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Evaluation of a Sensor-Based System for Ergonomic Risk Assessment among Hairdressing Students

Utvärdering av ett sensorbaserat system för ergonomisk riskbedömning i frisörarbete

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Abstract

Occupational upper extremity disorders have become a major issue in modern society. Poorly designed workplaces, high job demands, and incorrect work-habits can lead to the development of upper extremity disorders (UEDs) in the workplace. This issue not only causes health-related problems for the individual but also forms a significant economic burden on society due to sick leaves, healthcare and untimely exit of affected individuals from the workforce.

The risk of developing occupational UEDs varies with different professions. The European Agency for Safety and Health at Work (EU-OSHA) has recognized significant occupational health risks associated with the hairdressing profession. It has been estimated that UEDs are five times more prevalent amongst hairdressers than other professions.

Qualitative risk assessment tools based on self-reports and observation have been used to identify the risks of developing UEDs with hairdressing profession before. However, a quantitative risk assessment tool that provides objective data on work posture is more precise and objective than self-report and observation. This data can help to identify the risks of developing UEDs associated with each hairdressing task. Furthermore, it can enable self-assessment of workload and posture awareness by providing feedback to the user.

Inertial Measurement Units (IMU) as part of a wearable system developed at KTH were used in this study to investigate the risks of developing UEDs for hairdressing students. The feasibility of using a feedback function for providing posture awareness was also evaluated by comparing the measurements obtained with and without using the feedback function. Twelve hairdresser students were enrolled in the study.

The percentage of time for elevated angles above 30°, 60° and 90° for arms, and above 45° or less than 0° for the trunk flexion is presented. In addition, 10th and 90th percentiles (°) of arms and trunk angular distribution is presented. The result of a statistical analysis performed on data with and without feedback was used to evaluate the effectivity of using the feedback function in preventing the development of occupational UEDs. A System Usability Scale (SUS) questionnaire was used to evaluate the overall usability of the system.

The result of this study confirms that the hairdressing profession falls in the high-risk category for developing UEDs. The use of this technical system has enabled a precise risk assessment evaluation of each hairdressing task. Such data can be used as a foundation for improving the ergonomic design of the workplace. The feasibility of using the feedback function as a prevention tool on the individual level is highly dependent on the individuals' motivation and their attitude towards changing their work habits. However, the results in general, indicate a decrease in the abduction angle (°) for both left and right arm when the feedback function is used. For example, the 90^{th} percentile abduction angles (°) for left arm (all 12 subjects) during the drying part of one fundamental work-cycle decreased from a value of 60.4° to 58.2° when the feedback function was used. The 90^{th} percentile abduction angles (°) for the right arm during the same part of the fundamental work-cycle decreased from an angle of 53.1° to 51.4°.

The SUS score of 75.6 indicates good overall usability for the system.

Sammanfattning

Besvär i det muskuloskeletala systemet i överkroppen som uppkommer på grund av påfrestande arbetsställningar och icke-optimala arbetsvanor blir allt vanligare i det moderna samhället. Besvären orsakar inte bara hälsorelaterade problem för individen utan även en avsevärd ekonomisk börda för samhället.

Risken för att utveckla skador i överkroppen varierar med olika yrken. Europeiska arbetsmiljöbyrån (EU-OSHA) har identifierat betydande hälsorisker i samband med frisörarbete. Det har uppskattats att besvär i överkroppen är 5 gånger mer förekommande hos frisörer jämfört med andra yrken.

Det finns många forskningsprojekt som har använt kvalitativa riskbedömningsverktyg, baserade på självrapportering och observation, som identifierar riskerna med att utveckla skador i överkroppen bland frisörer. Ett kvantitativt riskbedömningsverktyg som ger objektiva data om arbetsställning är dock mer exakt än självrapportering och observation. Ett sådant verktyg kan hjälpa till att identifiera risken för skadeutveckling i överkroppen.

Inertial Measurement Units (IMUs) är en del av ett bärbart mätsystem som har utvecklats på KTH. Systemet användes i denna studie för att identifiera risken för skadeutveckling i överkroppen bland frisörer. Riskidentifieringen gjordes genom att mäta vinkel på armar och rygg. Mätsystemet har även en inbyggd återkopplingsfunktion som uppmärksammar användaren om deras kroppsställning. Effektiviteten av att använda återkopplingsfunktionen för att förebygga jobbrelaterade skador utvärderades genom jämförelse av mätningar som erhållits med och utan återkopplingsfunktion. Tolv frisörstudenter deltog i studien.

Överkroppspositionen definierades av vinklar över 45° eller mindre än 0° från en position där ryggen är rak. Abduktionsvinklar över 30°, 60° och 90° mättes för armar. Tidsperioden för dessa vinklar d.v.s. hur lång tid överkroppen hölls i dessa vinklar räknades. Armar och överkroppvinklar för 10:e och 90:e percentilen (°) samt resultat av en statistisk analys som utfördes på data samlade med och utan återkopplingsfunktionen presenterades. Analysen utfördes för att utvärdera hur effektiv återkopplingsfunktionen är för att förhindra arbetsskadeutveckling. En *System Usability Scale* (SUS) frågeformulär användes för att utvärdera systemets övergripande användbarhet.

Resultatet av denna studie bekräftar att frisöryrket faller i högriskkategorin för arbetsskadeutveckling. Användningen av detta bärbara mätsystem har möjliggjort en exakt riskbedömning för olika arbetsuppgifter. En sådan information kan användas som grund för att förbättra ergonomiska förhållanden på arbetsplatser. Effektiviteten av återkopplingsfunktionen som ett förebyggande verktyg på individnivå är starkt beroende av individernas motivation och deras inställning till att ändra sina arbetsvanor. Emellertid anger resultaten en generell minskning av armvinklar (°) för både vänster och höger arm när återkopplingsfunktionen används. Till exempel har den 90:e percentil vinklarna (°) för vänsterarm (alla 12 personer) under hög belastning minskat från ett värde av 60.4° till 58.2 °. Den 90:e percentil vinklarna (°) för höger arm under hög belastning har också minskat från ett värde av 53.1° till 51.4°.

SUS-poängen på 75.6 indikerar en bra användbarhet för systemet.

Acknowledgments

First and foremost, I would like to thank my supervisor, Dr. Farhad Abtahi for all his help and guidance throughout this project.

I would like to express my gratitude to all the students at Hair Style Education who participated in this study. This research would not have been possible without their help and cooperation.

Last but not least I would like to thank my family, especially my mother whose unconditional love and support have always been my only source of strength and endurance in life. Words cannot express how grateful I am for having you in my life.
In addition, I would like to thank Timm Schneider for all his love and support. Thank you for proofreading my thesis and for your many constructive suggestions. I am forever thankful for your presence in my life.

I would like to leave the remaining space in memory of Dennis Borgström, a brilliant young scholar whose work I have referenced in my thesis.

Table of Contents

1.Introduction

Upper extremity disorders (UEDs) have become a major problem in modern society. UEDs or in other terms repetitive strain injury (RSI), physical overuse syndrome or occupational cervicobrachial disorder can be due to several facts. Occupational use of the upper limb, high job demand and personal characteristics such as coping are a few to mention [1]. Some of the less-well defined UEDs are manifested in the patient by discomfort, pain or tingling in regions such as neck, shoulders, arms, wrists, and hand. Other UEDs that have well-defined symptoms and signs include tendonitis, carpal tunnel syndrome, osteoarthritis, vibration white finger, and thoracic outlet syndrome. However, many of the UEDs are non-specific thus making it very difficult to obtain a specific diagnosis. Another issue is that Symptom manifestation can take up to weeks, months or even years [2]. Besides the work-related issues caused for the workers, UEDs also form a huge economic burden due to healthcare and sick leave costs [1]. According to a new global study by the European Agency for Safety and Health at Work (EU-OSHA), the cost of poor occupational safety and health has been estimated to 3.3% of the European Union GPD. That is €476 billion a year which could be saved with the right health strategies and practices [3]. Therefore, it is crucial to identify the risks of developing UEDs in every work environment and act at an early stage [2].

There are approximately 400 000 hair salons and 940 000 hairdressers in Europe. The European Agency for Safety and Health at Work (EU-OSHA) has recognized serious occupational health risks associated with hairdressing tasks. It has been estimated that musculoskeletal disorders (MSDs) are five times more prevalent among hairdressers than other occupations [3]. Repetitive and constant movements of various body parts or holding awkward positions for long periods may result in MSD problems [3].
Common MSDs along hairdressers include lower back problems that are usually caused by prolonged standing, spinal twisting or bending. Sitting on stools with no leg or back support can aggravate this problem. Shoulder problems occur due to prolonged holding of arms in abduction (upper arm positioned out to the side) which is common during hair cutting and styling. Occupational hazards linked with hairdressing tasks can lead to lower productivity, sick leaves and untimely exits from the occupation. Therefore, the improvement of working conditions for this group should be a major priority [4].

This thesis is part of a bigger project at We@Work. They have developed an integrated solution for promoting safety and health at work by combining wearable technology, ergonomics, Big Data analytics and information and communication technologies. The aim of the project is to ensure a healthy working environment through pervasive monitoring as well as enabling accurate risk assessment acquisition and self-management of physical workload [5,6].

This study has been ethically approved by the Regional Ethics Committee in Stockholm (Dnr 2016/724-31/5).

2.Aims

The aim of this thesis is to investigate the feasibility of using a wearable system for minimizing occupational injuries for hairdressers.
This project specifically aims to answer the following research questions:

Is there adverse biomechanical exposure associated with hairdressing tasks for the specific group chosen for this study?
Can audio feedback reduce adverse biomechanical exposure in hairdressing?
Is the system perceived as usable amongst hairdressing students?

3.Method and Materials

In this section, the measurement system and its components are introduced. The measurement procedure is explained and information on which the feedback function has been based on is provided.

3.1 measurement system

The set of the wearable system used in this study consisted of a sensorized t-shirt, 3 wireless miniature Inertial Measurement Units (LPMS-B2, LP Research, Tokyo, Japan, size 39×39×8 mm) and an Android smartphone (SAMSUNG SM-A520F). Three small pockets woven into the Smart shirt housed the IMU sensors at the neck and upper shoulder areas (figure 1). The accelerometer in the IMU had a range of±16 G with a 16-bite resolution and a sampling frequency of up to 400 Hz. In this study, the sampling frequency was set to 30 Hz. The data from the IMUs were wirelessly transmitted through Bluetooth to an Android smartphone where the data were stored and processed.

An android-compatible application was connected to the system via Bluetooth. It integrated a graphical user interface and a communication system that provided the users with both visual and auditory feedback. Data collection for post-analysis and real-time analysis of the data for providing feedback were performed by the application simultaneously. The application could run on smartphones with the operative system Android Marshmallow 6.0 or higher. The smartwatch was not used during this study.

