

OPTIMIZING MANUAL ASSEMBLY OPERATIONS: ERGONOMICS ANALYSIS AND HUMAN-ROBOT COLLABORATION

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Abstract: *This paper aims to provide a comprehensive overview of the field of ergonomics, with a specific focus on the application of virtual simulation in the context of manual assembly stations assisted by collaborative robots. The theoretical part of this paper presents a concise introduction to the origins and key figures in the field of ergonomics, highlighting the importance and relevance of this discipline. It also discusses the current methods of ergonomic evaluation and the necessary steps involved in conducting such assessments. Furthermore, it delves into the existing standards, associations, and organizations related to ergonomics, as well as the software solutions available for ergonomic analysis. A case study is presented which demonstrates how to perform an ergonomic analysis using the Ergonomics Evaluation module within the 3D Experience platform. The methodology follows a systematic approach, starting with a physical environment simulation to identify key positions for virtual evaluation. These positions are then simulated using a representative 3D model of the assembly station and selected manikins. The chosen ergonomic analysis method is tailored to the specific movements involved in the assembly activity.*

Key words: *Ergonomic analysis, manual assembly, collaborative robot, human-robot interaction, occupational biomechanics, collaborative robotics.*

1. Introduction

Ergonomics is the application of scientific principles, methods, and data from various disciplines to develop and integrate efficient and safe systems or products for users.

Ergonomics is categorized into three distinct areas: Physical ergonomics, which focuses on human anatomy, anthropometry, and the biomechanical and psychological characteristics related to physical activities. Cognitive ergonomics, which is concerned with mental processes such as memory, perception, reasoning, and the motor response of individuals in contact with people and elements of a system. Organizational ergonomics, which emphasizes the socio-technical optimization of systems, including organizational structures, policies, and processes [1].

The field of ergonomics encompasses multiple disciplines, including biomechanics, psychology, anthropometry, physiology, physics, and engineering. Each of these disciplines contributes to gaining a comprehensive understanding of ergonomics. Biomechanics sheds light on the mechanical aspects of the human body, while occupational biomechanics studies the mechanical characteristics and movements of the human body in the context of work.

The primary objective of ergonomics is to prevent work-related musculoskeletal disorders. These disorders can affect muscles, tendons, ligaments, peripheral nerves, as well as joints, cartilage, bones, and blood vessels. Such disorders usually develop over time, resulting from the presence of various risk factors. While a single risk factor may not directly cause musculoskeletal disorders, the combination of multiple risk factors can lead to their occurrence [2].

An important concept in this context is that of micro-trauma, which refers to minor tissue injuries or small ruptures that are repeated over a long period. When the body is unable to heal from these micro-traumas acquired throughout the day, cumulative trauma can occur. This can lead to joint disorders, sprains or dislocations, and diseases of muscles, tendons, or ligaments. Additionally, it can cause compression in nerves and reduced blood flow to muscles, nerves, or joints [3].

Considering the human body as a mechanical system governed by the laws of physics, posture plays a crucial role. Proper posture supports the body in performing tasks correctly and efficiently, while poor posture can result in health problems [4].

Posture stability is achieved when the combined centres of gravity of different body parts fall within the support base. In other words, posture stability occurs at the intersection of the supporting surface and the contact area of the body. When standing, the weight of the body should be evenly distributed on the floor through the position of the legs. Maintaining proper alignment of body parts ensures continuous stability, but it can also create tension [5].

Static posture refers to maintaining the body in a fixed position for an extended period. This can hinder normal blood flow and exert significant pressure on muscles, resulting in fatigue. Adequate blood flow supplies the body with essential nutrients and helps eliminate toxins. [6]

The neutral position represents the natural posture of the body, optimizing its support for work tasks. The body is in a neutral posture when muscles are not actively engaged in maintaining posture, and joints are naturally aligned. Adopting a neutral posture minimizes muscle pressure and allows for better control and force during work tasks [7].

The neutral position entails the lowest level of tension on muscles, tendons, joints, and intervertebral discs. This position allows muscles to relax without the need for excessive contraction or stretching.

An abnormal posture refers to a position outside the neutral position that stretches the body's physical limits, leading to prolonged muscle contraction, nerve compression, and overuse of tendons and ligaments. While short-term exposure to an uncomfortable posture may not cause disease, it significantly contributes to the development of musculoskeletal disorders. Maintaining an uncomfortable posture requires greater physical exertion [8].

Repetition becomes a health risk factor when the same movement or sequence of movements is repeated extensively. Additionally, when different work tasks involve the same muscle groups, they do not allow the muscles to relax or alleviate stress. Repetitive motion alone may not cause significant issues, but when combined with other risk factors, it can have serious consequences.

Strength refers to the physical effort required to perform a work task. Tasks that demand increased physical effort exert greater forces on muscles, tendons, and joints, leading to fatigue. The force required for task completion increases when accompanied by another risk factor.

