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Digitalization of Musculoskeletal Risk Assessment in a Robotic-Assisted Assembly Workstation

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Abstract: The ergonomic assessment of adopted working postures is essential for avoiding musculoskeletal risk factors in manufacturing contexts. Several observational methods based on external analyst observations are available; however, they are relatively subjective and suffer low repeatability. Over the past decade, the digitalization of this assessment has received high research interest. Robotic applications have the potential to lighten workers' workload and improve working conditions. Therefore, this work presents a musculoskeletal risk assessment before and after robotic implementation in an assembly workstation. We also emphasize the importance of using novel and non-intrusive technologies for musculoskeletal risk assessment. A kinematic study was conducted using inertial motion units (IMU) in a convenience sample of two workers during their normal performance of assembly work cycles. The musculoskeletal risk was estimated according to a semi-automated solution, called the Rapid Upper Limb Assessment (RULA) report. Based on previous musculoskeletal problems reported by the company, the assessment centered on the kinematic analysis of functional wrist movements (flexion/extension, ulnar/radial deviation, and pronation/supination). The results of the RULA report showed a reduction in musculoskeletal risk using robotic-assisted assembly. Regarding the kinematic analysis of the wrist during robotic-assisted tasks, a significant posture improvement of 20–45% was registered (considering the angular deviations relative to the neutral wrist position). The results obtained by direct measurements simultaneously reflect the workload and individual characteristics. The current study highlights the importance of an in-field instrumented assessment of musculoskeletal risk and the limitations of the system applied (e.g., unsuitable for tracking the motion of small joints, such as the fingers).

Keywords: kinematic analysis; ergonomics and human factors; musculoskeletal risk; industrial manufacturing

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1. Introduction

Contrary to several occupational diseases originating from exposure to specific hazardous agents, most work-related musculoskeletal disorders (WMSD) have a multifactorial origin. According to the European Agency for Safety and Health at Work, the WMSD risk factors include: (i) physical causes (such as repetitive movements, awkward and static postures, fast-paced work); (ii) individual factors (e.g., workers' age); and (iii) organizational and psychosocial factors (e.g., high-demand jobs or low autonomy, low job satisfaction) [1]. Assembly workers from manufacturing companies are continuously exposed to these WMSD risk factors [2,3]. To act on this problem, the scientific literature presents several methods validated for WMSD risk assessment. These methods and tools have been categorized [4,5] according to the following headings (Figure 1):

(i) Self-reports and checklists collect more generic workers' perceptions and/or identify risk factors;
(ii) Observational methods may be subdivided into simple and advanced techniques/methods;
(iii) Direct measurements that rely on sensors that are attached directly to the workers for the measurement of the risk factors' effect on physiological and biomechanics parameters, for example, surface electromyography to assess muscular activity [6–8].

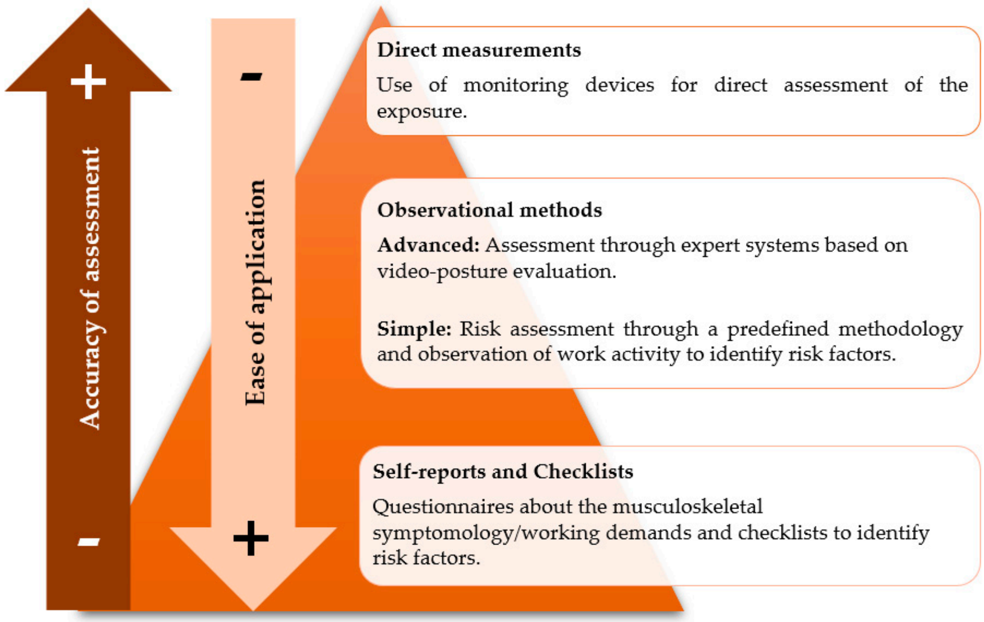

Figure 1. Representation of the methods classifying WMSD risk assessment into categories.

The observational methods are commonly applied in industrial environments and allow risk assessment through a predefined procedure, including real-time observation of the work activity and workers' respective postures. The Rapid Upper Limb Assessment (RULA) [9] is one of the most popular ergonomic assessment methods applied in the manufacturing industry [10–12]. However, RULA results based on external analyst observations are relatively subjective and suffer low repeatability [13]. The process of automating this assessment has received high research interest. A few software-based approaches and video-posture evaluation systems have been proposed to increase measurement precision and simultaneously provide ease of use in industrial working environments [14]. These advanced methods often consider the criteria and algorithms proposed by simple observational methods [4].

