings and observer ergonomist ratings for hand activity and hand force was motivated by the aim to explore potential sex/gender differences in exposure rating, and whether these differences vary depending on the perspective, internal (self) or external (observer).

During the clinical examination, each worker was familiarized with the HAL and Borg CR-10 scales by showing them the laminated scales. For each scale, the verbal anchors and corresponding values were read and pointed to by the author of this thesis, and the worker test-rated each scale. Worker-rated hand activity (HAL) and hand force (Borg CR-10) were collected immediately after the work task in a quiet room. The laminated HAL scale was shown, followed by the question: "What number best describes your hand activity in the measured hand?" For hand force (Borg CR-10), the worker was asked: "What number best describes your hand force?"

The ergonomists had access to both scales in writing. For the ergonomists, the questions were for HAL: "What number best describes the hand activity in the measured hand?", and for Borg CR-10: "What number best describes the hand force?" All rated and technical measures were conducted on the worker's dominant hand.

Hand activity ratings (HAL)

Hand activity was rated using the HAL scale (Latko et al., 1997), in accordance with the HA TLV framework. The scale consists of numerical values with corresponding verbal anchors for assessing hand exertions, rest pauses, and movement speed: 0 = hands idle most of the time; no regular exertions, 2 = consistent, conspicuous, long pauses or very slow motions, 4 = slow, steady motion/exertion with frequent brief pauses, 6 =

steady motion/exertion with infrequent pauses, 8 = rapid, steady motion/exertion with no regular pauses, and 10 = rapid, steady motion with difficulty keeping up or continuous exertion. Average exposure was rated based on several complete work cycles of the task.

Hand force ratings
Hand force was rated according to the HA TLV framework using the Borg CR-10 scale (Borg, 1982). The scale consists of numerical values with corresponding verbal anchors: 0 = nothing at all; 0.5 = very, very easy; 1 = very easy; 2 = easy; 3 = moderately hard; 4 = somewhat hard; 5 = hard; 6–7 = very hard; and 8–10 = very, very hard. Only hand exertions that exceeded 10% of posture-specific strength (roughly equal to a Borg CR-10 rating above 1) were considered. The average exerted force during task cycles was estimated as a proportion, the normalized peak hand force, of the individual's maximal force, peak hand force, in the given working posture (like pinch grip, wrist deviation, or forearm rotation), in accordance with the HA TLV recommendations. Other factors that could be considered were contact stress, temperature, and vibration.

Technical Measurement System

Measured wrist joint angular velocity (°/s) using inertial measurement units (IMUs) was used to represent HAL, and measured FCR and ECR relative muscle activity (%MVE) using surface electromyography (sEMG) was used to represent rated hand force (Borg CR-10).

These technical measures are considered gold standards for their respective assessments (Hubaut et al., 2022). SENIAM guidelines (Hermens et al., 2000) were followed to ensure the reporting of sEMG data was consistent and comparable across studies.

Sensor system and signal acquisition. The Delsys Trigno Wireless Biofeedback System Duo (Delsys Inc., Natick, MA, USA) was used. This system integrates Trigno Avanti sensors, which combine IMUs and sEMG into a single wireless sensor system.
Each IMU includes a triaxial gyroscope (Trigno Avanti Sensors, 27 × 37 × 13 mm, 14 g) with a dynamic range of ± 250 degrees per second (dps). The data sampling frequencies of the IMU gyroscopes were 296 Hz for the hand and 222 Hz for the forearm.
FCR and ECR forearm muscle activity was measured with two sEMG electrodes (Trigno Duo Sensors, 25 x 12 x 7 mm, 21 g), each with two silver bars (99.9% silver) with a center-to-center inter-electrode space of 10 mm and contact dimensions of 5 x 1 mm (5 mm^2). The sEMG data were

collected at a sampling rate of 2000 Hz and bandpass filtered between 20 and 450 Hz, following SENIAM guidelines (Hermens et al., 2000). The sEMG signal was converted to a root mean square signal via an onboard function in the Trigno system. The used window length was 0.1 second. The RMS of the work task duration was then computed and normalized to the individual maximal voluntary electrical activation (MVE). This RMS-value is the square root of the average power of the sEMG signal during the task.

Sensor and electrode placement. The IMUs were mounted on the dorsal hand (over the third metacarpal) and the dorsal forearm (midline of the distal radius and ulna), near the wrist joint positioned to avoid collision with each other during maximal extension.
The FCR and ECR muscles were selected based on prior pilot testing and previous studies that identified them as primary contributors to wrist motion (Meyland et al., 2014; Nordander et al., 2008). The FCR electrode pair was placed 3 to 4 fingerbreadths distal to the midpoint between the medial epicondyle and the biceps tendon (Perotto, 2011). The ECR electrodes were placed on the radial forearm, approximately one-third the distance from the elbow along a line from the lateral epicondyle (Dahlqvist et al., 2020; Nordander et al., 2004). Muscle bellies were palpated during voluntary contractions to ensure accurate placement.
Skin preparation included shaving (if needed), abrasion, and cleaning with 70% isopropyl alcohol. Sensors were affixed using Delsys adhesive interfaces, with silver sensor bars aligned parallel to the muscle fibers. Cables were secured using Fixomull stretch tape and self-adherent wraps to maintain signal quality during movement.