Compression occurs when pressure is concentrated over a small area. Compression can impede blood flow or irritate adjacent tissues or structures (such as tendons and nerves) due to constant pressure [9].

There are two distinct types of vibration based on their point of impact:

Localized vibration occurs when only a specific part of the body, such as the upper extremity, is exposed to vibrations. This type of vibration is commonly experienced when using handheld tools. Its effects include reduced blood flow to the extremities, which can lead to vascular spasms or compression of blood vessels in the fingers.

Whole-body vibration, on the other hand, affects the entire body and is caused by external vibrations emitted from machinery such as forklifts, cranes, aircraft, or seagoing vessels. Prolonged exposure to whole-body vibrations can result in skeletal muscle problems, digestive system complications, lower back pain, and even complications during pregnancy [10].

Reducing any of these risk factors simultaneously decreases the likelihood of developing musculoskeletal conditions.

There are additional factors that contribute to musculoskeletal disorders, including: Duration and intensity of exposure; Extreme temperature conditions; Lack of adequate recovery time; Organizational issues; Individual factors such as age, gender, previous injuries, and mental condition;

An effective approach to prevent such diseases is to pay close attention to the following warning signs: Joint or muscle pain; Paraesthesia (tingling, numbness); Stinging pain; Feeling of warmth; Rigidity or reduced mobility; Burning sensation; Night pain; Decreased muscle strength

Ergonomic analysis is a method specifically designed to identify risk factors that can lead to musculoskeletal disorders over time and impact the well-being of employees. By evaluating processes using ergonomic assessment methods, it becomes possible to determine the presence of high-risk factors and take appropriate measures [11].

1.1 Classification of methods for carrying out ergonomic analysis

The existing methods for conducting ergonomic analysis can be classified into three categories based on the data collection approach:

Self-report analysis methods

This category involves gathering data through diaries, interviews, and questionnaires administered to operators to identify potential risk factors. An example of a self-report assessment method is the Nordic

standardized questionnaire, which consists of two sections. The first section comprises 40 questions designed to determine the areas of the body where symptoms of musculoskeletal disorders have been experienced in the past 12 months. It also assesses the extent to which these symptoms have significantly impacted the normal execution of activities within the past 7 days [12]. The questionnaire includes a visual representation highlighting the nine body areas. The second section contains additional questions targeting the neck, shoulders, and lumbar region.

It is worth noting that self-report analysis methods are sometimes perceived as less effective due to the subjective nature of operators performing their own assessments.

Observational methods

The observational method involves using established analytical tools that rely on the observation of operators during their tasks. Recordings of operators performing work tasks can also be utilized for subsequent analysis. Commonly employed analysis methods include the NIOSH lifting equation, RULA (Rapid Upper Limb Assessment), REBA (Rapid Entire Body Assessment), and several other assessment tools tailored to specific body areas and work activities.

Observational analysis methods are known for their ease of use, efficiency, and cost-effectiveness.

Direct analysis methods

This category entails conducting analysis using specialized devices such as the Lumbar Motion Monitor (LMM), Electromyography (EMG), and Electro goniometer. These devices are employed to monitor the dynamic movements and postures of operators. Given the complexity of such measurements, software is typically employed for analysis purposes.

The LMM device is specifically designed for angular measurements of body segments in dynamic postures. It can accurately track the position, speed, and acceleration of the spine across three planes of movement. EMG is utilized to determine muscle activity in relation to the workstation. It analyses and measures electrical signals emitted during muscle contractions. It is important to note that direct analysis methods tend to be more costly due to the required equipment.

2. METHODOLOGY AND IMPLEMENTATION

The most commonly used methods of observational analysis include the following are the procedures for performing the RULA, REBA, NOISH Lifting Equation, and HAV analysis [13-15]:

RULA-Rapid Upper Limb Assessment

This method evaluates the risk factors affecting the upper limbs during sedentary activities. It monitors the accumulated pressures in the neck, trunk, and upper extremity areas resulting from work activity. The analysis is conducted using an evaluation sheet divided into two sections:

Section A - Assesses the posture of the arms and wrists.

Section B - Assesses the position of the neck, trunk, and legs.

After obtaining these values, they are converted using the provided tables to obtain the RULA index. This method is straightforward and does not require advanced training. Decisions regarding the need for changes are based on the obtained index value.

It is important to note that this method does not allow analysing multiple positions simultaneously. Similarly, the left and right sides of the body cannot be analysed together, and separate sheets are required.

REBA- Rapid Entire Body Assessment

This evaluation method identifies risk factors present in both the upper and lower body. The REBA method is user-friendly and does not require specialized training. It operates on the same principle as the RULA method. The body is divided into segments, and each segment is evaluated individually. The final result is represented by the REBA index, which determines the level of risk and the need for process changes.