Camera-based motion capture systems have been widely used for quantifying and analyzing body movements in this domain [15]. This method is not only time-consuming but also inaccurate [16]. Regarding in-field instrumented ergonomic risk assessment, human-occlusion and object-occlusion cause inconsistency in the data collected by motion cameras. For this reason, wearable inertial motion units (IMU) have been deemed more suitable in real-industry environments [13]. This technology consists of lightweight devices and allows the direct measurement of angular variation during performance tasks [4].

Over the past decade, inertial motion capture has been used in a wide range of applications [17] and appears to have many advantages over previous measurement systems in terms of flexibility and ensuring real-time human motion analysis. It does not interfere with the body's movements by being completely non-invasive [17,18] and immune to occlusion, signal blocking, or label confusion [13,18]; it can also adapt to any environment, indoor and outdoor. Moreover, its reliability and feasibility for assessing human movement are recognized and designed for intuitive use [15]. This technology has been applied in studies focused on work tasks and/or conditions that increase the risk for WMSD occurrence [19,20]. Previous studies demonstrate that the IMU is a promising technology for motion analysis and WMSD risk assessment in several occupational contexts, such as clinical practices [21], automotive assembly [22], farming activities [23], and human–robot collaboration settings [24].

In assembly manufacturing, the ergonomic assessment of working postures is essential for preventing WMSD risk factors [11,25,26]. XSens Technologies B.V. recently developed an algorithm that incorporates motion data and calculates the RULA score [25]. This computation tool, called the RULA report, was previously applied to support the design phase of the human–robot collaboration assembly workstation. In our previous study [26], we tested different workbench configurations in a laboratory context; the RULA report helped select the optimal ergonomic configuration for the wrist–hand system. However, it became necessary to assess the ergonomic suitability of the workstation installed on the shop floor since it was created for workers with musculoskeletal disorders. The novel assembly workstation, with the collaborative robot implemented, is described in [12], as well as its impact on productivity and improving work conditions (assessed by direct observational approaches). Nevertheless, some complaints were registered, mainly for the workers with pain/musculoskeletal disorders in the hand–wrist, justifying the need for a more comprehensive assessment with direct measurements (as performed in the current study). Hence, the aims of this study were:

(i) To compare the musculoskeletal risk before and after the robotic implementation of an assembly workstation using IMU-based technology;
(ii) To analyze wrist postures in detail during assembly tasks before and after the implementation;
(iii) To highlight the importance of using this technology to assess musculoskeletal risk in real-industry manufacturing scenarios.

2. Materials and Methods

2.1. Participants and Assembly Workstation Description

The current study was conducted in the assembly section of a furniture manufacturing company operating in Portugal. The assembly tasks are characterized by repetitive manual tasks, which expose the workers to significant musculoskeletal risks. The company has registered the existence of several workers with WMSD. Based on this problematic situation, an ergonomic study was developed to characterize the initial condition and support the design of a hybrid assembly workstation (comprising a collaborative robot and automation)—previously published in [27]. The novel assembly workstation is described in [12], as well as its impact on productivity and improving work conditions (assessed by direct observational approaches). This workstation was specially created to accommodate workers with WMSD.

In the assembly workstation studied, the work activity consisted of gluing medium density fiberboard (MDF) components (blocks and stripes) to origin frames (represented in Figure 2), which constitute tabletops and desktops. The tasks performed are presented below:

Task 1—reach stripes and place them on the workbench;
Task 2—reach blocks and glue them to the stripes;
Task 3—rotate the stripes;
Task 4—reach blocks and glue them on the other side of the stripes;
Task 5—palletize the product/frames.

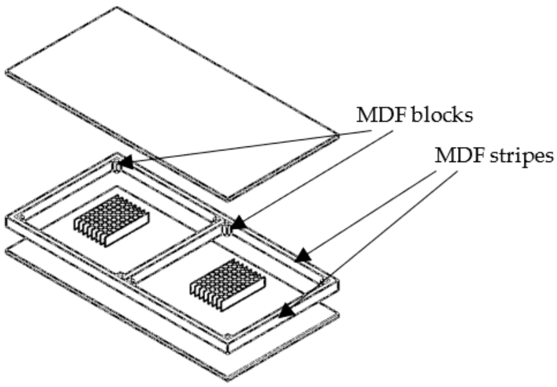

Figure 2. Representation of the frames produced in the assembly section.

In the manual assembly, the most critical subtask was applying the glue onto the blocks and stripes, mainly for the hand–wrist system. This application was performed by activating a glue pistol with a finger trigger. In the hybrid workstation, the robotic system applies the glue; then, the workers must reach the blocks and glue them onto the stripes. It should be noted that the main musculoskeletal complaints of the assembly workers focused on the hand–wrist region and existing WMSD previously reported by the company's occupational health department, such as tendinitis and carpal tunnel syndrome (as described in [12]).

The company allocated two female workers during the robotic implementation of the new assembly workstation. The demographic characterization of the workers involved (hereinafter referred to as Worker 1—W1 and Worker 2—W2) is summarized in Table 1.

Table 1. Summary of analyzed worker characteristics (W1 and W2).