SEMG normalization. To enable comparison of sEMG activity in the same muscles between workers, sEMG RMS values were normalized. Prior to the work task, each worker performed three maximal voluntary isometric contractions (MVICs), and the highest obtained muscle voluntary effort (MVE) was used for normalization (Besomi et al., 2020).

MVIC testing was conducted with the worker comfortably seated beside a table, the forearm resting on an anti-slip cloth at elbow height. The forearm was semipronated, with a straight wrist and the hand extended beyond the table's edge. Resistance was applied perpendicularly to the center of the third metacarpal using a dynamometer (MicroFET, Hoggan Scientific, LLC; round attachment, 4 cm diameter). For FCR, the pressure was applied voluntarily in the hand. For ECR, the pressure was applied at the opposing center dorsally of the hand. The worker was verbally encouraged to resist force gradually to a maximum. Three five-second

MVICs were performed, followed by five seconds of rest, for each muscle. All MVICs were instructed and supervised by the (author) researcher of this thesis.

Data processing. The recorded IMU and sEMG data were imported and processed using custom-written software in MATLAB (R2022B Update 2, The MathWorks Inc., Natick, MA, USA).

Wrist joint angular velocity (°/s) derived from IMU gyroscope data along the x-axis representing wrist flexion-extension. Data was calculated after applying a fourth-order Butterworth low-pass filter with a 5 Hz cut-off frequency and then down-sampling to 20 Hz. To isolate wrist motion, the forearm gyroscope signal was subtracted from the hand to isolate wrist motion. This method aligns well with goniometer-based measures (Manivasagam and Yang, 2022). From the processed signal, 10th, 50th, and 90th percentile velocities were computed in Studies II and III.

The resulting signal was normalized to each worker's MVE, as described. The sEMG signals were normalized to each worker's MVE, defined as the highest 1-second moving root mean square value obtained from three maximal voluntary isometric contractions for each muscle (Besomi et al., 2020).
For the sEMG data, the normalized 50th percentile and relative time in the work task with > 10%MVE, > 30%MVE, and < 5%MVE representing recovery were computed in Study II, following Jonsson's fatigue model (Jonsson, 1982). In study III the workload distribution was analyzed for the 10th, 50th, 90th percentile amplitudes, and time in recovery <0.5%MVE in Study III were extracted (Arvidsson et al., 2021). Further details of the technical measures and analysis are provided in Papers II and III.

Statistical analysis

Different statistical analysis methods were employed in the four studies, depending on the type of data (Table 4). Ratings were treated as continuous variables to facilitate robust statistical analysis.

Table 4. Summary of statistical methods in Papers I–IV.

Paper I	Paper II	Paper III	Paper IV
Power analysis Paired samples t-test Linear mixed model	Kendall's tau-b correlation	Non-parametric Wilcoxon signed rank test	Linear mixed effects models, lmer function from the R-package, interaction

Power analysis
A power analysis was conducted for Study I to determine the minimum sample size needed to detect a significant difference in HA TLV between genders. Under the assumption that the standard difference (i.e. Cohen's d) between genders is 0.8, the calculation showed that 54 ergonomists (27 women, 27 men) would be required to achieve 80% power ($\beta = 0.20$) when using an independent samples t-test at the 5% significance level ($\alpha = 0.05$).

Mean, median
Normality was assessed using visual inspection of histograms, Q–Q plots, and the Shapiro–Wilk test. For normally distributed data, the mean and standard deviation (SD) were reported. For skewed distributions, the median and interquartile range (IQR: Q1, Q3) were used to better represent central tendency and spread. Descriptive statistics used in Studies I–IV included the mean, standard deviation (SD), median, and interquartile range (IQR: Q1, Q3). The mean (SD) was reported for normally distributed data, as these data accurately represent central tendency, and SD reflects variability. For skewed distributions, the median (Q1, Q3) was used to better capture central tendency and data spread, while minimizing the influence of outliers.

Paired samples t-test
Study I used paired samples t-tests for normally distributed data to compare exposure levels between women and men, based on self-ratings and ergonomist ratings. This test evaluates whether the mean difference between two related groups (in this case women–men pairs) is statistically significant. The paired t-test was chosen as an appropriate method for comparing mean exposure levels between the groups.

Linear mixed model
In Study I, a linear mixed model was used to compare exposure levels between women and men, adjusting for right-hand grip strength, forearm length, and finger abduction width. This model was selected because it

accounts for within-pair dependencies and individual variability, as the data were structured in 28 women-men pairs performing identical tasks. The model included fixed effects for intercept, gender, hand grip strength, forearm length, finger abduction width, and random effects to account for variability between pairs. Gender was modeled as a binary variable, and the primary parameter of interest was the fixed effect of gender, representing the difference in exposure assessments between men and women. A linear mixed model assumes normally distributed residuals.

Wilcoxon signed rank test
In Study III, the non-parametric Wilcoxon signed-rank test was used to assess significant differences between paired female and male workers across all variables, including wrist angular velocity and sEMG muscle activity at the 10th, 50th, and 90th percentiles. This test was selected as appropriate for paired data and non-normally distributed variables, assessing differences by ranking paired observations.

