Investigation of Spraying process: a Simulation-based Comparison of Human Approach and Robotic Application

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Abstract –

The construction industry faces low productivity, high physical workload, and workforce shortages, especially in repetitive tasks like wall and ceiling spraying. Despite the potential of construction robotics, adoption is limited by insufficient process-oriented development and lack of systematic performance validation. This study evaluates robotic assistance on ergonomics and efficiency using a digital process twin combining a digital human model with motion-captured movements. Manual, semi-automated, and fully automated spraying processes were assessed for ergonomic risk (EAWS), process duration, and worker pathway length. Manual ceiling spraying posed the highest risk (EAWS = 102), while robotic assistance reduced physical strain (EAWS ≤ 7.5), musculoskeletal load, and walking distances. Humans completed small-scale tasks faster, but robots provided consistent workflows with minimal intervention. The process-simulation-based method offers a targeted approach to optimize robotic integration in construction, transferable to other processes. Results highlight the trade-off between process duration and ergonomic safety, demonstrating that human-centered automation can improve worker health, retention, and efficiency.

Keywords –

Construction Automation; Robotic Spraying; Human-Centered Work Design; Process Simulation; Ergonomics; Occupational Health; Economics.

1 Introduction

Over the past decades, construction automation has gained increasing importance as a response to growing demands for primarily efficiency and quality in the building sector. [1–3] Numerous approaches have been proposed to integrate robotics and automation into various construction processes, such as brick laying, coating, concrete works or formworks. Despite decades of research, high costs, and uncertain returns continue to limit the adoption of advanced automation in construction. [4] However, the practical application of many robotic systems remains limited, as they are often insufficiently developed from a process-oriented perspective and greatly lack systematic performance validation within real construction workflows. [5]

Additionally, the construction industry continues to struggle with low productivity growth, particularly in on-site operations, where work remains highly manual, variable, and difficult to standardize.

Besides these economic factors, the construction industry faces the persistent challenge of social sustainability and safety, which constrains the effective deployment of automated technologies in construction. [6] Construction work is traditionally associated with physically demanding and repetitive tasks impacting worker health, safety, and performance. As a result of workers being frequently affected by musculoskeletal disorders, respiratory diseases, and long-term health impairments, this often leads to reduced working capacity or early exit from the profession. [7–9] These conditions strongly contribute to the ongoing labor shortage in the construction sector, which threatens the long-term sustainability of the industry. In this context, there is a growing need for approaches that adapt construction processes not only for efficiency, but also with respect to human well-being. Human-centered automation strategies aim to reduce physical strain, improve occupational health, and make construction work more attractive, thereby supporting the sustainable retention of skilled workers. [10]

To address these challenges, robotic systems of different construction applications have been increasingly introduced to support workers and reduce ergonomic risks while maintaining productivity with still persistent demand. [11]

Among existing robot-assisted construction solutions, this work investigates the integration of robotics into paint spraying, a highly repetitive and physically demanding wall and ceiling finishing task, as an example of labor-intensive construction work and focuses on the physical influence on the worker.

Compared to other construction tasks such as bricklaying, concrete works, or assembly operations, spraying remains a comparatively under-investigated field, particularly regarding the strong physical involvement of workers and their exposure to sustained postures.

The objective of this work is to analyze the traditional craftsmen-involved on-site wall and ceiling spraying process regarding economics and with particular focus on human-related parameters and to investigate how the application of a spraying robot in a semi-automated as well as automated way influences both the process characteristics and the role of the human worker within a simulation approach. This approach according to Fig. 1 aims to facilitate the adaptation of the robot and the corresponding construction process, thereby promoting the integration of robotics into the building workflow.

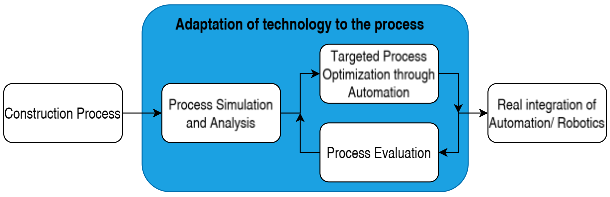


Figure 1. Integration of robotics and automation into construction. The blue box represents the simulative approach of this work allowing process investigation for a targeted integration of robotics into construction.

2 State of the Art

To investigate manual spraying processes in comparison with semi-automated and automated robotic spraying processes in terms of economic and human-related process characteristics, we employ simulation to evaluate these process variants.

