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Digital Human Modeling for Long, and Low-Volume Assembly Processes: Gas Turbine Assembly Case Study

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Abstract

Musculoskeletal disorders (MSDs) are prevalent among workers in industrialized countries, reducing productivity, affecting business profitability, and causing personal discomfort. Poor workplace design is a key contributing factor to the phenomenon. The Digital Human Modeling (DHM) approach, initially developed and primarily used for large-scale, repetitive production environments, facilitates the early identification of potential risks associated with tasks in design situations. This paper aims to investigate the extent to which existing Digital Human Modeling (DHM) tools, such as Jack 7.1, can accurately assess ergonomic risks in long, low-volume assembly processes. To this end, a single case involving the work of tightening in a position above the heart, as part of the assembly of gas turbines in a restricted space, was analyzed using Jack 7.1. The work system was simulated in JACK 7.1 and the Predetermined Time Standard tool based on MTM-1, included in the software, was used for time calculations. The rest allowances were calculated in accordance with the guidelines set forth by the International Labour Office and Kanawaty (1996). The MSD risk assessment for over-the-heart work was performed in two phases: initially, a simulation and RULA ergonomic analysis in JACK 7.1, followed by additional ergonomic evaluations using the OCRA Index and KIM-MHO. This paper concludes that JACK 7.1 can be used to analyze ergonomic risks in long, and low-volume assembly processes. However, the analysis needs to be completed using other methods not available in the software, such as the OCRA Index and KIM-MHO.

Keywords

Ergonomics, Musculoskeletal Disorders, Digital Human Modeling, Overhead Work, Ergonomics Assessment

1. Introduction

It is a common occurrence for workers in industrialized countries to experience musculoskeletal disorders (MSDs) [1]-[3]. These disorders have a considerable impact on employee productivity and business profitability, in addition to causing personal suffering for those affected [2]. Nearly 60% of workers in the European Union facing work-related health issues identify MSDs as their main concern [4]. In Quebec, in 2022, MSDs accounted for 28.3% of all recorded and accepted workplace injuries, which represents 26,814 cases out of a total of 94,760 injuries. Among these cases, back injuries were the most common, representing 54.2% of MSDs, followed by shoulder injuries at 15.3% and wrist injuries at 5.7% [5]. As a result, the incidence of sick leave has increased, and the duration of rest and recovery periods has lengthened [6].

MSDs are conditions that affect the soft tissues of the human body [7]. While they are often associated with prolonged exposure to risk factors such as repetitive movements or constrained postures, a single event can also lead to an MSD.

Manufacturing, and more precisely assembling, often leads to workers performing tasks at or above shoulder level, which is the case for workers assembling gas turbines, for example. These workers perform repetitive tasks in a seated position with arms elevated in a tight space, using relatively heavy tightening tools.

Workers in the aviation sector are also confronted with this challenge. Aircraft maintenance technicians, who are responsible for maintaining airplanes and assembling engine parts, often report issues related to musculoskeletal disorders (MSD) [8].

Working above heart level exposes workers to an increased risk of developing MSDs [1] [7] [9] [10]. This type of work entails raising the arms, which forces the heart to overcome the effects of gravity and pump blood to the upper limbs. This can lead to a reduced maximum strength [10], an increase in the respiratory rate, decreased blood circulation and greater energy expenditure [11]. Additionally, it can contribute to muscle fatigue [12] and an elevated heart rate.

In manufacturing, many work systems force operators to adopt uncomfortable postures, perform repetitive tasks, and handle heavy tools, thereby increasing the risk of musculoskeletal disorders. According to Beuß, Sender, and Flügge (2019) [13], three key factors must be considered when assessing these risks: duration, frequency, and force. The most commonly used methods that take these risk factors into account include the Rapid Upper Limb Assessment (RULA) [14], the Key Indicator Method for Manual Handling Operations (KIM-MHO) [15], and the Occupational Repetitive Action Index (OCRA Index) [16].

In design situations or situations where field data are not fully accessible, the literature recommends the use of Digital Human Modeling (DHM), which involves creating a virtual scene that integrates a digital mannequin representing the worker, capable of interacting with its virtual environment. This approach enables the early identification of potential risks associated with the tasks performed. Siemens' Jack 7.1 [17] is one of the most widely used Digital Human Simulation