Linear mixed-effects model
In Study IV, a linear mixed-effects model was used to analyze rated levels of force and hand activity, with the gender of the ergonomist and the sex of the workers included as fixed factors. Worker, worker pair, ergonomist, and ergonomist pair were included as random effects to account for dependencies in the data. Due to the incomplete block design, where not all workers were assessed by all ergonomists, a mixed-effects approach was necessary to appropriately model variability. The models were fitted using the lmer function from the R package lme4, and p-values, based on Satterthwaite's degrees of freedom, were obtained using the lmerTest package. In separate analyses, the model was extended to include an interaction term between ergonomist gender and worker gender.

Kendall's tau-b correlation
In Study II, Kendall's tau-b correlation, a non-parametric statistical method, was used to assess the strength and direction of associations between subjective ratings of hand activity and wrist angular velocity (10th, 50th, and 90th percentiles), as well as between force ratings and sEMG measures at the 50th percentile, >10%MVE, >30%MVE, and <0.5%MVE (time in rest). Interpretation of correlation values is described in Paper II.

This method was selected because it handles non-normally distributed variables by ranking pairs of observations to quantify the level of association between them. It is also robust to whether the analyzed variables are measured on an ordinal or interval ratio scale.

Significance level
A significance level of 5% ($p < 0.05$) was applied to all statistical analyses. This threshold balances the risk of Type I errors (false positives) while ensuring sufficient sensitivity to detect meaningful differences in the data.

Ethical considerations

All participants, including both workers and ergonomists, were informed about the studies during information meetings held at each company or regional network meetings. Written informed consent was obtained from all participants prior to data collection, in accordance with international ethical standards for research involving human subjects. Consent was given by responding "yes" in writing to the question of whether their responses and data could be used for research and publication purposes. The participant companies signed a letter of intent to enable workers to participate in the studies. No ethical approval was applicable to the companies. The studies were conducted in accordance with the Declaration of Helsinki and were approved by the Swedish Ethical Review Authority (ref: 2021-01815, date: 2021-05-20).

Changes and reflections
As the emergency phase of the COVID-19 pandemic overlapped with the data collection period for this thesis, the data collection process was rigorously planned and co-created with each company to ensure the safety of all involved and to minimize data loss. Additional workers were recruited in advance to help reach the target number of workers. On some occasions, planned data collection dates had to be rescheduled. Personal protective equipment was used during worker preparation.

The ergonomists' individual video analysis (Study IV) was initially planned to be conducted in groups at set time points. However, as it was difficult for the ergonomists to participate at specific times, the process was rearranged to allow them to rate the videos at a self-chosen time during the data collection period, using a secure web-based application (REDCap).

RESULTS

Below is a brief summary of the key results of this thesis. More detailed information can be found in the results sections of the respective papers.

Workers

As expected, in general the men were taller and heavier and exhibited greater grip strength compared to women. Men also reported longer work experience. The average number of hours spent in hand-intensive work per day was similar between the sexes (Table 5).

Table 5. Worker characteristics by gender (n = 59) (Study II).

Characteristic	Female n = 29	Male n = 30
Age (years)	33.1 (12.1)	36.9 (12.3)
Body weight (kg)	72.2 (5.6)	94.1 (15.7)
Height (cm)	168.7 (7.2)	183.1 (8.4)
Grip strength (N)	343.4 (67.7)	571.0 (96.1)
Forearm length (cm)	43.9 (2.0)	48.5 (2.3)
Finger abduction width (cm)	19.8 (1.3)	22.2 (1.5)
Work experience (years) [a]	5.6 [1.3, 13.0]	9.9 [2.3, 22.0]
Hand-intensive work (h/normal workday)	5.5 (2.0) [b]	5.3 ± (1.9)

Data are presented as mean (standard deviation) unless otherwise specified.
[a] *Median [Q1, Q3].*
[b] *Women n=28.*

Wrist angular velocity and muscle activity measures

Wrist joint angular velocity (°/s) did not differ significantly between female and male workers performing identical tasks at any percentile (Table 6). Notably, the median velocity for both female and male workers was at or above the proposed action limit of 20°/s, or 15°/s if the work is also force demanding (Arvidsson et al., 2021).

Table 6. Wrist angular velocity (°/s) during identical hand-intensive work tasks performed by 28 female-male worker pairs.

	Wrist joint angular velocity (°/s)		
	10th percentile	50th percentile	90th percentile
Female	2.8 [1.9, 3.6]	19.9 [14.9, 30.2]	77.3 [68.6, 108.2]
Male	2.7 [2.0, 3.5]	21.1 [13.5, 29.9]	89.9 [65.7, 108.4]
p-value	0.741	0.374	0.425

Data are presented as median [Q1, Q3].
[a] *Wilcoxon signed rank test.*

Forearm muscle activity (sEMG) in the FCR and ECR differed significantly between female and male workers across all percentiles (10th, 50th, and 90th) during identical hand-intensive tasks (Table 7). Additionally, recovery time (% of time with <0.5 %MVE) was significantly lower in female than in male workers for both muscles.