2.1 Spraying Process

Spraying is widely used for interior wall and ceiling coating due to its high application speed and ability to achieve uniform surface coverage compared to roller or brush application. [1, 9] It is performed in variable, unstructured environments, where room layout, obstacles, and overhead work significantly affect task execution. [3]

The spraying process is predominantly based on manual airless spraying systems operated by skilled workers on site. The coating material is atomized at high pressure without compressed air, enabling high transfer efficiency and fast surface coverage. Traditional spraying craftsmanship relies on the continuous manual control of the spray gun and visual inspection of the coated surface as well as knowledge in spray distance, angle, overlap and speed to ensure constant material distribution. [1] While this approach offers flexibility on site, it involves repetitive arm movements, sustained overhead work, and frequent repositioning, especially during ceiling spraying, increasing the risk of musculoskeletal disorders. [7]

To improve surface quality and adhesion, spraying is commonly combined with backrolling, where the sprayed surface is rolled manually. The combination of techniques reduces spray marks, improves texture uniformity, and is considered standard practice in construction painting. [9]

The spraying process follows a standardized sequence of steps. After the inspection of the walls and ceiling to be sprayed, areas not intended for coating, such as doors and windows, are protected by. After material preparation, including mixing and conditioning of paint or plaster, the coating is applied by spraying with controlled distance, overlap, and movement speed. Immediately after spraying, backrolling is performed.

2.2 Assessment of Processes with Computer-Aided Process Planning

The assessment of work processes using Computer-Aided Process Planning (CAPP) has become a key element in modern industrial, construction, and robotic system design. CAPP within adequate simulation software allows engineers to evaluate task feasibility, process efficiency, ergonomic risks and the influence of changed process parameters, such as the integration of additional robotic devices, at an early design stage, before realizing avoiding trial implementation costs and exposing workers to potential risk.

Already widely implemented in the automotive industry, this approach is particularly relevant for construction-related activities, where manual tasks are physically demanding. [10, 12] Simulation software, such as ema Work Designer by imk Industrial Intelligence or Technomatix by Siemens, allows evaluation of process parameters including timing, layout effects, and ergonomic risks using standardized assessments methods and digital human models (DHMs). The DHMs enable the virtual representation of human workers interacting with tools, machines, and robotic systems.

By considering posture, movement frequency, exerted forces, or task duration, ergonomics evaluation criteria, such as the standardized Ergonomic Assessment Worksheet (EAWS), Rapid Upper Limb Assessment (RULA) or Rapid Entire Body Assessment (REBA), serve as evaluation criteria for the risk of getting affected by musculoskeletal disorders in a working context. [13]

Motion capture tracks human movements in real time, enabling more objective and dynamic ergonomic evaluations than traditional observation methods. [14] These systems record 3D joint angles and body movements with high precision while minimally interfering with natural work activity, making them suitable for field assessments in real industrial environments. Recent advancements in ergonomic assessment highlight the increasing role of sensor-based motion capture technologies in workplace ergonomics. [15]

2.3 Robotic and Automated Solutions

The construction industry has increasingly adopted robotic systems to assist with repetitive and physically demanding tasks such as wall and ceiling spraying. These systems are designed to enhance productivity, improve quality, and reduce ergonomic strain on workers and therefore face common challenges in construction environments due to labor shortages, safety concerns, and the need for consistent high-quality work.

The latex paint spraying robot developed by Legend Robot Technology is an autonomous mobile system for interior walls and ceilings. It combines an omnidirectional chassis with a 6-DOF robotic arm and integrated perception and control software to ensure uniform paint application over large areas. Continuous mobile spraying allows simultaneous movement and coating, improving efficiency compared to traditional stop-and-spray methods, with coverage rates up to 3 000 m²/day for larger models. The robot supports semi-supervised operation, requiring only a single worker for paint refills and repositioning, and its compact design enables access to narrow corridors and complex indoor layouts. Performance metrics show consistent coating thickness, over 95 % coverage, reduced material waste, and stable operation for up to 12 h per battery cycle. The system is suited for repetitive large area spraying, occupying a mid-to-high automation segment in construction finishing. In terms of cost, the Legend Robot system is positioned in the upper-mid range among comparable construction spraying robots. [16]

