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A Model for a Real-time Ergonomics Assessment

Using a 3D Motion Tracking Sensor Suit: Model Development and Evaluation in Electronic Manufacturing

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DIPLOMA THESIS

submitted in partial fulfillment of the requirements for the degree of

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in

Business Informatics

by

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to the Faculty of Informatics

at the TU Wien

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Vienna, 1st September, 2021

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Feraldi Zahrial Zahir

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Wien, 1. September 2021

Feraldi Zahrial Zahir

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Kurzfassung

Krankheiten und Verletzungen am Arbeitsplatz, die durch Überanstrengung oder arbeitsbedingte Muskel- und Skeletterkrankungen (WMSDs) verursacht werden, sind vor allem in der Fertigungsindustrie sehr häufig. Da arbeitsbedingte Verletzungen zu langfristigen Muskel-Skelett-Erkrankungen führen können, Krankenstandstage, eingeschränkte Arbeitstätigkeit oder sogar den Tod zur Folge haben können, sollten sie unbedingt vermieden werden. In dieser Studie werden mögliche Verletzungen eines Arbeiters mit Hilfe eines am Körper getragenen Sensoranzugs analysiert. Bei einer Durchführung bestimmter Aufgaben in einem Montageprozess, werden Bewegungsdaten des Arbeiters erfasst und zurückgeliefert. Außerdem wird ein Modell zur Bewertung der Ergonomie in einem Fertigungsprozess vorgestellt. Dieses dient als Konzeptnachweis (Proof-of-Concept) für eine Echtzeitauswertung der Ergonomie um festzustellen, ob es dazu beitragen kann, arbeitsbedingte Verletzungen zu verhindern.

Der Design Science Forschungsmethode nach Hevner folgend wird ein Artefakt erstellt, das in dieser Studie in Form einer Softwareanwendung zur Bewertung der Ergonomie eingesetzt wird. Das Artefakt wird anhand eines konkreten Falles evaluiert; Der Identifikation und Evaluation von ergonomischen Abläufen und Gesundheitsrisiken von Fließbandarbeitern während der Montage von 3D-Druckern. Die Arbeiterinnen und Arbeiter setzen besonders verletzungsanfällige Körperteile ein, speziell die Arme, die Hände, die oberen Gliedmaßen, die Schultern, den Nacken und den Kopf. Um Ausfallzeiten an realen Fließbändern zu vermeiden, wurde das Experiment in einer kontrollierten Umgebung und mit einer kleinen Anzahl von Teilnehmern durchgeführt.

Mit dieser Studie sollen insbesondere zwei Hauptforschungsfragen beantwortet werden. Erstens sollen "sichere" Schwellenwerte, die zu einem positiven Ergebnis bei der Ergonomie-Auswertung führen können, identifiziert werden. Zweitens soll ermittelt werden, inwieweit ergonomische Auswertungen in Echtzeit das Verletzungs- oder Krankheitsrisiko in einer 3D-Drucker-Montagelinien verringern können.

Mit Hilfe einer Technologie zur 3D-Bewegungsverfolgung, in Kombination mit einer selbst entwickelten Bewertungsanwendung, welche die Leitmerkmalmethode zur Beurteilung und Gestaltung von Belastungen (LMM) als Hauptmethode zur Risikobewertung verwendet, werden Daten gesammelt und Sicherheitsschwellenwerte für die Ergonomie-Auswertung definiert.

Die TeilnehmerInnen wurden gebeten, in zwei Versuchsreihen einen 3D-Drucker zusammenzubauen. Die ergonomischen Werte wurden bei beiden Versuchen gemessen, wobei der zweite Durchgang zu einer Verbesserung der Werten führte. Dies ist auf die akustischen und visuellen Warnungen zurückzuführen, welche die entwickelte Anwendung ausgibt, wenn ergonomische Fehlverhalten festgestellt werden. Es wird erwartet, dass das aus dieser Studie hervorgegangene Modell dazu beitragen wird, die ergonomische Sicherheit an Montagelinien zu verbessern.

Abstract

Sickness and workplace injuries caused by overexertion or Work-Related Musculoskeletal Disorders (WMSDs) related incidents, especially in manufacturing industries, are common. As work-related injuries and illnesses could result in long-term musculoskeletal conditions, which can cause days away from work, restricted work activity or even death, they should be avoided at all costs. In this study, possible injuries of a worker are analyzed using an on-body sensor suit that obtains and delivers movement data of the worker while performing certain tasks of an assembly process. Furthermore, a model to assess ergonomics in a manufacturing process is presented. It serves as a proof of concept of a real-time ergonomics assessment with an objective to identify whether or not it could contribute in preventing work related injuries.

Relying on Hevner's design science as a research method, an artifact, presented in the form of an ergonomics assessment software application in this study, is built and evaluated. The artifact is evaluated against a specific case by assessing ergonomics and identifying health risks faced by 3D printer assembly lines workers. These workers use body parts that are most prone to injuries, such as the arms, hands, upper limb, shoulder, neck and head. To avoid downtime on actual assembly lines, the experiment was conducted off-premise, in a controlled environment, involving a small number of participants.

This study attempts to address two main research questions in particular. First, to identify "safe" threshold ranges that could lead to a positive ergonomic assessment measurement result. Second, to identify to what extent can real-time ergonomic measurement activities decrease the risk of injuries or illness in 3D printer assembly lines.

With the help of a 3D motion tracking technology [1], combined with a self-developed assessment application that uses the Key Indicator Method (KIM) [2] as the main risk assessment methodology, data are gathered and ergonomics assessment safety thresholds are defined.

Participants were asked to assemble a 3D printer in two runs of experiments. Ergonomics scores are measured on both of the experiments, where the second round resulted in a better ergonomics scores. This is due to the audio and visual warnings given by the application when ergonomics violations are identified. It is highly expected that the model produced from this study will contribute in improving the ergonomics safety in assembly lines.

Contents

CHAPTER 1

Introduction

This introduction chapter provides a quick overview about the master's thesis. The chapter is composed of a motivation, a problem statement, the aim of the work including the research questions, methodological approaches and an outline of the work.

1.1 Motivation

A worker not being satisfied with his working environment due to health issues, or even being absent from work due to injuries, is a loss for both the employer and the worker himself. It is a loss for the worker due to the fact that the worker could not perform his daily job at maximum capacity or complete his task on time, which could lead to a monetary penalty, for example for workers getting paid by the hours or by the quantity of product. It is loss for the employer due to the fact that missing resources could lead to shortages of production or missed deadlines.

Sickness and workplace injuries due to incidents related to work-related musculoskeletal disorders, especially in manufacturing industries, are common. Incidents and long-term musculoskeletal disorders side effects to workers should be avoided at all costs.

Possible injuries or hazards of a worker can be analyzed using an on-body sensor suit, that obtains and delivers movement data of the worker while performing certain tasks, for example in an assembly process. The delivered data by the sensors can then be matched against ergonomics standards. A software application can be used to gather, match the data, as well as to provide real-time warnings to the worker when needed, so injuries and incidents could be avoided. Data gathered can be used for further study of ergonomics related to the specific sector of industries. This analysis is best performed in a fabricated situation, where real conditions of the working environment could be simulated.

The Pilot Factory Industry 4.0 at the Vienna University of Technology aims to improve how intelligent production works, by simulating almost-real factory conditions. These conditions provide industries a neutral test and an authentic research environment. At the Pilot Factory, industries are able to perform analyses without having to shut down real production operations.

One very important aspect that is being researched at the Pilot Factory Industry 4.0 is the study of ergonomics. The study of ergonomics can already be seen as early as the 19th century when the industrial revolution begun, as it was introduced by Frederick Taylor in his "The Principles of Scientific Management" [3]. However, current studies of ergonomics are still relevant and still contribute to the prevention of musculoskeletal disorders (MSDs) and Work-related musculoskeletal disorders (WRMSDs).

This Master's thesis will attempt to address the study of ergonomics with a use case of an assembly line in a 3D printer manufacturing factory where ergonomics measurements are delivered by a set of motion sensors that are attached on a suit worn by a factory worker.

The monitored worker performs specific tasks in assembling a 3D printer, simulating a real process in the factory line. In order to fetch and deliver the measurement data, a software application is developed.

The motion sensors are provided by Xsens [4]. The sensors are wireless trackers that act as inertial measurement units, containing 3D linear accelerometers, rate gyroscopes, magnetometers and barometer. When active, the trackers sends out raw data to its base unit. The raw data on the base unit are captured by a proprietary software provided by the sensors' company. This software acts as a middleware.

In order to analyze the data further, a compatible software application has to be written. This application is written in the programming language Visual Basic .NET. The purpose of this application is to collect the data from the middleware application and then assess them according to standard ergonomics risk assessment methods.

The Ergonomics risk assessment method that dominates this study is the so called "Leitmerkmalmethode" or the Key Indicator Method (KIM). In addition to KIM, other assessment methods are also discussed and taken into consideration.

1.2 Problem Statement

In the United States, as an example, there were approximately 2.8 million nonfatal workplace injuries and illnesses reported by private industry employers in 2019, which occurred at a rate of 2.8 cases per 100 full-time equivalent (FTE) [5]. In Austria, in the year of 2019 the rate was 2.4 cases per 100 FTE for employment conditions [6]. As a comparison, in the year 2019 in Germany, there were 780,581 workplace-related incidents, where 107.761 were reported in the area of assembly. The rate of incident was 2.1 cases per 100 FTE in Germany[7].

An injury or illness is considered to be work-related if it is caused by an event or an exposure in the work environment. The results of work-related injuries and illnesses could range from days away from work, job transfer, restricted work activity, loss of consciousness or it could even lead to death. These effects have negative impacts for both the workers and the employers. One case-characteristic that caused occupational illness or injury, according to US Bureau of Labor Statistics, is overexertion from exposures or events at work [8].

Overexertion could be avoided through ergonomics measures. A study in the area of occupational health and safety literature have suggested that incidences can be reduced by implementing ergonomic principles [9, 10, 11, 12, 13, 14, 15]. This study in particular will attempt to address the ergonomic principles using an ergonomic assessment model. Ergonomic assessment deals with the assessment of characteristics resulted in regards to interaction with tools, machines, tasks, jobs and environment in order to achieve a higher safety, productivity, comfort and effectiveness level [16].

Many studies on ergonomic assessment have been done [17, 18, 19, 20, 21, 22, 23, 24]. However, there are not many studies done involving real-time ergonomic assessments in a controlled environment where real manufacturing workplace environment is simulated. Real-time ergonomic assessment itself is rather complicated. It needs to use sets of reliable equipment, such as body sensors, which act as motion trackers, combined with a proper software application to capture and analyze the data that is sent by the sensors. In order to ensure the ergonomic value of the application, ergonomic assessment standards have to be embedded in the system [25, 26, 27]. There are currently few studies being done with devices attached to a test person directly. With this kind of procedure, a higher level of accuracy can be expected.

The challenges on this study would be: creating the suitable software to capture the data from the motions; finding current ergonomic models that can support the process in the factory area; and at the end, validating and perfecting the model according to the data collected by the software in a controlled environment.

1.3 Aim of the Work

Taking in consideration the above problem statement, this study aims to answer two research questions, *what are the "safe" threshold ranges that could lead to a positive ergonomic assessment measurement result?* and *to what extent can real-time ergonomic measurement activities decrease the risk of injuries or illness in 3D printer assembly lines?*

Thus, the main objectives of this study are to develop a conceptual framework of a real-time ergonomics assessment activities and also to investigate the use of KIM ergonomics assessment method on a specific manufacturing assembly activity.

The main expected achievement of this study is to establish an ergonomic assessment model as a proof of concept of a real-time ergonomics assessment of human work tasks in an assembly line. The data in this model creation is provided through a self-developed software application. The model will contribute in general to the ergonomic studies by providing performance safety thresholds of basic manual handling operation that will avoid overexertion, which leads to injuries and illness of a worker. As most of the tasks in assembling 3D printers involves common assembly movements, the study can also then be applied to other manufacturing assembly lines similar to 3D printers' factory.

1.4 Methodological Approach

In this study, the simulated workplace situation is a factory that produces 3D printers. The tasks investigated is an assembling process of a printer in a workstation by a worker. The chosen worker monitored wears a suit equipped with motion tracking sensors. The worker's body parts are mapped into different anatomic regions and specific regions are then measured. The sensors send out data, and a software tool captures the data, analyzes, evaluates and compares them against common ergonomic standards. The combination of the measured data and result of the questionnaires of the workers, contribute then in an ergonomic model creation.

The research methods used in this study would primarily be based on "changing things as they are by creation", which is known as design science [28]. The main contribution of design science is the building of an artifact. In this study, the ergonomic assessment model is the artifact. This model is evaluated through case studies and experimentations. In addition to this, the scientific experiment research method is also used in this study. Equal demographic of group of people are given visual or written instructions to perform specific tasks in a controlled environment. The result of this study will create innovative constructions to solve real world problems. The methods used can also be considered as a Constructive Research Approach (CRA) [29], which is based on a 3-phases approach: analysis phase, design phase and evaluation phase.

In regards to knowledge contribution, according to the Knowledge Innovation Matrix (KIM) [30] this contribution would be referred to as the so-called exaptation. The knowledge solution maturity level is high, but the problem maturity is low. The validation effort of the strategy emerged from this study is in the form of a software package as a proof of concept. A feasibility study will also be conducted through direct experiment of the participants. The methodological approach consists of the following steps:

1. Analysis
    a) State-of-the-art Analysis
        i. Informal literature review on the following terms
            A. Work-related musculoskeletal disorders (WRMSDs)
            B. Ergonomic assessment methods using wearable sensors
            C. Ergonomic assessment software
        ii. Evaluation of provided tools
            A. Motion trackers hardware

B. Out of the box software

b) Requirement Analysis

i. Informal literature review on the following terms

A. Physical ergonomics risk assessment methods

B. Cognitive ergonomics risk assessment methods

C. Human body anatomy and postures

D. Data transfer and data exchange

2. Develop/Build

a) Software development

An application is developed. This application serves as a prototype and proof-of-concept of the to-be developed model. The application will collect the data from the motion sensors and checked them against the standards ergonomics reviewed from the analysis phase.

b) Experiment

An experiment is done on an equal demographic gender classification of groups of people. The different groups are given the same instructions one as visual and the other as textual to perform a specific task.

c) Model creation

An ergonomic assessment model is created, based on the application developed and experiment performed above. The model contains current state analysis and requirement analysis, state of the art and is validated against the data gathered by the developed software.

3. Evaluation

The validity of the model produced on this study will be evaluated through mean of validation by matching the data gathered by the software against the cognitive experience of the experiment participants. The methodology used for the cognitive experiment and for the acceptance evaluation would be in a form of a semi structured interview [31].

1.5 Outline of the Work

The specific foundation of the research method used is the design science by Hevner et al. [28]. The core process of the research method in this study is the so-called design cycle. The design cycle consists of two building blocks, the build design artifacts & processes block and the evaluation block. In general, the product, or the output of the developed/built process in this research method are artifacts or theories.

The developed product will then be assessed through the evaluation block. The objective of the evaluation is to observe how the product from the building block is suitable in

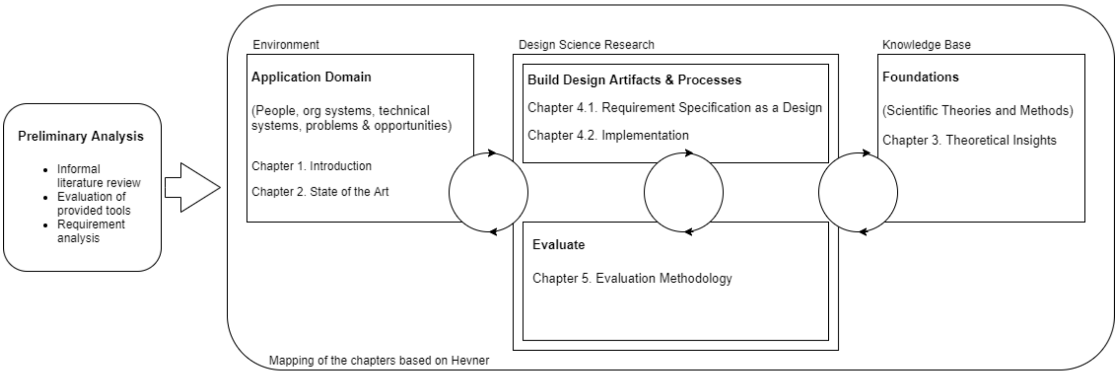


Figure 1.1: Mapping of chapters of this study into the design science research method by Hevner et. al (2004).

helping to introduce a solution to the problem. The evaluation result will then be used to refine the building block that created the artifacts. Thus, creating an iteration cycle.

The evaluation method that will be used for this study would be experimental with an emphasis on controlled experiment. In addition to the experimental method, in order to build a convincing argument for the experiment result, a survey in the form of questionnaires would be used.

CHAPTER 2

State of the Art

Many studies have been conducted in the area of ergonomics measurement using sensors devices. Examples of previous studies on this topic are elaborated in this chapter. The state of the art study is done through literature review, and is structured through the following: setting the eligibility criteria, setting the search strategy and performing the actual study selection. How the artifact is built and how the evaluation is done are discussed in the first section. The environment part of the design science will also be discussed in the first section. The second section covers common technology used by other studies, while the third section elaborates on ergonomics standards.

⇒ Design science environment

⇒ Technologies used by other studies

⇒ Ergonomics assessment standards

2.1 Design Science Build & Evaluation, Environment

In this section, the building and evaluation block of the study is evaluated.

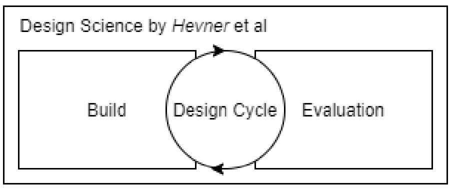


Figure 2.1: Build and Evaluate based on Hevner's

Building block

The artifact or software built was based on a developed requirement. The requirement is abstracted into three levels according to Kotonya et al. [32], which are the user requirements, system requirements and design specifications. The requirements specifications are further taxonomized into three requirements; Functional requirements, nonfunctional requirements and domain requirements according to Laplante et al. [33].

Based on this requirement, the software will then be developed. The software development follows the waterfall method suggested by Bell et al. [34]. The verification and validation efforts on the software will be embedded into the evaluation block of the design science framework.

During the building of the artifact, external knowledge gathered from numerous literature reviews in the form of ergonomics assessment standards, are applied into the artifact. This supports the design science framework in a way that knowledge base is connected to the design science research through the rigor cycle.

Evaluation Block

The evaluation in this study is fulfilled through an experiment and surveys.

Experiment

The required means of evaluation in design science in this study will be satisfied through an experiment method. To be more precise the method chosen is the controlled experiment method. The environment simulated is taking place in a controlled laboratory setting. The laboratory setting is provided by Pilot Factory Industry 4.0 of the Vienna University of Technology. A work station of a 3D printer factory assembly line is set-up at the Pilot Factory Industry 4.0 in order to simulate a real 3D printer factory situation.

The Experiment technique that is used in this study leads back to the Hawthorne experiment back in the 1920s [35, 36]. In this experiment, two groups of workers were observed. One with new experimental light being installed in their working area and one without. Comparisons were then made in regards to the work output of the two different groups. At a later stage, it was also found out that work output increased, regardless whether the group area was being exposed by the new lighting or not. Thus, creating the so-called “before-after” design [37]. Particular to this study, the before-after design will be exposed to all of the participants.

In a further experiment, also by Hawthorne, one group of female workers was exclusively supervised intensively by managers, whereas the rest of the workers were not. Here, again, the output of the workers in the exclusive group are compared to the output of the remaining workers, who are not being exclusively supervised. This technique introduced the so-called separation between a “control” and a “treatment” group, where the treatment group gets the special treatment or being observed exclusively and the control group being left untreated.

According to MacKenzie [38], a controlled experiment is identified through two variables which is a response variable and a manipulated/independent variable.

In a Human-Computer Interaction (HCI) environment, the term manipulating the variable has the meaning of presenting the experiment participants with different settings or configurations. In order to be considered as a controlled experiment, a minimum of two settings of a manipulated variable are needed. Specific to this study, the two configurations of the independent variable would be the different presentation of tasks/work instructions in assembling the 3D Printer.

The first configuration would be a visual instruction using a video recording, and the second configuration would be a plain textual instruction which will be printed out. The instructions presented to the participants, contain steps made in such a way that assembly ergonomics and assemblability/assembly complexity level are classified according to Falck et al. [39, 40, 41] in order to ensure the health and safety of the worker.

The response variable in HCI, on the other hand, shows the measurability, quantifiability, and observability of the human behavior when interacting to the manipulated variable described above. In this study the response/dependent variable would be how "well" the participants can understand, follow and perform the steps given. The definition of well can then be measured through the result of ergonomics scores achieved after using the built artifacts/software.

The amount of participants for the experiment are chosen based on sampling method. Due to the fact that tasks to be completed are designed in a way that no prior knowledge in a specific area is needed, and for the sake of simplicity which contributes to the limitation of this study, the convenience sampling method [42] is used in choosing the participants. Yet equal demographics of gender is still maintained. Participants will then be divided into two groups, to proceed according to different settings of manipulated variable mentioned above.

The data and analysis result of a controlled experiment, also according to MacKenzie [38], will create a strong conclusion. The cause and effect variables will contribute to the conclusion building, and this would be the major advantage of using experimental method, compared to other methods. The limitation of the controlled experimental method conducted in a laboratory setting would be the diminishing of relevance due to artificial tasks.

However, in our study, this artificiality will be reduced tremendously through a real-life factory simulation provided by the smart Pilot Factory Industry 4.0 of the Vienna University of Technology. In addition, the control instance of the methodology will bring in precision, due the fact that the chaos and diversity of the real world are limited or even removed.

Survey

The result of the experiment will be further fortified through the mean of a survey. This method is in line with the evaluation patterns for design science suggested by Sonnenberg et al. [43]. It is suggested that the evaluation that occurs after the construction of the artifact, which is called "Ex post" evaluation, could use surveys as a mean of evaluation.

The evaluation has the purpose of showing that the artefact is both useful and applicable. The design criteria should take other factors into consideration, such as applicability, efficiency, effectiveness, similarity to real world situation, as well as symbiosis between the artefact environment and user. Questions in the survey should be made in way that they relate to things like study subjects, experimental settings, artifact characteristics, manipulation procedures, experimental results and the evaluation metrics, according to Mettler et al. [44].

A study where evaluation of an artifact using a survey method was done by Koppenhagen et al. [45]. In this example, the survey was in the form of a questionnaire, using a five-point Likert scale [46]. Based on this, this master's thesis study will also survey the experiment participants in order to provide additional evaluation to the model.

Design Science Environment

Through this state of the art research, the environment part of the design science research method is fulfilled. The environment part of design science identifies the application domain through the people involved, organizational systems as well as technical systems.

The following eligibility criteria are imposed in the selection of the literature:

- The literature has to be written in English
- The literature has to be published between the year of 2010 to 2020
- The literature should propose the usage of tools or devices on a person in order to measure ergonomics values or KPIs
- The literature should include at least one ergonomics assessment standard or method
- The literature should propose an application on a real-life use case or implementation on commercial areas

The following exclusion criteria are imposed after literature are chosen:

- The literature should not be a study involving a virtual reality model or measurement of ergonomics using a virtual model
- The literature should discuss the detail of the technology used by the measurement devices or tools

The search process is done in two phases. The aim of the first phase search is to extract the technology used in general ergonomics measurements using devices. The second phase is to search for ergonomics standards available that are relevant to the measurement techniques.

The literature search is done through Google Scholar. The following keywords are entered: "motion tracking manufacturing" and "real time motion tracking ergonomics". The first 10 pages result of each keyword are then analyzed. After applying the inclusion and exclusion criterion on the title, abstract and full text, the results are filtered down into 33 literatures. These literatures are then classified and categorized based on: years of publication, scientific or commercial papers, implementation area, ergonomics methods, technology used and research facility. After classifying and categorizing based on the technology used, further literature research is done by searching for the technology used as keywords. This process added 8 further literatures, therefore there are a total of 41 literatures that can be identified.

People & Organizational Systems

Based on the literature review above, most of the studies are done in the manufacturing area (56%). Examples of these manufacturing area are the assembly process done by workers in the automotive industry, water pump manufacturing industry and also other general assembly and disassembly operations done by manufacturing workers. Second most common area of study (20%) is done in the area of healthcare. Example of these are operations procedures performed by the doctors. The third most common experiments (17%) are done in the construction area. Common procedures in this area are the typical general lifting, pushing and carrying operations done by the construction's workers. Other area of implementation is for example the dairy industry and in the supermarket sectors.

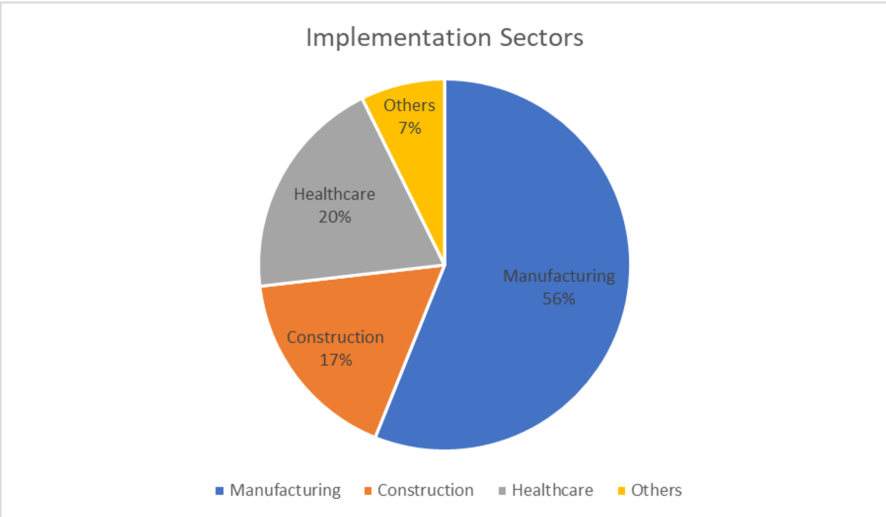


Figure 2.2: Common areas where ergonomics studies are done.

Based on these provided data, the environment component of the design science research method can be built. The relevant actor or people in this area of study are workers, either in the area of manufacturing, construction, health sectors or others who are exposed regularly to the ergonomics situations. The employees or organization that employ these workers are benefiting from the ergonomics studies. They could be the one initiating the studies or just the ones implementing the ergonomics measurements resulted from the study for the sustainable ergonomics or health of the workers.

Technology

One objective of the state of the art review study is to identify the technology used to perform the ergonomics evaluations. Through this study technologies are identified. Sorted from the latest technology to the "ancient" technology these are the technologies identified: Electromyography (EMG), Inertial Measurement Units (IMU), Leap, Kinect, e-Gloves, smartwatch, cameras, ultrawideband RFID, physio meter, sound meter and light meter.

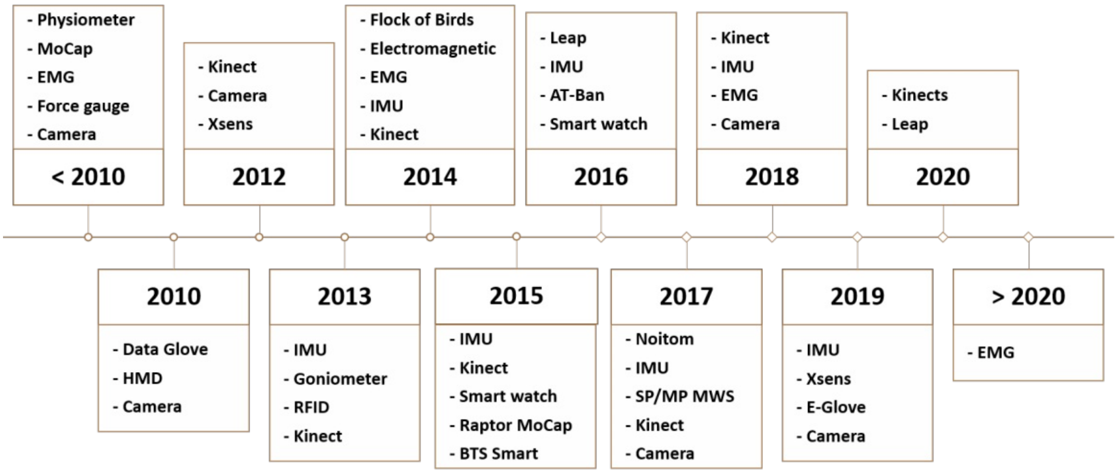


Figure 2.3: Technology Timeline.

2.2 Data Source/Collector Technology

The devices found on the literature review above are listed in this section. These devices function as source of data/data collector either alone or combined together with other devices.

Electromyography (EMG)

The electromyography (EMG) technology has been used to measure ergonomics since 1658. Clarys (2000), [47], mentioned that EMG uses ancient biological measuring techniques and scientific detection. EMG is used to diagnose fatigue, muscle weaknesses and also supports the study in the area of muscular function and muscle coordination through different postures and movements.

The EMG technique is based on the muscle electromechanical coupling phenomenon. The muscle generates electrical signals that will lead to the phenomenon where the muscle will contract through processes. The coupling of the muscle is mediated through biochemical means, which results in different conditions, such as fatigue, duration and motion. The EMG recording is done by picking up electrical potential different between two nodes, commonly using a bipolar electrode configuration. The bipolar electrodes can be in a form of wire or needles electrodes.

Figure 2.4: MyoWare™ Muscle Sensor SEMGs by Advancer Technologies

Source: Advancer Technologies, http://www.advancertechnologies.com/p/myoware.html

In the ergonomics research areas, surface type electrodes are commonly used (sEMG) [48]. Through sEMG signal alterations, muscle fatigue could be identified [49]. This is done through the observation of parameters obtained, such as amplitude, frequency and time dimension.

Current studies show that manual material handling (MMH) from industrial workers could be measured using precision bipolar sEMG sensors [50]. In the supermarket area, a study was done recently in order to analyze working postures and muscular effort during MMH. The sEMG sensors are combined together with Inertial Measurement Units (IMU) from Xsens. [51].

In the area of manual precision tasks, a study was done to identify sustained strenuous postures through trapezius muscles measurement using sEMG [52], combined with cameras. Another study is done in the human body region of pectoralis major/shoulder. SEMGs were used in this study to measure the movement of participants doing movements in back and shoulder [53]. In the health sector, a study was done to health care workers performing pill crushing. SEMGs were used to analyze shoulder and forearm muscles based on work surface heights and the number of pills crushed [54].

Another example from the industry sector, is a study performed to workers wrapping pallets. sEMGs were used and combined together with motion capture optoelectronic infrared cameras to measure the movement of upper arm and the trunk area [55]. A study in the area of automotive assembly was done using a combination of a Right-Angle Power Tool (RAPT) and sEMGs. RAPTs are commonly used to fasten nuts and bolts during automotive assembly process. The objective of the study was to find the right fastening strategy to reduce the physical demand of the worker [56].

Inertial Measurement Unit (IMU)

Inertial Measurement Units (IMUs) are also commonly used in ergonomics assessment. Units can either detect parts of body or work as a full body motion capture solution. The units are usually made available by companies as commercial solutions. Examples of these solutions are products from Xsens, Colibri wireless, generic Degree of Freedom (DOF) boards that could be found for example on a nine-axis motion tracking from Invensense and on a 9-axis IMU from Adafruit, I2M motion tracking and perception neuron. These units are mostly wireless and will send data to their base system. The data can then be extracted and analyzed.

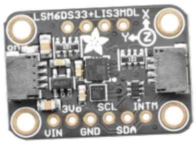


Figure 2.5: 9-Axis IMU by Adafruit

Source: Adafruit, https://learn.adafruit.com/adafruit-9-dof-imu-breakout

One commercial solution that is currently similar to this study is already available in the motion sensor assisting tools market. There is currently a registered trademark solution called motionminers [57]. Motionminers are mobile sensors that can be worn on wrists and belts that can anonymously record various activities. The sensors are inertial measurement units that can collect data, such as hands gestures and vibrations. It is also possible to equip sensors to helping tools, such as forklifts or transport equipment, in order to provide more accurate data. The sensors are not affected by the EU General Data Protection Regulation (GDPR), as the data tracking occurs locally using miniature radio transmitters.

Figure 2.6: IMU by MotionMiners

Source: MotionMiners, https://www.motionminers.com

The chosen technology used for this master's thesis study is the Xsens technology. Details about the tool are discussed in a later section of this study.

Examples of areas where ergonomics studies have been done using IMUs and also IMUs combined with other tools are: industrial manual tasks in a smart factory [58], study in a supermarket sector [59], dairy workers cow milking activity [60], a study in a healthcare sector [61], studies in construction area [62, 63, 64, 65] and in an automotive industry [66].

Leap

The Leap Motion Controller is an optical hand tracking module that captures hands movements. The controller is able to track hands movement within a 3D interactive zone extending up between 60 – 80 cm and extending to 140x120 degrees field of view [67]. The accompanying software is able to identify and track 27 different hand elements, including joints and bones.

The leap motion controller is built with two infrared cameras and three infrared light emitters. It can be categorized as optical tracking systems based on Stereo Vision. The cameras captured the motion hands data and send them back through a USB cable to a proprietary Leap Motion software. Based on a study, a high precision measurement with an overall accuracy of 0.7mm can be achieved [68].

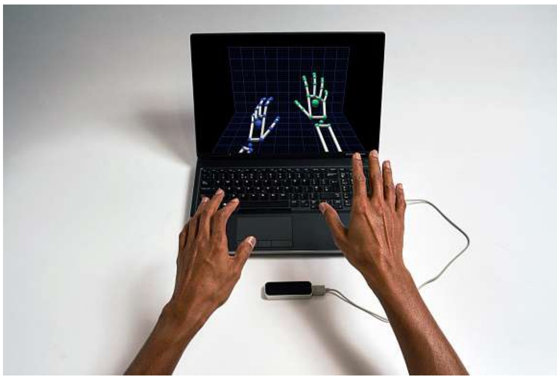


Figure 2.7: Leap Motion Controller by Ultraleap, Inc

Source: Ultraleap, Inc, https://www.ultraleap.com

A study was done using leap motion controller as an information provider tool, providing fingers movement, palm movement and forearm movement. These movements were gathered and analyzed in a form of a game prototype. This game prototype contributed as therapy method for conditions in upper extremity area [69].

Another study was done using leap motion as a tool to capture the movement of the right index finger to point at a certain specific location at a screen. General comfort, finger, wrist, arm, shoulder and neck fatigue are then measured through this experiment [70].

A study in the area of manufacturing was done with a case study on maintenance and disassembly of an industrial gearbox assembly model. In this study, the leap motion controller is used to track the movement of the forearm and calculate the forearm angle. The RULA scale is then used at the end as an ergonomics evaluation method [71].

Kinect

Kinect is a Microsoft product that was released back in 2010. Kinect uses the following hardware infrastructure: 3D depth sensors, RGB cameras and a microphone array. It provides a full-bodied 3D motion capture, a facial and voice recognition capabilities [72]. One of the major features of the Kinect solution is its skeletal tracking feature. Kinect uses per-pixel, body part recognition as an intermediate step in order to determine different human body joints. Due to this advance feature, many studies of ergonomics are done using the Kinect technology alone or combined with other sensor technologies. The latest Kinect technology is called the Azure Kinect.

One study using Kinect not long after the technology was introduced, was done in the area of construction industries. The study involved the analysis of common workers activities, such as standing, squatting, sitting, stooping, bending and crawling in connection to WMSD. Kinect was used to estimate and classify the posture of the workers while doing the activities. A middleware software is used to estimate the pose. The NIOSH ergonomics definition is used in this study to determine the ergonomics violations [73].

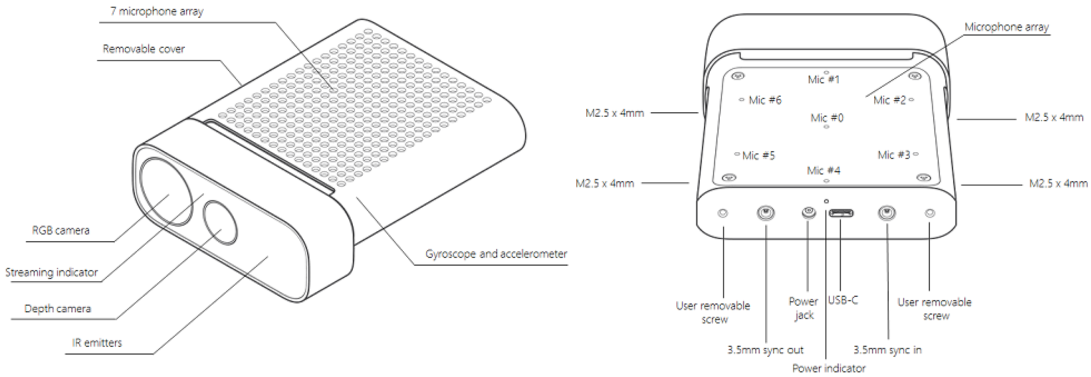


Figure 2.8: Azure Kinect by Microsoft

Source: Microsoft, https://docs.microsoft.com/en-us/azure/Kinect-dk/hardware-specification

There is also a study comparison effort, comparing Kinect with a more sophisticated solution in the area of working ergonomics assessment in the manufacturing area. The high-end system requires reflective markers to be put on the participant's body. The standard ergonomics used was the lifting equation proposed by NIOSH. There were three different activities performed by the workers. The first was coating process of a ceramic product using a spray gun. Second activity was grabbing, lifting and carrying a ceramic plate. The third activity was mounting the bathroom fixture, which includes handling, rotating and moving a product. This process also includes the possibility of bending movements of the worker's body. The study proposed that the low-cost Kinect solution may be successfully used for assessing the risk of the working activities for ergonomics purposes that do not require very high precision. The differences of the assessment from the two different devices are only bounded below 7% [74].

In the same year with the previous experiment, another experiment was done using the Kinect solution combined with a Pebble smart watch and smart phones. The study was done in the health sector, among nurses and health caregivers. The Kinect sensor was used to map the 3D joint positions of the caregiver. The pebble watch was used as an identification tool and also as an accelerometer to measure the movement. The tasks done were activities of patient handling including typical tasks, such as reaching, lifting, pushing, pulling and twisting. A set of ergonomics rules were defined. When a movement violated these rules, the pebble smartwatch will vibrate and show a short text describing the violation [75].