Personal Data	W1	W2
Age (years)	46	36
Stature (cm)	155	170
Dominant hand	Right	Right
WMSD diagnosed	Carpal tunnel syndrome	Lumbar disc herniation

These workers participated in the study voluntarily and signed an informed consent term in agreement with the Committee of Ethics for Research in Social and Humans Sciences of the University of Minho (approval number CEICSH 095/2019) and the Declaration of Helsinki.

2.2. Data Acquisition and Processing

An upper-body MVN motion capture system (XSens Technologies B.V., Enschede, The Netherlands) constituted by 11 IMU (XSens MTw2 trackers with a 3D accelerometer, 3D gyroscope, and 3D magnetometer) was used to record the kinematic data during the assembly tasks (as performed by [22,28]). The IMU fixed on different body landmarks according to the manufacturer's guidelines. This technology was selected due to its potential for assessing human movement in various environments with reliable accuracy [17,29].

For each participant, anthropometric data were collected, including stature, shoe height, foot length, arm span, shoulder width, shoulder height, ankle height, knee height, hip height, and hip width. These measurements were used to generate the MVN human model of Xsens through regression equations [29]. Then, the IMU system was calibrated in the standing N-pose and underwent a walking trial.

The sampling frequency was 1000 Hz, and the output was 60 Hz. The orientation, position, movement, and center of mass were tracked for different parts of the body. The data collected by this technology were transmitted wirelessly to the computer. The raw data were collected and processed by XSens MVN software version 2019.2.1 (XSens Technologies

B.V., Enschede, The Netherlands). Then, the data were exported to the *.xlsx* and *.mvnx* formats and uploaded to the *mvncloud.xsens.com*.

Two workers performed an experimental trial of four work assembly cycles before and after the robotic implementation of the current study. These trials were performed in a real industry context (Figure 3), and the distance between the workers and the materials' palletizing position was maintained across these tests. The subjects were asked to keep pace with the trials, but no instructions were provided regarding assembly technique, thereby simulating a realistic working performance (as applied in [8,30]).

Figure 3. Workers performing assembly tasks with IMU before (**left**) and after robotic implementation (**right**).

2.3. Data Analysis

The RULA score was determined considering the data obtained with IMU for each work cycle. RULA consists of a systematic process for evaluating the musculoskeletal risk of postures, muscle use frequency, and external load for a particular task. This method considers the biomechanical and postural load requirements on the upper limb (arm, forearm, and wrist), neck, trunk, and the stability of the lower limbs [9]. Traditionally, it is a well-known pen–paper observational method. The worksheet presents ordered sequential steps to calculate a score for the posture of each body part. A score of 1 represents the optimal or neutral posture since greater deviations relative to this posture increase the score attributed. Higher scores indicate a greater risk of experiencing WMSD. A final RULA score derived from this procedure relates to an action level, indicating the urgency of ergonomic intervention (Table 2).

Table 2. Meaning of the final RULA scores.

RULA Score	WMSD Risk Level	Action Level	Meaning
1 or 2	Negligible	1	The posture is acceptable if it is not maintained or repeated for long periods.
3 or 4	Low risk	2	Further investigation is needed and changes may be required.
5 or 6	Medium risk	3	Investigation and changes are required soon.
7	Very high risk	4	Investigation and changes are required immediately.

The RULA score was obtained by an algorithm—XSens MVN RULA report (XSens Technologies B.V., Enschede, The Netherlands)—that integrates the ergonomic joint angles measured by the IMU instead of using observational quantification. In addition, the analyst introduces information about the external load, muscle use frequency, and stability of the lower limbs. This algorithm estimates the WMSD risk level (according to the RULA score, see Table 2) across all movement frames rather than a single snapshot in time that relies on subjective analysis [25]. The algorithm provides a report showing the distribution of RULA scores over the recorded period (e.g., for the entire trial) and a pie chart representing the total percentage of time spent in each WMSD risk level.

Then, considering the previous musculoskeletal problems reported by the company, our assessment was centered on the kinematic analysis of the wrist and *.xlsx* outputs corresponding to its angular variation. Each recorded file was analyzed for the 5 assembly tasks (described in the previous subsection), and sets of frames associated with each task were identified.

The joint angles were calculated from segment orientations following the *z*-*x*-*y* sequence of the Euler angles (as applied in [31]). For the wrist joint, its functional movements and rotations about the *z*-, *x*-, and *y*-axes are the following:

(i) Flexion/Extension: *z*-axis;
(ii) Ulnar/Radial deviation: *x*-axis;
(iii) Pronation/Supination: *y*-axis.

Therefore, the angular variability of a joint assumes positive and negative values, signifying different functional movements. The system uses a hand coordinate system meaning. For example, in "*Wrist Flexion/Extension*", a positive value indicates wrist flexion, whereas a negative value indicates wrist extension [32,33]. For this reason, the wrist angular variation was analyzed across the assembly tasks and for each participant, segregating the values according to the joint movements mentioned. This kinematic analysis was performed only for the workers' dominant side (in this case, the right side, as applied in [34]).

2.4. Statistical Analysis

A descriptive analysis was performed for the data obtained by the RULA report. The results obtained before and after robotic-assisted assembly were discussed after segregating the workers.

