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Lean Manufacturing and Ergonomics Integration: Defining Productivity and Wellbeing Indicators in a Human–Robot Workstation

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Abstract: Lean Manufacturing (LM), Ergonomics and Human Factors (E&HF), and Human–Robot Collaboration (HRC) are vibrant topics for researchers and companies. Among other emergent technologies, collaborative robotics is an innovative solution to reduce ergonomic concerns and improve manufacturing productivity. However, there is a lack of studies providing empirical evidence about the implementation of these technologies, with little or no consideration for E&HF. This study analyzes an industrial implementation of a collaborative robotic workstation for assembly tasks performed by workers with musculoskeletal complaints through a synergistic integration of E&HF and LM principles. We assessed the workstation before and after the implementation of robotic technology and measured different key performance indicators (e.g., production rate) through a time study and direct observation. We considered 40 postures adopted during the assembly tasks and applied three assessment methods: Rapid Upper Limb Assessment, Revised Strain Index, and Key Indicator Method. Furthermore, we conducted a questionnaire to collect more indicators of workers' wellbeing. This multi-method approach demonstrated that the hybrid workstation achieved: (i) a reduction of production times; (ii) an improvement of ergonomic conditions; and (iii) an enhancement of workers' wellbeing. This ergonomic lean study based on human-centered principles proved to be a valid and efficient method to implement and assess collaborative workstations, foreseeing the continuous improvement of the involved processes.

Keywords: ergonomics and human factors; lean manufacturing; collaborative robotics; productivity; musculoskeletal risk

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1. Introduction

1.1. Sinergy between Lean Manufacturing and Ergonomics

Currently, Lean Manufacturing (LM) and Ergonomics and Human Factors (E&HF) are trending topics for companies [1–4]. LM focuses on reducing waste—everything that does not add value to the product or service. The system developed by Eiji Toyota, named Toyota Production Systems (TPS), pioneered this waste elimination/reduction vision and has been recognized as doing more with less [5]. To identify, eliminate and prevent wasteful operations, several techniques and tools compose the LM, such as 5S workplace organization, Total Productive Maintenance (TPM), Just-In-Time (JIT), Standard Work, pull production, or Value Stream Mapping (VSM) [6,7]. LM is widely applied in industrial settings and facilitates companies' competitiveness by reducing production costs and at the same time improving working conditions [2].

Regarding the downside of LM, companies with JIT practices and work standardization have reported an increase in work pace and lack of recovery time, which leads to a higher musculoskeletal strain [8]. Moreover, previous studies correlated LM with a negative impact on workers' autonomy and psychosocial strain [4]. Unfortunately, several companies that introduce LM practices forget the human factors and do not integrate ergonomic principles [1,3]. The LM principles should not lead, by definition, to a deterioration of ergonomic conditions. Arezes et al. [9] argued that some drawbacks associated with LM are related to a possible misunderstanding of the Lean principles and incomplete Lean interventions.

Foreseeing the continuous improvement of manufacturing processes, the association of LM with E&HF potentiates productivity gains, enhances working conditions [3,4,10], and reduces workers' absenteeism [2]. On the same topic, Nagaraj et al. [10] argued that this integrated approach decreases the adverse effects of lean on the workers' quality of life, improving operational efficiency (such as workers' performance, value-added ratio, errors' reduction). Lean and Ergonomics can reduce lead time by eliminating waste from non-productive manual materials handling and awkward postures as well as increasing workers' effectiveness, safety and health [11,12].

1.2. Impact of Collaborative Robotics in the Manufacturing Industry

Researchers are also studying how industrial collaborative robots can improve both LM and ergonomic conditions [4,13]. With the advent of Industry 4.0 (I4.0), the level of automation of manufacturing workstations has increased. Novel technologies allow for a more efficient and flexible production setup to target large-scale product customization without loss-of-competitiveness or increased production costs [2,14]. This trend is evident in the manufacturing industry, with HRC being one of the most discussed topics [13,15]. In contrast to standard automation, collaborative robots (cobots) permit a closer and safer interaction between humans and machines, drawing the advantages of both parts, according to international standards of operation and safety [16].

One of the most accepted definitions for cobot stands as a robot that can share its workspace with human workers. HRC has been considered as a viable strategy to assist human workers by taking over hazardous and/or physically demanding tasks. This mutual relationship between humans and robots leads to a powerful collaborative framework with a positive impact on productivity, flexibility, and the creation of new jobs rather than replacing workers [17]. Previous studies state that the principal impact of this technology relates to the reduction of physical and cognitive loading associated with manufacturing tasks, improving safety, quality, and productivity [18]. Villani et al. [19] pointed out, as the main advantage of HRC, the opportunity to combine the benefits of automation with the human workers' skills and cognitive flexibility.

In these novel work systems, however, safety and human wellbeing are still open challenges. Further research, particularly in real-industry environments, is necessary to test and validate the HRC implementation [20,21]. Therefore, it is essential to develop specific and detailed assessment methods to optimize the design of these workstations with collaborative robotics [21–23], taking into account the industrial conditions, the characteristics of human workers and cobots, as well as the type and level of collaborative interaction [24].

At the same time, E&HF are still underrepresented in the I4.0 research topic, resulting in a relevant research and application gap [25]. Gualtieri et al. [26] reviewed the emergent research challenges on ergonomics and safety in industrial HRC and noted the lack of studies on ergonomics when compared to safety-related research. They argue about the need to align HRC with E&HF considering the workers' wellbeing, sustainability, human-centered design, and psychosocial aspects. There is also a lack of studies providing empirical evidence about the adoption of I4.0 technologies in manufacturing companies [27]. Finally, the coexistence of LM and I4.0 technologies, including HRC, is still an open research challenge [28].

1.3. Research Objectives

The current study presents a real-industry implementation of HRC in a sustainable workstation adapted to workers having musculoskeletal problems (such as carpal tunnel syndrome). This hybrid workstation aims to improve ergonomic conditions without a negative impact on the work cycle times. We will also demonstrate the synergistic integration of E&HF and LM principles in a collaborative robotics workstation. This paper pursues three specific research objectives:

(i) Assess the performance of the workstation before and after the HRC implementation;
(ii) Assess the musculoskeletal risk associated with preassembly workstation before and after cobot implementation, applying a multi-method approach;
(iii) Analyze wellbeing and robotics acceptance indicators based on the workers' perceptions.

2. Description of the Case Study

The current study results from the cooperation between a large Portuguese site of furniture manufacturing, a Portuguese University and the Collaborative Laboratory DTx, which carries out its activity doing applied research in different areas linked to the digital transformation of the industry. This work studies a workstation created to accommodate workers with Work-related Musculoskeletal Disorders (WMSD). The workstation is part of a frame assembly process (Figure 1) of which the final products are MDF (Medium-Density Fiberboard) frames for tabletops and shelves. The subject of this paper—the preassembly workstation—fabricates preforms, an intermediate product composed of stripes and blocks that are hot-glued in a rigorous and specific structure. The glue is applied to the blocks forming a middle cord along the length of its largest side. Three preforms are built per cycle, having to glue the blocks in 36 points (18 per worker, 6 per stripe) for DS preforms and 18 points (9 per worker, 3 per stripe) for SS preforms.