A few years later, there where two experiments in the same year using Kinect technology together with the RULA standard ergonomics evaluation method. One study introduced the implementation of a software tool parallel to the Kinect. The tasks done were the typical standing, kneeling and sitting positions and five most common awkward postures were also included in the experiment. To support the validation effort, an optical motion capture system, composed of 8 infrared digital cameras, was also used in parallel [76].

The second study was a validation study of RULA ergonomics assessment method based on Kinect solution. There were two parts of the study: a lab environment part and a real work condition part. In the lab study, parallel to the Kinect system, a 15-cameras optical motion capture system was used. The participant was equipped with 47 reflective markers to measure the reference postures. The tasks were the common lowering and lifting motions. In the real work study, the experiment was done in a car manufacturing factory. The tasks were done in five different workstations. Here, solely Kinect was used. The result of the study, both in the controlled and real environment, was that the RULA method could accurately assess the RULA score using Kinect [25].

One year later a study was done to an operator performing assembly operations, in a two-sided assembly line, in a European automotive manufacturer. The tasks were done in an assembly workstation. Needed tools and components to be mounted are located on three different trolleys. In this study a hardware-software architecture setting called Motion Analysis System (MAS) was introduced. The MAS architecture adopted the Kinect architecture. The ergonomics standards used in this experiment was OWAS, REBA, RULA, NIOSH and part of EAWS [77].

Recently, there was a study conducted in the area of manufacturing/assembly. The study also proposed an MAS architecture using Kinect, combined with an ad hoc software developed for ergonomics and productive analysis. The experiment took place in a real simulated environment industrial workplace in a university. The workstation replicated a real assembly station designed to assemble industrial water pumps. The ergonomics of the operator, including walking path within the station, hand distribution on the bench and body postures, were analyzed. Ergonomics standards used for this study were OWAS, REBA, NIOSH and EAWS [78].

E-Gloves

Electronic gloves (e-gloves) are commonly hand gloves that are equipped with electronic circuits and sensors. Most of the e-gloves solutions are commercial solutions.

One example is the e-glove from Emphasis Telematics. This e-glove was used together with Xsens sensors and cameras in a study. The study simulated screwing operations, untying knots and carrying operations commonly done in assembly lines. The E-glove sensors in this study sent back the flexion angle of the first three fingers of the right hand and the pressure force on the fingertip of the first three fingers and the right palm of the right hand. The ergonomics assessment methods used in this study was EAWS, RULA, REBA, OWAS and postural evaluation.

An example from the healthcare section, is the usage of the e-glove from CyberGlove. The e-glove is equipped with 18 sensors which could record fingers deviation, distance of the fingers, turning of the thumb and the little finger, extension and flexion of the risk and radial or ulna deviation of the wrist, while doing laparoscopic maneuvers [79]. The ergonomics evaluation method used in this study was the RULA method.

Figure 2.9: CyberGloveIII by CyberGlove Systems

Source: CyberGlove, http://www.cyberglovesystems.com/cyberglove-iii

A study in the area of an electrotechnical industry was once done using an e-glove from ErgoGlove. The selected workload was pinching and gripping operation such as pinch-grip, hook-grip and power-grip, during the electronic assembly of a vehicle front light. The objective of the study was to analyze the exerted force and pressure to the hand and fingers during work activities. The 14 sensors that were attached to the glove sent out measured pressure data using a Bluetooth system to a PC [80].

A study of low-cost-designed wearable e-glove was once done using Force-Sensitive Resistor (FSR) sensors. These sensors were attached to conductive materials, which were then connected to a controller. The placement of the sensors was strategically chosen on a region of the hand that are exposed to the object of the study. The experiment simulated the door assembly in a vehicle manufacturer. The ergonomics standard used in this study was the EAWS evaluation [81].

There are other technologies that are used in the studies of ergonomics. For example the use of a higher-end motion capture performance camera Raptor 12HS from motion analysis. This camera was used in a study in a healthcare sector [82]. Another example of a study in the healthcare sector, was the usage of Flock of bird or trakSTAR / driveBAY Electromagnetic transmitter from Ascention Technology Corporation [83]. An ultrawideband RFID technology was once used for a study in a construction sector [84]. A study in a workplace situation was once done using a physiometer [85]. And a study in a manufacturing shop floors was once conducted using the help of a sound meter and a light meter [86].

2.3 Ergonomics Standards

The second phase of the search involves using the keywords found in the classification of ergonomics methods column from the first phase search. These keywords are: KIM, OWAS, RULA, REBA, NIOSH and QEC.

The Key Indicator Method (KIM) of ergonomics assessment [87] will be used as the foundation/starting point of the model that is produced in this study. The KIM method chosen is the KIM variant to assess physical workload during manual handling operations and the assessment is divided into three steps. The first step is the determination of time rating points. Step two is the determination of the rating points for the type of force exertion, gripping conditions, work organization, working conditions, posture and hand/arm position and movement. The last step is the evaluation and assessment step.

This method assesses activities involving load on finger-hand-arm area when doing manual jobs. The activities are typically identified through frequent repetitions of similar tasks which require attention to small details. The method conducts an evaluation on the most important work requirements combined with the level of the total physical load situation. The final score of the assessment shows the risk score of the activity. The higher the score, the more risks are available.

As it is prescribed in the KIM-MHO assessment sheet, the boundaries between the risk ranges are fluid [88]. Thus, the observer or company, could raise or lower the limit according to the worker conditions inside the company. As an example, when it is assumed that the score of less than 20 in the range score is the limit of a particular activity that can be carried out safely by workers, another 5 points could be added to the safe limit to create a buffer for more trained and fit workers. Therefore, scores above

25 will mean a slightly increase in risk of physical overload, which will have an effect on workers' health condition.

The OVAKO Working posture Assessment System OWAS [89] analyzes body postures during working processes and rate them based on the caused strains. OWAS identifies most common body regions (e.g., backs, arms, legs). These regions are evaluated using postures, such as straight, bending forward, straight and twisted, bent and twisted, against a particular load weight. The result will show whether a corrective action should be taken any time soon or immediately.

The Rapid Entire Body Assessment (REBA) [90], divides the body regions into two analysis areas, neck-trunk-leg and arm-wrist analysis. Each area is further divided into different steps that can be scored. The scores are added up, with low scores corresponding to a negligible risk and high scores to high risks for the workers.

Another assessment method is the Rapid Upper Limb Assessment or RULA [26]. RULA offers more thorough body region assessment, including the differentiation between the left and right body regions.

The National Institute of Occupational Safety and Health or (NIOSH) [91], came up with the calculation of Composite Lifting Index (CLI), thus, creating a Recommended Weight Limit (RWL). These calculations were invented to assist the localization of ergonomic approaches for reducing injuries associated with manual lifting.

The Quick Exposure Check (QEC) [92], assesses activities from both the observer's and worker's view. This method takes the worker's experience into consideration. The observer's assessment divides the body region into back, should/arm, wrist/hand and neck, whereas workers are interviewed on their experiences when performing the tasks.

In addition to these global assessment methods, individual countries also issue their own assessment standards. United States, for example, has a patent on the method and system for ergonomic assessment and reduction of workplace injuries introduced in 2005 [93].

Problems and opportunities

Based on this review, which only considers literatures in the English language, the trend of ergonomics assessment methods, commonly uses RULA, REBA, NIOSH or EAWS. Studies using KIM assessment method are still lacking. Most of the studies never reveal how much and how long a person could perform a certain task until an ergonomic incident/hazard occurred or is claimed. Therefore, an ergonomic study, using KIM as an assessment method, combined with current and validated [94, 95, 96, 97] IMU sensors device technology from Xsens, could fill in the gaps and contribute to the study of ergonomics with an application in the manufacturing industry. This is what the study will attempt to do. Through the Xsens IMUs, it is expected that the threshold data could be delivered and later analyzed to show a threshold range of how much and how long a person can last without having any ergonomics-related complaints.

In the area of ergonomics design model, a model from Elbert et al. [98] is used as a base for the model that can be adapted or adjusted out of this study. This model takes into consideration a worker, a task, the design of the workstation, the work posture and the work activities. All of these factors should be approached using a holistic approach. These factors should support each other in order to achieve the well-being status, which, in the end, could lead to better output performance. This study will take this model into close consideration.

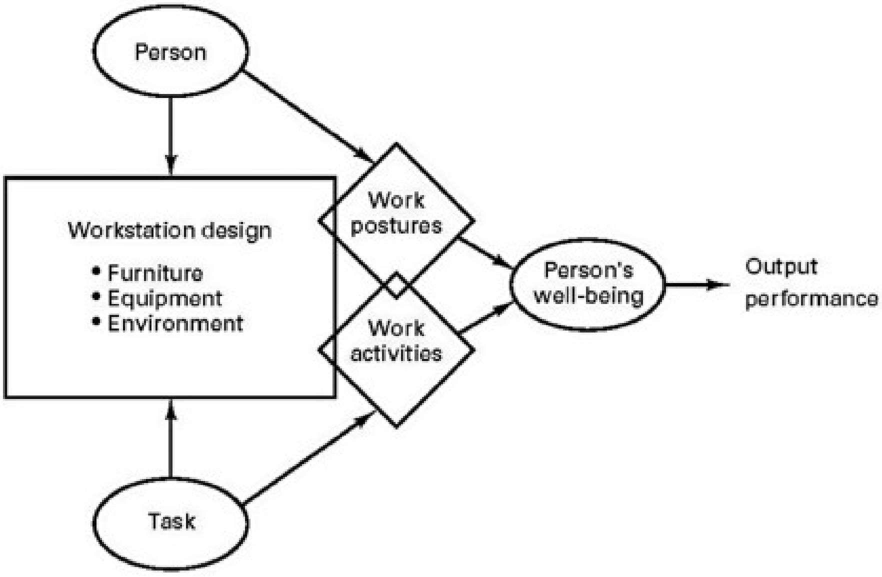


Figure 2.10: Holistic workstation model from Elbert et al. (2018)

CHAPTER 3

Theoretical Insights

The aim of this chapter is to introduce the supporting theories used in the study. The chapter will first describe the occupational safety and health theories in manufacturing industry sectors. Next, it will provide work-related musculoskeletal disorders (WRMSD) insights. The Pilot Factory Industry 4.0 will be portrayed in this chapter as a simulation of real assembly lines. Further on, risk assessment standards that are commonly used in the area of manufacturing will be explained. The motion sensors technologies theory will also be discussed in this chapter. The last section of this chapter will describe the theory on requirement specification needed, to develop a proper software application for this study.

3.1 Occupational Safety and Health in Manufacturing Industries

The Occupational Safety and Health (OSH) principles especially in the area workplace design, based on ILO recommendation [99] should be introduced, adopted and maintained in manufacturing industries [100]. Industries would benefit from healthy and incidents/accidents free workers, which will result in less absent days of workers or being away from work. As a result, steady or even an increase in sustainability and production can be expected. From a worker's point of view, being healthy will lead to better well-being and satisfaction [101].

The World Health Organization (WHO) recognizes the correlation between working conditions and health. Studies done by WHO shows that occupational diseases and other health issues could be caused by health hazards at workplace [102]. One of the most common occupational diseases identified is musculoskeletal disorders.

The International Labour Organization (ILO) also recognizes the importance of occupational injuries and diseases in workplaces. ILO takes measures to ensure and protects workers health conditions in their workplace through conventions C155, C161, C187 and recommendation 197 [103, 104, 105, 106].

Even though precautions are taken in many factories, injuries, incidents and accidents still happen, especially in the area of manufacturing [107]. Typical health issues that are common to occur in the area of manufacturing are upper-body, neck pain, back pain, fatigue and hand or arm soreness [108]. In one of many cases in electronics industries, most of the occupational ergonomics hazards observed on 7610 workers, are in the area of backache, and musculoskeletal system strains, which are caused by repetitive tasks performed in the assembly lines [109]. Other cases show pains and cuts in the fingers area due to missing helping tools to perform the needed tasks [110].

Another study involving 906 workers shows problems in lower back, lower limbs, neck, shoulders and upper back body area, which also involves performing repetitive tasks [111]. Another study in the area of electronics assembly industry back in the early 80s, shows that a high percentage of workers' pains are in the area of the neck region [112].

Both WHO and ILO as well as authorities and agencies at the national level, agree that the health of workers should be promoted and protected through controlling and preventing occupational diseases and accidents. The primary prevention method to achieve this is through the elimination of hazardous conditions to health and safety at work.

3.2 Work-related Musculoskeletal Disorders: definition, cause, effect, prevention

Per definition of US Centers for Disease Control and Prevention's (CDC), Musculoskeletal disorders (MSD) are injuries or disorders of body parts particularly in the area of muscles, nerves, tendons, joints, cartilage, and spinal discs. Related to this study in general, work-related musculoskeletal disorders or also known as (WRMSD), are the disorder conditions that are significantly caused by the work environment and the performance of work, or these conditions persist longer or made worse by the work conditions [113].

According to WHO International Classification of Diseases (commonly referred to as ICD-9) 353-355, 722-724, and 726-729 [114], the most common WRMSDs are low back pain, shoulder-neck pain, carpal tunnel syndrome. These conditions are affected from work factors and biomechanical [115]. Studies were done in the area of intervention and prevention.

Prevention of MSDs can be done through evaluations, for example, evaluating lifting tasks and evaluating highly repetitive manual tasks and also through engineering controls [116]. Preventions are done in ways that tasks should be designed with the objective of ensuring stresses will not cause back injuries or shoulder and neck pains, also by introducing new helping tools. These steps could also be outlined as engineering redesigns [117]. Another way to prevent MSDs is to introduce proper workplace design in order to reduce the risk of cumulative trauma disorders [118].

In the area of intervention studies, effects of MSDs are evaluated by affecting the work conditions [119]. These can be done through two ways, standard experimental paradigm and before-and-after paradigm. In order to align with the effort of MSDs prevention, an ergonomics study is best done in a simulated, realistic enhanced pilot factory. However, prior to implementing any interventions, an evaluation plan should be developed.

3.3 Commonly used Risk Assessment Standards

In order to evaluate the previously mentioned ergonomics hazards, the following common ergonomics evaluation methods are taken into further consideration: KIM, RULA, REBA, OWAS.

KIM

KIM, which stands for Key Indicator Methods, can be seen as screening tools [120]. KIM which in German language is called "Leitmerkmalmethode" was founded by the German Federal Institute for Occupational Safety and Health in 2012 [88]. KIM identifies the structural deficits of a workplace ergonomics design. At the same time, delivers measurement that can potentially contribute to reduce the risks of workplace health hazards [121]. KIM comprehensively evaluate manual pushing, pulling, lifting, holding, carrying of loads and also other manual handling operations. It evaluates awkward body postures and body movements, as well as whole-body forces.

Based on other relevant study, the KIM that fits perfectly to our study is the so-called KIM for assessing and designing physical workloads during Manual Handling Operations (KIM-MHO) [122]. Typical activities that are suitable to be measured with this evaluation methods are assembly tasks of electrical appliances such as soldering, joining, shifting, pressing, lifting and holding. The tasks are done either using small helping tools/instruments or hand-guided machines. The workers are in sitting or standing stationary working positions. Tasks are mostly processing a working object or handling small-light objects with a weight of a maximum of three kilograms. [123]. As it was previously mentioned, many of the industry in the area of electronic manufacturing have uniform, repetitive motions in their tasks. The body parts that are affected by force are the upper extremities [111]. The weight range is also corresponding to the lowest approximation done by Health and Safety Executive of the United Kingdom for female workers [124].

The KIM assessment form is composed of many sections. At the very beginning of the form, the workplace/sub-activity/task description, duration of the working day, duration of the task, evaluator's name and the date are to be filled. The evaluation is further divided into three steps. The first step is the determination of time rating points, followed by the determination of time rating points for other indicators. The third step is the evaluation and assessment.

The determination of time rating points takes into consideration how many hours in total a particular task is executed per working day, also taking the repetition of the tasks into consideration. The more hours are repeated for this task, the more points will be given in this section.

KIM for assessing and designing physical workloads during Manual Handling Operations (KIM-MHO)

Workplace/sub-activity:			
Duration of the working day:		Evaluator:	
Duration of the sub-activity:		Date:	

1st step: Determination of time rating points

Total duration of this sub-activity per working day [up to … hours]	up to 1	2	3	4	5	6	7	8	9	10
Time rating points:	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

2nd step: Determination of the rating points for other indicators

Type of force exertion in the finger/hand area within a "standard minute"		Holding[1)]			Moving				
		average holding time [sec. per minute]			average movement frequencies [number per minute]				
		31-60	16-30	≤ 15	< 5	5-15	16-30	31-60	61-90[3)]
Level	**Description, typical examples**	Rating points			Rating points				
low	**Very low / low forces** (up to 15% $F_{max}M$) e.g. button actuation / shifting / ordering / material guidance / insertion of small parts	**5.5**	**3**	**1.5**	**0.5**	**1**	**2.5**	**5**	**7**
	Moderate forces (up to 30% $F_{max}M$) e.g. gripping / joining small work pieces by hand or with small tools	**9**	**4.5**	**2.5**	**0.5**	**2**	**4**	**7.5**	**11**
	High forces (up to 50% $F_{max}M$) e.g. turning / winding / packaging / grasping / holding or joining parts / pressing in / cutting / working with small powered hand tools	**14**	**7**	**3.5**	**1**	**3**	**6**	**12**	**18**
	Very high forces (up to 80% $F_{max}M$) e.g. cutting involving major element of force / working with small staple guns / moving or holding parts or tools	**22**	**11**	**5.5**	**1.5**	**5**	**10**	**19**	
	Peak forces[2)] (more than 80% $F_{max}M$) e.g. tightening, loosening bolts / separating / pressing in	**100**		**35**	**8**	**30**	**100**		
high	**Powerful hitting**[2)] with ball of the thumb, palm of the hand or fist				**8**	**30**			

The work cycle must be observed and the rating points for the force categories marked. Added (left and right hands separately), these produce the force rating point. To calculate the total score (step 3), the higher value must be used.

Rating points of force exertion:	Left hand	Right hand

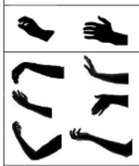
1) The amount of time of holding work is only considered as such in the assessment if one arm is held continuously statically for at least 4 seconds!
2) Please note: If one of these categories was chosen, it is recommended to evaluate this sub-activity also using the KIM-BF! These forces might not be exerted at all or might no longer be exerted reliably. This applies to women in particular.
3) In case of even higher frequencies, the resulting risk score must be extrapolated linearly or the E version (KIM-MHO-E) must be applied.

Figure 3.1: KIM assessment sheet containing the basic information fields, assessment of time rating points and rating points for other indicators.

The first evaluation on the next step is the rating points for other indicators section. Measurements are done in regards to force exertion in the hand or finger area with the measurement time of within a standard minute. Force is to be observed from very low, as in actuating a button, ordering or insertion of small parts, high forces, as in turning, winding, holding and working with small powered hand tools, up to the use of powerful hitting with body parts, such as thumb, palm of hand or even fist. Force exerted are then further classified into holding or moving. Movements are identified as the move before one arm is holding continuously and statically for at least four seconds. Furthermore force exertion will be differentiated for the left and the right hand.

Still on the second step, the next evaluation is the gripping conditions and the force transfer. Points are given while evaluating whether forces transfer are optimum, restricted or hindered and whether working objects are easy to grip, not easy to grip or rather hard to grip. The next evaluation is the position of the arm or the hand. This part evaluates the wrist joints between the hand and arm in regards to movements and how often the movements are. Lower points are given to good position or movements where joints are in the relaxed range. Higher points are given when movements of the joints are at the limit ranges and movements are more often. Most points are given when the movements are constant or, at worse constant positions of the static arm posture.

Force transfer / gripping conditions	Rating
Optimum force transfer/application / working objects are easy to grip (e.g. bar-shaped, gripping grooves) / good ergonomic gripping design (grips, buttons, tools)	0
Restricted force transfer/application / greater holding forces required / no shaped grips	2
Force transfer/application considerably hindered / working objects hardly possible to grip (slippery, soft, sharp edges) / no or only unsuitable grips	4

	Hand/arm position and movement[4]	Rating points
	**Good**: position or movements of joints in the middle (relaxed) range, only rare deviations / no continuous static arm posture / hand-arm rest possible as required	0
	Restricted: occasional positions or movements of the joints at the limit of the movement ranges / occasional long continuous static arm posture	1
	Unfavourable: frequent positions or movements of the joints at the limit of the movement ranges / frequent long continuous static arm posture	2
	Poor: constant positions or movements of the joints at the limit of the movement ranges / constant long continuous static arm posture	3

[4] Typical positions are to be considered. Rare deviations can be ignored.

Unfavourable working conditions (specify only where applicable)	Rating points
Good: there are no unfavourable working conditions, i.e. reliable recognition of detail / no dazzle / good climatic conditions	0
Restricted: occasionally impaired detail recognition due to dazzle or excessively small details difficult conditions such as draught, cold, moisture and/or disturbed concentration due to noise	1
Unfavourable: frequently impaired detail recognition due to dazzle or excessively small details frequently difficult conditions such as draught, cold, moisture and/or disturbed concentration due to noise	2

Indicators not mentioned in the table are to be taken into account accordingly.

Figure 3.2: KIM assessment sheet containing the assessment of body posture/movement and work organisation or temporal distribution.

The KIM does not only take workers' body into consideration, but also the surrounding conditions. The next conditions that are evaluated are the working conditions. It takes into consideration whether there are no unfavorable conditions such as no dazzle, perfect working temperature. More points are given when the conditions are sometimes impaired due to dazzle or restricted conditions due to difficulties such as cold, moist, wind draft, or when tasks are disturbed due to noises. Most points are given when conditions are unfavorable, and, due to these factors, tasks are difficult to be completed.

The KIM evaluates the worker's body posture and movement. The next evaluation emphasizes the body posture, especially the lower back, lower limbs, trunk, upper back and also the head and neck regions. No points are given when tasks are done in alteration between sitting and standing, when trunk posture is inclined forward, or when the head not is inclined backward or more to the front. More points are given when alteration between sitting and standing are less, trunks and heads or necks are inclined into deviated positions, or when hands and arms are raised above the shoulder in order to reach up or gripping objects that are further away from the body. Most points are given when the trunk is severely inclined, twisted or bended into a deviated position, tasks being done while kneeling, squatting or lying down, head and neck are constantly deviated from neutral position, or when gripping above shoulders are done constantly.

The last evaluation on this step is also an evaluation that does not involve the worker's body directly. KIM evaluates the work organization and temporal distribution in regards to the variation of the tasks being done. The work organization is considered to be

Body posture/movement[5) 6)]	Rating points
- Alternation between sitting and standing, alternation between standing and walking, dynamic sitting possible - Trunk inclined forward only very slightly - No twisting and/or lateral inclination of the trunk identifiable - Head posture: variable, head not inclined backward and/or severely inclined forward or constantly moving - No gripping above shoulder height / no gripping at a distance from the body	0
- Predominantly sitting or standing with occasional walking - Trunk with slight inclination of the body towards the work area - Occasional twisting and/or lateral inclination of the trunk identifiable - Occasional deviations from good "neutral" head posture/movement - Occasional gripping above shoulder height / occasional gripping at a distance from the body	2
- Exclusively standing or sitting without walking - Trunk clearly inclined forward and/or frequent twisting and/or lateral inclination of the trunk identifiable - Frequent deviations from good "neutral" head posture/movement - Head posture hunched forward for detail recognition / restricted freedom of movement - Frequent gripping above shoulder height / frequent gripping at a distance from the body	4
- Trunk severely inclined forward / frequent or long-lasting bending - Work being carried out in a kneeling, squatting, lying position - Constant twisting and/or lateral inclination of the trunk identifiable - Body posture strictly fixed / visual check of action through magnifying glasses or microscopes - Constant deviations from good "neutral" head posture/movement - Constant gripping above shoulder height / constant gripping at a distance from the body	6[7)]

5) Typical body postures are to be taken into account. Rare deviations can be ignored.
6) If the manual handling operations are not carried out in a stationary sitting, standing, kneeling, squatting, lying position, but in motion (walking, crawling), it is recommended to evaluate the sub-activity also using the KIM-BM.
7) Please note: If this category was chosen, it is recommended to evaluate this sub-activity also using the KIM-ABP!

Work organisation / temporal distribution	Rating points
Good: frequent variation of the physical workload situation due to other activities (including other types of physical workload) / without a tight sequence of higher physical workloads within one type of physical workload during a single working day.	0
Restricted: rare variation of the physical workload situation due to other activities (including other types of physical workload) / occasional tight sequence of higher physical workloads within one type of physical workload during a single working day.	2
Unfavourable: no/hardly any variation of the physical workload situation due to other activities (including other types of physical workload) / frequent tight sequence of higher physical workloads within one type of physical workload during a single working day with concurrent high load peaks.	4

Figure 3.3: KIM assessment sheet containing the rating of force transfer, hand position and movement and also working conditions.

good when the physical workloads vary frequently, due to alteration with other activities, during a single working day. More points are given when the variations are rare and sequences of high physical loads are more frequent in a single working day. Most points are given when the temporal distribution is unfavorable. This is the condition when there are no, or hardly any variations in the physical workload situation in regards to other activities and the sequence of the physical workload tasks are frequent and tight between a single working day.

3rd step: Evaluation and assessment

	Type of force exertion in the finger/hand area	
	Force transfer / gripping conditions	+
	Hand/arm position and movement	+
	Unfavourable working conditions	+
	Body posture	+
	Work organisation / temporal distribution	+
Time rating points x	Total of indicator rating points:	= Result

Figure 3.4: KIM assessment sheet containing the calculation fields where all sections are added up and multiplied by the time rating points.

The last step in the KIM assessment method is the evaluation and assessment method. At this stage, the rating points or scores from the second step are added up and consolidated. The sum of second step is multiplied with the first step, which is the time rating points. which will give out the total result indicator rating points that can be matched against an assessment table.

The risk score calculated and the table below can be used as the basis for a rough evaluation:

Risk	Risk range		Intensity of load*)	a) Probability of physical overload b) Possible health consequences	Measures
	1	< 20 points	low	a) Physical overload is unlikely. b) No health risk is to be expected.	None
	2	20 - < 50 points	slightly increased	a) Physical overload is possible for less resilient persons. b) Fatigue, low-grade adaptation problems which can be compensated for during leisure time	For less resilient persons, workplace redesign and other prevention measures may be helpful.
	3	50 - < 100 points	substantially increased	a) Physical overload is also possible for normally resilient persons. b) Disorders (pain), possibly including dysfunctions, reversible in most cases, without morphological manifestation	Workplace redesign and other prevention measures should be considered.
	4	≥ 100 points	high	a) Physical overload is likely. b) More pronounced disorders and/or dysfunctions, structural damage with pathological significance	Workplace redesign measures are necessary. Other prevention measures should be considered.

*) *The boundaries between the risk ranges are fluid because of the individual working techniques and performance conditions. The classification may therefore only be regarded as an orientation aid. Basically, it must be assumed that the probability of physical overload will increase as the risk scores rise.*

Figure 3.5: KIM assessment sheet containing the final scoring of the assessment

The assessment table are classified into 4 risk section with the first/lowest range comprising of points less than 20, the load intensity is low, there is an unlikely event of physical overload and no health risks are to be expected from the tasks. No measures are needed to be taken for this risk range. The next risk range is range level 2 with the points range from 20 until less than 50, where the load of intensity is slightly increased or moderate. Physical overload and fatigue can be expected for less resilient workers, which can be compensated by leisure time. The measures that should be taken are workplace redesign initiatives or other measures that are helpful. The third risk range where the intensity of load is substantially increased are in the range of 50 to less than 100 points. At this range, physical overload can be also observed for normally resilient workers. Reversible body parts dysfunctions and disorders/pains without morphological manifestation could be observed. The preventive measures that should be taken are consideration of preventive measures and workplace redesign. The highest risk range is anything above 100 points. At this stage, the intensity of load is high and physical overload will happen, which could lead to body disorders, dysfunctional or even further structural damage with pathological significance. The preventive measures that have to be taken immediately are workplace redesign and other preventive measures.

RULA

The Rapid Upper Limb Method (RULA) is a survey method that was proposed in 1993 [26]. This evaluation method is suitable for this study as it emphasizes on the evaluation of the upper limb area. The objective of this survey method is to “rapidly” evaluate the exposure of working population to work-related upper limbs disorders. The method also identifies muscular effort that contributes to muscular fatigue. The RULA assesses the postures of upper limbs along with muscle functions, external loads experienced and also trunk and neck. Same as the previous method, no special equipment is needed to do the evaluation. Through a coding system, an action list, which consists of intervention measures required to reduce the hazards of injury in working place due to physical actions, are created. These measures should then be applied in order to prevent work-related disorders in the area of upper limb of the workers.

The RULA worksheet is divided into three sections, Part A on the left, scores in the middle, and Part B on the right.

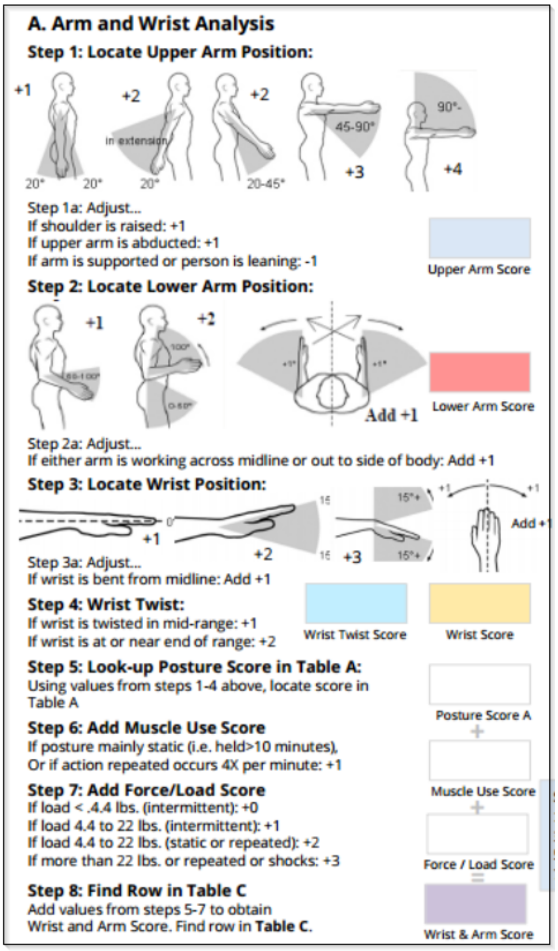


Figure 3.6: RULA part A, analysis of arm and wrist.

Part A evaluates the arm and wrist. The first step is to locate the position of the upper arm. Scores are given according to how great the angle of flexion or extension of the upper arm. Adjustments are needed when shoulder is raised and the upper arm is abducted and also when the arm is supported. The second step is to locate the lower arm position. Again, the angle of elevation of the lower arm is measured. Adjustment is needed when either arm is working out to side of body or across midline. The third step locates the position of the wrist, whether the wrist is on flexion or extension, the angle will be measured. Adjustment should be made if wrist is bent from midline. The fourth step is to evaluate wrist, whether twisted in mid-range or at near end of range. The fifth step is to consolidate the postures score from step 1 to step 4 and match the score that is listed on Table A in the score section. In addition to body parts evaluation RULA also includes the measurement of muscle at step 6, whether posture is mainly static or a repetition of actions occurred. Force or load is measured at step 7 where load is classified by its weight. The last step of part A is to find the wrist and arm score by adding up scores from step 5, 6 and 7 and obtaining the matching score from Table C on the score section.

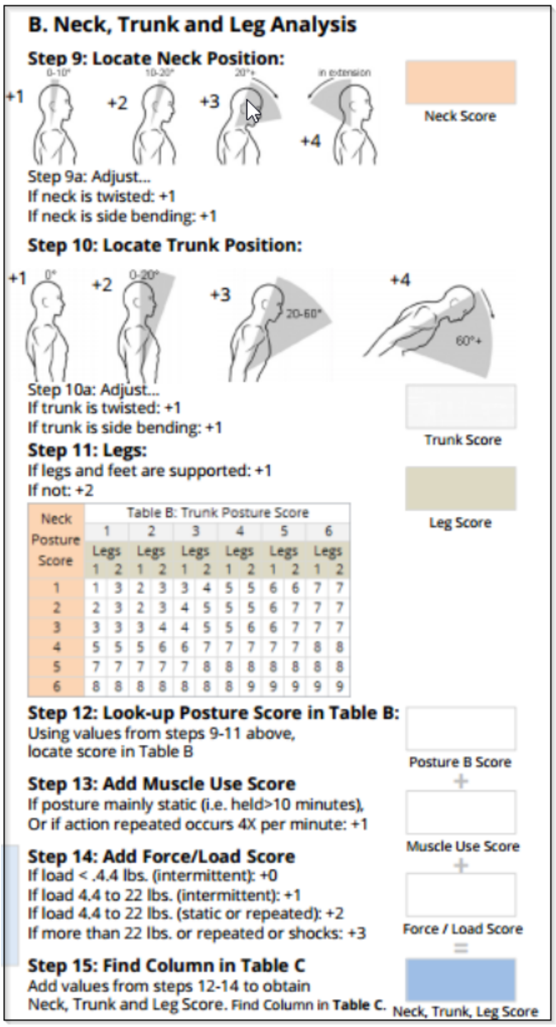


Figure 3.7: RULA part B, analysis of neck, trunk and leg.

Part B is the analysis of neck, trunk and leg. The first step in part B, continuing from the previous part A is step 9, where neck positions are observed. The angle of head and neck extension and flexion are measured. Adjustment shall be made when neck is twisted and bended to the side. The next step is to locate the trunk position. The angle of trunk flexion will be measured. Adjustment should be made when the trunk is twisted or bended to the side. Step 11 will evaluate the legs of the workers, whether the legs are supported or not. Step 12 will use the scores from 9 to 11 and matched against table B. Similar to the previous part A, muscles, and force are measured subsequently in step 13 and 14. The final step, step 15 is the sum of steps 12 to 14. This score, combined with the score from wrist and arm will be checked against the table C, and the result will be the final RULA score.

Scores

Table A		Wrist Score 1		2		3		4	
		Wrist Twist		Wrist Twist		Wrist Twist		Wrist Twist	
Upper Arm	Lower Arm	1	2	1	2	1	2	1	2
1	1	1	2	2	2	2	3	3	3
	2	2	2	2	2	3	3	3	3
	3	2	3	3	3	3	3	4	4
2	1	2	3	3	3	3	4	4	4
	2	3	3	3	3	3	4	4	4
	3	3	4	4	4	4	4	5	5
3	1	3	3	4	4	4	4	5	5
	2	3	4	4	4	4	4	5	5
	3	4	4	4	4	4	5	5	5
4	1	4	4	4	4	4	5	5	5
	2	4	4	4	4	4	5	5	5
	3	4	4	4	5	5	5	6	6
5	1	5	5	5	5	5	6	6	7
	2	5	6	6	6	6	7	7	7
	3	6	6	6	7	7	7	7	8
6	1	7	7	7	7	7	8	8	9
	2	8	8	8	8	8	9	9	9
	3	9	9	9	9	9	9	9	9

Table C		Neck, Trunk, Leg Score 1	2	3	4	5	6	7+
Wrist / Arm Score	1	1	2	3	3	4	5	5
	2	2	2	3	4	4	5	5
	3	3	3	3	4	4	5	6
	4	3	3	3	4	5	6	6
	5	4	4	4	5	6	7	7
	6	4	4	5	6	6	7	7
	7	5	5	6	6	7	7	7
	8+	5	5	6	7	7	7	7

Scoring: (final score from Table C)
1-2 ▪ acceptable posture
3-4 ▪ further investigation, change may be needed
5-6 ▪ further investigation, change soon
7 ▪ investigate and implement change

RULA Score

Figure 3.8: RULA scoring table.

Scores table in the middle will act as a check table where matching scores should be read horizontal against vertical and the product matrix will be the result. The final RULA score is divided into 4 ranges, where the least points mean the posture and task is acceptable, next ranges are where further investigations are needed, and either change is needed or soon, and the last range of scoring is when investigation is needed and changes should be implemented.

REBA

Rapid Entire Body Assessment (REBA), was proposed in 2000, seven years later after RULA [90]. The REBA evaluations work with the same principle as the RULA method, with the objective of rapidly evaluating the risk of MSDs. REBA goes even further by taking more body parts into consideration. The concept and design are the same as the RULA method. The sheet is also divided into two parts and score tables.

The difference between the REBA and the RULA methods is that REBA takes legs evaluation into more details by measuring if the legs are standing properly, if one leg is raised, or if the knees are bent in particular angles. The REBA also includes coupling scores in one of its steps. The coupling score evaluates whether items or tools are easy to grip or hold, acceptable in handling or even awkward or unsafe with any body part.

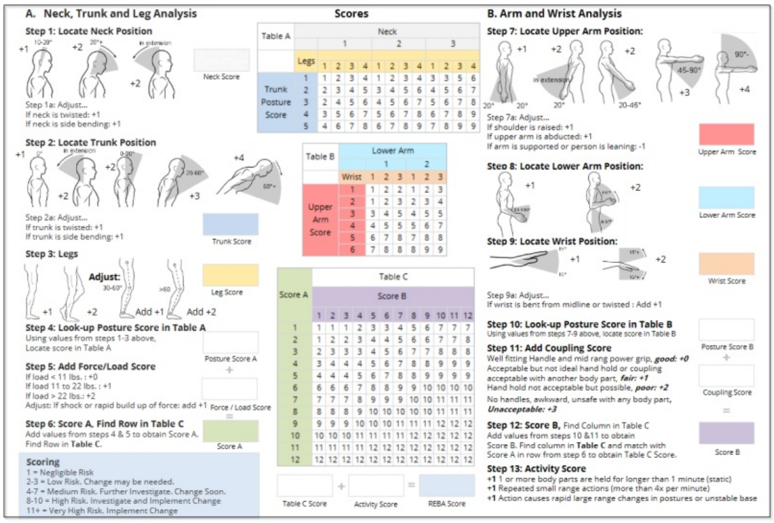


Figure 3.9: REBA assessment sheet containing part A, neck, trunk and leg analysis, scores table and part B, arm and wrist analysis.

One other step that is evaluated further by the REBA is the activity score. In this evaluation, the holding of items by one or more body parts is evaluated. This is done by determining if there is a repetition in actions taken or the actions taken causes large rapid changes in body posture. The scoring of the REBA is divided into five ranges. The first range could be interpreted that the risk is negligible. The next range is the low risk range, where change could be needed. The third risk is the medium risk, where further investigation is needed and change is soon to be implemented. The high risk shows that investigation is immediate and changes could be implemented, whereas in the very high-risk, implementation of changes is immediate and unavoidable.