Table 7. SEMG measurements of forearm muscle activity in female and male workers performing identical hand-intensive tasks.

	Forearm muscle activity		
	Female	Male	*p*-value [a]
Flexor carpi radialis			
10th percentile, %MVE	1.4 [1.1, 2.3]	0.5 [0.4, 1.0]	**<0.001**
50th percentile, %MVE	4.3 [3.1, 7.2]	2.2 [1.3, 4.1]	**0.001**
90th percentile, %MVE	13.2 [8.2, 24.5]	9.5 [5.0, 13.7]	**<0.001**
Recovery, %time	0.0 [0.0, 1.3]	8.1[0.2, 19.5]	**<0.001**
Extensor carpi radialis			
10th percentile, %MVE	3.4 [2.6, 5.3]	1.3 [1.0, 2.9]	**<0.001**
50th percentile, %MVE	12.2 [9.8, 15.3]	7.0 [4.7, 9.6]	**0.003**
90th percentile, %MVE	29.3 [24.2, 44.3]	21.8 [16.7, 28.7]	**0.004**
Recovery, %time	0.0 [0.0, 0.0]	0.2 [0.0, 4.1]	**0.002**

Data are presented as median [Q1, Q3], for each of the 10th (low muscular load), 50th (median), and 90th (peak) percentiles of the percentage of the maximal voluntary electrical activation (%MVE), as well as percentage of time spent below 0.5% of MVE (recovery time). For example, on average, women had extensor carpi radialis muscle activity levels below 12.2% of MVE for 50% of the time, and below 29.3% of MVE for 90% of the time.
[a] *Wilcoxon signed rank test. Bold font indicates statistically significant differences between women and men.*

Ratings – HAL and Borg CR-10

Figure 2 shows the association between hand activity (HAL) and hand force (Borg CR-10) ratings made by workers and ergonomists. There seemed to be a pattern of a positive association for ratings made by workers and a negative association for ratings by ergonomists (Study I).

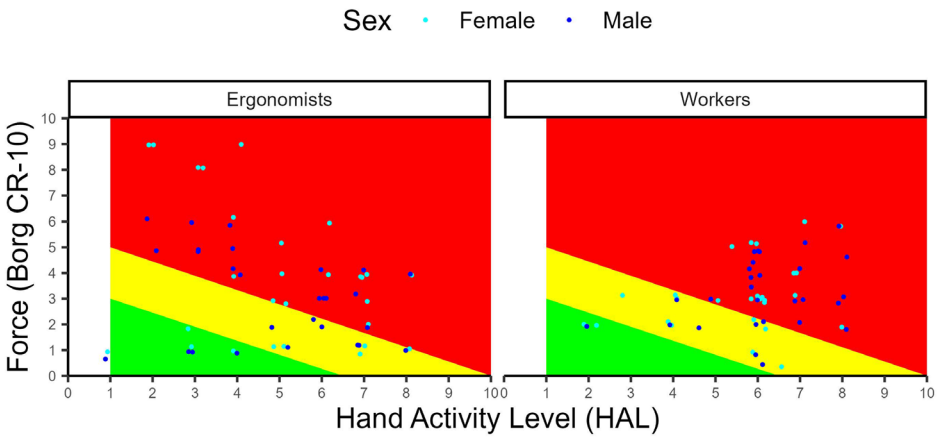

Figure 2. Female and male workers' Hand Activity Threshold Limit Value risk category as rated by ergonomists (left) and by the workers themselves (right). Green: under the action limit, yellow: between the action limit and threshold limit value, red: above the threshold limit value.

Note that the ratings were made on a discrete scale. To reduce overlap and improve visualization, the data points have been jittered, meaning that each point has been slightly and randomly displaced from its original position.

Rated *hand activity* (HAL) did not differ significantly between female and male workers, according to workers' self-ratings (Study I), paired-ergonomist ratings (Study I), or individual ergonomist ratings (Study IV). Moreover, workers' self-rated *hand force* (Borg CR-10) did not differ between female and male workers (Study I). However, hand force rated by ergonomist pairs and individual ergonomists was significantly higher for female workers than for their male counterparts (Studies I and IV). This difference in hand force ratings remained statistically significant after adjusting for grip strength, forearm length, and finger abduction width (Study I) (Table 8).

Table 8. Self-ratings and ergonomist ratings of hand activity and hand force in male and female workers: mean values and between-sex differences (Study I).

	Women [a]	Men [a]	Unadjusted		Adjusted [b]	
			Diff [95% CI]	*p*-value [c]	Diff [95% CI]	*p*-value [d]
Hand activity self-rating [e]	5.6 (1.6)	6.2 (1.4)	−0.6 [−1.22, 0.04]	0.07	0.4 [−0.98, 1.77]	0.57
Hand activity ergonomist pairs [e]	5.0 (1.9)	4.9 (2.0)	0.1 [-0.57, 0.79]	0.75	−0.1 [−1.84, 1.61]	0.90
Hand force self-rating [f]	3.1 (1.4)	3.3 (1.4)	−0.2 [−0.89, 0.50]	0.57	0.2 [−1.23, 1.54]	0.82
Hand force ergonomist pairs [f]	3.9 (2.7)	3.1 (1.8)	0.8 [0.26, 1.42]	**0.01**	1.7 [0.05, 3.29]	**0.04**