Figure 3.1. Measurement system with three IMU sensors

3.1.1 Inertia Measurement Units components

IMU sensors gather data on displacement and angular velocity using accelerometers, gyroscopes, and magnetometers. The best way to explain the accelerometer in an IMU sensor is to think of a system consisting of a spring that is attached to a weight called proof mass. The spring constant and the weight of the proof mass are both known. Acceleration of the system will cause the movement of the proof mass. MEMS accelerometers measure this movement either by using capacitors (Figure 7a) or piezoresistors (Figure 7b). A tri-axial MEMS accelerometer can calculate the tilt angles due to the fact that the force of gravity at sea level is static everywhere on the earth's surface [7].

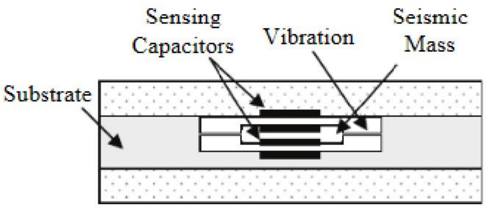


Figure 7a. Capacitive MEMS accelerometer

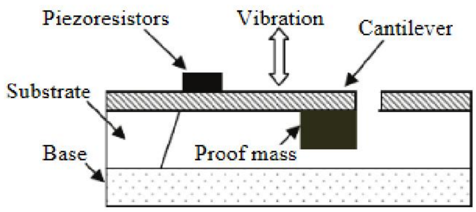


Figure 7b. Piezoresistive MEMS accelerometer

A gyroscope is a device that measures angular velocity. MEMS gyroscopes use vibrating mechanical elements (proof mass) to sense rotation. All vibratory gyroscopes measure rotation through Coriolis force. The Coriolis force is an inertial force that can be explained as follows: a stationary mass particle (m) with a distance **R** from the Centre of rotation in a rotating system (**Ω**) appears to be affected by an inertial force called the centrifugal force (C) for an observer that is in a rotating frame of reference [8].

$$C=m\,(\boldsymbol{\Omega}\times(\boldsymbol{\Omega}\times\boldsymbol{R})) \tag{1}$$

If the particle moves with velocity $\mathbf{V_r}$ relative to the rotating system it will appear to be affected by an additional inertial force called the Coriolis force (**F**) [8].

$$\boldsymbol{F}= -2m\boldsymbol{\Omega}\times\boldsymbol{V_r} \tag{2}$$

A MEMS gyroscope consists of a vibrating structure (proof mass) which can oscillate freely with a certain frequency on the X-Y plane. The two modes of vibration are referred to as drive-mode and sense-mode respectively. Measurement of the shift in the amplitude of proof mass oscillation in the sense-mode, which is caused by the Coriolis force, is a direct measurement of the angular rotation [9].

Magnetometers are used to determine the orientation of the device with respect to its environment. MEMS magnetometers exploit the Lorentz force principle for the detection of the external magnetic field. According to the Lorentz force principle, if current flows through a conductor in the presence of a magnetic field, a force is generated. This force can be calculated by the Lorenz force equation:

$$F_{lorentz} = (IL \times B) \tag{3}$$

Where
$$I = I_0 \sin\omega t \tag{4}$$

In the above equation, $F_{lorentz}$ is the generated force, I is the alternating current, L is the length of the conductor where current is flowing and B is the applied magnetic field density [10]. MEMS magnetometers are composed of structures that are excited at their resonant frequencies. The excitation source can be the Lorentz force that is caused by the interaction of an external magnetic field and excitation current.

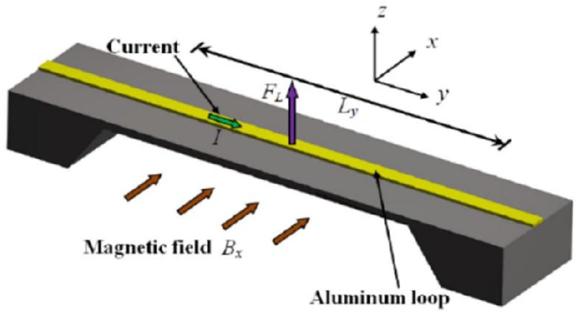


Figure 8. Schematic view of the Lorentz force

This excitation causes a displacement in the resonant structure of the magnetometer, which can be measured by optical, piezoresistive or capacitive techniques. The magnitude of this displacement depends on the Lorentz force amplitude, which is directly proportional to the external magnetic field. Figure 8 shows a schematic view of the Lorentz force F_L acting on an aluminum loop with length L_y perpendicular to the magnetic field B_x. The force causes a displacement of the loop at its midpoint [11].

3.2 Field study setup

This section contains information about the participants and the measurement procedure.

3.2.1 participants

Twelve hairdressing students were recruited (11 females and 1 male). Only students were chosen to partake in this study due to the assumption that they have not yet developed unhealthy work habits and are able to change their posture with less difficulty. The subjects were between 21-44 years old.

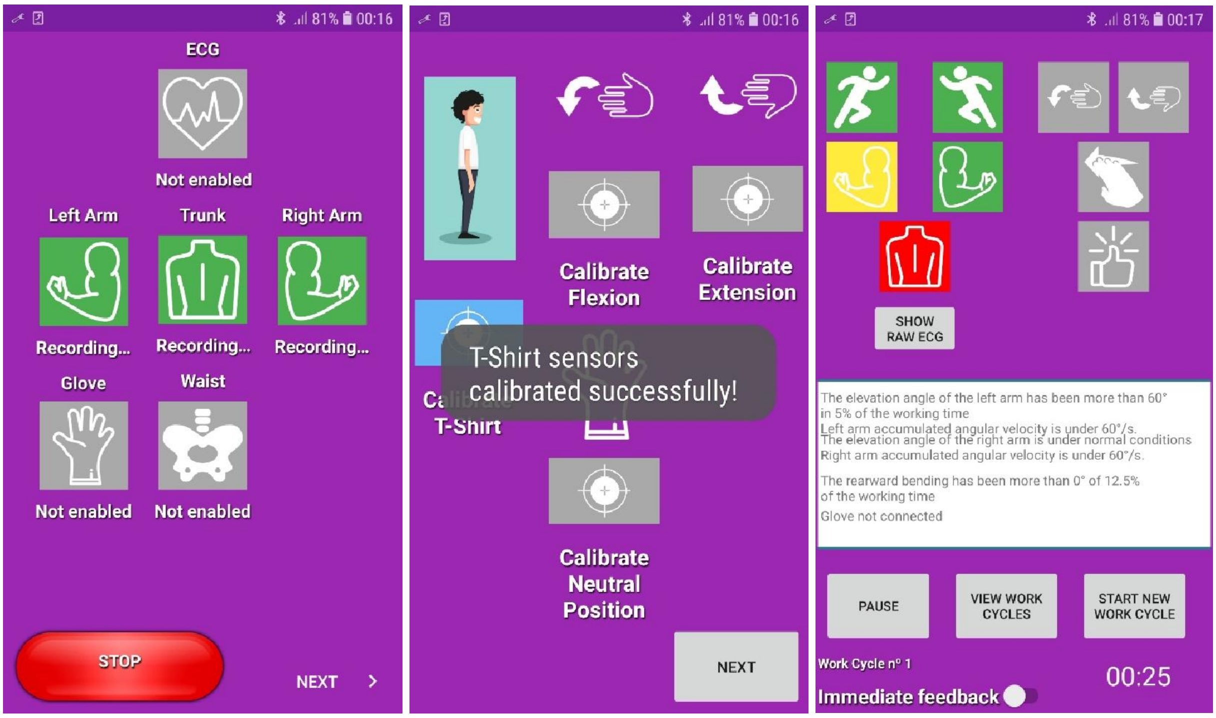
3.2.2 Procedure

The measurements were conducted in a real work environment. Each participant was asked to sign a consent form and fill a pre-study questionnaire including demographic and physical discomfort data (Appendix). Afterward, the participant was instructed to wear the shirt with small pockets for sensor placement. The IMUs for trunk and arms were turned on and placed inside respective pockets. The name of the subject was entered in the profile section.

The sensors were connected. The subject was asked to stand straight as a reference posture and the Smart shirt was calibrated.

When the participant was ready to start a haircut session the system was started. Each participant was observed during data gathering and notes were taken regarding time points. Each haircut session took about 1-2 hours and included tasks such as washing, cutting and blow-drying. Measurements were performed during two haircut sessions for each participant. The first round of measurement was performed with no feedback from the system. The second round of measurement provided the subject with auditory feedback on the position of the trunk and the arms. The interval between each audio feedback was set to 300 seconds. The subjects were asked to change their position in case they received a negative feedback on their posture. After each session, the measurement was stopped, and the participant was asked to remove the system. After the second round of measurement, the participants were asked to fill a post-study questionnaire based on a System Usability Scale (SUS) form. The data gathered from this questionnaire were analyzed to assess the overall usability of the system.

a b c



Figures 3.2 a, b and c. Screenshots of the android application interface

Figures 3.2 a, b and c are screenshots of the android application used in this study which demonstrate the user interface for connection of the sensors to the application, calibration of the sensors and data recording, respectively.

3.3 Feedback function

The feedback function of the system was based on the following values[1].

Exposure variable	Risk limits	Category	Source	Comments
Upper arm lifting angle	Flexion or abduction, > 90°, <6% of working time	Green	RAMP II	
Upper arm lifting angle	Flexion or abduction, > 90°, >6% of working time	Yellow	RAMP II	
Upper arm lifting angle	Flexion or abduction, > 90°, >12.5% of working time	Red	RAMP II	
Upper arm lifting angular velocity	Average angular velocity <60°/s	Green	Hansson	
Upper arm lifting angular velocity	Average angular velocity >60°/s	Red	Hansson	
Trunk/back angle	Bending forwards <20°	Green	SES	
Trunk/back angle	Bending forwards >20°	Yellow	SES	Static work posture held >5s, otherwise Green
Trunk/back angle	Bending forwards >45° or > 0° bending backward	Red	SES	Static work posture held >5s, otherwise Green

Table 3.1 Recommended values for ergonomic risk assessment

Each color (red, yellow and green) indicates a different risk level of developing UEDs associated with a task. Each risk level and the color associated with it is explained according to RAMP II - In-depth analysis for assessment of physical risks for manual handling [12].

High risk. The loading situation has such a magnitude and characteristics that many employees are at an increased risk of developing MSDs. Improvement measurements should be given a high priority.

Risk. The loading situation has such a magnitude and characteristics that certain employees are at an increased risk of developing MSDs. Improvement measures should be taken.

Low risk. The loading has such a magnitude and characteristics that most employees are at low risk of developing MSDs. However, individuals with reduced physical activity may be at risk. Individually tailored improvement measures may be needed [12].

[1] 1. RAMP II - In depth analysis for assessment of physical risks for manual handling, English version 1.00, 2014
2. Hansson, G.-Å., Arvidsson, I., Nordander, C. - Riktvärden för att bedöma risken för belastningsskador, baserade på tekniska mätningar av exponeringen, Arbets- och miljömedicin, Lund, 2016, Rapport nr 4/2016
3. SES - Scania Ergonomic Standard for Design, Ergonomic Load Evaluation Manual, Issue 3, 2015-08-14

3.4 statistical data analysis

A paired sample t-test was performed on the data obtained from the measurements using IBM SPSS software.