(DHS) software applications in the field of ergonomics and work analysis [18] [19]. The application features a digital human model with 26 anthropometric dimensions and 62 joints, supported by databases representing various populations (Canadian, American, French, etc.). It includes various ergonomic analysis tools, such as RULA for upper limb assessment, Force Solver and Static Strength Prediction (SSP) to estimate the percentage of the population capable of adopting a posture or performing a task, as well as Predetermined Time Standards to evaluate the time required for a task. These software tools were initially developed and are used mainly for large-scale, repetitive production environments. A comprehensive ergonomic analysis in a DHM requires complex data (forces, time, workstation layout, production organization), which are not always available or easily simulated with current software packages [20]. Companies must collect this data through other means and provide it to users to enhance the reliability of ergonomic analyses [20]. Regarding posture, designers manually adjust the key postures of a digital human model (DHM) [21]. This requires in-depth expertise in ergonomics as well as extensive experience to manage the numerous degrees of freedom of the DHM. These models are efficient for simple tasks (e.g., entering/exiting a vehicle, driving postures), but difficult to use for complex assembly postures or movements [21].

To what extent can existing Digital Human Modeling (DHM) tools, such as Jack 7.1, accurately assess ergonomic risks in long, low-volume assembly processes?

To answer this question, we analyzed a single case study tightening work in a position above the heart as part of the assembly of gas turbines. Using the Jack 7.1 digital modeling tool, we described the work system, simulated the postures adopted by operators and assessed the MSD risks of a single case-based study.

It was found that JACK 7.1 can be used to analyze ergonomic risks in long, and low-volume assembly processes. However, the analysis needs to be completed using other methods not available in the software, such as the OCRA Index and KIM-MHO. Further studies are needed to validate these results.

2. Methodology

This study focuses on the ergonomic analysis of workers involved in the assembly of gas turbines, a process characterized by repetitive motions performed in a seated position with the arms raised above heart level. Conducted in a tight working space, this assembly process, combined with prolonged postures, long assembly cycles, and low production volumes, presents a challenge in the prevention of musculoskeletal disorders (MSDs) [22].

For this analysis, we chose to study a single case, specifically a workstation within the gas turbine assembly process. This choice is justified by the representative nature of this case, which illustrates common work situations in similar industrial environments.

To describe the work system used, measurements of the workstation and tools were gathered, and detailed photographs were collected. The task description was carried out through a process involving the consultation of existing literature, tool usage documentation, and a formulation of hypotheses based on analyses of similar documented workstations.

The over-the-heart work MSD risk assessment was conducted in two stages, namely, a simulation and a RULA ergonomic analysis [23] in JACK 7.1, followed by a complementary ergonomic analysis using the OCRA Index and KIM-MHO (see Figure 1). Ergonomic analysis methods differ in analysis approach, level of detail of the analysis and in scales used [24]. Triangulation with different methods is therefore imperative. The academic version of JACK 7.1 was used.

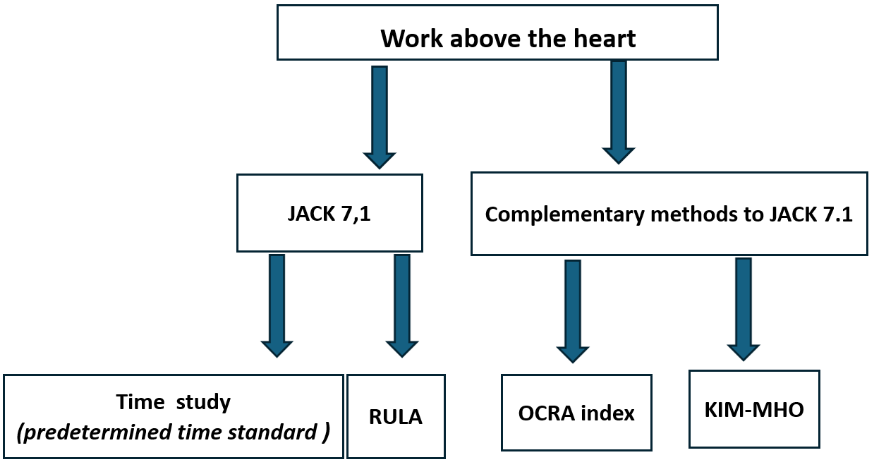


Figure 1. Methods used in this study.

First, the work system was simulated in JACK 7.1 (see Figure 1) and the Predetermined Time Standard tool based on MTM-1, included in the software, was used for time calculations. The rest allowances were calculated in accordance with the guidelines set forth by [18]. Subsequently, an ergonomic analysis in JACK 7.1, using the NA-Auto anthropometric database and the RULA method, also included in the software, was conducted, and a variety of realistic postures were simulated. We initially considered digital mannequins representing the 5th and 95th percentiles of men and women. However, beyond the 5th percentile male, the virtual mannequins did not have enough space to perform the tasks effectively, as the workspace became too tight for larger percentiles (see Figure 2 below). Therefore, the analyses were conducted using the 5th percentile male mannequin, which was the largest model capable of fitting within the available space. The RULA analysis included two scenarios: Scenario 1, which involves a static torso and neck position for more than one minute, and Scenario 2, which involves head rotation.