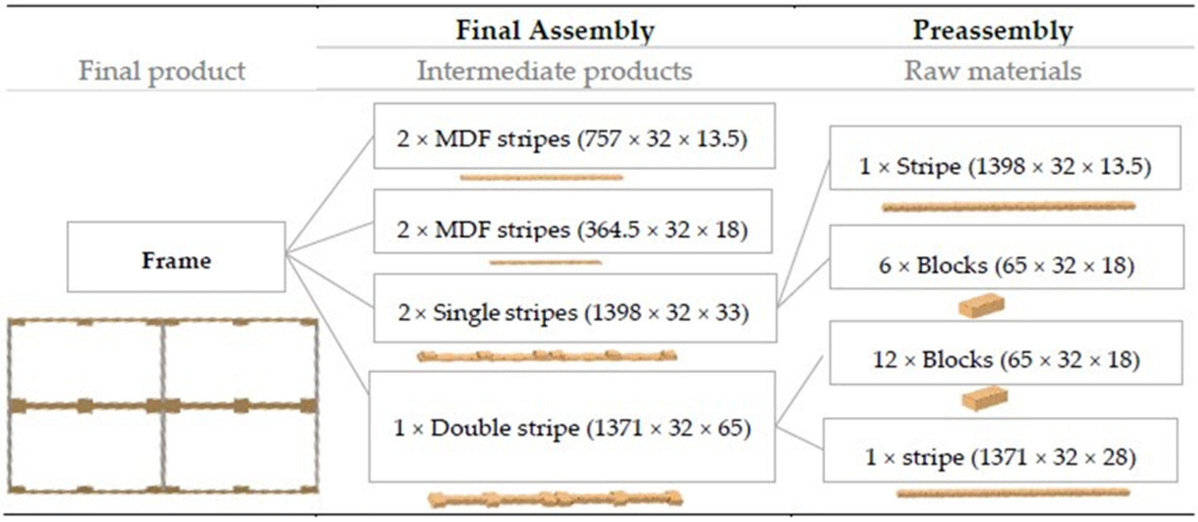

Figure 1. Bill of Materials, products, and phases of the assembly process (dimensions in mm). MDF: Medium-Density Fiberboard.

Initially, the frames' assembly process (including the preassembly and the final assembly) was entirely manual. The workers involved were continuously exposed to several musculoskeletal risk factors (such as repetitive movements, hand-force application, and awkward postures), and some of them presented WMSD. Consequently, the company selected the preassembly workstation to implement HRC to create an ergonomic and adaptive workstation for workers with limitations that arose due to WMSD.

The design of the collaborative workstation was partially presented in Colim et al. [23,29]. Figures 2 and 3 present the physical configuration of the manual and collaborative preassembly. The collaborative workstation subtracts the hot-glue manual application task, now performed by the robotic system. An initial risk assessment screening identified the hot-glue application task as the most critical concerning ergonomics and physical demand due to the repetitive actions. Moreover, the burns caused by the hot-glue constituted the most frequent accident in this workstation [23].

Figure 2. Manual preassembly layout.

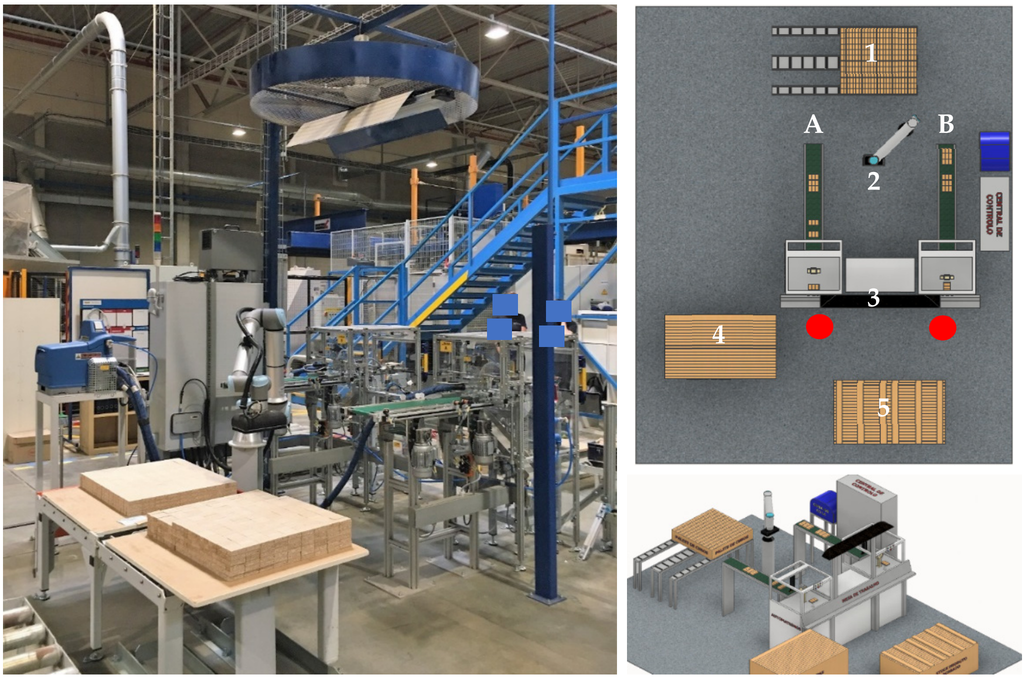

Figure 3. Layout of the final preassembly collaborative workstation.

The new workstation is composed of automation and a cobot (Universal Robot UR10e) with a vacuum end-effector, to assist two workers that operate side-by-side (red points in Figure 3). The function of this system is to dispense MDF blocks with a cord of hot-glue.

The system applies hot-glue to a group of blocks and delivers these blocks with the glue faced down to facilitate the worker's handling. The main parts of this system are described below:

(i) Indexer blocks pallet entry station (1 in Figure 3);
(ii) Collaborative robotic system (cobot, 2 in Figure 3), consists of a collaborative robot with an area vacuum gripper to depalletizing a determined number of blocks from the indexer to the lines A and B, per request (as represented in Figure 4);
(iii) Lines A and B, sets of conveyors, sensors and glue dispensers (represented in Figure 4), which are used to apply hot-glue to the blocks and deliver them to the workers with the glue on the underside;
(iv) Assembly workbench (3 in Figure 3), the area where the workers place the stripes and glue the blocks that are delivered by the system.

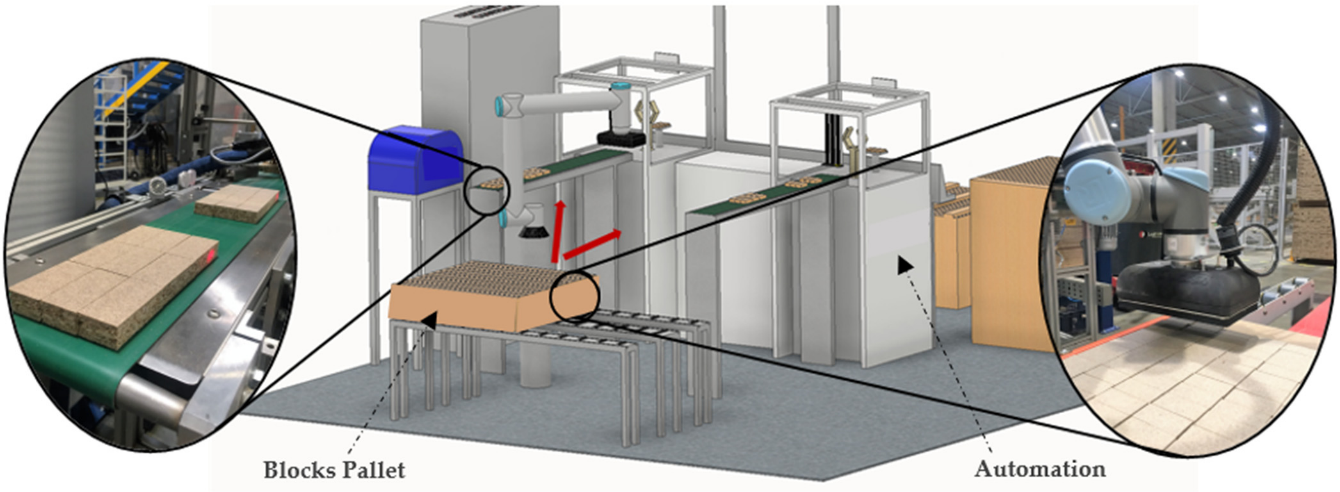

Figure 4. Representation of the blocks depalletizing.