4.Results

4.1 General representation of data from 12 subjects

Section 4.1 contains the data gathered from 12 participants without using the feedback function.

4.1.1 Time percentage of various exposure variables

Table 4.1 shows the exposure variables for all 12 subjects. The values represent the time percentage of each exposure variable for one work-cycle which is defined as one haircut session. Each work-cycle is then divided into three fundamental work-cycles, washing, cutting and drying.

Exposure variable	Risk limits	12 subjects
Upper arm lifting angle (right arm)	Flexion or abduction > 90°	0.8% (6.9min)
Upper arm lifting angle (left arm)	Flexion or abduction, > 90°	0.6% (5.2min)
Trunk/back angle	Bending backwards >20°	0%
Trunk/back angle	Bending forwards > 45° or bending backwards > 0°	53.2% (427.8min)

Table 4.1 Time percentage of different exposure variables during one work-cycle for all subjects (min stands for minutes)

a b

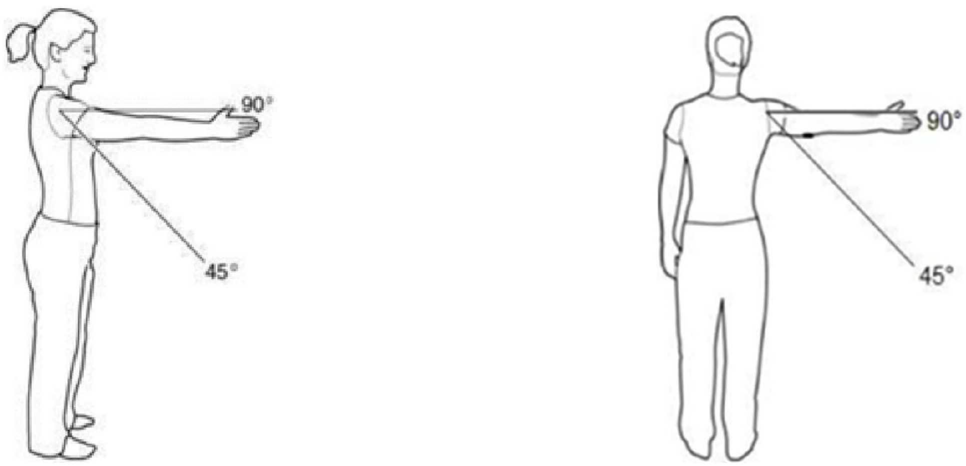


Figure 4.1 a and b, demonstration of measured angles in Flexion and Abduction respectively

Data in table 4.1 represent the total measurements from 12 subjects recorded without using the feedback function. Values in table 4.1 point a high value (53.2% of one work-cycle) for trunk's duration of bending forwards > 0°.

4.1.2 10th and 90th percentiles of arms and trunk angular distribution

Figure 4.2 demonstrates the 10th and 90th percentiles (°) of the angular distribution for arms and trunk during one work-cycle without feedback function for all 12 subjects.

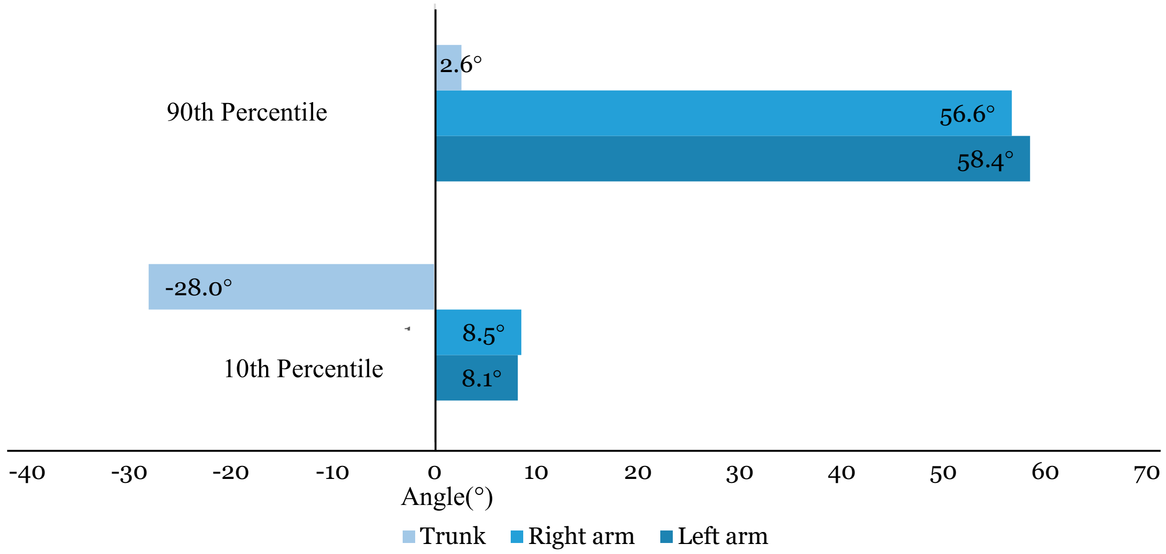


Figure 4.2 10th and 90th percentiles (°) of left arm, right arm and trunk (12 subjects)

The 90th percentiles of right and left arm angular distribution are 56.6° and 58.4° respectively, showing a high value for 90 percent of the total data gathered from every 12 subjects during one work-cycle. The 90th percentile of trunk shows that 90 percent of the data is below 2.6°.

4.1.3 Graphical representation of angular distribution for 12 subjects

Figures 4.2 and 4.3 demonstrate the angular distribution of arms and trunk during one work-cycle.

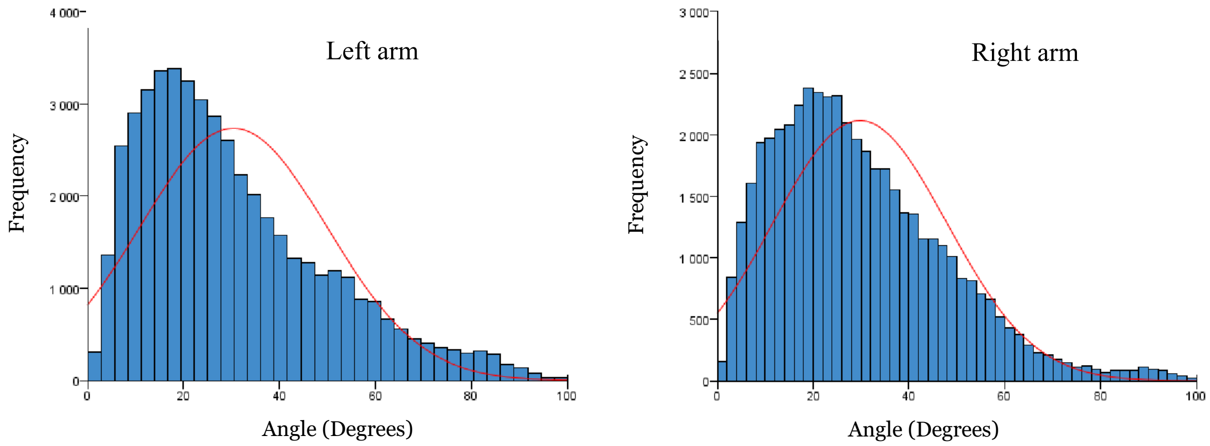


Figure 4.2 Angular distribution of left and right arm for 12 subjects

Figures 4.2 and 4.3 demonstrate that the data approximately follows a normal distribution (red curve represents the normal distribution). The normal distribution shows that 65 percent of the values lie between 10 to 50 degrees with a mean value of 30.3^0 for the left arm and 29.7^0 for the right arm.

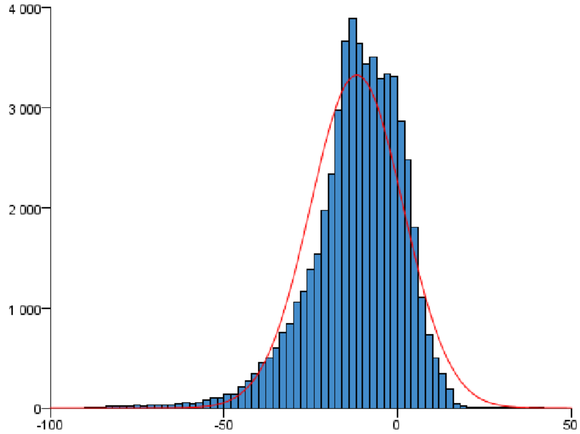


Figure 4.3 Angular distribution of trunk

12 subjects	Mean(Degree) ±SD
Left-arm	30.3 ± 19.5
Right arm	29.7 ± 18.1
Trunk	-11.7 ± 13.3

Table 4.2 Mean (Degrees) ±SD for arms and trunk

Figure 4.3 demonstrates the angular distribution for the trunk during one work-cycle without the feedback function. negative values represent bending forwards from the upright position. According to table 4.3, 65 percent of the values for trunk angles lie within 1° to -25° approximately with a mean value of -11.7°.

4.1.4 Comparison of data with and without a load on forearms

Table 4.3 shows the time percentage of right and left arms elevation angles during a fundamental work-cycle when there is a load on forearms (drying) and during the 2 other fundamental work-cycles when there is no load on forearms. The data in the table represents elevation angles > 60° for the fundamental work-cycles with no load on forearms and elevation angles > 30° for the fundamental work-cycle with a load on forearms. The time percentage is with respect to each fundamental work cycle duration and represents the percentage of time for which the mentioned elevation angles were held. The load (dryer) is between 1-2 Kg depending on the dryer. No load and load conditions are defined as work elements in each fundamental work-cycle. The time percentage in this table is with respect to the time it takes to perform each work- element. The values for strenuous work for shoulders demonstrated in this table are with respect to values published by AMM (arbets och miljömedicinsk) in Lund[2].

[2] See table.2 in Appendix

Strenuous work for shoulders	Right arm elevation angle				left arm elevation angle			
	Time (percent)	10^{th}	90^{th}	Mean(Degree)±SD	Time	10^{th}	90^{th}	Mean(Degree) ± SD
No load on forearms (>60^0)	6.3%	9.1	54.5	30.0±18.2	8.7%	9.0	58.2	30.1± 19.5
Load on forearms (>30^0)	41.0%	8.4	53.1	28.9±17.8	43.3%	8.7	60.4	30.9 ±19.6

Table 4.3-exposure variables with and without a force on forearms (data from measurements with no feedback)

Values in Table 4.3 show that when there is a load on forearms, the arms are elevated more than 30° for higher than 10 percent of the fundamental work-cycle duration. Elevation angles higher than 60° when there is no load on forearms occur less than 10 percent of the work-cycle duration. The rest of the data is similar for both work elements.

4.1.4 comparison of data with and without feedback during one fundamental work-cycle during drying

A comparison of data for measurements with and without feedback is represented in table 4.4. The data represents measurements performed during the drying fundamental work-cycle, therefore, the arm abduction angles above 30° have been considered.