A notable development in automated construction finishing is the Painter Robot from ConBotics GmbH, a company specializing in robotic solutions for interior tasks. The system combines a mobile base with an articulated robotic arm and an airless paint sprayer to perform automated wall and ceiling coating with high consistency and reduced manual effort. Integrated sensing and control allow the robot to navigate indoor environments, maintain spraying distance and angle, and access hard-to-reach areas such as corners and elevated sections. Positioned as a practical assistance tool, the Painter Robot enhances efficiency in construction finishing without fully replacing human labor and targets the mid-to-high automation segment. In terms of purchasing costs, the robot addresses the low to mid pricing segment. [17]

Fig. 2 shows the NOVA-S system from Nova Spraytec, a semi- and fully automated solution for interior wall and ceiling spraying. The system weighting approximately 85kg consists of a mobile base with a mountable spray column and uses a modular external piston pump. In semi-automated mode, the operator manually pushes the robot, activating the spraying sequence with a button, inducing a vertical motion of both nozzles. The system maintains consistent spray height up to 3.3m, while the worker ensures correct distance to the wall and overlap in guided application. In fully automated mode, the operator activates the sensors before starting the process. The robot navigates autonomously alongside walls while safety sensors halt operation if obstacles or people are detected but requires human intervention in moving around inner or outer corners. The NOVA-S is particularly suited for large or repetitive surfaces, providing consistent coating quality. The system is positioned in the low-cost segment, making it especially suitable for small and medium-sized construction companies. [18]

Figure 2. Nova-S spraying modular robot with dual nozzle. The external pump attached to the robot ensures material flow. [18]

The construction spray robot ProPainter by WEIBUILD is a mobile robotic system designed for automated interior wall and ceiling coating in building construction. Its operating principle is based on autonomous navigation within indoor environments combined with a multi-axis robotic spraying unit that executes predefined coating paths. The system integrates sensing and control functions to enable consistent paint application over large surfaces while reducing manual spraying tasks. Due to its focus on automated large-area coating, the ProPainter is primarily suited for residential and commercial construction projects with repetitive spraying operations. Compared to the other robots, the ProPainter is assigned to the highest cost segment. [19]

In summary, these construction spraying robots represent the options currently available, from modular assistants to autonomous systems. [11]

3 Methodology

This study compares manual, semi-automated as well as automated interior spraying of walls and the ceiling to evaluate process characteristic indicators.

3.1 Setup

Due to its flexible design, dual spraying tips, and moderate cost, we selected the Nova-S robot (see Fig. 2) with a nozzle speed of 0.4 m/s for semi-automated wall and ceiling and fully automated wall spraying scenarios with driving speed of 0.3 m/s in construction. Hardware constraints limit the selected robot version to spray the ceiling in automated mode. To establish an encompassing digital process twin for simulation, we combine the given setup including the robot with a digital human model (DHM) representing the worker incorporating the CAPP software ema Work Designer (emaWD) by imk Industrial Intelligence.

The setup includes a test room of the dimension 3.0m×3.5m and a wall height of 2.5m. It consists of three walls and one ceiling as depicted in Fig. 3, resulting in a wall area of 68.6m^2 and a ceiling area of 10.5m^2.

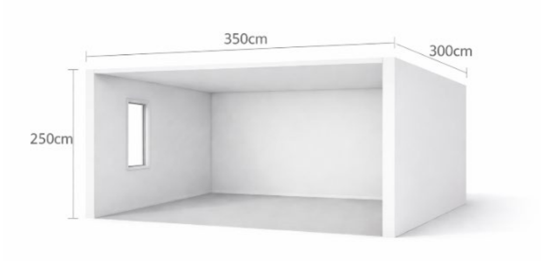


Figure 3. Test setup consisting of three walls and the ceiling.

To create a realistic digital process twin as shown in Fig. 4, we integrated motion capture data from an experienced painter using the Xsens Awinda IMU system by Movella, accurately representing human movement in the DHM.
Equipped with an airless spray gun (see Fig. 5) to attach paint to the walls and ceiling of the setup, the worker performs five spraying scenarios with a measured speed of 0.6 m/s allowing a direct comparison between manual and robot-based operations:

1. Spraying the walls manually with the airless spray gun
2. Spraying the ceiling manually with the airless spray gun
3. Spraying the walls with the robot in the semi-automated operation mode
4. Spraying the ceiling with the robot in the semi-automated operation mode
5. Spraying the walls with the robot in the automated operation mode

In real-world applications, additional tasks precede and follow the spraying process. These are not considered in this work, as they are consistent for all five process variants. This includes, i.a., masking areas to be protected, preparing materials such as mixing paint, and backrolling to achieve the desired texture after applying paint with the spraying technique.