Regarding to the wrist kinematic data, the statistical analysis was performed using IBM SPSS (Statistical Package for Social Sciences, IBM Corp, Armonk, NY, USA) Statistics version 27.0. Given the nature of the variables involved (quantitative measures), Student *t*-tests were applied to compare the differences between two conditions (before and after the implementation of the collaborative solution) in the wrist postures for each assembly task. This statistical analysis was applied since the before and after conditions implied changes in the task's duration. The two samples (consisting of the angular data before and after) were independent, and their sizes were different (number of frames registered); as a result, it was impossible to pair the data. The different kinematic variables for each worker were >30 under each condition and task. The conditions of the Central Limit Theorem (large samples) were also applied, ensuring the power of the parametric tests. Statistical significance was considered at $p < 0.05$.

3. Results

As previously mentioned, a RULA report was created for each trial, comparing the initial condition (manual assembly) with the final condition (robotic-assisted assembly). The algorithm estimates the RULA score for each timeframe, and the RULA report contains a visual demonstration of the data with the ability to toggle through the timeline of the recording (Figure 4, bottom graph). The graph's colors denote the musculoskeletal risk level calculated based on RULA (presented in Table 2). Additionally, the report provides the total RULA score for each respective timeframe of the trial, along with a pie chart summarizing the total percentage of time spent in each musculoskeletal risk level (Figure 4, top right). Based on each trial's percentages, Table 3 summarizes the comparison before and after robotic implementation for both workers (W1 and W2).

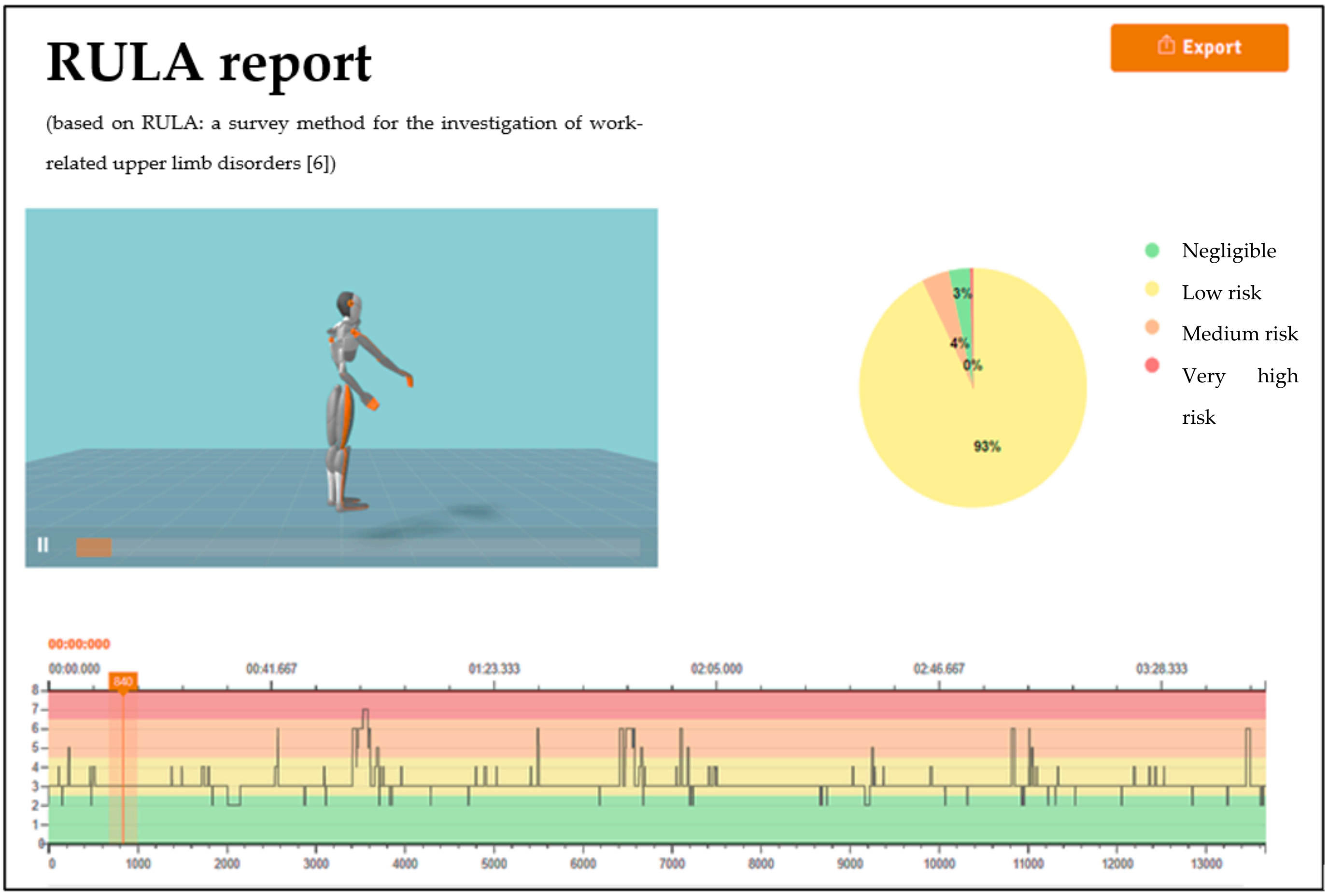

Figure 4. Example of a RULA report calculated for W2 after robotic implementation during the trial.

Table 3. Summary of the RULA report outcomes before and after robotic implementation for both workers.