OWAS

Ovako Working posture Assessment System (OWAS) was invented in Finland's industrial sector back in 1973 [89]. The objective of this assessment method is to identify the stress on the musculoskeletal system by identifying the time and frequency spent in body postures on specific tasks. The situation is studied and evaluated in order to recommend corrective action measures.

The OWAS evaluation sheet is divided into six sections. The first section describes the task identification and the actual task description. This section also lists the percentage of time spent in this task. The next section is the evaluation of the back posture. The back area is identified through 4 postures and evaluated whether it is straight, bent, twisted or both bent and twisted. The next section evaluates the arms with three postures.

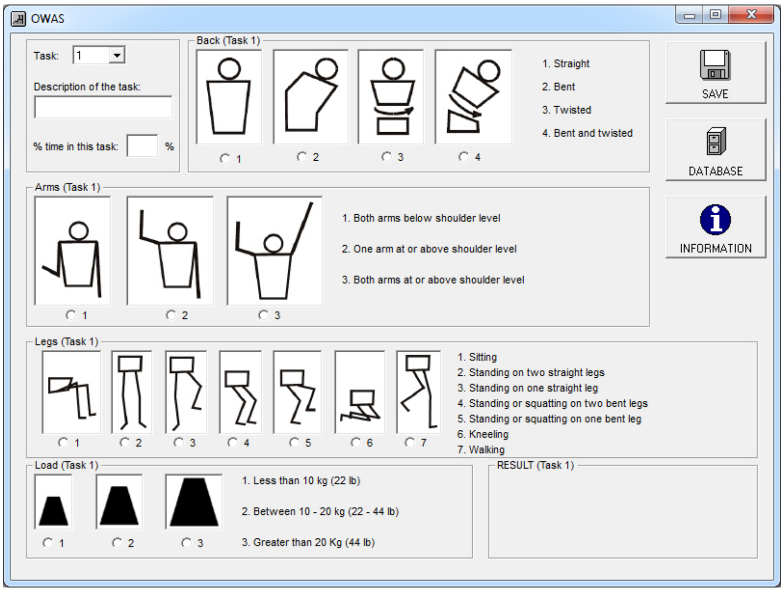
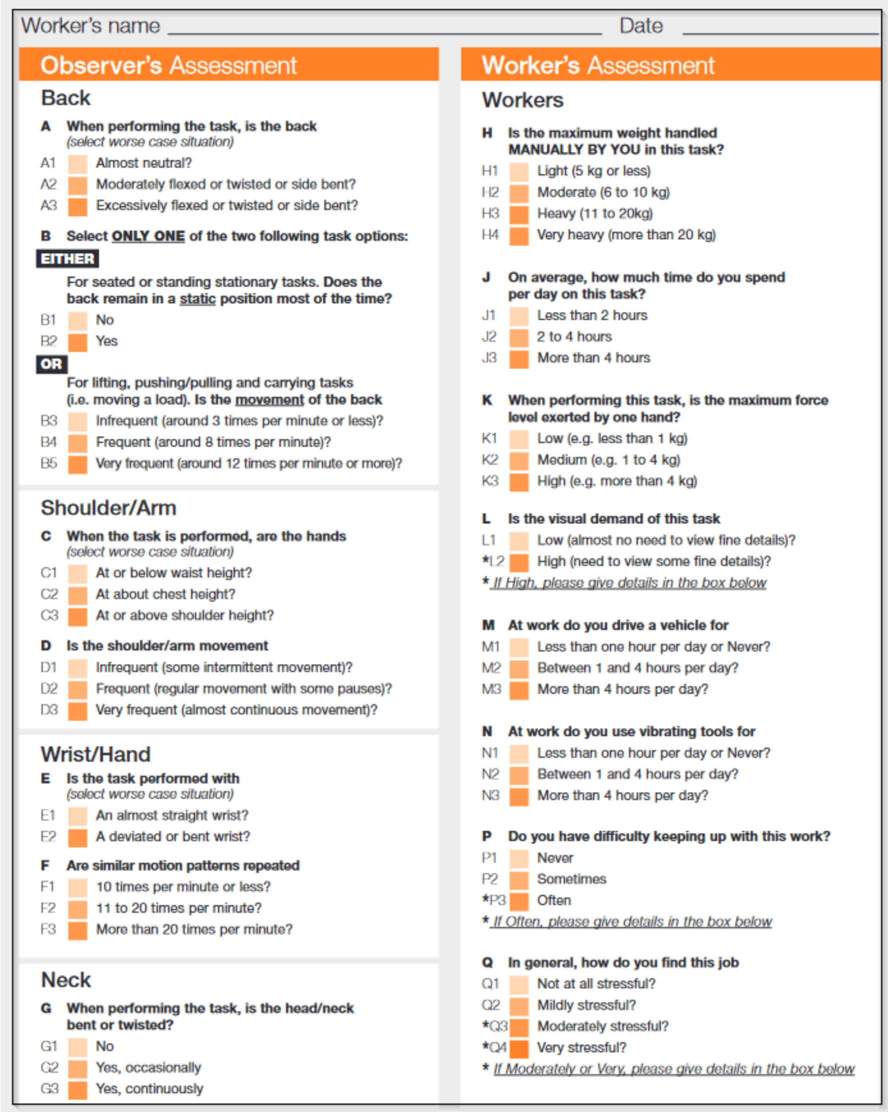


Figure 3.10: OWAS assessment sheet containing assessment of back, arms, legs and load.

The evaluation differentiates whether arms are below shoulder level and one, or both arms, at, or above, the shoulder level. The next evaluation section is the legs with seven postures. It evaluates whether the person is sitting, standing on one, or two legs straight or standing or squatting on one or both bent legs. It also evaluates whether the person is either kneeling or walking. In addition to the body posture, the evaluation also takes load into consideration. It evaluates whether load is less than 10 kg, between 10 and 20 kg, or heavier than 20 kg into three categories. At the end the code given on this evaluation is combined, categorized and checked against preventive measures. There are four action categories. First is where the postures are normal and no special attention is required. The next category is where postures must be examined. The category after is when examinations are required within a due time. The last category is when re-examination and modification rather urgent and immediate.

QEC Quick Exposure Check (QEC) was developed back in 1999 [92]. The objective is to enable safety and health practitioners to evaluate tasks by assessing the exposure of a worker to musculoskeletal hazard factors. It has been designed to identify the increase in exposure to musculoskeletal risks in the posture area of neck, shoulders, back, wrists, hands and arms. The assessment is valid both before and after an ergonomic intervention. The evaluation involves the observer which this case is the practitioner and the person who is actually executing the task. It could also indicate the shift in exposure scores after an intervention. The QEC primarily assess the physical factors of the work situation, but it also includes the psychosocial factors such as complexity and pace. Common tasks in QEC can be assessed within the first 10 minutes.



Worker's name ______________________ Date __________

Observer's Assessment

Back

A When performing the task, is the back
(select worse case situation)
A1 Almost neutral?
A2 Moderately flexed or twisted or side bent?
A3 Excessively flexed or twisted or side bent?

B Select ONLY ONE of the two following task options:
EITHER
For seated or standing stationary tasks. Does the back remain in a static position most of the time?
B1 No
B2 Yes
OR
For lifting, pushing/pulling and carrying tasks (i.e. moving a load). Is the movement of the back
B3 Infrequent (around 3 times per minute or less)?
B4 Frequent (around 8 times per minute)?
B5 Very frequent (around 12 times per minute or more)?

Shoulder/Arm

C When the task is performed, are the hands
(select worse case situation)
C1 At or below waist height?
C2 At about chest height?
C3 At or above shoulder height?

D Is the shoulder/arm movement
D1 Infrequent (some intermittent movement)?
D2 Frequent (regular movement with some pauses)?
D3 Very frequent (almost continuous movement)?

Wrist/Hand

E Is the task performed with
(select worse case situation)
E1 An almost straight wrist?
E2 A deviated or bent wrist?

F Are similar motion patterns repeated
F1 10 times per minute or less?
F2 11 to 20 times per minute?
F3 More than 20 times per minute?

Neck

G When performing the task, is the head/neck bent or twisted?
G1 No
G2 Yes, occasionally
G3 Yes, continuously

Worker's Assessment

Workers

H Is the maximum weight handled MANUALLY BY YOU in this task?
H1 Light (5 kg or less)
H2 Moderate (6 to 10 kg)
H3 Heavy (11 to 20kg)
H4 Very heavy (more than 20 kg)

J On average, how much time do you spend per day on this task?
J1 Less than 2 hours
J2 2 to 4 hours
J3 More than 4 hours

K When performing this task, is the maximum force level exerted by one hand?
K1 Low (e.g. less than 1 kg)
K2 Medium (e.g. 1 to 4 kg)
K3 High (e.g. more than 4 kg)

L Is the visual demand of this task
L1 Low (almost no need to view fine details)?
*L2 High (need to view some fine details)?
* *If High, please give details in the box below*

M At work do you drive a vehicle for
M1 Less than one hour per day or Never?
M2 Between 1 and 4 hours per day?
M3 More than 4 hours per day?

N At work do you use vibrating tools for
N1 Less than one hour per day or Never?
N2 Between 1 and 4 hours per day?
N3 More than 4 hours per day?

P Do you have difficulty keeping up with this work?
P1 Never
P2 Sometimes
*P3 Often
* *If Often, please give details in the box below*

Q In general, how do you find this job
Q1 Not at all stressful?
Q2 Mildly stressful?
*Q3 Moderately stressful?
*Q4 Very stressful?
* *If Moderately or Very, please give details in the box below*

Figure 3.11: QEC assessment sheet containing two sections, the observer's assessment and worker's assessment.

3.4 Technologies Used by the Motion Sensors

The motion sensors used in this study is the motion capture hardware MVN combined with the MVN analyze software, both from Xsens Technologies B.V. The sensors are attached to a wearable body suit and the suit is worn by the person whose ergonomics is being measured. The rest of the sensors could be attached using straps, onto any human body parts to be evaluated. Each sensor acts as an inertial measurement unit (IMU) based on micro-electro-mechanical systems (MEMS) technology [125]. MEMS are technologies to produce complex structures or devices on the scale of micrometers [126].

Xsens IMU sensor modules are inertial and magnetic measuring units. Each unit contains 3D magnetometers, 3D accelerometers and 3D gyroscopes [127]. A magnetometer measures the direction, strength or relative change of a magnetic field at a particular location. A gyroscope is used to measure and maintain orientation and angular velocity based on earth gravity. An accelerometer measures the proper non-gravitational acceleration [128]. Using these a position, movement and acceleration of a body part where a sensor is attached to can be measured.

(a) IMU sensors (b) Receiving unit

Figure 3.12: IMU and base station

Measurement data is then transmitted wirelessly between sensor units onto a receiving station. At the receiving end, the Xsens MVN software engine will then combine the individual data received with human body biomechanical models in order to calculate the segments/sensors orientations and positions. Some of these segments are already pre-set to particular body parts. Movement data from segments that do not belong to a particular body part are estimated through a combination with biomechanical model.

Particular to this study, two methods of Xsens MVN measurements are used. The first one is the kinematic quantities mode (21), and the other one is the Euler (01) measurement method. For the kinematic, quantities are described in a local right-handed Cartesian coordinate frame [4].

Figure 3.13: Right-handed Cartesian coordinate frame

The definition is as follows: The X coordinate is positive when the object is moving ahead along the horizontal plane. The Y coordinate would be orthogonal to X and Z along the horizontal plane, based on the right-handed coordinate system. The Z coordinate would be along the vertical plane, influenced by gravity and greater than zero when pointing up.

In addition to measuring the position X, Y, Z just like the kinematic mode, the Euler measurement method in Xsens MVN also measures the coordinate of segments rotations in degrees. The coordinates rotations are based on Euler angles orientation describing the pitch, roll and yaw rotations on the X, Y, Z axes [129].

The Euler angles rotation in Xsens MVN are three successive rotations in a particular sequence. The sequence of rotations follows the air vehicles convention which is the Z-Y'-X" sequence. For the sake of illustration, the global co-ordinate system is referenced with (L) and the coordinate of the sensor system is illustrated by (S). The first rotation is symbolized by Ψ is the so-called yaw rotation (azimuth, heading, pan) is the rotation along the Z axes, (Z_L) with the value of -180° to 180°. The second rotation is symbolized with Θ is the pitch (tilt, elevation) rotation. This is the rotation on the Y axes, (Y_L') after the first rotation. The value is from -90° to 90°. The third rotation is symbolized with Φ, is the roll or bank rotation. The rotation is around the X axes (X_L"), which happens after the second rotation. The value for this would be from -180° to 180°.

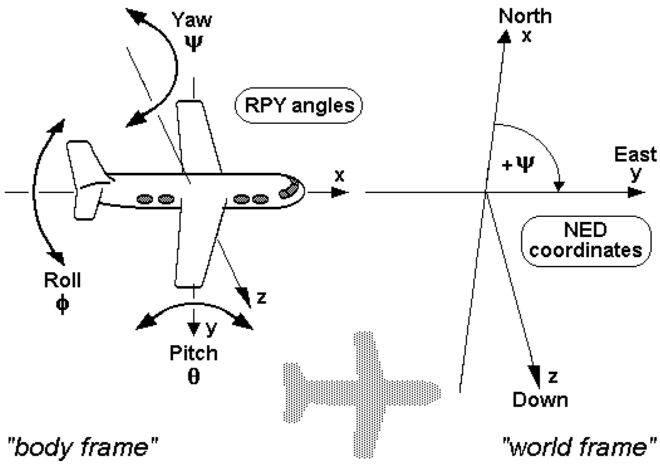


Figure 3.14: Air vehicles inertial frame

Source: By Qniemiec - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=10893303

The rotation orientation could be described through the so-called Direction Cosine Matrix (DCM) [130]. This rotation matrix is actually Sensor coordinate system S, expressed in L-coordinate system, resembling unit-vector components. If Rotation is denoted as R, R_{LS} will consist of unit Vectors S, which resides in the columns site of a matrix. Column 1 of the Matrix represents the X_S expressed in L, column 2 represents Y_S expressed in L, and column 3 represents Z_S expressed in L. A rotation matrix norm is equal to 1 and when the R_{LS} is seconded by an inverse rotation of R_{LS} the identity matrix I^3 is obtained.

$$|\boldsymbol{R}| = \mathbf{1}$$

$$\boldsymbol{R}_{\mathbf{LS}}\boldsymbol{R}_{\mathbf{SL}} = \mathbf{I^3}$$

A rotation of a vector X to the global reference System (L) in the sensor co-ordinate system (S) is represented by the following equation.

$$\boldsymbol{x}_{\mathbf{L}} = \boldsymbol{R}_{\mathbf{LS}}\boldsymbol{x}_{\mathbf{s}} = (\boldsymbol{R}_{SL})^{\tau}\mathbf{x}_{\mathbf{s}}$$

In this study, for the sake of simplicity, the segments/sensors of hand and forearm is positioned on a straight plane. By doing this rotation of the hand sensor could be identified and measured based on the vector of the forearm sensor. As an example, a hand rotation to the right (along the Roll plane) will change the rotation coordinates of Y and Z of the hand sensor, whereas the coordinates of Y and Z of the forearm will not change. Both of the methods are needed for this study in order to obtain a realistic data for the ergonomics assessment. The X, Y, Z position coordinates are needed in the KIM assessment method to calculate the degree of neck or posture flexion using the Pythagorean theorem. The rotation coordinates are needed in the KIM assessment method to measure how often certain joints are moved during a certain period of time. Study on accuracy of the MVN system and the IMU sensor technology compared to a system called opensim, and using Optotrak as a tool shows a rather less deviation, with a maximum deviation of 5.6 degrees [129]. Other articles show that, when comparing IMU with camera-based measurement, the IMU system shows a high degree of precision [131].

3.5 Application Gap Analysis through a Requirement Specification

Prior to the development of the application/software, a requirement specification has to be written. The requirement specification translates the needs of the stakeholder into the language that the developer understands in a form of a formal documentation. A stakeholder could be anybody who has a justifiable necessity in influencing the requirements. This could be users, people who are affected by the system, managers who are interested on the project success as well as regulators such as the government or other entities who are concerned about the effect the software has in general space.

A requirement is a system constraint and system service. It defines the boundaries under which the system could operate and also defines the expected functionality of the to-be developed system. It sets the control states on how the system should be implemented. It contains the minimum acceptance criterion and it should also specify the maximum acceptable time to demonstrate the system usage. The effort of the process involved in developing such requirements should be about 15% of the overall development costs [132].

Writing a good requirement is difficult due to the fact that requirements do not reflect the real needs of the directly impacted customers. This could be caused by intervention by managers or business units. Incomplete and incorrect requirements and misunderstandings between customers, analysts and software engineers could also lead to the lack of quality and correctness of requirement specifications. If the requirements are not specified correctly the delivered product could be late, less accepted or will not satisfy the customers need.

The requirement is abstracted into three levels which according to (Kotonya and Sommerville, 1998), are the user requirements, system requirements and design specifications. The requirements specifications are taxonomized in three requirements; functional requirements, nonfunctional requirements and domain requirements according to (Laplante, n.d.) [32]. The software will then be developed based on this requirement. The software development follows the waterfall method suggested by (Bell and Thayer, n.d.) [34].

User requirements is written in a non-technical point of view perspective. They include problems, wishes, goals and specifies what needs to be fulfilled. The requirements are defined using common social words, or natural language, or through visualizations using diagrams or tables. The requirement should describe the functional and non-functional aspects of the needed software so they are understandable to the users who do not possess the technical knowledge about the needed product (Ian Sommerville 2000 SE) [133].

System requirements have a more technically detailed point of view and describes the solution. They describe the capability of the software despites its limitations. The system requirements serve as a basis for designing the system. Most of the time system requirements are included in the contract. In order to further detail the system requirements, modeling approaches could be used. These models could be described as: context, process, behavioral, data flow, state machine, semantic, object or UML models.

The design specifications specify how the requirements described in the functional requirements are handled or being done. Ideally, there should be a clear separation between what the product should do (the requirements) and how the product does it (the design). In common practice, the two are inseparable. A structure of a requirement could be based on a system architecture. Systems interoperability could generate design requirements and a requirement could also possibly be fulfilled with a prior-known specific design.

The design should represent the product in an abstraction level that should resemble the codes. The design should contain the algorithms used, data structures, interfaces among system, and other features that could help the developers in developing the products. These could be in the form of testing instructions, configuration and customizing settings, documentations of functions or codes. During this requirement phase, the software designer should also be involved for providing inputs. It is very important on this phase that all the requirements on the functional specifications are addressed. The linkage of the requirements and the design specification could be evaluated through a traceability matrix [134].

The functional requirements define the basic services a system must provide, how a system will process particular inputs and how a system will behave in a particular situation.

It describes the functionality of a product. The functional requirements are dependent to the type of the software, known users and the specific system where the software is used. Non-functional requirements specify the limitations/boundaries the product has, in either services or functionalities, such as timing constraints, development process constraints, input/output constraints, reliability, loading times, storage management, etc. They could also contain particular specific code instructions, as well as programming methods and languages. Non-functional requirements are often seen as critical. If these are not met, the delivered product will be useless. The domain requirements define the system features and characteristics that reflect the domain. The domain requirements could be shaping a new functional requirement, a limitation of an existing requirements or even a specific computation set of definitions. If these requirements are not tackled, the product could be unworkable.

CHAPTER 4

Ergonomics Evaluation Application Framework

The purpose of this chapter is to elaborate more on the design of the application and how the application is actually implemented. It is divided into two parts. The first part is the design/concept part, which takes the form of a requirement specification. A requirement specification is used as the foundation/basis in creating a software application. It contains the necessary information for an application to be working as it is intended to. The second part of the chapter is the implementation part. It highlights the environment where the application is developed as well as the classes, algorithms and the database that are used.

4.1 Design of the Application

This section of the chapter provides the functional and technical design specification which serves as a requirement specification. The following are the general description and the requirement description.

General Description

The project is a part of a Master's thesis, with the main objective of enhancing an ergonomics evaluation application, based on KIM's method using an interface provided by MVN from Xsens. In the current situation, there is currently an application available that is reading the sensor data and showing user's ergonomics violations. This application provides minimum functionality and needs to be enhanced as it is required by the stakeholder. The stakeholders are the master's thesis supervisor, the institute and the Pilot Factory Industry 4.0 of TU Vienna.

The to be developed software application will function as an interface and a data analysis tool. The title of the software application is "Ergonomics evaluation interface and data analysis tool". The objective of the software application is to serve the purpose as a "Proof of Concept". The product user interface and visualization should be available for the user as an information and warning notification method to avoid injuries. The technology used should be compatible with the MVN environment. MVN is acting as an interface from the motion sensors to deliver data to the to be developed application. The application and the processes are executed on demand, thus results shown are actual.

The application performance should meet the minimum standard requirement. The application should run and does not break down. The maintenance of the application should be made possible, information should be given in a form of a documentation. The codes should include inline comments so they are self-explanatory and will be possible to be maintained by other persons who did not write the code. The delivery components include a software and a documentation. There are two actors on the system: The user, also called the participant, and the admin, also called the observer. The user is given read only access, while the admin has read and write access. The data saved in the application could fall into the EU GDPR policy. Therefore, anonymity is required when saving the data.

Requirement Description

In order to build the software application, a requirement description is needed. This description describes what the application does or what functions it should deliver. The methods used for the requirement gatherings are combinations of interviews and discussions with the stakeholder, provided document and tools analysis and brainstorming (Young 2002) [135].

The following findings were recognized during the first interview/discussion round with the stakeholder: the required tool/software should act as an interface, reading the data sent by the proprietary MVN software, delivered by the motion tracker vendor. The KIM method should be used as the main ergonomics evaluation method, and data obtained through the sensors should be run against this method. The final product should serve as a proof of concept that a software application, together with motion sensors, could reduce or even avoid work related musculoskeletal disorders by providing live notifications based on specific ergonomics standards.

Through brainstorming and comparison with other commonly available software solutions in the market, the following requirements were added: the software should support create, read, update, delete (CRUD) operation to/from a database solution. The software should be able to be used by different persons and records the data of different persons. The person should perform tasks based on work instructions. The work instructions contain different tools/items needed to complete the tasks. The software should be able to capture data based on defined work-packages and also non-defined works/free-run. The software should provide users with information and warning.

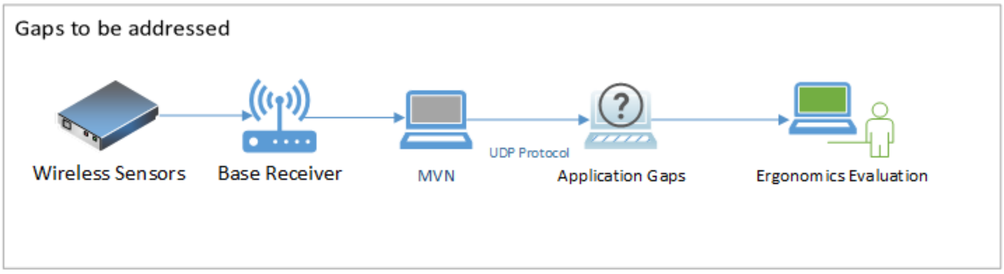


Figure 4.1: Required solution, application gaps to be addressed

The main gap that is identified and should be addressed, is the reading of sensors data from MVN using a UDP protocol. This should be realized through a self-developed application.

The Scope

Currently, there is a basic application that reads the data sent by MVN. This application should be enhanced, and when needed, re-written in order to be able to analyze workers' ergonomics while doing certain tasks, based on KIM ergonomics evaluation method. The final product can then be used to identify, reduce and avoid injuries related to incorrect movement based on ergonomics standards.

In order to build the application, the following end to end process should be taken into consideration: Sensors transmit wireless data -> Sensors base unit receives data -> sensor base unit transmits data to MVN application -> MVN application reads and compiles the data and apply logics and adjustments -> MVN transmits data using a protocol to the application -> application reads the data, analyses and displays.

The product should be able to do the following business process: reading data from MVN, analyze data based on previously defined logics/ergonomics standards/work steps and inform the users about the findings. Anything other than the listed processes are out of scope and will not be implemented in the application.

Constraints, Naming Convention, Facts and Assumptions

As it is mandated by the stakeholder, the application uses the KIM method as standard ergonomics evaluation method. In addition to this, the application should only function together with the MVN. When the MVN is not active the application will not work, thus the usage of the MVN application is unavoidable. When writing the code, programming language specific standard naming conventions are used. These include naming of buttons, timers, database and other relevant variables. Body parts variables are clearly identified using the differentiation right of left. For example, a right upper am X coordinate is identified by RUAX variable.

Facts and assumptions are taken into consideration while writing the application. MVN sensors cannot work individually, only when all the sensors are activated presumably correct coordinates are sent by the sensors. There is a slight delay from the first time data are sent out by the sensors, then read by MVN and sent to the application, analyzed until finally shown in the application. This delay could put the user in a situation where the data shown is not anymore actual (e.g., there would be a 5 second delay from the first time violation is identified by the sensor until it is shown in the application user interface).

The sensors are not able to identify any change in coordinates if the movements are sudden. Sensors' data could be disturbed by external factors like magnetic field or other electronic devices. The Sensors deliver exact data at current position at a particular time, same positions at different point time of time later could be interpreted as different coordinates with significant deviations. Therefore, a recalibration should be done often.

Detail Process & Features

The business processes of the application are built based on core processes, including reading data transmitted by different sensors, identifying different people based on their IDs, recording different work packages, recording people's results, evaluating against ergonomics standards and also warning a user whenever a violation against an ergonomic standard is identified. See Figure 4.2 for an abstract business process modeling.

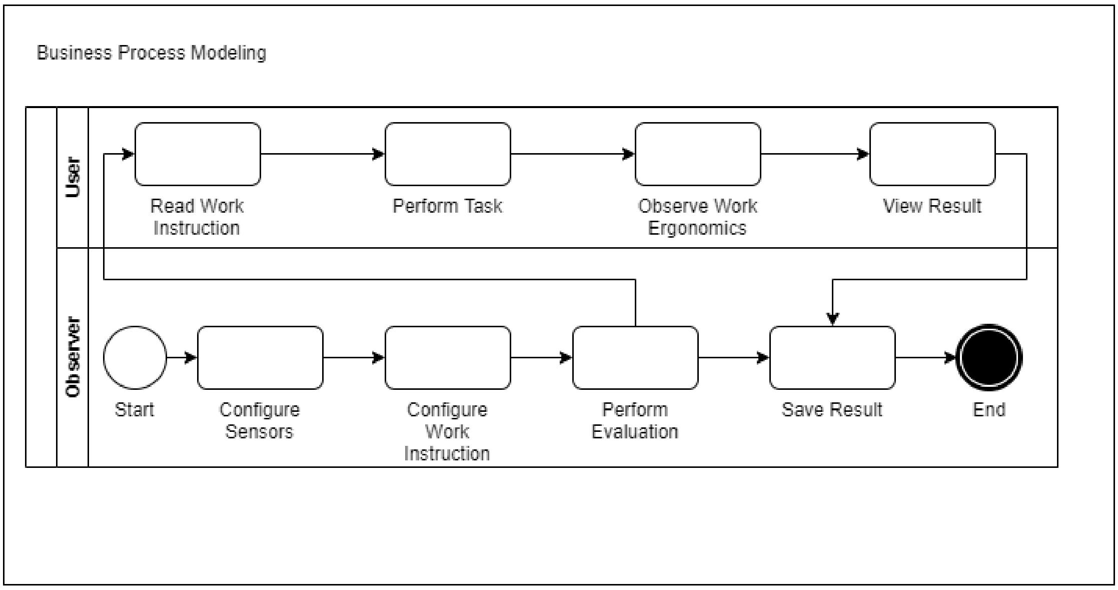


Figure 4.2: BPMN of the 3D printer assembly ergonomics assessment application.

Based on the described processes above, the following features are available to observer and user:

In the observer's sensors configuration use cases, (see table 4.1), available processes are: entering a personnel number of a worker/user in a field, entering each sensor ID according to the current MVN sensor ID settings in the system and capturing the initial standard N-Pose of the worker at the beginning of the experiment. The latter three use cases ensure the correct mapping of the MVN with the application and correct measurement of movement by the application accordingly. Table 4.2 describes further use cases available for the observer. These use cases are the work instruction use cases, including mandatory features such as entering new work instruction, entering needed parts and entering needed tools. Table 4.3 listed all mandatory work instruction use cases available for the user. These are use cases such as read instruction, read parts and read the needed tools. Table 4.4 listed all mandatory evaluation use cases available for the user. These are use cases such as read warning, hear warning, read score and read suggestion.

Below are the four tables that provides an overview of the use cases with their priorities. Priority 1 use cases are the mandatory features that must be implemented.

Sensors configuration Use cases (observer)		
Actor	Name	Priority
Admin	Enter a personnel number	1
Admin	Enter individual sensor id mapping configuration	1
Admin	Capture initial position	1
Admin	Save sensor mapping configuration	2
Admin	Update sensor mapping configuration	2
Admin	Load sensor mapping configuration	2

Table 4.1: Sensors configuration use cases, these functionalities are available for the observer.)

Work instruction use cases (observer)		
Actor	Name	Priority
Admin	Enter work instruction	1
Admin	Enter needed parts	1
Admin	Enter needed tools	1
Admin	Enter assigned person	2
Admin	Enter work type category based on KIM	2
Admin	Enter force exertion type based on KIM	2
Admin	Enter size type based on KIM	2
Admin	Enter tool grip type based on KIM	2
Admin	Enter shape type based on KIM	2

Table 4.2: Work instruction use cases, these functionalities are available for the observer.

Work instruction use cases (user)		
Actor	Name	Priority
User	Read instruction	1
User	Read next instruction	1
User	Read needed parts	1
User	Read needed tools	1

Table 4.3: Work instruction use cases, these functionalities are available for the user.

Evaluation use cases (user)		
Actor	Name	Priority
User	Read warning notification	1
User	Hear warning notification	1
User	Read score	1
User	Read suggestion	1

Table 4.4: Evaluation use cases, these functionalities are available for the user

Layout and Usability

The application graphical user interface (GUI) should have different tabs for different purposes (e.g., one tab only for entering person data, another tab for reading KIM data). In addition, it should be able to be viewed in a non pc environment such as mobile devices or tablets. The application GUI should have different colors and the warnings should be visible to the users. Audio warning should also be implemented.

The application should be easy to use and should provide important information at once. The navigation should be short and easy. For example, one click to switch from information on method a to method b.

Personalization of user is not offered and internationalization are also not needed. The language used is English. The application GUI should be intuitive and easy to follow and easy to understand when reading it for the first time.

The application performance should meet the minimum standard requirement. The application should run and does not break down. The maintenance of the application should be made possible, information should be given in a form of a product documentation. The codes should include inline comments so they are self-explanatory and will be possible to be maintained by other persons who did not write the code.

4.2 Requirement Specification Diagrams

The following diagrams are provided to illustrate the software application: domain model, activity diagram, dataflow diagram, entity-relationship diagram and use case diagram.

Domain Model

The domain model describes the concept of the real world. It describes the objects in the system. The following elements are taken into consideration when creating the domain model; The role or functions of the Actors who are interacting within the system, objects that return the status of a process, objects that describe important items of a process, objects that cannot be separated from the domain application and objects that describe the infrastructure.

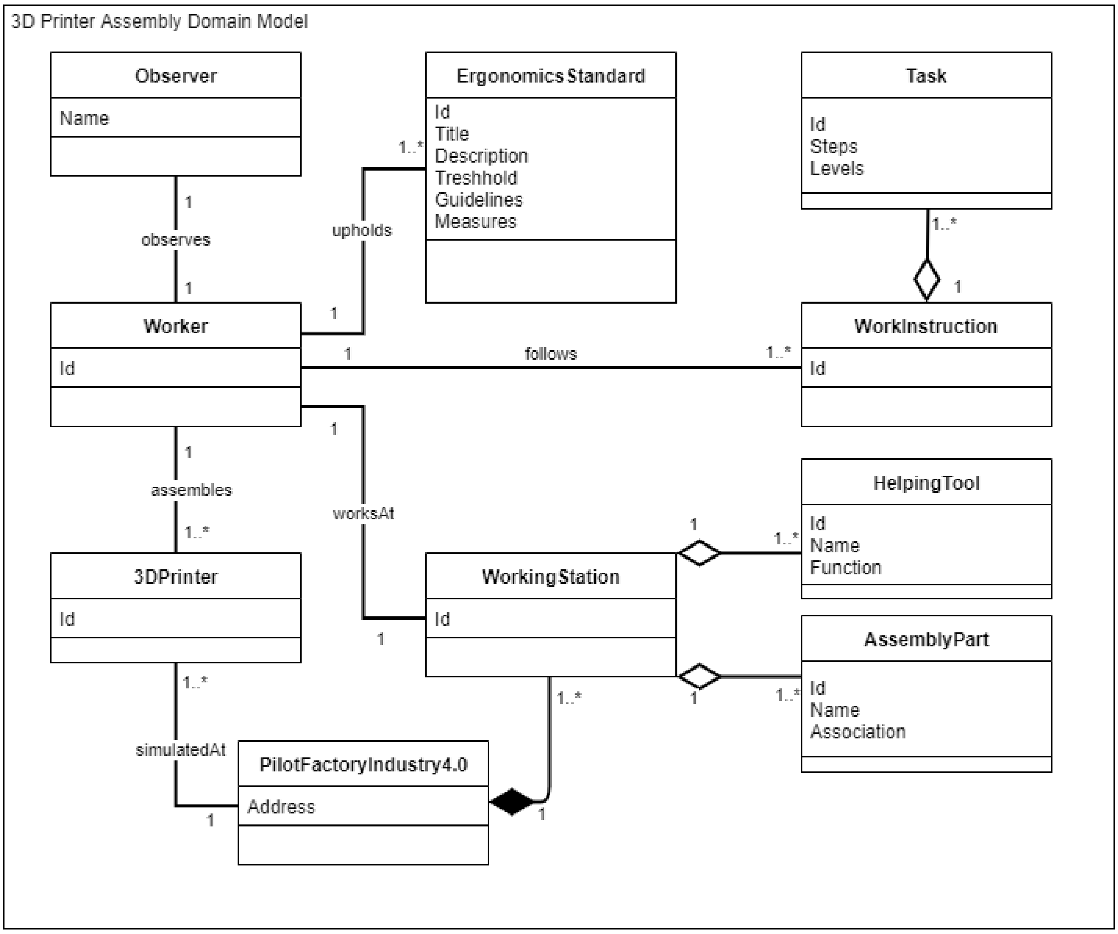


Figure 4.3: Domain model of the 3D printer assembly ergonomics assessment application.

The domain model can be illustrated as follows: The observer in the system observes a worker assembling a 3D printer, the worker follows work instructions containing tasks, while working, the worker upholds ergonomics standards, the worker works on a working station, the working station is provided with the needed parts to be assembled and helping tools needed to assemble the parts and the overall process takes place in the Pilot Factory Industry 4.0.

Activity Diagram

The activity diagram shows the activities performed by the different actors or system logic. It begins with the observer starting the application and ends with the observer shutting down the application, (see figure 4.4 Activity diagram.) Actor observer is provided with activities such as: loading work instructions, creating new work instructions, entering new tasks, tool and items and also saving the final results. Actor user is able to perform activities such as reading work instructions, perform the actual work and view the results.

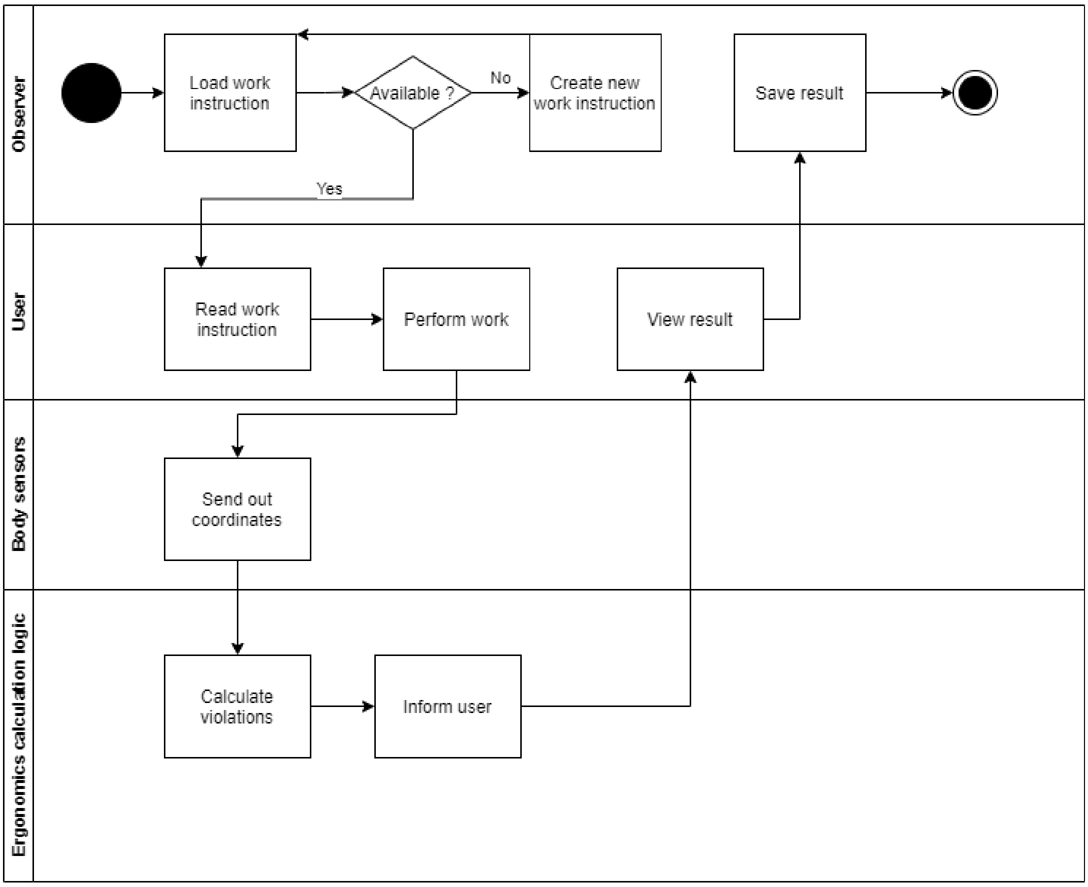


Figure 4.4: Activity diagram of 3D printer assembly ergonomics assessment application.

Dataflow Diagram

The dataflow diagram represents the flow of data from the different processes triggered by different entities and written on different data storages/tables. For example, the observer enters a new work instruction (Process 1.0), work details data will flow from the work instruction user interface into the works table in the database (storage 1).