Arm abduction angle (degrees) >30°	Right-arm		Left-arm	
	No feedback	With feedback	No feedback	With feedback
Time percentage	41.0%	36.3%	43.3%	37.1%
10^{th}	8.4	7.8	8.7	8.3
90^{th}	53.1	51.4	60.4	58.2

Table 4.4 Comparison of data with and without feedback

The time percentage of arm elevation angles > 30° has decreased for both arms with the feedback function. There is also a slight decrease in the 10^{th} and 90^{th} percentile values of both arms when the feedback function was used.

The Mean angle for both right and left arm with and without using the feedback function as well as the Standard Error Mean (SEM) are represented in table 4.5.

Paired Samples statistics	Mean (degree) ± SD	Standard. Error. Mean (SEM)
Left arm-no feedback	30.9 ±19.6	0.180
Left arm-with feedback	28.8 ±19.5	0.187
Right arm-no feedback	28.9±17.8	0.169
Right arm- with feedback	27.1 ±17.5	0.168

Table 4.5 Mean values (angles) for left and right hand with and without the feedback function

As it is seen from the values represented in table 4.5 the mean value of both left and right-hand angles have decreased when the feedback function was used. SEM < 1 indicates a low variation in the sample data meaning the sampled data can be a good representative of the general population.

4.1.5 Graphical comparison of data with and without feedback

Figure 4.4 demonstrates a graphical comparison of data with and without using the feedback function during one fundamental work-cycle (drying).

a

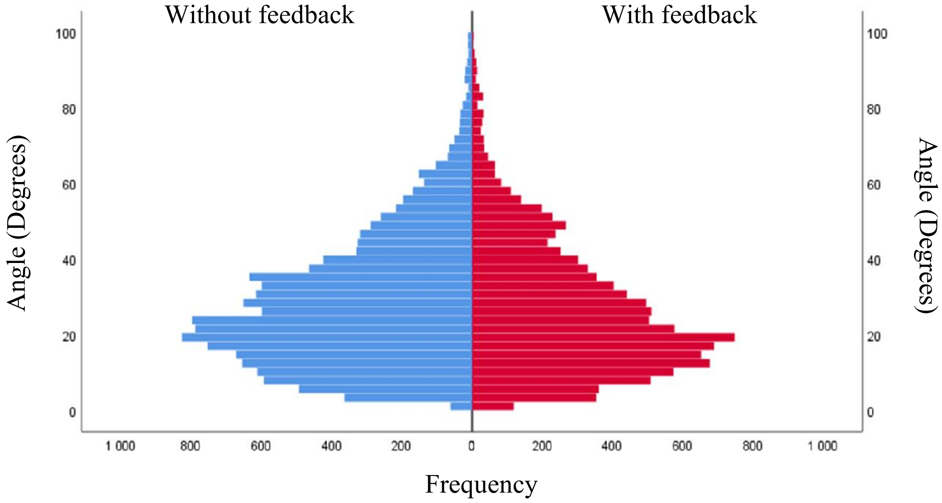


Figure 4.4 a, Right arm comparison of elevation angles with and without feedback

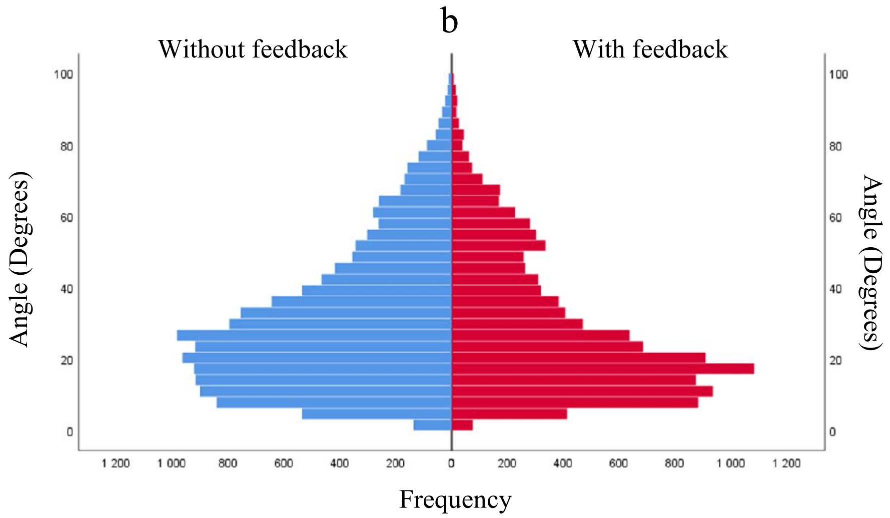


Figure 4.4 b, Left arm comparison of elevation angles with and without feedback

According to the figure, 4.4 lower elevation angles have similar frequencies for data with and without the feedback function. However, a decrease in frequency for elevation angles > 40° is seen for both arms when the feedback function was used.

Figure 4.5 a-c demonstrates some of the positions during one work-cycle.

Figure 4.5 a, b, c Demonstration of shoulders and trunk position during one work-cycle

4.2 Comparison of 90th percentiles (°) with and without feedback for 4 random subjects

Figure 4.6 demonstrates a comparison between 90th percentiles of the left arm with and without using the feedback function for 4 participants chosen randomly (for one work-cycle).

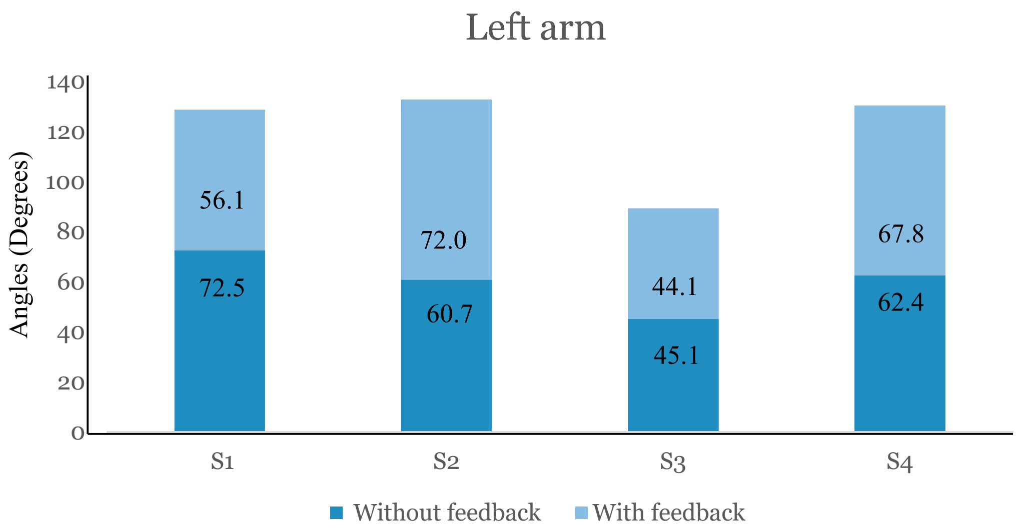


Figure 4.6 90th Percentiles (°) of left arm for 4 random subjects (S stands for Subject)

According to figure 4.6, the 90th percentile value has decreased considerably for subject 1 when the feedback function is used. Values for subject 3 are almost the same for both measurements while subjects 2 and 4 show an increase of the 90th percentile when the feedback function is used.

Figure 4.7 demonstrates the 90th percentiles of the right arm with and without using the feedback function. The same pattern is seen for the left arm as well as for the right arm. Subject 1 shows a decrease in the 90th percentiles angles when the feedback function is used while S2 and S4 show an increase.

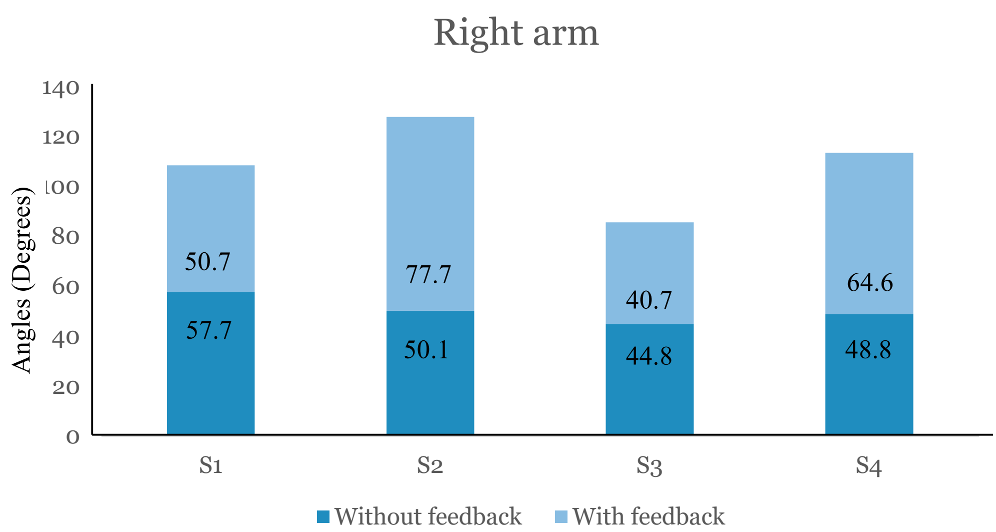


Figure 4.7 90th Percentiles (°) of right arm for 4 random subjects (S stands for Subject)

4.3 Comparison of data with and without feedback for one subject

In this section, a comparison of data with and without using the feedback function is presented.

4.3.1 Time percentage of various exposure variables with and without feedback function

Table 4.6 shows the time percentage of various exposure variables with respect to the duration of one work-cycle. The values represent measured data without and with feedback for one subject. This data was chosen for this comparison since the length of both work-cycles was approximately the same with a difference of 16 minutes. Each work-cycle was divided into three fundamental work-cycles namely washing, cutting and drying. The comparison of data with and without feedback function was done for two arm abduction angles in Table 4.6. Values for the angles above 30^0 represent the more demanding fundamental work cycle (drying) due to a load on forearms (~1 kg) and holding the arms at high angles in extended periods. The length of the drying fundamental work-cycles differs with only 2 minutes meaning 120 more data points for the measurement with feedback.

The data in Table 4.6 demonstrates a comparison of measurements with and without feedback for subject 6 with respect to recommended values by AMM (arbets och miljömedicinsk) in Lund for strenuous work for shoulders.

Arm abduction angle (degrees)	Time percentage of Right-arm elevation angle		Time percentage of left-arm elevation angle	
	No Feedback	Feedback	No Feedback	Feedback
No load on forearms (>60^0)	19.2% (7.3min)	3.8% (2.2min)	11.1%(4.2min)	7.6%(4.4min)
Load on forearms (>30^0)	63.0%(12.6min)	33.3% (7.3%)	52.2%(10.4min)	35.1%(7.7min)

Table 4.6 comparison of arm abduction angle for subject 6

Table 4.6 shows that the duration of holding a strenuous position has decreased in almost all cases when the feedback option was used. Duration of holding the left arm elevated more than 60° has increased with the feedback function even though the time percentage has decreased which can be due to the inequality of the measurement data points.