Figure 4. Digital twin (left) of real robot-based spraying process (right) within the simulation software ema Work Designer.

Figure 5. Manual spraying comparison of real process (left) and the digital human model within the digital process twin generated by ema Work Designer.

3.2 Simulation and Evaluation with CAPP Software

The pushing force for the robot depends on the ground material moving on, where hard materials reduce the pushing resistance and soft materials are likely to induce higher required pushing forces. In this work, the measured force amounts to 65 N and is transferred to the DHM of the simulation.

According to the digital process twin, the emaWD software allows comprehensive assessment and evaluation of the simulated spraying processes based on the determination of three key performance indicators (KPIs):

- The EAWS score (cp. section 2.2) is classified into three categories indicating the risk of developing musculoskeletal disorders: values from 0 to 25 indicate no or low risk, scores between 25 and 50 represent moderate risk and scores above 50 indicate a high risk necessitating urgent human-centred process adaptation. [13]

- Process time as economic measure for efficiency
- Length of worker's pathways as additional indicator for worker's endurance [20]

4 Results

The ergonomic assessment comprises the KPIs EAWS score, process time and length of pathways and are presented for each of the five given spraying process variants as declared in section 3.1.

4.1 EAWS Score

The EAWS scores of the five variants of the spraying process are listed in Table 1. Variant *2. Spraying the ceiling manually with the airless spray gun* reveals the highest value with a score of 102 indicating a process with high risk of getting affected by musculoskeletal disorders, whereas the automated robotic process of variant 5 shows an EAWS score of 5.5 representing no or a low risk.

The score of variants 1 and 2 fully origin from poor and extreme posture such as bending over or standing straight with raising the arms. The weight of the airless spray gun of 1.5kg has no influence on this physical strain. Processes 3 and 4, which include semi-automated robotic assistance, showed low EAWS scores of 4 and 7.5, respectively. As the robot primarily is responsible in the task of paint application in an automated operation the worker's EAWS score cannot be applied in variant 5.

Table 1. EAWS scores of the five process variants

Process variant	EAWS score
1: manual, walls	46
2: manual, ceiling	102
3: semi-automated, walls	4
4: semi-automated, ceiling	7.5
5: automated, walls	5.5

4.2 Process time

Table 2 contains the process duration of each spraying process variant ranging from 85s in *2: Spraying the ceiling manually with the airless spray gun* to 251s for the semi-automated wall spraying. In general, the results indicate that wall processing requires more time than the ceiling.

Table 2. Process duration of the five process variants

Process variant	Process time [s]
1: manual, walls	209
2: manual, ceiling	85
3: semi-automated, walls	251
4: semi-automated, ceiling	146
5: automated, walls	250

4.3 Worker's Pathway

The pathway length ranges from 16.3m within the automated wall spraying to 40.4 within the semi-automated ceiling process as Table 3 displays.

Table 3. Worker's pathway lengths of the five process variants

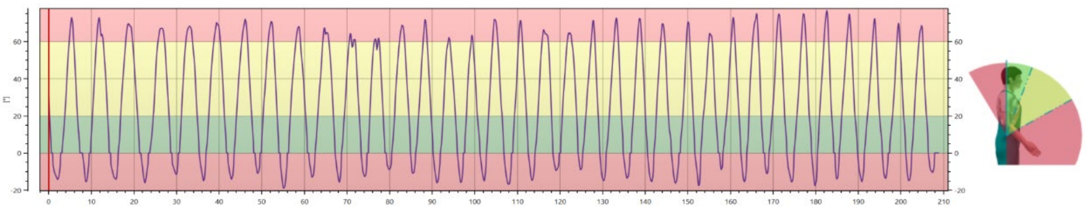
Process variant	Pathway length [m]
1: manual, walls	32.4
2: manual, ceiling	36.8
3: semi-automated, walls	18.5
4: semi-automated, ceiling	40.4
5: automated, walls	16.3