The stripes input pallet is at the workers' left side (4 in Figure 3), and the output pallet (preforms palletizing) at the workers' back (5 in Figure 3). Each worker has a button interface console to interact with the collaborative workstation to request more blocks or to stop the system (Figure 5).

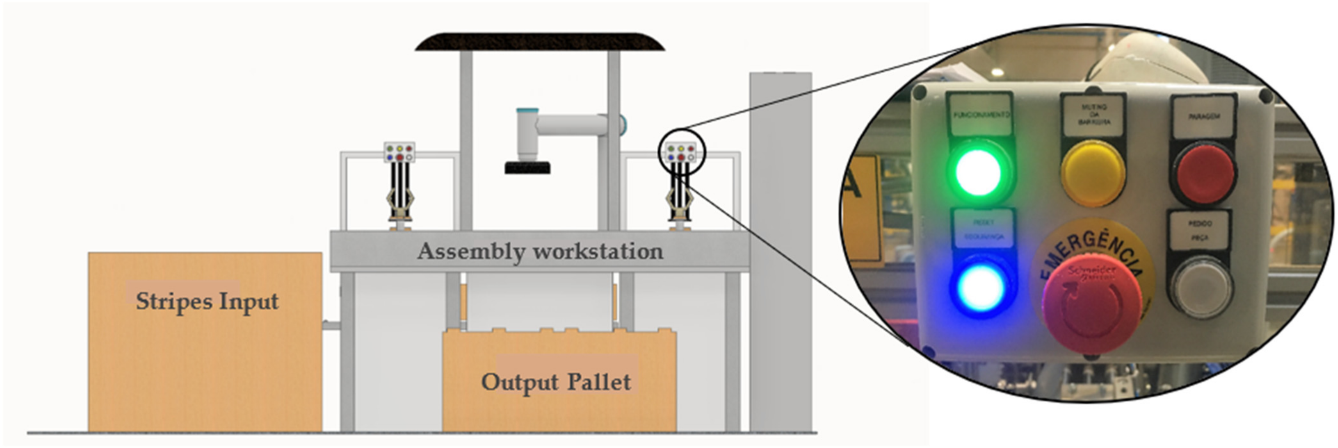

Figure 5. System interface console.

3. Materials and Methods

We explore the implementation of an HRC workstation, integrating ergonomic and lean principles. For this, a comparison between the manual and the collaborative preassembly was developed, according to the parameters:

(i) Indicators of performance and waste analysis;
(ii) Musculoskeletal risk level according to a multi-method approach for physical ergonomic assessment;
(iii) Workers' perceptions about robotics and psychophysical assessment of the collaborative workstation.

The manufacturing workers participated in the study voluntarily. All participants 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 in agreement with the Declaration of Helsinki.

3.1. Assessment of Performance Indicators

We assessed and compared both preassembly workstations (manual and collaborative) considering different Key Performance Indicators (KPI). As developed by Bait et al. [7] and Bauters et al. [30], the KPI were classified into four groups:

(i) Time data: all the KPI measuring the performance of preassembly in terms of time consumed (e.g., cycle time and non-productive times);
(ii) Variability: measures the variability of production times;
(iii) Production rate: KPI measuring the performance in terms of number of pieces produced in a specified time interval (e.g., number of preforms per hour);
(iv) Material consumption: KPI related to glue consumption.

The assessment following these KPI does not include E&HF indicators. We describe the ergonomic approach followed in detail in Section 3.2. For each preassembly condition, a time study with a confidence level of at least 90% and a superior error limit error of ±5% was developed, observing two workers along 25 work cycles. To assess the performance rating, obtaining the leveling factor, the objective assessment technique was used. The work cycle was decomposed in elementary tasks and the normalized time for each element was calculated. This time study provided data for the KPI of time data, variability and production rate.

The LM approach intends to minimize/eliminate non-value tasks (i.e., wastes) [4]. Through direct observation, we conducted a task value analysis and identified the production wastes—tasks that do not add value to the process (as performed by [30]). We labeled the preassembly tasks as one of three types:

(i) Value-adding tasks (V);
(ii) Non-value-adding tasks (nV);
(iii) Non-value-adding tasks but necessary (nVN)—no direct relevance for the process, but essential to creating the final product. These tasks cannot be eliminated, just reduced as much as possible.

Regarding the non-value task analysis, we considered the definition of Botti [4] that focused on seven types of waste that can be identified, with material movement, inventory and waiting as the ones with the most impact in the preassembly. Those three wastes are responsible of increasing the time of the global process by decreasing its flow; at the same time, it reduces the workers' productivity and increases the occupied area, respectively.

As studied by El Makrini et al. [31], the glue consumption was also considered as a KPI measured. For manual and collaborative conditions, the glue consumption was measured by weighing cubes with and without glue, extrapolating the consumption. This was calculated for a preforms' pallet of 720 Single Stripes (SS) and 360 Double Stripes (DS).

3.2. *Assessment of Physical Ergonomics*

Complementarily to the performance assessment, the manual and collaborative workstations were evaluated through a multi-method approach in terms of physical ergonomics. This approach allows a more comprehensive task assessment, integrating a wide range of musculoskeletal risk factors. Considering four preassembly workers and the observation of several work cycles, a total of 40 postures were assessed by the following methods:

(i) Rapid Upper Limb Assessment (RULA) [32];
(ii) Revised Strain Index (RSI) [33];
(iii) Key Indicator Method for assessing physical workload during Manual Handling Operations (KIM-MHO) [34].

For posture selection, we applied the following criteria: (i) selection of the most frequent postures; (ii) selection of either right or left-hand based on higher exertion; (iii) for complex bi-manual tasks, assessment of both hands separately. The studied tasks are part of a cyclic process that subjects workers to repetitive motions, which primarily affect the upper limbs.

RULA is an observational method [35] for assessing the upper limbs' WMSD risk, which also considers the neck, the trunk, and the position of the lower extremities during the work activity. Its application involves the assessment of postures adopted by the worker as well as the exerted forces, the repetitiveness of movements, and external loads (such as handling heavy materials) [32]. We scored each posture based on the set of considered joint angles and according to the predefined range. These joint scores amount to a final RULA score and respective recommendations, according to Table 1.

Table 1. Final risk levels of the three methods considered.

RULA [32]		**RSI [34]**		**KIM-MHO [35]**	
Final Score	**Risk Level—Meaning**	**Final Score**	**Risk Level—Meaning**	**Final Score**	**Risk Level—Meaning**
1 or 2	A—The posture is acceptable if it is not maintained or repeated for long periods.	≤10	Safe workplace, with no probability of distal upper extremity WMSD occurrence.	<20	1—Low load situation, the health risk from physical overload is unlikely to appear.
3 or 4	B—Further investigation is needed and changes may be required.	>10	Hazardous workplace.	20 to <50	2—Slightly increased load situation; physical overload is possible for less resilient persons. For this group, redesign of the workplace is helpful.
5 or 6	C—Investigation and changes are required soon.			50 to <100	3—Substantially increased load situation, physical overload also possible for normally resilient persons. The redesign of the workplace should be reviewed.
7	D—Investigation and changes are required immediately.			≥100	4—High load situation, physical overload is likely to appear. Workplace redesign is necessary.