Finally, to triangulate and respect epistemological rules, we complemented our DHM analysis (see Figure 1) with external ergonomics evaluation methods, the OCRA Index and KIM-MHO.

The OCRA Index [16] is a precise upper limb MSD risk analysis method. It considers risk factors such as work organization, task frequency, and rest periods. The OCRA Index analysis was conducted using an eight-hour shift work scenario, including a one-hour lunch break and rest time equivalent to 17% of the total working time (The rest allowances were calculated in accordance with the guidelines set forth by Bureau international du travail & Kanawaty (1996) [18].

The OCRA Index is calculated by dividing the number of technical actions performed during work (ATA) by the reference value (RTA).

Here, the reference value (RTA) is given by:

$$\text{RTA} = \sum_{j=1}^{n} \left(\text{CF} \times \left(\text{FOM}_j \times \text{POM}_j \times \text{REM}_j \times \text{ADM}_j \right) \times D_j \right) \times \left(\text{RCM} \times \text{DUM} \right) \quad (1)$$

where CF is the frequency constant for technical actions per minute; FOM, POM, REM and ADM are multipliers chosen based on the characteristics of force, posture, repetitiveness, and additional risk factors included in each task j being examined; D is the duration (in minutes) of each repetitive task j; RCM is the multiplier for the "lack of recovery period" risk factor, and DUM is the duration multiplier for the overall task duration.

The KIM-MHO method [15] is intended for the assessment of risk inherent in the manual handling of materials weighing less than 3 kg. KIM-MHO considers risk factors such as the posture, grip conditions, the type of force exerted, the task duration, work organization (in terms of time distribution), and working conditions (in terms of noise, temperature, humidity, and lighting). To use the KIM-MHO analysis, it was hypothesised that:

- A 60 Nm torque is applied in accordance with the specifications of the bolts used, in alignment with aerospace industry standards and the practices of the industrial partner.
- The worker performs the initial tightening with a pneumatic ratchet wrench, reaching a torque of approximately 46 Nm, and then completes it with a torque wrench.
- To estimate the maximum forces exerted by the hand-arm system, taking into account the body position and direction of force, we used the Siemens method, and it was estimated to be 465 N.
- Tightening force required to use the pneumatic ratchet wrench: At a torque of 46 Nm, the measured manual force was estimated to be 129 N (27.74%) [25] in Radwin *et al.*'s (1989) [25] study, which we used.
- Required tightening force for precision work: The torque wrench user manuals were consulted. For a torque wrench with a maximum torque of 210 Nm and a length of 470 mm, the maximum force was estimated to be 446 N. Given that the target torque in this study was 60 Nm, the required tightening force to achieve this was estimated to be 127.5 N (28.5% Fmax).
- No static holding work was performed, requiring the worker's arm to remain still for a minimum of four seconds.
- The tools employed were ergonomic, thereby facilitating efficient force transmission.

- The work was organized appropriately, with well-distributed rest periods.
- Unfavourable working conditions, such as a tight spatial environment that may limit vision, can negatively impact worker safety and performance.

As KIM-MHO considers the overall duration of the task, analyzing the initial tightening step, which lasts less than two hours, and the precision tightening step, which lasts less than three hours, would not provide a comprehensive understanding of the daily workload. A more reasonable approach is to carry out both analyses as a single task. In proceeding as such, we consider the workday that encompasses both the initial and precision tightening steps, thereby facilitating a more comprehensive evaluation of the workload related to bolting. Additionally, it is important to consider whether the sequence of these activities may not only lead to fatigue effects but also allow for recovery due to a change in load, potentially influencing overall workload assessment. The resultant forces are found to be approximately equivalent for both the initial and precision tightening procedures, with a maximum value of 30% Fmax. However, this does not account for arm postures above the heart or other manual forces. Accordingly, an analysis was conducted to consider forces up to 50% of Fmax. Given the difference in the number of actions between the initial tightening phase and the precision tightening phase, it was observed that the initial tightening involves 48 actions per minute. This corresponds to 24 actions for positioning the tool and 24 actions for tightening. On the other hand, the precision tightening requires only 20 actions per minute, with 10 actions for positioning the wrench and 10 actions for tightening. We will use average values (17 actions per minute for tool positioning and 17 actions per minute for tightening).