Bold text indicates statistical significance. CI=confidence interval.
[a] *Mean (standard deviation).*
[b] *Adjusted for grip strength, forearm length and finger abduction.*
[c] *Paired samples t-test.*
[d] *Linear mixed model.*
[e] *Hand Activity Level.*
[f] *Borg CR-10.*

In Study IV, individual ratings did not differ significantly between female and male ergonomists for either hand activity (HAL) or hand force (Borg CR-10) (rows 2 and 4 of Figure 3), and ergonomist-rated HAL did not differ significantly between female and male workers (row 1). However, hand force was rated significantly higher for female workers than for male workers (row 3); this is consistent with the findings from the ergonomist pair ratings in Study I.

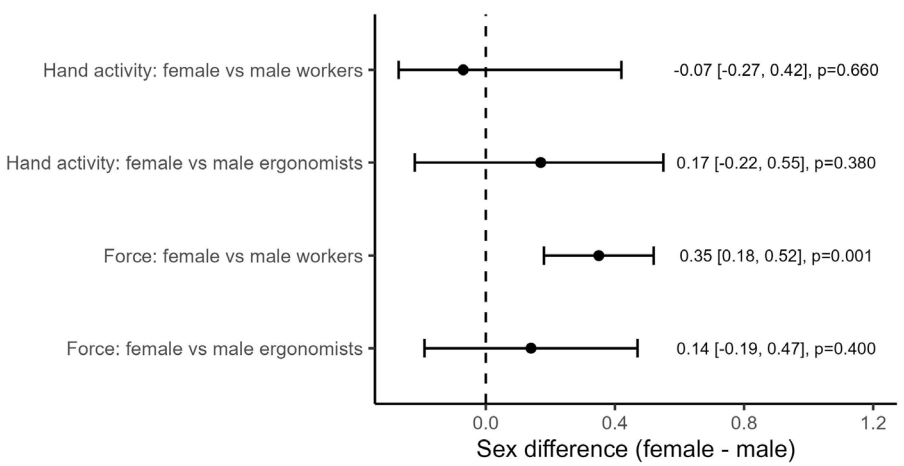

Figure 3. Sex differences in ratings of hand activity (Hand Activity Level) and hand force (Borg CR-10), divided by ergonomist gender and worker sex, based on individual ergonomist ratings. Values show mean differences (female-male) with 95% confidence intervals.

There was no significant interaction between worker sex and ergonomist gender for either HAL (mean difference = 0.11, 95% CI [−0.16, 0.42], p = 0.43) or Borg CR-10 (mean difference = 0.04, 95% CI [−0.17, 0.26], p = 0.70).

Correlations – ratings and technical methods

Hand activity (HAL) as rated both by workers (self-ratings) and by ergonomist pair-ratings was significantly correlated with wrist angular velocity across the 10th, 50th, and 90th percentiles (Table 9).

In contrast, for *hand force,* only observer ratings (Borg CR-10) correlated significantly with forearm muscle activity (sEMG) in 4 of the 6 measures of ECR and FCR (Table 10), and only for time in rest for FCR. Self-rated hand force showed no significant correlations with sEMG measures (Table 10) (Study II).

Table 9. Kendall's tau-b correlation and p-values (2-tailed) between self-ratings and observer ratings of hand activity (Hand Activity Level) and wrist angular velocity in the 10th, 50th, and 90th percentiles (n = 56).

Hand activity	10th	p-value	50th	p-value	90th	p-value
Self-rated	0.26	**0.005**	0.31	**0.002**	0.23	**0.024**
Ergonomist-rated	0.32	**<0.001**	0.41	**<0.001**	0.34	**<0.001**

Bold text indicates statistical significance.

Table 10. Kendall's tau-b correlations between self- and observer ergonomist-rated hand force (Borg CR-10) and forearm muscle activity (FCR and ECR) at the 50th percentile, and for time spent above 10% MVE, above 30% MVE, and below 5% MVE (recovery) (n = 59).

FCR	50th	p-value	>10%MVE	p-value	>30%MVE	p-value	<5%MVE	p-value
Self-rated hand force	0.00	0.975	0.05	0.650	0.09	0.388	0.005	0.963
Observer-rated hand force	0.29	**0.004**	0.43	**<0.001**	0.44	**<0.001**	-0.47	**<0.001**
ECR								
Self-rated hand force	-0.10	0.320	-0.08	0.419	0.02	0.854	0.01	0.963
Observer-rated hand force	0.11	0.264	0.11	0.267	0.26	**0.010**	-0.09	<0.537

Bold text indicates statistical significance. ECR=extensor carpi radialis, FCR=flexor carpi radialis, MVE=maximal voluntary electrical activation.

DISCUSSION

This thesis found no systematic differences in measured wrist velocity (°/s) between female and male workers performing identical tasks. Furthermore, the corresponding measured hand activity (HAL) as rated by all rater groups: workers' self-ratings, ergonomist mixed-gender pair ratings, and individual ergonomists' ratings did not differ significantly between female and male workers.