The NIOSH Lifting Equation

The NIOSH lifting equation focuses on assessing the risks associated with handling objects, specifically lifting, or lowering them during work tasks. It is the most widely used observational analysis method for identifying risk factors in the lumbar area. It consists of six variables related to work activity and multipliers obtained from tables to calculate the final result. A lifting activity involves gripping an object with both arms and vertically moving it without the assistance of a mechanism.

HAV- Hand-Arm Vibration Calculator

The HAV assessment method aims to determine the level of risk that an operator may face when using vibration equipment. It focuses on detecting vibrations transmitted from the equipment to the operator's hand and arm during work activities. Some examples of tools that produce vibrations include chainsaws, concrete breakers, saws, drills, grinders, and electric grinders.

According to [16] exposure to physical agents or vibrations in the workplace, the permissible limits for vibrations transmitted to the hand and arm are:

- The limit value for standardized daily exposure over an 8-hour interval is: $5 \text{ m/s}^2 \leq$ (ELV-Exposure Limit Value)

- The standardized daily exposure action value for an 8-hour interval is: $2.5 \text{ m/s}^2 \leq$ (EAV-Exposure Action Value)

According to [17], the vibrations transmitted to the arms and hands during a working day are calculated using the formula:

$$A(8) = a_{hv} \sqrt{\frac{T}{T_0}}$$

Where:

- $A(8)$ represents the vibration exposure for an 8-hour interval;

- T represents the total duration of vibration exposure in hours;

- T_0 represents the reference duration, which is 8 hours.

Since vibration exposure during a working day involves performing several operations with different vibration magnitudes, the formula is used as follows:

$$A(8) = \sqrt{\frac{1}{T_0} \sum_{i=1}^n a_{hvi}^2 T_i}$$

Where:

- a_{hvi} represents the vibration values for each individual operation;

- n represents the number of individual vibrations exposures;

- T_i represents the duration of operation i .

2.1 Case Study - Ergonomic Assessment of Manual Assembly Station Assisted by a Collaborative Robot

This study aims to conduct an ergonomic evaluation of a manual assembly process assisted by a collaborative robot. The Ergonomics Evaluation module available in the 3D Experience platform was utilized to perform this analysis. This software allows for the ergonomic analysis of workstations by simulating the task performance using a virtual manikin. The module provides a range of anthropometric data representing different population segments from America, Canada, China, India, Japan, Korea, France, and Germany.

The workflow for this study is organized into the following stages:

1. Collecting data on the assembly station to be analysed. This involves visiting the station, recording a video demonstration of the assembly process, and identifying the specific positions that require ergonomic assessment.
2. Setting up the virtual assembly station in the 3D environment, which serves as the starting point for the analysis.
3. Performing the necessary analysis using the 3D Experience platform. The type of analysis is determined based on the nature of the task, and manikins from the program's database are used for simulation.

For the current use case, two manikins with anthropometric data were used as follows: a female mannequin, with a height of 153.25 cm and a weight of 48.5 kg and a male manikin, having a height of 185.85 cm and a weight of 97 kg (figure 1).

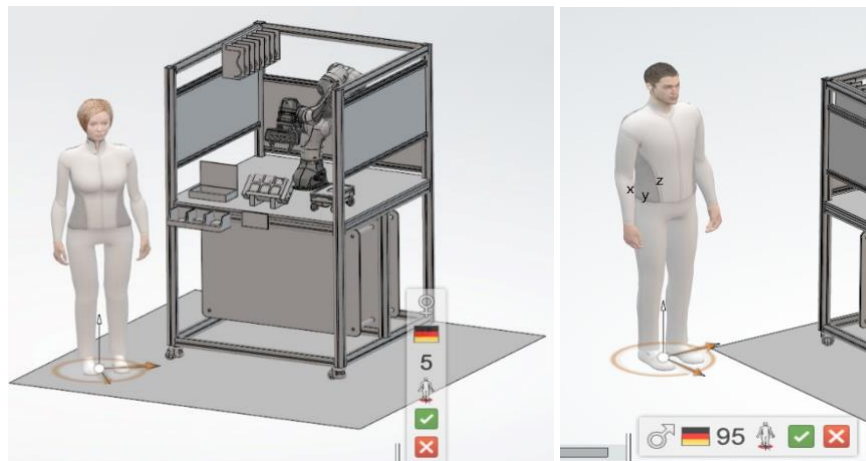


Figure 1 Manikins used for the ergonomics analysis

Assembly process planning and design

The production system on which the product is fabricated is a cyber physical production system demonstrator composed by 8 modules, each with a different purpose [18-19]. The production process is 90% done automatically, it requires operator intervention exclusively in the last production phase. The analysis present in this paper is focused exclusively on the module in which the operator performs the manual assembly tasks.

The product used in ergonomic analysis is represented by a modular tablet. This tablet consists of 8 components, namely: A display, a bus and 6 modules. The modules are of 3 different types namely battery, GPS receiver and speaker. The product is shown in figure 2 where each component can be observed separately.