3. Results

3.1. Description of Assembly Tasks

The following realistic scenarios were designed. The assembly takes place in a tight and difficult to ingress/egress workspace, using a pneumatic and a manual ratchet. The assembly operations are conducted while seated on an adjustable chair. The bolts are arranged in a circle around the workers, who can rotate the chair by turning their feet to access each bolt without turning their head. The task involves tightening bolts distributed across three concentric circles at different heights: 40 bolts in the first row at 2.16 m from the ground, 76 bolts in the second row at 2.285 m from the ground, and 80 bolts in the third row at 2.43 m from the ground. The work is carried out in two phases: an initial tightening, which involves the use of a pneumatic ratchet and a simple manual wrench, followed by a precision tightening, which involves the use of a torque wrench. In this context, a "row" refers to a group of bolts arranged regularly along the same circumference, forming a complete circle around the center of the assembly (see **Figure 2**). As part of the operational procedure for the initial tightening, it is assumed that the worker first positions all the bolts in the holes (see **Table 1**, steps 1 to 3). **Table 2** provides a description of the steps involved in the precision tightening phase.

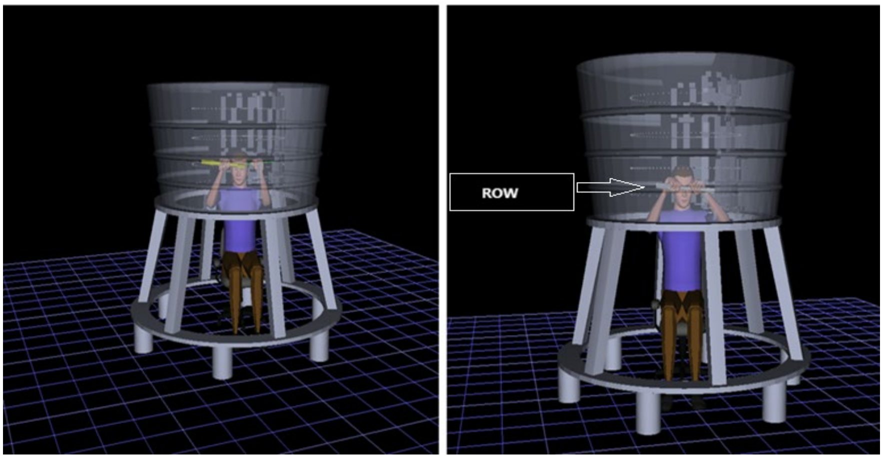


Figure 2. Initial tightening (Left side), Precision tightening (Right side).

Table 1. Description of the initial tightening phase.

Step	Activity	Parts involved	Tools/limbs	Other necessary means	Estimated time required for the worker according to JACK 7.1 Predetermined Time Standards (sec)
1	Grasp and identification of the bolt	Bolt, nut, washer	Right hand	Chair	0.8
2	Inserting the bolt into the hole and positioning the washer	Bolt, washer	Right hand, left hand	Chair	1.7
3	Positioning of the nut	Nut	Left hand	Chair	0.2
4	Grasping and positioning of the tools	Bolt	Pneumatic ratchet wrench and conventional manual wrench	Chair	5.11
5	Tightening of the bolt	Bolt	Pneumatic ratchet wrench and conventional manual wrench	Chair	0.6

Table 2. Description of the precision tightening phase.

Step	Activity	Parts involved	Tools/limbs	Other necessary means	Estimated time required for the worker according to JACK 7.1 Predetermined Time Standards (sec)
1	Grasping and positioning of the tool	Bolt	Torque wrench	Chair	6.1
2	Tightening of the bolt	Bolt	Torque wrench	Chair	4

Table 3 provides the expected task loads (static and dynamic) for the assembly tasks associated with the initial and precision tightening at the different rows and for a 5th percentile male. The initial tightening activity involves static postural work combined with dynamic hand-finger movements, while the precision tightening activity includes static holding combined with dynamic hand-arm-shoulder movements. Static holding work can transmit external forces to the tools, and unlike dynamic work, may impair blood circulation, disrupting muscle metabolic waste removal. For the arm position above the head, the third row imposes a restrictive posture with maximum arm extension, resulting in a very high physical effort demand. In contrast, the second row corresponds to a moderate demand (3), as the arm elevation is reduced, while the first row, where arm elevation is even more limited, presents no overhead work demand (0). The finger-hand system is heavily engaged during the initial tightening, as the activation of the pneumatic ratchet tool requires significant finger movement (5), whereas the fingers are not engaged during the precision tightening (0). Conversely, the hand-arm-shoulder system is more involved during precision tightening, as the use of the torque wrench requires continuous pressure on its handle, involving arm movement (5), compared to a moderate demand (2) during the initial tightening. Regarding force, the effort required is low (1) to activate the pneumatic ratchet, as the tool generates torque through external air supply. However, it becomes moderate (2) for the precision tightening, as the worker generates the torque, although this effort is reduced due to the initial tightening, which eases the final resistance. Finally, high repetitiveness (5) is observed in both phases due to the cyclical nature of the tasks. During the initial tightening phase, there is an overlap of static postural work with the unilateral dynamic work of the finger-hand system. During precision tightening, there is an overlap of static holding work with the unilateral dynamic work of the hand-arm-shoulder system.