4.3.2 Comparison of arms angular distribution with and without feedback function

Figure 4.5 a and b show a comparison of angular distribution for left and right arm respectively with and without the feedback function. The fundamental work-cycle with a load on forearms was chosen for this comparison.

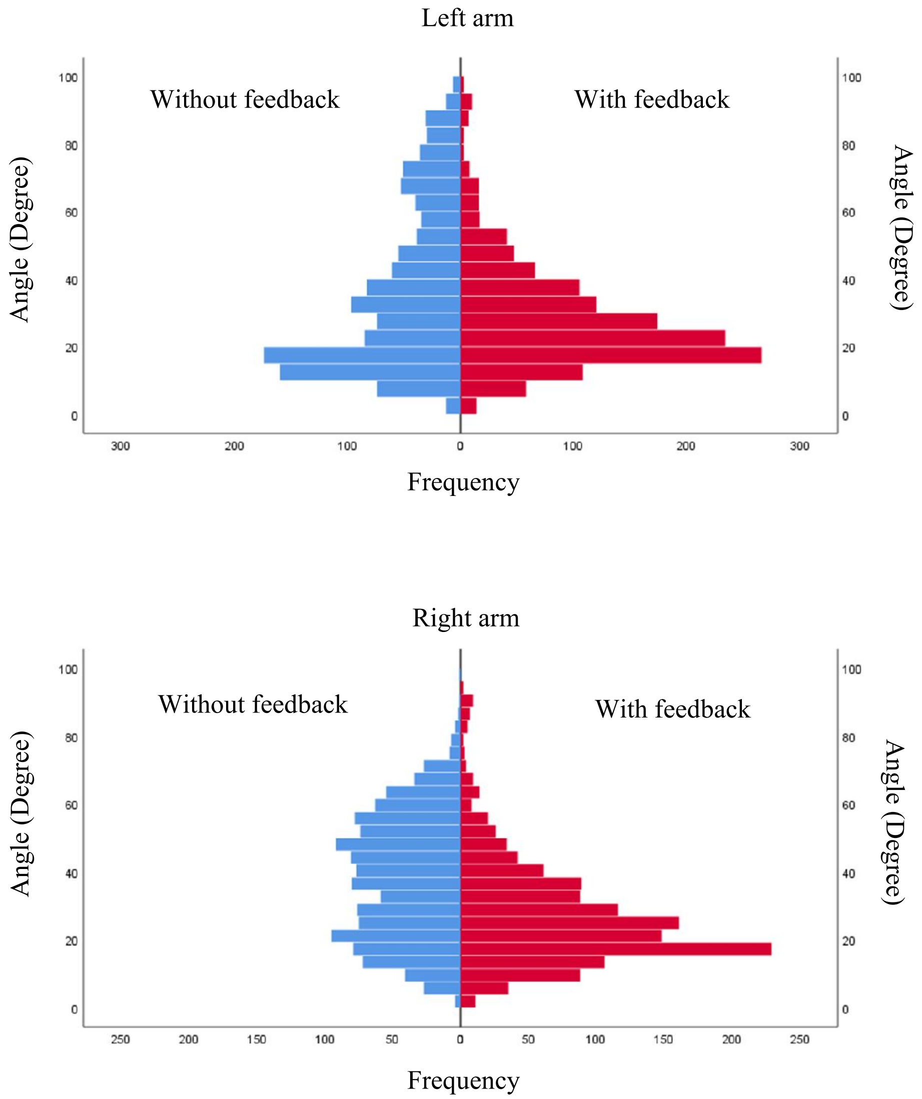


Figure 4.8 A comparison of arms elevation angles for data with and without feedback function

Figure 4.8 demonstrates an overall decrease in frequency for arm abduction angles above 50^0 approximately, when data was recorded while feedback was available to the participant compared to data recorded without the feedback function. The distribution shift from higher angles to lower angles with the feedback function indicates that the arms were held at lower angles rather than higher angles (>50°), giving rise to an increased frequency for lower angles.

4.3.3 Statistics for data with and without feedback function

Table 4.7 contains the result of a paired sample statistics analysis performed on measurements with and without feedback during one fundamental work-cycle (drying).

Paired samples statistics	Mean (degree) ± SD	Std.Error Mean (SEM)	t-value	p-value
Left arm- no feedback	37.0° ± 24.33°	0.69	10.711	0.000
Left arm-with feedback	28.5° ±16.5°	0.45		
Right arm- no feedback	38.4° ±18.8°	0.53	16.620	0.000
Right arm-with feedback	27.4° ±15.7°	0.43		

Table 4.7 paired sample statistics for subject 6

Values in Table 4.7 indicate that the mean value of the angular distribution for both arms has decreased when the feedback function was used. SEM < 1 indicates a low variation in the sample data meaning the sampled data can be a good representative of the general population. T-values > 0 and p-values equal to 0.000 indicate a significant difference between the set of angles measured with and without the feedback function

4.3.4 10th and 90th angular distribution percentiles

10th and 90th percentiles (°) for arm angular distribution during drying when there is a load on forearms are demonstrated in figure 4.9.

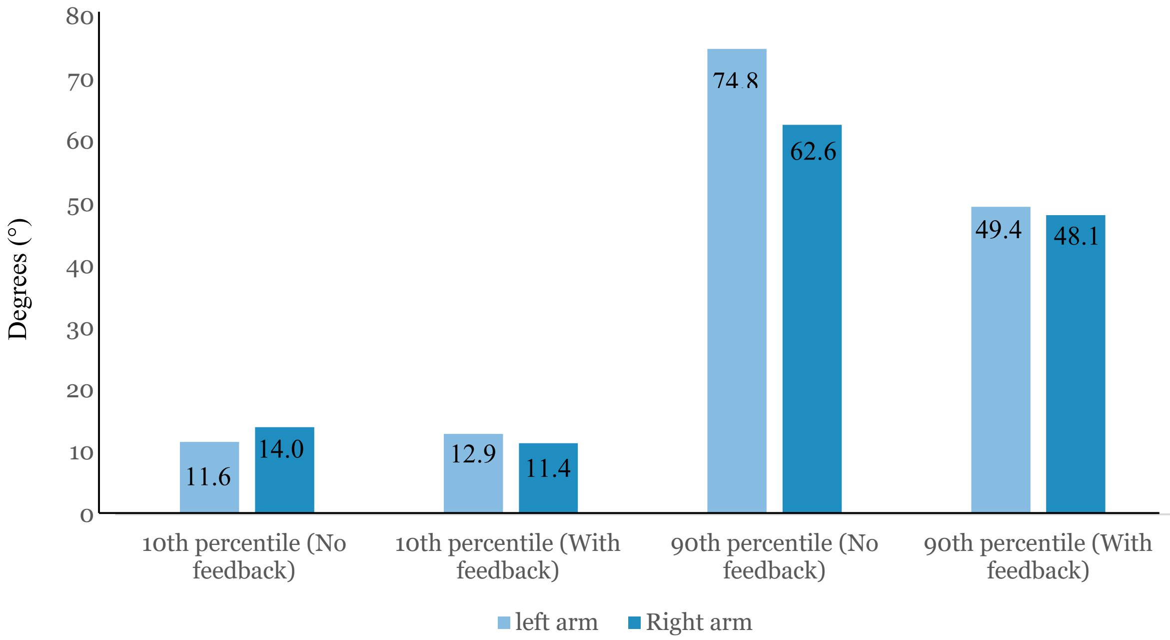


Figure 4.9 10th and 90th percentiles (°) for arm angular distribution

Figure 4.9 shows that the 10th percentile (°) for the right arm has decreased from 14.0 to 11.4 and the 90th percentile has decreased from 62.6 to 48.1 when the feedback function was used. There is also a decrease for the 90th percentile of the left arm angle from 74.8 to 49.4 with the feedback function but an increase from 11.6 to 12.9 for the 10th percentile.

4.4 System Usability Scale (SUS) Questionnaire

The SUS questionnaire is a reliable way to investigates the overall usability of a system. The SUS numeric score determines the overall usability of the system from a scale of 0-100. The SUS score for the system used for this study was calculated to 75.625. A graphic presentation of the result of the questionnaire filled by all 12 participants is demonstrated in figure 4.10. The questionnaire contains the following questions:

1. I would use the device often
2. I experienced the device as too complex to use
3. I think the device was easy to use
4. I need help from a technical person in order to be able to use the device
5. I think different parts of the device work coherently with each other
6. I think the device was inconsistent
7. I think it is possible to learn how to use the device in a short period
8. I experienced the system difficult to use
9. I feel confident about how to use the device
10. I needed to learn a great deal before being able to use the device

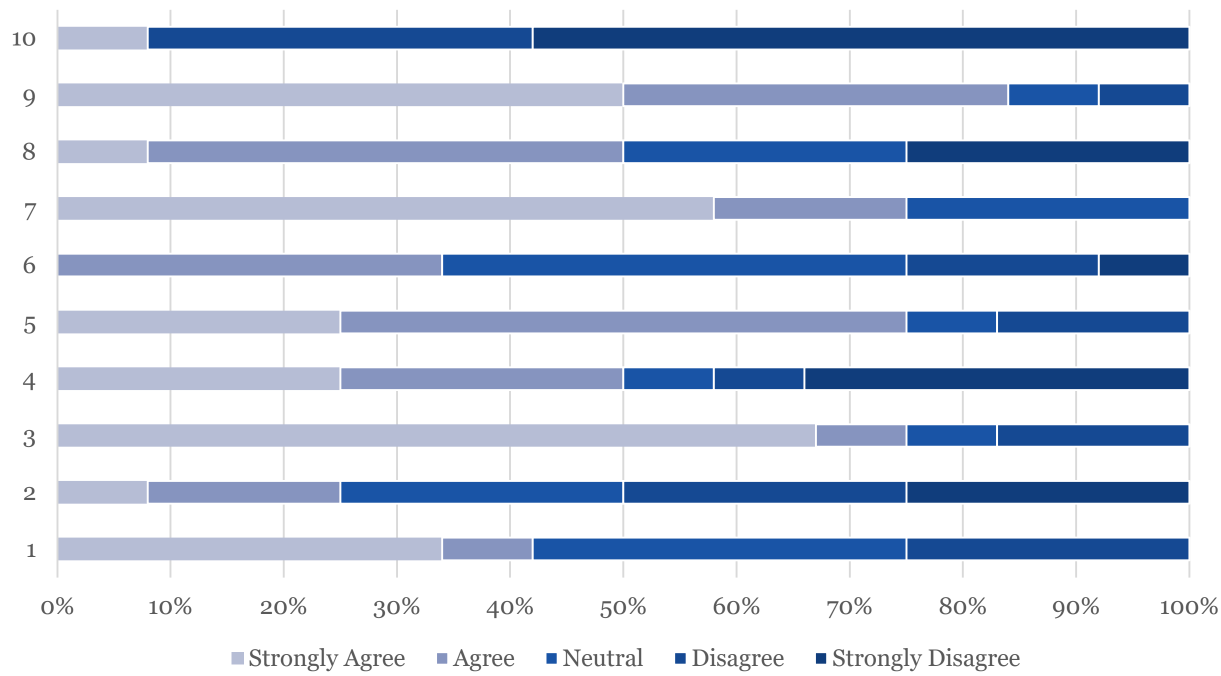


Figure 4.10 Graphic presentation of system usability questionnaire (Likert scale).