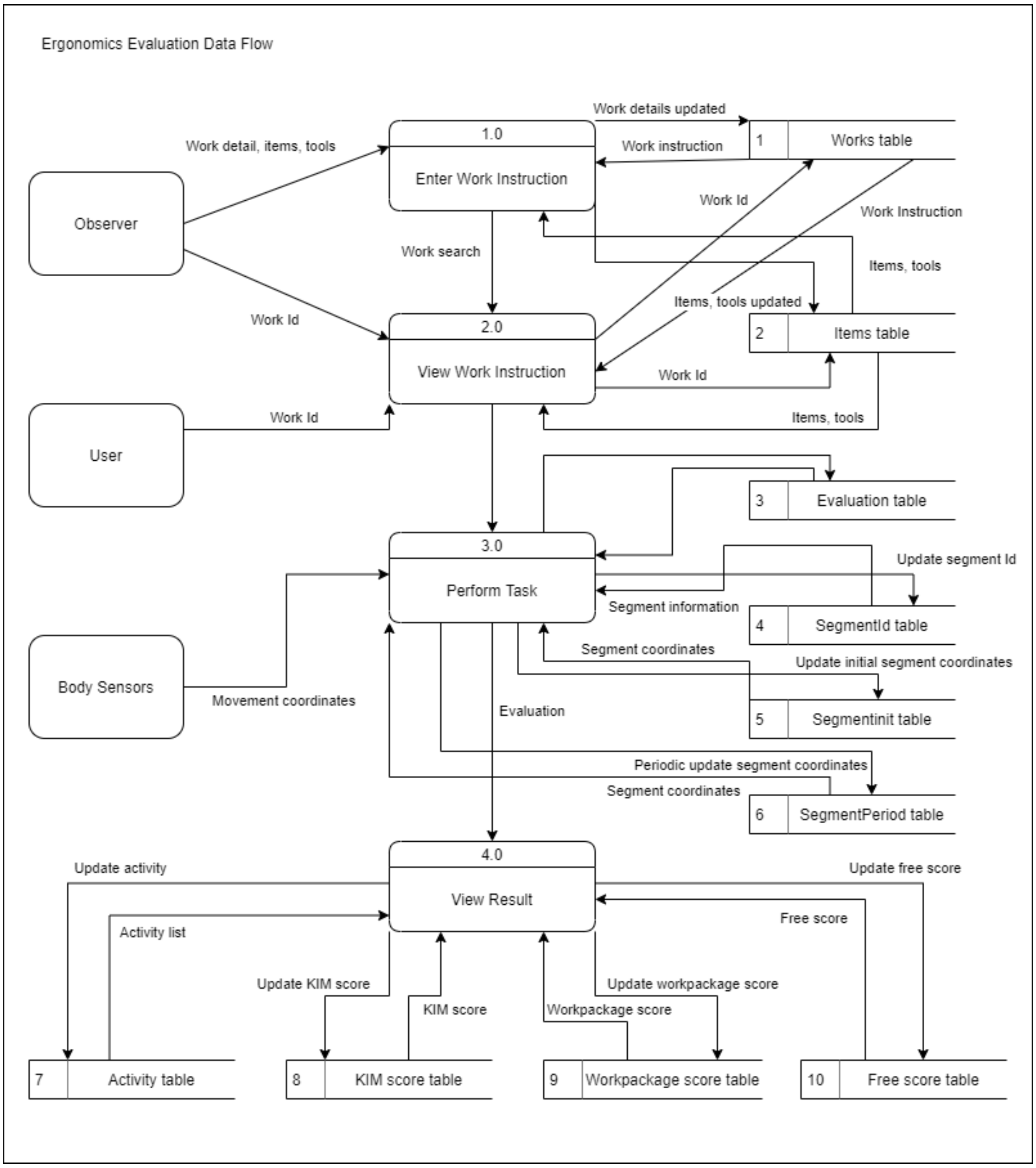


Figure 4.5: Data flow diagram of 3D printer assembly ergonomics assessment application.

Entity-Relationship Diagram

The entity-relationship (ER) diagram represents the different actions taken by different entities. Entities are connected to attributes, which annotate different storage/tables in the system.

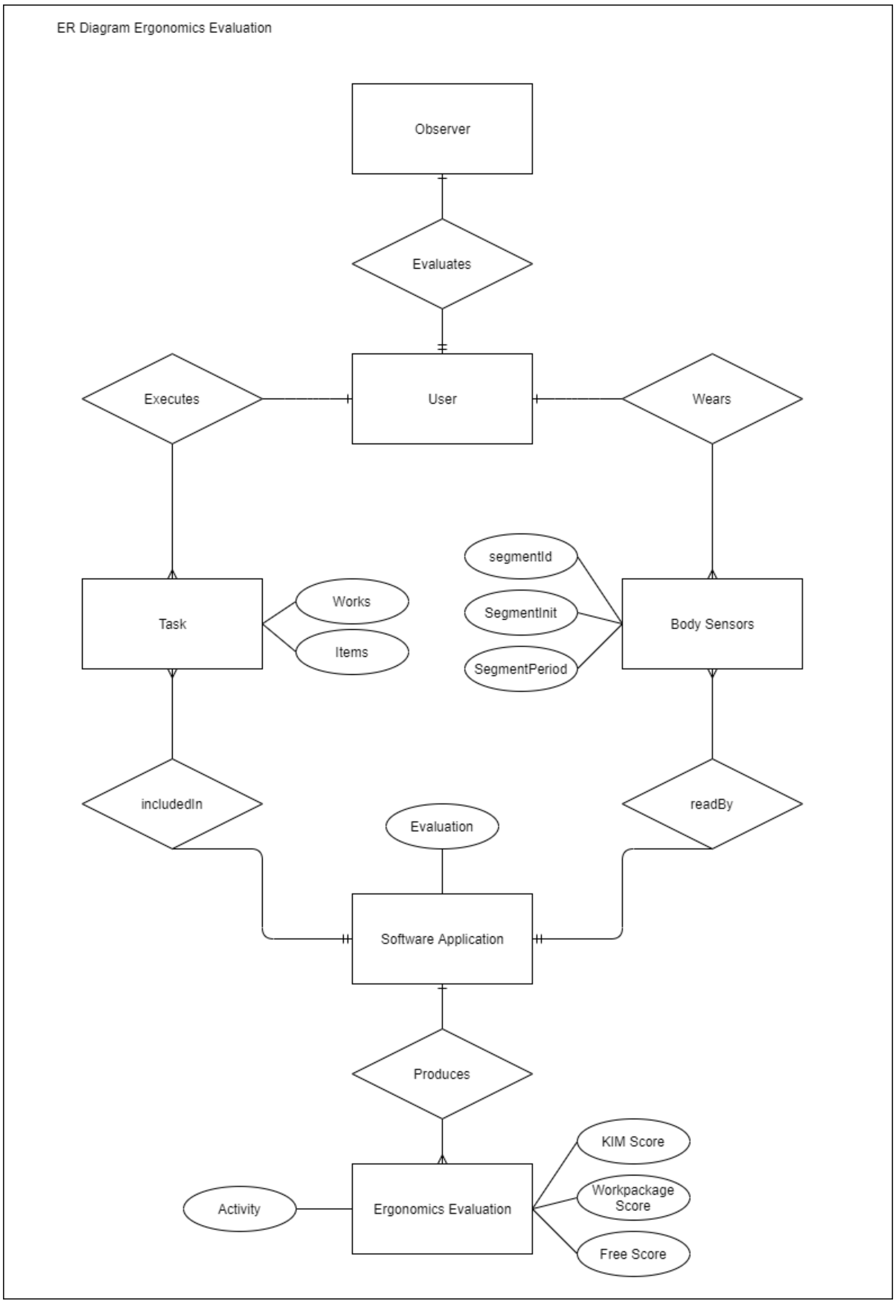


Figure 4.6: ER diagram of 3D printer assembly ergonomics assessment application.

It can be illustrated here that, an observer evaluates one user. This user then executes many tasks that are listed in the software application while wearing body sensors that are also read by the software application. The software application then provides the ergonomics evaluations.

Use Case Diagram

For a better overview of the use cases described in the previous section, the figures, 4.7 use case diagram user and 4.8, 4.9 use case diagram observer, provide use case diagrams for both the observer and the user.

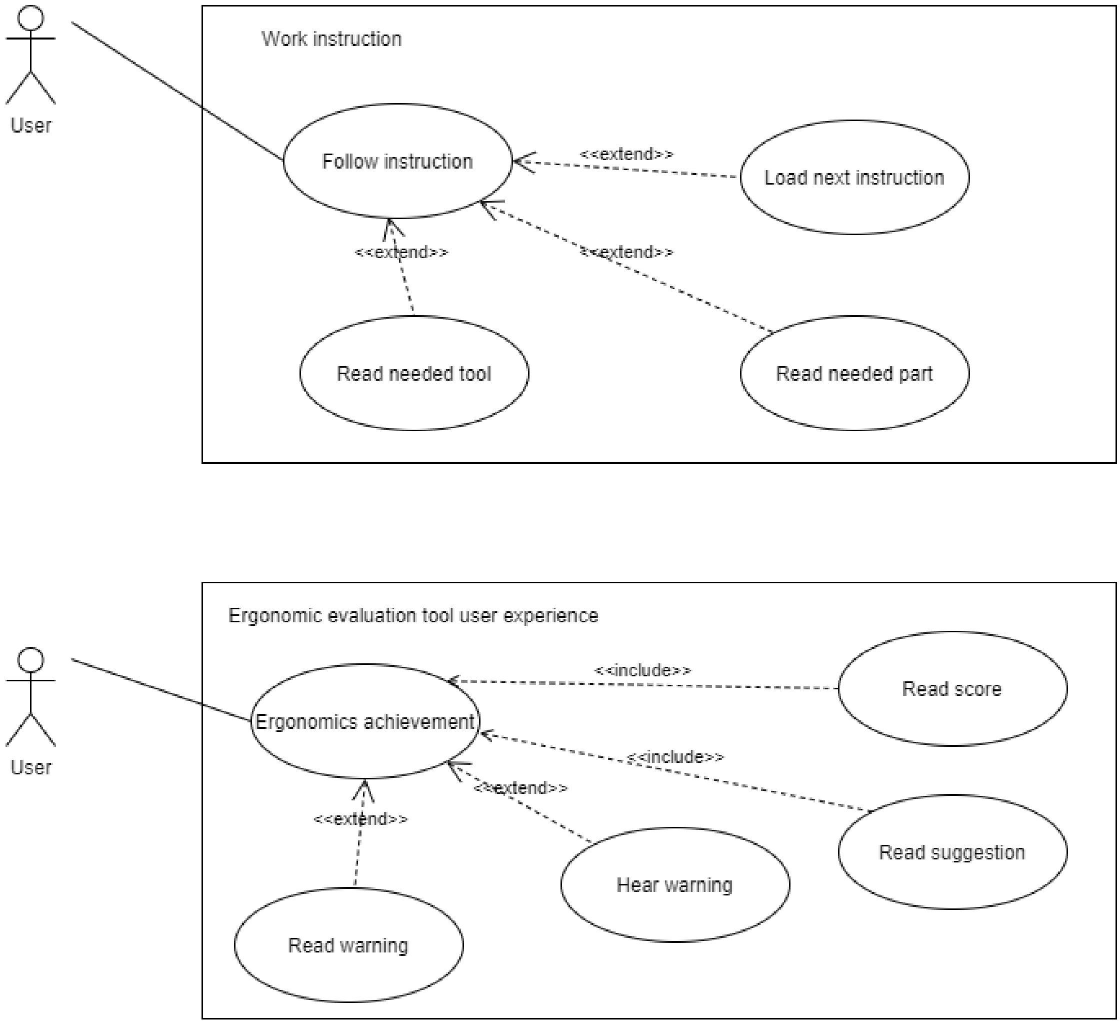


Figure 4.7: User's Use Case Diagram.

The work instruction use case for the user, provides the user with the following actions: a user can follow instructions, a user can read the needed tools to complete the task, a user can read the needed part to complete the task and a user can also load the next instruction. The ergonomic evaluation use case for the user on the other hand provides more actions to the user, such as: a user can observe his ergonomics achievement, a user can read textual warning, a user can hear audio warning, a user can read ergonomics scores and a user can also read the suggested preventive measures.

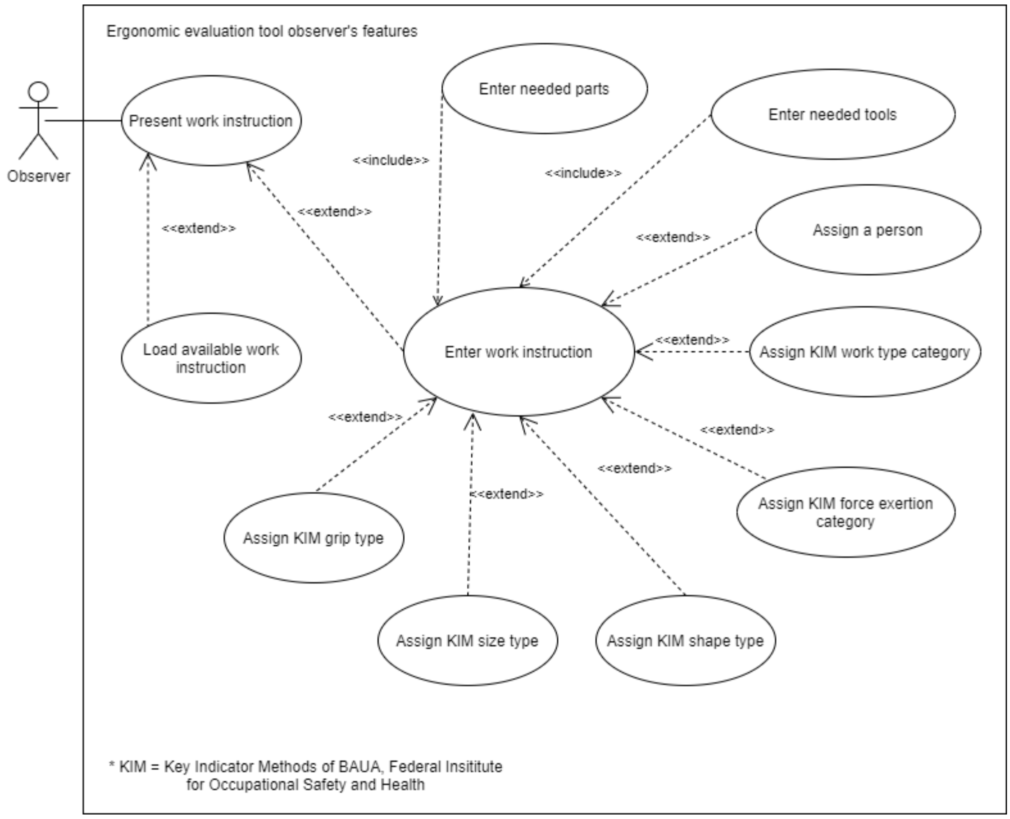


Figure 4.8: Observer's Main Functions Use Case Diagram

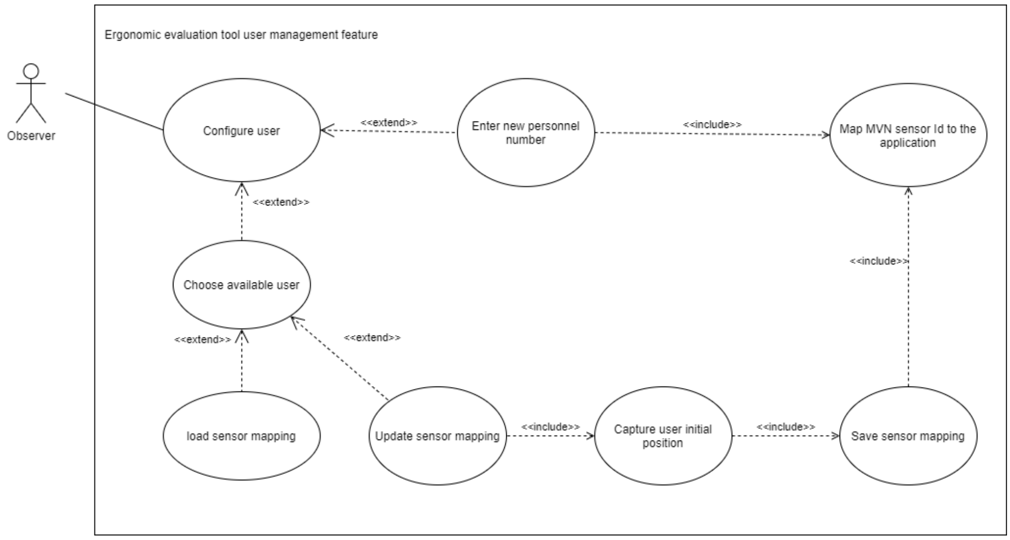


Figure 4.9: Observer's User Management Use Case Diagram

The work instruction use case for the observer, provides the following actions for the observer: an observer can present a work instruction, an observer can enter a work instruction, an observer can load a previously entered work instruction, an observer can enter needed parts, needed tools, assign a person, assign KIM categories, assign KIM types. The sensor config use case provides the following actions to the observer: configure a user, enter new personnel number, map MVN sensors, choose a user, load sensor mapping, update sensor mapping, capture initial positions and save sensor mapping.

4.3 Implementation of the Application

The application is written in Visual Basic .net programming language. The database used is MSSQL and is embedded in the environment. The structure of the application is as follows: graphical user interfaces, interface logic to receive data from the sensors using a network protocol, algorithms logics, and data storage reading and writing in a database. (Please see figure 4.10)

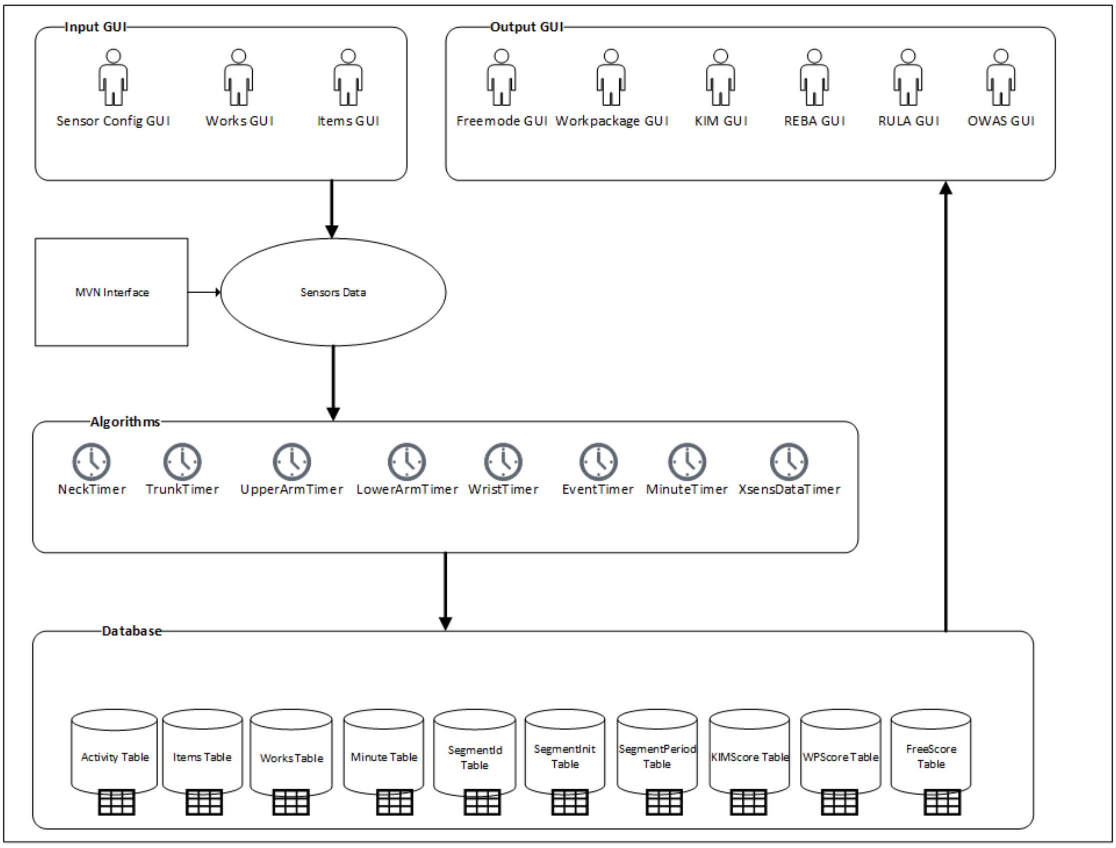
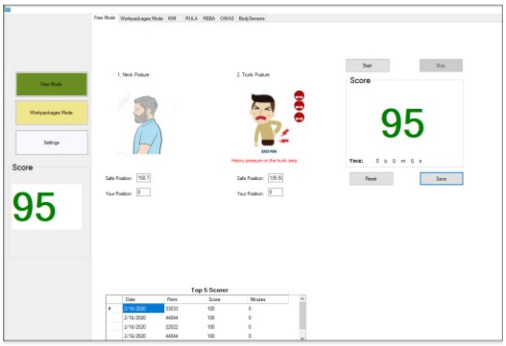


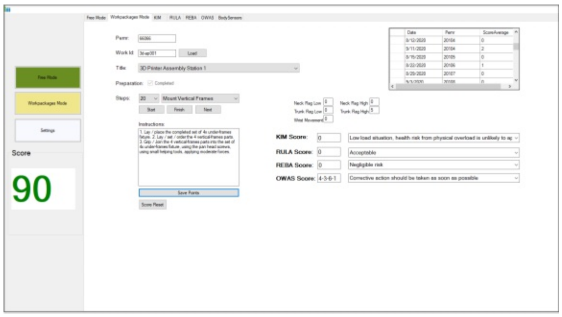
Figure 4.10: Application Structure Overview.

4.3.1 GUI

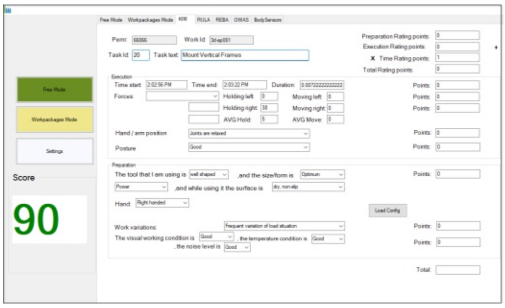
Followings are the GUI illustrations from the software application (please see figure 4.11a - 4.11f)



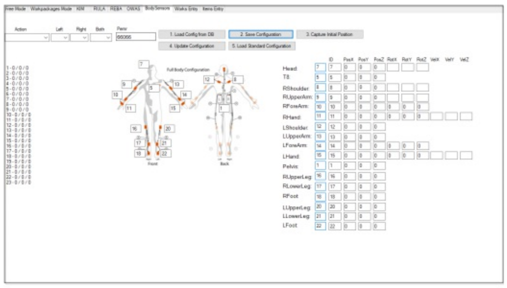
(a) Free Mode UI



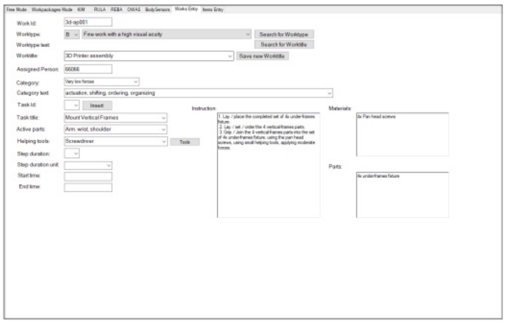
(b) Work Package UI



(c) KIM UI



(d) Sensors Configuration UI



(e) Works Entry UI

(f) Items Entry UI

Figure 4.11: Illustrations of the application's user interface

4.3.2 Component Diagram

The main application is divided into nine graphical user interfaces (GUI) in different tabs. Each GUI uses similar interfaces to write and read data to and from the database.

(See figure 4.12 Component Diagram Overview.)

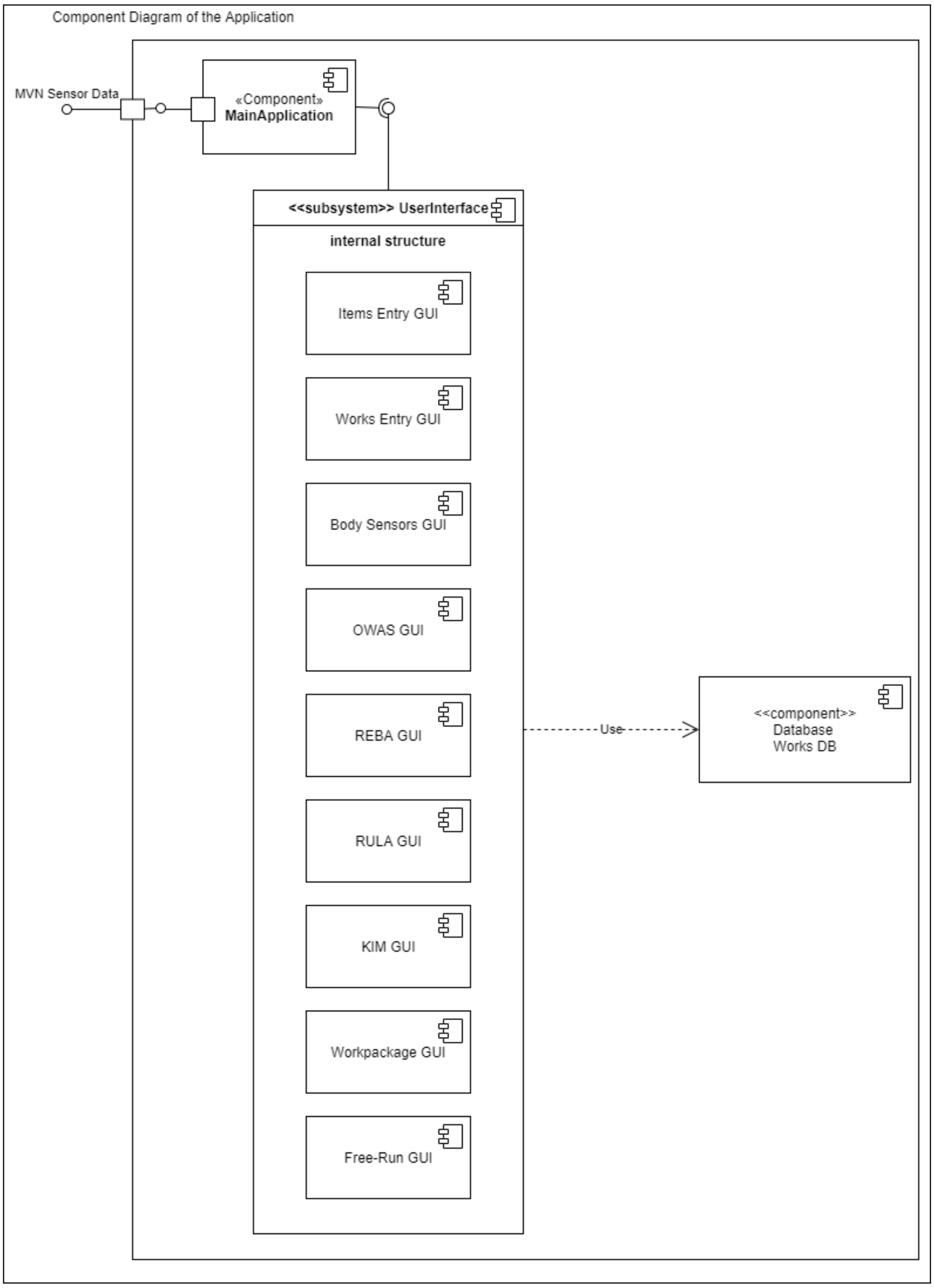


Figure 4.12: Component Diagram Overview.

As illustrated, the main application component acts as a providing interface for the MVN application. The main application requires nine different user interfaces. The user interface subsystem uses the database component. The data flows from the MVN application into the self-developed application/interface and then written into the database.

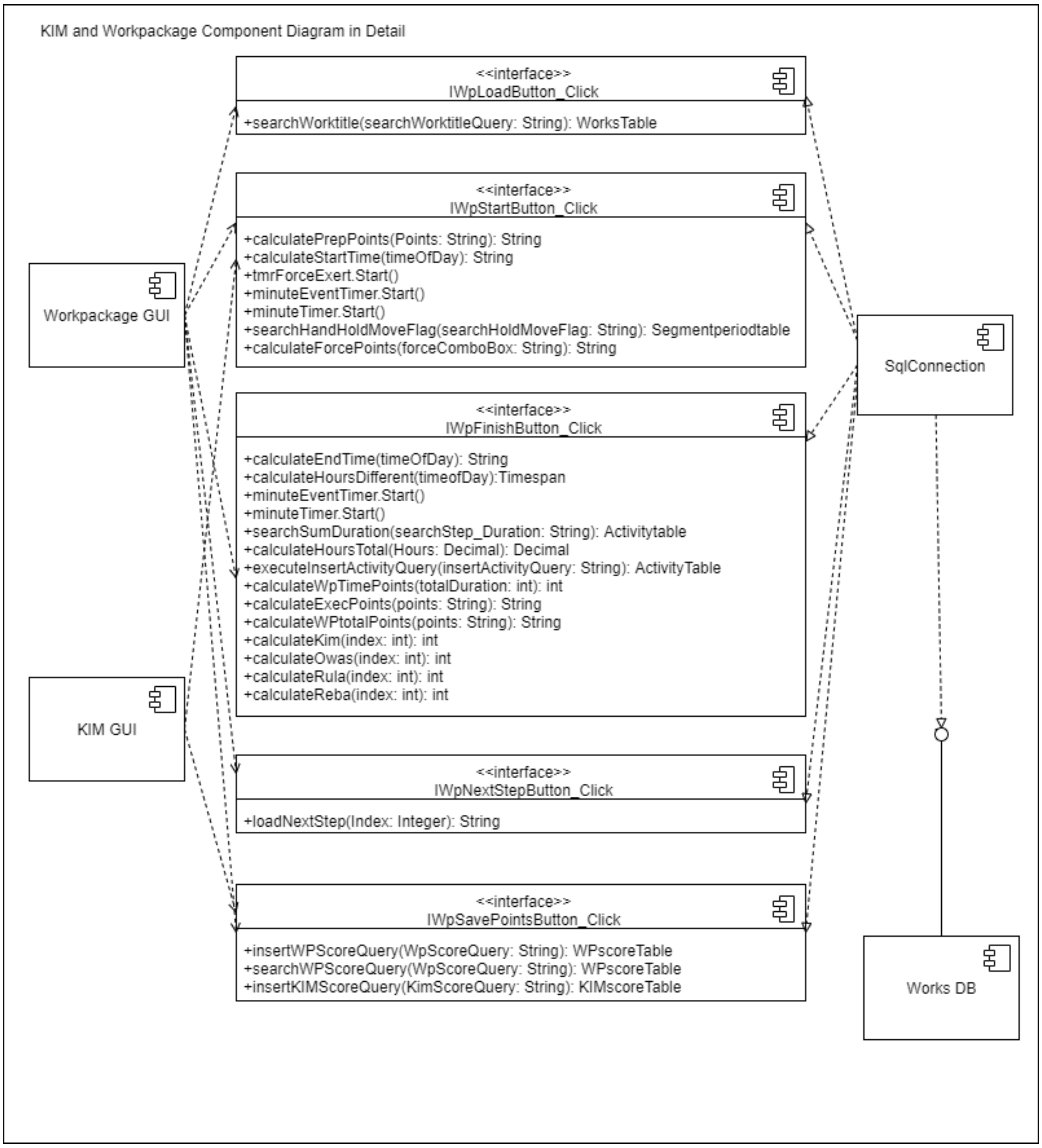


Figure 4.13: Component Diagram Expanded with Interfaces.

As it is illustrated in the diagram above, a component can use one or more interfaces. For example, the KIM GUI component uses the start and finish button interfaces. If the finish button interface is called, the calculateKim calculation inside it will be activated. This class will then use the sql connection to access the database.

4.4 Algorithm, Procedures and Database

Name: TimerFlag1_Tick / TimerNeck

Type: Timer Sub

Description:

This sub procedure is triggered through a timer. The timer runs every five seconds. The main function of this procedure is to calculate the neck posture violation, showing visual warning and also sounding the audio warning to warn the user. This procedure also calculates the score achieved by the user.

The calculation of the violations is based on the triangle's trigonometric function using the sensors coordinates. First, constant variables are defined, 10° for neutral, 20° for moderate and 30° for dangerous. The procedure will differentiate whether sensors are being sent by the MVN using Kinematic or Euler mode. If Kinematic mode is being sent, safe positions are calculated based on the Z coordinates of the head. If Euler mode, safe positions are calculated based on the Y coordinates of the head. The head and right also left upper arm basic coordinates are read from the database [Segmentinittable].

Using left and right shoulder coordinates as a base reference, the distance to the head sensor will be calculated. This distance, marked as Z in the illustration (see figure 4.14) resembles the adjacent length of a triangle with constant angles previously defined (10°, 20°, 30°). With this information, using the tangent law, opposite length of the angle can then be determined (marked as X in the illustration).

Once the length is determined, this length will then be added to the original coordinates of the head sensor in order to create the coordinates range (safe/neutral, awkward and dangerous).

If the current head sensor coordinates is located between neutral and moderate coordinates, no warning is given. When the current head sensor coordinates are currently located between moderate and awkward, the first level warning in the form of yellow colored visual and deeply pitched audio tone is given, the user score is then lightly deducted. When the current head sensor coordinates are currently located greater than the awkward coordinates limit, the second level warning in the form of red colored visual and highly pitched audio tone is given, the score is then greatly deducted. This procedure also adjusts REBA and RULA calculations accordingly.

Name: TimerTrunk1_Tick

Type: Timer Sub

Description:

Similar to the previous procedure, this procedure is also triggered using a timer mechanism. The objective of this procedure is to measure the violation in the trunk area. The sensors being measured are the upper arm sensors. The reference sensors used are the upperleg

Algorithm 4.1: Calculating regions based on sensor location

```
input  : Head and Shoulder Coordinates
output : Violation Warnings
'Calculate the tangent of 10° to get the "safe range".
angle = 10
radians = angle * (Math.PI / 180)
resultneutral = Math.Tan(radians)
'Calculate the tangent of 20° to get the "awkward range".
angle = 20
radians = angle * (Math.PI / 180)
resultmoderate = Math.Tan(radians)
'Calculate the tangent of 30° to get the "dangerous range".
angle = 30
radians = angle * (Math.PI / 180)
resultawkward = Math.Tan(radians)
'Calculate distance of two sensors.
Zdist = Z1head - Z0head
'Distance from head to shoulder
'Calc.° of neutral, moderate (low) and awkward (high)
X1safe = X0head + (Zdist * resultneutral)
X1moderate = X0head + (Zdist * resultmoderate)
X1awkward = X0hdead + (Zdist *resultawkward)
'Calc.  new head sensor's coordinates violation
if Ynewhead-Y0head >= X1safe  and Ynewhead-Y0head < X1moderate -1
 then
    'Show image, no warning
    PictureBox4.Image = GetObject("neck-straight")
    TrunkTextLabel.ForeColor = Color.Blue
    TrunkTextLabel.Text = " "
    else if Ynewhead-Y0head >= X1moderate  and Ynewhead-Y0head <
     X1awkward then
        'Show image, low audio, textual warning
        PictureBox4.Image = GetObject("neck-up")
        TrunkTextLabel.ForeColor = Color.Yellow
        TrunkTextLabel.Text = "Light neck tension, please level your neck"
        Console.Beep(400, 80)
    else if Ynewhead-Y0head >= X1awkward then
        'Show image, high audio, textual warning
        PictureBox4.Image = GetObject("neck-up")
        TrunkTextLabel.ForeColor = Color.Red
        TrunkTextLabel.Text = "Dangerous neck tension, immediately lift your
         head up/down"
        Console.Beep(3000, 150)
end
```

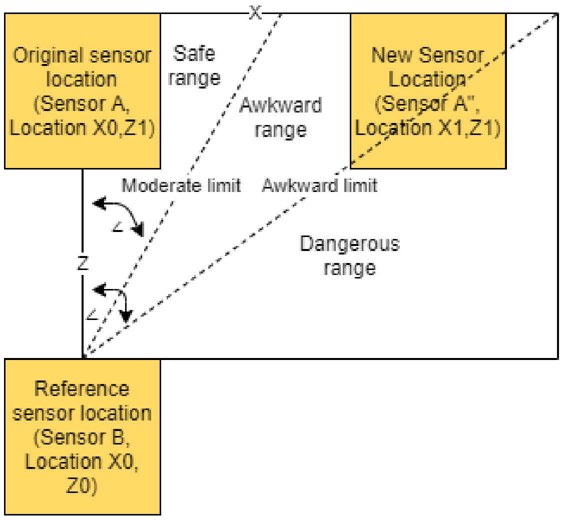


Figure 4.14: How ranges are calculated.

sensors. The logic of this procedure is similar to the previous procedure. In this procedure, the needed calculations for REBA, RULA and OWAS are also performed

Name: MinuteEventTimer_Tick

Type: Timer Sub

Description:

Similar to the previous procedure, this procedure is also triggered using a timer mechanism. The objective of this procedure is to calculate other features that cannot be included in the trunk or neck calculation procedures. One example is the calculation of the foot movement. If a change in foot coordinates is detected, the application will register this as a movement.

Algorithm 4.2: Calculating foot movements based on foot coordinates

input : Foot Coordinates
output : Movement Counts
if $RfposX$ - $RfxPrev > 0.001$ ***and*** $RfposY$ - $RfyPrev > 0.001$ ***and*** $RfposZ$ - $RfzPrev > 0.001$ **then**
  $Move = 1$
end

Another example is the calculation of the hand and wrist movement. The calculation is done based on the different mode sent by MVN. If kinematic mode is used, the hand movement is used, if euler is being sent, the hand rotation is then used.

Algorithm 4.3: Calculating movements and holdings based on hand coordinates

```
input  : Forearm, Hand Coordinates
output : Holding and Moving Counts
if mymode = 21 then
    if RFAX - RfaxPrev < 0.001 or RFAY - RfayPrev < 0.001 or
     RFAZ - RfazPrev < 0.001 then
        Hold = 1
        Move = 0
    end
    if RHVX > 0.001 or RHVY > 0.00 or RHVZ > 0.00 then
        Move = 1
        Hold = 0
    end
else
    if mymode = 1 then
        if RHrotX - RhrotxPrev < 0.001 or RHrotZ - RhrotzPrev < 0.001
         then
            Hold = 1
            Move = 0
        end
        'This is where to define wrist movement
        Move = 1
        if (RHrotY - RhrotyPrev < -3 and RHrotY - RhrotyPrev > 3 and
         RHrotZ - RhrotzPrev < -20) then
            SytemNotificationLabel.ForeColor = Color.Blue
            SytemNotificationLabel.Text = "Right Wrist Extension detected"
            Hold = 0
            extension1 = 1
        end
    end
end
```

4.4.1 Database

Output data from the application is saved in a relational database system. This application is using the built in MSSQL database. There are a total of 10 tables used by the application. Each table has a primary key which is an identification. The following ER table represents the detail of the database used in the system.