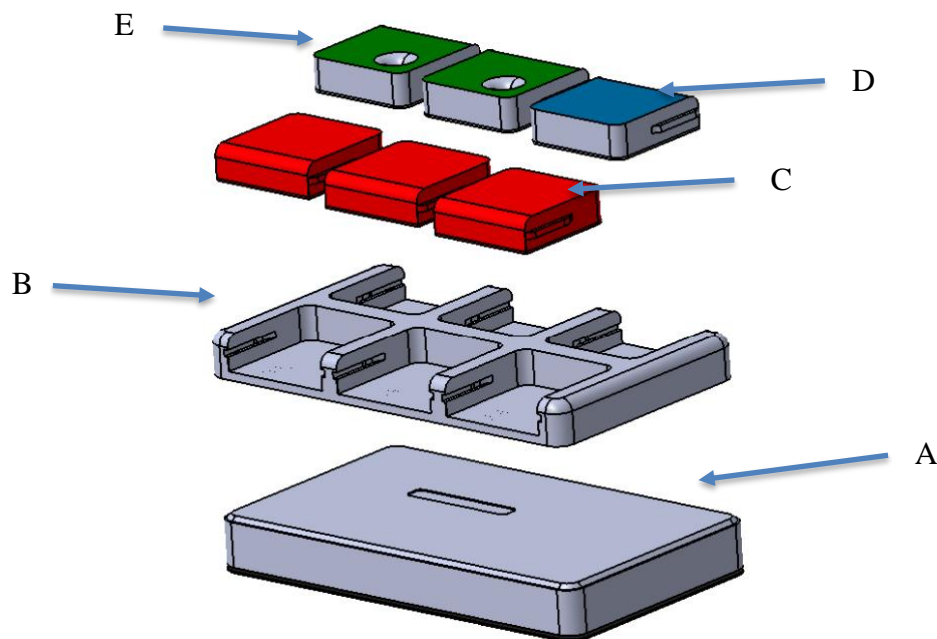


Figure 2 – Assembled product exploded view (A-Display; B-Bus; C-Type 1-battery module; D-Type 2-GPS module; E-Type 3-speaker module)

In order for the analysis itself to be carried out, it is necessary to create in advance the 3D model of the assembly station. The modelling of the station was done using CATIA V5 software, each component being made separately and subsequently assembled (figure 3). The station is imported into the 3D Experience platform and the Ergonomics Evaluation module is selected where the dummy is to be inserted and positioned.

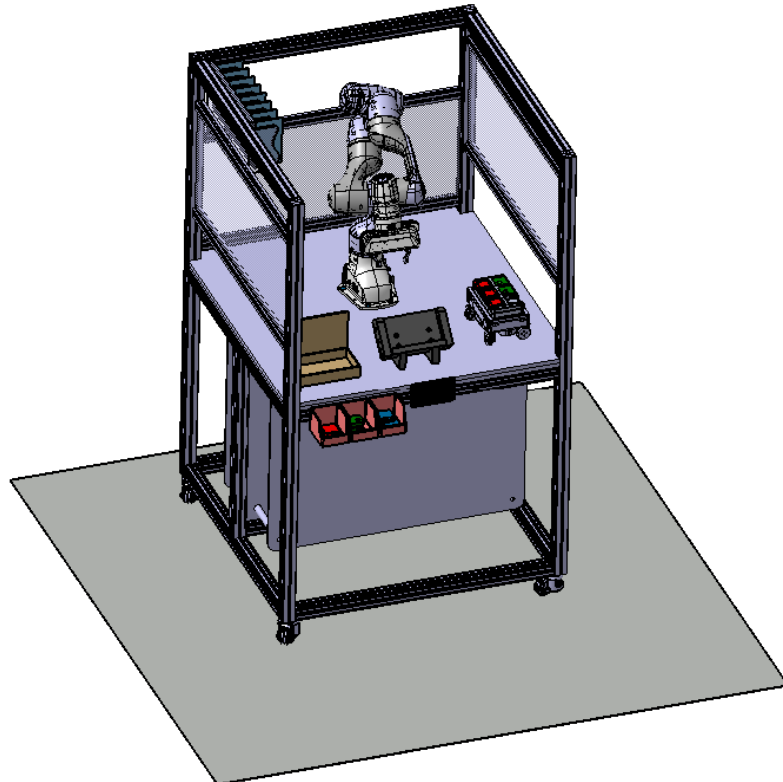







Figure 3 Manual assembly module

The manual assembly tasks addressed in this case study are detailed in table 1 in chronological order.