Figure 4.10 demonstrates the Likert scale percentage for each question. As it is seen above, 40% of the participants would use the device often. However, 67% think that the device is too complex to use. 50% of the participants think they would need the help of a professional to be able to use the device. However, 75% think that it is possible to learn to use the device after a short period of training and use.

5.Discussion

Lifting unsupported arms decrease the blood supply of supraspinatus already at 30° abduction. The blood supply ceases completely at 60° abduction. This indicates a risk of developing Musculoskeletal Disorders (MSDs) especially if the positions are held in long periods and with no rest in between [13]. RAMP - Risk Assessment and Management tool for manual handling Proactively, has three risk and priority levels which are as follows [12]:

High risk. The loading situation has such a magnitude and characteristics that many employees are at an increased risk of developing MSDs. Improvement measurements should be given a high priority.

Risk. The loading situation has such a magnitude and characteristics that certain employees are at an increased risk of developing MSDs. Improvement measures should be taken.

Low risk. The loading has such a magnitude and characteristics that most employees are at low risk of developing MSDs. However, individuals with reduced physical activity may be at risk. Individually tailored improvement measures may be needed.

Comparison of values in table 4.1 with the values recommended by the RAMP study (section 1.4 back postures) suggests that the back/trunk posture (bending forwards > 45° or bending backward> 0°) falls in the high-risk category and improvements should be a high priority. It should be mentioned that the measurements belong to one work-cycle. However, the values increase for one 8-hour working day. Each subject has about 2 to 3 haircuts per day which means that the values increase by a factor of 2 to 3 approximately for one full working day.

RAMP also suggests values for risk assessment of work-elements while there is a load on forearms. According to section 3. Lifting work in RAMP, the drying work-cycle falls in the high-risk category with the weight and frequency factor of 0.6 (weight of approx. 1-2 kg and frequency between 13-24). The lifting area factor is 2.8 plus the 1.7 factor for lifting the load with only one hand. The overall score is 5.1 > 5 which is the recommended value for high-risk lifting tasks by RAMP.

Table 4.3 shows a high time percentage (>50% of the work cycle length) for elevation angles >30° during the drying work-cycle which indicates that the arms were elevated >30° for more than half of the fundamental work-cycle duration. According to AMM (arbets och miljömedicinsk) in Lund these values indicate a risk for developing MSDs. The 10^{th} and 90^{th} percentiles are similar for both work-elements; however, the angles were held while there was a load on forearms during the drying fundamental work cycle which adds to the overall risk score of the task for developing MSDs according to the RAMP study. Therefore, this study has mostly focused on analyzing the data for the drying fundamental work-cycle.

Table 4.4 shows that the angular distribution average for arms have decreased when the feedback function was made available to the participants. The 10^{th} and 90^{th} percentiles have also decreased with the feedback function. However, the values are very close to each other. This can be due to the individual contribution of each participant to the total data. A comparison of the exposure variables values for measurements with and without the feedback function for individual participants shows various results. In some cases, the values such as 10^{th} and 90^{th} percentiles have decreased when the feedback function was used and for other cases, it has not changed significantly or has even increased. This variation can be due to several factors such as an individual's knowledge of ergonomics and how to change their posture when they receive negative feedback from the system.

A better comparison of data with and without the feedback function is possible when looking at the data individually. Measurements from one of the participants were chosen for this comparison. Figure 4.5 a and b show a shift in angular distribution from higher degrees to lower degrees (<40°) for both arms when the feedback function was used. This indicates that the participant has worked with lower arm angles during the measurement with feedback compared to the measurement without feedback which has given rise to an increased frequency for lower angles.
Values in Table 4.7 also agree with the graphic presentation of the angular distribution in figure 4.5. It is indicated that the mean angular distribution for both arms has decreased when the feedback function was available to the participant. The results from paired t-tests performed on each arm measurement with and without the feedback function indicate a significant difference between each data set. T-value > 1 and p-value < 0.5 indicate that the null hypothesis can be rejected which means that there is a significant difference between the dataset recorded during the feedback function compared to the dataset recorded without the feedback function.

Table 4.7 indicates that for all cases except left arm 10^{th} percentile, the 10^{th} and 90^{th} percentiles (°) have decreased significantly when the feedback function was used. Decreased percentile values show that the arms elevation angles were lower when the participant received feedback on their posture meaning the feedback function was efficient in making the participant aware of their posture.

5.4 Interpreting System Usability Scale (SUS) Score

The average SUS score is 68 which means the system is at the 50^{th} percentile. A score between 68-80.3 gives the adjective rating Good (B) for the system.[3] A system with a score of 75.625 is at the 73^{th} percentile meaning it has higher perceived usability than 73% of all products tested with this system.

[3] https://uiuxtrend.com/measuring-system-usability-scale-sus

6.Conclusion and Future Work

The result of this study agrees with the previous studies presenting the hairdresser profession as a high-risk profession for developing UEDs. This means that hairdressers are at a high risk of developing occupational UEDs such as tendinitis, osteoarthritis and carpal tunnel syndrome to name a few. Therefore, there is a need for a system that provides objective data for risk assessment of hairdressing tasks. This data could be useful for optimizing the ergonomic design of the workplace.

The variation of data amongst different subjects suggests that the feasibility of the feedback function is enormously dependent on the individual's knowledge of ergonomics and willingness to change work habits. Therefore, it is suggested that the device be used together with providing educational programs on ergonomics at work and the consequences of unhealthy work habits.

The ergonomic design of the workplace also plays an important role since it becomes very difficult to change a posture if the workplace is not ergonomically optimized. The height of the participant and the customer plays an important role in arm elevation angles. In some cases, the chairs had to be put in a higher or lower position. However, this was not possible with the chairs available at this specific hair salon.

For future studies, it could be effective to increase the number of measurements in order to compensate for the variability of work cycle duration by increasing the amount of sampled data. Ideally, the length of both datasets should be the same for a more accurate comparison of individual data. However, this is not possible for the hairdresser profession since the costumer determines many of the working conditions.

The participants in this study were all students. Their lack of experience, their need to focus extra on each task and having to communicate with their supervisor while working made it extra difficult for them to focus on the feedback given to them by the device. The participant that was more experienced (section 4.3) was able to focus more on the feedback and change her posture more easily. Therefore, it would be interesting to repeat the measurements with professional hairdressers since the result of the effectivity of the feedback function could change considerably.

Appendix

A. State of the Art

A.1 Introduction

According to the sixth European Working Conditions Survey (EWCS) in 2015, 44.4% of workers had reported suffering from muscular pain in the shoulders, neck or upper limb in the last 12 months [2]. The Swedish Work Environment Authority (2008) reported that 14.8% of female hairdressers in Sweden reported occupational UEDs in the past 12 months [14]. However, since the surveys are mostly based on self-reported health problems it is difficult to estimate the true extent of the problem. Table 1 < indicates the type of work-related issues and their prevalence amongst different professions reported by the European Union [2].

Type of work-related health problem	Workers (%)
Muscle problems affecting the back region	29.5
Neck, shoulders, arms or hands	20.1
Hips, legs or feet	11.3

Table 1. Type of work-related health problem indicated as the most serious among persons with a work-related health problem in the EU27 (%) [2]

Many kinds of research have been carried on evaluating the ergonomic conditions in salons. However, most of them rely on observational studies and surveys as a means of data collection. For example, according to a study conducted by students at the University of Central Florida cosmetologists are at moderate risk of developing injuries over a long-term period [15]. In another study based on self-reported surveys, it is concluded that hairdressers are at no high risk of developing MSDs due to occupational circumstances [16]. However, according to the European Agency for Safety and Health, cosmetologists are exposed to serious occupational health risks that can lead to developing MSDs especially in neck, shoulders and back regions [17]. The inconsistency in the data collected by different research groups is an indication of a need for a more objective system. This study aims to evaluate the feasibility of using a measurement system that has been developed to quantify the ergonomic risk assessment process for different occupations. This quantification allows for obtaining a more concrete and objective data which could lead to a more accurate and effective problem-solving.

A.2 Quantification of Repetitive Work

Ergonomics is the science of designing work environment and equipment with regards to the worker's health and safety. "Ergonomic factors" is the term referring to situations where there is a misfit between the working environment and worker's health. Ignoring ergonomic factors in the work environment design can lead to physical and mental exhaustion for the workers. These issues usually arise from constant and repetitive work or holding prolonged incorrect positions [4]. Repetitive work can be defined as similar physical work that is repeated under a specific period of time. In order to quantify this definition, repetitive work should be specified with regards to the duration and frequency of work cycles. For the prevention of musculoskeletal disorder studies, it is desirable to include parameters such as external force, postures and static load. According to biomechanical characteristics repetitive work can be classified into two categories, intermittent static or dynamic. However intermittent static movements should be distinguished from static movements. Static movements differ from the two movement categories mentioned above in the muscle activation between contractions. In such movements, there are no muscle breaks (or micropauses) in between contractions. There is no minimum duration available for a movement to be categorized as static. However, in most studies contractions exceeding 30-60 seconds are accounted as static movements [18].

A 2.1 Work-cycles

A cycle of work is the duration in which a task is performed. This cycle is subdivided into fundamental work cycles. Each fundamental work cycle is composed of work elements. Each work element puts a demand on a different region of the body involved in the task performing. For example, in the case of packing a box of fruit, packing the box defines the cycle of work. Packing each fruit is the fundamental work cycle. Grabbing, holding and wrapping the fruits are the work elements in the fundamental work cycle. Identifying the tolerance for each work element with regard to the risk of fatigue can be effective in designing prevention plans for musculoskeletal injuries [18].

A 2.2 repetitiveness

There are different definitions available for repetitive work. However, these definitions are mostly very close to each other in quantifying repetitive work. A few of these definitions are mentioned below.

In a study in Ergonomics considerations in hand and wrist tendinitis, high-repetitive tasks were defined as tasks with a time-cycle of less than 30 seconds or tasks with the same motion pattern for more than 50% of the whole cycle time. Jobs with an average hand force requirement of 40 N were considered as high-force jobs and those with an estimated average of 10 N were considered as low-force jobs [19]. Another study defines repetitive work as work elements with more than 15 times of repetition per minute and engaging less than 1/7 of the muscle mass [18]. A study in Ergonomic Design for People at Work defines highly repetitive work as tasks with cycle times below 30 seconds [20].

A 2.3 Task Similarity

Motor actions can be similar in three aspects:

- Time, i.e. similarity in the duration of work cycles
- Space, i.e. similarity in the spatial pattern of work cycles
- Force, i.e. similarity in force exertion over time [21]

A 2.4 posture

Musculoskeletal disorders due to repetitive work can depend highly on task performance posture [21]. According to the American College of Orthopedic Surgery, postures for different joints can be defined by the degree of deference from the neutral position of the joint. The degree deference can be measured using goniometers during the task performance [22]. It has also been found that the posture duration of a performed task is likely to have an influence on the risk of developing musculoskeletal disorders due to repetitive work [23]. According to several studies with access to technical instrumentation, repetitiveness and posture of different movements can be assessed by spectral analysis of goniometer recordings. These recordings provide information on the speed and acceleration of the movements [21].