The distal upper extremity (DUE) WMSD are among the most costly injuries for today's manufacturing industry [36]. One of the most known methods to measure DUE job physical exposures is the Strain Index (SI) proposed by Moore and Garg in 1995. This method was recently revised (RSI), reflecting recent research findings and addressing limitations of the original version [33]. To guide the assessment for the DUE disorders, the RSI was also applied. The RSI consists of a five-variable model using continuous multipliers, involving the measurement of five variables/risk factors, namely: the intensity of exertion (force), exertions per minute (frequency), duration per exertion, hand–wrist posture and duration of a task per day. For each variable, an ordinal rating is assigned following the exposure conditions, after which a multiplier value corresponding to the rating is assigned. Borg's scale is an option to measure the intensity of exertion. This scale consists of a psychophysical approach that takes into account the workers' perceptions [37]. This strategy could increase the reliability of the RSI results, and it was applied in the current study.

An RSI score of 10 or less is classified as "safe" and a score higher than 10 is considered "hazardous." However, the authors [33] highlighted that this method is valid to determine the DUE WMSD risk among a cohort of workers who perform the same tasks (as applied in the current study) and is not designed to assess the risk for an individual worker.

We also applied the KIM-MHO method because the preassembly tasks are frequently associated with Work-related Upper-Limb Disorders (WULD), such as carpal tunnel syndrome. Klussmann et al. [34] demonstrated that KIM-MHO risk scores have a statistically significant correlation to the prevalence of musculoskeletal symptoms (assessed by Nordic questionnaire) and clinical conditions in the shoulder, elbow and hand–wrist body regions between more than 600 employees exposed to MHO. Its application is, therefore, deemed relevant to this study due to the type of selected tasks and the clinical background of musculoskeletal problems in upper limbs among the selected workers. Table 1 presents the final risk levels obtained by these three methods.

We assessed each preassembly task before and after the cobot implementation. Each task is defined as a unique combination of risk factors: posture, the intensity of exerted force, duration and frequency of exertion. The RULA and RSI scores represent the biomechanical stress associated with each task. However, the workers are exposed to a risk resulting from the different risk factors' combination along with their workday. The multi-task assessment is possible by applying the Composite Strain Index (COSI) [38] and the RULA weighted score (considering the individual scores and the tasks' normalized times) [32].

3.3. Assessment of the Workers' Perceptions

We designed and applied a questionnaire to assess the workers' perceptions about robots in the industry, and the associated ergonomic improvements. It was applied to preassembly workers before and after operating in the collaborative workstation. The sample (four workers) was limited due to the company allocation of workers. All workers were interviewed during their workday, performing a normal working activity. While the workers had a copy of the questionnaire, the researcher asked the questions in the form of an interview, noting the worker's answers and providing explanations whenever necessary. Workers participated in the study voluntarily and signed informed consent.

We present the questionnaire summary, structure and tools in Table 2. The questionnaire starts with a characterization of the population (A category). Then, the questionnaire addresses two main areas: robotics (B category) and ergonomics (C and D categories). B category explores generic knowledge about robotics and its potential, as well as possible concerns and expectations. We formulated 12 statements to achieve an equal distribution between positive and negative perceptions (Table 3). These statements were randomly presented in the questionnaire and the workers had to indicate their degree of agreement on a five-point Likert scale (0—No opinion; 1—Total disagreement; 2—disagreement; 3—Neutral; 4—Some agreement; 5—Totally agree). The questions/statements were adapted from previous studies that applied questionnaires about this research topic [39–41].

In the C category, the self-reported physical exertion for the preassembly tasks was evaluated according to the "Category Ratio-10" (CR-10). Borg [37] argued that the application of scales similar to CR-10 is necessary as a way to quantify subjective perceptions of physical overloads, such as effort and discomfort. An advantage of the CR-10 scale is that each score correlates to an effort that is well perceived by different individuals. Therefore, these values can be used as references for physical effort for different workers or work conditions. Previous studies [41–43] supported that this psychophysical scale is a valid and reliable tool for monitoring the exertion self-assessment by workers exposed to WMSD risk factors during handling tasks.

Table 2. Summary of the questionnaire's structure.

Questions' Category		Parameters Assessed	Objectives	Tools Applied
A.	Workers' characterization	Age; work experience; WMSD.	To characterize the workers' sample with demographic data.	Not applicable.
B.	Robotics impact in the occupational context	Perception about robotics implementation in workstations.	To analyze workers' perceptions about robotics impact on productivity, work conditions, job requirements and human collaboration and acceptance.	Five-point Likert scale; topics based on the bibliographic review.
C.	Perceived exertion associated with the tasks	Perceived exertion for each preassembly task.	To assess physical exertion perceived by the workers; To identify the most demanding tasks.	CR-10 Borg scale [37].
D.	Global assessment of the workstation	Global opinion about the preassembly workstation.	To compare the initial and final preassembly; To assess workers' opinions about possible improvements to introduce in the preassembly workstation.	Five-point Likert scale.

Table 3. Statements included in the questionnaire's B section and their classification according to the type of perception (negative/positive) about robotics' impact.

Statement (S)	Type of Perception
S1. Robotics can put jobs occupied by people at risk.	Negative
S2. Robots can share tasks with humans.	Positive
S3. The robots' inclusion in the shop floor allows adjusting working hours and improving working conditions.	Positive
S4. The integration of robotics can create more jobs than it can destroy.	Positive
S5. Robotic work will increase repetitive tasks and/or monotony.	Negative
S6. It is possible for humans to feel insecure and threatened by robotics risks.	Negative
S7. Robotics helps to reduce repetitive and/or higher intensity efforts.	Positive
S8. With the introduction of robotics, humans will have more complex/mentally demanding tasks.	Negative
S9. Robots are a source of development and added value for companies in all sectors.	Positive
S10. The existence of tasks with robots increases the stress and anxiety of workers.	Negative
S11. Robotics can increase the productivity of assembly workstations.	Positive
S12. Robots can cause accidents and injuries to workers.	Negative

The D category intends a global assessment of the preassembly workstation. This part was composed of six statements related to the changes introduced at the work activity (Table 4). This approach was also applied in the design phase of this project [23]. The workers have to classify the statement using five-point Likert scale. In this case, workers are requested to indicate their level of agreement with each particular statement.

The mentioned scoring scales are based on closed-form response where workers choose between a set of options. Whenever the workers felt that the available options failed to convey their perception, we provided the opportunity to freely expressed their opinion on the subject (open comments and suggestions). As previously mentioned, the questionnaire was applied pre- and post-implementation of the collaborative workstation. In the first session, the questionnaire was limited to categories A and B. After the installment of the collaborative cell, the full questionnaire was presented, to assess their opinions on the ergonomic conditions of the new workstation.

Table 4. List of statements used for a global opinion about preassembly workstation.

Statements Assessed
The new workstation makes the preassembly tasks easier.
I feel that my work posture is better.
The exertion associated with manual work is lower.
At the end of the work shift, my musculoskeletal discomfort decreases.
The work is more monotonous.
I think that this workstation could be improved.

4. Results and Discussion

4.1. Performance Improvement of the Preassembly Workstation

The preassembly cycle was decomposed in the elementary tasks. As aforementioned, we performed a value analysis on these tasks and present the results in Table 5.

Table 5. Elements classification according to the value analysis.