	Before	After
W1	30% Low risk 63% Medium risk 7% High risk	1% Negligible 52% Low risk 42% Medium risk 5% High risk
W2	100% Medium risk	3% Negligible 93% Low risk 4% Medium risk

As previously mentioned, robotic-assisted assembly was aimed at improving working conditions. The digital transformation of the manual workstation gave particular attention to the improvement of wrist posture based on the assembly workers' complaints and the occurrence of carpal tunnel syndrome. Figures 5–7 summarize the wrists' angular variation about the *z*-, *x*-, and *y*-axes for each worker before and after robotic implementation.

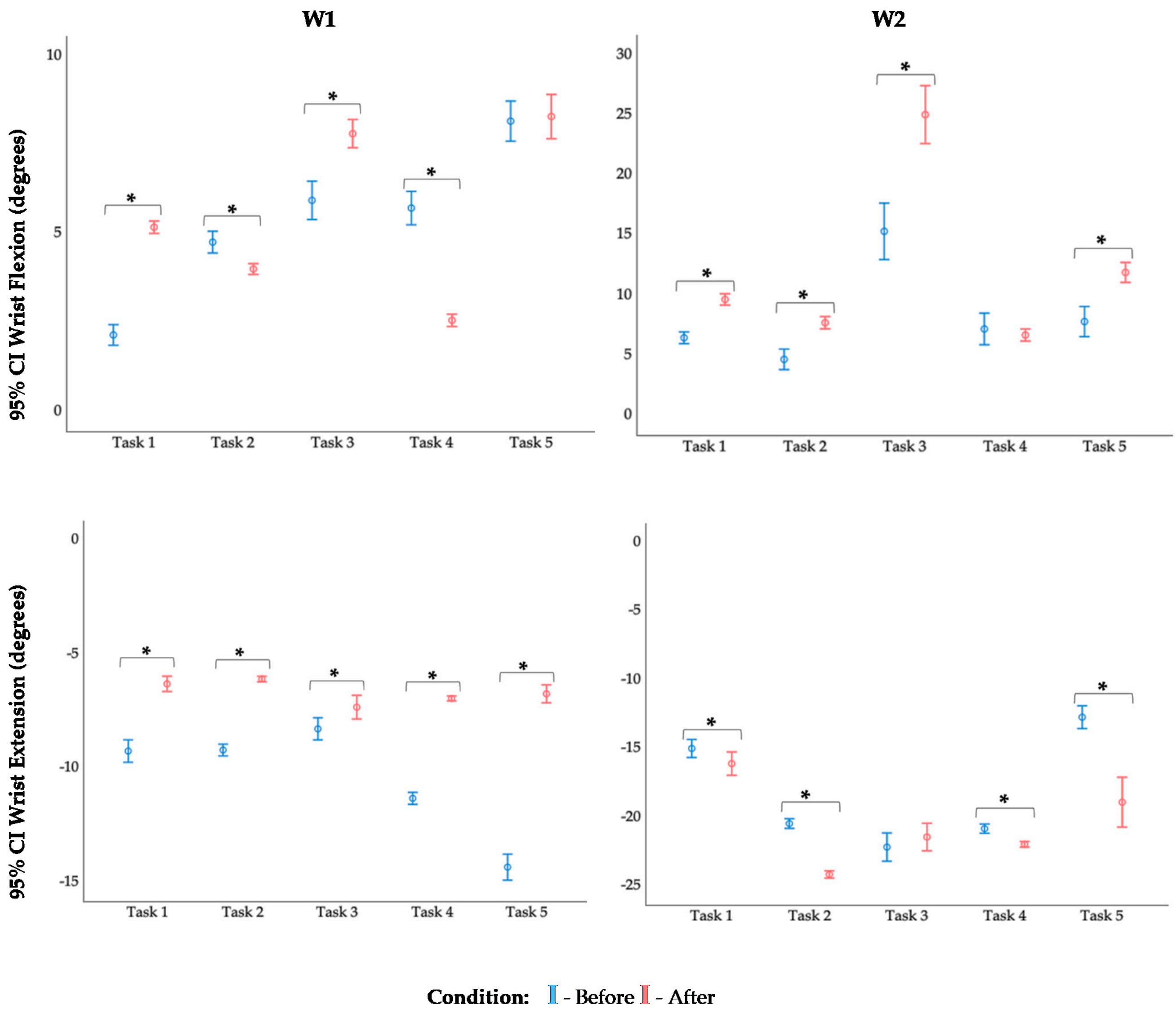

Figure 5. Mean value and respective 95% confidence interval (CI) of wrist flexion and extension degrees for both workers. Significant results ($p < 0.05$) are marked with *. Task 1-Reach stripes and place them on the workbench; Task 2-Reach blocks and glue them to the stripes; Task 3-Rotate the stripes; Task 4-Reach blocks and glue them onto the other side of the stripes; Task 5-Palletize the product/frames. Mean value and respective 95% CI of wrist pronation and supination degrees for both workers.