In contrast, measured forearm FCR and ECR muscle activity (%MVE) was significantly higher in female than in male workers. Both groups of ergonomists rated hand force (Borg CR-10) significantly higher for female workers. However, hand force ratings using the Borg CR-10 scale did not systematically detect sex differences when rated by the workers themselves.

The following sections outline the relationships between HAL ratings and wrist velocity, as well as between Borg CR-10 ratings and muscle activity, with a focus on the differences between female and male workers in these relationships.

HAL ratings and wrist velocity

The lack of significant differences in wrist angular velocity and HAL ratings between female and male workers suggests that measured wrist velocity and rated HAL do not differ across sexes/genders (Studies I, III, IV). For instance, median wrist velocity was nearly identical: 20°/s for women and 21°/s for men (Table 6). Similarly, ergonomist pairs rated HAL at 5.0 ± 1.9 for women and 4.9 ± 2.0 for men, while the corresponding workers' ratings were 5.6 ± 1.6 and 6.2 ± 1.4 (Table 8). The lack of significant differences suggests that neither measured wrist velocity nor rated HAL differs systematically between women and men who work in identical tasks, implying that both measured wrist velocity and rated HAL methods may, on average, be expected to be similar between women and men (Studies I and II).

It is worth considering possible reasons for this lack of systematic sex/gender differences in measured wrist velocity and rated HAL. In this context of hand-intensive work in identical tasks by women and men, both objective measures and ratings may reflect productivity speed and external pacing, rather than physical capacity, which may explain the

absence of systematic sex/gender differences observed in both objective and subjective assessments. However, this interpretation remains tentative, as there is little knowledge about how sex/gender influences the relationship between task demands, worker capacity, and exposure metrics such as HAL ratings and measured wrist velocity.

For wrist velocity comparisons, the present lack of sex/gender differences in 50th percentile wrist velocity is supported by similar findings by Heilskov-Hansen et al. (2014) and Nordander et al. (2008). In contrast, the present results of no sex/gender difference in the 90th percentile wrist velocity differ from the results reported by Nordander et al. (2008). This might be due to methodological differences, such as full-day measures or task types. To the knowledge of the present author, no previous studies have compared HAL ratings between sexes, whether self- or observer-rated. Therefore, direct comparisons with existing literature are not possible.

The significant correlations between rated HAL (worker self-rated and ergonomist pair-rated), though at low levels (tau = 0.23–0.41) (Study II), suggest the use of HAL as a screening tool. However, using technical methods in risk assessment should be preferred. A similar study by Dahlqvist et al. (2024) compared ergonomist-rated hand activity (HAL) with measured wrist angular velocity during sub-samples of a full working day in 11 assembly workers. Despite these methodological differences, Dahlqvist et al. and the present study report similar significant correlations for measured wrist velocity at the 50th percentile and ergonomist-rated HAL (our study: tau 0.41, p = <0.001; Dahlqvist: Spearman's rho = 0.4, p = 0.001). The findings of Dahlqvist et al. support the present findings. No comparable studies could be found on self-rated hand activity (HAL) and wrist velocity.

In summary, both measured wrist velocity and rated HAL were consistent across sexes, suggesting equivalent exposure level under identical tasks. The low correlations suggest that technical methods should be preferred.

Borg CR-10 ratings and muscle activity (sEMG)

The finding that female workers showed significantly higher FCR and ECR forearm muscle activity, and lower time in recovery compared to male workers (Table 7) suggests that this reflects actual biological sex differences related to the women's average lower absolute grip strength (on average 60.1% of male workers), similar to reference populations.

This result is supported by empirical studies comparing female and male workers in ureteroscopy, house painting, rubber manufacturing, and assembly work (Kim et al., 2024; Meyland et al., 2014; Nordander et al., 2008). The compared studies vary in terms of study type, number of participants, measurement duration, and tasks (Table 1).

Furthermore, the ergonomists (both in pairs and individual ergonomists) systematically rated hand force (Borg CR-10) higher in female workers (3.9 ± 2.7) than in male workers (3.1 ± 1.8, $p = 0.001$) (Table 8), suggesting that ergonomists rated hand force detects sex differences that align with these workers' measured muscle activity (Papers I, III, IV). No comparable studies could be found on ergonomist-rated Borg CR-10 comparing women and men to confirm this result.

In contrast, the lack of sex-differences between female and male workers in self-rated hand force by the Borg CR-10 scale (mean 3.1 in female workers, and 3.3 in male workers, Table 8), (Paper I), not aligning with their muscle activity, suggests that the Borg CR-10 scale may not be sufficiently sensitive to detect sex differences that reflect actual measured muscle activity. This, in turn, implies a risk of underestimating the physical load of female workers when relying on the Borg CR-10 for self-rated hand force.
The present result of self-rated force (Borg CR-10) is supported in a laboratory study by (Meyland et al., 2014) who similarly showed no significant difference in self-rated force (Borg CR-10) between female and male house painters in tasks rated below 4. Meyland et al. showed a systematic sex difference in tasks rated above 4. The present results also align with (Jakobsen et al., 2014) who showed weak correlations between measured muscle activity and force ratings (Borg CR-10) below 4 (and strong correlations above 4) in a gender-mixed worker population (n = 200), previously described in the theoretical framework. Jacobsen had a mixed-gender population.