Task	Value Classification	Type of Waste
Reach the stripes and place them on the workbench.	nV	Material movement.
Wait due to the robotic system's delay.	nV	Waiting.
Write a note.	nVN	Inventory.
Block selection (in the manual preassembly).	nV	Material movement.
Reach the blocks with glue (in the new preassembly).	V	n.a.
Apply glue to the blocks (in the manual preassembly).	V	n.a.
Fix the blocks.	V	n.a.
Turn/Rotate the stripes.	nVN	Material movement.
Palletize preforms.	nV	Material movement.

Legend: V—value-adding task (highlighted with green color); nVN—non-value-adding tasks but necessary (orange color); nV—non-value-adding task (red color).

Table 6 summarizes the main results of the comparison between the manual and the collaborative preassembly, considering the KPI defined to study the workstation performance.

Table 6. Comparison of the KPI between manual preassembly and collaborative preassembly.

KPI	Manual Preassembly	Collaborative Preassembly
Normalized cycle time (sec)	51.46 (DS) 28.38 (SS)	47.46 (DS) 27.19 (SS)
Variability (sec)	±1.98 (DS) ±2.01 (SS)	±2.40 (DS) ±2.71 (SS)
Preforms produced per hour	209.87 (DS) 380.55 (SS)	227.56 (DS) 397.20 (SS)
Non-productive times	2.13 h (DS) 2.07 h (SS)	2.62 h (DS) 2.40 h (SS)
Tasks value analysis (%)	47—11—42 (DS) 46—5—49 (SS)	42—12—46 (DS) 49—5—46 (SS)
Glue consumption (cm^3/pallet preforms)	799.2	565.92
Number of manual glue applications *	36 (DS) 18 (SS)	0

Legend: SS—Single stripe; DS—Double stripe; in tasks value analysis green color represents the values of value-adding tasks, orange color the values of non-value-adding tasks but necessary, and red color the values of non-value-adding tasks; * per cycle and for two workers.

The value analysis of tasks is similar between both preassembly conditions. Comparing the new preassembly to the manual version, we noted a 3% increase of the add-value tasks for the SS preform and a 5% decrease for the DS preform. These differences are not significant but highlight the superfluous time spent on non-value tasks in the new workstation.

The new preassembly requires a significant amount of time to organize the workspace, involving exchanging finished product pallets, carrying stripes and block pallets (input), filling the glue system, among other non-productive times. All of these operations are necessary, but allocating them to the preassembly workers translates into a significant reduction in their daily production time, as evidenced in Table 7. If we considered an extra worker to take over these non-value-added tasks, we could expect a production increase of 15% (+382.9 SS preforms/day) and 17.4% (+256.7 SS preforms/day).

Table 7. Non-productive times per workday in the new preassembly.

	SS Preform	DS Preform
Start time	4 min 45 s/workday	
Lunch break	30 min/workday	
Mid shift break	5 min/workday	
Stripes pallet change (input)	5 min/workday	
Check first preform	1 Stripe/hour × 30 s/stripe × 8 h/workday	
Workstation cleaning	20 min/workday	
Block pallet change (input)	3 min/change × 5.7 changes/day	3 min/change × 6.3 changes/day
Palletize/align blocks in the indexer (input)	1.5 min/change × 11.4 changes/day	1.5 min/change × 12.7 changes/day
Preform pallet change (output)	2.5 min/pallet × 5 pallets/day	2,5 min/pallet × 5.6 pallets/day
Close the pallet (output)	16 s/pallet × 5 pallets/day	16 s/pallet × 5.6 pallets/day
Put tape between preforms layers	3 times/pallet × 15 s/time × 5 pallets/day	2 times/pallet × 15 s/time × 5.6 pallets/day
Fill glue system	30 s/time × 1.55 pallets/filling × 5 pallets/day	30 s/time × 1.55 pallets/filling × 5.6 pallets/day
Problem solving/Other delays	≈30 min	
Total non-productive time	2.4 h	2.62 h

We noted that the glue amount applied in the manual workstation was sufficient to promote fixation, but it also varied significantly between applications. In the new preassembly system, the glue application is more consistent due to the involvement of automation (as evidenced in Figure 6).

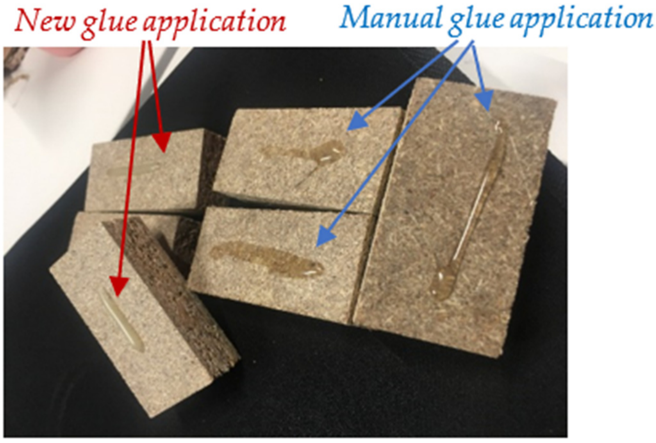

Figure 6. Differences in the glue application.

To measure this KPI, we weighted the blocks before and after the glue application for the manual and collaborative workstations. Even though the glue type differs (tube and granulated), the density of both matches 1 g/cm^3. Results show that the new preassembly reduces glue consumption by 30% when compared to the manual workstation (previously presented in Table 6).

In the collaborative preassembly, the repetitive action of applying glue was eliminated. The comparison (presented in Table 6) shows that the collaborative cell produces a positive impact on this ergonomic condition.

Finally, the normalized cycle time is lower in the collaborative preassembly, increasing the number of pieces produced per hour. Bauters et al. [30] highlighted the cycle time as one of the most important KPI in a repetitive production context as it directly correlates to the system productivity.

Furthermore, in the LM implementation, high variability in cycle times is an indicator of high complexity or problematic tasks and could have important implications on the value stream [30]. In the collaborative preassembly, the variability of cycle times increased, when compared to the manual preassembly. This increase in variability could be attributed to the work-experience—one month—in the new workstation and to the introduction of new technologies. This analysis indicates that this study shall be repeated as future work. The cycle time variation is a commonly used metric for the continuous improvement of assembly workstations. Its analysis aims to reduce the time deviations between consecutive cycles to create a more reliable work-flow [30]. It should be noted, however, that this workstation was created to accommodate workers with disabling WMSD. Therefore, this study must avoid conditions that could increase the musculoskeletal risk, such as the increase of work pace and lack of recovery time, frequently associated with JIT practices and work standardization in some companies [8].

4.2. Physical Ergonomics Improvement of the Preassembly Workstation

The ergonomic assessment across these tasks is summarized in Tables 8 and 9. Figure 7 presents examples of postures adopted during the preassembly tasks before and after the collaborative workstation implementation.

Table 8. Manual preassembly—summary of time study, RULA, RSI and KIM assessment.

		RULA Assessment		RSI Assessment		KIM Assessment	
Task	**Normalized Time Mean (s)**	**Rating Mean (SD)**	**Risk Level**	**Rating Mean (SD)**	**Risk Level**	**Risk Score**	**Risk Level**
Task 1—Reach stripes and align.	4.16	3.2 (0.4)	B	1.9 (0.1)	Safe	84	3
Task 2—Reach blocks and stack.	6.98	3.6 (0.9)	B	6.6 (1.1)	Safe	84	3
Task 3—Apply glue to the blocks.	4.52	3.0 (0.0)	B	**12.3** (3.3)	**Unsafe**	**112**	**4**
Task 4—Fix blocks on the stripe.	8.05	**4.4** (0.5)	**B**	2.3 (0.0)	Safe	84	3
Task 5—Relocate or reverse the stripe.	3.48	3.0 (0.0)	B	1.0 (0.0)	Safe	70	3
Task 6—Transfer preforms to the pallet.	3.46	**4.4** (1.3)	**B**	1.0 (0.0)	Safe	80.5	3

Legend: Bold denotes the major mean for each method.