Table 1 Manual assembly tasks performed by human operator

Operation description	Visual representation
<p>1. Picking the product from the Autonomous Guided Vehicle (AGV) and placing it on the assembly device. And touching the collaborative robot to transmit the command “return to original position”.</p> <p>Human movements addressed for this task: Initial posture; Grabbing and lifting the product from the AGV; Placing the product on the assembly device; Return to the original posture.</p>	
<p>2. Inserting the modules to the product’s main bus.</p> <p>Human movements addressed for this task: Grabbing and lifting the module to be assembled from the deposit tray; Inserting the module in the main bus; Return to the original posture.</p>	

<p>3. Placing the product in the delivery box.</p> <p>Human movements addressed for this task: Pick up the product from the assembly device; Placing the product in the delivery box; Return to the original posture.</p>	
<p>4. Transmitting the command to the collaborative robot to bring the product manual.</p> <p>Human movements addressed for this task: Command transmission to the robot; Picking the manual from the robot's gripper.</p>	
<p>5. Placing the product's manual in the delivery box and closing the box.</p> <p>Human movements addressed for this task: Placing the flyer in the delivery box; Clamping the top of the box; Closing the delivery box.</p>	

Ergonomic simulation using 3DExperience

The first step in performing ergonomic analysis is to understand the environment, the work tasks and the population that performs it. This step is essential because it allows to identify abnormal postures for further simulation in the Ergonomics Evaluation module of the 3D Experience software.

Determining the positions and the selection of the appropriate assessment type are carried out in strict accordance with ISO/TR 12295 guidelines, ensuring the utmost accuracy and adherence to international standards. These decisions are made based on an evaluation through the following key questions:

-Is there any lifting, lowering, or carrying movements involving objects weighing 3 kg or more?

If the answer is affirmative, the NOISH Lifting evaluation is chosen; otherwise, the evaluation process continues. In our scenario the Answer is: No, the piece is under 3 kilograms.

-Are there any activities that require the pushing or pulling of weights?

If the answer is affirmative, the Push and Pull evaluation is chosen; otherwise, the evaluation process continues. In our scenario the Answer is: No

- Are there one or more repetitive upper limb activities totalling an hour or more per shift?

If the answer is affirmative, the meticulous evaluation incorporates the RULA or OCRA analysis to ensure comprehensive assessment. In our scenario the Answer is: Yes. The task lasts 30 seconds and is repeated for a normal working interval of 8 hours a day.

- Are there any static, abnormal postures of the head, neck, torso, or upper and lower limbs that are adopted and sustained continuously for more than 4 seconds, repeatedly occurring for a significant portion of the working time?

If the answer is affirmative, the RULA evaluation is employed to provide an assessment of the ergonomic implications. In our scenario the Answer is: Answer: Yes.

Following the tasks evaluation, two uncomfortable positions were found that require further evaluation.

Posture A

The chosen task is represented by a posture that is repeated during the manual assembly operation, both at the stage when the signal is sent to the robot that it must bring the product's manual, and at the moment when it has to release it. In this position, the hand position is uncomfortable because it involves stretching the arm and positioning the wrist uncomfortably.

Both the posture performed by the two mannequins and their field of vision are visible in Figures 4 and 5.

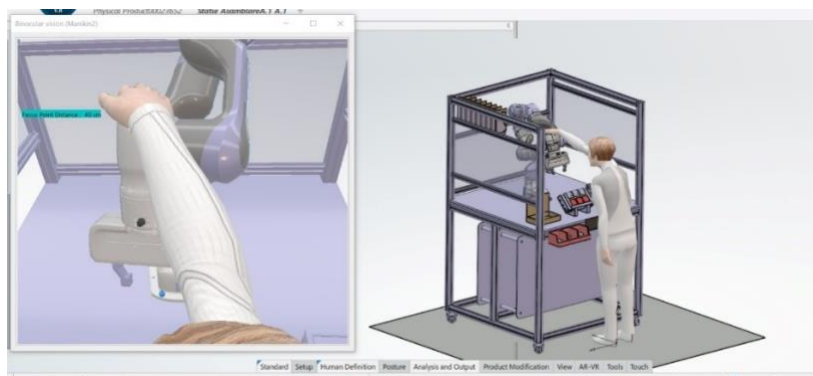


Figure 4 Posture A performed by the female manikin

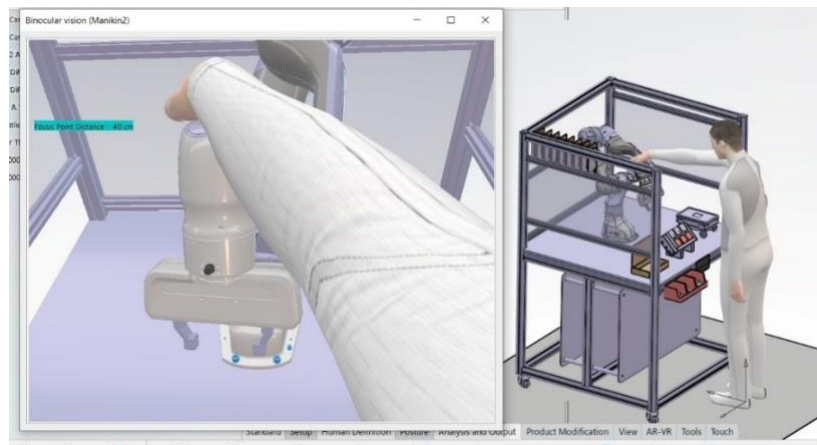


Figure 5 Posture A performed by the male manikin

Posture B

This posture is generated by the first manual assembly operation, when the operator needs to pick up the product from the AGV and position it on the assembly device. The posture in question was selected because the dummy needs to adopt an uncomfortable position that may involve bending, twisting or tilting the torso or pelvis in order to manipulate the part.