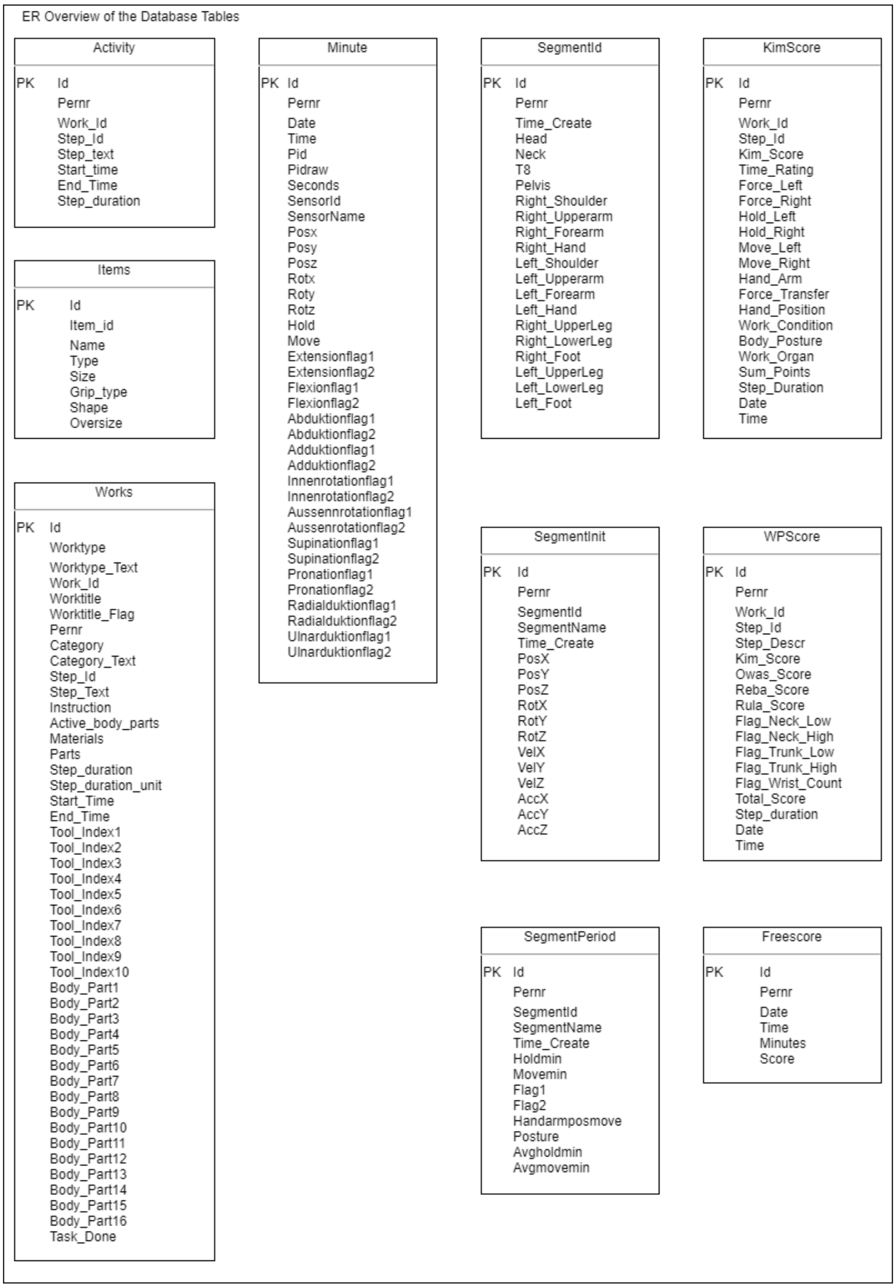


Figure 4.15: Entity-Relationship table.

CHAPTER 5

Evaluation Methodology

The objective of this chapter is to explain and demonstrate the evaluation methodology of this study. The design of the experiment will be explained first. This includes the environment where the experiment takes place, how the sessions are held, what questionnaires are to be filled out by the participant, how the instruction sheets look like, how the scorings are calculated and what the role of the researcher is. The next section describes the ethical aspects of the experiment, including the GDPR policy and obtained consents from the participants. The ethical aspects of the study have been discussed with the ethics office of the Vienna University of Technology. The sections after, elaborates on how the participants are chosen and the environment where the experiment takes place. This evaluation chapter also describes the locations of where the sensors are placed in the participant's body parts. In addition, this chapter also sets out cognitive ergonomics as an important aspect of an assessment methodology. The importance on how the work instructions are designed are also dealt in this chapter. The last section of this chapter reveals the results of the risk assessment and the body postures and movements observed from the experiment.

5.1 Experiment Design

5.1.1 Pre-experiment Formalities

The experiment took place at the Pilot Factory Industry 4.0 of the Technical University of Vienna. The participants varied on gender, ages and educational background. The experiment took, in average of two hours per participant to complete. The experiment was conducted at one session per person.

The experiment starts with an introduction session where the participant was given an oral briefing on the experiment to be conducted. After a brief introduction, the participant was given a set of information and consent sheet, containing the experiment information,

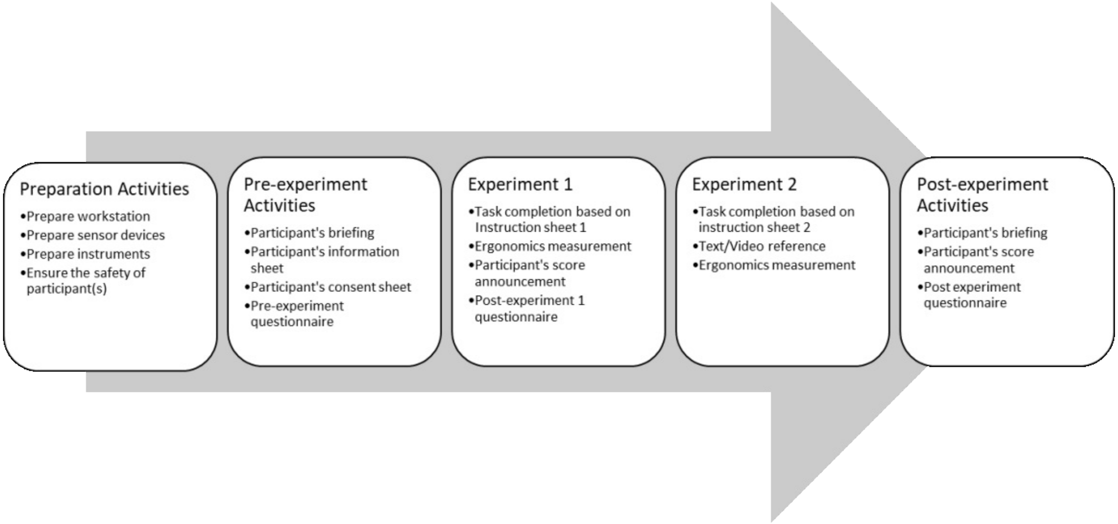


Figure 5.1: Experiment design.

the involvement in the experiment, contact detail about the person conducting the experiment, information regarding ethical conducts, risks the experiment may hold, anonymity, GDPR, confidentiality agreement as well as how the data will be obtained, processed and presented. The participant was informed that his participation is based on a voluntary basis and a possibility is given should a participant decided to not take part in the experiment anymore. At the end, the participant needed to sign the consent sheet in order to take part in the experiment.

After agreeing to the terms, the participant filled out the pre-experiment questionnaire. This questionnaire consisted of questions regarding the information about the participant, such as name, age, gender, height, last education and hand dominance. On this page, the participant's anonymous ID was also assigned. The anonymous ID is a running number that starts with 20100 which is assigned to the first participant.

(See figure 5.2 Pre-experiment questionnaire.)

On the next page, the participant was asked to describe his condition before taking the experiment and whether he feels fit for the experiment. In addition to this, the participant was then also asked about the current feeling toward the experiment. Questions such as whether the participant was feeling curious, excited, motivated toward the experiment and in general, were also asked.

(See figure 5.3 Pre-experiment condition questionnaire.)

After filling out the pre-experiment questionnaire, the participant was given a tour on the working station. This includes the explanation of where the work should take place, which tools and equipment can and should be used and where these tools and equipment are located. The participant was also informed about the locations of the parts that were needed for the experiment. After the work station was explained, the participant was

Pre-experiment Questionnaire

Type: Fill up, or one correct answer

Instruction: Please fill up or mark one answer with an X

Your assigned Anonymous ID: ______

1. Gender (Please mark one answer):
   a. Female
   b. Male
   c. Wish not to declare
2. Age range (Please mark one answer):
   a. 18 – 24
   b. 25 – 34
   c. 35 – 44
   d. 45 – 54
   e. 55 – 60

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3. Height range (Please mark one answer):
   a. Less than 150 cm.
   b. 150 – 159 cm.
   c. 160 – 169 cm.
   d. 170 – 179 cm.
   e. 180 cm and above.
4. Highest education level completed (Please mark one answer):
   a. High School
   b. Apprenticeship
   c. University
5. Hand dominance (Please mark one answer):
   a. Right-handed
   b. Left-handed

Figure 5.2: Pre-experiment questionnaire

equipped with the motion sensors. The motion sensors were calibrated to ensure the correct measurement of the participant and were connected to the software application to measure the ergonomics values.

Interaction between participant and researcher/operator

On every task performed, the participant's movement is evaluated. This is possible through the data delivered by the motion trackers/sensors. The participant needs to explicitly notify the operator that they are ready to perform the needed task. The operator will then confirm to the participant that he can start the experiment. At the same time, the operator will hit the start button on the software application so the recording of the data is also started. After completing the task, the participant calls upon the operator, stating that he is finished with the task. The operator will then hit

These questions are about your condition before taking the experiment	Not at all	A little	Not sure	Some	A lot
I am somehow tired, exhausted					
I am currently not relaxed					
I am currently tensed					
I am currently irritated					
My muscles are currently tensed					
Your current condition	Not at all	A little	Not sure	Some	A lot
I am fit for the experiment					
I feel curious					
I feel excited					
I feel energetic					
I feel motivated					

Figure 5.3: Pre-experiment condition questionnaire

the finish/end button and also confirm to the participant that the task is finished. The next tasks will then follow the same procedures all over again.

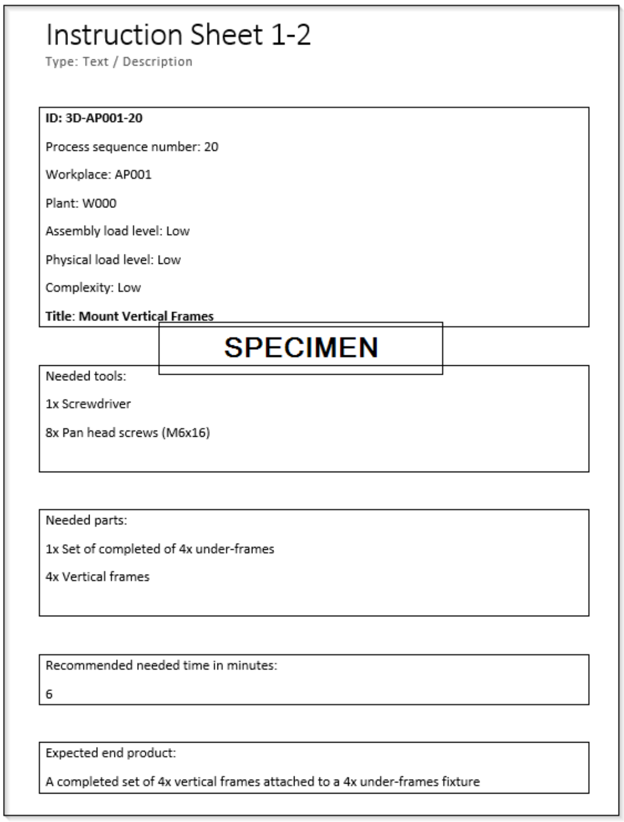
5.1.2 Instruction Sheet 1

After the motion sensor suit was connected to the software application, the participant was given a set of instructions to be followed. The participant was also informed that the experiment will be conducted in two rounds. One instruction sheet is divided into five sections.

The first section consists of basic data of the task such as:

- Task ID
- Sequence ID
- Workplace ID
- Plant ID
- Load classification level
- Complexity classification level
- Title of the task

The second section is the section where the tools or equipment needed are listed. The third section is the section where the needed parts are listed. The fourth section shows the recommended time needed to finish this particular task in minutes. The fifth section shows the description of the expected end product in words. There are six instruction sheets for the first run of experiment.



Instruction Sheet 1-2
Type: Text / Description

ID: 3D-AP001-20
Process sequence number: 20
Workplace: AP001
Plant: W000
Assembly load level: Low
Physical load level: Low
Complexity: Low
Title: Mount Vertical Frames

SPECIMEN

Needed tools:
1x Screwdriver
8x Pan head screws (M6x16)

Needed parts:
1x Set of completed of 4x under-frames
4x Vertical frames

Recommended needed time in minutes:
6

Expected end product:
A completed set of 4x vertical frames attached to a 4x under-frames fixture

Figure 5.4: Instruction sheet 1

The tasks were made in a way that the task complexity is increasing from the first task to the sixth/last task.

Task 1

On the first task, with the lowest complexity level, the participant was asked to identify 4 different parts of under frames, lay them all together on top of a working station in such a way that the four under frames formed a fixture that acts as a support foundation of the 3D printer. Based on the KIM-MHO, the force exerted will be very low, and the force transfer will be optimum.

Task 2

The next task is to mount the vertical frames. The complexity level in this task increases, as the task requires the participant to use extra tools such an electronic screwdriver and pan head screws. The requirement for the participant was to mount 4 vertical frames onto the under-frames fixture. The correct solution is to have a completed set of 4 pieces of vertical frames attached to a 4-piece under-frames fixture. The participant will have to attach the frames using screws with the help of an electronic screwdriver. Based

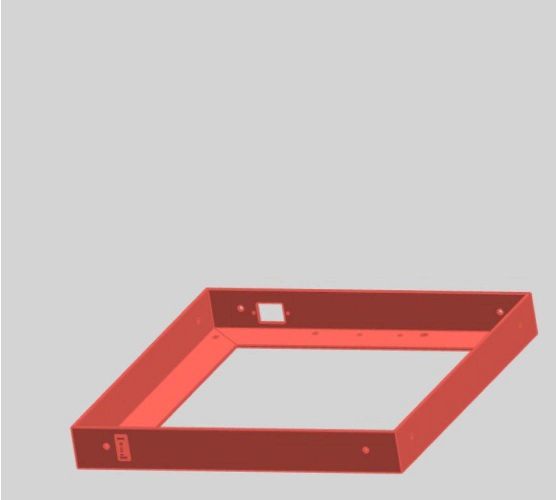


Figure 5.5: Task 1

on the KIM-MHO, the screwdriver is classified as a small (powered) hand tool, with a good ergonomics gripping design. This step/task will exert force between very low and moderate level and force transfer will still be optimum.

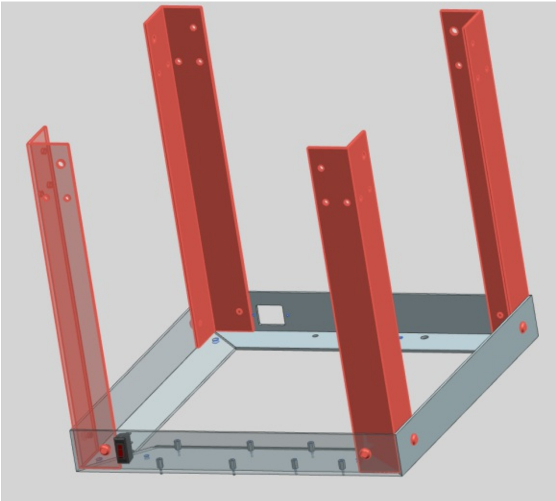


Figure 5.6: Task 2

Task 3

The third task is to attach 4 adjustable feet onto the under-frame fixture. A foot has a bottom base and is in the form of a thread that can be fitted into the under-frame fitting hole. The expected end product is a completed set of four adjustable feet, attached to a 4-pieced under-frames fixture, attached to a 4-pieced vertical-frames fixture. According to the KIM-MHO, the force exerted would be between very low to high forces, the gripping conditions would be restricted and the hand/arm position and movement would be restricted. This is due to the fact that no helping tools can be used in screwing the adjustable foot. Only the combination of hand and arm in screwing motions can be used in finishing this task.

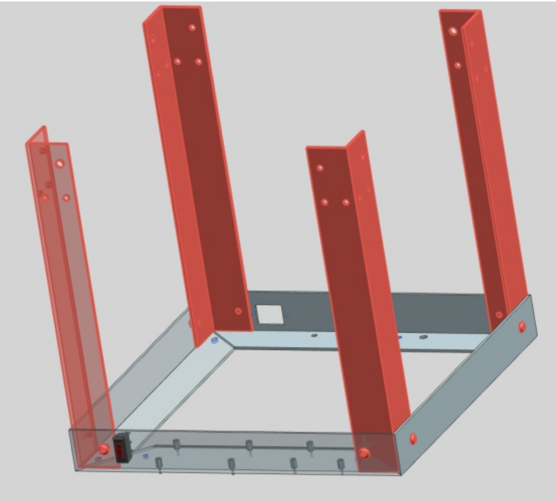


Figure 5.7: Task 3

Task 4

The fourth task is to mount an x-axis 3D printer motor. The participant would need to attach a motor to a vertical frame with the help of a filament mounting bracket. An electronic screwdriver, screws are needed for this task. The expected end product for this step is to have the X-axis motor attached to a vertical frame away from the power switch. According to KIM-MHO, the force exerted would be very low to high. The participant would need to use one hand to grip and hold the motor, screw and filament mounting bracket while another hand is used to screw, using the electronic screwdriver. The force transfer and gripping conditions would still be optimum, the hand/arm position and movement would be at the worst case, restricted.

Task 5

The fifth task is to mount a Y-axis 3D printer motor. Same as the previous task, the participant would also need to attach a motor to a vertical frame with the help of a filament mounting bracket, parallel to the motor x. The expected end product of this step is a to have a Y-axis motor that is attached to a vertical frame parallel to the attached X-axis motor, away from the power switch. The KIM-MHO conditions are the same as the previous steps.

Task 6

The last task in the experiment is to mount the Z-axis 3D printer motor. The last task has the highest complexity level. The participant would need to attach the motor onto

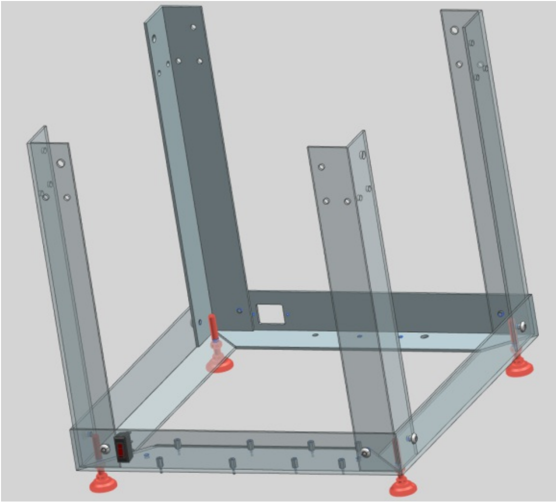


Figure 5.8: Task 4

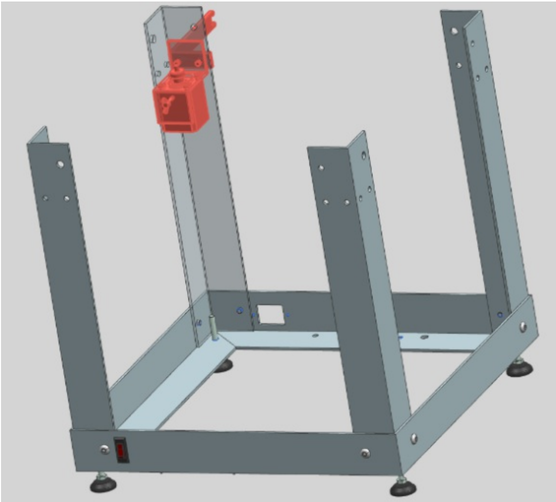


Figure 5.9: Task 5

the under frame. The holes to fit the screws are in a location where they are hard to be accessed by an electronic screwdriver/helping tool. In addition to this the participant would also need to fix the screws using nuts, which can only be done manually using hands. The final expected end product for this last step would be to have a Z-axis motor that is attached to an under frame, between 2 vertical frames where the X-axis motor and Y-axis motor are mounted, away from the power switch. According to the KIM-MHO, the force exerted would be from very low to high forces. The force transfer or gripping conditions would be, at worst, restricted. The hand/arm positions and movements are rather inconvenient but, at worst case, restricted.

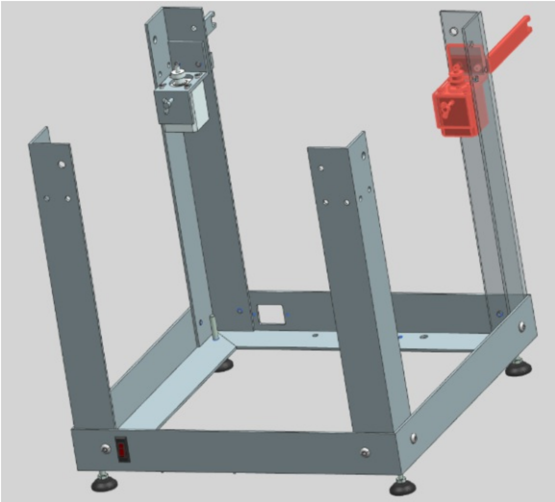


Figure 5.10: Task 6

5.1.3 Scoring

While the application is in the evaluation mode, the actions taken by the participant are marked with a score. The initial score of 100 decreases if actions taken by the participant does not follow the ergonomics standards. Points are subtracted if after repeated audio and visual warnings, the participant still does not correct his posture, movement or action. During the first run of experiment, the audio and visual warnings are turned off and the participant is only shown his final score after completing the last step of the experiment.

5.1.4 End of Experiment 1 Questionnaire

After the participant completed the first part of the experiment, he is asked to fill out a questionnaire in regard to the completed actions. The aim of the questionnaire is to assess how the experiment was. The participant needs to express his feelings or opinions based on a 1-5 Likert scale. The post-experiment 1 questionnaire is divided into 4 groups of questions. (See figure 5.11 After-experiment 1 condition questionnaire.)

The first group of questions refers to perception of the participants towards the tasks. The questions are made in negative tones. The possible answers are: strongly disagree, disagree, neutral, agree and strongly agree. If the participant puts an answer in strongly disagree or disagree, it means that the participant shares a disagreement with the statement of the questionnaire. If the participant answers with agree or strongly agree, he shares the agreement with whatever is stated in the questionnaire. The following negative statements are asked on the first group of questions: whether tasks were demanding, whether available time was short, whether participant has failed in doing the task, whether participant was working very hard and whether participant was unsure in what to do.

Post-experiment 1 Questionnaire

Type: Likert Scale 1 – 5

Instruction: Please rate accordingly by putting an X inside the box, max of one X per row.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The tasks were demanding.					
The given pace while completing the tasks was rushed or hurried.					
I was not successful in accomplishing what I was asked to do.					
I had to work very hard in order to accomplish my level of performance.					
I was feeling unsure, discouraged, irritated, stressed, annoyed while completing the tasks.					
It took me a lot of time and effort to find the relevant information needed to complete the tasks.		SPECIMEN			
It would be helpful to have a step by step instructions of what to do.					
It would be helpful to see related information to accomplish the tasks are visually linked (e.g. similar parts are grouped together, same shaped and colored).					
It would be helpful if simultaneous information is presented in text, graphics, and sounds.					
It would be helpful when textual information is legible (e.g. sufficient text size, clear font), audio information audible (e.g. loud enough).					
It would be helpful for me when the information given is kept to an appropriate length (e.g. three level).					
It would be helpful for me when the information given can be correctly interpreted (e.g. messages are emphasized, centered-displayed, size increased, colored, warning tone).					

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Figure 5.11: After-experiment 1 condition questionnaire

The next set of questions is regarding the information structure and format of the information given and how this information should be presented. This set of questions are made in a positive tone. The following positive statements are asked on this group of questions: step by step instruction is helpful, visual linkage of related information is helpful, presentation in text, graphics and sounds are useful, legible text and audible sound are useful, information length should be kept appropriate, correct interpretation of information is helpful, same information should be presented in many ways, clear definition of similar information is helpful.

The next set of questions is regarding the need and functionality of an assisting tool/software. This set of questions are made in a positive tone, whether: a computer application should act as assisting tool, the assisting tool should be made close to reality, the assisting tool should be dynamically represented, the assisting tool should help in avoiding injuries, the assisting tool should help in avoiding long term disorders.

The next set of questions refers to the well-being of the participant after completing the first experiment. The questions are made in negative tones. The possible answers are: not at all, a little, not sure, some, a lot. If the participant puts an answer in not at all or a little, it means that the participant shares a disagreement with the statement of the questionnaire. If the participant answers with some or a lot, he shares the agreement with whatever is stated in the questionnaire.

The following negative keyword statements are asked on this group of questions: dizziness, tiredness, headache, body parts pains, discomfort, soreness and needs of breaks.

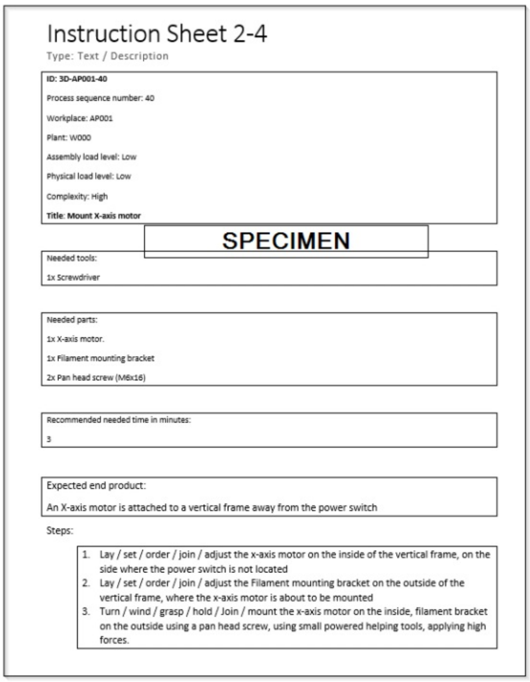
The next set of questions asks the participant about the ergonomics standards, the questions are made in positive tones The following positive statements are asked on this group of questions: injuries avoidance in general, tasks were done according to ergonomics standards and if tasks are repeated in the same way, injuries will be avoided.

5.1.5 Instruction Sheet 2

The second set of instruction resembles similarity with the first set of instruction, what differs is that the second part of instruction set consists of two extra sections on the sheet. The first extra section is a step-by-step instruction on how to assemble. The additional section is an image of the expected end product.

5.1.6 Video Guide

As a further source of information, some of the participants will also be given the possibility to refer to videos of how the expert completes the tasks. The video is available at any point of time for the participant to access.


Instruction Sheet 2-4

Type: Text / Description

ID: 3D-AP001-40
Process sequence number: 40
Workplace: AP001
Plant: W000
Assembly load level: Low
Physical load level: Low
Complexity: High
Title: Mount X-axis motor

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Needed tools:
1x Screwdriver

Needed parts:
1x X-axis motor.
1x Filament mounting bracket
2x Pan head screw (M6x16)

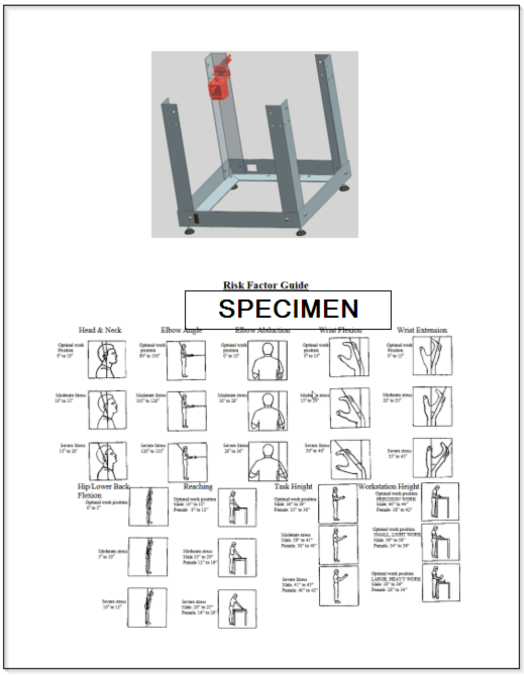
Recommended needed time in minutes:
3

Expected end product:
An X-axis motor is attached to a vertical frame away from the power switch

Steps:

1. Lay / set / order / join / adjust the x-axis motor on the inside of the vertical frame, on the side where the power switch is not located
2. Lay / set / order / join / adjust the Filament mounting bracket on the outside of the vertical frame, where the x-axis motor is about to be mounted
3. Turn / wind / grasp / hold / Join / mount the x-axis motor on the inside, filament bracket on the outside using a pan head screw, using small powered helping tools, applying high forces.

(a) Instruction sheet 2 page 1



(b) Instruction sheet 2 page 2

Figure 5.12: Instruction sheet 2

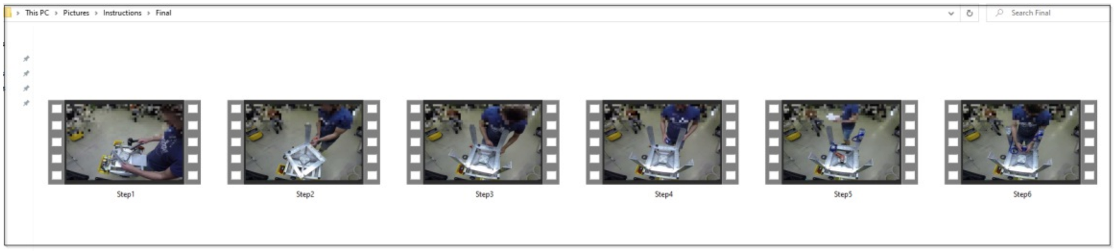


Figure 5.13: Video guide available as reference.

5.1.7 Software Application as Ergonomic Standards Guidance and Control Mechanism

The software application serves two main purposes. Primarily it serves as a control mechanism to avoid injuries to the participant while performing the tasks during the experiment. The second purpose is to ensure that ergonomics standards are maintained by the participants throughout the second part of the experiment. The software also harvests and evaluates data delivered by the motion sensors attached on participants body parts.

Visualization

The software application is presented to the participant at the beginning of the second experiment and made available throughout the second experiment until the end. The application can be accessed and viewed using either a 7-inch or 10-inch tablet with an appropriate eye-level viewing height. The software provides audio and visual features.

The main screen of the application is divided into sections where the participant can easily identify tensions on two main area of body parts, the neck and the trunk. It visualizes the tensions of the neck and trunk using graphical illustrations so whenever there is a tension on either trunk or neck, the participant can identify the tension area, read up the information and adjust or adapt accordingly.

Figure 5.14: Software application visualization.

(See figure 5.14 application visualization.)

The first part of the visualization is of the neck area. There are two levels of tensions, which are identified as just “tension”, which means there is a low tension in the neck area and “dangerous tension”, which means there is a heavy tension in the neck area. The visualization also shows that pains on the neck area could be caused by this position.

The second visualization is of the trunk area. The trunk area is identified using the term pressure. There are two levels of pressures. The first level is the “moderate” pressure, which means there is a low pressure in the trunk area. The second level is the “heavy” pressure, which means there is a strong/high pressure in the trunk area. The visualization also shows that pains on shoulder and back area could be caused by this position.

In addition to the visualization, the application also warns the participant through audio warnings whenever certain violation of "safe" threshold is reached. The treshold is the angle of inclination of the particular body part. There are two levels of audio warning, the first level is a low-frequency deeper-toned audio warning that can be heard in a short time of period. This warning is played when either the lower tension of the neck and lower pressure of the trunk threshold is reached. The other level of audio warning is a higher-frequency rapid-toned audio warning that can be heard in a longer period of time. This warning is played when the higher tension of the neck or higher pressure of the trunk threshold is reached.

Smileys

Further visualization includes the placement of small smile emoticons/smileys that appears every minute on the screen. There are 3 types of smileys: a neutral smiley with a yellow color, a sad smiley with an orange color and an angry smiley with a red color. The smileys are shown on the left or on the right side of the neck or trunk image visualization descending from top to bottom. The smileys shown are based on how well the participant is doing on the experiment based on the ergonomics standard. When the participant is doing well the image shown is yellow. The shown image is orange when standard ergonomics are violated but is still not dangerous. On the other hand, when the standard ergonomics are violated and it is dangerous, the image shown will be red. The smileys measurement is done in an interval with a maximum of 6 smileys.

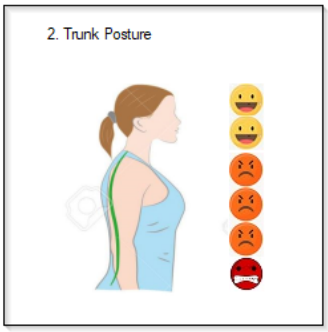
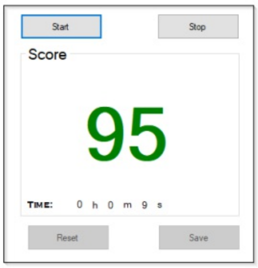


Figure 5.15: Smileys as a quick ergonomics reference.

5.1.8 Scoring

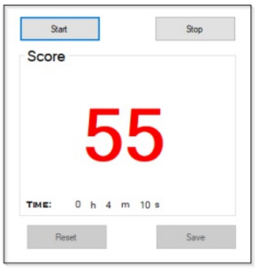
The participant is also provided with a scoring feature that can be used as a reference on how well the participant is doing in completing the required tasks. The initial score is set to 100 points. The score decreases if the participant receives orange or red smileys. If the participant is doing well on the experiment, the points could increase again. The application also records the best scores of other participants and shows them on the same screen. The scores are shown in 3 different colors, green, yellow and red. Green colored scores are in range of between 81 – 100, yellow-colored scores are ranging between 60 to 80 and scores that are ranging under 60 are colored red.

The participant could also access another tab where the details of the working package and scoring of different ergonomics standards are shown. In further tabs the participant could access the detail scoring of the ergonomic standards especially the KIM methods.



(a) Score green.

(b) Score yellow.



(c) Score red.

Figure 5.16: Scoring

5.1.9 End of Experiment 2 Briefing and Questionnaire

After finishing with the last task of the second experiment round, the final score of the participant is announced. The participant is also briefed about how his performance was on the tasks, based on the four ergonomics standards, the KIM method, the RULA method, the REBA method and the OWAS method. After the participant confirmed that he understood the achieved score, the participant is asked to fill out the final set of questionnaires.

Post-experiment 2 Questionnaire

After the participant completed the second part of the experiment, he is asked to fill out a questionnaire in regard to the completed actions. The aim of the questionnaire is to assess how the experiment was. The participant needs to express his feelings or opinions based on a 1-5 Likert scale. (See figure 5.17 After-experiment 2 condition questionnaire.)

The post-experiment 2 questionnaire is divided into 5 groups of questions. The first group of questions refers to well-being of the participant after completing the second round of the experiment. The questions are made in negative tones. The possible answers are: Not at all, a little, not sure, some, a lot. If the participant puts an answer in not at all or a little, it means that the participant shares a disagreement with the statement of the questionnaire. If the participant answers with some or a lot, he shares the agreement with whatever is stated in the questionnaire.

Post-experiment 2 Questionnaire

Type: Likert Scale 1 – 5

Instruction: Please rate accordingly by putting an X inside the box, max of one X per row.

After completing the tasks	Not at all	A little	Not sure	Some	A lot
Are you feeling dizzy?					
Are you feeling tired or having low energy?					
Do you now have a headache?					
Do you now have a neck pain?					
Do you now have shoulder pain?					
Do you now have a back pain?					
Do you now have pains in your wrist?					
Did you feel any discomfort in your hand?					
Do you now have muscle soreness?					
Were you sure while doing the tasks you avoided any possible injuries?					
Do you think you did the tasks according to the ergonomics standard?					
	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The height of the working station was proper.					
The space on the working station was sufficient.					
The surrounding lighting was sufficient.					
There was no noise disturbance.					
The temperature was appropriate.					
I was satisfied with my working environment					
The helping tools fit to my hand.					
The helping tools were essential in helping me to finish my tasks.					
Frequently used items were within easy reach.					
Application	Not at all	A little	Enough	Much	Very much
Did you feel that the software application was useful?					
Did you think that the software application was simple and easy to use, commands were easy to understand, easy to follow?					
Did you think that the software application was attractive, to the point and sufficiently designed?					
Were you able to find the information you needed, was the way easy?					
Did you find the combination of text, audio warning and visuals was sufficient?					

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Figure 5.17: After-experiment 2 condition questionnaire

The following negative keywords are asked on the first group of questions: dizziness, tiredness, headache, body parts pains, discomfort and soreness.

The next set of questions asks the participant about the ergonomics standards, the questions are made in positive tones

The following positive statements are asked on this group of questions: injuries avoidance in general and whether tasks were done according to ergonomics standards

The next set of questions refers to the working environment supporting the experiment. The questions are made in positive tones. The possible answers are: strongly disagree, disagree, neutral, agree and strongly agree. If the participant puts an answer in strongly disagree or disagree, it means that the participant shares a disagreement with the statement of the questionnaire. If the participant answers with agree or strongly agree, he shares the agreement with whatever is stated in the questionnaire.

The following positive statements are asked on this group of questions: the proper height and space of the working station, the lighting, noise disturbance, temperature, general satisfaction on the working environment, helping tools satisfaction.

The next set of questions are regarding the acceptance of the application tool. The questions are made in positive tones. The possible answers are: Not at all, a little, not sure, some, a lot. If the participant puts an answer in not at all or a little, it means that the participant shares a disagreement with the statement of the questionnaire. If the participant answers with some or a lot, he shares the agreement with whatever is stated in the questionnaire.