Table 3. Expected task loads for assembly*.

Step + Activity		Static load				Dynamic load	
		Arm position above head		Hand-Arm-Shoulder System	Finger-Hand System	Force	Repetitiveness
1	Initial tightening	5th percentile male	1st row: 0 2nd row: 3 3rd row: 5	2	5	1	5
2	Precision tightening	5th percentile male	1st row: 0 2nd row: 3 3rd row: 5	5	0	2	5

(0 Does not apply, 1 Very low, 2 Low, 3 Moderate, 4 High, 5 Very high)*

3.2. Time Calculation

Table 1 and Table 2, previously presented, outline the tasks and indicate the duration of the different stages in the initial tightening and precision tightening procedures. Time calculations were made using the Predetermined Time Standard tool in JACK 7.1, assuming that the worker was experienced. The hand movement distance considered is linear, as the tool does not provide a way to calculate a curvilinear movement distance.

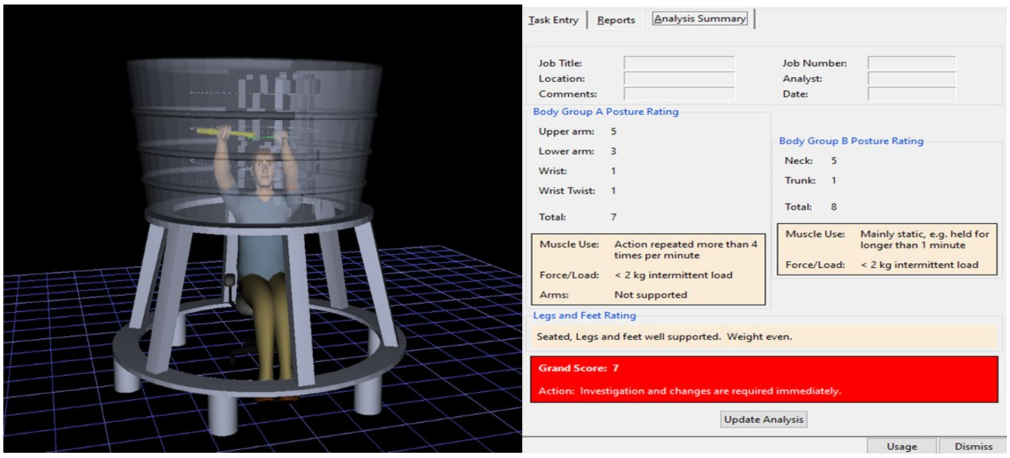
In the case of tightening, the time required for the operation depends on several specific characteristics of the tools and the bolt, including its dimensions and the desired tightening torque. The tightening times associated with these two tools, namely, the pneumatic ratchet and the torque wrench, cannot be equivalent. Indeed, the tightening force of the pneumatic ratchet is automatically generated by the tool through an external power supply, whereas the use of the manual torque wrench requires controlled and continuous pressure applied by the operator to its handle.

The initial tightening time with the torque wrench is 0.5 seconds, calculated using the Predetermined Time Standard tool in JACK 7.1, and represents only the time required to perform the basic mechanical movement. However, this does not account for the additional effort involved in the precision tightening phase with the torque wrench, which requires manual adjustment and prolonged pressure to achieve the exact torque. To reflect these additional requirements, 3.5 seconds were added. This increase in time is justified by the static holding work assumption, which involves applying pressure forces to the tool for a duration of 4 to 6 seconds.

Moreover, the torque wrench is used exclusively during the final tightening phase. This means that the worker has already performed an initial tightening with the pneumatic wrench, reaching a torque of approximately 46 Nm. The torque wrench is then used to finalize the tightening and reach the required torque of 60 Nm. The gap between the two torque levels (46 Nm to 60 Nm) also justifies a slower, more precise finalization phase, characteristic of using a torque wrench in industrial environments. To determine the required rest allowances, we used the recommendations of the International Labour Organization & Kanawaty, 1996 [18]. These take into account the physical exertion, mental strain and the characteristics of the work environment. In the context of our study, we estimated the total rest allowances to be 17%.