Table 9. Collaborative preassembly—summary of times' study, RULA, RSI and KIM assessment.

		RULA Assessment		RSI Assessment		KIM Assessment	
Task	**Normalized Time Mean (s)**	**Rating Mean (SD)**	**Risk Level**	**Rating Mean (SD)**	**Risk Level**	**Risk Score**	**Risk Level**
Task 1—Turn on the system, reach a stripe, and align.	5.84	2.5 (0.5)	A-B	1.8 (0.0)	Safe	45.5	2
Task 2—Reach blocks and fix them to the stripes (3 times/single cycle).	11.44	3.3 (0.6)	B	**9.6** (0.8)	**Safe**	**70**	**3**
Task 3—Wait for the automation (2 times/single cycle).	4.95	2.0 (0.0)	A	0.1 (0.0)	Safe	14	1
Task 4—Relocate or reverse the stripes.	4.55	3.1 (0.6)	B	3.7 (0.0)	Safe	**70**	**3**
Task 5—Transfer preforms to the pallet.	3.14	**3.8** (1.7)	**B**	2.9 (0.3)	Safe	59.5	3

Legend: Bold denotes the major mean for each score.

The RULA results for the manual preassembly indicate a risk of level B, meaning that further investigation and changes are required. These results indicate that tasks 4 and 6 have a higher biomechanical risk when compared to other tasks.

For the collaborative preassembly, the RULA results indicate that, globally, tasks present a lower musculoskeletal risk. Specifically, Tasks 1 and 3 show a global risk of level A and the other three tasks have a global risk of level B. The preforms' palletization task obtained the worst RULA score. This score is aggravated by the group B posture, including the neck, trunk and legs. The current workstation layout compromises the workers' posture when transferring the stripes to the pallet. An adaptation of the workstation has been suggested, particularly the elimination of the lateral rollers next to the outfeed pallet.

The global decrease of RULA scores reflects the ergonomic improvement, evidenced in Tables 10 and 11. Nonetheless, the level B of the final risk score means that the new workstation requires observation and possible changes, especially if postures are maintained for long periods.

By the method's design, the RULA accounts for the entire upper extremity, including the shoulder, as well as the posture of the neck and trunk and lower limbs stability, while the RSI is specific to DUE. The RSI results indicate that the collaborative preassembly decreased significantly the risk for DUE WMSD. With the robotic support, the task of manually applying glue was eliminated, mitigating unfavorable postures for the hand–wrist system and force exertions during glue pistol activation. All tasks of collaborative preassembly demonstrate to be safe for DUE, according to RSI scores. When considering the COSI values, following the preassembly process repetitive multi-task, the work conditions are still labeled hazardous for both manual and collaborative workstations. That being said, the COSI risk index for the collaborative preassembly denotes a decrease of 40% (for

DS) and 45% (for SS), reflecting the significant decrease of musculoskeletal risk for the hand–wrist system.

Task	Manual Preassembly	Collaborative Preassembly
Reach stripes and align.		
Reach blocks.		
Apply glue and fix blocks.		
Reverse stripes.		
Transfer preforms to the pallet.		

Figure 7. Tasks performed in the manual and collaborative preassembly.

Table 10. Manual preassembly—Weighted RULA and COSI assessment.

	Tasks	Cycle Normalized Time Mean (s)	Weighted RULA	COSI
Double stripe 	Task 1 + (2 × Task 2) + (2 × Task 3) + (2 × Task 4) + Task 5 + Task 6	50.20	3.7—Risk Level B	41.7—Hazardous
Single stripe 	Task 1 + Task 2 + Task 3 + Task 4 + Task 6	27.14	3.8—Risk Level B	29.0—Hazardous

Table 11. Collaborative preassembly—Weighted RULA and COSI assessment.

	Tasks	Cycle Normalized Time Mean (s)	Weighted RULA	COSI
Double stripe 	Task 1 + (2 × Task 2) + (2 × Task 3) + Task 4 + Task 5	46.31	2.9—Risk Level B	25.3—Hazardous
Single stripe 	Task 1 + Task 2 + Task 3 + Task 5	25.37	2.9—Risk Level B	16.2—Hazardous

The KIM-MHO assessment is in concordance with the RSI assessment. This highlights the tasks of reaching/fixing the blocks and relocating the stripes as presenting the higher musculoskeletal risk. In fact, for collaborative preassembly, the task of reaching and fixing the blocks to the stripes poses a higher risk level according to the three methods applied.

These results demonstrate that the collaborative preassembly induced a significant ergonomic improvement; however, if these tasks are carried out over a seven-hour shift (as considered in the current assessment), preventive measures are recommended, especially for workers with disorders:

(i) Adjust the system to dispense only two blocks (instead of three) for workers with carpal tunnel syndrome;
(ii) Organize the workday to include recovery times, introducing micro-breaks throughout the shift to relax the musculoskeletal system. This recommendation applies to any workstation where movements and postures are repeated more than four times per minute [13];
(iii) Introduce labor gymnastics, personalized to meet these workers' limitations;
(iv) Study and implement job rotation schemes to vary the workers' activities and expose them to alternative musculoskeletal system activation [42].

These preventive measures are frequently linked to WMSD prevention and a positive bump in the workers' job satisfaction and productivity [42].

The current findings demonstrate that a multi-method approach allows a more comprehensive ergonomic assessment to support a more extensive and intrusive intervention to address a set of risk factors. The improvement of ergonomic conditions also potentiates waste reduction, which is frequently associated with human efforts [12]. That is another premise that this study upholds.

The current study highlights the importance of robotics in reducing physical workload by adapting the work cycle to the workers' conditions, considering previous WMSD and the anthropometric data (as described in a previous study [23]). The act of applying hot-glue by pressing the glue gun trigger in the manual preassembly represented a relevant musculoskeletal risk for the hand–wrist system, a critical factor considering the workers' medical history of DUE WMSD. The adaptation introduced to the preassembly process permitted the reallocation of tasks to the robotic system. The collaborative workstation proved to be a sustainable production system as corroborated by the ergonomic and productivity results. These results are in line with previous studies that defend the HRC implementation as a solution to reduce physical workload [18], and it constitutes an emergent and relevant research challenge [26].

4.3. Workers' Perception of the Collaborative Preassembly

We applied the questionnaire to the four female workers that operate the preassembly workstation. Their ages were 40.8 ± 7.0 years old, with a work experience of 11.0 ± 5.7 months in the manual preassembly workstation. All reported at least one musculoskeletal problem, such as scoliosis, tendonitis, carpal tunnel syndromes or herniated disc.

Figures 8 and 9 depict the workers' opinions on the impact of robotics in the industry. The workers expressed their opinions through a five-point Likert scale before and after operating in the collaborative workstation. Therefore, the initial and final perceptions are presented separately.