5 Discussion

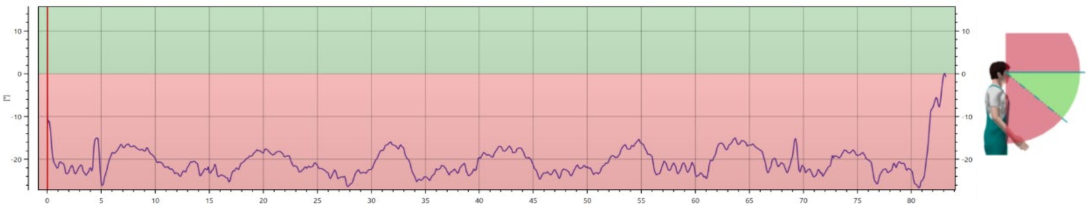
The following discussion interprets the simulation results by comparing manual and semi-/ automated robotic spraying processes on one subject in terms of process duration, human loading, and operator pathways, while considering system limitations and practical operational conditions. Using a simulation-based digital process twin incorporating a DHM, the analysis highlights both the performance potential and the existing technical and organizational constraints of robotic automation, particularly when essential accompanying human tasks are included.

Fig. 6 (a) shows spinal motion representative for the full body movement of process variant 1. The worker bent and straightened 37 times to spray three walls resulting in an EAWS score of 46. The figure's colour scheme allows interpretation of movement quality using a traffic light system: red indicates a high risk of getting affected by musculoskeletal disorders, while green represents an acceptable risk.

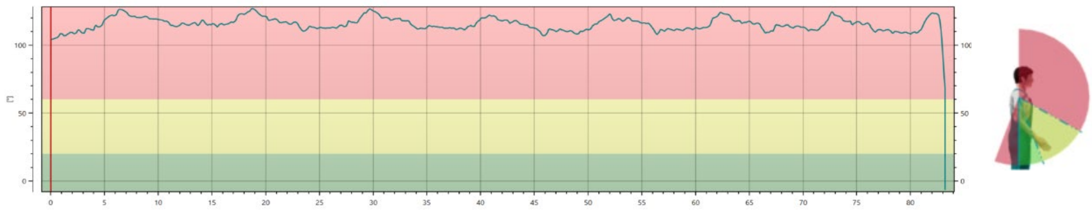
Although this EAWS score of 46 represents an existing risk of getting affected by health issues, manual ceiling spraying as in process variant 2 reaches an EAWS score of 102, more than twice the harm potential compared to variant 1, whereas the robotic supported process variants reveal low EAWS scores with comparable values of 4 and 7.5 in semi-automated as well



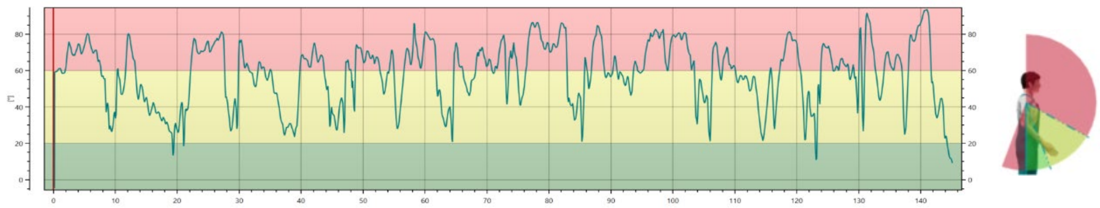
(a) Motion curve of worker's spinal flexion and extension in degree [°] over time of the manual wall spraying process, which refers to repeated bending over followed by straightening up.



(b) Motion curve of worker's head flexion in degree [°] over the time of the manual ceiling spraying process. The graph shows negative values in flexion.



(c) Motion curve of worker's right arm flexion in degree [°] over the time of the manual ceiling spraying process.



(d) Motion curve of worker's right arm flexion in degree [°] over the time of the semi-automated ceiling spraying process.

Figure 6 (a)-(d). Worker's motion graphs with colored risk indicator to get affected by musculoskeletal disorders. The color scheme follows the traffic light principle.

as 5.5 in automated variants.

As the head constantly flexed backwards with the viewpoint to the ceiling throughout, this pivotal head/neck posture leads to high EAWS score (cp. Fig. 6 (b)). Additionally, the constantly major flexion of the right arm as shown in Fig. 6 (c) induces the high EAWS score of the manual ceiling spraying. In contrast, during semi-automated robotic spraying, the worker's arm mainly remains in the yellow area (cp. Fig. 6 (d)) implying moderate flexion and resulting in a significantly lower EAWS score of 7.5.

With respect to ergonomic assessment, the results clearly indicate the advantage of robotic application in both semi-automated and automated spraying processes. Although the process simulation software ema Work Designer itself does not consider workers fatigue, this analysis indicates a huge potential to reducing cumulative fatigue, mitigating the risk of musculoskeletal issues related to the workers and therefore counteracting the shortage of skilled workers. By shifting the primary physical load from the worker to the robot, the task becomes less demanding, which is particularly important in repetitive or physically challenging operations.