3.3. Ergonomic Evaluations

The initial tightening procedure requires more space, as the operator uses two tools, making movement challenging and increasing the risk of collisions within the workstation.



Job Title:
Location:
Comments:
Job Number:
Analyst:
Date:

Body Group A Posture Rating

Upper arm: 5
Lower arm: 3
Wrist: 1
Wrist Twist: 1
Total: 7

Muscle Use: Action repeated more than 4 times per minute
Force/Load: < 2 kg intermittent load
Arms: Not supported

Body Group B Posture Rating

Neck: 5
Trunk: 1
Total: 8

Muscle Use: Mainly static, e.g. held for longer than 1 minute
Force/Load: < 2 kg intermittent load

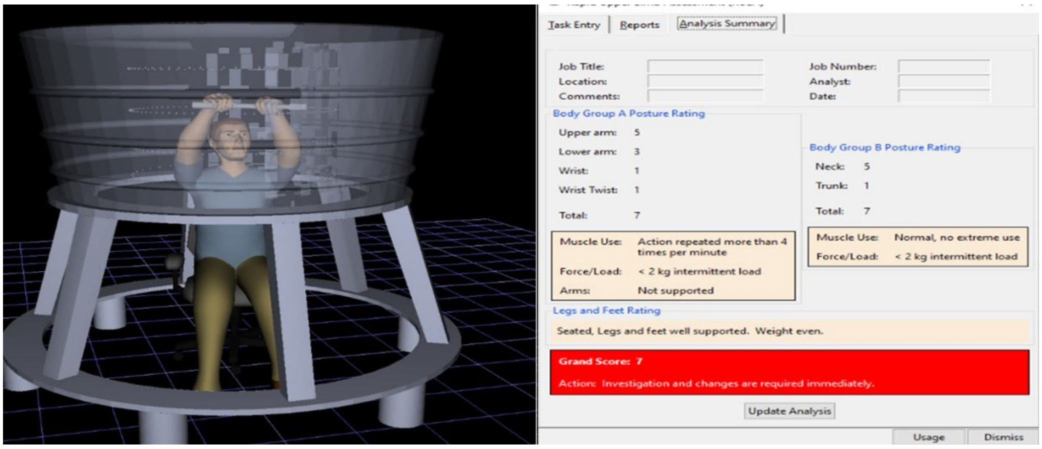
Legs and Feet Rating

Seated, Legs and feet well supported. Weight even.

Grand Score: 7
Action: Investigation and changes are required immediately.

Figure 3. Posture, initial tightening: 3rd row, 5th percentile male (Left), RULA analysis (Right side).

Figure 3 presents a digital mannequin of a worker with a 5th percentile male body size tightening a bolt in the 3rd row, with the arm position significantly raised. The RULA analysis for this posture, conducted under Scenario 2 (see methodology), resulted in a high risk score of 7. In the case of precision tightening, the worker's movements are more fluid, as shown in **Figure 4**, where the RULA analysis also resulted in a score of 7 for Scenario 2.



Job Title:
Location:
Comments:
Job Number:
Analyst:
Date:

Body Group A Posture Rating
Upper arm: 5
Lower arm: 3
Wrist: 1
Wrist Twist: 1
Total: 7

Muscle Use: Action repeated more than 4 times per minute
Force/Load: < 2 kg intermittent load
Arms: Not supported

Body Group B Posture Rating
Neck: 5
Trunk: 1
Total: 7

Muscle Use: Normal, no extreme use
Force/Load: < 2 kg intermittent load

Legs and Feet Rating
Seated, Legs and feet well supported. Weight even.

Grand Score: 7
Action: Investigation and changes are required immediately.

Figure 4. Posture, precision tightening: 3rd row, 5th percentile male (Left), RULA analysis (Right side).

Table 4. Results of the three methods used*.

Method		**Left side**	**Right side**
KIM-MHO		7.5	10
OCRA index		11.3	9.9
RULA (5th percentile)	**Row**	**Scenario**	**Score**
Precision tightening	3rd row	Scenario 1	7
		Scenario 2	20
		Scenario 2 (head rotation)	7
	2nd row	Scenario 1	7
		Scenario2	7
	1st row	Scenario 1	4
		Scenario 2	4
		Scenario 2 (head rotation)	5
Initial tightening	3rd row	Scenario 1	7
		Scenario 2	7
	2nd row	Scenario 1	6
		Scenario 2	5
	1st row	Scenario 1	4
		Scenario 2	4

KIM-MHO (Min < 20, Max ≥ 100), RULA (Min 1, Max 7), OCRA Index (Min ≤ 1.5, Max ≥ 100)*.