A.3 Anatomy of the Affected Areas

A 3.1 Tendon, muscle and ligament

Tendons are connective tissues that connect muscle to bone. Static or prolonged movements can cause stress that is beyond the strength of the tendon. This stress will lead to small tears in the tendon. Another issue is inflammation of the tendons which is caused by friction due to overuse. Tendons in the hand and wrist are at a higher risk of injury due to overuse because of their smaller structure when compared to other tendons in the upper extremity. This condition is called tendinitis which is most common for tendons of the fingers, thumb, forearm, elbow, and shoulder. Tendinitis in the shoulder area can occur if the arms are held out in front or off to the side for long periods. Symptoms include pain, stiffness, tightness and burning sensation in the affected area [24].

Muscle injury which is caused by overuse leads to tissue scarring, inflammation, and stiffness in the affected muscle. The result can be the formation of trigger spots in the overused muscle. The pain from these spots is called referral pain due to the fact that the pain travels from the point of the trigger to a distant area and then recedes. Muscles in the neck refer pain to the shoulders, upper back, and hand. Muscles in the arms can refer pain to the neck, shoulders, wrists, and hands [24].

Ligaments are connective tissues that connect bones. Ligaments can also be injured by static, prolonged postures. This can cause inflammation of the ligaments especially for the cervical spine ligaments that are more susceptible to strain [24].

A 3.2 Human torso

The human torso is the central platform of the human body from which neck and limbs extend. Its anatomy consists of a skeleton with many muscle pairs, ligaments, and nerves with different functions [25]. The skeleton in the human torso consists of the cervical spine (C1-C7), thoracic spine (T1-T12) Lumbar spine (L1-L5), 4 sacrum vertebrae and 4 coccyx. Torso rotation is enabled by axial rotation between vertebrae pairs. An intervertebral disk between each two vertebrae pair reduces friction between the pairs and functions as a shock absorber. Degenerated disks have an increased risk of rupture. They also cause the vertebrae to be placed closer to each other, which increases the risk of nerve compression. This is one of the common causes of thoracic spine pain which can be due to incorrect body posture, aging or disease [26]. Another common cause of thoracic spine pain is Muscle spasm or strain caused by poor posture such as forward head bending [25].

Movement of the human body is usually modeled using three imaginary planes: the sagittal plane, coronal plane, and transverse plane. Sagittal plane (anteroposterior) divides the body vertically into right and left halves. The coronal plane (frontal) divides the body vertically into the front and back. The transverse plane (horizontal) divides the body horizontally into top and bottom halves of equal mass [27]. In the anatomical reference position, all body segments are positioned at 0 degrees. Rotation of a body segment away from the reference position is named by the direction of motion and the angle between the body segment's position and the reference position. Figure 1 illustrates the motion ranges of the human torso on three body planes [27]. Combined rotation around two or more axes of the torso increases the risk of attaining work-related injuries [26].

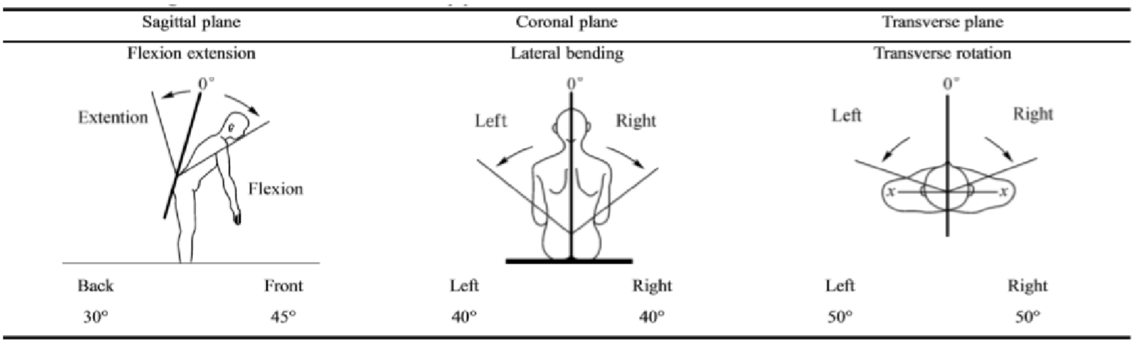


Figure 1. Human torso rotation on three body planes

A 3.3 Shoulder

The movements of the human shoulder are possible by a complex and dynamic relationship between many muscle forces, bony articulations, and ligament constraints. Figure 2 illustrates the shoulder's range of motion in three body planes.

The shoulder joint has the most extensive range of motion in the body which is due to static and dynamic stabilizers. Injury of these stabilizers either by trauma or overuse will increase the risk of shoulder related injuries significantly. A different group of stabilizers is responsible for joint stabilizing in the shoulder region depending on the degree of abduction [28].

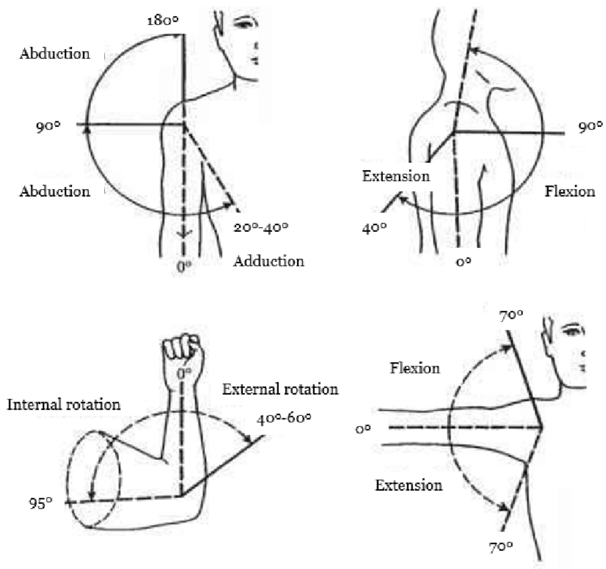


Figure 2. Shoulder range of motion

Repetitive arm motions in a certain direction can lead to the injury of different groups of stabilizers [21]. The table below shows the recommended values for risk assessment of developing occupational musculoskeletal disorders in the upper arms. According to AMM (arbets och miljömedicinsk) in Lund, a work is counted as strenuous for upper arms if it surpasses the following values [13]:

Strenuous work for shoulders	Arm elevation angle(degrees)	Time(% of a workday time)
No load on forearms	>60	10
Load on forearms	>30	>= 50
Average movement speed of shoulders	>60/seconds	
Recovery time (neutral posture)		<5

Table 2. Recommended values by AMM indicating strenuous positions for shoulders

A.4 Risk Assessment Methods

In general, there are three ways of obtaining risk assessment for different exposure variables. They include Self-reports, observations and technical measurements [29].

A 4.1 Self-reports

Self-reports of workload exposure are very common in ergonomics research. The data is either reported by the workers themselves or by the employers and group leaders. Self-reported data is obtained through different methods such as using questionnaires, diaries, rating-scales and/or interviews [29]. There are advantages and disadvantages of using self-reports as a means of ergonomics risk assessment. The advantages include easiness of data gathering from a large study population, more economical compared to other methods and low participant burden [29, 30]. The disadvantages include low precision, the requirement of a large study population in order to increase the precision and low reliability [31, 29]. Studies show that the correlation between self-reports and technical measurements is low to moderate with a mean value of 0.37 ± 0.25 [32]. Another issue with self-reports could be the fact that people with pain tend to rate their exposures higher than people without pain for the same workload [31].

A 4.2 Observations

For observational studies usually, a trained person will make observations by using checklists and video recording [29]. When it comes to ergonomics studies using observation, there is a similarity in reported data for exposure of large-scale body movements. However, for small and quick movements such as trunk rotation, the reliability for reported data is low [33].

A 4.3 Technical measurements

There are several types of technical measurements method for ergonomic risk assessment such as optical capture system, sonic system, goniometric system and accelerometer system [34]. However, only a minor part of ergonomics studies has been conducted using technical measurements. This could be due to the high economic burden of these measurements with respect to both time and cost [32]. Other limitations of this method include having to learn how to use the device, analyze the data and also the requirement of different software depending on the type of study [29].

A 4.3.1 Current technical measurements devices

Integrated sensors in clothing have been used before for physiological signals and movement pattern recording. Wearable technology has existed in healthcare for over a decade now. Efforts by the European Union have led to remarkable research development and commercial attempts. However, only a few products have been successful in reaching the mainstream market [6]. Table 2 contains some examples of research projects and commercial products in wearable technology for healthcare funded by the European Union.

European research projects:

- Bio-sensing textiles so support health management [35]
- Compliance and effectiveness in HF and CHD closed-loop management and HeartCycle [36]
- Contactless sensors for body monitoring incorporated in textiles [37]
- Medical remote monitoring of clothes [38]
- MyHeart [39]
- OFSETH Optical fiber sensors embedded into technical textile for healthcare monitoring [40]
- Protection e-Textiles: micro nanostructured fiber systems for emergency disaster wear [41]

Commercial products:

- Hexoskin smart shirt [42]
- Nuubo. nECG shirt L1 [43]
- Polar Electro Oy. Polar H10 Hear Rate Sensor [44]
- Vivonoetics. The Equivital TnR Product Range [45]

the wearable sensors market has experienced a standstill mostly due to lack of an actual application that is able to pull the technology through and also the pricing of textile-electronic manufacturing. However recent developments in preventive and personalized health monitoring systems support expansion for smart clothing and wearable sensors' market [6].

A.5 Motion Capture (MC) Systems

Most risk assessments of work-related musculoskeletal disorders (WMSDs) today are based on self-reporting the issues. This data usually does not correlate well with actual data [31]. Quantifying WMSDs is the first step towards an objective risk assessment, which is essential in the implementation of preventive plans and policies. This quantification can be done using Motion Capture (MC) systems [26].

There are many different types of motion capture systems available today. However, they are all similar in one aspect. They capture the movements and rotation of a rigid body. One method of MC is to use Inertia Measurement Unit (IMU) sensors. The benefits of using IMU sensors compared to other MC systems include low weight, small size, potential to be wireless or waterproof and a considerably lower cost compared to other MC systems. Even though the accuracy is not the highest compared to other MC systems, IMUs are most beneficial for their mobility. The small size and possibility to make them wireless make it possible to wear the sensors by either sewing them into clothes or taping them to the skin [26].