The significant though low correlations between ergonomist-rated hand force and measured muscle activity (tau = 0.26 to 0.44) (Table 13), and only in four of six measures, and only significant in rest for FCR, imply that ergonomist-rated hand force using Borg CR-10 could be used for screening when technical methods are not available. The absence of comparable studies further underscores the need for caution in interpreting the results.

The low and non-significant correlation between self-rated hand force (Borg CR-10) and EMG levels, i.e., %time at >30% MVE, suggests that

self-rated force is not a reliable indicator of physiological muscle load (Paper II).

A similar study by Dahlqvist et al. (2024) also compared self-rated hand force (Borg CR-10) with measured ECR muscle activity. While the present study used a time-based threshold for high muscle activity (time at >30% MVE), Dahlqvist et al. applied the 90th percentile of sEMG based on the amplitude probability distribution function; both approaches aim to capture high muscular loads. Despite minor methodological differences, both studies report similarly non-significant low correlations between self-rated hand force (Borg CR-10) and sEMG-measured forearm muscle activity at high intensity (our study: tau = 0.02; Dahlqvist: Spearman = 0.02). The findings of Dahlqvist et al. support the present conclusion that self-rated hand force (Borg CR-10) may not adequately represent measured muscle activity exposure in hand-intensive work.

In summary, self-rated force using Borg CR-10 should be avoided since it does not detect sex differences and does not correlate with muscle activity. Only ergonomist-rated force detects sex differences, in line with measured muscle activity. Due to the generally low correlations and only partially significant associations between ergonomist-rated Borg CR-10 and measured muscle activity, technical measurements should be preferred for workplace risk assessment when possible.

The discrepancy between self-rated and ergonomist-rated hand force, as measured using the Borg CR-10 scale, can be understood in light of the theoretical framework. This highlights how perceived exertion is shaped by contextual, psychological, and social factors. The fact that ergonomists identified hand force sex differences may be explained by their professional knowledge of biological differences and risk assessment, and in their role as external experts, being less influenced by workplace roles, norms, or work task experiences (Eagly and Wood, 2012; Macintyre et al., 1996; Verbrugge, 1989). The lack of expected hand force differences when workers self-rate may also be influenced by expectations related to workplace social norms, roles, or work task experiences. Also, the Dual Mode Theory and Stevens' Power Law describe difficulties in rating lower intensities (vs higher) (Ekkekakis and Petruzzello, 1999; Stevens, 1957) may indicate that the Borg CR-10 lacks sensitivity in hand force ratings <4 (as in this thesis). However, the theoretical explanations for the discrepancy between ergonomist and worker hand force ratings using Borg CR-10 have not been empirically tested in this study and therefore remain speculative, underscoring the need for further research.

Strengths and limitations

Key contributions and study designs
A key strength of the study designs used in this thesis is their contribution to understanding measured exposure differences between women and men. Pairing workers in identical tasks enabled direct comparisons under the same conditions, thereby minimizing organizational influences such as task type and duration. Combining observational ratings (hand activity, force) with technical measures (wrist velocity, muscle activity) strengthened the insight into how perceived and objective exposures align. The non-intrusive, field-based design captured natural work behavior, thereby enhancing ecological validity for both workers and ergonomists. While field data introduces variability, it also increases relevance and supports the detection of meaningful exposure differences, including gender-related rating biases.

Context
Exposure measures may have been influenced by task variability, observer effects, and the use of wearable sensors. While the COVID-19 pandemic imposed some restrictions, disruptions were minimal. Ergonomist ratings were based on real-life videos of workers performing their tasks, allowing multiple ergonomist raters to evaluate hand activity (HAL) and hand force (Borg CR-10) under actual working conditions. Limited camera angles or missing context may have affected some evaluations. However, this limitation is considered minor and unlikely to have influenced the results.

Sample and rating considerations
To ensure a homogeneous sample, only workers without MSDs affecting performance were included, as symptoms can raise exertion ratings (Balogh et al., 2004; Evanoff et al., 2019; Viikari-Juntura et al., 1996). Still, both sexes reported recent upper-body discomfort, which may have influenced their ratings. A male and female researcher were present to reduce gender-related observer bias (Sellgren Engskov, 2023). Minor wording differences in the Swedish hand activity scale may have introduced slight inconsistencies, though these were considered unlikely to have affected the results.

Generalizability
The results of these studies show overall similarity to previous studies where comparable research existed. This supported internal validity by confirming consistent exposure patterns. However, there is a limited number of studies for rated exposures, which makes it difficult to determine whether the observed patterns align with existing research.

Given that the study was conducted in industrial settings in Sweden, its external validity is strongest within similar occupational contexts. Future research is needed to assess its generalizability to other occupational sectors and countries.

Implications for clinicians and future research

The primary and most noteworthy finding is that sex/gender differences were detected only in the ergonomists' hand force ratings, aligning with muscle activity (sEMG), while workers' self-rated force did not detect sex differences. Key implications, future practices, and research ideas stemming from the four studies are highlighted below. While not exhaustive, these studies contribute to understanding exposure differences between sex/gender and the intersection of observational and direct methods.