The following positive statements are asked on this group of questions: the application is useful, intuitive, attractive, sufficient, trustworthy and contributing to ergonomics safety

The next set of questions are a set of questions taken from the quick exposure check method (QEC) for workers. The questions taken are from part H to Q. The participant needs to pick one single answer from the multiple answers provided.

The following questions are asked: manual weight, time spent, maximum force exerted, visual demand, driving vehicle, usage of vibrating tools, task difficulty and job stress level. After finishing this part of the questionnaire, the experiment is officially finished.

5.1.10 Role of the Researcher During the Experiment

Throughout the experiment, the researcher plays both role as an observer and an instructor. The researcher conducts the experiment and instructs the participant to start and end the tasks. The researcher also answers questions whenever any question arises. The researcher pays extra attention in the well-being of the participant and ensures the safety of the participant. On the second experiment explicitly, the researcher observes the participant and fills out the observer's assessment sheet part of the QEC.

Worker's Assessment

Workers

H Is the maximum weight handled MANUALLY BY YOU in this task?

- H1 Light (5 kg or less)
- H2 Moderate (6 to 10 kg)
- H3 Heavy (11 to 20kg)
- H4 Very heavy (more than 20 kg)

J On average, how much time do you spend per day on this task?

- J1 Less than 2 hours
- J2 2 to 4 hours
- J3 More than 4 hours

K When performing this task, is the maximum force level exerted by one hand?

- K1 Low (e.g. less than 1 kg)
- K2 Medium (e.g. 1 to 4 kg)
- K3 High (e.g. more than 4 kg)

L Is the visual demand of this task

- L1 Low (almost no need to view fine details)?
- *L2 High (need to view some fine details)?

* _If High, please give details in the box below_

M At work do you drive a vehicle for

- M1 Less than one hour per day or Never?
- M2 Between 1 and 4 hours per day?
- M3 More than 4 hours per day?

N At work do you use vibrating tools for

- N1 Less than one hour per day or Never?
- N2 Between 1 and 4 hours per day?
- N3 More than 4 hours per day?

P Do you have difficulty keeping up with this work?

- P1 Never
- P2 Sometimes
- *P3 Often

* _If Often, please give details in the box below_

Q In general, how do you find this job

- Q1 Not at all stressful?
- Q2 Mildly stressful?
- *Q3 Moderately stressful?
- *Q4 Very stressful?

* _If Moderately or Very, please give details in the box below_

Figure 5.18: Quick Exposure Check Worker's Sheet

5.2 Ethical Aspects

In regards to this study, ethical aspects and issues of the participants are taken into great and careful consideration, particularly when providing information to the participants, collecting data of the participants and selecting the right questions including the right selection of words for the participant's questionnaires.

At the beginning of the experiment, the participant will be provided with a package that contains: set of participant information sheet, which pertains important information about the study, a consent sheet, a pre-experiment questionnaire set, a set of instruction sheets for experiment 1, a post-experiment 1 questionnaire set, a set of instruction sheets for experiment 2, a risk factor guide sheet for experiment 2 and a post-experiment 2 questionnaire set.

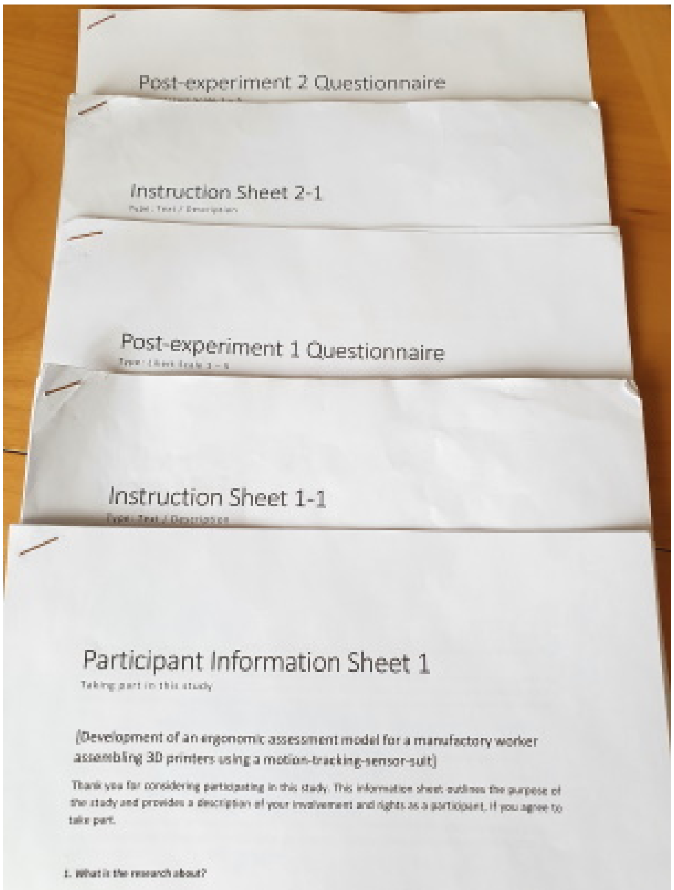
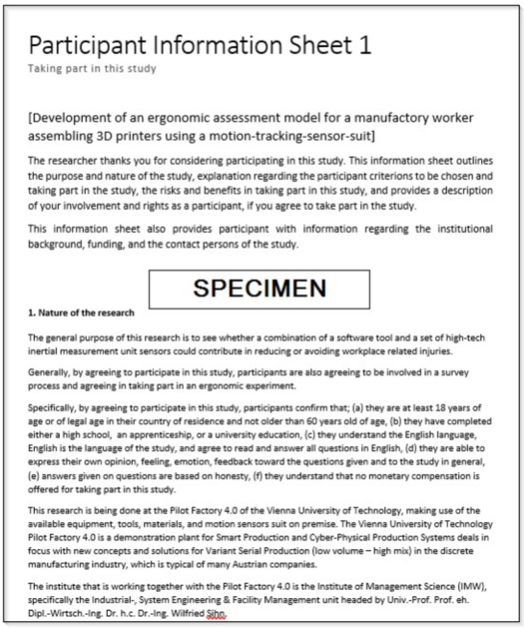


Figure 5.19: Participants' package

How this study is conducted and the contents of this package have been discussed with and reviewed by the ethics office and the EU General Data Protection Regulation (GDPR) responsible person at the Technical University of Vienna.



Participant Information Sheet 1

Taking part in this study

[Development of an ergonomic assessment model for a manufactory worker assembling 3D printers using a motion-tracking-sensor-suit]

The researcher thanks you for considering participating in this study. This information sheet outlines the purpose and nature of the study, explanation regarding the participant criterions to be chosen and taking part in the study, the risks and benefits in taking part in this study, and provides a description of your involvement and rights as a participant, if you agree to take part in the study.

This information sheet also provides participant with information regarding the institutional background, funding, and the contact persons of the study.

SPECIMEN

1. Nature of the research

The general purpose of this research is to see whether a combination of a software tool and a set of high-tech inertial measurement unit sensors could contribute in reducing or avoiding workplace related injuries.

Generally, by agreeing to participate in this study, participants are also agreeing to be involved in a survey process and agreeing in taking part in an ergonomic experiment.

Specifically, by agreeing to participate in this study, participants confirm that; (a) they are at least 18 years of age or of legal age in their country of residence and not older than 60 years old of age, (b) they have completed either a high school, an apprenticeship, or a university education, (c) they understand the English language, English is the language of the study, and agree to read and answer all questions in English, (d) they are able to express their own opinion, feeling, emotion, feedback toward the questions given and to the study in general, (e) answers given on questions are based on honesty, (f) they understand that no monetary compensation is offered for taking part in this study.

This research is being done at the Pilot Factory 4.0 of the Vienna University of Technology, making use of the available equipment, tools, materials, and motion sensors suit on premise. The Vienna University of Technology Pilot Factory 4.0 is a demonstration plant for Smart Production and Cyber-Physical Production Systems deals in focus with new concepts and solutions for Variant Serial Production (low volume – high mix) in the discrete manufacturing industry, which is typical of many Austrian companies.

The institute that is working together with the Pilot Factory 4.0 is the Institute of Management Science (IMW), specifically the Industrial-, System Engineering & Facility Management unit headed by Univ.-Prof. Prof. eh. Dipl.-Wirtsch.-Ing. Dr. h.c. Dr.-Ing. Wilfried Sihn.

Figure 5.20: Participant's information sheet.

The following is the structure of the information sheet:

1. Nature of the research
2. Taking part in the study
3. Participant involvement
4. Benefits in taking part
5. Withdrawal from the study
6. Usage of information
7. Data confidentiality
8. Who has reviewed the study
9. Data protection privacy notice
10. Danger during the experiment
11. Right to ask questions or to complaint

This consent sheet will then be dated, named and signed both by the participant and the researcher.

5.3 Participants

As also agreed with the ethics office, the participant of this study should be in the minimum age of 18 years old to be lawfully legal, and in the maximum of 60 years old, to avoid any dangers. The participant should have minimum education of either high school, apprenticeship or a university education in order to understand the instructor commands. The participant should understand the English language and able to read and answer all questions in English. The participant should be able to express their feeling and opinion, being honest in answering the questions and agree that no monetary compensation is offered for taking part in this study.

Participants of the study are chosen based on a convenience sampling method [136]. The researcher has either previous knowledge of the participants or has previous working relations with the participants, thus participations are not completely available for random people/sample. The study tries to have equal amount of participation gender represented.

5.4 Environment

The Pilot Factory Industry 4.0 of the Vienna University of Technology provides a real-life environment modelling of a specific area of a factory manufacturing process [137].

Figure 5.21: A work station in the Pilot Factory Industry 4.0

One specific example of this process is the assembly of a 3D printer. Using the pilot factory, industries are able to develop, implement and evaluate work processes without having to shut down or disrupt the production line.

In regards to the result of a simulated work process from the ergonomics point of view, one paper shows that certain workloads might be detected reliably in a simulated environment and a correlation between real life assessment result and in a simulated condition are fairly high [138]. Another study from Germany shows that a model resulted from a smart factory is implemented and even validated during the engineering process in an automotive manufacturing branch [139]. Last but not least, acceptance of simulations done in a smart/learning factory, especially by industry related employees are positive according to one study at the University of Split in Croatia [140].

The working station is a movable, robotic working station. The illumination of the working station is appropriate to provide a good working condition. As the working station is inside a shared facility, there are sometimes noise disturbance from other machines, equipment or other works in progress. The temperature of the working environment is appropriate to provide a good working condition.

Figure 5.22: AGV (Automated Guided Vehicle).

The tools and parts needed for the experiment are located either on or underneath of the working station or on the shelf in front of the working station, within easy reach. The shelf itself has stackable containers inside, containing the parts that are needed for the experiment. The working station platform can be turned and rotated but the height cannot be adjusted.

5.5 Sensors Locations

The participant will be equipped with 17 different sensors that are placed on the following body parts: head, right shoulder, left shoulder, sternum, right upper arm, left upper arm, right forearm, left forearm, right hand, left hand, pelvis, right upper leg, left upper leg, right lower leg, left lower leg, right foot and left foot.

Figure 5.23: A participant wearing a sensor suit.

Head

The head sensor is located in the back of the head on the lower region close to the neck. This sensor measures the movement of the head when the head is either inclining, declining or when the head is rotating. On the standard MVN measurement mode, the X axis is perpendicular to the Y and Z axis. The Y axis shows the height of the sensor and the Z axis measures the movement of the sensor on the horizontal plane.

Shoulders

The shoulder sensors consist of 2 sensors, left and right and are positioned on the top of the left and right shoulder blade. The sensors measure the movement of the shoulder. On the MVN measurement mode, the X coordinates are pointing forward. The Y coordinates are perpendicular to X and Z. The Z coordinates are either the left or right shoulder to the C7 shoulder along the horizontal plane.

Upper Arms

The sensors on the upper arms are located between the top of the shoulders and the left and right elbows. These sensors measure the movement of the upper arms. On the MVN measurement mode, the X coordinates are pointing forward on sagittal plane. The Y coordinates show the height of the sensors between the left and right joint elbow to the left and right shoulder joint, the Z coordinates are perpendicular to X and Y along the horizontal plane, pointing to the right.

Forearms

The left and right forearm sensors are located between the elbows and the wrists. The sensors measure the movement of the arms. On the MVN measurement mode, the X coordinates are pointing forward and the Y coordinates are the height of the sensors between the right wrist and right elbow as well as the left wrist and the left elbow. The Z coordinates are perpendicular to X and Y along the horizontal plane, pointing to the right.

Hands

The sensors on the arm are located between the wrist and the fingers on the other side of the left and right palms. The sensors measure the movements of the hands. On the MVN measurement mode, the X coordinates are pointing forward the Y coordinates are between the top of the right hand to the right wrist as well as between the top of the left hand to the left wrist, pointing in the vertical direction. The Z coordinates are perpendicular to X and Y along the horizontal plane, pointing to the right.

Sternum

The sternum sensor is located on the front-body part, between the top part of the chest and the neck. The sternum sensor measures the body movement by working together with other sensors in order to make accurate calculations. On the MVN measurement mode, the X coordinate is pointing forward, the Y coordinate is the height of the sensor from the ground between joint to joint pointing up and the Z coordinate is perpendicular to X and Y along the horizontal plane, pointing to the right.

Pelvis

The pelvis sensor is located on the back-body part in the midpoint between the right and left hip center of rotation. Together with other sensors, the pelvis sensor also measures the body movement in order to add to the accurate overall calculations. On the MVN measurement mode, the X coordinate is pointing forward, perpendicular to Y and Z. The Y coordinate is the height of the sensor from the ground between the hip origin and a joint, pointing up. The Z coordinate is in between the left hip joint and the right hip joint, along the horizontal plane, pointing to the right.

Upper legs

The upper leg sensors are located on the thigh area between the hip and the knee, on both sides of the legs. The upper leg sensors measure the movement of the upper legs. On the MVN measurement mode, the X coordinates are perpendicular to Y and Z and pointing forward on the sagittal plane. The Y coordinates are the vertical position of the sensors, between the left knee and the left hip as well as between the right knee and right hip. The Z coordinates are located between the left/right medial to the left/right lateral along the horizontal plane, pointing to the right.

Lower legs

The lower leg sensors are located between the knees and the ankle on both side of the legs, left and right. The lower legs sensors measure the movement of the lower legs. On the MVN measurement mode, the X coordinates are pointing forward in sagittal plane and perpendicular to Y and Z. The Y coordinates are the vertical position of the sensors, between the left ankle and the left knee and also between the right knee and right ankle. The Z coordinates are located between the right medial to the right lateral and between the left lateral to the left medial along the horizontal plane, pointing to the right.

Foot

The foot sensors are located between the ankles and the toes, on both sides of the foot. The foot sensors measure the movement of the foot. On the MVN measurement mode, the X coordinates are pointing forward on the sagittal plane. The Y coordinates are vertical, aligned with gravity and pointing up. The Z coordinates are perpendicular to X and Y along the horizontal plane, pointing to the right.

5.6 Cognitive Ergonomics

Parallel to the classical ergonomics observation from the actual 3D printer building tasks, the well-being of the participants is also observed through the so-called cognitive ergonomics. Cognitive ergonomics, seen as a division of ergonomics [141], aims to ensure the appropriate symbiosis among human needs, limitations, capabilities and the environment where the human is working, together with work and the product. It can be seen as a human-system interaction where the focus lies on the mental processes, especially on interactions on the level of psychological/behavioral and cognitive functions. The theoretical background are cognitive science and cognitive psychology.

Specifically, the aim of cognitive ergonomics is to design working conditions and working environments that support and enhance human performance and cognitive functioning at work, which, as a consequence, improves productivity, safety and health at work.

The nature of the human cognitive system, especially the knowledge, is needed in the design of applications, equipment, appliances, etc. It is useful in outlining the important aspects when working environment is fitted to the human cognitive functions that are relevant to the tasks, thus, creating an acceptance of the required tasks by the human.

One of the aims of cognitive ergonomics in the IT area is to ensure that working with computer application provided information should be effortless and ICT should not create unnecessary burdens but should improve workers ability to perform instead.

The following cognitive functions of the participants are evaluated in this study through questionnaire questions: sensation and perception, attention and working memory that includes short-term memory and long-term memory.

Sensation and perception are feeling and recognition gathered through senses, such as hearing and sight. The software application provides audio warnings and visualization warnings throughout the experiment. Attention is paid throughout the experiment on the information given by the software application as the software provides the necessary information on how the participant should work safely, avoiding injuries and dangers. Short term memory, which is available for up to 30 seconds, is evaluated through information provided on the instruction sheets. Participants are required to remember the items and parts needed for a particular task stage. Long term memory is evaluated through anchoring, on participant's mind that he has to work in a safe manner and avoid danger whenever possible. In addition, at the beginning of the second experiment, the safe and correct way of working according to ergonomics standards are briefed. The participant should always put this in mind.

Cognitive ergonomics obtains specific knowledge during a specific task completion process and situation, based on experimental and behavioral methods. In everyday contexts, the results of human cognition studies have ecological validity, which means, the obtained result also applies outside the experiment. In addition, the generalizability rule is also obtained, which means that the results can also be applied outside of the specific experiment contexts. This fits nicely with the concept of pilot factory which is simulating the real-world manufacturing environment. In addition to the physiological and behavioral methods, questionnaires are also another important method that could be used to evaluate the cognitive ergonomics. This method is also used in this study.

5.7 Work Instructions

The work instructions (see section 5.1.2) are divided into different sections. The first section contains the three important levels of the task; assembly load level, physical load level and the complexity level. The levels are either low or high. These tasks level classifications are adopted from complexity level study by Falck and Rosenqvist [41]. The complexity criteria in this study is based on the standard postures/movement of two trained lab personnel who have repeatedly performed the tasks many times. These personnel also undergone a questionnaire session where they all explicitly stated that nothing harmful came up from the tasks performed. The 3D printer assembly tasks executed in this study were mainly assessed based on the KIM Method.

High ergonomics tasks are classified by following conditions: Complexity is considered high when more than one way is possible to accomplish the task, many individual details and parts, no clear mounting positions, poor access, poor ergonomics conditions, steps must be done in certain orders, precision and accuracy are expected, and etc. Assembly load and physical load level are high when tasks require the participant to carry heavy items, bent in such posture that the angle is more than 60 degrees, heavy force exertion is needed and other factors that drains participants energy.

In this study out of the six tasks, there are no high assembly load and physical load level. However, there are three high complexity level tasks toward the end of the experiment.

The aim of classifying the assembly load level, physical load level and the complexity level is to prevent injuries, incident, accident and also work-related musculoskeletal disorders while building a 3D printer. The levels in this study are designed to be compatible for any gender of employee, as well as employees between the ages of 18 and 60 years old of age.

5.8 Model

In order to conclude this study, the following model is developed. This model is originated from the workstation ergonomic design model by Katrin E. Kormer Elbert et al. in her book Ergonomics How to Design for Ease and Efficiency. Based on this study, three factors are inserted in the model. These factors are: proper working station, proper work instructions and proper assistant system/software application. The assistant system contains data from previous experiment that can be used in creating proper work instructions. The three factors contribute to proper ergonomic working postures. These postures can be observed and recorded in the assistant system. These proper postures at the end contributed to the well-being of the workers.

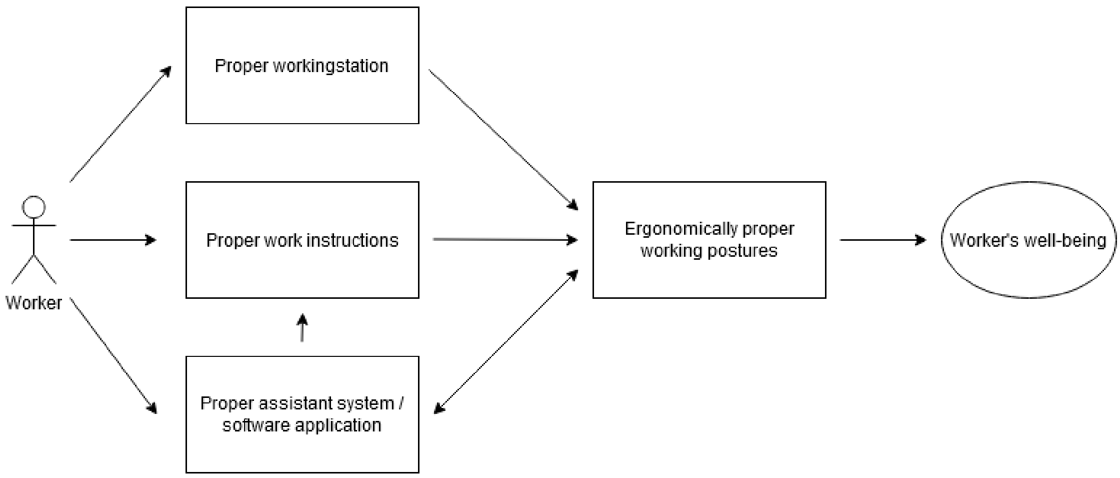


Figure 5.24: Proposed model, developed in this study, based on Holistic Workstation Model from Elbert et al. (2018).

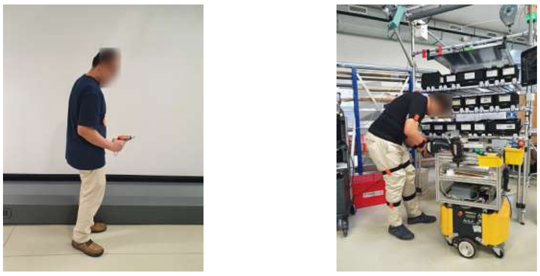
5.9 Postures and Movements Including Risk Assessment Results

The software application developed for this study gathers data from the experiment. The following body parts/regions are relevant to the study, therefore these body parts are mainly examined in the experiment.

5.9.1 Body Parts

Neck

The neck posture is in the neutral posture when the person is standing straight, head facing front, relaxed in the so-called N-Pose. When the person head is inclined or declined, the neck would be in either in extension or flexion posture and this would be awkward postures. Also, when the neck flexion is on lateral plane the posture would be awkward (see figure 5.25 neck awkward).



(a) (b)

Figure 5.25: Neck awkward positions

Wrist

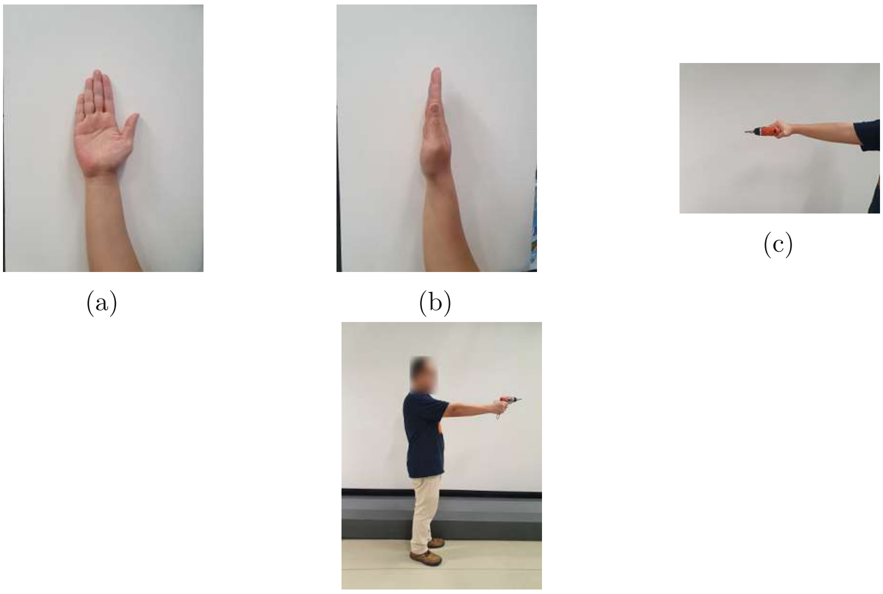
The definition of neutral posture is when there is a minimal deviation of radial or ulnar and minimal flexion or extension of the hand/arm/wrist (see figure 5.26 wrist neutral), other than that, the hand/arm/wrist postures are in awkward postures [142] (see figure 5.27 wrist awkward).

Elbow

The neutral posture of an elbow is when the angle of inclination of the elbow joint is exactly of 90 degrees (see figure 5.28 elbow neutral). The awkward position will be when the elbow is flexed less than 90 degrees or when it is extended between 90 to 180 degrees (see figure 5.29 elbow awkward).

Shoulder

The shoulder is in a neutral posture when the elbow is neutral position, and kept close and attached to the body. Once the shoulder is moved up to the front away from the body, flexing and also when the shoulder is moved to the back away from the body or extending then the shoulder is in awkward postures. Also, when the shoulder is elevated to the side parallel to the shoulder blade, abducting and further beyond that higher, extending, the posture of the shoulder would be awkward (see figure 5.30 shoulder awkward).



(a) (b) (c) (d)

Figure 5.26: Wrist neutral positions

Back

The back posture is in the neutral posture when the person is standing straight and relaxed or the so-called N-pose (see figure 5.31 back neutral). When the person is leaning to the front so the back is flexing and also when the person is leaning to the back so the back is on extension the posture will be awkward. When the person twists his body along the waist and also bending to left or right the posture will also be awkward (see figure 5.32 back awkward).

The software application performs following evaluation methods based on the above body parts postures:

- Time evaluation.
- General Scoring from 0 to 100 using back, neck and wrist postures.
- OWAS evaluation using back, elbow and shoulder postures.
- REBA evaluation using neck, back, arm, elbow and wrist postures.
- RULA evaluation using arm, wrist, neck and back postures.

In addition to the above list, a QEC is also performed to visually assess the ergonomics of the experiment.

The followings are the results of the observation.

5.9.2 Time

The following time has been recorded by the software application The timing starts when the researcher clicks the start button on the application after the participant confirms that he is ready and ends when the researcher hits the finish button after the participant confirms that his task is finished.

First Round in Minutes				
Task	Task ID	Min	Max	Avg
1	3D-AP001-10	0.48	2.76	1.20
2	3D-AP001-20	2.04	6.90	3.20
3	3D-AP001-30	0.78	2.10	1.42
4	3D-AP001-40	0.60	2.04	1.46
5	3D-AP001-50	0.66	2.22	1.11
6	3D-AP001-60	0.72	2.88	1.50

Table 5.1: Summary table of minimum, maximum and average time needed to finish tasks in the first round

Second Round in Minutes				
Task	Task ID	Min	Max	Avg
1	3D-AP001-10	0.42	1.86	0.86
2	3D-AP001-20	2.22	5.40	3.33
3	3D-AP001-30	0.78	2.22	1.32
4	3D-AP001-40	0.90	2.34	1.61
5	3D-AP001-50	0.72	1.92	1.10
6	3D-AP001-60	1.02	4.20	2.07

Table 5.2: Summary table of minimum, maximum and average time needed to finish tasks in the second round

It can be observed that only for the first task, that the completion of the second round is faster than the first round. The completion of the rest of the tasks during the second round are not faster than the first round.

5.9.3 Scoring 0 - 100

Based on the scoring from 0 to 100 (described in chapter 4.1) the following minimum, maximum and average scores have been achieved by the participants:

First round, the minimum score achieved on the first round was 20, the maximum point was 96 and the average was 67.21 points.

Second round, the minimum score achieved on the second round was 63, the maximum point was 100 and the average was 91.36 points.

It can be observed that the scores on the second round is much better than the first round.

5.9.4 Holding and Moving according to the KIM's method

Based on the holding and moving definition of the KIM's method (described in chapter 3.4), the following data have been gathered from the experiment:

First Round							
Task	Task ID	Min Hold	Max Hold	Avg Hold	Min Move	Max Move	Avg Move
1	3D-AP001-10	0	9	3	0	3	2
2	3D-AP001-20	15	40	24	4	14	9
3	3D-AP001-30	23	46	33	6	16	12
4	3D-AP001-40	24	49	39	14	20	17
5	3D-AP001-50	17	48	35	13	22	17
6	3D-AP001-60	32	49	43	12	23	18

Table 5.3: Summary table first round holding and moving

The table 5.4 shows the minimum, maximum and average of holding and moving data from the second experiment.

Second Round							
Task	Task ID	Min Hold	Max Hold	Avg Hold	Min Move	Max Move	Avg Move
1	3D-AP001-10	21	52	43	11	20	15
2	3D-AP001-20	32	49	44	11	18	15
3	3D-AP001-30	36	50	43	13	22	16
4	3D-AP001-40	40	50	44	14	22	18
5	3D-AP001-50	19	49	38	15	24	17
6	3D-AP001-60	33	52	43	9	24	15

Table 5.4: Summary table second round holding and moving

It can be observed that holding and moving on the second round are not less than the first round.

5.9.5 KIM Body posture scores

Based on the KIM's standard scoring method (described in chapter 3.4), the following data have been gathered from the experiment:

The table 5.5 shows the minimum and best KIM score achieved from the first experiment, the lower the number the better ergonomics value is achieved.

First Round			
Task	Task ID	Min	Best
1	3D-AP001-10	0	0
2	3D-AP001-20	1	0
3	3D-AP001-30	3	0
4	3D-AP001-40	3	0
5	3D-AP001-50	3	0
6	3D-AP001-60	3	0

Table 5.5: Summary table KIM minimum and best first round

The table 5.6 shows the minimum and best KIM score achieved from the second experiment, the lower the number the better ergonomics value is achieved.

Second Round			
Task	Task ID	Min	Best
1	3D-AP001-10	1	0
2	3D-AP001-20	1	0
3	3D-AP001-30	1	0
4	3D-AP001-40	1	0
5	3D-AP001-50	1	0
6	3D-AP001-60	3	0

Table 5.6: Summary table KIM minimum and best second round

It can be observed that 83.33% of the score changes are changes into the best score. It can observed too that 51.19% of the score did not change from the first round to the second round, 35.71% of the score changed by 1 score better, 7.14% changed by 2 scores better, and by 5.95% changed 3 scores better.

5.9.6 OWAS

Based on OWAS' method (described in chapter 3.4), the following data have been gathered from the experiment:

Back

The table 5.7 shows the percentage comparison between better changes and no changes from the first round to the second round based on OWAS.

Forearm

It is observed that the forearm remained neutral from the first round into the second round

First to Second Round Back Posture Changes			
Task	Task ID	Better	Neutral
1	3D-AP001-10	42.86%	42.86%
2	3D-AP001-20	35.71%	50.00%
3	3D-AP001-30	35.71%	35.71%
4	3D-AP001-40	42.86%	28.57%
5	3D-AP001-50	42.86%	28.57%
6	3D-AP001-60	35.71%	28.57%

Table 5.7: Summary table OWAS back posture changes first round to second round

Leg

The table 5.8 shows the percentage comparison between better changes and no changes from the first round to the second round based on OWAS.

First to Second Round Leg Posture Changes			
Task	Task ID	Better	Neutral
1	3D-AP001-10	28.57%	50.00%
2	3D-AP001-20	21.43%	71.43%
3	3D-AP001-30	14.29%	42.86%
4	3D-AP001-40	21.43%	57.14%
5	3D-AP001-50	14.29%	78.57%
6	3D-AP001-60	14.29%	78.57%

Table 5.8: Summary table OWAS Leg posture changes first round to second round

5.9.7 REBA

Based on REBA's' method (described in chapter 3.4), the following data have been gathered from the experiment:

The table 5.9 shows the percentage comparison between worse changes and no changes from the first round to the second round based on OWAS.

5.9.8 RULA

It is observed that the maximum points of RULA is reached on the first round and did not change in the second round

5.9.9 Neck

The application recorded the violations in the neck area based on the following criteria: the first, low level of violation with inclination of 10 – 15 degrees and the second, high level of violation with inclination greater than 15 degrees.

First to Second Round Changes			
Task	Task ID	Worse	Neutral
1	3D-AP001-10	85.71%	14.29%
2	3D-AP001-20	85.71%	14.29%
3	3D-AP001-30	78.57%	21.43%
4	3D-AP001-40	50.00%	42.86%
5	3D-AP001-50	21.43%	71.43%
6	3D-AP001-60	7.14%	92.86%

Table 5.9: Summary table posture changes first round to second round

		First Round		Second Round		
Task	Task ID	Max Low	Max High	Max Low	Max High	Total
1	3D-AP001-10	14	5	21	10	50
2	3D-AP001-20	21	27	49	39	136
3	3D-AP001-30	8	11	24	14	57
4	3D-AP001-40	10	13	21	17	61
5	3D-AP001-50	10	6	16	8	40
6	3D-AP001-60	11	11	32	15	69
	Total	74	73	163	103	413

Table 5.10: Summary of maximum low and high level neck violations

5.9.10 Trunk

The application recorded the following violations in the trunk/back posture, the first, low level of violation with inclination of 10 – 15 degrees and the second, high level of violation with inclination greater than 15 degrees.

		First Round		Second Round		
Task	Task ID	Max Low	Max High	Max Low	Max High	Total
1	3D-AP001-10	3	5	1	2	11
2	3D-AP001-20	9	25	12	8	54
3	3D-AP001-30	4	17	1	5	27
4	3D-AP001-40	2	0	5	1	8
5	3D-AP001-50	3	0	4	0	7
6	3D-AP001-60	4	16	3	11	34
	Total	25	63	26	27	141

Table 5.11: Summary of maximum low and high level trunk violations

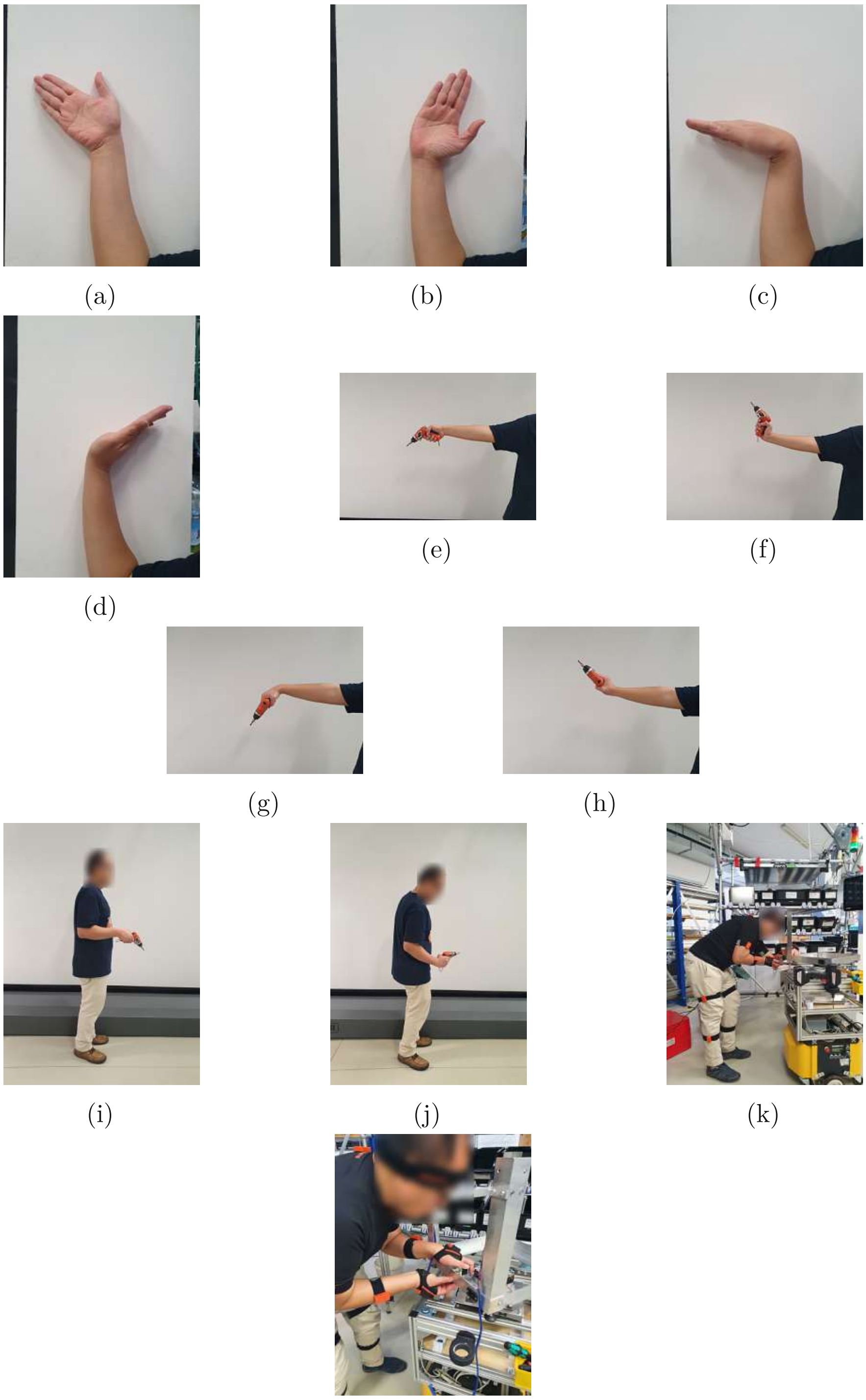
5.9.11 Wrist

The maximum wrist movement recorded on a task in the first round was 23, and in the second round was 24.

5.9.12 QEC (Quick Exposure Check)

Parallel to the data collected by the application tool, a manual visual ergonomics exposure checks were also done by 3 different observers alternatively not in parallel. The result showed that on all of the 6 tasks done twice by each participant, when maximum measurement results are taken, the exposure levels of the back is low (14), shoulder/arm is low (18), wrist/hand is low (16), neck is moderate (8), driving is low (1), vibration is low (1), work pace is moderate (4) and stress is moderate (4).