Table 4 presents the RULA analyses for the initial and precision tightening. The results show that the second and third rows present a high risk of musculoskeletal disorders, while the first row shows a low risk. Head rotation increases the RULA score for the first row.

3.4. Analysis with OCRA Index

The OCRA Index considers specific factors such as task repetitiveness and risks associated with tool positioning, not included in a RULA JACK 7.1 analysis. It also includes an additional phase for bolt positioning, the frequency of each tightening phase, and non-repetitive tasks such as connecting the air hose, adjusting the torque, and picking up tools. The OCRA scores obtained, 9.9 for the right side and 11.3 for the left side, indicate a significant risk.

3.5. Analysis with KIM-MHO

The KIM-MHO method realistically simulates the gripping of tools and offers hand evaluation methods that are relevant to the work system under study. The KIM-MHO score of 105 indicates a high risk.

Table 4 presents the results obtained using the three analytical methods, namely, KIM-MHO, OCRA INDEX, and RULA. The results demonstrate that the different evaluated methods are associated with elevated risk levels.

4. Discussion

The creation of the digital mannequin was a lengthy and challenging process. The JACK 7.1 DHMs required a 5-day training session. This time was necessary to gain a full understanding and mastery of the software's features, as well as to adjust to the functions for customizing the digital mannequin's joints. The simulation lasted 40 minutes due to difficulties encountered while creating the digital mannequin, particularly because of the restrictive posture. The realistic postures were adjusted manually, joint by joint. The accuracy of the analyses depends on a precise understanding of joint movements. Discrepancies in this coordination may lead to less accurate results [26]. Caution is thus recommended when interpreting the findings. Furthermore, the restricted workspace made it challenging to adjust the mannequin's posture without causing collisions with the workstation. Indeed, the algorithms currently used for DHM operation planning are not designed for tasks performed in such a restricted space [27]. It is also important to highlight that the worker is seated on an office chair with wheels, which requires additional stabilising forces. To maintain equilibrium, the body must compensate for the uncontrolled movements of the chair.

The time required for the worker to complete their task was calculated using the tool available in JACK 7.1, which is based on the MTM-1. The distance between the hands was calculated as a linear distance, rather than a curvilinear one. Furthermore, some parameters related to the calculation of tightening times were not considered. Indeed, the time required for tightening is also influenced by several factors, including the type of bolt, its dimensions, the torque applied, the precision of the torque wrench, the tool speed, and the air pressure used when employing a pneumatic ratchet wrench. Furthermore, the simulation in Jack 7.1 does not accurately model the bolt tightening process. The estimation of the rest of the allowances was based on multiplication tables derived from point-based systems [18], developed from laboratory experiments. Since JACK 7.1 does not account for rest time, this method was used as a supplementary approach. However, it may not provide sufficient recovery time, suggesting that further revisions are needed to better align with real-world working conditions. Additionally, other methods, such as adjustments in collective agreements, could also be considered for more accurate rest time estimations.

The RULA analysis was carried out quickly and provided a general assessment of the upper limb risks, focusing primarily on the posture of the digital mannequin. The highest RULA score, 7, was recorded during the tightening of the third row in both the initial and precision tightening phases, where the worker's arms are in an extended position. In contrast, the lowest RULA score, 4, was obtained during the tightening of the first row. In this instance, an elevation of the shoulder exceeding 60 degrees, which may contribute to the development of musculoskeletal disorders [7] [28], was observed. Additionally, the posture of the neck was found to influence the RULA score. Postures requiring head rotation to access bolts beyond the visual field were observed. To illustrate, a tightening posture in the first row with a neutral neck position yielded a score of 4, whereas the same posture with head rotation resulted in a score of 5. A non-neutral neck position has been identified as a contributing factor to the onset of musculoskeletal disorders, as it increases muscle tension in the neck by requiring the flexor muscles to work harder to maintain head balance [9] [28] [29]. Additionally, forearm pronation was noted. When the hand is in a pronated position, the arm is typically more abducted, meaning it is positioned further from the body. Should a task involve the raising of the arm, the use of a pronated hand posture may serve to accentuate this elevation [30] (Chaffin *et al.*, 2006). The factor that had the greatest impact on the RULA score was arm elevation. The frequency of work was also taken into account, with a minimum of four actions per minute. It is also important to note that the RULA method does not take into account other factors that may contribute to the onset of musculoskeletal disorders, such as work duration, frequency, worker recovery periods, or environmental factors [31].