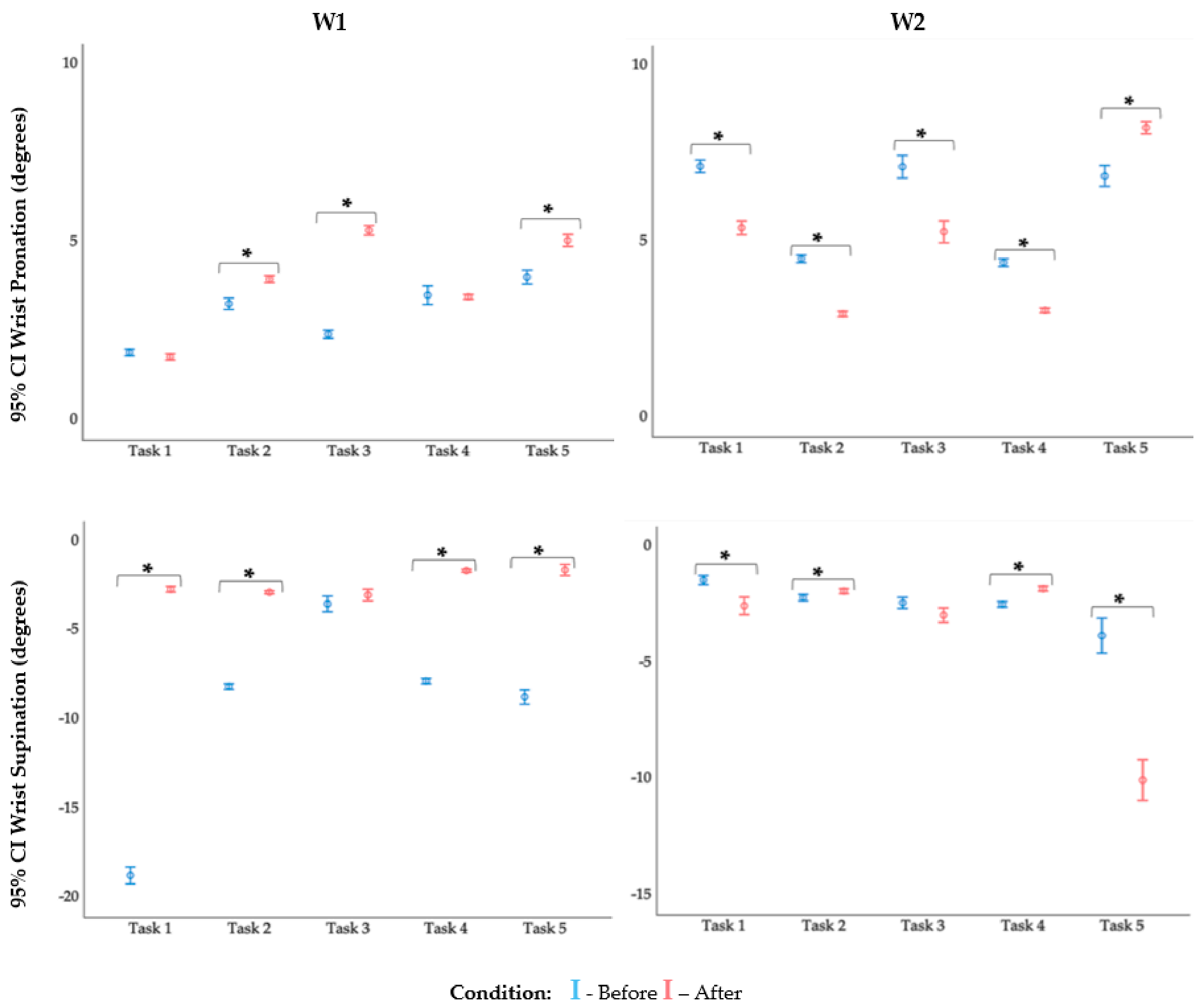

Figure 6. Mean value and respective 95% CI of wrist pronation and supination degrees for both workers. Significant results ($p < 0.05$) are marked with *. Task 1-Reach stripes and place them on the workbench; Task 2-Reach blocks and glue them to the stripes; Task 3-Rotate the stripes; Task 4-Reach blocks and glue them onto the other side of the stripes; Task 5-Palletize the product/frames. Mean value and respective 95% CI of wrist pronation and supination degrees for both workers.