Subjective rating of exertion and tiredness, and the usability and acceptance of the software are also rated in this study through the participants questionnaire.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Figure 5.27: Wrist awkward positions


(a)


(b)


(c)

Figure 5.28: Elbow neutral positions

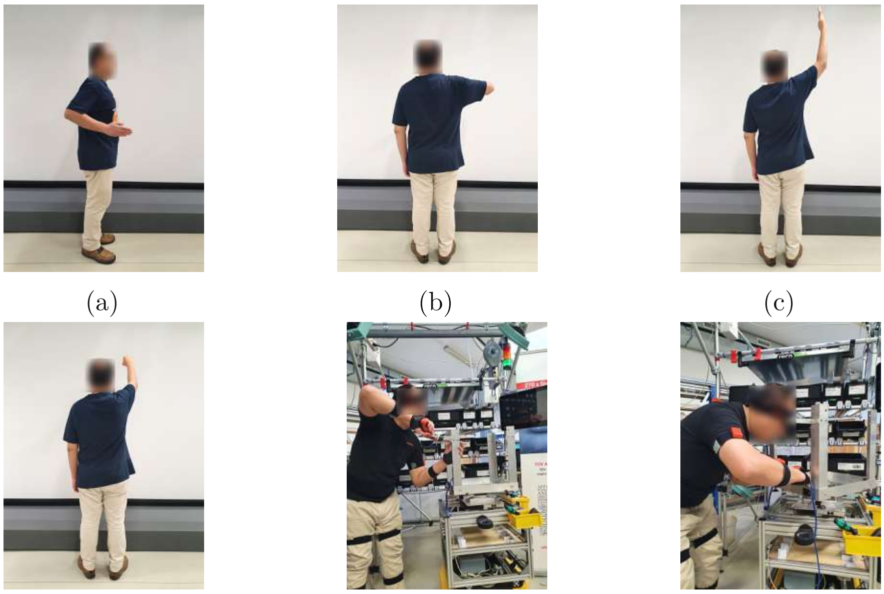

(a)


(b)


(c)


(d)

Figure 5.29: Elbow awkward positions



(a) (b) (c) (d) (e) (f)

Figure 5.30: Shoulder awkward positions

(a) (b) (c)

Figure 5.31: Back neutral positions


(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

(j)

Figure 5.32: Back awkward positions

CHAPTER 6

Discussion

Findings from the study will be reviewed in this chapter. The first section discusses the response rates of this study. The section after, will describe the demographics of the participants. Responses to the survey questions will be discussed in the section afterwards. The last section on this chapter will highlight the limitations on this study.

6.1 Participation and Response Rate

The experiment participation and questionnaire response rate is 100%, with 14 respondents (N=14). In addition to these 14 participants, there were three additional referral participants whose scores and results were taken as standard scores and measurements. Two out of the three referral participants are employees of the Pilot Factory Industry 4.0. These two have been properly trained and have done the assembly many times in the safest and most efficient ways. The one extra referral participant is an external participant. This participant was completely guided throughout the experiment, based on the experiment done by the two previous experts. The objective of a fully-guided experiment is to achieve the maximum score and maximum ergonomics safety. All respondents completed the questionnaires, answering all the questions provided and gave responses to all the five demographics questionnaires asked.

6.2 Demographics

6.2.1 Gender

The gender balance is guaranteed in this experiment. There were 7 female participants and 7 male participants out of total 14 participants.

(see figure 6.1 Participants' gender.)

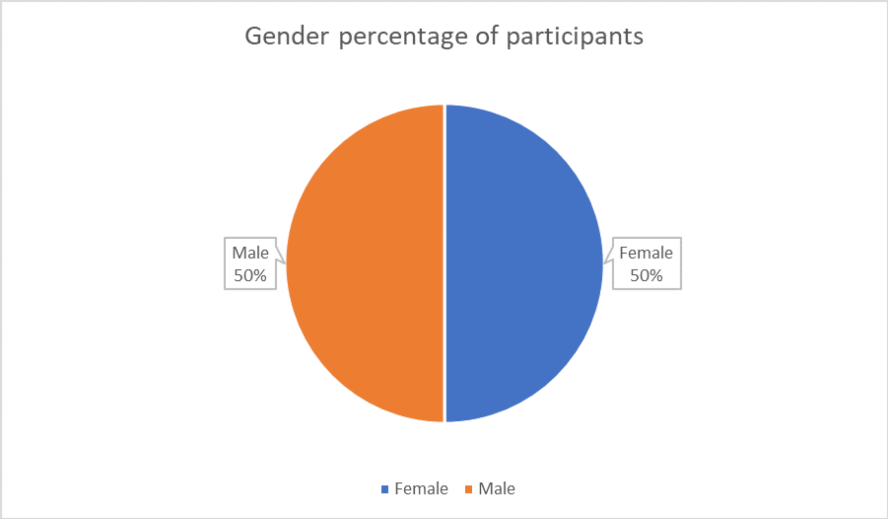


Figure 6.1: Participants' gender.

6.2.2 Age ranges

The age range of the participants is from 25 to 54 years old. 57% of the participants are on the age range of 25 to 34, 29% of the participants are within the range of 35 to 44 years old and 14% are within the range of 45 and 54 years old (see figure 6.1 Participants' age.)

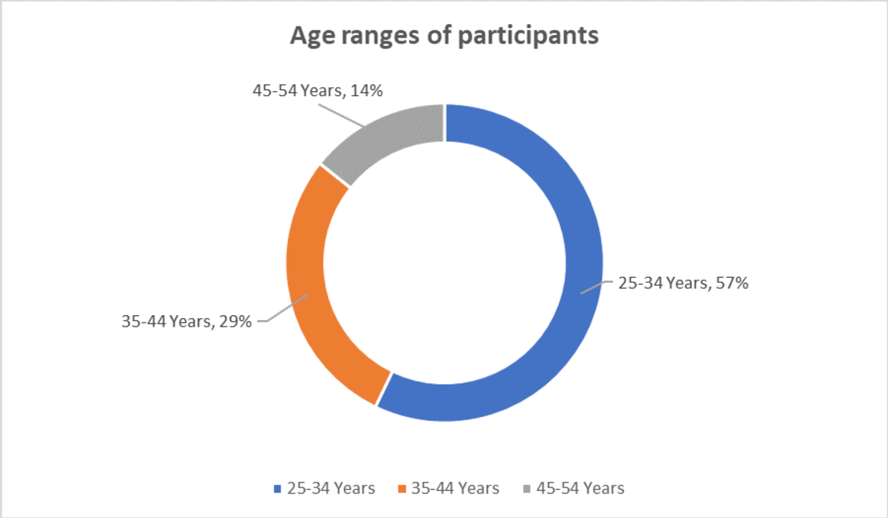


Figure 6.2: Participants' age.

6.2.3 Height range

The height ranges of the 14 participants are almost equally distributed from 160 cm to 180 cm and above. 36% of the participants height are within the range of 160 to 169 cm. Another 36% are within the range of 170 to 179 cm and the other 26% are within the range of 180 cm and above (see figure 6.3 Participants' height.)

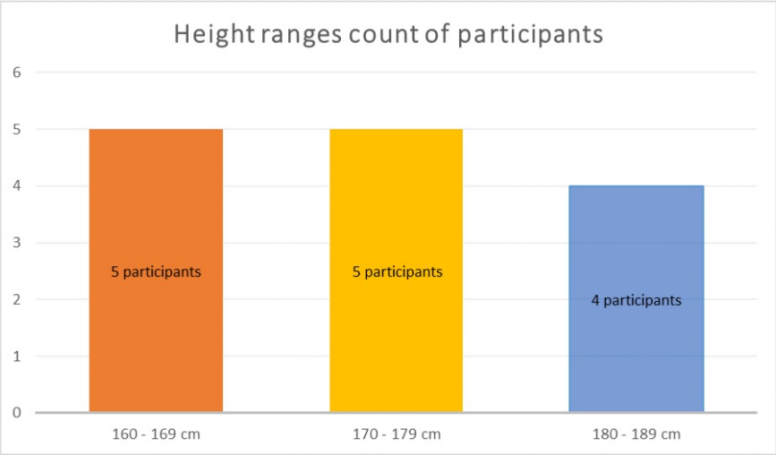


Figure 6.3: Participants' height.

6.2.4 Hand dominance

Most of the participants have their right hands as the dominant hand, whereas one participant was left-handed. Therefore, both sides of hand dominance are represented. (see figure 6.4 Participants' dominance hand.)

Figure 6.4: Participants' dominance hand.

6.2.5 Highest education level completed

The highest education level achieved by the 14 participants are ranging from apprenticeship, high school and university. Each of the education level is represented. 86% of the participants have a highest education level of university, 7% has the apprenticeship as the highest level of education and the other 7% has high school as the highest level of education. (see Figure 6.1 Participants' completed education.)

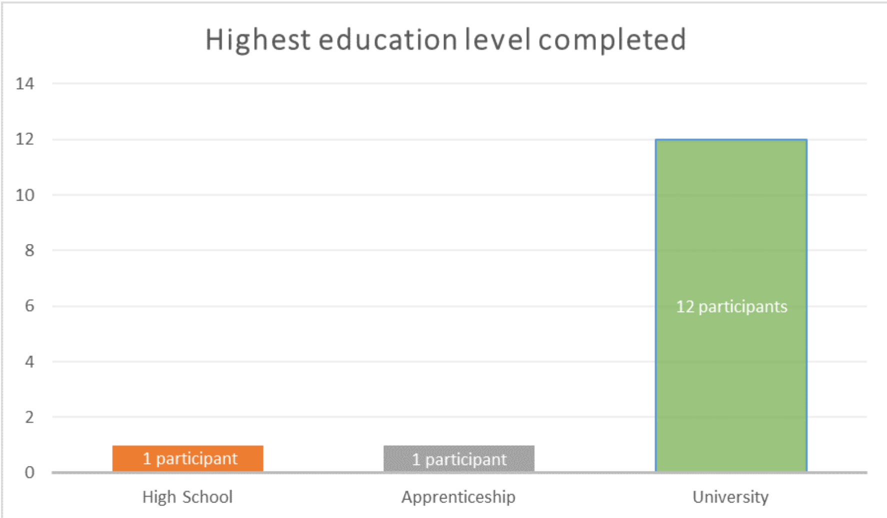


Figure 6.5: Participants' completed education.

6.3 Responses to the Survey Questions

All of the questions were responded by the participants. The questions were grouped into the following groups:

1. Questions regarding to participants' conditions and well-being prior to taking the experiment.
2. Questions regarding participants feeling towards the experiment.
3. Post experiment 1 questionnaire regarding the tasks performed.
4. Post experiment 1 questionnaire regarding participation expectation and requirement toward an assisting computer application tool/solution and how information and instructions should have been presented.
5. Post experiment 1 questionnaire regarding participants' conditions and well-being after taking the first experiment.

6. Post experiment 1 questionnaire regarding participants' opinion about ergonomics standards.
7. Post experiment 2 questionnaire regarding participants' conditions and well-being after taking the second experiment.
8. Post experiment 2 questionnaire regarding participants' opinion about ergonomics standards.
9. Post experiment 2 questionnaire regarding working environments and helping tools based on the KIM's conditions.
10. Post experiment 2 questionnaire regarding participants acceptance towards the application tool/solution.

Grouping of survey responses

In order to distinguish whether responses are actually positive or negative, closer sentiment answers by the participant will be grouped together (e.g., strongly disagree is grouped together with disagree to represent negativity and some with agree a lot are grouped together to represent positivity). These groupings are done on both for the response count calculation and the Likert score calculation. Example: if a participant responds on strongly disagree and another participant responds with disagree, the total count of general disagree responses is counted as 2 points. The likert score is 1 (strongly disagree) + 2 (agree) which is equal to 3 points. The resulting percentage calculations are also based on this grouping.

Conditions prior to taking experiment questions

There are a total of 7 questions regarding negative conditions of the participants such as tiredness, muscle tensity and etc. The result of this sets of questions shows that 82.86% participants are not at all agreed or only a little agreed of having negative conditions prior to experiment. 21.16% Likert score percentage is achieved from this set of questions, with the majority answers of not at all and a little. This shows that only minimum points can be achieved from agreement of the negative conditions of the participants prior to the experiment.

Participants feeling towards the experiment

There are a total of 5 questions regarding positive attitude and feeling of the participants such as fitness, curiosity, excitement, motivation toward the experiment. The result of this sets of questions shows that 91.43% participants are somehow agreed or agree a lot to the positivity toward the experiment. The Likert score percentage achieved of this set of questions for the majority answers of some and a lot is 86.29%, which shows rather high points can be achieved from agreement of the participants positive attitude toward the experiment.

Post experiment 1 questionnaire regarding the tasks performed

There are a total of 6 questions regarding negative sentiments toward the tasks performed, situations like the rushing pace of the experiment, not being successful, insecurity while completing the tasks, complexity and etc. The result of this sets of questions shows that 79.76% participants are either strongly disagreed or disagreed of having negative sentiments to the tasks in the experiment. The Likert score percentage achieved of this set of questions for the majority answers of strongly disagree and disagree is 22.00%, which shows only minimum points can be achieved from agreement of the negativity toward the tasks of the experiment.

Post experiment 1 questionnaire regarding participation expectation and requirement toward an assisting computer application tool/solution, and how information and instructions should have been presented

(a). How information and instruction should be presented:

There are a total of 10 questions regarding of suggestions of how the information or instruction should be presented, factors like design, visualization, text legibility, audio audibility, structure and etc. The answers provided are based on a 5 Likert score of agreement, starting from strongly disagreed, up to strongly agreed, points are given from 1 to 5 where 1 is the lowest which is equal to strongly disagree and 5 is the highest score which is equal to strongly agreed. The answer percentage calculated on this set of questions show the percentage of participants agreement towards certain group of answer sets, either in the combination of strongly disagree and disagree (which represents negativity) or combination of agree and strongly agree (which represents positivity).

The Likert score percentage achieved on this set of questions shows how high or low participant's agreement with the design of the information and instruction suggested. The result of this sets of questions shows that 67.14% participants are either strongly agreed or agreed to the suggested design. The Likert score percentage achieved of this set of questions for the majority answers of strongly agree and agree is 58.71%, which shows that barely majority of points can be achieved from agreement of the suggested design

(b). Whether an assistant computer application could help in accomplishing the tasks:

There are a total of 3 questions regarding of whether an application could help in accomplishing the tasks, avoiding injuries and long-term effects. The result of this sets of questions shows that 67.35% participants are either strongly agreed or agreed that a computer application tool could help in completing the tasks.

The Likert score percentage achieved of this set of questions for the majority answers of strongly agree and agree is 49.29%, which shows that majority of points can be achieved from agreement of the help from a computer application tool. A neutral percentage of 15.00% can be observed from this sets of questions, which resulted that the majority of the participants either having neutral opinions toward the assistant tool or agreed and strongly agreed.

(c). Computer application tool design

There are a total of 2 general questions regarding of how the application should be designed. The result of this sets of questions shows that 71.43% participants are either strongly agreed or agreed on how the computer application tool should be designed, based on the suggested questionnaire. The Likert score percentage achieved of this set of questions for the majority answers of strongly agree and agree is 63.57%, which shows that majority of points can be achieved from agreement on how the computer application tool should be designed.

Post experiment 1 questionnaire regarding participants' conditions and well-being after taking the first experiment

There are a total of 10 questions regarding negative conditions of the participants after taking the first experiment, such as tiredness, dizziness, pains, discomfort and etc. The result of this sets of questions shows that 99.29% participants are not at all agreed or only a little agreed of having negative conditions after the first experiment. The Likert score percentage achieved of this set of questions for the majority answers of not at all and a little is 21.29%, which shows only minimum points can be achieved from agreement of the negative conditions of the participants after the first experiment.

Post experiment 1 questionnaire regarding participants' opinion about ergonomics standards

There are a total of 3 general questions regarding the ergonomics standard, whether the participant was sure that he avoided any possible injuries, whether he did tasks according to ergonomics standard, and whether if he repeats the same tasks again that there is a chance that he could be injured or having pains. The response to the question of whether possible injuries are avoided are 35.71% participants are not at all agreed or only a little agreed, 35.71% participants are somehow agreed or agreed a lot, and 28.57% of the participants responded with neutral. Therefore, a clear agreement could not be observed out of this response.

The response to the question of whether the participants did the asks according to ergonomics standards are 57.14% participants are not at all agreed or only a little agreed, only 14.29% participants are somehow agreed or agreed a lot, and 28.57% of the participants responded with neutral. Therefore, a slight majority of the participants agreed that they did not do the tasks according to the ergonomics standards.

The response to the question of whether if the participants repeat the tasks again that that there is a chance that they could be injured or having pains are responded with 78.57% of the participants are not at all agreed or only a little agreed, therefore, a majority of the participants agreed that they won't be injured or having any pains when repeating the tasks.

Post experiment 2 questionnaire regarding participants' conditions and well-being after taking the second experiment

There are a total of 9 questions regarding negative conditions of the participants after taking the second experiment, such as tiredness, dizziness, pains, discomfort and etc. The result of this sets of questions shows that 100% participants are not at all agreed or only a little agreed of having negative conditions after the first experiment. The Likert score percentage achieved of this set of questions for the majority answers of not at all and a little is 21.27%, which shows only minimum points can be achieved from agreement of the negative conditions of the participants after the second experiment.

Post experiment 2 questionnaire regarding participants' opinion about ergonomics standards

There are a total of 2 general questions regarding the ergonomics standard, whether the participant was sure that he avoided any possible injuries, and whether he did tasks according to ergonomics standard. The response to the question of whether possible injuries are avoided are 71.43% participants are somehow agreed and agreed a lot, therefore a majority of participants agreed that possible injuries are avoided using the software application tool. Comparing to the response of the same questions while asked after the first experiment there is an increase of 35.72% response in the positive agreement, and a decrease of 28.57% of the negative agreement.

The response to the question of whether the participants did the asks according to ergonomics standards are 78.57% of the participants are somehow agreed or agreed a lot, therefore, a majority of the participants agreed that they did the tasks according to the ergonomics standards using the software application. Comparing to the response of the same questions while asked after the first experiment there is an increase of 64.28% response in the positive agreement, and a decrease of 50% of the negative agreement.

Post experiment 2 questionnaire regarding working environments and helping tools based on the KIM's conditions

There are a total of 9 questions regarding the working environments satisfaction, and helping tools, based on the KIM's conditions. The result of this sets of questions shows that 77.78% participants are either agreed or strongly agreed with the positivity of the working environment and the tools. The Likert score percentage achieved of this set of questions for the majority answers of strongly agree and agree is 62.00%, which shows that majority of points can be achieved from agreement of the satisfaction toward the working environment and the tools.

Post experiment 2 questionnaire regarding participants acceptance towards the application tool/solution

There are a total of 7 questions regarding the usability, acceptance, attractivity, trust in software, and contribution of the software in ergonomics safety. The result of this sets of questions shows that 82.65% participants are either much agreed or very much agreed with the usability, the function, the design, the acceptance and the contribution of the software application tool. The Likert score percentage achieved of this set of questions for the majority answers of strongly agree and agree is 70%, which shows that majority of points can be achieved from agreement on how the usability and acceptance of the software application.

6.4 Study Limitations

As it is common with other studies, this study also has its limitations. Technical limitations caused by the supporting tools (in this case, the sensors) and previously unknown/unpredictable behavior of the instruments lead to three major limitations. First, although performed real-time, ergonomics measurement delays are unavoidable. Second, the sensitivity of the provided sensors have its own performance limitations. Third, movements are occasionally incorrectly identified by the sensors.

Real Time Ergonomics Assessment with Delays

Due to delays caused by transmission time of data from the sensors, analyzed by the software until it finally triggers the alarm, there will be a slight delay from when the violation actually happens until the warning is shown/sounded to the participant. This creates confusion to participants as they were trying to figure out what they did wrong. This issue is handled by showing the last violation through a visual and textual description on the screen. Due to this reason, there will also be a slight delay until the system recognizes that the person has returned to a safe/correct postures.

Undetectable Movements

Due to the nature of the motion sensors that records the changes of position of the sensor units, sudden jolted movement were not recorded by the system. Only slow movement can be identified by the sensors, as it is gradually identifying the change of the sensors' locations.

False-Identified Movements

The application, sometimes falsely interpreted the inclination of the body posture either to the front or to the back. This is caused by the incorrect data sent by the sensors. The sensors have sometimes difficulties of identifying the direction of movement when they are idling in the same positions for a longer period. For this study this does not create an issue, as the measurement of inclination to the front and to the back are classified into the same violations based on the degrees of the inclination (positive/negative). In order to fix the issue, a recalibration of MVN should be performed, or the participant should move around in a greater area.

CHAPTER 7

Conclusion and Future Work

Due to the high response rate of the participants (all the questions were answered), the non-response bias is minimized [143]. The questionnaires responses suggested that 85.71% of the respondents see the application as either much or very much useful. In addition to this, measurement data are collected and analyzed by the application. These data and the analysis process create ergonomics KPI, contributing toward safer and healthier working conditions. The questionnaires responses also suggested that 82.65% respondents show much or very much acceptance toward the application. This shows that the application is well accepted by the participants. The application served its purpose as a "Proof of Concept" of a supplementary factor, in combination with a 3D motions tracking suit, in preventing work related musculoskeletal disorders and injuries.

One participant pointed out that the sounded-off audio warnings were disturbing and created unnecessary additional stress. This resulted in poor scoring of the participant, as the participant accelerated the working speed with the intention of getting rid of the sound. Another participant suggested that the audio warning should inform the participant about the source of the violation. The warning should state the location of the body region. The participant can then react accordingly to adjust the posture for example by correcting the back posture.

It is observed that the nonadjustable height of the working station has negative impacts on positive ergonomics scores in completing tasks. Taller participants tend to have lower scores than shorter ones.

It is not possible to observe that productivity was increased after the second round. What was possible to be observed is that participants have better ergonomics score on the second round. Participants are more aware of the ergonomics values. This could lead to injuries and long-term disorders reduction and avoidance in a working condition. It was also possible to observe that in general the second round of the experiment ended four minutes faster than the first one, but this cannot be traced to the same participants.

Research Questions Discussions

RQ1: What are the "safe" threshold ranges that could lead to a positive ergonomic assessment measurement result?

This research question can be answered using the data gathered through the experiment. There were no incidents of any kind recorded during all the experiment, thus following collected data (duration, movements, neck violation, trunk violation, wrist movement) by the software application can be used by workers performing assembly tasks as a threshold to ensure workers safety.

Time

The maximum time achieved was 17 minutes on the first round and 13 minutes on the second round. There was a one-minute break after each task to read the instructions and a 5-minutes break between the first and second round to fill out surveys. In total, there were 45 minutes of working time, including the obligatory breaks, or 30 minutes of pure working time without any incidents.

Movements

In these 30 minutes of pure working time, there was an average of 432 seconds of holding action and 171 occurrences of movements.

Neck

In these 30 minutes of pure working time there were maximum of 237 first-level neck violation and 176 second-level neck violation recorded

Trunk

In these 30 minutes of pure working time there were maximum of 51 first-level trunk violation and 90 second-level trunk violation recorded

Wrist

In these 30 minutes of pure working time there were maximum of 47 occurrences of wrist joint movements recorded.

RQ2: To what extent can real-time ergonomic measurement activities decrease the risk of injuries or illness in 3D printer assembly lines?

Real-time ergonomics measurement activities in a controlled lab environment can contribute to the decrease of injuries and illness in 3D printer assembly lines in twofold, preventive and correction efforts.

Based on this study, real-time data can be gathered from the real-time ergonomics measurement. These data can be immediately harvested, recorded and later on analyzed. The data collected from the measurement can be used to create ergonomics boundaries/threshold avoiding incidents and injuries. These threshold should not be violated in order to maintain the well-being of the worker.

Prevention and Correction Effort

A self-developed application, that is equipped with ergonomics standards can maintain the safety of the workers by sounding warning whenever the ergonomics standard safe limits, such as neck and trunk postures, are violated. The real data gathered are immediately evaluated and matched with the standard ergonomics values in the system. With a slight delay, whenever a limit is violated, an alarm will be sounded. Through the alarm, the worker is warned that he is doing something wrong and should stop or act accordingly to correct his posture/movement.

The boundaries data collected act as a preventive mechanism that keeps the workers away from work-related musculoskeletal disorders and any other illness or injuries related to this particular work. These boundaries data can then be integrated in writing future work instructions, for example in 3D printer factory assembly lines, ensuring the safety of the workers by referring to the experiment that has been done in a simulated 3D printer factory assembly line based on specific ergonomics standards.

Future Work

The experiment in the current study has been scoped to a limited extent in order to ensure participants' comfort and safety, while still serving its purpose as a proof of concept. It is designed in a way that participants' energy, time and effort are spent effectively.

The chosen tasks in this study were limited to the tasks to be completed at the first working station of a 3D Printer assembly line. After the completion of the first station, there are no incidents or accidents nor any signs of fatigue or exhaustion of the participants. Therefore, there is still room to improve the complexity of the experiment. One example is to expand the tasks by including the second work stations of the 3D Printer assembly line. This will increase the effort and time needed by the participant as the tasks on the second station are more complex and detailed, involving more specific activities. On the other hand, this will increase the risk of participants being exposed to injuries or exhaustion. By increasing the number of tasks, new thresholds, where injuries, incidents or exhaustions still can be avoided, could be discovered.

As this study also contributes to the Information and Technology (IT) field, it would be interesting to see this ergonomics study be expanded to IT workers. IT workers, especially developers, spend many hours sitting on a chair, at a desk, typing on a keyboard, scrolling a mouse and staring at a monitor when doing their work. Similar to a 3D printer/electronic manufactory worker, IT workers are prone to injuries in the upper limb areas (shoulder and neck), wrist and arm joints as well as pelvis and hip joints.

What differentiates them is that manufactory workers rely only on instructions and skills in order to complete assembly tasks, whereas IT workers rely more on their algorithmic and logical skill when developing codes. Through specific sets of instructions, movements of manufactory workers could be predicted. For example, when it is written to screw, there is a high probability that a manufactory worker will use his hands and perform turning motions. On the other hand, the movements of an IT worker would be harder to predict when he is given instructions to build a website for a snow removal company based in a town in the Sahara Desert.

The combination of body ergonomics and cognitive ergonomics could support and expand the common classical ergonomics studies. It would be interesting to observe whether correct sitting body postures at desk could make IT workers to use their mind more efficiently. Another way it could expand the study is to explore the threshold of how long an IT worker can sit before any injuries or back pain occurs.

List of Figures

List of Tables

List of Algorithms

Code dumps

```
Imports System.Threading
Imports System.Net.Sockets
Imports System.Text
Imports System.ComponentModel
Imports System.Net
Imports System.Data.SqlClient
Imports System.IO
Imports Tesseract

Public Class frmMain

   Private Sub frmMain_Load(sender As Object, e As EventArgs)
      Handles MyBase.Load

   Private Sub frmMain_Closing(sender As Object, e As
      CancelEventArgs) Handles MyBase.Closing

   Public Sub udp_start()

   Private Sub client_SendMessage(ByVal ip As String, ByVal
      port As Integer, ByVal msg As String)

   Private Sub tmrWriteSql_Tick(sender As Object, e As
      EventArgs) Handles tmrWriteSql.Tick

   Private Sub BackgroundWorker1_DoWork(sender As Object, e As
      DoWorkEventArgs) Handles BackgroundWorker1.DoWork

   Private Sub tmrXsensData_Tick(sender As Object, e As
      EventArgs) Handles tmrXsensData.Tick

   Private Sub tmrWorker_Tick(sender As Object, e As EventArgs)
       Handles tmrWorker.Tick
```

```
Private Sub btnCalibrate_Click(sender As Object, e As
   EventArgs)

Private Sub btnReset_Click(sender As Object, e As EventArgs)

Public Function unixTime() As Integer

Private Sub Button1_Click(sender As Object, e As EventArgs)

Private Sub pic1dis_Click(sender As Object, e As EventArgs)

Private Sub picBalkenNacken_Click(sender As Object, e As
   EventArgs)

Private Sub TabPage2_Click(sender As Object, e As EventArgs)

Private Sub picBalkenNacken_Click_1(sender As Object, e As
   EventArgs) Handles picBalkenNacken.Click

Private Sub picCursorNacken_Click(sender As Object, e As
   EventArgs) Handles picCursorNacken.Click

Private Sub Label3_Click(sender As Object, e As EventArgs)

Private Sub TabPage2_Click_1(sender As Object, e As
   EventArgs) Handles OldKIMTabPage.Click

Private Sub WorksTableBindingNavigatorSaveItem_Click(sender
   As Object, e As EventArgs)

Private Sub Button2_Click(sender As Object, e As EventArgs)

Private Sub Button3_Click(sender As Object, e As EventArgs)

Private Sub Button9_Click(sender As Object, e As EventArgs)

Private Sub Button5_Click_1(sender As Object, e As EventArgs
   ) Handles Button5.Click

Private Sub Button4_Click(sender As Object, e As EventArgs)
   Handles Button4.Click
```

```
Private Sub ComboBox1_SelectedIndexChanged(sender As Object,
    e As EventArgs)

Private Sub Button8_Click(sender As Object, e As EventArgs)
   Handles Button8.Click

Public Sub executeyourquery(ByVal query As String)

Public Sub executeinsertquery(ByVal query As String)

Public Sub executenewstepquery(ByVal query As String)

Public Sub executeinsertitemquery(ByVal query As String)

Public Sub executeinsertsegmentquery(ByVal query As String)

Public Sub executeinsertactivityquery(ByVal query As String)

Public Sub executeinsertscorequery(ByVal query As String)

Private Sub Button10_Click(sender As Object, e As EventArgs)
    Handles Button10.Click

Private Sub Button11_Click(sender As Object, e As EventArgs)
    Handles Button11.Click

Private Sub Button12_Click(sender As Object, e As EventArgs)
    Handles Button12.Click

Private Sub Button6_Click_1(sender As Object, e As EventArgs
   ) Handles Button6.Click

Private Sub Button3_Click_2(sender As Object, e As EventArgs
   ) Handles Button3.Click

Private Sub Button2_Click_1(sender As Object, e As EventArgs
   ) Handles Button2.Click

Private Sub Button14_Click(sender As Object, e As EventArgs)

Private Sub Button7_Click(sender As Object, e As EventArgs)
   Handles Button7.Click
```

```
Private Sub Button16_Click(sender As Object, e As EventArgs)
    Handles Button16.Click

Private Sub Button18_Click(sender As Object, e As EventArgs)
    Handles Button18.Click

Private Sub Button19_Click(sender As Object, e As EventArgs)
    Handles Button19.Click

Private Sub CategoryTextInsertComboBox_SelectedIndexChanged(
   sender As Object, e As EventArgs) Handles
   CategoryTextInsertComboBox.SelectedIndexChanged

Private Sub tmrForceExert_Tick(sender As Object, e As
   EventArgs) Handles tmrForceExert.Tick

Private Sub MinuteTimer_Tick(sender As Object, e As
   EventArgs) Handles MinuteTimer.Tick

Private Sub Button21_Click(sender As Object, e As EventArgs)
    Handles Button21.Click

Private Sub Button22_Click(sender As Object, e As EventArgs)
    Handles Button22.Click

Private Sub Button23_Click(sender As Object, e As EventArgs)
    Handles FreeModeButton.Click

Private Sub Button24_Click(sender As Object, e As EventArgs)
    Handles WorkpackagesButton.Click

Private Sub TimerFlag1_Tick(sender As Object, e As EventArgs
   ) Handles TimerNeck1.Tick

Private Sub Button25_Click(sender As Object, e As EventArgs)
    Handles Button25.Click

Private Sub TimerTrunk1_Tick(sender As Object, e As
   EventArgs) Handles TimerTrunk1.Tick

Private Sub ScoreResetButton_Click(sender As Object, e As
   EventArgs) Handles ScoreResetButton.Click
```

```
Private Sub ScoreStartButton_Click(sender As Object, e As
   EventArgs) Handles ScoreStartButton.Click

Private Sub ScoreStopButton_Click(sender As Object, e As
   EventArgs) Handles ScoreStopButton.Click

Private Sub FreeScoreTimer_Tick(sender As Object, e As
   EventArgs) Handles FreeScoreTimer.Tick

Private Sub ScoreSaveButton_Click(sender As Object, e As
   EventArgs) Handles ScoreSaveButton.Click

Private Sub WPLoadButton_Click(sender As Object, e As
   EventArgs) Handles WPLoadButton.Click

Private Sub WPStepComboBox_SelectedIndexChanged(sender As
   Object, e As EventArgs) Handles WPStepComboBox.
   SelectedIndexChanged

Private Sub WPNextStepButton_Click(sender As Object, e As
   EventArgs) Handles WPNextStepButton.Click

Private Sub VariationComboBox_SelectedIndexChanged(sender As
    Object, e As EventArgs) Handles VariationComboBox.
   SelectedIndexChanged

Private Sub VisualComboBox_SelectedIndexChanged(sender As
   Object, e As EventArgs) Handles VisualComboBox.
   SelectedIndexChanged

Private Sub TempComboBox_SelectedIndexChanged(sender As
   Object, e As EventArgs) Handles TempComboBox.
   SelectedIndexChanged

Private Sub NoiseComboBox_SelectedIndexChanged(sender As
   Object, e As EventArgs) Handles NoiseComboBox.
   SelectedIndexChanged

Private Sub GripShapeComboBox_SelectedIndexChanged(sender As
    Object, e As EventArgs) Handles GripShapeComboBox.
   SelectedIndexChanged
```

```
Private Sub GripSizeComboBox_SelectedIndexChanged(sender As
    Object, e As EventArgs) Handles GripSizeComboBox.
    SelectedIndexChanged

Private Sub GripTypeComboBox_SelectedIndexChanged(sender As
    Object, e As EventArgs) Handles GripTypeComboBox.
    SelectedIndexChanged

Private Sub GripSurfaceComboBox_SelectedIndexChanged(sender
    As Object, e As EventArgs) Handles GripSurfaceComboBox.
    SelectedIndexChanged

Private Sub GroupBox2_Enter(sender As Object, e As EventArgs
    ) Handles GroupBox2.Enter

Private Sub WPPernrTextBox_TextChanged(sender As Object, e
    As EventArgs) Handles WPPernrTextBox.TextChanged

Private Sub WPStartButton_Click(sender As Object, e As
    EventArgs) Handles WPStartButton.Click

Private Sub WPFinishButton_Click(sender As Object, e As
    EventArgs) Handles WPFinishButton.Click

Private Sub WPSavePointsButton_Click(sender As Object, e As
    EventArgs) Handles WPSavePointsButton.Click

Private Sub MinuteEventTimer_Tick(sender As Object, e As
    EventArgs) Handles MinuteEventTimer.Tick

Private Sub Button23_Click_1(sender As Object, e As
    EventArgs) Handles Button23.Click

Private Sub TimerUpperArm1_Tick(sender As Object, e As
    EventArgs) Handles TimerUpperArm1.Tick

Private Sub TimerLowerArm1_Tick(sender As Object, e As
    EventArgs) Handles TimerLowerArm1.Tick

Private Sub TimerWrist1_Tick(sender As Object, e As
    EventArgs) Handles TimerWrist1.Tick
```

Excel dumps

Pernr	Task	MoveL	HoldR	MoveR	HandArm Joints	Posture	Time1	Kim	OWAS
20110									
	1	0	0	0	relaxed	0	0.011	0	4-1-2-1
	2	0	15	9	relaxed	1	0.051	1	4-1-3-1
	3	0	31	11	relaxed	3	0.035	3	4-1-3-1
	4	0	46	14	relaxed	3	0.018	3	4-1-3-1
	5	0	48	13	relaxed	3	0.015	3	4-1-3-1
	6	0	49	12	relaxed	3	0.025	3	4-1-3-1
20111									
	1	0	9	3	relaxed	0	0.046	0	4-1-2-1
	2	0	40	14	relaxed	1	0.115	1	4-1-3-1
	3	0	46	16	relaxed	1	0.034	1	4-1-2-1
	4	0	42	19	relaxed	1	0.034	1	4-1-2-1
	5	0	44	17	relaxed	1	0.027	1	4-1-3-1
	6	0	43	18	relaxed	3	0.03	3	4-1-2-1
20112									
	1	0	2	1	relaxed	0	0.024	0	4-1-2-1
	2	0	29	10	relaxed	0	0.054	0	4-1-3-1
	3	0	38	13	relaxed	1	0.015	1	4-1-3-1
	4	0	49	15	relaxed	1	0.032	1	4-1-2-1
	5	0	0	0	relaxed	1	0.012	1	4-1-3-1
	6	0	48	16	relaxed	1	0.029	1	1-1-2-1

Table 1: Experiment 1 Result table

Pernr	Task	REBA	RULA	NeckL	NeckH	TrunkL	TrunkH	WristMove	ScoreFinal
20110									
	1	0	0	2	5	1	0	0	
	2	0	0	3	34	0	25	9	
	3	0	0	1	24	4	17	11	
	4	0	0	3	9	1	0	14	
	5	1	0	1	8	0	0	13	
	6	1	0	2	11	1	5	12	43
20111									
	1	0	0	14	13	0	0	3	
	2	0	0	21	49	0	1	14	
	3	1	0	8	5	0	0	16	
	4	1	0	5	19	0	0	19	
	5	1	0	10	7	1	0	17	
	6	1	0	2	19	0	0	18	53
20112									
	1	0	0	0	17	0	0	1	
	2	0	0	3	36	0	0	10	
	3	0	0	0	10	0	0	13	
	4	1	0	2	21	0	0	15	
	5	1	0	2	2	0	0	0	
	6	1	0	0	3	1	1	16	75

Table 2: Experiment 1 Result table

First experiment

Pernr	Task 1 - 1	Task 2 - 1	Task 3 - 1	Task 4 - 1	Task 5 - 1	Task 6 - 1	Total
20110	0.011	0.051	0.035	0.018	0.015	0.025	0.155
20111	0.046	0.115	0.034	0.034	0.027	0.03	0.286
20112	0.024	0.054	0.015	0.032	0.012	0.029	0.166
20113	0.029	0.047	0.016	0.018	0.014	0.02	0.144
20114	0.029	0.053	0.019	0.026	0.015	0.012	0.154
20115	0.008	0.039	0.013	0.026	0.015	0.03	0.131

Second experiment

Pernr	Task 1 - 2	Task 2 - 2	Task 3 - 2	Task 4 - 2	Task 5 - 2	Task 6 - 2	Total
20110	0.011	0.066	0.037	0.019	0.018	0.064	0.215
20111	0.03	0.057	0.024	0.031	0.016	0.07	0.228
20112	0.014	0.048	0.019	0.026	0.019	0.02	0.146
20113	0.013	0.079	0.015	0.028	0.018	0.046	0.199
20114	0.013	0.069	0.031	0.038	0.018	0.021	0.19
20115	0.012	0.038	0.018	0.038	0.019	0.027	0.152

Table 3: Participants' Time in Hours

Pernr	Experiment1	Experiment2	Diff	% Increase
20110	43	65	22	51.16%
20111	53	100	47	88.68%
20112	75	100	25	33.33%
20113	80	91	11	13.75%
20114	87	100	13	14.94%
20115	96	100	4	4.17%

n	14	14	
Min	20	63	43
Max	96	100	4
Avg	67.2143	91.3571	24.1428

Green	28.57%	85.71%
Yellow	35.71%	14.29%
Red	35.71%	0.00%

Table 4: Participants' Final Score

Holding	counts					
	T1Hold	T2Hold	T3Hold	T4Hold	T5Hold	T6Hold
	45	43	47	40	22	33
	44	44	44	44	45	47
	51	49	50	50	49	52
	40	45	38	44	45	46
	52	45	41	41	39	39
	46	47	47	46	19	40
	21	32	36	45	44	42
min	21	32	36	40	19	33
max	52	49	50	50	49	52
avg	43	44	43	44	38	43

Moving	counts					
	T1Move	T2Move	T3Move	T4Move	T5Move	T6Move
	16	18	14	20	18	10
	16	16	17	18	16	14
	13	15	14	14	15	12
	20	15	16	17	16	15
	11	18	22	22	24	24
	15	14	14	19	15	9
	17	11	13	16	17	19
min	11	11	13	14	15	9
max	20	18	22	22	24	24
avg	15	15	16	18	17	15

Table 5: Participants' Hold and Move Counts

Back	(+)	(-)	Neutral	(+)	(-)	Neutral	Total
Task 1	6	2	6	42.86%	14.29%	42.86%	100.00%
Task 2	5	2	7	35.71%	14.29%	50.00%	100.00%
Task 3	5	4	5	35.71%	28.57%	35.71%	100.00%
Task 4	6	4	4	42.86%	28.57%	28.57%	100.00%
Task 5	6	4	4	42.86%	28.57%	28.57%	100.00%
Task 6	5	5	4	35.71%	35.71%	28.57%	100.00%

Forearm	(+)	(-)	Neutral	(+)	(-)	Neutral	
Task 1			14			100.00%	
Task 2			14			100.00%	
Task 3			14			100.00%	
Task 4			14			100.00%	
Task 5			14			100.00%	
Task 6			14			100.00%	

Leg	(+)	(-)	Neutral	(+)	(-)	Neutral	
Task 1	4	3	7	28.57%	21.43%	50.00%	
Task 2	3	1	10	21.43%	7.14%	71.43%	
Task 3	2	6	6	14.29%	42.86%	42.86%	
Task 4	3	3	8	21.43%	21.43%	57.14%	
Task 5	2	1	11	14.29%	7.14%	78.57%	
Task 6	2	4	8	14.29%	28.57%	57.14%	

Table 6: Participants' OWAS Score

Back	(+)	(-)	Neutral	(+)	(-)	Neutral	Total
Task 1	0	12	2	0.00%	85.71%	14.29%	100.00%
Task 2	0	12	2	0.00%	85.71%	14.29%	100.00%
Task 3	0	11	3	0.00%	78.57%	21.43%	100.00%
Task 4	1	7	6	7.14%	50.00%	42.86%	100.00%
Task 5	1	3	10	7.14%	21.43%	71.43%	100.00%
Task 6	0	1	13	0.00%	7.14%	92.86%	100.00%

Table 7: Participants' REBA Score

Bibliography

[1] M. Schepers, M. Giuberti, and G. Bellusci, "Xsens MVN : Consistent Tracking of Human Motion Using Inertial Sensing," *Xsens Technologies*, no. March, pp. 1–8, 2018.