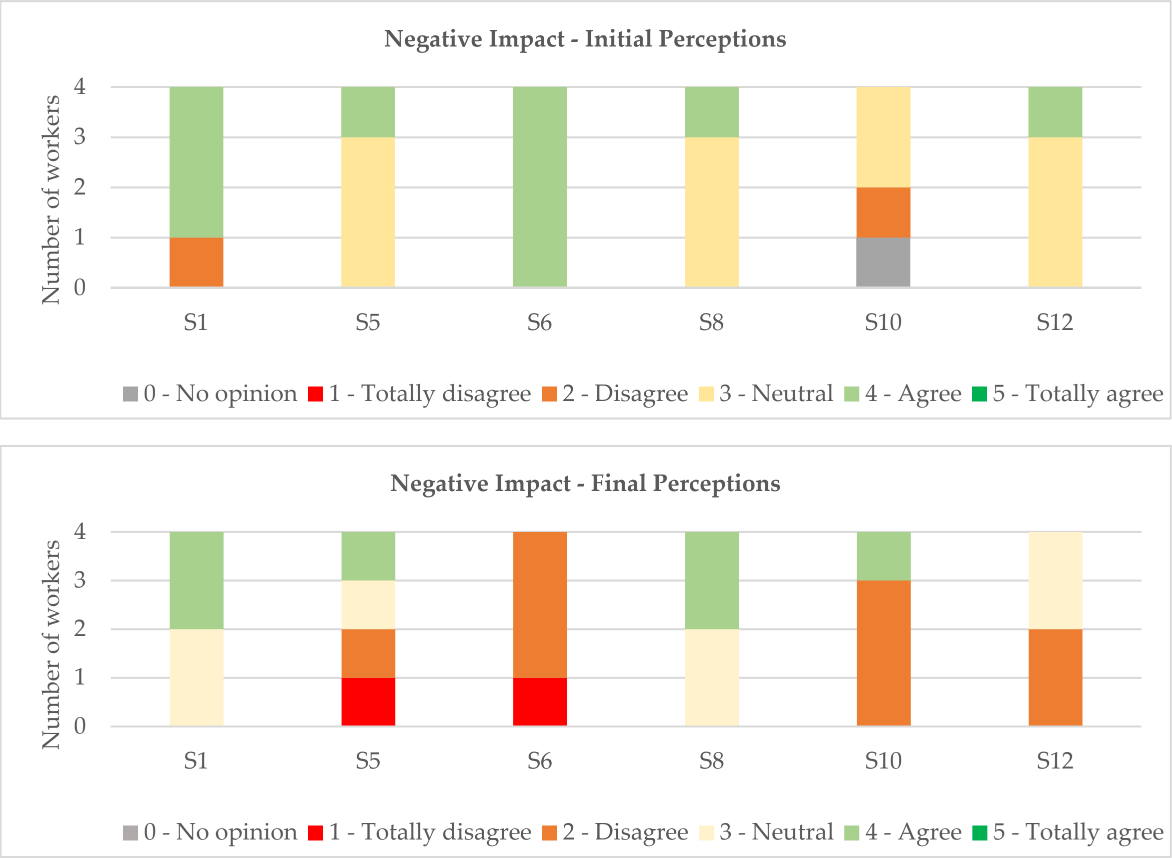

Figure 8. Answers distribution for the statements related to a negative impact of robotics, comparing the initial and final workers' perceptions.

After working in the collaborative preassembly, the workers demonstrated a higher disagreement with the statements: S5 ("Robotic work will increase repetitive tasks and/or monotony"); S6 ("It is possible for humans to feel insecure and threatened by the robotics risks"); S10 ("The existence of tasks with robots increases the stress and anxiety in workers"); and S12 ("Robots can cause accidents and injuries to workers"). The experience of working in this workstation seems to increase workers' confidence in robotics, mainly in terms of safety.

In general, the workers' opinions persisted when consulted a month after beginning to work in the collaborative workstation. There were two exceptions, first regarding the statement "the integration of robotics can create more jobs than it can destroy" and second "robotics can increase the productivity of assembly workstations." On both topics, opinions diverged. However, working in the collaborative workstation induced a more positive perception about the collaboration/work between robots and humans as well as the improvement of work conditions by relying on robotic technology.

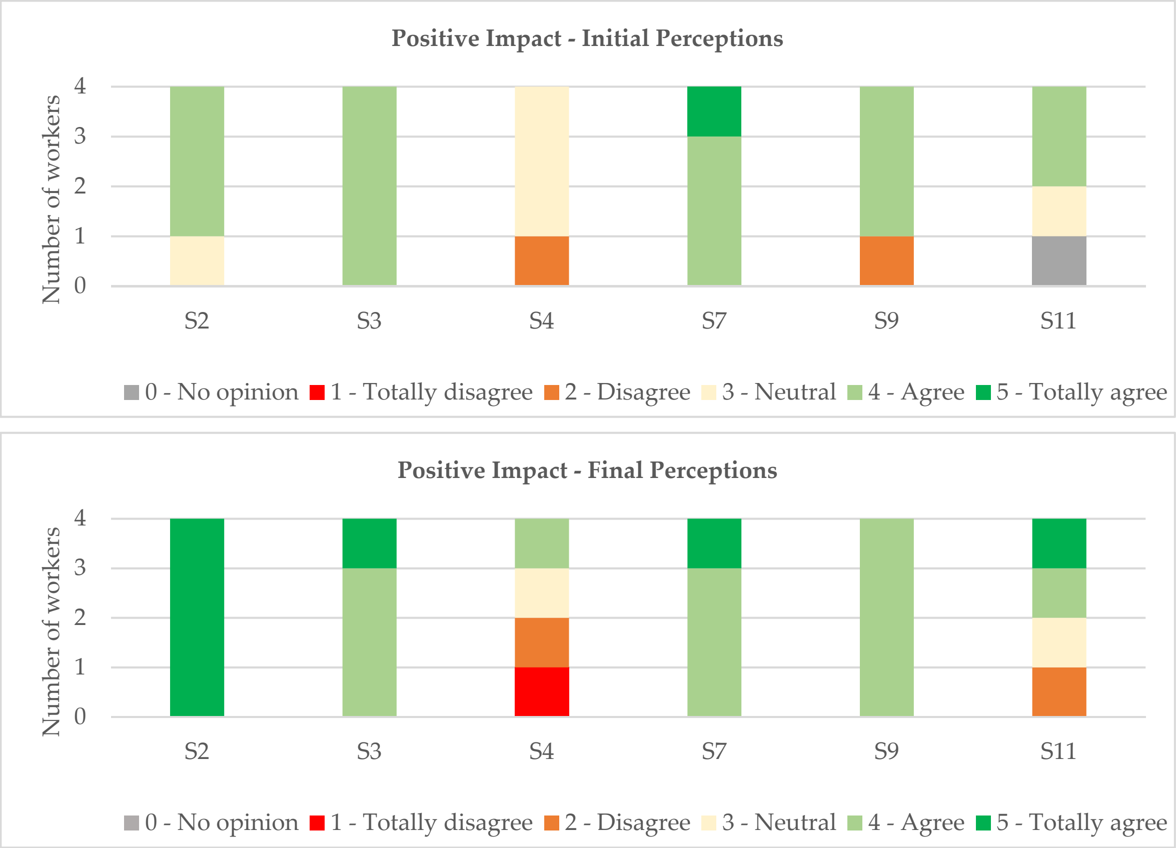

Figure 9. Answers distribution for the statements related to a positive impact of robotics, comparing the initial and final workers' perceptions.

Initially, all workers reported unfamiliarity with the collaborative robotics terminology, and all preferred to work with caged robots. After a month of operating in the collaborative cell these opinions changed, and all of them answered that they would like to work with robots that do not need to be physically protected by grids.

The workers' perceived exertion across the different collaborative preassembly tasks is depicted in Figure 10. The "reach for the blocks" and "dislodge/rotate the stripes" tasks are considered the most demanding. The "fix blocks" and "remove preforms from the workbench" tasks registered high average scores.