The OCRA index required a two-day training, based on the available literature. The OCRA Index scores for the right and left sides were 9.9 and 11.3, respectively reflecting a significant risk. This method is demonstrably more precise and addresses some of the limitations encountered with RULA. It takes into account additional factors that present a risk, including the frequency and duration of work, as well as worker recovery time. Furthermore, the analysis encompassed a phase dedicated to the positioning of bolts. The frequency of work and the posture score had a significant impact on the final score, particularly in relation to the posture of the shoulders. It should be noted, however, that the OCRA Index does not take into account the posture of the neck. The discrepancy in scores between the left and right sides can be attributed to the fact that, inclusive of the bolt positioning phase, the work frequency was higher on the left side than on the right side. The frequency of work had a significant impact on the OCRA Index evaluation. According to [32], injuries caused by repetitive movements and insufficient recovery evolve gradually. The force exerted on the tissues should remain below the tolerance threshold, but the repetition of movements and a lack of rest gradually lower this threshold until it is surpassed.

Regarding the evaluation of the musculoskeletal system of the hand-arm, the score obtained with KIM-MHO was 105. As with the OCRA Index, a two-day training based on the available literature was required for KIM-MHO. Although less detailed than the OCRA Index, this method considers many work parameters (duration, frequency, posture, environmental factors). The force index, body posture, and arm posture are the elements that most influenced the KIM-MHO score. Manual strength exercise is a contributing risk factor for the emergence of musculoskeletal disorders [7]. In the context of using a tool, the grip strength varies as a function of the target torque, the tool spindle rotation speed, the resistance of the joints, and the torque buildup duration [33], the type of grip [31], the grip diameter [34]-[36], and the weight of the tool [37] [38]. In our KIM-MHO analysis, we focused on the tightening force to determine the force index, but this approach did not account for other manual forces, potentially underestimating the physical load of the task.

In the analysis conducted using three methods and respecting epistemological rules, the work posture was identified as the predominant factor. These findings are consistent with those of Asadi, Yu, and Mott (2019) [8], who, in their study of aerospace technicians, found that tasks performed overhead received the highest score on the REBA (Rapid Entire Body Assessment) [39] compared to other postures. Indeed, work performed over the heart level has been identified as a contributing factor in the onset of musculoskeletal disorders [7] [12] [40] [41]. An arm elevation above 60˚ has been demonstrated to reduce the subacromial space due to the movement of the supraspinatus tendon, which may result in its positioning beneath the acromion and the subacromial bursa [42]. A reduction in subacromial space can result in compression of the supraspinatus tendon [43]. Moreover, it has been demonstrated that arm elevation results in muscle fatigue [12], reduces blood circulation [11], and increases intramuscular pressure [11].

The Siemens method, used to determine the maximum force in the pneumatic wrench tightening process, is effective and widely used in Germany. However, it lacks detailed documentation on its scientific principles and theoretical foundations. We assessed the force required to use the pneumatic wrench based on Radwin *et al.* (1989) [25], who studied tightening parameters under ideal laboratory conditions. However, the study had limitations, including a small sample size and differences in the tools used, and therefore, a careful interpretation of the results is therefore recommended.

Force assessment could rely on workers' perceptions [44] or be measured. Basing assessments of the force required for technical actions on the technical characteristics of the tools alone may prove inadequate for capturing the actual experience of the worker. However, as the study was conducted in a design context, field work with workers was not planned, which could be achieved in a subsequent study. Alternative methods were employed to estimate the effort required to utilize these tools. Research was conducted through various information sources, including websites, technical documentation, and user manuals, to understand the characteristics and force requirements of each tool. Simulations were then conducted with the tools in the laboratory to further analyze their use. Furthermore, an exploratory study using the VMG30 data gloves, focusing on the tightening tools used, was conducted at the human factors engineering laboratory [45]. In simulations, many tasks are performed to determine if a part can be manually handled, with several considerations needing to be addressed: is there enough space, are the handles suitable, etc. Simulation engineers can spend up to 50% of simulation time adjusting the hands and fingers to achieve a realistic configuration [46]. Additionally, complex tasks such as tightening cannot be simulated effectively using Digital Human Models (DHM). Therefore, virtual glove technology is a major area of interest [47].

5. Conclusion

This single case-based study concluded that JACK 7.1 can be used to analyze ergonomic risks in long, and low-volume assembly processes. However, such analyses must be complemented by other ergonomic analysis methods not available in the software version used in this study. Further multiple case studies are needed to validate the results obtained herein. We recommend improving the process of creating the digital mannequin in JACK 7.1 to make it more intuitive and less effort-intensive for the user, as well as integrating a more realistic gripping functionality capable of simulating natural and varied grips based on the tools used. Additionally, we recommend integrating tools that allow for a more comprehensive ergonomic analysis of the studied work system, including several factors that could contribute to the onset of MSD risks, such as the OCRA Index and KIM-MHO.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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