In terms of duration, the human operator demonstrated a clear advantage over the robot, completing the walls and ceiling faster. The present data set considers only the paint application process. For the robotic automated process, the worker currently intervenes only at the room's edges when changing the direction of robotic movement. However, in practical operation, the worker performs additional tasks, such as masking further areas and replenishing paint with potential influence on the whole spraying process, indicating that the time advantage of the robotic process should be evaluated in the context of these essential accompanying activities within further research.

While the human operator completed the walls and ceiling slightly faster, this speed comes at the cost of greater physical exertion. The operator covered a longer distance and performed repeated arm and upper-body movements, contributing to higher cumulative strain. In contrast, the robot's operation, with a measured pushing force of 65 N, provided a smooth, controlled workflow, requiring minimal intervention and maintaining consistent motion patterns.

Although the analysis conducted considers only a single test subject, the movement speed during manual spraying objectively depends on the material used and should be kept constant. Therefore, the results of a potential cohort study involving a larger number of participants would not be expected to differ substantially. With respect to movement pathways, the human operator generally exhibits a higher overall walking distance across the investigated manual process variants. An exception is observed in the robotic semi-automated ceiling application, in which the operator is required to accompany the robot along the entire spraying path. This results from the current mechanical design of the robot, which does not yet permit independent nozzle movement for ceilings. Consequently, the operator must compensate with additional repositioning and continuous spatial adjustment, partially offsetting the expected ergonomic benefits of semi-automation. These findings indicate that further mechanical and control-system improvements are necessary to fully realize the potential reductions in human movement and physical workload, particularly for overhead spraying tasks.

These findings emphasize the trade-off between task duration and ergonomic safety including pathways. Humans may be faster in limited settings, but robots reduce physical effort, walking distance, repetitive strain, and injury risk underlining the potential of robotic systems like Nova-S to support workers in physically demanding environments.

While time savings were limited in small-scale tests, robotic assistance is likely to offer great benefits in larger-scale operations. In larger rooms or multi-story buildings, reductions in pathway distances, prolonged poor postures and repetitive motions could result in significant cumulative decreases in physical strain, highlighting the importance of considering ergonomic impact alongside task duration. Moreover, the robot ensures consistent application of motion and workflow, which may further improve task precision, quality of spraying and reduce errors associated with human fatigue.

Compared to the Nova-S robot used, other models offer a higher degree of automation, which is reflected in the costs of purchase as well as the distribution of tasks. The higher acquisition costs of robotics with a high degree of automation (e.g., the autonomous painting robot from WEIBUILD, see section 2.3) tend to be more affordable for large and wealthy construction companies than for small- and medium-sized ones. More cost-effective spraying robotics solutions therefore represent an opportunity to support small craft businesses with a (partially-)automated solution, thereby increasing the ergonomic protection of their employees and counteracting the existing shortage of skilled workers.

6 Conclusion

This study provides a comprehensive assessment of manual and semi-/ automated wall and ceiling spraying using a digital process twin with motion-captured human data and DHMs. Robotic assistance significantly reduces ergonomic risks, cumulative musculoskeletal load, and worker movement while ensuring consistent coating quality. Although manual spraying can be faster in small-scale settings, it imposes substantial physical strain, particularly for overhead tasks, highlighting the trade-off between speed and occupational safety. Semi-automated and fully automated systems shift primary physical effort to the robot, supporting worker health, retention, and long-term workforce sustainability.

Combining process simulation with ergonomic evaluation, the method applied in this work demonstrates a robust, human-centered framework for assessing construction automation prior to deployment and can be generalized to other construction processes, supporting the purposeful integration of robots into real-world applications. Future studies should investigate larger operational environments and consider the full spraying workflow, including preparatory and follow-up tasks such as masking, paint preparation, and backrolling, to capture the complete impact on efficiency and ergonomics.

Overall, the study illustrates that semi-automated robotic systems not only enhance ergonomic safety but also provide a foundation for optimizing workflow efficiency, improving consistency, and reducing cumulative musculoskeletal load. These insights open opportunities for further research in larger or complex scale environments, multi-operator scenarios, analysis of a higher number of subjects and robot types, consideration of accompanying tasks and the integration of additional ergonomic risk metrics, reinforcing the value of automation in modern industrial workplaces.

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