[2] U. Steinberg, F. Liebers, A. Klußmann, H. Gebhardt, A. Rieger, S. Behrendt, and U. Latza, "Leitmerkmalmethode Manuelle Arbeitsprozesse 2001- Bericht über die Erprobung, Validierung und Revision," p. 203, 2011. [Online]. Available: http://www.baua.de/de/Publikationen/Fachbeitraege/F2195.html

[3] F. W. Taylor, *Scientific management.* Routledge, 2004.

[4] D. Roetenberg, H. Luinge, and P. Slycke, "Xsens MVN: Full 6DOF human motion tracking using miniature inertial sensors," *Xsens Motion Technologies BV, Tech. Rep*, vol. 1, 2009.

[5] U. B. o. L. Statistics, "Employer-Reported Workplace Injury and Illnesses, 2019," Tech. Rep., 2020. [Online]. Available: https://www.bls.gov/news.release/osh.nr0.htm

[6] Allgemeine Unfallversicherungsanstalt (AUVA), "Auszug aus der Statistik 2018," Tech. Rep., 2019. [Online]. Available: https://www.auva.at/cdscontent/?contentid=10007.670939

[7] Deutsche Gesetzliche Unfallversicherung e.V. (DGUV), "Arbeitsunfallgeschehen 2019 | DGUV Publikationen," Tech. Rep., 2019. [Online]. Available: https://publikationen.dguv.de/zahlen-fakten/schwerpunkt-themen/3893/arbeitsunfallgeschehen-2019

[8] B. o. L. S. (BLS), "BLS OSH Definitions," 2016. [Online]. Available: https://www.bls.gov/iif/oshdef.htm

[9] W. M. Keyserling, T. J. Armstrong, and L. Punnett, "Ergonomic job analysis: A structured approach for identifying risk factors associated with overexertion injuries and disorders," *Applied Occupational and Environmental Hygiene*, vol. 6, no. 5, pp. 353–363, 1991.

[10] P. J. Carrivick, A. H. Lee, K. K. Yau, and M. R. Stevenson, “Evaluating the effectiveness of a participatory ergonomics approach in reducing the risk and severity of injuries from manual handling,” *Ergonomics*, vol. 48, no. 8, pp. 907–914, jun 2005. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/16147411/

[11] W. S. Marras, W. G. Allread, D. L. Burr, and F. A. Fathallah, “Prospective validation of a low-back disorder risk model and assessment of ergonomic interventions associated with manual materials handling tasks,” *Ergonomics*, vol. 43, no. 11, pp. 1866–1886, nov 2000. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/11105977/

[12] S. Nagavarapu, S. A. Lavender, and W. S. Marras, “Spine loading during the application and removal of lifting slings: the effects of patient weight, bed height and work method,” *Ergonomics*, vol. 60, no. 5, pp. 636–648, may 2017. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/27400731/

[13] A. Nelson, M. Matz, F. Chen, K. Siddharthan, J. Lloyd, and G. Fragala, “Development and evaluation of a multifaceted ergonomics program to prevent injuries associated with patient handling tasks,” *International Journal of Nursing Studies*, vol. 43, no. 6, pp. 717–733, aug 2006. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/16253260/

[14] P. Carneiro, A. C. Braga, and M. Barroso, “Work-related musculoskeletal disorders in home care nurses: Study of the main risk factors,” *International Journal of Industrial Ergonomics*, vol. 61, pp. 22–28, sep 2017.

[15] B. Evanoff, L. Wolf, E. Aton, J. Canos, and J. Collins, “Reduction in Injury Rates in Nursing Personnel through Introduction of Mechanical Lifts in the Workplace,” *American Journal of Industrial Medicine*, vol. 44, no. 5, pp. 451–457, nov 2003. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/14571508/

[16] H. S. E. Books, “Reducing error and influencing behaviour,” 2009.

[17] I. L. Janowitz, M. Gillen, G. Ryan, D. Rempel, L. Trupin, L. Swig, K. Mullen, R. Rugulies, and P. D. Blanc, “Measuring the physical demands of work in hospital settings: Design and implementation of an ergonomics assessment,” *Applied Ergonomics*, vol. 37, no. 5, pp. 641–658, 2006. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/16226213/

[18] B. Juul-Kristensen, G. Å. Hansson, N. Fallentin, J. H. Andersen, and C. Ekdahl, “Assessment of work postures and movements using a video-based observation method and direct technical measurements,” *Applied Ergonomics*, vol. 32, no. 5, pp. 517–524, 2001. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/11534797/

[19] R. Feyen, Y. Liu, D. Chaffin, G. Jimmerson, and B. Joseph, “Computer-aided ergonomics: A case study of incorporating ergonomics analyses into workplace

design," *Applied Ergonomics*, vol. 31, no. 3, pp. 291–300, 2000. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/10855452/

[20] A. J. Van Der Beek, M. J. Hoozemans, M. H. Frings-Dresen, and A. Burdorf, "Assessment of exposure to pushing and pulling in epidemiological field studies: An overview of methods, exposure measures, and measurement strategies," *International Journal of Industrial Ergonomics*, vol. 24, no. 4, pp. 417–429, aug 1999.

[21] D. B. Chaffin, "Ergonomics Guide for The Assessment of Human Static Strength," *American Industrial Hygiene Association Journal*, vol. 36, no. 7, pp. 505–511, jul 1975. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/0002889758507283

[22] J. R. Wilson and S. Sharples, *Ergonomics assessment of thermal Environments by K.C. Parsons*. CRC Press, apr 2015. [Online]. Available: http://www.taylorandfrancis.com

[23] K. G. Schaub, J. Mühlstedt, B. Illmann, S. Bauer, L. Fritzsche, T. Wagner, and A. C. Bullinger-Hoffmann, "Ergonomic assessment of automotive assembly tasks with digital human modelling and the 'ergonomics assessment worksheet' (EAWS)," Tech. Rep., 2012. [Online]. Available: https://www.fondazionergo.it/upload/press/Ergon{_}assessm{_}Schaub{_}2013.pdf

[24] K. Ohlsson, R. G. Attewell, B. Johnsson, A. Ahlm, and S. Skerfving, "An assessment of neck and upper extremity disorders by questionnaire and clinical examination," *Ergonomics*, vol. 37, no. 5, pp. 891–897, 1994. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/8206057/

[25] P. Plantard, H. P. Shum, A. S. Le Pierres, and F. Multon, "Validation of an ergonomic assessment method using Kinect data in real workplace conditions," *Applied Ergonomics*, vol. 65, pp. 562–569, nov 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S000368701630240X

[26] L. McAtamney and E. Nigel Corlett, "RULA: a survey method for the investigation of work-related upper limb disorders," *Applied Ergonomics*, vol. 24, no. 2, pp. 91–99, apr 1993.

[27] H. Haggag, M. Hossny, S. Nahavandi, and D. Creighton, "Real time ergonomic assessment for assembly operations using kinect," in *Proceedings - UKSim 15th International Conference on Computer Modelling and Simulation, UKSim 2013*, 2013, pp. 495–500.

[28] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design science in information systems research," *MIS Quarterly: Management Information Systems*, vol. 28, no. 1, pp. 75–105, mar 2004. [Online]. Available: https://www.jstor.org/stable/25148625

[29] K. Piirainen and R. A. González, "Constructive Synergy in Design Science Research: A Comparative Analysis of Design Science Research and the Constructive Research Approach," *undefined*, pp. 206–234, 2014.

[30] S. Gregor and A. R. Hevner, "The Knowledge Innovation Matrix (KIM): A Clarifying Lens for Innovation," *Informing Science: The International Journal of an Emerging Transdiscipline*, vol. 17, pp. 217–239, 2014.

[31] H. Rubin and I. Rubin, *Qualitative Interviewing (2nd ed.): The Art of Hearing Data*. SAGE Publications, Inc., apr 2012.

[32] G. Kotonya and I. Sommerville, *Requirements engineering: processes and techniques*, 1998. [Online]. Available: https://dl.acm.org/citation.cfm?id=552009

[33] P. A. Laplante, *Requirements engineering for software and systems, second edition*, 2013.

[34] T. E. Bell and T. A. Thayer, "Software requirements: Are they really a problem?" Tech. Rep., 1976. [Online]. Available: https://dl.acm.org/citation.cfm?id=807650

[35] F. Roethlisberger, W. Dickson, and H. Wright, "Western Electric Company. Management and the worker: an account of a research program conducted by the Western Electric Company, Hawthorne," 1939.

[36] E. Mayo, *The human problems of an industrial civilization*, 2004. [Online]. Available: https://books.google.com/books?hl=en{&}lr={&}id=OQcBYqgKh5cC{&}oi=fnd{&}pg=PT8{&}dq=Mayo+E.+The+human+problems+of+an+industrial+civilization+1933+MacMillan+New+York,+NY+{&}ots=RvDv{_}Vqgyo{&}sig=RP{_}coS4StDhkpoe7H9KvdqH5ezA

[37] S. L. Payne, "The Ideal Model for Controlled Experiments," *Public Opinion Quarterly*, vol. 15, no. 3, p. 557, 1951. [Online]. Available: https://academic.oup.com/poq/article-lookup/doi/10.1086/266335

[38] I. S. MacKenzie, "Scientific Foundations," in *Human-computer Interaction*. Elsevier, jan 2013, pp. 121–156.

[39] A. C. Falck, R. Örtengren, and D. Högberg, "The impact of poor assembly ergonomics on product quality: A cost-benefit analysis in car manufacturing," *Human Factors and Ergonomics In Manufacturing*, vol. 20, no. 1, pp. 24–41, 2010.

[40] A. C. Falck, R. Örtengren, and M. Rosenqvist, "Assembly failures and action cost in relation to complexity level and assembly ergonomics in manual assembly (part 2)," *International Journal of Industrial Ergonomics*, vol. 44, no. 3, pp. 455–459, may 2014.

[41] A. C. Falck, R. Örtengren, M. Rosenqvist, and R. Söderberg, "Criteria for Assessment of Basic Manual Assembly Complexity," in *Procedia CIRP*, vol. 44. Elsevier B.V., 2016, pp. 424–428.

[42] I. Etikan, "Comparison of Convenience Sampling and Purposive Sampling," *American Journal of Theoretical and Applied Statistics*, vol. 5, no. 1, p. 1, 2016. [Online]. Available: https://www.researchgate.net/publication/304339244

[43] C. Sonnenberg and J. vom Brocke, "Evaluation Patterns for Design Science Research Artefacts," in *Communications in Computer and Information Science*, 2012, vol. 286 CCIS, pp. 71–83. [Online]. Available: http://link.springer.com/10.1007/978-3-642-33681-2{_}7

[44] T. Mettler, M. Eurich, and R. Winter, "On the use of experiments in design science research: A proposition of an evaluation framework," *Communications of the Association for Information Systems*, vol. 34, no. 1, pp. 223–240, 2014.

[45] N. Koppenhagen, N. Katz, B. Müller, and A. Mädche, "How do procurement networks become social? Design principles evaluation in a heterogeneous environment of structured and unstructured interactions," Tech. Rep., 2011.

[46] H. Taherdoost, "What Is the Best Response Scale for Survey and Questionnaire Design; Review of Different Lengths of Rating Scale / Attitude Scale / Likert Scale," Tech. Rep. 1, 2019. [Online]. Available: https://hal.archives-ouvertes.fr/hal-02557308

[47] J. P. Clarys, "Electromyography in sports and occupational settings: An update of its limits and possibilities," *Ergonomics*, vol. 43, no. 10, pp. 1750–1762, oct 2000. [Online]. Available: https://doi.org/10.1080/001401300750004159

[48] S. Kumar and A. Mital, *Electromyography in ergonomics.* CRC Press, 1996.

[49] R. Merletti and P. J. Parker, *Electromyography: physiology, engineering, and non-invasive applications.* John Wiley & Sons, 2004, vol. 11.

[50] M. Wilson Kumar, G. B. Rao, K. Balasubramanian, and I. Kantharaj, "Experimental Investigations of Initial Push Forces on an Industrial Trolley," in *Lecture Notes in Mechanical Engineering.* Springer Science and Business Media Deutschland GmbH, 2021, pp. 149–158. [Online]. Available: https://doi.org/10.1007/978-981-15-4488-0{_}13

[51] S. Skals, R. Bláfoss, M. S. Andersen, M. de Zee, and L. L. Andersen, "Manual material handling in the supermarket sector. Part 1: Joint angles and muscle activity of trapezius descendens and erector spinae longissimus," *Applied Ergonomics*, vol. 92, p. 103340, apr 2021.

[52] J. Gräf, K. Mattes, K. Luedtke, and B. Wollesen, “Improved neck posture and reduced neck muscle activity when using a novel camera based workstation for manual precision inspection tasks,” *Applied Ergonomics*, vol. 90, p. 103147, jan 2021.

[53] T. Lulic-Kuryllo, F. Negro, N. Jiang, and C. R. Dickerson, “Standard bipolar surface EMG estimations mischaracterize pectoralis major activity in commonly performed tasks,” *Journal of Electromyography and Kinesiology*, vol. 56, p. 102509, feb 2021.

[54] N. J. La Delfa, A. Kunasegaram, R. Whittaker, and C. R. Dickerson, “Determining best practices for manual pill crushing through evaluation of upper extremity muscle exposures,” *Applied Ergonomics*, vol. 90, p. 103275, jan 2021.

[55] J. M. Maciukiewicz, R. L. Whittaker, K. B. Hogervorst, and C. R. Dickerson, “Wrapping technique and wrapping height interact to modify physical exposures during manual pallet wrapping,” *Applied Ergonomics*, vol. 93, p. 103378, may 2021.

[56] C. Steingraber, D. Devries, L. Eaton, M. Smets, A. Stephens, G. Malone, R. Porto, and J. Cort, “Physical demands associated with right-angle direct-current power-tools: An evaluation of current technology,” *Applied Ergonomics*, vol. 93, p. 103374, may 2021.

[57] MotionMiners GmbH, “EEicient Processes through Motion-Mining® Capture and Analyze your Manual Processes Automatically and Anonymously Stay in Motion,” Tech. Rep., 2020.

[58] N. Vignais, M. Miezal, G. Bleser, K. Mura, D. Gorecky, and F. Marin, “Innovative system for real-time ergonomic feedback in industrial manufacturing,” *Applied Ergonomics*, vol. 44, no. 4, pp. 566–574, jul 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003687012001858

[59] L. Peppoloni, A. Filippeschi, and E. Ruffaldi, “Assessment of task ergonomics with an upper limb wearable device,” in *2014 22nd Mediterranean Conference on Control and Automation, MED 2014*. Institute of Electrical and Electronics Engineers Inc., nov 2014, pp. 340–345. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/6961394

[60] M. C. Schall, N. B. Fethke, H. Chen, S. Oyama, and D. I. Douphrate, “Accuracy and repeatability of an inertial measurement unit system for field-based occupational studies,” *Ergonomics*, vol. 59, no. 4, pp. 591–602, apr 2016. [Online]. Available: http://www.tandfonline.com/doi/full/10.1080/00140139.2015.1079335

[61] J. Kuschan, H. Schmidt, and J. Krueger, “Improved Ergonomics via an Intelligent Movement and Gesture Detection Jacket,” in *Proceedings of ISR 2016: 47st International Symposium on Robotics*, jun 2016, pp. 1–6. [Online]. Available: https://ieeexplore.ieee.org/document/7559141

[62] E. Valero, A. Sivanathan, F. Bosché, and M. Abdel-Wahab, "Musculoskeletal disorders in construction: A review and a novel system for activity tracking with body area network," pp. 120–130, may 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003687015301204

[63] W. Lee, E. Seto, K. Y. Lin, and G. C. Migliaccio, "An evaluation of wearable sensors and their placements for analyzing construction worker's trunk posture in laboratory conditions," *Applied Ergonomics*, vol. 65, pp. 424–436, nov 2017.

[64] X. Yan, H. Li, A. R. Li, and H. Zhang, "Wearable IMU-based real-time motion warning system for construction workers' musculoskeletal disorders prevention," *Automation in Construction*, vol. 74, pp. 2–11, feb 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580516303314

[65] J. Chen, J. Qiu, and C. Ahn, "Construction worker's awkward posture recognition through supervised motion tensor decomposition," *Automation in Construction*, vol. 77, pp. 67–81, may 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580517300651

[66] M. G. L. Monaco, L. Fiori, A. Marchesi, A. Greco, L. Ghibaudo, S. Spada, F. Caputo, N. Miraglia, A. Silvetti, and F. Draicchio, "Biomechanical overload evaluation in manufacturing: A novel approach with sEMG and inertial motion capture integration," in *Advances in Intelligent Systems and Computing*, vol. 818. Springer Verlag, aug 2019, pp. 719–726. [Online]. Available: https://doi.org/10.1007/978-3-319-96098-2{_}88

[67] Ultraleap, "Leap Motion Controller TM," Tech. Rep., 2021. [Online]. Available: https://www.ultraleap.com/product/vr-developer-mount/

[68] F. Weichert, D. Bachmann, B. Rudak, and D. Fisseler, "Analysis of the accuracy and robustness of the Leap Motion Controller," *Sensors (Switzerland)*, vol. 13, no. 5, pp. 6380–6393, may 2013. [Online]. Available: /pmc/articles/PMC3690061//pmc/articles/PMC3690061/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC3690061/

[69] S. N. Gieser, A. Boisselle, and F. Makedon, "Real-Time static gesture recognition for upper extremity rehabilitation using the leap motion," in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, vol. 9185. Springer Verlag, 2015, pp. 144–154. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-319-21070-4{_}15

[70] K. S. Jones, T. J. McIntyre, and D. J. Harris, "Leap Motion- and Mouse-Based Target Selection: Productivity, Perceived Comfort and Fatigue, User Preference, and Perceived Usability," *International Journal of Human–Computer Interaction*, vol. 36, no. 7, pp. 621–630, apr 2020. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/10447318.2019.1666511

[71] C. Siew, M. Chang, S. Ong, and A. Nee, "Human-oriented maintenance and disassembly in sustainable manufacturing," *Computers & Industrial Engineering*, vol. 150, p. 106903, dec 2020.

[72] Z. Zhang, "Microsoft kinect sensor and its effect," pp. 4–10, 2012.

[73] S. J. Ray and J. Teizer, "Real-time construction worker posture analysis for ergonomics training," *Advanced Engineering Informatics*, vol. 26, no. 2, pp. 439–455, apr 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1474034612000183

[74] A. Patrizi, E. Pennestrì, and P. P. Valentini, "Comparison between low-cost marker-less and high-end marker-based motion capture systems for the computer-aided assessment of working ergonomics," *Ergonomics*, vol. 59, no. 1, pp. 155–162, jan 2016. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00140139.2015.1057238

[75] W. Zhao, D. D. Deborah, M. A. Reinthal, B. Ekelman, G. Goodman, and J. Niederriter, "Privacy-Aware Human Motion Tracking with Realtime Haptic Feedback," in *Proceedings - 2015 IEEE 3rd International Conference on Mobile Services, MS 2015*. Institute of Electrical and Electronics Engineers Inc., aug 2015, pp. 446–453.

[76] V. M. Manghisi, A. E. Uva, M. Fiorentino, V. Bevilacqua, G. F. Trotta, and G. Monno, "Real time RULA assessment using Kinect v2 sensor," *Applied Ergonomics*, vol. 65, pp. 481–491, nov 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003687017300510

[77] M. Bortolini, M. Gamberi, F. Pilati, and A. Regattieri, "Automatic assessment of the ergonomic risk for manual manufacturing and assembly activities through optical motion capture technology," in *Procedia CIRP*, vol. 72. Elsevier B.V., jan 2018, pp. 81–86. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827118303573

[78] M. Bortolini, M. Faccio, M. Gamberi, and F. Pilati, "Motion Analysis System (MAS) for production and ergonomics assessment in the manufacturing processes," *Computers and Industrial Engineering*, vol. 139, p. 105485, jan 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360835218305266{%}0A

[79] F. M. Sánchez-Margallo, J. A. Sánchez-Margallo, J. B. Pagador, J. L. Moyano, J. Moreno, and J. Usón, "Ergonomic assessment of hand movements in laparoscopic surgery using the CyberGlove®," in *Computational Biomechanics for Medicine*. Springer New York, 2010, pp. 121–128.

[80] S. Borik, A. Kmecova, M. Gasova, and M. Gaso, "Smart glove to measure a grip force of the workers," in *2019 42nd International Conference on Telecommunications*

and Signal Processing, TSP 2019. Institute of Electrical and Electronics Engineers Inc., jul 2019, pp. 383–388.

[81] L. Francés, P. Morer, M. I. Rodriguez, and A. Cazón, “Design and development of a low-cost wearable glove to track forces exerted by workers in car assembly lines,” *Sensors (Switzerland)*, vol. 19, no. 2, jan 2019. [Online]. Available: /pmc/articles/PMC6359512//pmc/articles/PMC6359512/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC6359512/

[82] D. Yu, B. Lowndes, M. Morrow, K. Kaufman, J. Bingener, and S. Hallbeck, “Impact of novel shift handle laparoscopic tool on wrist ergonomics and task performance,” *Surgical Endoscopy*, vol. 30, no. 8, pp. 3480–3490, aug 2016. [Online]. Available: https://link.springer.com/article/10.1007/s00464-015-4634-7

[83] K. H. Kramp, M. J. Van Det, E. R. Totte, C. Hoff, and J. P. E. Pierie, “Ergonomic assessment of the French and American position for laparoscopic cholecystectomy in the MIS suite,” *Surgical Endoscopy*, vol. 28, no. 5, pp. 1571–1578, jan 2014. [Online]. Available: https://link.springer.com/article/10.1007/s00464-013-3353-1

[84] T. Cheng, G. C. Migliaccio, J. Teizer, and U. C. Gatti, “Data Fusion of Real-Time Location Sensing and Physiological Status Monitoring for Ergonomics Analysis of Construction Workers,” *Journal of Computing in Civil Engineering*, vol. 27, no. 3, pp. 320–335, may 2013. [Online]. Available: http://ascelibrary.org/doi/10.1061/{%}28ASCE{%}29CP.1943-5487.0000222

[85] L. Straker, A. Campbell, J. Coleman, M. Ciccarelli, and W. Dankaerts, “<i>In vivo</i> laboratory validation of the physiometer: a measurement system for long-term recording of posture and movements in the workplace,” *Ergonomics*, vol. 53, no. 5, pp. 672–684, may 2010. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/00140131003671975

[86] A. Shikdar, S. Al-Araimi, and B. Omurtag, “Development of a software package for ergonomic assessment of manufacturing industry,” *Computers and Industrial Engineering*, vol. 43, no. 3, pp. 485–493, sep 2002. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360835202001213

[87] U. Steinberg, S. Behrendt, G. Caffier, K. Schultz, and M. Jakob, “Key indicator method manual handling operations. design and testing of a practical aid for assessing working conditions,” *Berlin: Bundesanstalt Für Arbeitsschutz und Abeitsmedizin*, 2008.

[88] ——, *Leitmerkmalmethode Manuelle Arbeitsprozesse Forschung Projekt F 1994*, 2007. [Online]. Available: www.baua.de

[89] V. Louhevaara, T. Suurnäkki, S. Hinkkanen, and P. Helminen, *OWAS: a method for the evaluation of postural load during work*. Institute of Occupational Health. Centre for Occupational Safety, 1992.

[90] S. Hignett and L. McAtamney, "Rapid entire body assessment (Handbook of Human Factors and Ergonomics Methods (pp. 97–108)," 2004.

[91] T. R. Waters, V. Putz-Anderson, A. Garg, and L. J. Fine, "Revised NIOSH equation for the design and evaluation of manual lifting tasks," *Ergonomics*, vol. 36, no. 7, pp. 749–776, 1993. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/00140139308967940

[92] G. David, V. Woods, G. Li, and P. Buckle, "The development of the Quick Exposure Check (QEC) for assessing exposure to risk factors for work-related musculoskeletal disorders," *Applied Ergonomics*, vol. 39, no. 1, pp. 57–69, jan 2008.

[93] R. P. Wong, T. J. Cassar, and C. L. Roth, "Method and system for ergonomic assessment and reduction of workplace injuries," 2005.

[94] J. T. Zhang, A. C. Novak, B. Brouwer, and Q. Li, "Concurrent validation of Xsens MVN measurement of lower limb joint angular kinematics," *Physiological Measurement*, vol. 34, no. 8, p. N63, aug 2013. [Online]. Available: https://iopscience.iop.org/article/10.1088/0967-3334/34/8/N63https://iopscience.iop.org/article/10.1088/0967-3334/34/8/N63/meta

[95] T. Khurelbaatar, K. Kim, S. K. Lee, and Y. H. Kim, "Consistent accuracy in whole-body joint kinetics during gait using wearable inertial motion sensors and in-shoe pressure sensors," *Gait and Posture*, vol. 42, no. 1, pp. 65–69, jun 2015.

[96] X. Robert-Lachaine, H. Mecheri, C. Larue, and A. Plamondon, "Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis," *Medical and Biological Engineering and Computing*, vol. 55, no. 4, pp. 609–619, apr 2017. [Online]. Available: https://link.springer.com/article/10.1007/s11517-016-1537-2

[97] M. P. Mavor, G. B. Ross, A. L. Clouthier, T. Karakolis, and R. B. Graham, "Validation of an IMU Suit for Military-Based Tasks," *Sensors*, vol. 20, no. 15, p. 4280, jul 2020. [Online]. Available: https://www.mdpi.com/1424-8220/20/15/4280

[98] K. K. Elbert, H. B. Kroemer, and A. D. K. Hoffman, *Ergonomics: how to design for ease and efficiency*. Academic Press, 2018.

[99] B. O. Alli, "Fundamental principles of occupational health and safety Second edition," *Geneva, International Labour Organization*, vol. 15, p. 2008, 2008.

[100] ILO, "Recommendation R164 - Occupational Safety and Health Recommendation, 1981 (No. 164)." [Online]. Available: https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100{_}INSTRUMENT{_}ID:312502

[101] S. Niu, "Ergonomics and occupational safety and health: An ILO perspective," *Applied Ergonomics*, vol. 41, no. 6, pp. 744–753, oct 2010.

[102] W. H. O. R. O. for the Eastern Mediterranean, “Occupational health: a manual for primary health care workers,” p. 175 p. ; 25 cm., 2002.

[103] ILO, “Convention C155 - Occupational Safety and Health Convention, 1981 (No. 155).” [Online]. Available: https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100{_}ILO{_}CODE:C155

[104] ——, “Convention C161 - Occupational Health Services Convention, 1985 (No. 161).” [Online]. Available: https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100{_}INSTRUMENT{_}ID:312306:NO

[105] ——, “Convention C187 - Promotional Framework for Occupational Safety and Health Convention, 2006 (No. 187).” [Online]. Available: https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100{_}INSTRUMENT{_}ID:312332:NO

[106] ——, “Recommendation R197 - Promotional Framework for Occupational Safety and Health Recommendation, 2006 (No. 197).” [Online]. Available: https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO:12100:P12100{_}INSTRUMENT{_}ID:312534:NO

[107] Eurostat, “Health and safety at work in Europe (1999-2007) - Products Statistical Books - Eurostat,” 2010. [Online]. Available: https://ec.europa.eu/eurostat/web/products-statistical-books/-/KS-31-09-290

[108] A. A. Shikdar and N. M. Sawaqed, “Worker productivity, and occupational health and safety issues in selected industries,” *Computers and Industrial Engineering*, vol. 45, no. 4, pp. 563–572, dec 2003.

[109] W. Yu, X. Q. Lao, S. Pang, J. Zhou, A. Zhou, J. Zou, L. Mei, and I. T.-s. Yu, “A Survey of Occupational Health Hazards Among 7,610 Female Workers in China’s Electronics Industry,” *Archives of Environmental & Occupational Health*, vol. 68, no. 4, pp. 190–195, oct 2013. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/19338244.2012.701244

[110] R. N. Sen and P. H. Yeow, “Ergonomic study on the manual component insertion lines for occupational health and safety improvements,” *International Journal of Occupational Safety and Ergonomics*, vol. 9, no. 1, pp. 57–74, 2003.

[111] H.-L. CHEE, K. G. RAMPAL, and A. CHANDRASAKARAN, “Ergonomic Risk Factors of Work Processes in the Semiconductor Industry in Peninsular Malaysia,” *INDUSTRIAL HEALTH*, vol. 42, no. 3, pp. 373–381, 2004. [Online]. Available: http://joi.jlc.jst.go.jp/JST.Journalarchive/indhealth1963/42.373?from=CrossRef

[112] W. M. Keyserling, M. Brouwer, and B. A. Silverstein, “A checklist for evaluating ergonomic risk factors resulting from awkward postures of the legs, trunk and neck,” *International Journal of Industrial Ergonomics*, vol. 9, no. 4, pp. 283–301, jun 1992.

[113] CDC, "Work-Related Musculoskeletal Disorders & Ergonomics | Workplace Health Strategies by Condition | Workplace Health Promotion | CDC." [Online]. Available: https://www.cdc.gov/workplacehealthpromotion/health-strategies/musculoskeletal-disorders/index.html

[114] WHO, "Classification of Diseases (ICD)." [Online]. Available: https://www.who.int/standards/classifications/classification-of-diseases

[115] N. R. Council, *Work-related musculoskeletal disorders: a review of the evidence*, 1998. [Online]. Available: https://books.google.com/books?hl=en{&}lr={&}id=EeduAgAAQBAJ{&}oi=fnd{&}pg=PT9{&}dq=+Work-Related+Musculoskeletal+Disorders:+A+Review+of+the+Evidence+(1998)+{&}ots=6ycnfW{_}3YK{&}sig=2KevT9W3gENBxj1ESDHjL2jAepA

[116] A. Luttmann, M. Jaeger, B. Griefahn, G. Caffier, F. Liebers, W. H. Organization, and Others, "Preventing musculoskeletal disorders in the workplace," 2003.

[117] G. M. Stave and P. H. Wald, Eds., *Physical and Biological Hazards of the Workplace*. Hoboken, NJ, USA: John Wiley & Sons, Inc., dec 2016. [Online]. Available: http://doi.wiley.com/10.1002/9781119276531

[118] R. Carson, "Reducing cumulative trauma disorders: use of proper workplace design," *AAOHN Journal*, vol. 42, no. 6, pp. 270–276, 1994.

[119] P. W. Buckle and J. Jason Devereux, "The nature of work-related neck and upper limb musculoskeletal disorders," pp. 207–217, may 2002.

[120] A. Klussmann, F. Liebers, F. Brandstädt, M. Schust, P. Serafin, A. Schäfer, H. Gebhardt, B. Hartmann, and U. Steinberg, "Validation of newly developed and redesigned key indicator methods for assessment of different working conditions with physical workloads based on mixed-methods design: A study protocol," *BMJ Open*, vol. 7, no. 8, p. 15412, aug 2017. [Online]. Available: http://bmjopen.bmj.com/

[121] A. Klussmann, F. Liebers, H. Gebhardt, M. A. Rieger, U. Latza, and U. Steinberg, "Risk assessment of manual handling operations at work with the key indicator method (KIM-MHO) - determination of criterion validity regarding the prevalence of musculoskeletal symptoms and clinical conditions within a cross-sectional study," *BMC Musculoskeletal Disorders*, vol. 18, no. 1, may 2017.

[122] A. Colim, C. Faria, A. C. Braga, N. Sousa, L. Rocha, P. Carneiro, N. Costa, and P. Arezes, "Towards an ergonomic assessment framework for industrial assembly workstations - A case study," *Applied Sciences (Switzerland)*, vol. 10, no. 9, p. 3048, may 2020. [Online]. Available: www.mdpi.com/journal/applsci

[123] BAuA, "Key Indicator Method for assessing and designing physical workloads during Manual Handling Operations (KIM-MHO)," Tech. Rep.

[124] Health And Safety Executive (HSE), *MANUAL HANDLING AT WORK : a brief guide (pack of 5*. Place of publication not identified: HSE Books, 2020.

[125] Xsens, "MEMS incorporated in MTw." [Online]. Available: https://base.xsens.com/knowledgebase/s/article/MEMS-incorporated-in-MTw-1605781843491

[126] J. W. Judy, "Microelectromechanical systems (MEMS): Fabrication, design and applications," *Smart Materials and Structures*, vol. 10, no. 6, pp. 1115–1134, dec 2001. [Online]. Available: https://iopscience.iop.org/article/10.1088/0964-1726/10/6/301https://iopscience.iop.org/article/10.1088/0964-1726/10/6/301/meta

[127] Xsens, "xsens mvn documentation." [Online]. Available: https://www.xsens.com/xsens-mvn-documentation

[128] M. Brodie, A. Walmsley, and W. Page, "The static accuracy and calibration of inertial measurement units for 3D orientation," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 11, no. 6, pp. 641–648, dec 2008. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/10255840802326736

[129] M. Schepers, M. Giuberti, G. Bellusci, and Others, "Xsens mvn: Consistent tracking of human motion using inertial sensing," *Xsens Technol*, pp. 1–8, 2018.

[130] W. Premerlani and P. Bizard, "Direction cosine matrix imu: Theory," *Diy Drone: Usa*, pp. 13–15, 2009.

[131] S. Hellmers, S. Fudickar, E. Lange, C. Lins, and A. Hein, "Validation of a motion capture suit for clinical gait analysis," in *ACM International Conference Proceeding Series*. New York, New York, USA: Association for Computing Machinery, may 2017, pp. 120–126. [Online]. Available: http://dl.acm.org/citation.cfm?doid=3154862.3154884

[132] P. Gruenbacher and F. Stallinger, "Requirements Engineering and Specification, Class Lecture TU - Vienna," p. 20, 2016.

[133] I. Sommerville, *Software engineering*. Addison Wesley, 2000, 2021.

[134] B. Ramesh, C. Stubbs, T. Powers, and M. Edwards, "Requirements traceability: Theory and practice," *Annals of Software Engineering*, vol. 3, no. 1, pp. 397–415, 1997. [Online]. Available: https://link.springer.com/article/10.1023/A:1018969401055

[135] R. R. Young, "Recommended requirements gathering practices," *CrossTalk*, vol. 15, no. 4, pp. 9–12, 2002.

[136] L. M. Given, *The Sage encyclopedia of qualitative research methods*. Sage publications, 2008.

[137] M. Hennig, G. Reisinger, T. Trautner, P. Hold, D. Gerhard, and A. Mazak, "TU Wien Pilot Factory Industry 4.0," in *Procedia Manufacturing*, vol. 31. Elsevier B.V., jan 2019, pp. 200–205.

[138] L. Fritzsche, "Ergonomics risk assessment with digital human models in car assembly: Simulation versus real life," *Human Factors and Ergonomics In Manufacturing*, vol. 20, no. 4, pp. 287–299, jul 2010.

[139] S. Weyer, T. Meyer, M. Ohmer, D. Gorecky, and D. Zühlke, "Future modeling and simulation of CPS-based factories: an example from the automotive industry," *Ifac-Papersonline*, vol. 49, no. 31, pp. 97–102, 2016.

[140] N. Gjeldum, M. Mladineo, and I. Veza, "Transfer of Model of Innovative Smart Factory to Croatian Economy Using Lean Learning Factory," in *Procedia CIRP*, vol. 54. Elsevier B.V., jan 2016, pp. 158–163.

[141] J. Long, A. Whitefield, and Others, *Cognitive ergonomics and human-computer interaction*. Cambridge University Press, 1989, vol. 1.

[142] J. J. Crisco, W. M. Heard, R. R. Rich, D. J. Paller, and S. W. Wolfe, "The mechanical axes of the wrist are oriented obliquely to the anatomical axes," *Journal of Bone and Joint Surgery - Series A*, vol. 93, no. 2, pp. 169–177, jan 2011. [Online]. Available: /pmc/articles/PMC3016043//pmc/articles/PMC3016043/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC3016043/

[143] M. Prince, "Epidemiology," in *Core Psychiatry: Third Edition*. Elsevier Inc., apr 2012, pp. 115–129.