Implementing sex/gender-inclusive hand force assessment
Using sEMG ensures that women's higher muscle activity is detected. If hand force is rated, ergonomists should perform the assessment using the Borg CR-10 scale, as they detect women's higher force levels. Workers' self-rated force should be avoided, as it may fail to detect sex/gender differences and may underestimate women's hand force exposure. Moreover, when both women and men perform identical tasks, female workers should be prioritized for hand force assessment to ensure that the group with the highest relative muscle activity is accurately identified. Hand force assessments that detect sex-based differences are essential for credible evaluations and for guiding well-informed, targeted actions that protect both women and men.

Due to overall low correlations between technical measures and their corresponding ratings, which are partially significant for ergonomist-rated hand force and non-significant for self-rated hand force, technical methods, such as IMUs and sEMG, should be preferred for risk assessment when feasible. While user-friendly IMUs are already available for workplace use, sEMG remains more complex in terms of setup, cost, and required expertise. To support inclusive risk assessment for all workers in hand-intensive jobs, there is a need for practical, affordable, and user-friendly solutions for measuring muscle activity that are suitable for clinical settings.

Other considerations
While not the main focus of this thesis, it is important to consider rated hand force more broadly. The Borg CR-10 scale was not originally designed for hand-intensive tasks and appears not to have been previously studied for sex-based differences in the context examined here. There is little known about whether other observational hand-intensive risk assessments detect hand force differences between women and men. Additionally, it is unclear if self-rated force in population studies using self-rating of job exposure detects sex differences. Future research should investigate whether alternative hand force ratings more accurately capture sex differences, ensuring that women's generally higher relative load is properly acknowledged.

Threshold limits

These workers were exposed to hazardous risk levels. For wrist velocity, both women and men exceeded the action limit of 15°/s. For muscle activity, both sexes had insufficient recovery time (<5% of the time). As expected, female workers exceeded the proposed action limit for muscle activity, defined as remaining below 10% of MVE for at least 50% of the workday. The higher risk for women was also detected via ergonomist-rated HA TLV (Table 8, Figure 2). In contrast, self-rated HA TLV showed a higher risk in men, which did not reflect the findings regarding objective technical measures. This implies a need to use sex-sensitive risk assessment methods, prioritize women for assessment as described, and apply technical measures, when possible, in order to accurately identify hazardous risks and ensure the protection of all workers.

Workplace design considerations
Workplaces are still designed on the basis of male body dimensions and strength capabilities, which can result in higher physical loads for female workers due to biological differences (Armijo et al., 2022; Kim et al., 2024; Kraut et al., 2024). Ideally, workplace design should minimize repetitive and forceful tasks in a way that is inclusive of all workers. However, limited research has examined how workplace design, tools, materials, and task organization affect hand activity and hand force exposure differently in women and men. Addressing these gaps is critical for developing safer, more inclusive, and higher-performing work environments.

Policy implications
Policymakers should consider mandating the use of risk assessment methods that detect sex-based differences in hand force, such as

ergonomist-rated Borg CR-10, prioritizing the assessment of women, and using technical measures, when possible, in ergonomic standards. To support the sustainable implementation of initiatives, collaboration among regulatory agencies, labor unions, industry groups, researchers, and worker populations is essential. This inclusive approach can foster shared understanding and long-term adoption of risk assessment practices that are protective of all workers.

Social and ethical implications

Relying on self-rated hand force using the Borg CR-10 scale may underestimate women's physical workload, leading to unequal protection and reinforcing structural biases in occupational health assessments. Ethically, refining assessment practices by using ergonomist-rated hand force (Borg CR-10) when ratings are applied, prioritizing assessments of female workers in shared tasks, and adopting technical measurements when feasible, offers a critical opportunity to improve precision and ensure fair protection for both women and men in hand-intensive jobs.

CONCLUSION

This thesis shows that when women and men perform identical hand-intensive tasks at their workplaces, there are no systematic sex/gender differences in measured wrist joint angular velocity (°/s) or rated hand activity (HAL). This suggests that their level of velocity and hand activity does not differ on average.

Measured muscle activity and ergonomist-rated hand force (Borg CR-10) detect systematic sex differences, with significantly higher values in female workers. In contrast, self-rated hand force does not detect sex differences and may systematically underestimate women's force. Therefore, if hand force is rated, only ergonomist ratings should be used. Self-ratings should be avoided. Moreover, women should be prioritized in assessments of muscle activity or hand force when tasks are identical.

Overall, all significant correlations for velocity and HAL, and muscle activity and Borg CR-10 were low. Ergonomist-rated hand force correlated significantly with muscle activity for the most part, while self-rated force did not correlate significantly with muscle activity. This suggests that technical measures should be preferred for wrist velocity and muscle activity in risk assessment, when possible. These strategies may contribute to a more inclusive and fair risk assessment to protect all workers.

Acknowledgements

Though this work stands under my name alone, it would never have been possible without the help and support of everyone who has been part of my life during these years. You have all contributed to the most fun, interesting, difficult, and exciting project I have ever had, and I am deeply grateful for this opportunity.

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