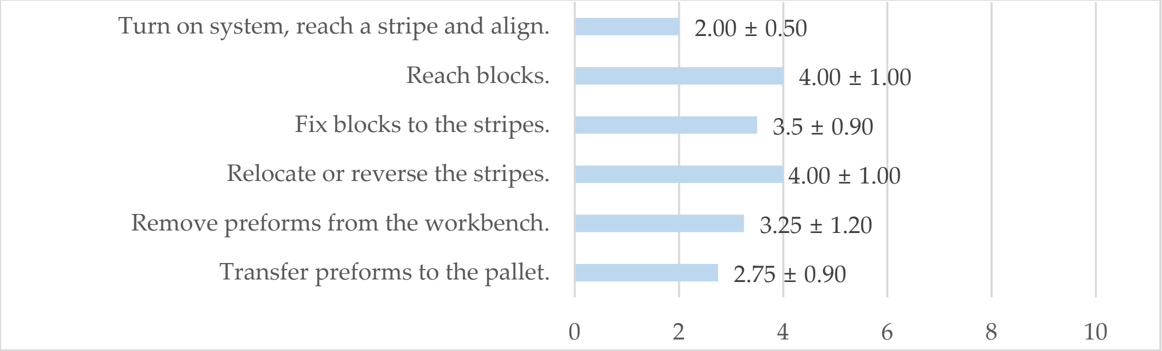

Figure 10. Perceived exertion (mean values ± SD) across the preassembly tasks (new workstation).

The workers' perceptions are in line with the ergonomic assessment, since the most demanding tasks were the ones with the highest risk scores according to the applied methods. However, it should be highlighted that in the manual preassembly, the task of applying glue stood out among other tasks in terms of difficulty perceived by the workers (this analysis was performed in the design project phase presented in a previous study [23]).

In the collaborative workstation, the workers' perceptions point out that all tasks present a similar difficulty level, being a light to moderate work, according to the CR-10 Borg scale.

The global opinions about the collaborative preassembly measured by the five-point Likert scale (Figure 11) demonstrated that the preassembly improved the workers' wellbeing. Some workers also suggested improvements, such as moving the workstation to a less noisy space.

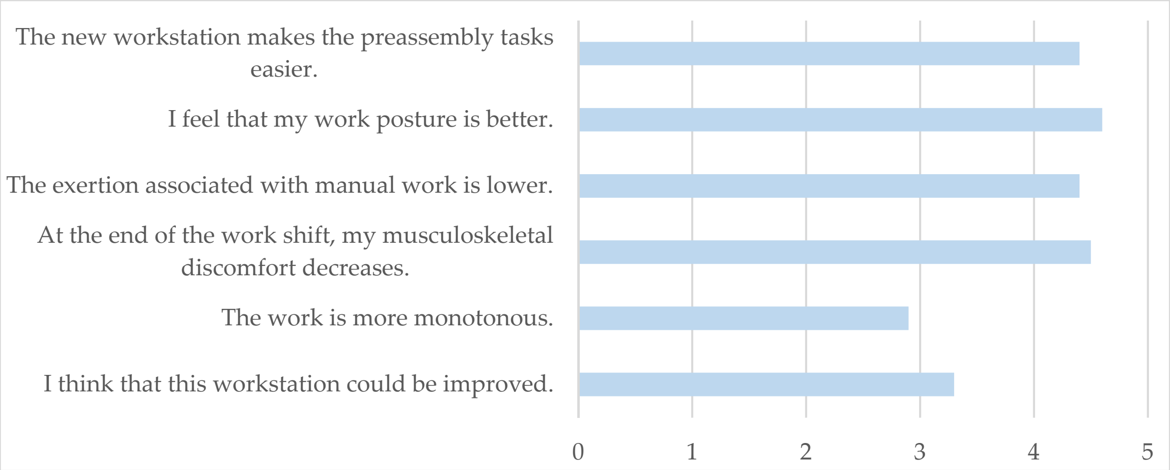

Figure 11. Global workers' perceptions about collaborative preassembly—Distribution of the mean results of the five-point Likert scale.

Finally, it should be highlighted that the workers' involvement in this process, including in the design and implementation stage of the new workstation, was crucial to anticipate and correct problems. The workers exhibited motivation and satisfaction with the new work design, showing themselves available to actively participate in the workstation transformation. This participatory ergonomics intervention in workstations is pointed out as the adequate approach for successful workstations and process modifications [13,43]. In terms of continuous improvement, it is suggested to consider workers' opinions when changing the workstations and/or working methods for a more efficient and proper adaptation of changes to their needs. This will lead to an increase in workers' satisfaction, while at the same time improving concrete goals.

The positive impact of the collaborative workstation in terms of work performance and physical ergonomics is evident, highlighting the importance of these work transformations that companies should implement. Another emergent research area is related to cognitive ergonomics because the introduction of the HRC could induce work-related psychosocial risks due to the sharing activities and workspaces [26]. A relevant parameter to be studied is the acceptability of the robotic systems by human coworkers. Based on this assumption, this study constitutes a pioneering effort that could be replicated and improved by other HRC implementations. However, in different HRC workstations, with more or less closed interaction, several advantages but also new forms of discomfort for the workers could appear. In this context, and according to the results, it will be important to develop methodologies to assess cognitive ergonomics related to collaborative robotic systems (as defended by other authors [26]).

5. Conclusions and Future Work

The proposed ergonomic lean approach for the hybrid assembly workstation relies on human-centered principles. Our main objective was to improve the ergonomic conditions for preassembly workers, with physical limitations, without compromising production. In the new collaborative workstation, the ergonomic conditions improved, and there was a reduction in cycle times and glue consumption. This study demonstrates that this collaborative workstation is a successful implementation of sustainable production systems.

Additionally, with regards to the physical ergonomics and performance improvements, we evaluated the workers' acceptability and wellbeing associated with the new collaborative workstation. This global assessment constitutes a relevant contribution to this research field. The workers were involved across the study, and they exhibited motivation and satisfaction with the new work design. Their perceptions were positive, which was in line with the ergonomic assessment, highlighting the importance of participatory ergonomics during these types of workstation interventions.

With different HRC workstations and different levels of human-robot collaboration, new forms of discomfort can arise. Thus, it will be paramount to develop methodologies for cognitive ergonomics assessment of HRC systems.

The limited sample of participating workers is the main limitation of this study. The workers were selected by the company based on their experience in the preassembly process and their clinical history of WMSD. In future work, the authors will extend the proposed methodology to a larger sample and conduct a longitudinal study based on the work experience with this novel technology.

Moreover, it will be important to verify the impact of the collaborative workstation in terms of production management. For instance, the economic payback of this implementation, the movements of materials and work-flow in the entire assembly section are issues that should be analyzed by the company managers.

Globally, the findings of the current study demonstrate that the integration of LM and E&HF in an HRC workstation potentiates the successful implementation of this technology and the continuous improvement of manufacturing processes. Therefore, this multimethod approach can be used in the development and implementation of Industry 4.0 environments, with the human factor being the focal point.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Committee of Ethics for Research in Social and Humans Sciences of the University of Minho (approval number CEICSH 095/2019).

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

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

COSI	Composite Strain Index
DS	Double Stripe
DUE	Distal Upper Extremity
E&HF	Ergonomics and Human Factors
HRC	Human-Robot Collaboration
I4.0	Industry 4.0
JIT	Just-In-Time
KIM-MHO	Key Indicator Method for assessing physical workload during Manual Handling Operations
KPI	Key Performance Indicator
LM	Lean Manufacturing
MDF	Medium-Density Fiberboard
MHO	Manual Handling Operations
RSI	Revised Strain Index
RULA	Rapid Upper Limb Assessment
SS	Single Stripe
TPM	Total Productive Maintenance
TPS	Toyota Production Systems
VSM	Value Stream Mapping
WMSD	Work-related Musculoskeletal Disorders
WULD	Work-related Upper-Limb Disorders

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