Both the posture performed by the two mannequins and their field of vision are visible in Figures 6 and 7.



Figure 6 Posture B performed by the female manikin

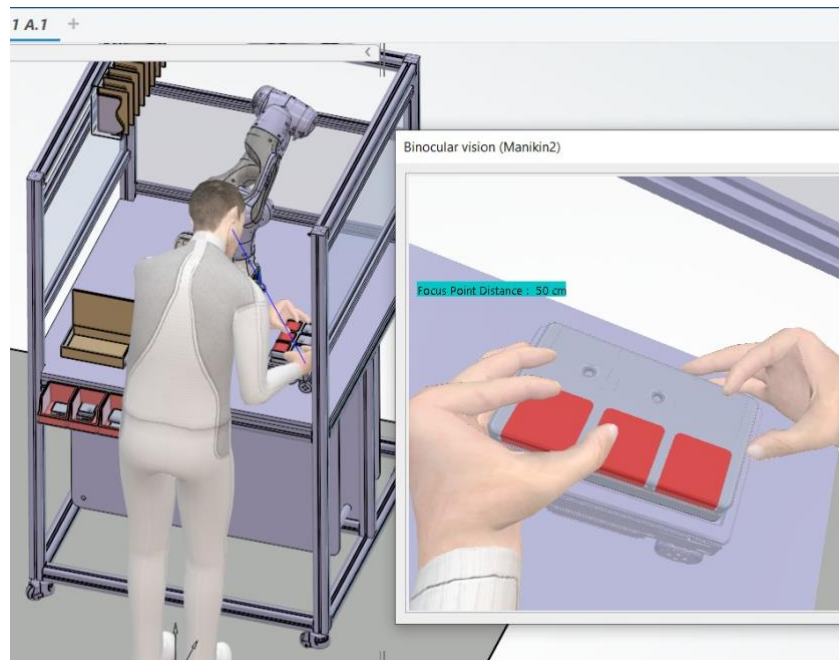


Figure 7 Posture B performed by the male manikin

3. RESULTS AND DISCUSSION

The aforementioned postures were analysed using anthropometric data of a female and a male manikin. The analysis chosen for this type of workload is RULA type, which focuses on determining the tensions that occur in the upper body, more precisely in the neck, trunk, leg, arm, forearm, wrist, but also the tension coming from twisting the wrist. The overall risk index which provides information on the need for a change in that process is determined using the 3D Experience software. At the same time, we can also determine the scores accumulated for each area of the body. The RULA analysis allows the evaluation of only one posture at a time, for only one side of the body (left or right).

For posture A, both manikins are analysed exclusively on the right side, since that is the only side involved in the task. The frequency with which the posture is executed was also selected, being intermittent (less than 4 times / min). The weight was not specified because for this posture it is necessary only to touch the upper part of the collaborative robot in order to transmit the necessary command. The results obtained for posture A are visible in figures 8 and 9.