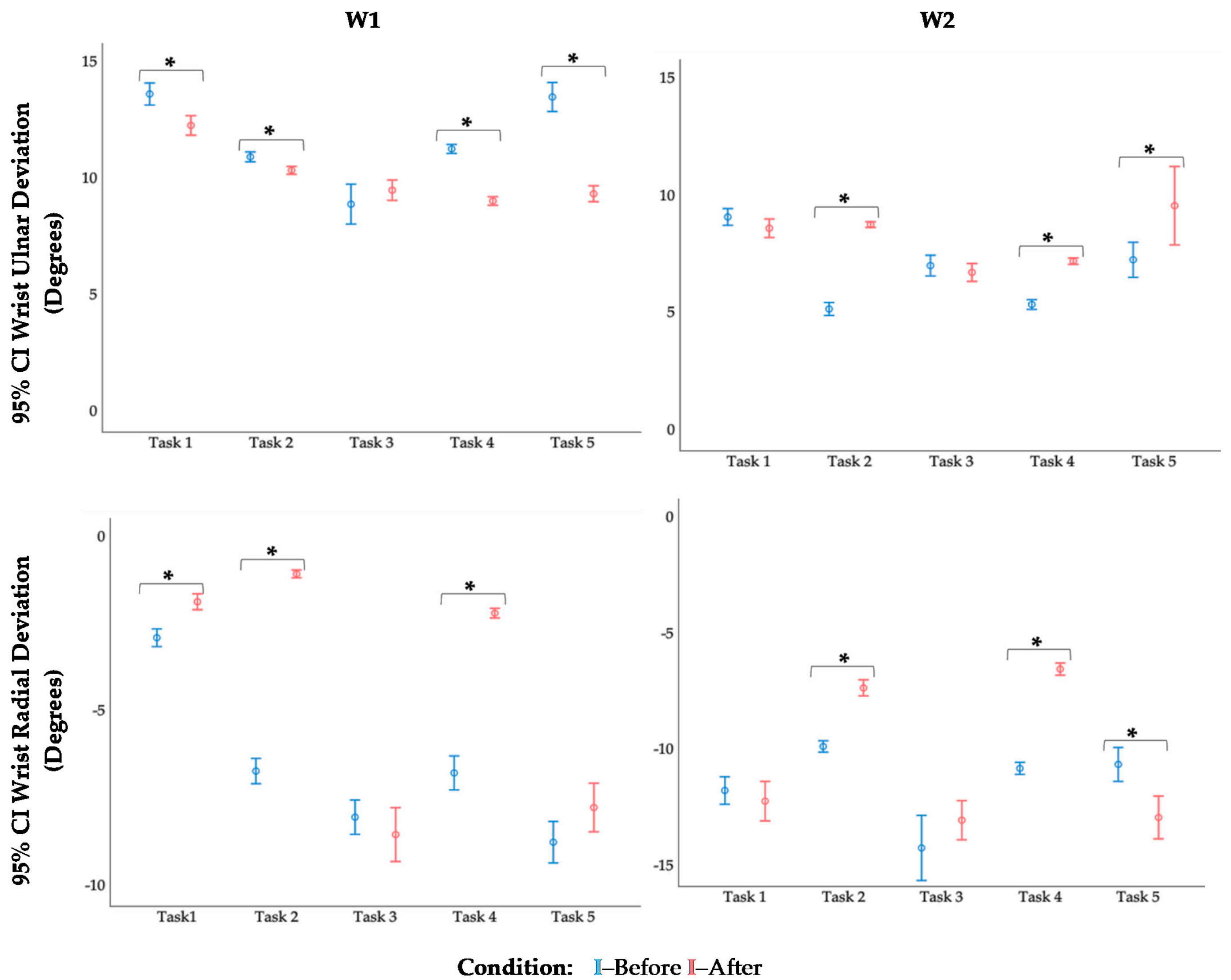

Figure 7. Mean value and respective 95% CI of wrist ulnar and radial deviations degrees for both workers. Significant results ($p < 0.05$) are marked with *. Task 1-Reach stripes and place them on the workbench; Task 2-Reach blocks and glue them to the stripes; Task 3-Rotate the stripes; Task 4-Reach blocks and glue them onto the other side of the stripes; Task 5-Palletize the product/frames.

4. Discussion

4.1. RULA Report

The RULA reports for each trial (Table 3) indicated a reduction in the musculoskeletal risk during the robotic-assisted assembly. Some differences between workers due to posture and individually adopted work methods were apparent in the data collected during the trial. For example, W1's stature was lower than W2's, leading to a greater arms flexion for reaching the system start button and the blocks (Tasks 2 and 4 after transformation—Figure 8a). Due to anthropometric characteristics, W'1s posture was also aggravated because she had more difficulty placing the stripes at the furthest point on the pallet (Figure 8b) during Task 5. The postures that W1 adopted throughout the cycle of fixing blocks were more unfavorable; for example, she crossed her forearms frequently (Figure 8c). This posture led to shoulder adduction, which may have overloaded the shoulder joint due to frequency [9,35]. Therefore, it is necessary to increase awareness and train workers about ergonomics and correct posture/handling techniques, as defended by [36].

Figure 8. Example of postures adopted during (**a**) reaching the start button (Tasks 2 and 4); (**b**) palletizing (Task 5); and (**c**) gluing blocks with forearms crossed (Tasks 2 and 4).

These results also demonstrate that collaborative robotics implementation improves assembly working conditions by reducing the frequency of awkward postures. These results align with previous studies indicating that robotics is a technological solution for improving workstations' safety and ergonomics [3,37–39].

A detailed analysis of the RULA report across each trial showed that the detected peaks (as shown in Figure 4) identified the worst postures across the work cycles. Therefore, this analysis demonstrates that tasks that involved applying glue and palletizing the product had a higher musculoskeletal risk for cycles assessed before the workstation transformation. Considering the cycles studied after robotic implementation, the task of palletizing was the worst in terms of risk level for both workers. Therefore, this assessment recommends intervention on the workstation. Upon observing the working conditions, the access to the pallet was laterally conditioned by the existence of roller conveyors (as shown in Figure 8b). Therefore, adapting this area is recommended for creating a free zone, which would allow the workers access to lateral parts of the pallet.

Regarding the musculoskeletal assessment, the current approach provided a detailed analysis of the RULA scores and highlighted the need for workstation readjustments. Previous studies in this domain [10,11,25] also presented RULA semi-automated systems that relied on motion cameras. However, some limitations were detected due to object occlusion and human occlusion during the performance of work tasks. The IMU technology applied in the current study overcame these limitations [13].