A 5.1 MicroElectroMechanical System

IMU sensors were first used in 1930 for aircraft navigation and in large devices. They were large in size and had a high cost and power consumption. The introduction of the micro-electromechanical system (MEMS) has made it possible to make compact, low cost and low processing IMU sensors [46]. Components in MEMS have a size between 1-100 µm. The small size of the components makes it possible to use materials that would be very costly in larger size sensors. Another benefit of MEMS is its robustness and energy efficiency, which is also due to the small size of the components. The cons of MEMS technology would be the high cost of MEMS building devices and the requirement of fabrication in cleanroom laboratories. Most dust particles have a size between 0.1-1000 µm. Therefore, they can potentially disturb sensors function if present during fabrication [26].

A 5.2 Inertia Measurement Unit Sensors

IMU sensors are widely applied in motion tracking devices today due to their small size, low weight and the ability to communicate wirelessly e.g. via Bluetooth. Data logging capability and sufficiently low uncertainty have made IMU sensors an attractive measurement technique for human movements [26]. They determine movement in terms of angular velocity, acceleration, and rotation. There are two types of IMU sensors. Those with two sensor types, namely accelerometer, and gyroscope.

Those with three sensor types namely accelerometer, gyroscope, and magnetometer [46]. The integration of the gyroscope measurements determines the orientation of the sensors. Double integration of the accelerometer measurements subtracted of the earth's gravity, provides information
about the position of the sensors. The subtraction of the earth's gravity requires the orientation of the sensors to be known. The process of attaining information about the orientation and position of sensors by integrating the measurements from the sensors is called *dead-reckoning*. Figure 3 illustrates the process [47].

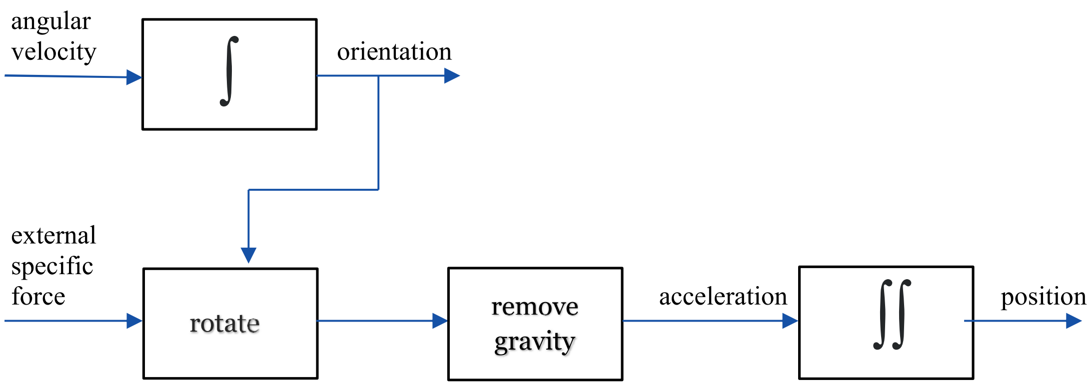


Figure 3. Dead-reckoning process

A 5.3 Degree of freedom (DOF)

The degree of freedom determines the number of independent parameters in a system. IMU sensors that are available in the market today vary from 2-9 DOF. The number of DOF depends on the type of sensors used in the IMU sensor and the number of the axis that it measures. In position tracking systems, 6-DOF for two-sensor type IMU or 9-DOF for three-sensor type IMU is usually used. The number of DOF represents the measurement in x, y, and z-axis for each sensor. The accuracy of the sampled data increases with a higher number of DOF [46].

A 5.4 IMU with two sensor types

This type of IMU consists of accelerometer and gyroscope sensors. Each sensor has between two to three DOF defined for x, y, and z-axis which will provide a total of four to six DOF. The information from each sensor is stored separately. Angles are measured from both sensors and the data is calibrated as shown in Fig. 4 in order to increase the accuracy of the output data [46]

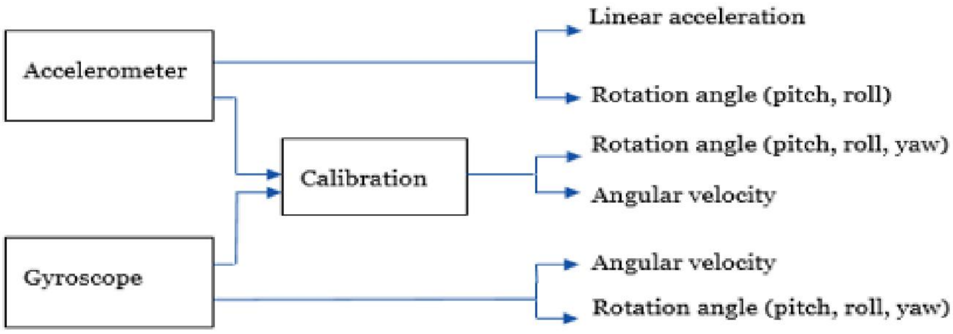


Figure 4. IMU with two sensors

A 5.5 IMU with three sensor types

This IMU with an accelerometer, magnetometer, and gyroscope, all in tri-axel commonly, provides measurements in nine DOF. Measurement of yaw angle rotation by the magnetometer provides the possibility to improve drift issues by calibrating this data to the gyroscope data [46]. Yaw, pitch, and roll (figure 6) are three rotation angles introduced by Euler that represent rotations of a rigid body in $\mathbb{R}^3$ [26]. Figure 5 illustrates the basic principle of a three-sensor type IMU [46].

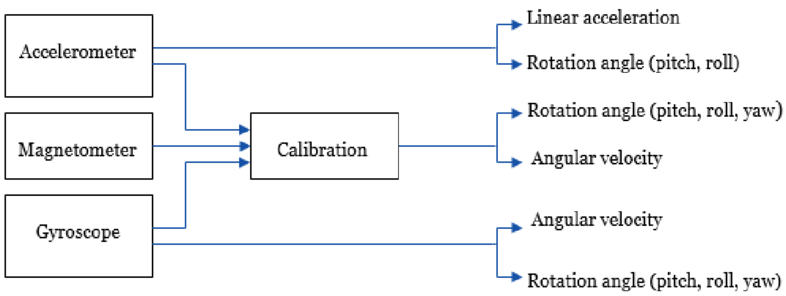


Figure 5. IMU with three sensors

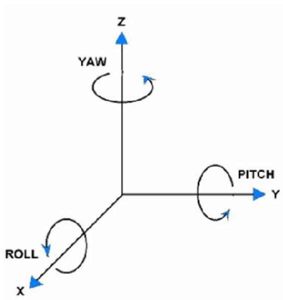


Figure 6. Angles of rotation

A 5.6 Sample rate

The sample rate is the number of sampled data per second. Higher sample rates provide better representations of the motion capturing. However high sample rates require increased processing power due to a large amount of data. Therefore, an average sample rate which is both a close representation of the movements and requires less processing power is preferred. 25 Hz is the sampling rate which is mostly used today [26].

A 5.7 Euler angles limitation for motion tracking in 3D

As mentioned before Euler angles use three sequential rotation angles (yaw, pitch, and roll) to describe rotations of a rigid body in $\mathbb{R}^3$ with respect to a fixed coordinate system.
Euler angles work well for small rotation angles but suffer from singularities when rotation angles attain larger values [26]. Matrices (1-3) define the three Euler rotation angles about X, Y and Z-axes.

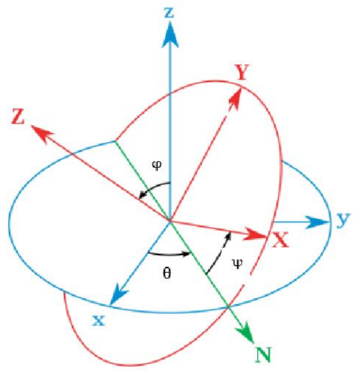


Figure 9. Euler angles geometrical definition (N is the line of nodes)

$$X(\psi) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\psi & \sin\psi \\ 0 & -\sin\psi & \cos\psi \end{pmatrix} \tag{1}$$

$$Y(\theta) = \begin{pmatrix} cos\theta & 0 & -sin\theta \\ 0 & 1 & 0 \\ sin\theta & 0 & cos\theta \end{pmatrix} \tag{2}$$

$$Z(\varphi) = \begin{pmatrix} cos\varphi & sin\varphi & 0 \\ -sin\varphi & cos\varphi & 0 \\ 0 & \sin Rt & 1 \end{pmatrix} \tag{3}$$

The product of the three rotation matrices is equal to the transformation matrix R.
The order of the rotation axes affects the result because matrix multiplication is not commutative [48]. In this text, the rotation is about the fixed axes z, y and x, $R_{XYZ} = X(\psi)\ Y(\theta)\ Z(\varphi)$ (in that order).

$R_{XYZ}=$

$$\begin{pmatrix} \cos(\theta)\cos(\varphi) & \cos(\theta)\sin(\varphi) & \sin(\theta) \\ \sin(\psi)\sin(\theta)\cos(\varphi) - \cos(\psi)\sin(\varphi) & \cos(\psi)\cos(\varphi) + \sin(\psi)\sin(\theta)\sin(\varphi) & \cos(\theta)\sin(\psi) \\ \sin(\psi)\sin(\varphi) + \cos(\psi)\cos(\varphi)\cos(\theta) & \cos(\psi)\sin(\theta)\sin(\varphi) - \cos(\varphi)\sin(\psi) & \cos(\psi)\cos(\theta) \end{pmatrix} \tag{4}$$

Equation (4) represents the general form of the rotation matrix. Due to equations (5-7), there are singularities in the transformation matrix (8) at angles $\theta = \pm\frac{\pi}{2}, \pm\frac{3\pi}{2} \ldots$

$$R = \begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix} \quad (5) \qquad \sin\psi = \frac{R_{23}}{\cos(\theta)} \quad (6) \qquad \sin\varphi = \frac{R_{1\ 2}}{\cos(\theta)} \quad (7)$$

$$R_{XYZ} = \begin{pmatrix} 0 & 0 & \pm 1 \\ \pm\sin(\psi)\cos(\varphi) - \cos(\psi)\sin(\varphi) & \cos(\psi)\cos(\varphi) \pm \sin(\psi)\sin(\varphi) & 0 \\ \sin(\psi)\sin(\varphi) & \pm\cos(\psi)\sin(\varphi) - \cos(\varphi)\sin(\psi) & 0 \end{pmatrix} \quad (8)$$

Motion tracking of human movements requires tracking in all directions. The singularities in Euler angles are not suitable for such applications since they give rise to an issue called the gimbal lock [26]. When using three concentric frames for motion tracking a degree of freedom is lost in certain positions. However, a minimum of three rotation angles must be combined to represent an angular displacement. The loss of a degree of freedom gives rise to the gimbal lock issue [49]. Euler angles are suitable for representing motions of a rigid body in $\mathbb{R}^3$ because they are intuitive and are more suitable for analysis and control [50]. However, to correct for the gimbal lock issue in angular displacement measurement for IMU sensors often the quaternions coordinate system is used. A Quaternion, $Q = q_0 + q_1 + q_2 + q_3 = \sum_{i=0}^{3} q_i$ is a four-element vector composed of one real element and three complex elements. A quaternion coordinate system can describe any rotation in $\mathbb{R}^3$ [26]. The quaternions coordinate system and Euler's angles can be used interchangeably for IMU sensors [47].

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