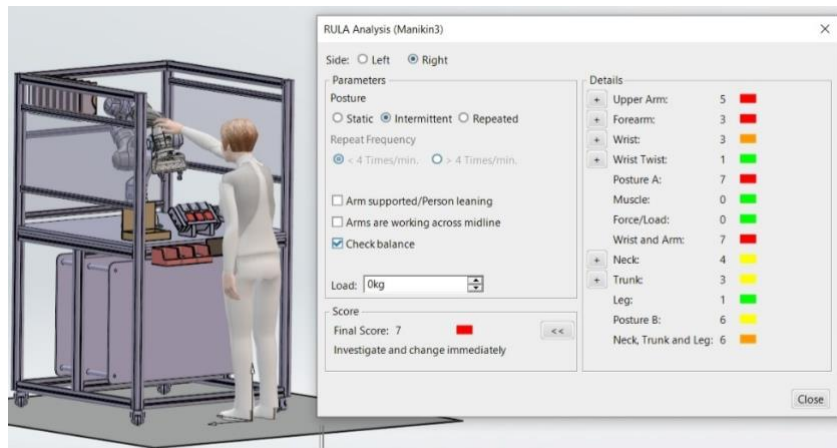


Figure 8 RULA analysis for posture A using the female manikin

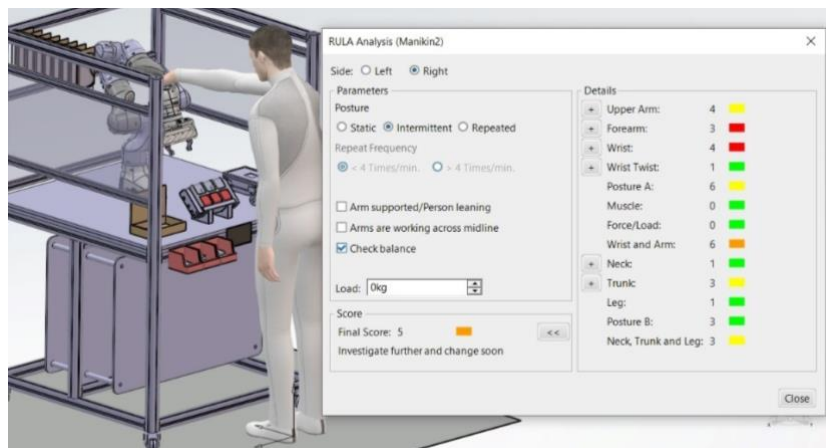


Figure 9 RULA analysis for posture A using the male manikin

To evaluate the posture B, both the left and right sides of the body were involved in the movement, so both manikins were analysed for both sides. The analysis included the weight of the object to be manipulated and the frequency of movement. Figures 10 and 11 show the results for the right side of the body, and Figures 12 and 13 show the results for the left side of the body.