4.2. Kinematic Analysis of the Wrist

The robotic-assisted assembly paid particular attention to improving wrist posture. For this reason, major improvements were implemented in Tasks 2 and 4 (due to the glue application, as mentioned in Section 2.1). The main change made to the manual workstation was the automatic glue application, which replaced glue guns activated by finger pressure. This change eliminated repetitive exertions and grip forces (caused by the poor design of the glue gun), which cause carpal tunnel syndrome [40,41].

Nevertheless, non-neutral hand–wrist postures are associated with increased risk of distal upper extremity symptoms and/or WMSD [41]. Therefore, the kinematic analysis performed in the current study is relevant to musculoskeletal risk assessment. An overall analysis of the outcomes showed a significant improvement in wrist posture with robotic-assisted assembly and, consequently, WSMD risk reduction. This improvement is demonstrated by the joint angular deviation levels from the neutral position (zero degrees on the *x*-, *y*-, and *z*-axes); by contrast, higher angular deviations are related to stressful postures and higher musculoskeletal risk levels [41–43].

The kinematic analysis performed for each task demonstrates that the workers' wrist posture significantly improved (45% for W1 and 20% for W2) under the robotic-assisted conditions and reflected a more neutral biomechanical position. The neutral position of the wrist works more efficiently and grips objects comfortably [40,42]. The improvements registered in wrist posture support the digital transformation of the assembly workstation and foresee the musculoskeletal overload reduction in the hand–wrist system.

For tasks that underwent the most changes (Tasks 2 and 4), the results demonstrate improved movement under robotic-assisted conditions. For instance, during Tasks 2 and 4, angular deviations about the functional movement of the flexion/extension and ulnar/radial deviations were <20° and 10°, respectively. These values constitute safe angular limits related to the comfort of the joint during manual exertions [42]. Both workers presented significant improvements in the two well-known risk factors for carpal tunnel syndrome—wrist extension and radial deviations [41,44].

W1 described lesser angular deviations from the neutral position than W2. Since the wrist is the most flexible joint in the human body [18], its angular variability may be more affected by individual factors. These kinematic differences may be related to the work method adopted and/or anthropometric data, as mentioned in the previous subsection.

The stature difference between the workers compromised their postures during the assembly tasks, as shown in Figure 9. The workbench's height was closest to the elbow height of W1, who had the shorter stature of the two workers. This factor aggravated angular deviations about the *z*-axis (wrist flexion/extension). In the robotic-assisted workstations for Tasks 2 and 4, W1 presented significantly lower values in the flexion and extension movements. Their postures for reaching the blocks in Figure 9 illustrate this evidence.

Figure 9. Postures adopted reaching blocks (Tasks 2 and 4) in the robotic-assisted workstation by both workers. W1—Worker 1; W2—Worker 2.

This analysis highlights the importance of anthropometric data inclusion during the configuration of these new work systems. As previously discussed, the mismatch between the work materials' height and the workers' stature appeared to interfere with postural deviations. Therefore, the height of the workbench should be adjustable to respect the workers' anthropometric variability (as defended by [45]). However, since assembly workers operate as a side-by-side duo on the same products, the workbench cannot be individually adjusted. For this reason, an organizational measure that defines work teams by similar stature may be a solution.

Finally, it should be noted that the results obtained by direct measurements reflect the work-related load and individual characteristics simultaneously [4]. This level of assessment, including the IMU, directly measures the angular variation during the performance of industrial tasks. This approach allows the musculoskeletal risk assessment to compare and select ergonomic interventions/solutions, as applied by [19,22].

4.3. Limitations, Main Contributions, and Future Work

Some limitations in the current study help define future work. First, the results were obtained from four work cycles of each trial tested. The results may have been different after a longer experimental period (can be posteriorly checked). Increasing the number of participants may also lead to clearer results. These limitations occurred because our research was developed in a real-industry context with specific requirements and restrictions defined by the manufacturing company. However, the authors acknowledge that this methodology allowed for the collection of reliable results and important outcomes for the WMSD assessment.

Regarding posture assessment, the set of IMU measures the joint angles for the body segments considered. However, the RULA report is a semi-automated solution requiring manual adjustments—namely, data concerning (i) the support and balance of the legs and feet, (ii) static posture or movements repeated four times per minute or more, and (iii) the load or muscle force (in kilograms) performed. Therefore, future advancements can focus on developing automated solutions and avoiding manual data information. These solutions assume a relevant role in WMSD risk assessment because they can guide users, even ergonomist novices, in interpreting precise data and forming conclusions [46,47].

Among the factors that play a decisive role in dysfunctions and injuries of the musculoskeletal system, manual exertion, task duration, and frequency of repetitive movement play significant roles [43]. These factors are included in RULA as a correction to predefined options. However, this method does not consider the exact values of manual forces, duration, and frequency of repetition. Moreover, the RULA excludes the fingers' position, and the current IMU system is unsuitable for tracking the motion of small joints, such as fingers. The kinematic analysis of these body extremities may be important for assembly tasks, particularly the wide finger grip, to encourage musculoskeletal risk reduction for the hand–wrist system [48]. For further advancement in the digitalization of musculoskeletal risk assessment, these shortcomings must be considered.

In conclusion, our study highlights the importance of applying an instrument-based method (in this case, IMU) to assess musculoskeletal risk. This in-field instrumented assessment provides important outcomes and a detailed analysis focusing on the problematic understudying of musculoskeletal risk. In our case, this comprehensive analysis supported different solutions for reconfiguring the assembly workstation considering the workers' anthropometric variability.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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