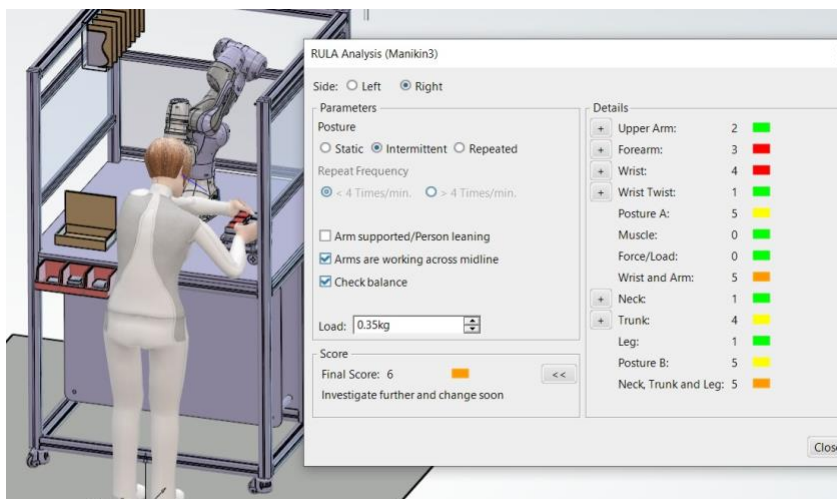


Figure 10 RULA analysis for posture B using the right side of the female manikin

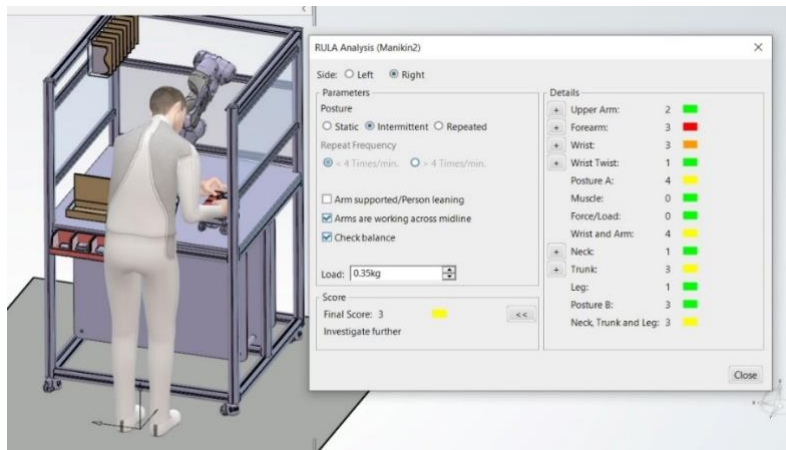


Figure 11 RULA analysis for posture B using the right side of the male manikin

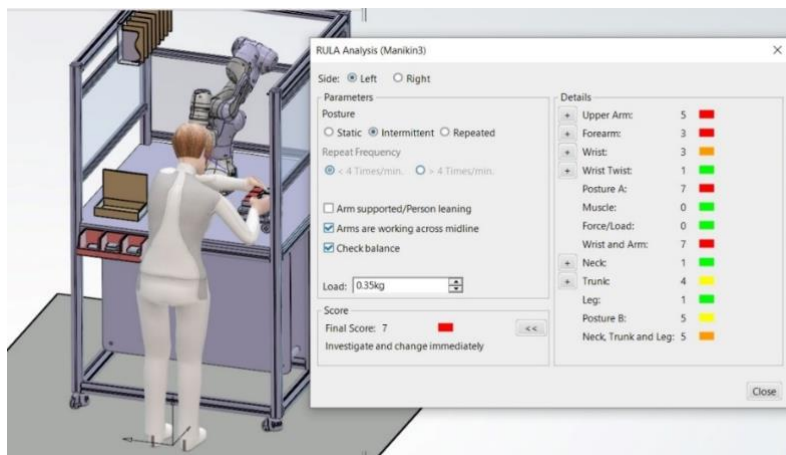


Figure 12 RULA analysis for posture B using the left side of the female manikin

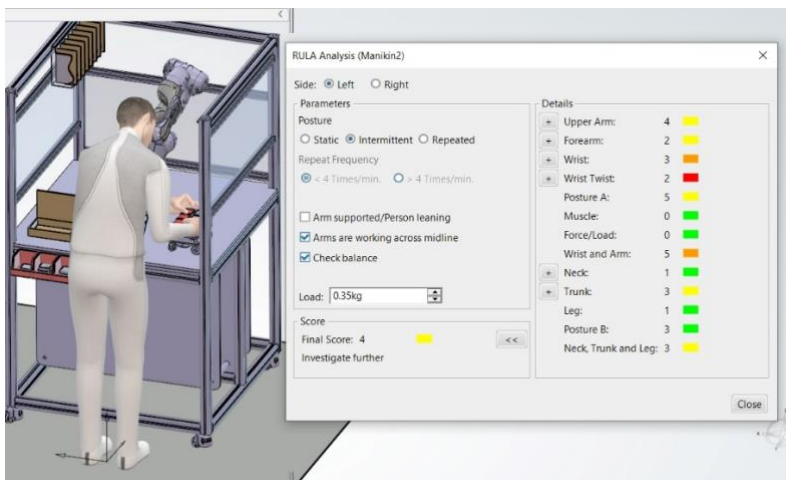


Figure 13 RULA analysis for posture B using the right side of the male manikin

The following table summarizes the RULA scores of postures A and B, which were evaluated using selected manikins. The table also indicates the level of risk and the recommended action for each posture, according to the RULA guidelines. Postures with higher scores pose greater risk of musculoskeletal disorders (MSD) and require more urgent intervention.

Table 2. Action levels and RULA score [20]

Action Level	RULA Score	
	Score	Level of MSD risk
1	1-2	Negligible risk, no action required
2	3-4	Low risk, improvement recommended
3	5-6	Medium risk, further investigation required. Modify soon
4	7+	High risk, modification required urgently

The RULA analysis revealed four levels of action for the different postures performed by the male and female mannequins. The highest level of action (level 4) was reached by posture A performed by the female mannequin and posture B also performed by the female mannequin (for the left side of the body). Both postures scored 7, indicating a high risk of musculoskeletal disorders and an urgent need for intervention. The main areas of strain for both postures were the arm, forearm and wrist.

The second highest level of action (level 3) was reached by posture B performed by the female mannequin (for the left side of the body), which scored 6. This posture also poses a high risk of injury and requires immediate improvement. Posture A performed by the male mannequin scored 5, which corresponds to level 3 as well. This posture needs to be investigated and modified in the near future.

The lowest level of action (level 2) was reached by posture B performed by the male mannequin, for both the right and left sides. These postures scored 4 and 3 respectively, suggesting a moderate risk of musculoskeletal disorders and a need for further investigation. However, these postures do not require immediate intervention.

CONCLUSIONS

The aim of this study is to conduct an ergonomic analysis of a manual assembly process assisted by a collaborative robot, using the Ergonomics Evaluation module within the 3D Experience platform. This module enables the application of various manikins with different anthropometric data, and the customization of the manikin data according to the specific context of the ergonomic evaluation. The module also allows the creation of scenarios with interfaces and human interactions, which can be applied to different manikins depending on the research objectives. For this study, manikins with anthropometric data specific to Europe were selected. A physical simulation was performed to identify the postures of interest for ergonomic analysis. The most uncomfortable postures were replicated and evaluated in the virtual environment using the RULA Analysis. This analysis is a good practice for determining the unsuitable positions adopted by operators in their daily activity, and providing the necessary information for decision making from the generated report. This analysis can also bring benefits in terms of employees' well-being and productivity, as well as reducing companies' costs from musculoskeletal disorders of their employees. The results of the analysis showed that there is a high risk of developing MSDs for people of low stature, especially for the female dummy with a height of 153.25 cm, who had the highest score. According to the action levels suggested by the analysis, it is recommended to investigate and improve the process for the postures performed by the female dummy.

The ergonomic analysis performed in the current paper is an observational analysis performed exclusively based on anthropometric data present in the platform, not including the data of a real operator.

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